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Biopolymer-Induced Stabilization of Sandy Soils for Enhanced Erosion Resistance

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ABSTRACT

Soil erosion is a critical issue for engineering structures exposed to water. Traditionally, inorganic additives like cement and lime have been used to enhance soil's resistance to erosion, but these materials can negatively impact the environment and water quality. Biopolymers have emerged as an environmentally friendly alternative, with previous studies validating their effectiveness in improving soil mechanical strength. However, the effect of biopolymers on resistance to erosion has not been adequately investigated. This study investigates the erodibility of a sandy soil treated with Xanthan Gum (XG), as a representative biopolymer. Using the Erosion Function Apparatus (EFA), we measured the critical velocity and established the erosion curve of treated and untreated soils. The results show that sand treated with 1% XG experienced a 575% increase in critical velocity and a tenfold shift in the erosion curve, demonstrating a significant improvement in erosion resistance compared to untreated sand.

INTRODUCTION

Soil erosion is a significant environmental and public health issue confronting human society (Pimentel 2006). The ASCE task force has identified soil erosion as one of the nine critical challenges currently facing the civil engineering community (Becerik-Gerber et al. 2014). The main external factors responsible for soil erosion are wind and water (Tran et al. 2019). Soil erosion takes place when the shear stress from moving fluids exceeds a certain threshold, known as the critical erosion shear stress (Jacobs et al. 2011). Soil erosion is a pervasive phenomenon that frequently leads to scouring and the failure of submerged geostructures (Khwairakpam et al. 2009). Erosion has a substantial impact on numerous engineering structures, including earthen dams, levees, bridges, and embankments, and is a major contributor to bridge failures (Wardhana et al. 2003).

The enhancement of soil resistance to erosion has traditionally been achieved using cement and lime. However, production of these materials emits substantial amounts of carbon dioxide and their presence in surface soils adversely affects vegetation growth. Therefore, there is a growing demand for environmentally sustainable alternatives to reinforce the soil supporting these

structures. Biopolymers, which are naturally occurring polymers derived from living microorganisms, have emerged as a promising solution for ground improvement (Chang et al. 2016). Biopolymers, being naturally derived and biodegradable, offer an effective and eco-friendly solution for improving soil cohesion and preventing erosion (Choi et al. 2020).

In the case of clays and fine-grained soils, the integration of biopolymers modifies soil particle size and morphology by facilitating inter-particle bonding, and aggregation (Chang et al. 2016). In the case of course-grained soils, biopolymers reduce soil permeability through bio-clogging of pore spaces which results in the reduction of water infiltration into soil slopes that would otherwise saturate the soil (increase of soil bulk density while decreasing unsaturated shear strength) (Chang et al. 2016, Arabani et al. 2024). This incorporation enhances the durability of the soil and improves adhesion within the soil matrix. These properties demonstrate the potential of biopolymers to effectively reduce soil erosion (Muguda et al. 2020). Research in this area is still in its early stages, with most studies focusing on fine-grained soils like Kaolinite (Kwon et al. 2023). Studies on coarse-grained soils are limited and often overlook the quantitative impact of biopolymer addition.

In this study, the critical velocity and erosion rate of commercially available coarse-grained sandy soil with and without xanthan gum was determined using EFA. Erosion curves for clean (i.e., untreated) sand and sand treated with xanthan gum are developed. Sand treated with 1% XG showed significantly higher erosion resistance compared to the untreated sand specimen.

MATERIALS AND METHODS

Sand. Acco Sand was used as the coarse-grained medium for the experiment. The sand is classified as well-graded sand with silt (SW-SM). The sand was washed using tap water on top of a #200 sieve to ensure all fines were removed. Washed sand was then dried in an oven at a constant temperature of 110°C to ensure the sand was completely dry. The washed sand had a specific gravity of 2.87, 1.3 mm D_{50}, and a maximum dry unit weight of 19.55 kN/m^3. It was compacted to 70% relative density. **Figure 1**a shows the particle size distribution of the Acco sand. Further details of the soil are presented elsewhere by the authors (Lamsal et al, 2024 & 2025).

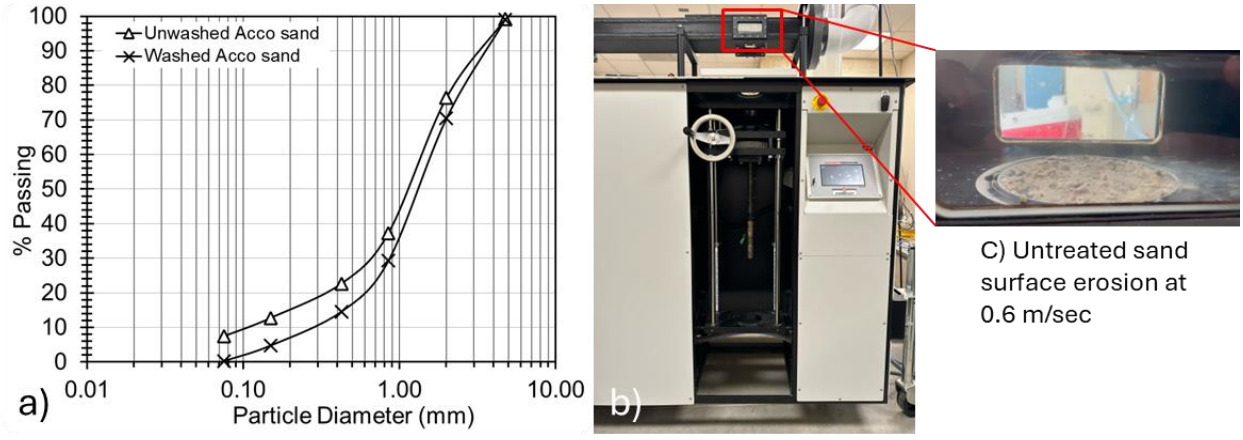

Figure 1. A) Particle size distribution of the Acco sand before and after washing; B) EFA equipment; and C) sample surface during erosion at the water velocity of 0.6 m/s.

Biopolymer. Xanthan gum (XG) was used as the representative biopolymer in this experiment. Xanthan Gum (XG) is a microorganism-based polysaccharide produced via fermentation of Xanthomonas campestris bacterium (Fatehi et al. 2021). Food-grade XG powder was purchased from the brand Judee's Gluten Free.

Shelby Tubes. The specimen was compacted within a Shelby tube with an inner diameter of approximately 73.0 mm, outer diameter of 76.2 mm, and length of 355.6 mm. The Shelby tube rests on a base within the platform of the Erosion Function Apparatus (EFA). EFA protrudes the specimen into the flume to a desired height.

Preparation of biopolymer-sand mixtures and compaction of the specimens. To prepare the specimen, 2500 g of dry sand was used, with the required mass of xanthan gum determined based on the concentration relative to the dry sand's weight. 36.15 gm of xanthan gum was mixed with 300 g of deionized water in a commercial blender. The biopolymer was added to the water in increments of 2.5 g, with each increment mixed for one minute to avoid clod formation and ensure a homogeneous gel. Xanthan gum gel consisting of 1% xanthan gum and 8.3% of water, was combined with 2500 g of sand using a kitchen mixer, mixed for 15 minutes at medium speed followed by 15 minutes at the highest speed, and then manually mixed for an additional seven minutes to achieve uniform distribution.

The under-compaction method (Ladd, 1978) was used to compact the Acco Sand and biopolymer mixture in the Shelby tube. The specimen was compacted in 10 layers to achieve total height of 304.8 mm. Layers of equal weight were compacted to ensure uniformity throughout the specimen.

Rheological properties of the prepared XG gel. Assessing the rheological properties of the XG gel is important since this non-Newtonian gel replaces water between the sand particles and significantly changes soil behavior. In this paper, the MCR 302e rheometer manufactured by Anton Paar was used to collect the flow characteristics of the gel. A 4-bladed vane-in-cup geometry (ST22-4V-16) was used for the measurements. The rheology test included subjecting the gel to shear rates ranging from $\dot{\gamma} = 100\ s^{-1}$ to 1E-7 s^{-1}. The magnitude of $\dot{\gamma}$ was decreased logarithmically, with 6 points collected during each decade decrease in strain rate. The machine remains at each strain rate until a steady state shear stress reading is obtained. This shear stress is then recorded as the data point at the corresponding shear rate.

EFA specifications and test method. The Erosion Function Apparatus (EFA) by Humboldt was used to measure soil erodibility, often alongside the SRICOS method for predicting scour rates at bridges, beach erosion, surface erosion, and dam piping. It operates by cycling water through a 1-meter-long rectangular flume at controlled velocities (0.2 to 7 m/s) to erode the soil specimen's surface, including undisturbed Shelby tube specimens. Key testing variables include water flow rate, specimen type, erosion duration, and specimen push rate.

The Shelby tube was positioned in the EFA with the treated sand specimen's surface aligned with the lower plate of the flume. The specimen was protruded 1 mm into the flume, and water was flowed at 0.2 m/s, gradually increasing by 0.1 m/s increments until particle erosion was observed, identifying this velocity as the critical velocity. Irregular erosion due to surface roughness was disregarded. After determining the first critical velocity, the flow was increased by

0.2 m/s, allowing the 1 mm protruded surface to erode, and then reduced to 0.2 m/s to protrude the next 1 mm. This process was repeated three times to obtain three independent critical velocity values, with their average taken as the critical velocity for the specimen. Subsequently, water was flowed at this critical velocity, and the specimen was protruded in 1 mm increments, with each increment allowed to erode until a total of 10 mm was eroded. The time taken to erode 10 mm was recorded, and the erosion rate, corresponding to the critical shear stress, was calculated. This process was repeated at velocities higher than the identified critical velocity to determine the erosion rate under varying shear stresses. Figure 1b and c show the EFA equipment and the surface of the sample during erosion.

Shear Stress Reduction. The flow of water in the EFA exerts shear stress on the surface of the treated soil specimen, with the magnitude of this shear stress being directly proportional to the water's flow velocity. To determine the shear stress, the flow velocity was used in conjunction with Moody's chart, following the methodology employed by Briaud et al. (2001). The shear stress was determined using Equation (1).

$$\tau = \frac{1}{8} f \rho v^2 \tag{1}$$

where τ is the calculated shear stress on the surface, f is the friction factor determined based on Reynold's number and relative pipe roughness, ρ is the density of water, and v is the average velocity of water flowing over the surface.

RESULTS AND DISCUSSION

Critical Velocity. The critical velocities for both untreated sand and sand treated with 1% XG were determined using the EFA. The critical velocity is defined as the water flow velocity at which particles from the surface of the soil specimen begin to erode. This metric indicates the soil's resistance to erosion under flowing water conditions and is determined visually by the operator. The measured critical velocities for both specimens are presented in Table 1. Two tests were performed for the untreated sand, and the results were reproducible for both tests, as shown in Table 1. The critical velocity for the sand treated with 1% XG showed a significant increase of 575% compared to the untreated sand. This substantial rise in critical velocity may have developed due to the higher yield stress of the xanthan gum gel.

Table 1. List of tests performed and critical velocity result of the test

Test No.	Specimen Type	Biopolymer Concentration (with respect to the dry weight of soil)	Critical Velocity (m/s)
1	Untreated Sand	-	0.4
2	Untreated Sand	-	0.4
3	Sand treated with XG	1%	2.7

Erosion Curve. Figure 2 presents the erosion curves for untreated sand and sand treated with 1% xanthan gum (XG). In this figure, shear stress (in pascals) is plotted on the primary x-axis using a logarithmic scale, the velocity of water in the flume (m/s) is plotted on the secondary x-axis in

arithmetic scale while the y-axis represents the erosion rate (in millimeters per hour) on an arithmetic scale. The relationships between shear stress and erosion rate for both untreated and treated sand were depicted, with a power curve applied to illustrate the trend of the data.

The comparison of these curves shows a substantial shift in the erosion behavior due to the XG treatment. Specifically, the erosion curve for sand treated with 1% XG shifts markedly to the right, indicating a tenfold increase in erosion resistance. This shift means that the treated sand requires significantly higher shear stress to achieve the same erosion rate as untreated sand. For example, untreated sand erodes at a rate of approximately 520 mm/hr. under a shear stress of about 2 Pa. In contrast, the same sand treated with 1% XG requires a shear stress of around 65 Pa to reach the same erosion rate. This notable increase in the required shear stress underscores the effectiveness of XG in enhancing the erosion resistance of sandy soils.

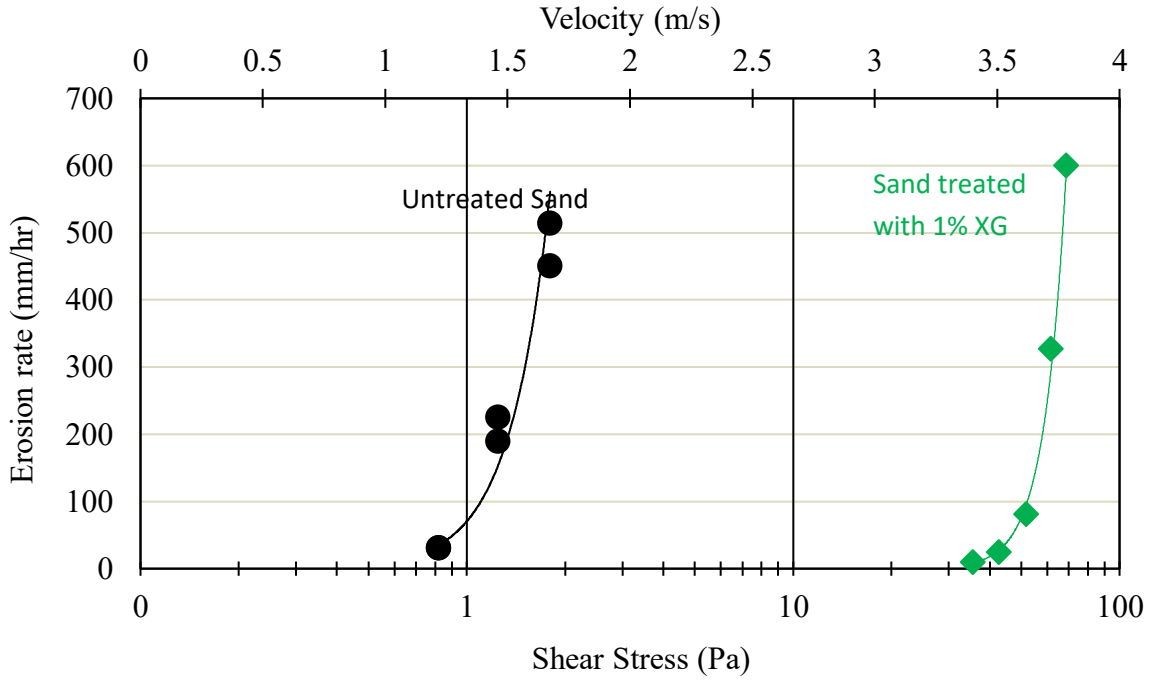

Figure 2. Erosion function curve of only sand and sand treated with 1% XG.

Rheology of the XG gel in the pore space of the soil. The flow curve test results for the XG gel is shown in Figure 3. The prepared XG gel was approximately 12% XG to water ratio. The data was fitted to the Herschel-Bulkly equation, which is shown in this figure using a solid line. Herschel-Bulkley model is of the form $\tau = \tau_0 + Kx^n$ where K and n are fitting parameters. τ_0, which is the magnitude of the shear stress as the applied shear strain approaches zero ($\gamma \rightarrow 0$), is

assumed to be the yield stress of the paste at that water content (Saasen et al. 2018) which is 247 Pa. The Origin Pro software (v. 2023b) was used for this curve-fitting process.

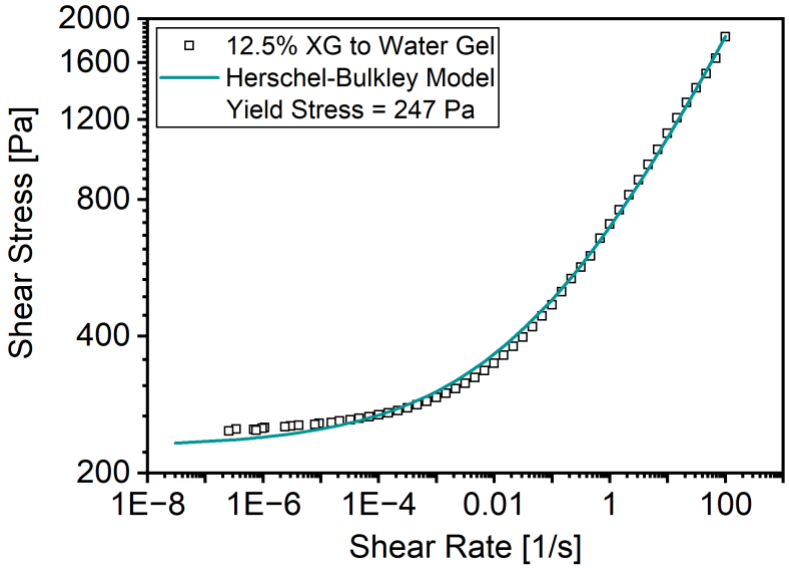

Figure 3. Flow curve for used XG gel.

The XG-treated specimen experienced erosion at calculated shear stresses that are significantly below the measured yield stress of the XG gel. This is because XG is only present at the pore spaces of the soil; therefore, only a segment of the entire specimen area exposed to the water flow consists of this yield stress non-Newtonian gel. Despite this, the increase in erosion resistance of the XG-treated specimen is significant.

CONCLUSION

In this study, the effect of biopolymer on erosion resistance of soil was assessed using the Erosion Function Apparatus (EFA). The results demonstrate that treating sandy soils with 1% xanthan gum (XG) to solid mass of the soil significantly enhances their erosion resistance, with a notable 575% increase in critical velocity. The erosion curve shifted to the right, indicating a tenfold increase in resistance to shear stress. This substantial rise in critical velocity and shift of the erosion curve demonstrates the effectiveness of the biopolymer treatment in improving the soil's stability and resistance to erosive forces. This suggests the broader application potential of biopolymers in preventing erosion in vulnerable landscapes, such as coastal areas, riverbanks, and infrastructure foundations, where improved erosion resistance is essential for long-term stability.

Finally, it must be noted that this paper studied the specific case of mixing the soil with biopolymer gel and compaction at optimum water content. The application of biopolymer treatment on a field scale is in its infancy. Several methods have been tried in field trials, including direct spraying of the gel on the soil surface (in some cases followed by shallow mixing using tilling equipment). The discussion of the effects of different mixing methods for field applications is beyond the scope of this paper.

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