

Article

Xanthan Gum-Stabilized Soils as a Sustainable Material for Coastal Restoration: Mechanical and Erosion Performance

Junjie Li, Bin Zhang and Kejun Wen *

Department of Civil and Environmental Engineering, Jackson State University, Jackson, MS 39217, USA; junjie.li@students.jsums.edu (J.L.); bin.zhang@students.jsums.edu (B.Z.)

* Correspondence: kejun.wen@jsums.edu; Tel.: +1-601-979-1094

Abstract

This study evaluates the feasibility of 1% xanthan gum-treated sandy soils (natural sand and recycled glass sand) as sustainable materials for coastal restoration applications. The long-term durability and water erosion resistance of treated soils were systematically investigated through wet–dry cycling, pH durability testing, Erosion Function Apparatus (EFA) tests, and rainfall simulation experiments. Particular attention was given to the combined use of xanthan gum and recycled glass sand (RGS) as an environmentally friendly alternative to conventional geomaterials. The results demonstrated that soil gradation and soil type significantly influenced the performance of the xanthan gum–soil matrix. Xanthan gum-treated pure recycled glass sand specimens lost their structural integrity within one day of water immersion, whereas xanthan gum-treated natural sand specimens resisted water erosion for up to 20 days. In contrast, xanthan gum-treated mixed sand (XTMS), prepared using RGS and natural dredged sand, exhibited significantly improved durability and erosion resistance. Although the unconfined compressive strength (UCS) of XTMS decreased by approximately 70% after three wet–dry cycles, accompanied by only 0.21% soil loss, the specimens maintained structural integrity throughout the testing period. The UCS results further indicated that XTMS exhibited relatively good durability under artificial seawater conditions but experienced significant degradation under acidic and alkaline environments. EFA results classified XTMS as having medium erodibility, representing a substantial improvement in water erosion resistance compared to untreated sand. In addition, rainfall simulation tests demonstrated that XTMS specimens were capable of withstanding very heavy rainfall conditions (120 mm/h) with minimal soil loss. Overall, the findings suggest that the combined use of xanthan gum and RGS provides a promising, sustainable, and environmentally friendly approach for improving soil stability and erosion resistance in coastal restoration applications.

Keywords: biopolymer; coastal restoration; sustainable approach; environmentally friendly materials



Academic Editor: Shibao Chen

Received: 21 May 2026

Revised: 29 June 2026

Accepted: 29 June 2026

Published: 2 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Coastal areas contain high population densities, major economic assets, and critical ecological resources, making them particularly susceptible to erosion, flooding, and the impacts of rising sea levels [1,2]. Coastal regions face severe flood-related risks worldwide, as nearly 600,000,000 people are exposed to coastal flooding, and insured residential and commercial assets in these areas exceed \$13 trillion [3,4]. In recent decades, increasing storm intensity, rising sea levels, and accelerated shoreline erosion have caused severe economic

and environmental losses in coastal communities [5]. Traditional shoreline protection methods, such as seawalls and bulkheads, have been widely used to mitigate erosion; however, these hard engineering approaches often disrupt coastal ecosystems, reduce biodiversity, and limit natural shoreline functions, including nutrient filtration and carbon sequestration [6,7]. As a result, there is growing interest in sustainable and nature-based solutions for coastal restoration and erosion mitigation.

Biopolymers have recently emerged as promising sustainable alternatives to conventional soil stabilizers because of their biodegradability, renewability, and low environmental impact [8,9]. Among various biopolymers, xanthan gum has attracted significant attention due to its strong binding capability, high viscosity, and ability to improve soil strength and erosion resistance even at low concentrations. Previous studies demonstrated that xanthan gum-treated soils can achieve substantial improvements in compressive strength and hydraulic erosion resistance compared to untreated soils or even cement-treated materials [10,11]. Lee et al. [12] investigated pier scour prediction using the SRICOS approach under river hydrograph conditions. A 1 m thick layer of xanthan gum–sand mixture was applied to the riverbed, and the simulation results demonstrated that xanthan gum treatment could effectively reduce scour development. In particular, increasing the xanthan gum concentration extended the time required to reach a 1 m scour depth by as much as 7.9-fold.

In addition, the use of recycled materials, such as recycled glass sand (RGS), offers additional environmental benefits by reducing waste disposal and decreasing the consumption of natural sand resources. Akoğuz [13] demonstrated that waste glass can be mixed with sand and reused as a soil improvement material. Although the treated sand showed improved strength, wet–dry cycling caused noticeable disintegration, suggesting that durability under repeated wetting and drying should be further considered. This highlights the potential of RGS as an alternative to natural sand in civil engineering applications. Therefore, the combined application of xanthan gum and RGS offers a sustainable strategy for reducing landfill disposal pressure, conserving natural sand resources, and developing environmentally friendly engineering materials. This study also provides new insight into the use of biopolymers for improving waste-derived materials and broadens their potential applications in sustainable geotechnical engineering.

One of the major limitations preventing the field implementation of biopolymer-treated soils is the insufficient understanding of their long-term durability under harsh environmental conditions. Most previous studies primarily focused on short-term mechanical performance, while the effects of prolonged water exposure, wet–dry cycles, seawater conditions, and pH variations remain poorly understood [14–16]. Furthermore, studies investigating the erosion resistance of sands with xanthan gum treatment under realistic coastal conditions, such as hydraulic scour and heavy rainfall events, are still limited. The interactions between xanthan gum and RGS are particularly important because recycled glass particles are relatively smooth and chemically inert, which may significantly influence the formation and durability of the biopolymer–soil matrix.

Therefore, this study aims to evaluate the feasibility of xanthan gum-treated RGS for sustainable coastal restoration applications. The innovative aspect of this research lies in the integration of RGS with xanthan gum treatment and the comprehensive evaluation of its long-term durability and erosion resistance under multiple environmental conditions relevant to coastal systems. UCS tests were conducted to evaluate the mechanical behavior of treated soils under wet–dry cycling, seawater exposure, and acidic and alkaline environments. In addition, Erosion Function Apparatus (EFA) tests and rainfall simulation experiments were performed to investigate the hydraulic erosion resistance and slope stability performance of the treated materials. This study provides new insight into the

durability mechanisms of xanthan gum-treated recycled geomaterials and demonstrates their potential as sustainable and environmentally friendly materials for coastal restoration and erosion mitigation.

2. Study Area

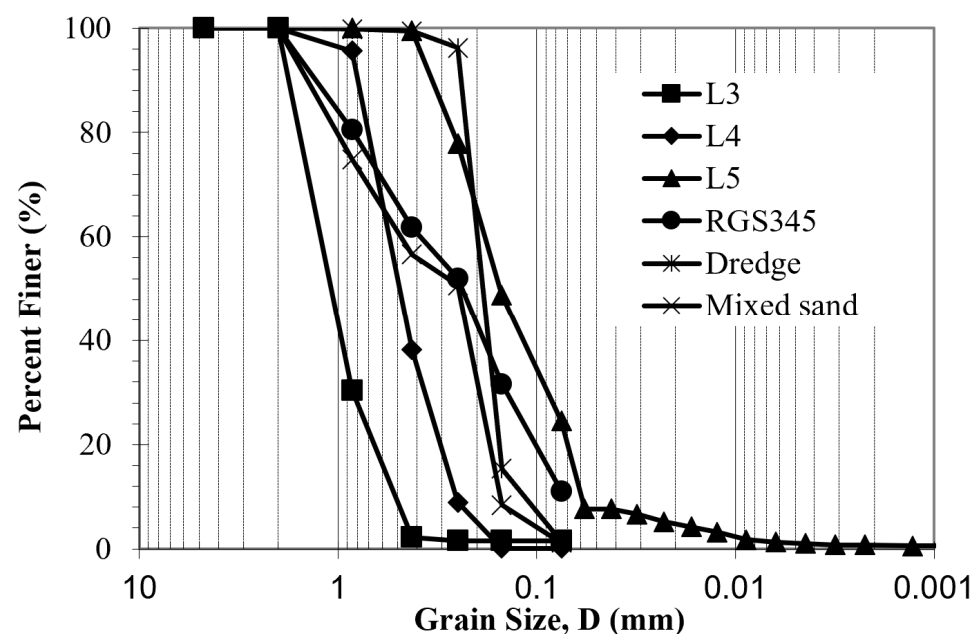
The study area is located in Jackson, Mississippi, USA, which has a humid subtropical climate characterized by hot summers, mild winters, and abundant rainfall throughout the year. According to the NOAA/NCEI U.S. Climate Normals [17], Jackson receives an average annual precipitation of approximately 59.15 in. (1502.41 mm). The region experiences strong summer heat, with recorded extreme high temperatures reaching up to 92.1 °F (33.4 °C). Natural wind exposure is generally moderate, with monthly average wind speeds typically ranging from approximately 3.8 to 6.2 mph (1.7–2.8 m/s).

3. Materials and Methods

3.1. Materials

3.1.1. Sand

The RGS was supplied by Glass Half Full (New Orleans, LA, USA) and produced from post-consumer soda–lime glass food collected between July 2021 and July 2022. The collected glass was mechanically crushed and processed into sand- and gravel-sized particles before being separated into different gradation fractions for engineering applications. Three RGS gradations, designated as L3, L4, and L5, were used in this study. Based on the Unified Soil Classification System (USCS), L3 and L4 were classified as poorly graded sand (SP), whereas L5 was classified as silty sand (SM). The particle size distributions of the RGS are presented in Figure 1, and the chemical compositions are summarized in Table 1.



The dredged material used in this study was supplied by Wood Dredging, L.L.C. (Avondale, LA, USA) and obtained from the Mississippi River. The measured organic content of the dredged material was approximately 0.9%. According to the USCS, the dredged material was classified as poorly graded sand (SP). The particle size distribution curve is shown in Figure 1, while the major chemical compositions are summarized in Table 1.

Mixed sand: The RGS and dredged material were combined at a mass ratio of 1:1:2 (i.e., 100 g of L3 RGS, 100 g of L4 RGS, and 200 g of dredged sand) to produce mixed sand. The mixed sand was employed to investigate the influence of naturally occurring biota on the biodegradation behavior of the biopolymer. According to the USCS, mixed sand was classified as poorly graded sand.

RGS345 sand: The RGS345 soil specimen was prepared by mixing glass sands L3, L4, and L5 at a mass ratio of 1:1:2. This proportion was selected to improve the particle gradation. The particle size distribution curve of the RGS345 soil is presented in Figure 1.

3.1.2. Xanthan Gum

Xanthan gum (XG), a naturally derived microbial biopolymer, was used as the stabilizing agent in this study. It is a high-molecular-weight extracellular polysaccharide produced by *Xanthomonas campestris*. The xanthan gum used in this study was supplied by Bio-World (Dublin, OH, USA), with a molecular weight of 933.748. Xanthan gum is widely used in agrochemical formulations due to its pronounced pseudoplastic behavior, good salt tolerance, and ability to enhance suspension stability and viscosity control [18]. The biopolymer consists of a cellulose backbone with trisaccharide side chains composed of mannose and glucuronic acid. Xanthan gum is highly soluble in water and forms viscous gel-like solutions even at low concentrations. Due to its biodegradability, renewability, and strong binding characteristics, xanthan gum has attracted increasing attention as an environmentally friendly soil stabilizer in geotechnical engineering.

3.2. Sample Preparation

Previous studies have shown that a 1% xanthan gum concentration is effective in improving soil strength; therefore, 1% xanthan gum by dry soil mass was used in this study [14]. An aqueous xanthan gum solution was prepared by dissolving xanthan gum powder in deionized (DI) water at room temperature. As xanthan gum undergoes self-gelation without requiring any external chemical reaction, the prepared solution was directly mixed with the sand to form a homogeneous biopolymer–sand mixture. The mixture was then compacted into cylindrical molds for subsequent curing. During compaction, the mixture was placed in 3 successive layers. The surface of each layer was lightly scarified to enhance interlayer bonding and ensure a continuous soil–biopolymer matrix.

Each specimen was prepared with a target mass of approximately 160 ± 5 g. The specimens had a cylindrical geometry, measuring 38.1 mm in diameter and 76.2 mm in height, which provided a height-to-diameter ratio of 2:1. All samples were prepared following the standard Proctor compaction procedure in accordance with ASTM D698 [19] to ensure reproducible density and compaction conditions. This approach promotes uniform distribution of the biopolymer within the soil matrix and minimizes voids, ensuring that subsequent mechanical and hydraulic testing accurately reflects the effects of xanthan gum treatment.

All specimens were cured under laboratory conditions prior to testing. Unless otherwise specified, all tests were conducted in triplicate, and the average values were reported to minimize experimental variability and improve the reliability of the results.

3.3. Methods

3.3.1. Unconfined Compressive Strength (UCS) Test

Unconfined compressive strength (UCS) tests were conducted to evaluate the mechanical behavior of xanthan gum-treated soils under different environmental conditions. The UCS tests were performed in accordance with ASTM D2166 [20]. The axial strain rate was controlled at 1.5%/min during testing. All specimens were tested in triplicate, and the average UCS values were reported.

3.3.2. Wet–Dry Cycle Test

Wet–dry cycle tests were performed to evaluate the long-term durability of xanthan gum-treated soils under repeated environmental exposure. The testing procedure was modified from ASTM D559 [21] to simulate more severe weathering conditions.

In each cycle, fully dried specimens were submerged in distilled water for 1 day to allow complete water absorption and then oven-dried (105 °C) for another 1 day to achieve full dehydration. The procedure was repeated 3, 6, 9, 12, and 15 times. After each cycle, specimen weight loss and visual changes were recorded, and UCS tests were conducted to evaluate the variation in mechanical performance.

3.3.3. pH Durability Test

To investigate the environmental durability of xanthan gum-treated soils under chemically aggressive conditions, specimens were immersed in acidic solution (pH = 3), alkaline solution (pH = 10), and artificial seawater environments (pH = 8.2). After complete drying, the specimens were placed in each solution and maintained for immersion periods of 3, 7, 14, and 28 days.

After each immersion period, the specimens were oven-dried at 105 °C for 24 h prior to UCS testing. Changes in specimen mass and compressive strength were recorded to evaluate the effects of pH conditions and seawater exposure on the durability of the xanthan gum–soil matrix.

3.3.4. Erosion Function Apparatus (EFA) Test

The erosion resistance of xanthan gum-treated soils was evaluated using an Erosion Function Apparatus (EFA). The EFA test is commonly used to quantify the erosion behavior of soils under controlled hydraulic flow conditions.

In this study, an HM-5940 Erosion Function Apparatus was employed (Humboldt Mfg. Co., Elgin, IL, USA). During testing, the specimen was exposed to controlled water flow velocities while maintaining approximately 1 mm protrusion from the sample holder. The erosion rate was measured at different flow velocities (0.3, 0.6, 1, 1.5, 2, 3, 4.5, 6 m/s), and the velocity–erosion rate relationship was used to determine erosion behavior and critical shear stress. The erosion resistance classifications were determined based on the erosion categories proposed by Briaud [22]. The EFA tests were conducted to compare the hydraulic erosion resistance of untreated and xanthan gum-treated soils.

3.3.5. Rainfall Simulation Test

To simulate coastal storm-induced rainfall, rainfall tests were carried out to compare the erosion behavior and hydraulic stability of XTMS with those of untreated mixed sand under extreme precipitation conditions. During large-scale model preparation, a xanthan gum gel solution was obtained by gradually dissolving xanthan gum powder in DI water. The RGS and dredged material were then mixed with the xanthan gum gel by a mechanical mixer to form a homogeneous mixture. The treated soil was compacted into a wooden mold (4 × 4 × 2 ft) in 3 layers using a mechanical compactor (H320-E Plate Compactor, Lowe's

Companies, Inc., Mooresville, NC, USA). Each layer was compacted for approximately 10 min to ensure uniform density and bonding.

Control specimens without xanthan gum were fabricated following the same preparation method. All specimens were then exposed to outdoor conditions for 7 days prior to rainfall testing. As illustrated in Figure 2, the rainfall simulation was carried out under an applied rainfall intensity of 120 mm/h. A shower head was used as the rainfall simulator. The specimen was placed on an inclined plate at an angle of 27° , and water was applied from a height of 1.0 m above the specimen surface. This intensity was selected to approximate an extreme storm event. During testing, surface erosion behavior, runoff development, and slope stability were visually monitored and recorded to evaluate the rainfall resistance performance of the treated soils.

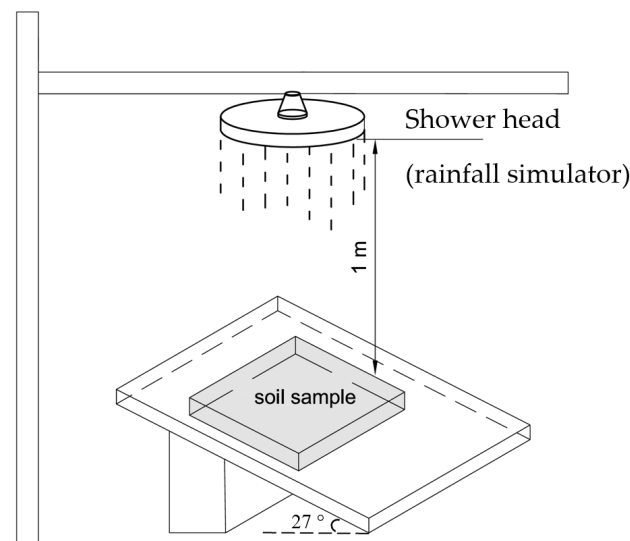


Figure 2. Rainfall Simulation Testing Model.

4. Results

4.1. Optimal Initial Moisture Content

In general, the UCS increased with increasing moisture content until reaching an optimum value, after which the strength decreased or remained relatively stable. For most recycled glass sand samples, the optimum mixing moisture content $(\omega_m)_{opt}$ ranged between 18% and 30%, depending on the gradation and fine content. By comparison, the RGS345 specimen stabilized with xanthan gum exhibited its highest UCS under the lowest moisture content, while the 15% $(\omega_m)_{opt}$ sample showed poor workability during sample preparation. Compared with natural sand, the treated RGS generally required a higher $(\omega_m)_{opt}$, particularly in the case of L5. This behavior may be related to the higher number of fine particles in the recycled glass sand. Fine particles provide a larger specific surface area, which requires more water and xanthan gum gel to achieve effective particle coating and bonding. As a result, samples containing more fines required higher moisture contents to develop optimal strength.

As shown in Figure 3, the peak UCSs of xanthan gum-treated RGS and natural sand were relatively similar, while the mixed sand showed noticeably higher strength. The mixed sample achieved a peak UCS of approximately 2200 kPa at around 18% moisture content. This improvement may be attributed to the formation of a xanthan gum–fines matrix, which enhanced particle bonding, while the coarse particles provided additional frictional resistance. In comparison, the RGS345 sample without fine particles exhibited lower UCS values, suggesting that fine particles positively contributed to strength development. These results are consistent with previous findings reported by Chang et al. [10], who

observed that XG generally performs better in well-graded soils because the fine particles enhance matrix formation and improve force transfer between coarse particles. Overall, the results indicate that xanthan gum-treated well-graded soils exhibited better mechanical performance than poorly graded soils.

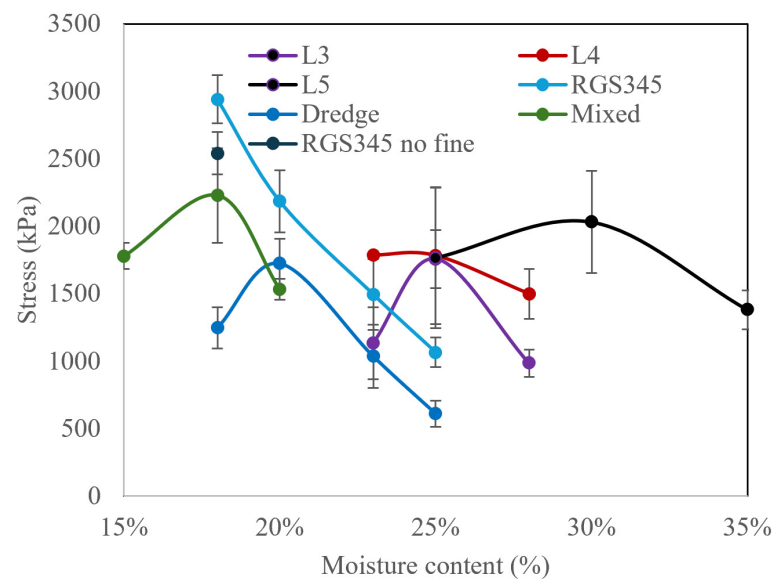


Figure 3. UCSs of samples with different initial moisture contents (error bars represent the standard deviation of triplicate measurements).

4.2. Effect of Wet–Dry Cycle on Mechanical Behavior

The structural response of xanthan gum-treated specimens under water immersion is shown in Figure 4. During the initial soaking period, the specimens gradually absorbed water while largely maintaining their original integrity. However, the treated RGS specimens exhibited early instability, with collapse initiating after approximately 1 h of immersion and complete failure occurring within 1 day. Among the recycled glass sand samples, the L3 specimen collapsed first, followed by the L4, RGS345, and L5 specimens. In general, samples with larger particle sizes exhibited faster collapse rates. This trend is consistent with the results of Chang et al. [10], who demonstrated that xanthan gum treatment was more effective in improving the compressive strength and stiffness of well-graded soils compared with poorly graded soils. This behavior was attributed to the formation of XG–fine particle matrices in pore voids, which improved inter-particle bonding, contact area, and force transfer. In addition, previous studies have suggested that the interaction between xanthan gum and soil particles is primarily governed by electrostatic attraction and hydrogen bonding. However, recycled glass sand particles are relatively smooth and electrically neutral, limiting the formation of strong particle–biopolymer interactions and resulting in poor water stability.

In contrast, XTMS and natural dredged sand demonstrated significantly better water resistance. These samples remained relatively stable during the early immersion stage and only began to show noticeable surface erosion after approximately 14 days of immersion, with complete collapse occurring after approximately 20 days of immersion. The improved durability may be attributed to the incorporation of fines and clay minerals in the dredged material, which possess negatively charged surfaces due to isomorphous substitution. These negatively charged particles can interact more effectively with xanthan gum, promoting the formation of a stronger and more continuous biopolymer–soil matrix throughout the pore spaces. These results indicate that XTMS and dredged sand developed a more stable soil structure and better durability when subjected to hydraulic loading. Fur-

thermore, XTMS exhibited higher UCS than XG-treated dredged sand alone, indicating that the incorporation of recycled glass sand may provide additional frictional resistance while reducing the consumption of natural sand resources. Therefore, the combined use of RGS and natural sand shows strong potential as a sustainable material for slope stabilization and coastal restoration under water exposure conditions.

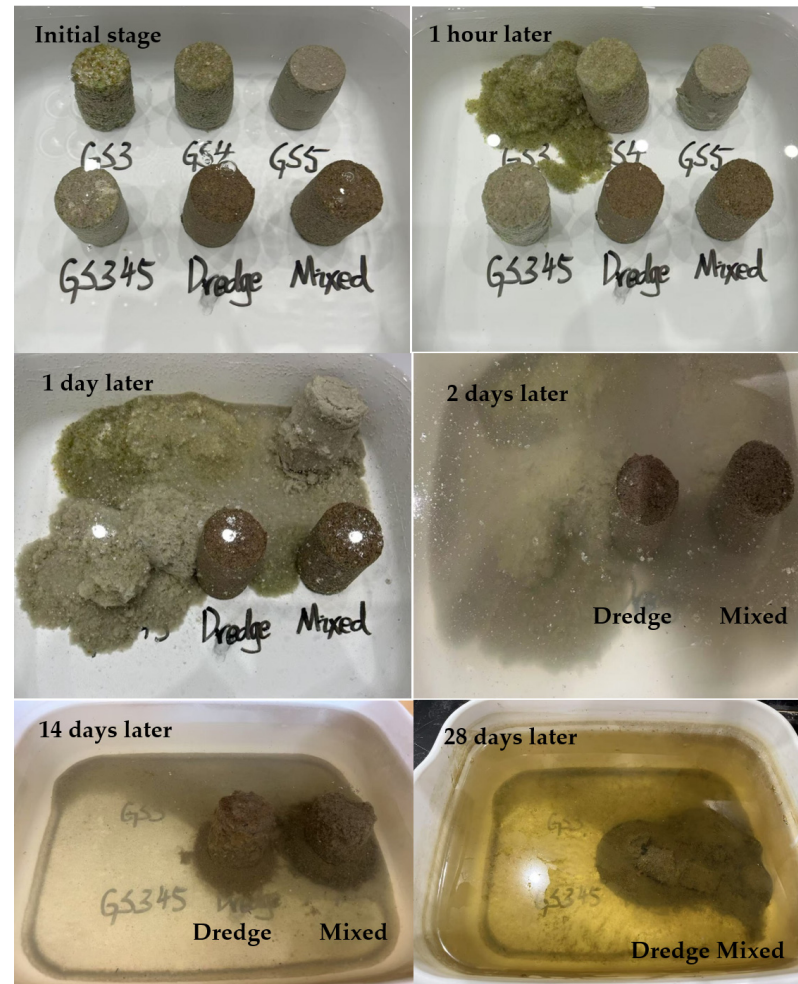


Figure 4. Pictures of xanthan gum-treated sample rewetting.

The effect of wet–dry cycles on the UCS of XTMS is presented in Figure 5a. The UCS decreased significantly after the first three wet–dry cycles, with an approximately 80% reduction in strength compared to the initial condition, followed by a more gradual decrease with additional cycles. This substantial strength loss was mainly attributed to the swelling and shrinkage behavior of xanthan gum during repeated wetting and drying processes. In contrast, Gao et al. [15] reported only a 24.1% strength loss after 10 wet–dry cycles for xanthan gum-treated soft soil containing 56.4% fine particles. This comparison suggests that fine particles may contribute to stronger xanthan gum–soil interactions and improve resistance to wet–dry-induced strength degradation. As shown in Figure 5b, the mass loss of the specimens decreased with increasing numbers of wet–dry cycles. In addition, Figure 6 indicates that the specimen diameter increased by approximately 0.25 inches (the initial sample diameter was 1.5 in) after three wet–dry cycles due to water absorption and swelling of the xanthan gum matrix. During drying, the xanthan gum shrank and generated additional pores and microcracks between soil particles, resulting in a reduction in dry density and UCS. Nevertheless, despite the significant decrease in strength, the specimens maintained their overall structural integrity during the wet–dry

cycles, indicating that xanthan gum continued to provide residual bonding and resistance against particle loss under repeated environmental exposure.

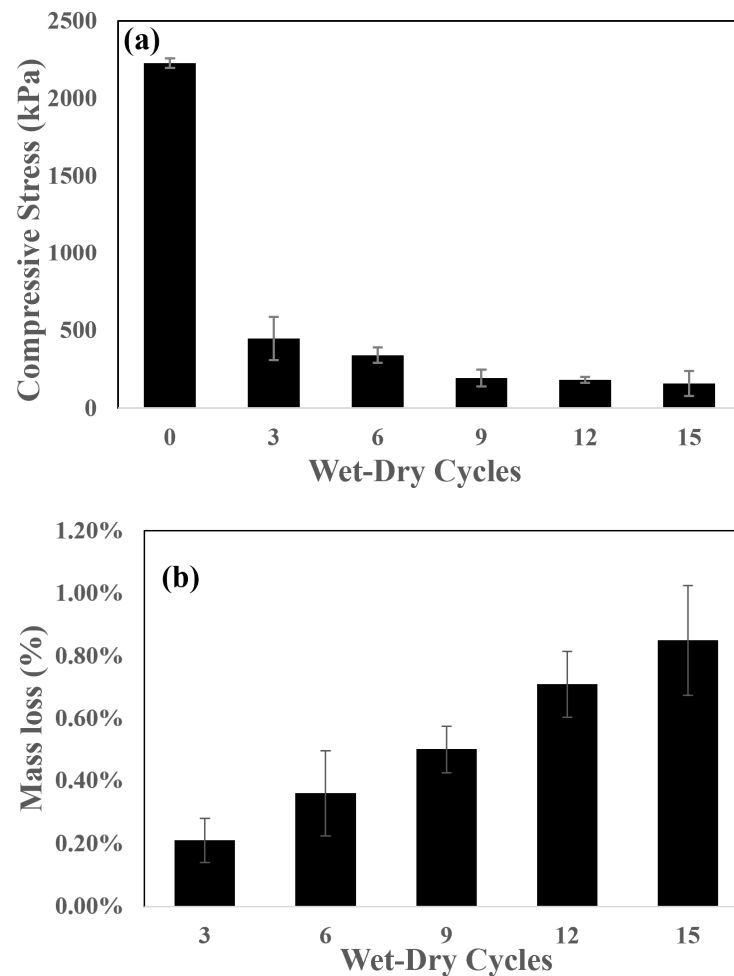


Figure 5. Effect of wet–dry cycle on the (a) mechanical properties and (b) sample mass of XTMS (error bars represent the standard deviation of triplicate measurements).

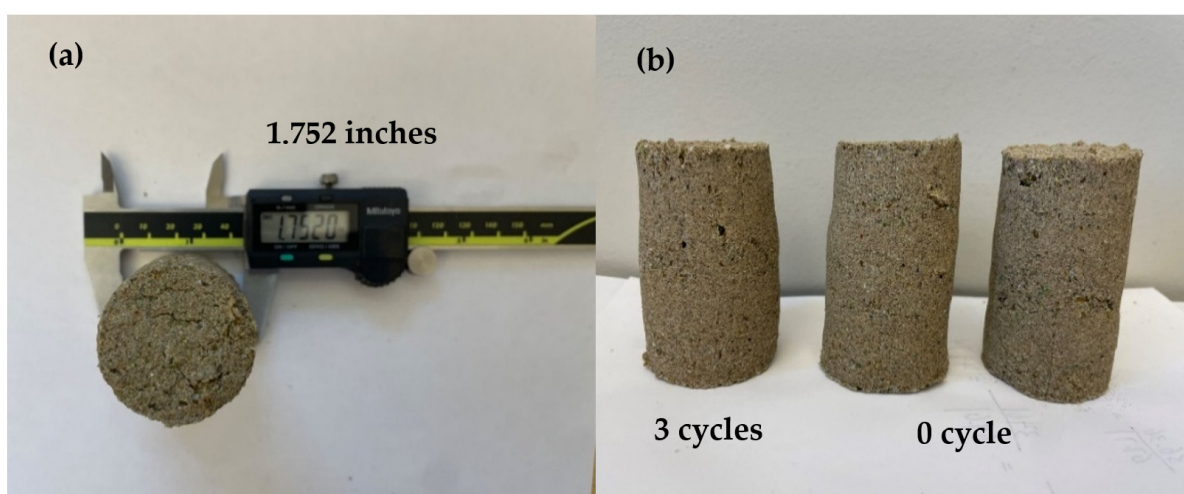


Figure 6. Photographs showing the dimensional change of XTMS specimens induced by wet–dry cycling: (a) The caliper measurements shown in the images provide direct scale references and indicate the changes in specimen dimensions after testing; (b) visual comparison between the specimen before cycling and that after three wet–dry cycles, where noticeable lateral expansion can be observed.

4.3. Effect of pH Environment on Mechanical Behavior

The variation in UCS of XTMS under different immersion conditions is presented in Figure 7. As shown in Figure 7a,b, the UCS decreased significantly after only 3 days of immersion in both acidic ($\text{pH} = 3$) and alkaline ($\text{pH} = 10$) solutions, with approximately 70% strength loss compared to the initial condition. The specimen immersed in the alkaline solution completely failed after 14 days, whereas the specimen exposed to the acidic solution preserved only about 18% of its original strength after 28 days. The substantial strength reduction under extreme pH conditions may be attributed to the degradation and dissolution of xanthan gum, which weakened the biopolymer bonding and reduced inter-particle cohesion within the soil matrix [23]. Previous studies have reported that xanthan gum exhibits moderate tolerance over a broad pH range; however, strongly alkaline conditions can accelerate polymer degradation and destabilize the xanthan gum network structure more rapidly than acidic environments [23]. In addition, alkaline environments may disrupt hydrogen bonding and intermolecular interactions within the xanthan gum matrix, leading to a more severe deterioration of the soil structure.

In contrast, Figure 7c shows that XTMS exhibited relatively stable mechanical performance under artificial seawater conditions with a pH of 8.2. After 28 days of immersion in seawater, the UCS decreased by only approximately 20%, which was significantly smaller than the reductions observed under acidic and alkaline conditions. These results suggest that XTMS possesses favorable durability in seawater environments and demonstrates strong potential for coastal restoration applications.

The improved performance in seawater may be attributed to several mechanisms. First, seawater contains various dissolved ions, including Na^+ , Ca^{2+} , Mg^{2+} , and Cl^- , which may enhance intermolecular interactions within the xanthan gum matrix. Previous studies reported that the viscosity and stability of xanthan gum solutions can increase in saline environments because dissolved salts promote molecular entanglement and strengthen the reticulated polymer network structure [23]. The presence of these ions may therefore help maintain the integrity of the xanthan gum–soil matrix under prolonged water exposure. In addition, multivalent cations such as Ca^{2+} and Mg^{2+} may contribute to ionic bridging between xanthan gum chains and soil particle surfaces, resulting in improved particle bonding and matrix stability.

Another possible mechanism is related to salt crystallization during drying. During the dehydration process, dissolved salts in seawater may precipitate and accumulate within the pore spaces of the soil matrix. These salt crystals can partially fill voids between particles and densify the soil structure, thereby contributing to the retention of compressive strength. Furthermore, the mixed sand contained natural fine particles and clay minerals, which likely improved the interaction between XG and soil particles through electrostatic attraction and hydrogen bonding. The combined effects of polymer–ion interactions, salt crystallization, and enhanced particle bonding likely contributed to the superior durability of XTMS under seawater conditions.

Overall, the results indicate that seawater exposure had a relatively limited negative effect on the mechanical behavior of XTMS compared to acidic and alkaline environments. This finding is particularly important for coastal engineering applications, where soils are continuously exposed to saline environments. The favorable seawater durability observed in this study highlights the potential of XTMS as a sustainable and environmentally friendly material for coastal restoration and erosion mitigation.

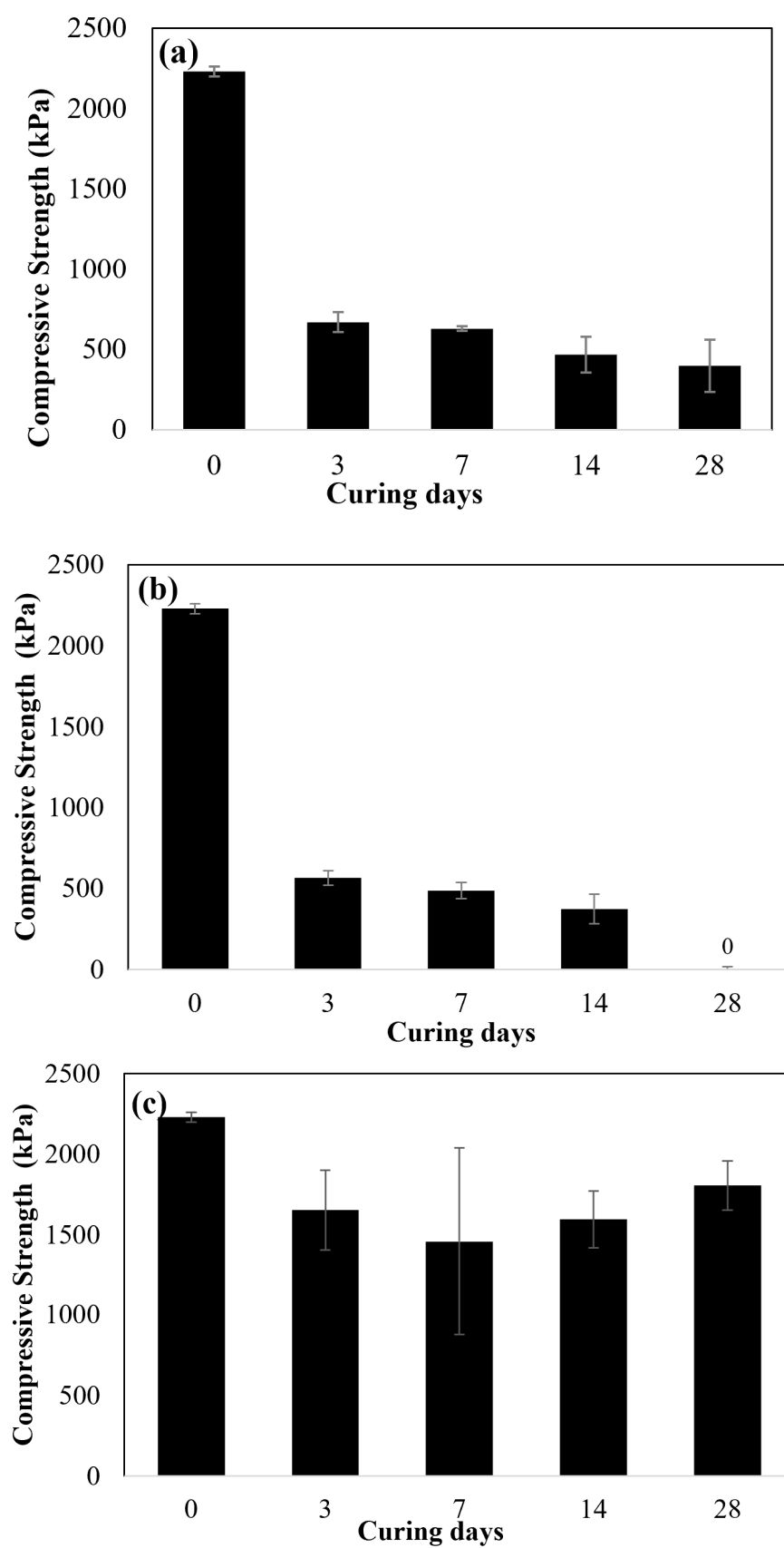


Figure 7. XTMS cured in (a) acid, pH = 3; (b) alkaline, pH = 10; (c) artificial seawater environment, pH = 8.2 (error bars represent the standard deviation of triplicate measurements).

4.4. Erosion Resistance of XTMS

Figure 8 presents time-sequenced photographic observations obtained from the EFA, showing the progressive erosion behavior of XTMS as the flow velocity increased. The results demonstrate that xanthan gum treatment significantly improved the erosion resistance of the mixed sand. The untreated sample exhibited noticeable erosion when exposed to a flow velocity of only 0.3 m/s, with severe material loss occurring within approximately 5 min. In contrast, the sample with xanthan gum treatment showed substantially greater resistance to hydraulic erosion and remained relatively stable under flow rates up to 2 m/s, although visible surface erosion began after 15 min of exposure. Complete erosion of the XTMS specimen was observed only after exposure to a flow rate of 3 m/s for 5 min. Lee et al. [12] also reported similar findings, showing that XG treatment could significantly enhance water erosion resistance. However, their EFA results indicated that erosion of the 1% XG-treated soil initiated at a flow velocity below 1 m/s, which was lower than that observed for the XTMS samples in the present study. This difference may be attributed to the particle size distribution of the tested materials. The soil used in their study was poorly graded sand, whereas the XTMS samples in this study were prepared by mixing sands with different particle sizes, resulting in a better-graded material. This improved gradation may have enhanced particle interlocking and strengthened the bonding between xanthan gum and soil particles, thereby contributing to greater erosion resistance. These results illustrate that xanthan gum treatment substantially enhanced the resistance of the soil matrix to resist hydraulic loading and scour erosion.

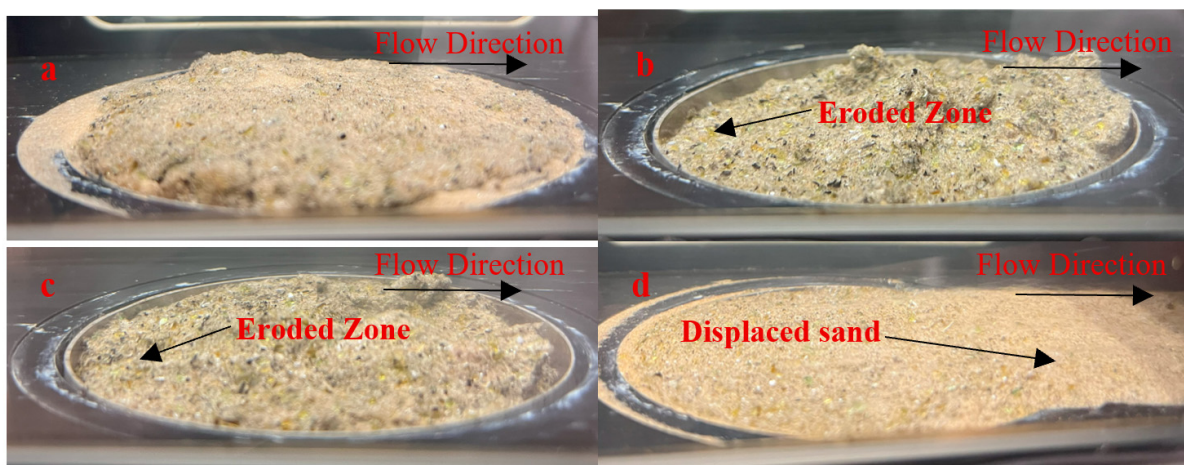


Figure 8. XTMS and untreated samples in EFA testing. (a) XTMS remained intact at a flow speed of 0.3 m/s for 30 min; (b) XTMS was eroded at a flow speed of 2 m/s for 15 min; (c) XTMS was eroded at a flow speed of 3 m/s for 5 min; (d) untreated sample was eroded at a flow speed of 0.3 m/s for 5 min.

The improved erosion resistance of XTMS is attributed to the formation of a continuous xanthan gum–soil matrix, which increased inter-particle bonding and soil cohesion. Xanthan gum acts as a natural cementing agent that binds soil particles together and reduces particle detachment under flowing water conditions. In addition, the fine particles in the mixed sand likely contributed to stronger xanthan gum–particle interactions through electrostatic attraction and hydrogen bonding, resulting in a denser and more stable soil structure. The combined effects of biopolymer bonding and improved particle interlocking enhanced the resistance of XTMS against hydraulic shear stresses.

From a coastal engineering perspective, the improved erosion resistance observed in XTMS is particularly important because coastal soils are continuously subjected to wave action, storm surge, and runoff-induced erosion. The ability of XTMS to maintain structural

stability under relatively high flow velocities suggests that xanthan gum-treated soils may provide an effective and sustainable alternative to conventional erosion control materials. Furthermore, the incorporation of recycled glass sand into the mixture reduces the consumption of natural sand resources and promotes the beneficial reuse of waste materials, further supporting the sustainability potential of this approach for coastal restoration and slope protection applications.

Figure 9a illustrates the relationship between scour rate and flow velocity for XTMS. The results indicate that XTMS exhibited relatively low scour rates under low flow velocities, suggesting strong resistance to hydraulic erosion during the initial stages of water flow. However, once the flow velocity exceeded approximately 2–3 m/s, the scour rate increased rapidly, indicating the initiation of significant particle detachment and erosion. Based on the EFA classification chart, XTMS can be categorized as having medium erodibility. Compared to untreated sand, which experienced severe erosion at relatively low flow velocities, xanthan gum treatment substantially improved the erosion resistance of the soil. This trend is consistent with the findings of Kwon et al. [24], who found that even a small amount of xanthan gum treatment could significantly improve the erosion resistance of sandy soils. Their study further suggested that achieving comparable erosion resistance using conventional treatment would require clay contents greater than 10%, highlighting the efficiency of XG as a sustainable erosion control material. The improved erosion resistance of XTMS further supports the effectiveness of XG in enhancing the hydraulic stability of sandy soils. Moreover, the present results indicate that XG treatment may be applicable to artificial and recycled sand-based materials, such as RGS, thereby broadening its potential use beyond conventional natural sandy soils. Nevertheless, the findings of this study are based on laboratory-scale experiments, and the long-term field performance of XTMS under natural conditions remains uncertain. Environmental factors, including UV exposure, temperature fluctuations, microbial activity, and biodegradation, may gradually affect the stability and durability of the XG–soil matrix. Therefore, the current results suggest that XG can be considered as a short-term or supplementary stabilization approach, while its long-term field applicability requires further verification through large-scale tests and field monitoring.

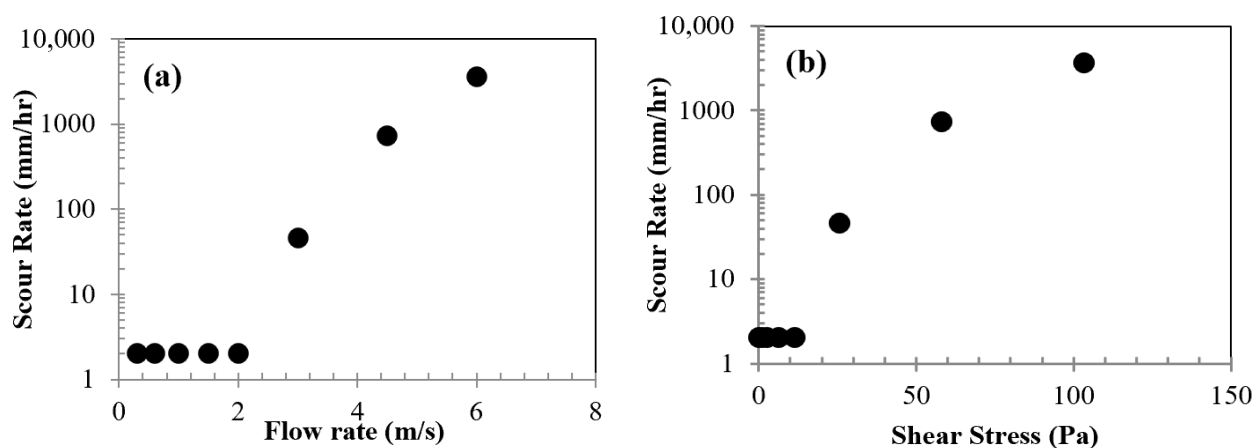


Figure 9. Scour rate as a function of flow rate (a) and shear stress (b) for XTMS.

The improved erosion resistance of XTMS is primarily attributed to the formation of a continuous XG–soil matrix, which enhanced soil cohesion and strengthened inter-particle bonding. In addition, the presence of fine particles likely promoted stronger electrostatic attraction and hydrogen bonding between xanthan gum and soil particles, resulting in improved particle interlocking and structural stability under flowing water conditions.

These mechanisms reduced particle detachment and delayed the initiation of erosion under hydraulic loading.

One of the most important parameters in erosion analysis is the critical shear stress, which represents the threshold at which soil erosion begins. Below the critical shear stress, soil particles remain stable, whereas erosion initiates once the applied hydraulic shear stress exceeds this threshold. As shown in Figure 9b, the critical shear stress of XTMS was determined to be approximately 11.5 Pa. This measured value exceeds the typical value reported for untreated or well-graded sands, which is about 0.4 Pa, and is comparable to the range commonly reported for medium-stiff clay, approximately 5–15 Pa. The significant increase in critical shear stress demonstrates that xanthan gum treatment effectively shifted the sandy soil toward more erosion-resistant behavior.

From a coastal engineering perspective, the enhanced erosion resistance and high critical shear stress of XTMS are particularly important because coastal soils are frequently exposed to wave action, tidal currents, and storm-induced hydraulic loading. The ability of XTMS to resist erosion under relatively high flow velocities suggests that xanthan gum-treated recycled geomaterials may provide a sustainable and environmentally friendly alternative for coastal restoration, slope stabilization, and erosion protection applications.

4.5. Rainfall Simulation

To further evaluate the field applicability of XTMS for coastal restoration, rainfall simulation tests were conducted under extreme precipitation conditions. As discussed in Sections 4.2–4.4, XTMS demonstrated improved durability under seawater exposure and significantly enhanced resistance to hydraulic erosion. However, coastal soils are frequently subjected to intense rainfall events, surface runoff, and prolonged wetting conditions, which can accelerate slope instability and erosion. Therefore, rainfall simulation testing was performed to assess the hydraulic stability and erosion resistance of XTMS under conditions representative of severe coastal storm events.

Prior to rainfall testing, all samples were exposed to the outdoor environment for 1 week to investigate moisture retention behavior under natural drying conditions. The moisture contents at different depths are summarized in Table 2. Holes were added into the model to replicate field drainage conditions. As a result, moisture tended to accumulate in the middle layer, where the highest value was recorded. After outdoor exposure, the untreated samples exhibited a substantial decrease in moisture content. For example, the untreated sample retained only approximately 4.5% moisture in the 4–6 cm layer after one week of exposure. In contrast, the XTMS specimens retained significantly higher moisture contents throughout the soil profile, with values exceeding 13% below 2 cm depth. This improved moisture retention behavior is consistent with the swelling and water-holding characteristics of xanthan gum discussed in Section 4.2. During dehydration, xanthan gum formed a gel-like matrix and surface film that reduced internal water evaporation by limiting moisture migration through the soil surface. These findings indicate that xanthan gum treatment can significantly improve the water retention capacity of sandy soils, which may be beneficial for vegetation growth and long-term surface stability in coastal restoration applications.

Representative photographs of untreated and xanthan gum-treated slopes during rainfall simulation are presented in Figure 10. The untreated sample exhibited severe surface erosion and runoff shortly after rainfall initiation. Significant soil loss and flow channel development were observed within the first 10 min, and erosion progressively intensified with continued rainfall exposure. In contrast, the XTMS specimen maintained strong surface stability throughout the testing period and showed minimal soil loss even under very heavy rainfall conditions of 120 mm/h, corresponding to an extreme precipitation event.

Table 2. Moisture content per layer.

Depth (cm)	Moisture Content (%)	
	XTMS	Untreated
0–2	4.8	0.8
2–4	15.3	2.3
4–6	17.3	4.5
6–8	15.1	3.8
8–10	13.3	2.6

**Figure 10.** *Cont.*



Figure 10. Photos of XTMS rainfall simulation.

The improved rainfall resistance of XTMS is closely associated with the enhanced inter-particle bonding and erosion resistance mechanisms discussed in Sections 4.3 and 4.4. Xanthan gum formed a continuous biopolymer–soil matrix that increased soil cohesion and strengthened particle interactions, thereby reducing particle detachment under rainfall-induced runoff conditions. In addition, the favorable durability of XTMS under seawater conditions suggests that the xanthan gum–soil matrix remained relatively stable in high-moisture environments, which likely contributed to the strong rainfall resistance observed during testing. Similar to the EFA results presented in Section 4.4, xanthan gum treatment

significantly improved the resistance of the soil against hydraulic erosion and delayed the initiation of surface failure.

Another important factor contributing to the improved rainfall performance was the increase in liquid limit and water-holding capacity resulting from xanthan gum treatment [25]. When untreated sandy soils approach saturation, the effective particle bonding rapidly decreases, causing the soil to transition into a flowable condition that is highly susceptible to erosion. In contrast, XTMS maintained sufficient structural integrity during prolonged rainfall exposure due to the stabilizing effect of the xanthan gum matrix. Furthermore, the formation of a dense surface layer during drying likely reduced direct infiltration and slowed the development of erosion channels on the slope surface. Overall, the rainfall simulation results further demonstrate that XTMS possesses strong resistance to rainfall-induced erosion and has significant potential as a sustainable and environmentally friendly material for coastal restoration and slope stabilization applications.

4.6. Research Limitations and Future Work

Although this study demonstrated the potential of xanthan gum-treated soils for improving erosion resistance and durability, the conclusions are currently based on laboratory-scale experiments. Strength reduction, long-term field performance, and biodegradation behavior under natural environmental conditions remain limitations of the present work. Therefore, xanthan gum treatment may be more suitable as an early-stage or complementary stabilization strategy rather than a standalone long-term reinforcement method. Conventional coastal restoration approaches, such as sand dune restoration, often use natural sand and vegetation to reduce coastal erosion. However, vegetation-based stabilization requires a relatively long establishment period before plant roots can effectively reinforce the soil. During this vulnerable early stage, restored sand deposits may still be susceptible to human disturbance, wave action, tidal currents, and seawater erosion. Excessive surface sand loss may expose developing plant roots and increase the need for re-covering, re-grading, or replanting, thereby increasing maintenance costs. In this context, xanthan gum treatment can provide temporary surface stabilization by binding sand particles and forming a stabilizing polymeric matrix, which improves erosion resistance during the initial restoration period and provides a more stable substrate for subsequent root development. From an economic perspective, this early-stage protection may reduce post-restoration maintenance by limiting surface sand loss and reducing the need for repeated material replacement or vegetation re-establishment. From an environmental perspective, the combined use of XG and RGS can reduce the consumption of natural sand resources while promoting the beneficial reuse of waste materials. Moreover, because xanthan gum is polysaccharide-based and biodegradable, its gradual degradation under natural conditions may reduce long-term environmental concerns and potentially support vegetation establishment. Future research will further examine the combined reinforcement effect of xanthan gum and plant roots, with emphasis on the mechanical behavior of the root–xanthan gum–soil composite system. Laboratory mechanical tests and large-scale model tests will be conducted to further evaluate the feasibility of applying xanthan gum treatment to field-scale slope stabilization and erosion control.

5. Conclusions

As a natural binder for sand stabilization, xanthan gum has demonstrated the ability to significantly improve soil strength and erosion resistance at low concentrations. However, the hydraulic and long-term durability performance of xanthan gum-treated soils under coastal environmental conditions remain insufficiently understood, limiting their broader application in coastal restoration and geotechnical engineering. In this study, the

long-term durability and water resistance of xanthan gum-treated soils were systematically evaluated through wet–dry cycling, pH durability testing, EFA testing, and rainfall simulation experiments.

The results demonstrated that soil gradation and soil type had significant effects on the performance of the xanthan gum–soil matrix. Well-graded soils exhibited substantially higher compressive strength and improved water stability compared to poorly graded soils due to enhanced particle interaction and matrix formation. Xanthan gum-treated RGS specimens lost their structural integrity within one day of water immersion, whereas specimens prepared with natural dredged sand maintained resistance to water erosion for up to 20 days. The incorporation of recycled glass sand with natural sand produced XTMS, which exhibited improved mechanical performance and durability under water exposure conditions. These findings suggest that combining recycled glass sand with natural sand provides an effective and sustainable approach for improving soil stabilization while reducing the consumption of natural sand resources.

Environmental durability testing further indicated that XTMS exhibited relatively good stability under seawater conditions, with only minor reductions in compressive strength after prolonged seawater exposure. In contrast, significant strength degradation was observed under acidic and alkaline conditions, particularly under alkaline conditions. The improved seawater durability was attributed to enhanced polymer–ion interactions and possible salt crystallization effects within the xanthan gum–soil matrix. These results highlight the strong potential of XTMS for coastal restoration applications where saline environments are commonly encountered.

The EFA and rainfall simulation tests further demonstrated the strong erosion resistance imparted by xanthan gum treatment. The critical shear stress of XTMS increased to approximately 11.5 Pa, indicating an erosion resistance level similar to medium-stiff clay and markedly higher than untreated sand. In addition, XTMS maintained strong structural stability under very heavy rainfall conditions (120 mm/h) for up to 1 h with minimal soil loss, whereas untreated samples experienced severe erosion and runoff shortly after rainfall initiation. The improved erosion resistance was mainly attributed to the formation of a continuous xanthan gum–soil matrix, which increased soil cohesion, strengthened particle bonding, and reduced particle detachment under hydraulic loading.

Overall, the findings of this study demonstrate that XTMS possesses favorable mechanical performance, seawater durability, and erosion resistance, making it a promising sustainable material for coastal restoration and slope stabilization applications. Based on the experimental results, the combined use of xanthan gum, RGS, and natural dredged sand is recommended for coastal environments where improved erosion resistance and sustainable material utilization are desired.

Author Contributions: Conceptualization, K.W.; Methodology, J.L. and K.W.; Validation, J.L.; Formal analysis, J.L. and B.Z.; Investigation, J.L. and B.Z.; Data curation, J.L. and B.Z.; Writing—original draft, J.L.; Writing—review and editing, B.Z. and K.W.; Supervision, K.W.; Project administration, K.W.; Funding acquisition, K.W. All authors have read and agreed to the published version of the manuscript.

Funding: This study is based on work supported by the U.S. National Science Foundation under Grant No. 2137730 and No. 2502828.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EFA	Erosion Function Apparatus
RGS	Recycled Glass Sand
XTMS	Xanthan Gum-Treated Mixed Sand
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System

References

1. Franzen, M.O.; Fernandes, E.H.; Siegle, E. Impacts of coastal structures on hydro-morphodynamic patterns and guidelines towards sustainable coastal development: A case studies review. *Reg. Stud. Mar. Sci.* **2021**, *44*, 101800. [CrossRef]
2. Kathijotes, N. Keynote: Blue economy-environmental and behavioural aspects towards sustainable coastal development. *Procedia-Soc. Behav. Sci.* **2013**, *101*, 7–13.
3. van Zelst, V.T.; Dijkstra, J.T.; van Wesenbeeck, B.K.; Eilander, D.; Morris, E.P.; Winsemius, H.C.; de Vries, M.B. Cutting the costs of coastal protection by integrating vegetation in flood defences. *Nat. Commun.* **2021**, *12*, 6533. [CrossRef] [PubMed]
4. Gittman, R.K.; Scyphers, S.B. The cost of coastal protection: A comparison of shore stabilization approaches. *Shore Beach* **2017**, *85*, 19–24.
5. Reguero, B.G.; Beck, M.W.; Bresch, D.N.; Calil, J.; Meliane, I. Comparing the cost effectiveness of nature-based and coastal adaptation: A case study from the Gulf Coast of the United States. *PLoS ONE* **2018**, *13*, e0192132. [CrossRef] [PubMed]
6. Dugan, J.E.; Emery, K.A.; Alber, M.; Alexander, C.R.; Byers, J.E.; Gehman, A.M.; Sojka, S.E. Generalizing ecological effects of shoreline armoring across soft sediment environments. *Estuaries Coasts* **2018**, *41*, 180–196.
7. Kornis, M.S.; Breitburg, D.; Balouskus, R.; Bilkovic, D.M.; Davias, L.A.; Giordano, S.; Heggie, K.; Hines, A.H.; Jacobs, J.M.; Jordan, T.E.; et al. Linking the abundance of estuarine fish and crustaceans in nearshore waters to shoreline hardening and land cover. *Estuaries Coasts* **2017**, *40*, 1464–1486. [CrossRef]
8. Baranwal, J.; Barse, B.; Fais, A.; Delogu, G.L.; Kumar, A. Biopolymer: A sustainable material for food and medical applications. *Polymers* **2022**, *14*, 983. [CrossRef] [PubMed]
9. Chang, I.; Lee, M.; Tran, A.T.P.; Lee, S.; Kwon, Y.M.; Im, J.; Cho, G.C. Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices. *Transp. Geotech.* **2020**, *24*, 100385. [CrossRef]
10. Chang, I.; Im, J.; Prasadhi, A.K.; Cho, G.C. Effects of xanthan gum biopolymer on soil strengthening. *Constr. Build. Mater.* **2015**, *74*, 65–72. [CrossRef]
11. Kwon, Y.M.; Moon, J.H.; Cho, G.C.; Kim, Y.U.; Chang, I. Xanthan gum biopolymer-based soil treatment as a construction material to mitigate internal erosion of earthen embankment: A field-scale. *Constr. Build. Mater.* **2023**, *389*, 131716. [CrossRef]
12. Lee, M.; Chang, I.; Cho, G.C. Hydraulic erosion mitigation in sandy soil using cation-crosslinked gelation biopolymer. *Acta Geotech.* **2025**, *20*, 3563–3580. [CrossRef]
13. Akoğuz, H. Performance evaluation of waste glass in soil improvement: Influence of particle size of waste glass on mechanical, microstructural, and durability characteristics. *Case Stud. Constr. Mater.* **2025**, *22*, e04241. [CrossRef]
14. Li, J.; Wen, K.; Zhang, B. Investigation of mechanical behavior of sustainable construction materials: Recycled glass sand stabilized with natural binder material—Biopolymers. *Constr. Build. Mater.* **2024**, *418*, 135359.
15. Gao, Q.F.; Shi, X.K.; Zeng, L.; Yu, H.C.; Hu, J.X. Characterization of the mechanical behavior and stabilization mechanism of soft soil treated with xanthan gum biopolymer. *Polymers* **2025**, *17*, 1532. [CrossRef] [PubMed]
16. Feng, D.; Liang, B.; Wan, Y.; Yi, F.; Liu, L.; Zhang, Y.; He, X. Mechanical and water stability properties of biopolymer-treated silty sand. *J. Rock Mech. Geotech. Eng.* **2025**, *17*, 3910–3924.
17. NOAA/NCEI. U.S. Climate Normals, 2006–2020. Available online: <https://www.ncei.noaa.gov/access/us-climate-normals/#dataset=normals-annualseasonal&timeframe=15&location=MS&station=USW00003940> (accessed on 11 June 2026).
18. Berninger, T.; Dietz, N.; González López, Ó. Water-soluble polymers in agriculture: Xanthan gum as eco-friendly alternative to synthetics. *Microb. Biotechnol.* **2021**, *14*, 1881–1896. [PubMed]
19. ASTM D698-12; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. ASTM International: West Conshohocken, PA, USA, 2012.
20. ASTM D2166/D2166M-13; Standard Test Method for Unconfined Compressive Strength of Cohesive Soil. ASTM International: West Conshohocken, PA, USA, 2013.

21. ASTM D559/D559M-15; Standard Test Methods for Wetting and Drying Compacted Soil-Cement Mixtures. ASTM International: West Conshohocken, PA, USA, 2015.
22. Briaud, J.L. Case histories in soil and rock erosion: Woodrow Wilson bridge, Brazos river meander, Normandy cliffs, and New Orleans levees. *J. Geotech. Geoenviron. Eng.* **2008**, *134*, 1425–1447. [[CrossRef](#)]
23. Chaturvedi, S.; Kulshrestha, S.; Bhardwaj, K.; Jangir, R. A review on properties and applications of xanthan gum. In *Microbial Polymers: Applications and Ecological Perspectives*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 87–107.
24. Kwon, Y.M.; Ham, S.M.; Kwon, T.H.; Cho, G.C.; Chang, I. Surface-erosion behaviour of biopolymer-treated soils assessed by EFA. *Géotech. Lett.* **2020**, *10*, 106–112.
25. Chang, I.; Im, J.; Cho, G.C. Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering. *Sustainability* **2016**, *8*, 251. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.