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RESEARCH ARTICLE

Environmental Science

Optimizing beach nourishment composition for coastal protection in Sri Lanka: Insights from flume experiments

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Abstract: Beach erosion is a significant threat to Sri Lanka's economically and ecologically valuable coastlines, particularly along the Southwest and Western regions. Traditional beach nourishment methods, such as use offshore sand are common but have limitations in terms of durability and recurring costs. This study investigates the potential benefits of incorporating crushed waste glass into offshore sand to enhance erosion resistance and cost-effectiveness towards beach nourishment. This study evaluated four materials; native sand, offshore sand, river sand, and crushed glass, through controlled hydraulic flume experiments and particle size analysis. Offshore sand was the most susceptibile to erosion with a transported sediment volume of 26%, while crushed glass showed superior stability with only 14% erosion. Blends of offshore sand and crushed glass containing 10–20% crushed glass (CG10–CG20) achieved an optimal balance between durability and material cost. The unique compacting properties and smoother surface texture of crushed glass contributed to reduced sediment mobility under wave action. Furthermore, the study highlighted the environmental benefits of utilising locally available glass waste, promoting sustainable waste management while enhancing coastal resilience. These findings provide practical insights for future beach nourishment projects in Sri Lanka, emphasizing the dual benefits of improved performance and ecological responsibility. Future research should focus on validating these results long-term field settings, assessing ecological impacts, and developing scaling methods for broader coastal management applications.

Keywords: Beach nourishment, coastal protection, crushed-glass, flume experiment, offshore-sand.

INTRODUCTION

Beach nourishment in Sri Lanka

Coastline retreat is an evident sign of the vulnerability of low-lying sandy coasts to erosion and sea level rise (Stronkhorst *et al*., 2018). Various solutions can be implemented to mitigate the effect of beach erosion. Among them, beach nourishment is a popular and non – structural solution (Atkinson *et al*., 2020). The importance of beach nourishment in shore protection projects is growing in parallel with environmental concerns associated with traditional hard coastal engineering projects (Hanson *et al*., 2002), and with the contribution to the tourist industry for beach based activities (Pranzini *et al*., 2018). However, nourishment is not a long-term solution to beach erosion as it requires periodic renourishments to enhance effectiveness (Miller, 2018).

The erosive forces of waves, storms, and rising sea levels do not cease after beach nourishment takes place. Beach nourishment is the process of placing additional sediment to a beach or nearshore area widening the beach, and increasing recreational opportunities while enhancing the local economy (Atkinson & Buldock, 2020). According to Climate-ADAPT (2016), beach nourishment can last anywhere from 2 to 10 years before needing to be repeated due to its temporary nature.

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Typically, offshore sand is use for beach nourishment, but other material alternatives such as pebbles or marble waste can be used based on design requirements.

As an island nation in the Indian Ocean, Sri Lanka relies heavily on the coastline for economic, domestic, recreational, and tourism activities. The West coast area, in particular, is a valuable beach zone, due to its strategic location. This, region has a thriving tourism industry with numerous hotels catering to visitors of all sizes. Moreover, the fishing industry provides livelihood for many of the residents in this area such as the Marawila beach (Samarasekera, 2018).

Hence, the life-style of the residents and industries in this area is heavily dependent on the beach. Therefore, the presence of a wide, nourished beach system that can absorb wave energy, and protect upland areas from flooding, and mitigate erosion is essential for this area . Offshore sand is commonly used for beach nourishment projects worldwide. However, the durability of these projects can vary according to environmental conditions and their locations. Beach nourishment is considered to be very expensive and needs to be periodically repeated in order to sustain the nourished beach (Schirmer, 2017). Thus, it is vital for beach nourishment locations to be accurately identified to ensure long lasting protection of the beaches.

Optimizing beach nourishment in Sri Lanka

Beach nourishment involves depositing additional sediments onto a beach or its adjacent nearshore areas to expand the beach, protect structures, and mitigate coastal erosion. However it necessitates periodic replenishment due to sediment erosion over time (Matthieu A de Schipper, 2018; Staudt *et al*., 2022). It serves several purposes aimed at sustainable coastal management and enhancing coastal community resilience, including erosion control, storm damage reduction, and providing recreational and tourism benefits. By restoring sediment, beach nourishment widens shorelines and acts as a buffer against coastal hazards, protecting infrastructure from wave damage and land loss. Nourished beaches absorb wave energy, reducing the impact on coastal structures and minimizing flooding and property damage during storms. They also offer wider and more attractive recreational spaces, attracting tourists and boosting local economies through increased tourism revenue, visitor spending, and job creation.

Additionally, nourished beaches enhance coastal property values by improving aesthetics, providing better access, and reducing erosion risks. In Sri Lanka, beach nourishment has been carried out in various locations such as Kalido Beach, Mt. Lavinia Beach, Uswatakeiyawa, and Marawila, underscoring the importance of these beaches to the economy through tourism and fishing (Maliq, 2015; Jayathilaka, 2023). Given their critical economic role, comprehensive studies on the beach nourishment practices are imperative (Jayathilaka, 2023).

The research objectives of this study are to determine the current state of upgraded offshore sand globally and assess the feasibility of using crushed glass to enhance offshore sand. Specifically, the study aims to investigate the material composition of river sand, natural beach sand, and offshore sand, and evaluate the erodibility of different nourished sands using hydraulic flume model studies. Additionally, the research seeks to identify the most suitable offshore sand-to-crushed glass ratio, considering beach erodibility.

Factors affecting the durability of beach nourishment

The durability of materials in beach nourishment projects is crucial for effective coastal management and is influenced by factors such as particle size and shape, tidal range, wave energy, climate, and compaction techniques. Larger, well-rounded particles offer better stability and resistance to erosion, while smaller particles are more susceptible. The tidal range affects material exposure, requiring resilience to varying submersion levels. High wave energy and climate change exacerbate erosion, transport sediments, and challenge the durability of the nourishment project (Dette *et al*., 2002). Proper compaction techniques, whether mechanical or natural, enhance stability by reducing pore space and increasing inter-particle contact, minimizing erosion and displacement (CEM, 2012).

Glass as waste material in Sri Lanka

Glass, usually regarded as a completely inert recyclable material, is a significant component of municipal solid waste streams across the world. Recycling glass is highly beneficial since improper disposal is an environmental hazard due to its non-biodegradable nature. Glass waste consists of a variety of items including a diverse collection of bottles, jars, windows, and as packaging materials. It is very tough and waterproof, therefore, it is mostly used for packing food and beverages. Based on 2014 data, Sri Lanka had a total of 309 local authorities, comprising 15 Municipal Councils, 37 Urban Councils, and 257 Pradeshiya Sabhas.

These authorities manage solid waste in various ways. However, according to municipal council databases for solid waste collection in Sri Lanka (2005), glass wastes accounted for 2.03% of the total solid waste collection and currently there is no proper method for collecting and recycling glass waste. Figure 1 illustrates the annual waste composition generated in Sri Lanka (CEA, 2014).

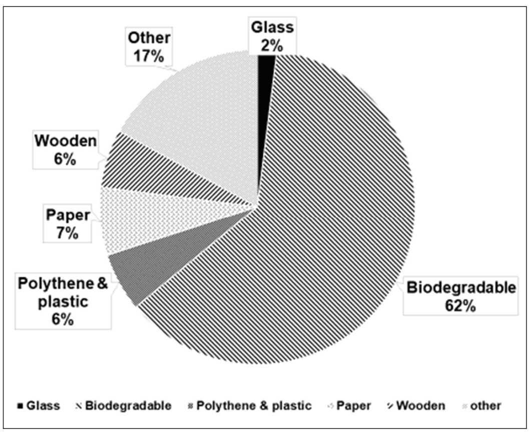


Figure 1: Annual waste composition in Sri Lanka (2014).

Similar studies

Worldwide, only a few similar studies have been conducted. In order for crushed glass 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). And also a study by Edge (2002) expanded on these findings by comparing the geotechnical properties of crushed glass to those of native sand in physical model experiments by using a 3-D wave basin. The basin was divided into two parts containing either crushed glass 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 crushed glass performed similarly to native sand showing little variation in beach profiles. The wave reflection coefficient for the crushed glass was slightly smaller than that for native sand, which the authors suggested indicated that crushed glass absorbs wave energy better than native sand (Edge *et al*., 2002).

In an effort to minimize negative impacts on coastal macrohabitats, a study was conducted to evaluate the effects of glass cullet on various abiotic factors. These factors were, including moisture content, temperature, and gas exchange, need to be similar to those of native sand to avoid disrupting 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%. After a two-month of period, several parameters were measured, such as water temperature, dissolved oxygen, pH, ammonia, nitrites, nitrates, hydrogen sulfide, and organic phosphate levels. Results showed no significant differences in temperature, dissolved oxygen, and pH among the five series. Although small amounts of hydrogen sulfide precipitate began to form in the absence of wave action, this disappeared once wave simulations were introduced. The study concluded that marine water chemistry was not negatively affected by recycled glass cullet contact (Makowski & Rusenko, 2007). In a separate study focusing on the effect of glass cullet on sea turtle nesting, important abiotic variables such as temperature, moisture content (dew point temperature and relative humidity), and respiratory gas exchange were measured. These variables are crucial for the sex ratios and survivability of sea turtle embryos. Simulated nesting boxes were filled with either 100% native sand (control) or sand/glass mixtures of 75%/25%, 50%/50%, and 25%/75%. Some measurements were taken over two nesting seasons, which were March through May and June through August. Analysis showed that simulated nests containing glass cullet had average temperatures (27.0–31.4°C) within the acceptable incubation range for sea turtles. Moisture content readings showed no significant differences from the beach sand controls. Similarly, high concentrations of oxygen (> 20.0%) were recorded in all experimental nests containing glass cullet, with no significant variations from the beach sand controls (Makowski *et al*., 2008).

MATERIALS AND METHODS

The methodology (see flow diagram Figure 2) involves collecting data from research papers, books, websites, and the Coastal Conservation and Coastal Resource Management Department (CC and CRMD). Samples were collected from the beaches of Kalutara (Kalu river), Panadura, Moratuwa, crushed glass, and offshore sand. Each sample was sieved to obtain the D_{50} value. Design values were calculated using scaling laws (geometric, material property, wave generation). Samples were prepared by varying the proportions of crushed glass and traditional sand to test the hypothesis that incorporating crushed glass improves erosion resistance and durability of beach nourishment materials. Sediment transportation and other relevant measurements were taken using a flume apparatus. The process was repeated for all samples, and the results were analyzed and compared to draw conclusions.

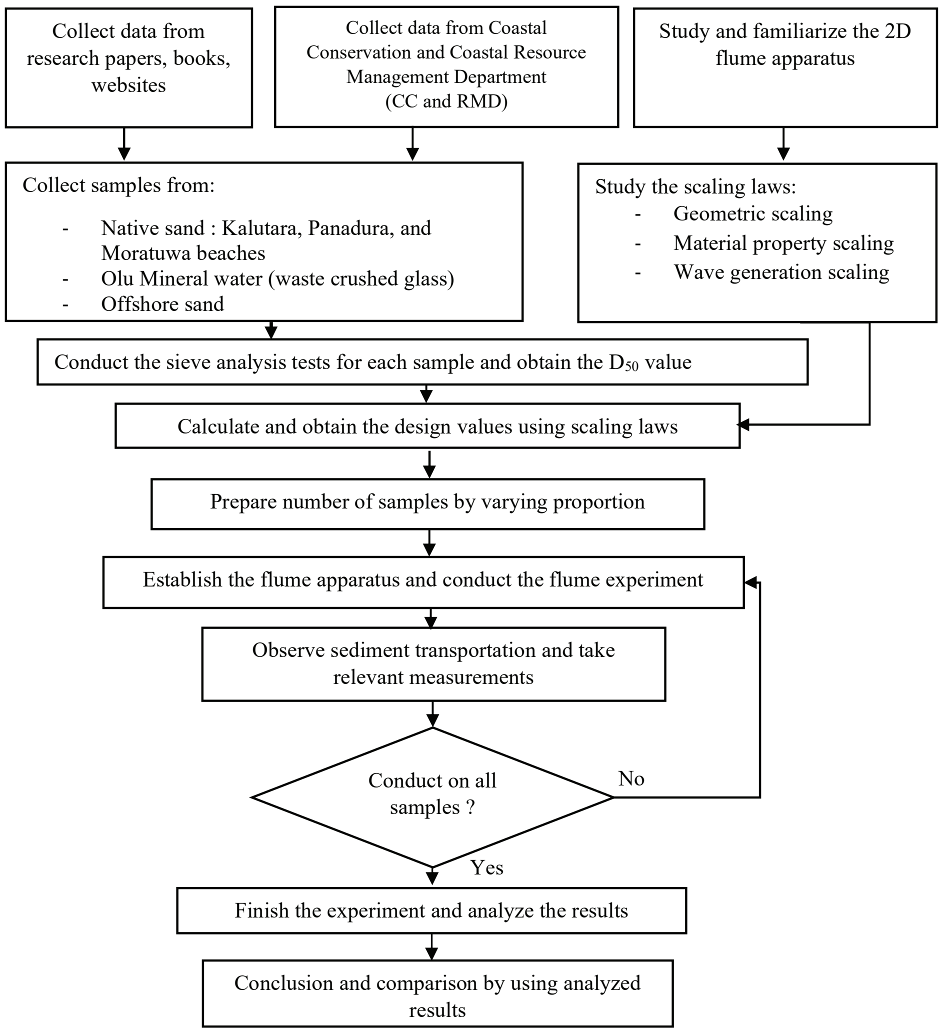


Figure 2: Methodology

Sample collection

The choice and provision of suitable materials for the model experiments affect the accuracy and reliability of the results. The four types of samples collected were:

- Native sand
- Offshore sand
- River sand, and
- Crushed glass

Five native sand samples were collected from the beaches of Kalutara, Moratuwa and Mount Lavinia. Offshore sand samples were collected from the Muthurajawela offshore sand banks. A large sample of offshore sand was collected from sand banks that belong to "*Sanstha Weli*", after obtaining permission. River sand samples were collected from the banks of the Kalu river.

The crushed glass sample was obtained from, Liquid Island (Pvt) Ltd., Narahenpita. The glass was carefully processed, to ensure that it was crushed to the desired particle size range and free from any contaminants. It was important to select a supplier that consistently supplied crushed glass with the required characteristics for the experiment. Quality control procedures were implemented to verify the suitability and quality of the acquired crushed glass. Glass bottles were crushed using a crusher at the company location to obtain the crushed glass.

Laboratory experiments

Grain size analysis

A field sample was used to determine the grain size and distribution in the experimental planning. These values were determined empirically after laboratory analysis of sediments collected from the corresponding coastal terrain. The study improved the reliability of the experiment by implementing the right material quality criteria. This implies that results obtained in the laboratory study matched with those observed in the natural beach environment. This enables the tracking of the behavior of the materials within an actual sediment mixture. Each sample of 2 kg was tested using the sieve analysis test with standard sieves, to determine particle size distribution and plotted to calculate the D_{50} value.

Wave flume experiment

The flume experiment is a controlled laboratory investigation used to study fluid flow in an open channel. It includes a water supply system that pumps water into the channel at a controlled rate, an inlet section for smooth flow, and flow control mechanisms such as gates or weirs. For instance, sediment transport studies may involve the addition of sediment particles to the water to observe their movement and deposition patterns. In the study, a wave generation system capable of producing a wide range of wave conditions was utilized. This system allows for the replication of realistic wave processes and the evaluation of beach nourishment materials under different wave scenarios.

Figure 3 shows the wave flume apparatus with a wave paddle and a wave generation control unit. The procedure for operating the wave flume is outlined below. First the apparatus is checked to ensure all the components such as the motor pump, gates etc are functioning properly. Then the required flume area is separated using a gate, which is sealed using modeling clay to ensure it is waterproof.

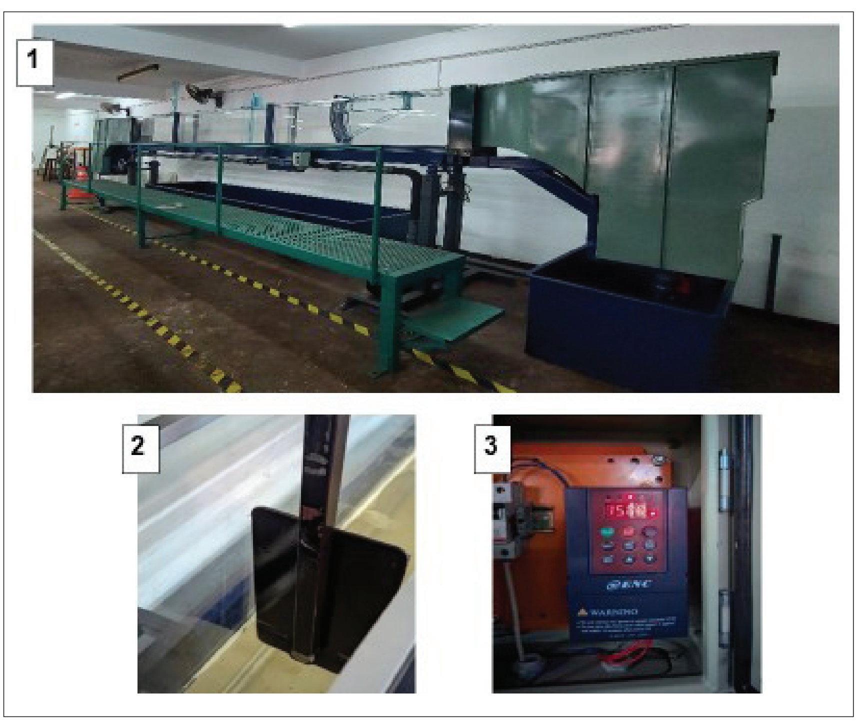


Figure 3: (1): Wave flume apparatus, (2): wave paddle, (3): wave generation control unit, Model: Hydraulic flume: HLE-100-HF-5000/150/500; preparation for experimental setup is described in the text.

Measuring lines are marked using masking tape for reference. Thereafter, the flume is filled with sediment at a 1:5 ratio to establish the desired slope. The inverter is powered on, and the frequency is set to 10 Hz. Water is added to the flume to a level of 20 cm. The inverter is started and the test is run to settle the beach slope. After a few minutes the beach slope is established and it may vary slightly. The experimental duration is set at 15 minutes. The experiments were conducted capturing the initial shape of the beach model and the slope. The inverter is stopped and the experiment results are observed. The shape of the beach (model) and the slope are adjusted as required and the experiment is repeated for two more additional trials per sediment sample. Once a sample is tested the above procedure is repeated for the remaining samples.

Scaling laws

To ensure the accuracy of the experiments, it is crucial to apply scaling laws. Specifically, geometric scaling, wave generation scaling, and material property scaling are fundamental principles that guide the experimental process. By referring to the following equations (Dalrymple, 1991), the deep sea wave length is calculated from equation 1. For shallow depths the condition for wave breaking is given by equation 2.

Deep sea wave length $(L_0) = \frac{gT_0^2}{2\pi}$ ...(1)

Where, L_0 = deep sea wave length in meters; T_0 = wave period; g = 9.81 ms^{-2}

$\frac{d_0}{L_0} = 0.7$ (since, for deep sea $\frac{d_0}{L_0} > 0.5$) ...(2)

Where, d_0 = depth at wave breaking point

It is assumed that the model flume will be one-twelfth the size of the prototype (scale factor of 1/12), using scaling laws according to Rijn (2011) and Wang *et al*. (1990). The two free parameters were determined from the scales below. Practical standard ranges were n_h = 1 to 50 and n_{d50} = 1 to 5.

Where, n_h = Depth scale and n_{d50} = Sediment size scale.

$\left(\frac{n_l}{n_h}\right) = (n_h)^{0.28}\,(n_{hd50})^{-0.5}(n_{s-1})^{0.28\text{ to }0.5}$ ...(3)

Where, n_{s-1} = relative density scale

Equation 3 provides a relationship of the distortion scale in a physical model accounting for the median sediment size (n_{hd50}), depth scale (n_h) and relative density scale (n_{s-1}). The range of the distortion scale (n_l/n_h) is between 1 to 2.

$(n_{Tm}) = (n_h)^{0.56}$ ...(4)

Where, n_{TM} = morphological time scale; h_m = model height

Equation 4 gives the relationship between the morphological time scale and model height. For the design, the following standard values were taken by from the above equations.

- $\left(\frac{n_l}{n_h}\right) = 2$
- $n_l = 24$
- $n_h = 12 = \frac{2.5\text{ m}}{h_m}$
- $h_m = 0.208$ m

Then, by using equation 5, which is given in the flume manual HLE-100-HF-5000/150/500, the number of oscillations of the wave generator is calculated.

$NOC = \left(\frac{1}{T_{m\ flume}}\right)$ ...(5)

(Flume manual)

Where, NOC – Number of oscillations of wave generator; Tm fulme = Time taken for one complete rotation of the wave paddle

Cost analysis

The unit price of crushed glass in LKR (PGP Glass Ceylon PLC) and the unit price of offshore sand were considered. Equation 6 was generated based on the unit cost of materials.

$C = Px + Q(100 - x)$ ...(6)

C - Unit cost of CG composition
P - Unit cost of crushed glass
Q - Unit cost of offshore sand
x - Percentage of crushed glass in the composition

Where, P = the unit cost of crushed glass is varied with the amount of material, with transportation cost and electricity cost; Q = the unit cost of offshore sand is varied with the amount of material, with transportation cost and environmental concerns.

Table 1: Proportions of glass material and offshore sand in the mixtures. 5CG represents a mixture of 5% crushed glass and 95% of offshore sand

Proportion sample	Crushed glass percentage	Offshore sand percentage
5CG	5 %	95 %
10CG	10 %	90 %
15CG	15 %	85 %
20CG	20 %	80 %
25CG	25 %	75 %

xCG – Mixture of crushed glass and offshore sand, x- percentage of crushed glass

Sample preparation

Five samples of glass material and offshore sand were mixed according to the proportions shown in Table 1. In addition to these mixed samples, one sample each of river sand, native sand, and glass material were prepared (Table 1).

Figure 4 represents the CG proportion of samples prepared and Figure 5 represents the native sand sample, river sand sample, crushed glass sample and offshore sand sample.

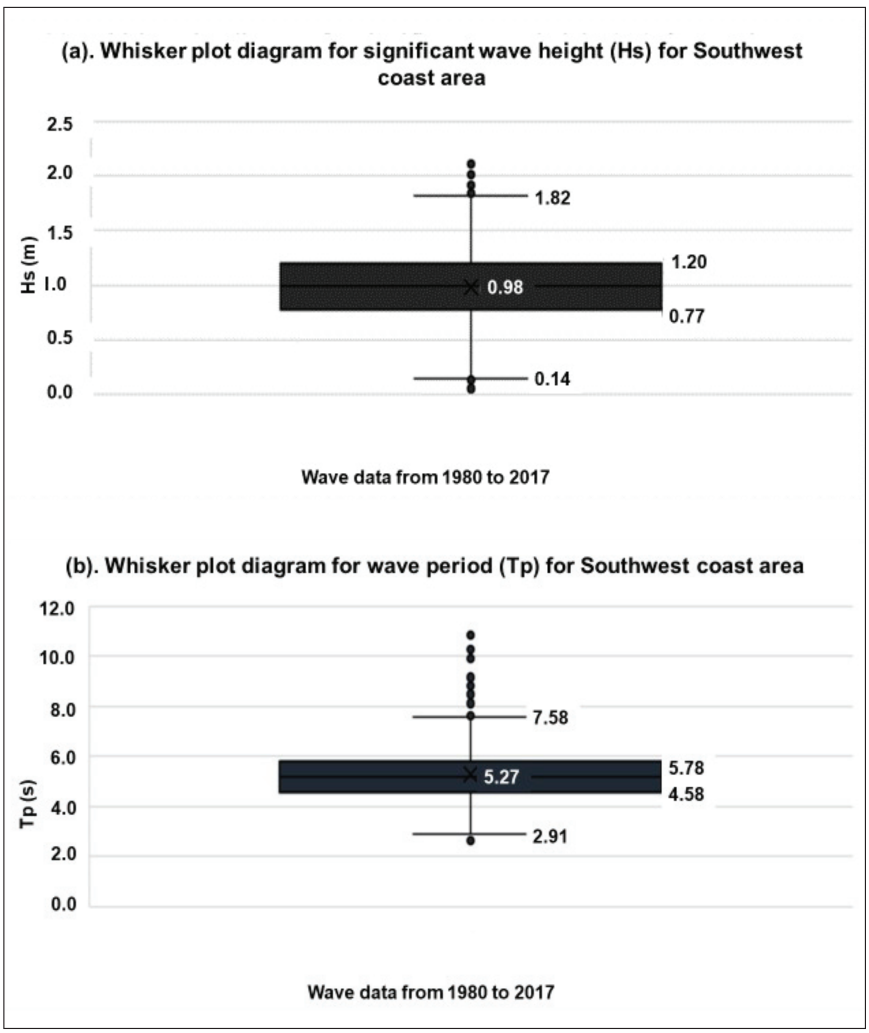


Figure 4: (a) Whisker plot diagram for significant wave height in the Southwest coastal area, and (b) Whisker plot diagram for wave period in the Southwest coastal area

RESULTS AND DISCUSSION

Design values gained from scaling laws

Figure 6 shows the significant wave heights (Hs) and wave periods in the Southwest coastal area. Chronological data of significant wave height (H_s), and wave peak period (T_p) were collected from 1980 to 2017 (Samarasekara, 2019; Samarasekara *et al*., 2022) and the average 3rd quartile (Q_3) was calculated. These were used as design values.

Furthermore it is shown in Figure 6 (a) the significant wave height (Hs) with a median value of 0.98 m. The interquartile range (IQR) spans from 0.77 to 1.20 m, indicating moderate variability in wave heights. The second plot (b) illustrates the wave period (Tp), with a median of 5.27 seconds. The IQR ranges from 4.58 to 5.78 seconds, highlighting the typical wave period variability. The outliers extend from a maximum of 7.58 seconds to a minimum of 2.91 seconds. The average 3rd quartile (Q_3) obtained through graphs were H_s = 1.20m and T_p = 5.8s.

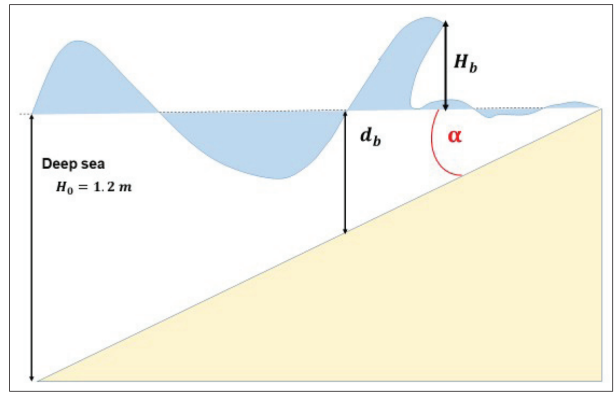


Figure 5: Wave breaking condition and related parameters

Figure 7 represents the conditions of wave breaking and related parameters. It shows that the ratio of wave height to water depth at wave breaking is 0.7 at a shallow depth (Dalrymple, 1991).

$\frac{d_0}{L_0} = 0.7$ (since, for deep sea $\frac{d_0}{L_0} > 0.5$)

Deep sea wave length (L_0) = 53 m (by using equation 1)

Table 2: Depth and height at wave breaking conditions were obtained by referring to wave tables

d_b (m)	L_0 (m)	$\frac{d_0}{L_0}$	$\sqrt{\frac{n_0 C_0}{n_2 C_2}}$	$\frac{d_b}{L_0}$	$\sqrt{\frac{n_0 C_0}{n_1 C_1}}$	H_b (m)	$\frac{H_b}{d_b}$	Condition
1.9	53	0.7	0.9988	0.0358	1.0899	1.31	0.698	0.698 ≤ 0.7

An iterative method was used to determine the depth and height of wave breaking. Table 2 gives the depth and height measurements at the wave breaking condition, by referring to wave tables. The final comparison is made between H_b/d_b and a threshold value of 0.7, showing that 0.698 is less than or equal to 0.7. This shows that the wave height relative to water depth meets the specified threshold. Therefore, the wave breaking depth and height are 1.9 m and 1.31 m, respectively. The calculated wavelength at the wave breaking point is L = 25 m.

Experimental parameters were determined by using the following scaling laws:

- Water depth (h) = 20 cm
- Water depth at wave breaking (h_m) = 16 cm
- Sediment diameter ($d50_m$) = Same as samples
- Experimental slope = 1:5

T_m flume = 1.44 s
NOC = 9.5f (Per minute; as flume manual)
f = 4.4 Hz

Since a frequency of 4.4 Hz produced only very small movements in the waves, a frequency of f = 10 Hz was used for all experimental trials to ensure optimum test procedures. By taking f = 10 Hz, the new design resulted in n_T = 2.56 s. This means, relatively fast waves with a higher frequency were considered.

Sediment characteristics analysis

Design values for sediment characteristics, such as grain size distribution, were utilized to create the experimental design. These values were derived from field observations and sediment sampling in the target coastal area. By incorporating the appropriate sediment characteristics into the experimental setup, the study ensures that the materials used accurately reflect the sediment found in natural beach environments. This enables the evaluation of the materials' behaviour and performance under realistic sediment conditions. To determine the particle size distribution and D_{50} values of the samples, standard sieve analysis test was conducted on the sediment samples collected from the west coast beaches and crashed glass from Liquid Island (Pvt) Ltd. Figure 8 displays the particle size distributions for native sand samples in part (a) and the particle size distribution of offshore sand samples, crushed glass and river sand sample in part (b).

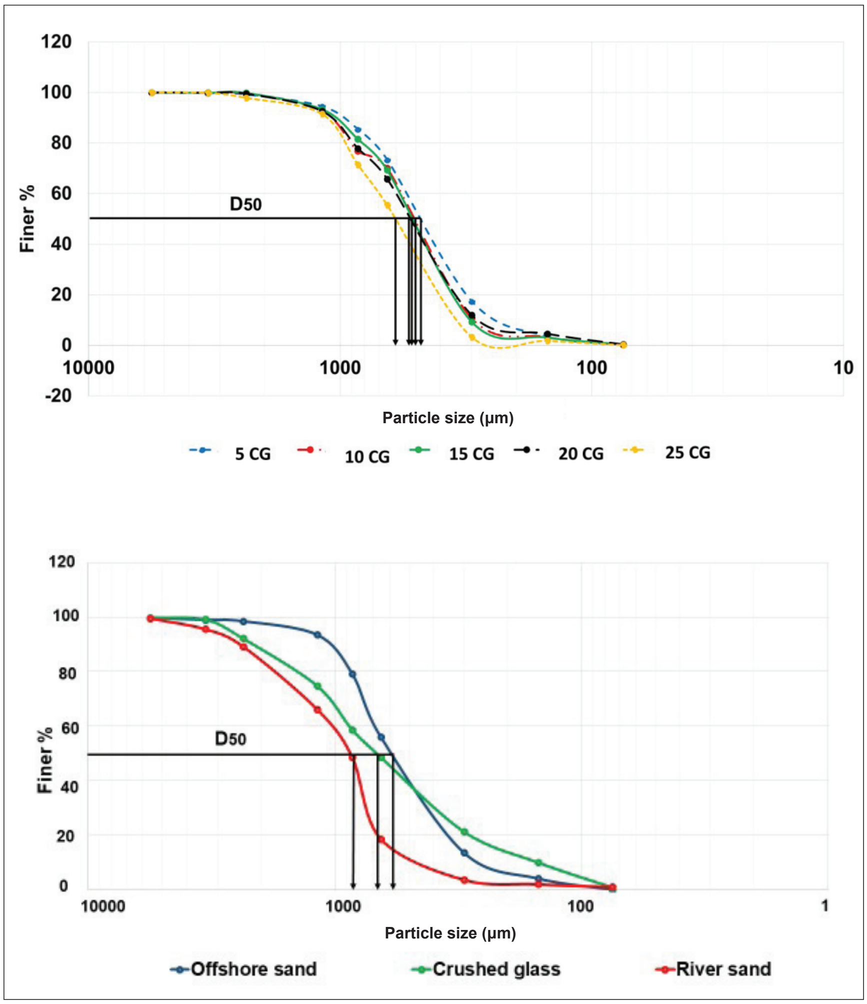


Figure 6: (a) Particle size distribution for five samples of native sand collected from the West coast area, and (b) Particle size distribution for offshore sand, crushed glass and river sand

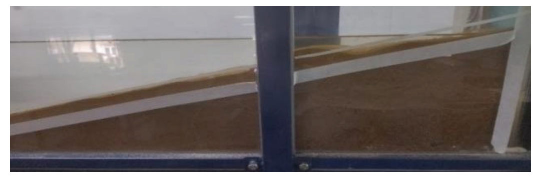
The five native sand samples in Figure 8-(a), each sorted with D_{50} values ranging from 470 to 598 *μm,* indicate a consistent sedimentary environment characterized by similar energy conditions during deposition. The average D_{50} value was 520.6 *μm*. This offshore sand sample is also well sorted and the curve is much smoother resembling a well-curved S-type graph in Figure 8.b. The D_{50} values for the offshore sand sample was 601 *μ*m, for the crushed glass sample was 676 *μ*m, and for the river sand sample was 860 *μ*m.

Flume experiment analysis and results

Sediments were placed in the flume at a 1:5 ratio to establish the slope. Water was added to a depth of 20 cm, and the inverter was set to 10 Hz. The initial shape of the beach model and slope were documented. The inverter was activated, and the experiment was conducted for 15 minutes.

Figure 9 shows the slope before conducting the experiment and the stabilized shapes or slopes after the experiment. Furthermore, Figure 10 shows that the schematic diagram for water level, initial slope of the beach, stabilized beach and erodible length due to wave. Eroded volume is represented as (A) and remaining volume as (B). The eroded lengths and eroded volumes were calculated in Table 3.

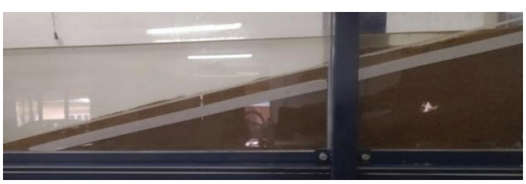
(a) The beach slope before conducting the experiment



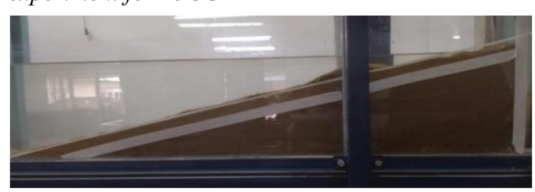
(b) The stabilized shape after conducting the experiment for 5CG

(c) The stabilized shape after conducting the experiment for 10CG

(d) The stabilized shape after conducting the experiment for 15CG



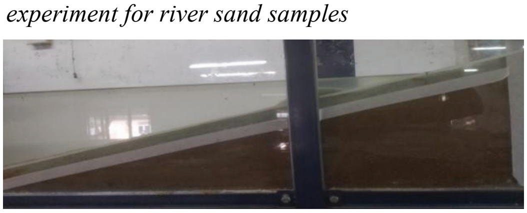
(e) The stabilized shape after conducting the experiment for 20CG



(f) The stabilized shape after conducting the experiment for 25CG

(g) The stabilized shape after conducting the experiment for river sand samples

(h) The stabilized shape after conducting the experiment for offshore sand samples



(i) The stabilized shape after conducting the experiment for crushed glass samples

(j) The stabilized shape after conducting the experiment for native sand samples

Figure 7: (a) The beach slope before conducting the experiments (b) to (j). The stabilized shape after conducting the experiment for crushed glass and sand samples.

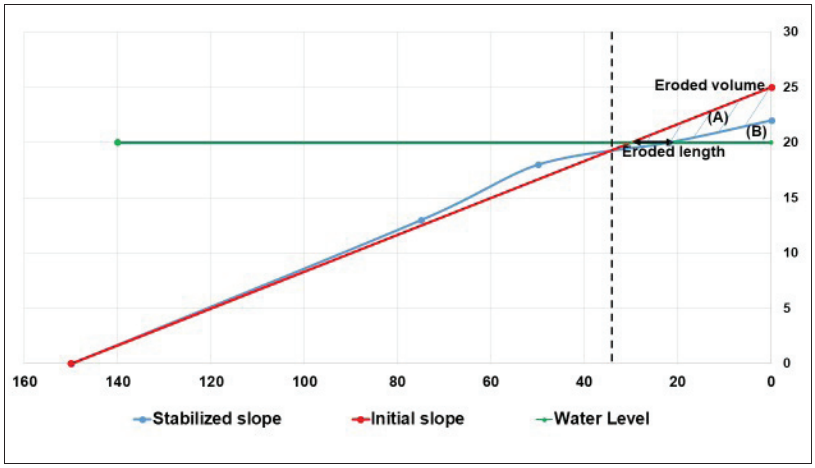


Figure 8: Schematic diagram for water level, initial slope of the beach, stabilized beach and erodible length due to wave action

Table 3: Average eroded length, average eroded volume, unit cost and percentage of eroded volume for each sample

Sample	Average eroded length (cm)	Average eroded volume (A-cm^3)	Unit cost (LKR/m^3)	Percentage of eroded volume (A%-cm^3)
5CG	7.4	581	18575	27
10CG	7.0	526	18650	24
15CG	6.2	461	18725	22
20CG	5.0	392	18800	18
25CG	4.4	358	18875	16
River sand	6.2	525	23750	24
Offshore sand	7.4	570	18500	26
Crushed glass	3.6	302	20000	14
Native sand	6.3	471	-	22

Table 3 gives the average eroded length in cm, average eroded volume in cm^3, unit cost in LKR/m^3 and percentage of eroded volume in cm^3. The correlation coefficient (r) was -0.99, indicating a very strong inverse relationship. The coefficient of determination (R^2) was 0.976, demonstrating that 97.6% of the variability in the measured value is explained by the percentage of crushed glass. The p-value was 0.0016, confirming that the relationship is statistically significant ($p < 0.05$). This suggests that as the proportion of crushed glass content increases, the measured property decreases consistently and predictably. Overall, there is a statistically significant, strong negative linear relationship between the percentage of crushed glass and the measured value.

Sieve analysis and flume tests were conducted to evaluate the properties of the materials. The sieve analysis determined the particle size distribution and D_{50} value of each sample. Flume experiments simulated wave conditions to observe the behavior of different sand and crushed glass mixtures. These experiments provided insights into the stability and erodibility of the nourishment materials. The sieve analysis revealed that native sand and offshore sand had a higher percentage of finer particles compared to river sand and crushed glass. The D_{50} values for each sample were calculated, providing a basis for comparing the suitability of the different materials for beach nourishment. (Figure 8). Larger, well-rounded particles generally offer better stability and resistance to erosion compared to smaller particles. The crushed glass used in this study had a varied particle size distribution but was primarily larger than the fine particles in natural sands. This contributed to the increased erosion resistance observed in the flume experiments. (CEM, 2012)

Proper compaction of nourishment materials is crucial for stability. The study ensured consistent compaction techniques across all samples, which helped isolate the effects of material composition on erosion resistance. The crushed glass mixtures benefited from the inherent density and interlocking properties of glass particles, enhancing stability.

The flume experiments revealed that mixtures containing crushed glass displayed different erosion patterns compared to those with only natural sand. The following trends were observed:

- **Native sand**: Showed moderate erosion, with an average eroded length of 6.3 cm and an average eroded volume of 471 cm³. The eroded volume percentage was 22% (Table 3)
- **Offshore sand**: Demonstrated similar erosion characteristics to native sand, with an average eroded length of 7.4 cm and an average eroded volume of 570 cm³ having 26% eroded volume (Table 3)
- **River sand**: The erosion resistance compared to offshore sand was lower, with an average eroded length of 6.2 cm and an average eroded volume of 525 cm³. Furthermore, the eroded volume percentage was 24%. (Table 3)
- **Crushed glass:** Showed minimal erosion, with an average eroded length of 3.6 cm and an average eroded volume of 302 cm³. This had the lowest eroded percentage of 14% (Table 3)
- **Crushed glass and offshore sand mixtures**: The erosion resistance increased with higher percentages of crushed glass. For instance, the 25% crushed glass mixture (25CG) had the lowest average eroded length of 4.4 cm and an average eroded volume of 358 cm³. The percentage of eroded volume varied from 16% (for CG25) to 27% (for CG5). (Table 3)

Additionally, Table 3 illustrates the relationship between the unit cost of CG compositions and the eroded volume of relevant compositions. It shows a linear increase from CG5 to CG25, with costs ranging from 18,575 LKR/m³ to 18,875 LKR/m³. This suggests that higher CG compositions incur higher unit costs. The eroded volume decreases from 581 cm³ for CG5 to 358 cm³ for CG25. This indicates that higher CG compositions result in lesser erosion, suggesting better durability. The trade-off between cost and durability, shows that higher CG compositions are more expensive, but offer better resistance to erosion (Table 3). The decreasing eroded volume trend underscores the improved performance of higher CG compositions in minimizing erosion, despite their increased cost. This information is critical for decision-making in optimizing beach nourishment compositions for coastal protection.

Environmental and economic considerations

Incorporating crushed glass in beach nourishment projects not only addresses the issue of coastal erosion but also provides an environmentally friendly solution for managing glass waste. Glass is a non-biodegradable material that poses environmental hazards if not properly managed. Utilizing it in coastal protection projects aligns with sustainable waste management practices (Griggs, 2023). Economically, crushed glass can be a cost-effective alternative to traditional sand sources, especially in regions where sand mining is restricted or expensive. The availability of waste glass in urban areas of Sri Lanka makes it a viable option for large-scale beach nourishment projects.

Challenges in using crushed glass

Using crushed glass for beach nourishment in Sri Lanka poses several challenges. Environmental concerns include potential habitat disruption and the risk of chemical leaching (Kenoin, 1997). Logistical issues involve the collection, processing, and transportation of glass, which can be costly and complex since currently there is no proper method to collect waste glass in the country. Economically, the high initial costs and the need for a sustainable market are significant hurdles. Social acceptance and regulatory compliance are also critical, as public perception and legal standards must be addressed. Additionally, technical challenges such as performance monitoring and adaptation to local conditions must be overcome to ensure the effectiveness and safety of using crushed glass in coastal protection efforts because of the lack of technology in Sri Lanka (Saja *et al*., 2022).

Future availability of crushed glass

Sri Lanka generates approximately 7000 MT of solid waste per day. Of this, glass waste accounts for 2.03% (i.e., around140 MT) and annually is about 50,000 MT – 55,000 MT (Darmasiri, 2019).

Study limitations

The study has several notable limitations, as sample collection was geographically restricted to specific beaches, potentially overlooking broader sediment variability across Sri Lanka's coastline. The data used for scaling laws was limited to the Southwest coastal area. Further, laboratory experiments were conducted under controlled conditions, which might not fully represent the complex and dynamic nature of actual coastal environments. The study utilized a single wave generation system, limiting the scope of wave conditions tested and there was no measurement gauge to measure the wave conditions generated. It also focused on a limited set of materials and short-term observations, without addressing long-term erosion effects or comprehensive economic and ecological impacts.

CONCLUSION

The inclusion of crushed glass in beach nourishment compositions presents a promising approach to enhancing coastal protection in Sri Lanka. The study demonstrates that crushed glass can enhance the erosion resistance of nourishment materials, providing a viable alternative to traditional sand sources. Based on these findings, offshore sand appears to have the least performance in terms of sediment transport and potential durability among the materials. However, the results suggest that mixtures with higher percentages of crushed glass exhibit superior erosion resistance compared to traditional sand materials. These findings have significant implications for future coastal management strategies, offering a sustainable and cost-effective solution to combat coastal erosion while addressing waste management challenges. The integration of crushed glass in beach nourishment compositions offers a sustainable and effective solution for coastal protection in Sri Lanka. Referring to Table 3, the best optimized beach nourishment composition for coastal protection in Sri Lanka is between CG10 and CG20. Therefore, by adopting innovative and environmentally friendly approaches, Sri Lanka can strengthen its coastal defenses and ensure the long-term resilience of its coastal ecosystems and communities. The promising results of this study open several avenues for future research. Long-term monitoring of beach nourishment projects using crushed glass will be essential to assess durability and ecological impacts over time. Collaboration with international researchers and institutions can also provide valuable insights and facilitate the exchange of best practices in coastal management. Future research should focus on long-term field studies to validate laboratory findings and assess ecological impacts. Additionally, exploring optimal crushed glass and sand proportions for different coastal settings can further refine and maximize benefits. Finally, expanding geographic sampling and wave condition testing will strengthen understanding and application of crushed glass in diverse coastal environments.

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REFERENCES

Atkinson, A. L., and Baldock, T. E. (2020). Laboratory investigation of nourishment options to mitigate sea level rise induced erosion. *Coastal Engineering*, *161*, 103769. https://doi.org/10.1016/ j. coastaleng.2020.103769

Beach nourishment (U.S. National Park Service). (2020). Nps.gov. https://www.nps.gov/articles/beachnourishment.htm

Central Environmental Authority. (2014). Annual report 2014. Central Environmental Authority of Sri Lanka. https://www.parliament.lk/uploads/documents/paperspresented/annual-report-central-environmental-authority-2014.pdf

Dalrymple, R. W. (1991). Coastal sedimentary environments (2nd ed.). Springer-Verlag.

de Oliveira, V. N., Gitirana, G. F. N., Jr., dos Anjos Mascarenha, M. M., Sales, M. M., Varrone, L. F. R., & da Luz, M. P. (2021). An enhanced flume testing procedure for the study of rill erosion. *Water*, *13*(21), Article 2956. https://doi.org/10.3390/w13212956

de Schipper, M. A., Luijendijk, A. P., van der Molen, J., Stive, M. J. F., & Ranasinghe, R. (2018). A field-scale experiment on the effects of a mega-nourishment on coastal safety. *Coastal Engineering*, *136*, 99–110. https://doi.org/10.1016/j.coastaleng.2018.02.005

Dette, H. H., Larson, M., Murphy, J., Newe, J., Peters, K., Reniers, A., and Steetzel, H. (2002). Application of prototype flume tests for beach nourishment assessment. *Coastal Engineering*, *47*(2), 137–177. https://doi.org/10.1016/s0378-3839(02)00124-2

Dharmasiri, M. L. (2019). Waste management in Sri Lanka: Challenges and opportunities. *Sri Lanka Journal of Advanced Social Studies*, *9*(1), 72–85. https://doi.org/10.4038/sljass.v9i1.7149

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 (pp. 3630–3641). World Scientific.

Finkl, C. W., and Kerwin, L. (1997). Emergency beach fill from glass cullet: An environmentally green management technique for mitigating erosional 'hot spots' in Florida. Proceedings of the 10th Annual National Conference on Beach Preservation Technology, 304–319.

Griggs, G. (2023, March 26). 'Recycling' glass back to sand for beaches? Coastal Care. https://coastalcare.org/2023/03/recycling-glass-back-to-sand-for-beachnourishment/

Guimarães, A., Coelho, C., Veloso-Gomes, F., & Silva, P. A. (2021). 3D physical modeling of an artificial beach nourishment: Laboratory procedures and nourishment performance. *Journal of Marine Science and Engineering*, *9*(6), 613. https://doi.org/10.3390/jmse9060613

Hanson, H., Brampton, A., Capobianco, M., Dette, H. H., Hamm, L., Laustrup, C., Lechuga, A., and Spanhoff, R. (2002). Beach nourishment projects, practices, and objectives—a European overview. *Coastal Engineering*, *47*(2), 81–111.

Jayathilaka, R., Ratnayake, N. P., Wijayaratna, N., & Arulananthan, K. (2023). A review of coastal erosion mitigation measures on Sri Lanka's western coast, an island nation in the Indian Ocean: Current gaps and future directions. *Ocean & Coastal Management*, *242*, Article 106653. https://doi.org/10.1016/j.ocecoaman.2023.106653

Jayathilake, D. (2020). Mount Lavinia beach nourishment project successful – DG Coastal Conservation Dept. https://www.defence.lk/Article/view_article/1679

Kerwin, L. (1997). Potential applications for recycled glass in beach management: Emergency stabilization of "hot spots" in Broward County, Florida (Master's thesis). Florida Atlantic University.

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.

Makowski, C., Finkl, C. W., and Rusenko, K. (2013). Suitability of recycled glass cullet as artificial dune fill along coastal environments. *Journal of Coastal Research*, *29*(4), 772–782.

Makowski, C., Rusenko, K., and Kruempel, C. J. (2008). Abiotic suitability of recycled glass cullet as an alternative sea turtle nesting substrate. *Journal of Coastal Research*, *24*(3), 771–779.

Maliq, R. (2015). Beach nourishment in Sri Lanka. Rukshan Maliq's Blog. https://rukshanmaliq.blogspot.com/2015/01/beach-nourishment-in-sri-lanka.html

Miller, B. (2018). 20 beach renourishment pros and cons. Green Garage. https://greengarageblog.org/20-beach-renourishment-pros-and-cons

Pagán, J. I., *et al*. (2021). Classification of sediment quality according to its behavior in the accelerated particle wear test (APW). *Sustainability*, *13*(5), 2633. https://doi.org/10.3390/su13052633

Pan, S. (2011). Modelling beach nourishment under macro-tide conditions. *Journal of Coastal Research*, (64), 6.

Pranzini, E., Anfuso, G., and Muñoz-Perez, J. J. (2018). A probabilistic approach to borrow sediment selection in beach nourishment projects. *Coastal Engineering*, *139*, 32–35.

Saja, A. M. A., Zimar, A. M. Z., and Junaideen, S. M. (2021). Municipal solid waste management practices and challenges in the southeastern coastal cities of Sri Lanka. *Sustainability*, *13*(8), 4556. https://doi. org/10.3390/su13084556

Samarasekara, R. S. M. (2019). Evaluation of coastal erosion processes and management in a developing country: A case study in Marawila Beach, Sri Lanka (Unpublished master's thesis). The University of Tokyo.

Samarasekara, R. S. M., Gijsman, R., Ganal, C., Mielck, F., Wolbring, J., Hass, H. C., Goseberg, N., Schüttrumpf, H., Schlurmann, T., & Schimmels, S. (2022). The sustainability of beach nourishments: A review of nourishment and environmental monitoring practice [Preprint]. OSF. https://doi.org/10.31223/osf.io/knrvw

Samarasekara, R. S. M., Sasaki, J., Jayaratne, R., Suzuki, T., Ranawaka, R. A. S., & Pathmasiri, S. D. (2018). Historical changes in the shoreline and management of Marawila Beach, Sri Lanka, from 1980 to 2017. *Ocean & Coastal Management*, *165*, 370–384. https://doi.org/10.1016/j.ocecoaman.2018.09.012

Schirmer, M. (2017). The sustainability of beach nourishments: A review of nourishment and environmental monitoring practice. *Journal of Coastal Conservation*, *21*(5), 873–884.

Staudt, F., Gijsman, R., Ganal, C., Mielck, F., Wolbring, J., Hass, H. C., Goseberg, N., Schüttrumpf, H., Schlurmann, T., & Schimmels, S. (2021). The sustainability of beach nourishments: A review of nourishment and environmental monitoring practice. *Journal of Coastal Conservation*, *25*(2), Article 34. https://doi.org/10.1007/s11852-021-00801-y

Staudt, F., Gijsman, R., Ganal, C., Mielck, F., Wolbring, J., Hass, H. C., Goseberg, N., Schüttrumpf, H., Schlurmann, T., & Schimmels, S. (2022). The sustainability of beach nourishments: A review of nourishment and environmental monitoring practice [Preprint]. OSF. https://doi.org/10.31223/osf.io/knrvw

Stronkhorst, J., Huisman, B., Giardino, A., Santinelli, G., & Mulder, J. (2018). Sand nourishment strategies to mitigate coastal erosion and sea level rise at the coasts of Holland (The Netherlands) and Aveiro (Portugal) in the 21st century. *Ocean & Coastal Management*, *156*, 266–278. https://doi.org/10.1016/j.ocecoaman.2017.11.017

The Coastal Engineering Manual. (2006). U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers. (2012). Coastal engineering manual (EM 1110-2-1100). U.S. Army Engineer Research and Development Center.

van Rijn, L. C., Tonnon, P. K., Sánchez-Arcilla, A., Cáceres, I., & Grüne, J. (2011). Scaling laws for beach and dune erosion processes. *Coastal Engineering*, *58*(7), 623–636. https://doi.org/10.1016/j.coastaleng.2011.01.008

Wang, H., Toue, T., and Dette, H. (1990). Movable bed modeling criteria for beach profile response. In Proceedings of the 22nd ICCE (Vol. 3, pp. 2566 2579). Delft, The Netherlands.