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Xanthan Gum Treated Sand as a Mechanism to Improve Resistance to Erosion with Application to Breach Development

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ABSTRACT

This study investigates how xanthan gum, a biopolymer, influences the resistance to erosion of sand with a potential application to enhance the stability of earthen embankments. A series of erosion tests were conducted in the Hydraulics laboratory at the University of South Carolina with xanthan gum concentrations ranging from 0.05% to 0.15%. Results show that increasing xanthan gum content significantly reduces erosion due to the formation of a biopolymer matrix within the soil structure. Erosion transitions from grain-by-grain detachment to macroabrasion and plucking as bed shear stress increases. These findings suggest that xanthan gum can be an effective additive in non-cohesive sands for improving erosion resistance, potentially reducing embankment failures.

INTRODUCTION

Dams and embankments have been essential structures for the development of modern civilization with early examples dating back thousands of years (Yang; et al., 1999). Despite the long existence, failures of earthen embankments have been a persistent issue with devastating consequences. Landmark failures such as the Buffalo Creek incident (1972) (Sharma and Kumar, 2013), the Teton Dam collapse (1976) (Bolton Seed and Duncan, 1987), and the Kelly Barnes Dam failure (1977) (DeNeale et al., 2019) led to the establishment of dam safety programs in the USA. In 1985, more than 93% of USA dams were earthen embankments (Costa, 1985), and today over 69,000 of these dams are classified as High Hazard Potential posing significant risks during floods (USACE, 2024).

A major cause of dam failure is overtopping, which accounts for more than one-third of all incidents (Costa, 1985). Overtopping erodes embankment materials, often leading to structural collapse and release of an upstream reservoir. To mitigate such risks, improving erosion resistance is critical. Conventional erosion protection methods such as geotextiles, vegetative cover, and cement-modified soils (Powledge et al., 1989) have raised environmental concerns for toxicity and high greenhouse gas emissions of the cement industry (Ko and Kang, 2018). Recent studies highlight the potential of biopolymers, which are environmentally friendly soil additives, to enhance soil stability by reducing erodibility without adverse ecological impacts (Abdelaziz et al., 2019; Chang et al., 2015).

The use of biopolymers, described as organic compounds formed through natural biological processes, is increasingly being explored for geotechnical applications. When mixed with soils, they increase soil liquid limits by enhancing pore fluid viscosity and water retention, forming hydrogels that reduce hydraulic conductivity and enhance soil strength (Chang et al., 2020). Xanthan gum, a widely used biopolymer derived from the bacterium Xanthomonas campestris (Cho and Chang, 2018), is particularly effective in stabilizing non-cohesive soils by creating a matrix with fine particles that resists erosion (Abdelaziz et al., 2019).

Different types of erosion can be observed in the field. This contribution considers the gradual removal of sediment due to flowing water that is influenced by factors such as flow velocity and sediment properties. Different erosion mechanisms have been defined depending on soil resistance and shear stress, including abrasion, plucking, and macroabrasion (Chatanantavet and Parker, 2009). Abrasion refers to the slow and gradual removal of sediments as individual grains. Plucking refers to removal of chunks or lumps of sediment, often leading to the formation of holes in the sample. Macroabrasion occurs when numerous lumps are eroded and transported downstream.

Soil erosion rates are measured with different methods, including jet erosion tests (JET), hole erosion tests (HET), and flume tests. JET is suited for cohesive soils, while HET examines piping erosion (Clar and T., 2007). Flume tests, which simulate high shear stress conditions, are particularly useful for studying erosion processes such as streambank or spillway erosion (McNichol et al., 2017).

In this study, flume tests were conducted to study erosion and transport of xanthan gum treated sand in relation to breach development in embankments during overtopping. In the experiments detailed here, xanthan gum was added to sand in different concentrations. Results show that xanthan gum can significantly improve soil resistance to erosion, making it a promising solution for enhancing the durability of earthen embankments under extreme conditions. Experiments with untreated sand would have been a valuable base case but could not be performed because the erosion rate would have been too high to be measurable with the set up described below.

EXPERIMENTAL SET UP AND METHODS

Sediment size distribution

The sand gradation in the experiments measured using the standard sieve analysis (ASTM, 2021) is shown in Figure 1a and resembles the particle size distributions used in prior studies investigating the use of xanthan gum as a soil additive to enhance mechanical properties (Abdelaziz et al., 2019; Chang et al., 2015, 2016). The sand used in this study has geometric mean size equal to 0.42 mm, median diameter 0.44 mm and geometric standard deviation 1.81. Per the Unified Soil Classification System (USCS) this sand is a well-graded sand (SW).

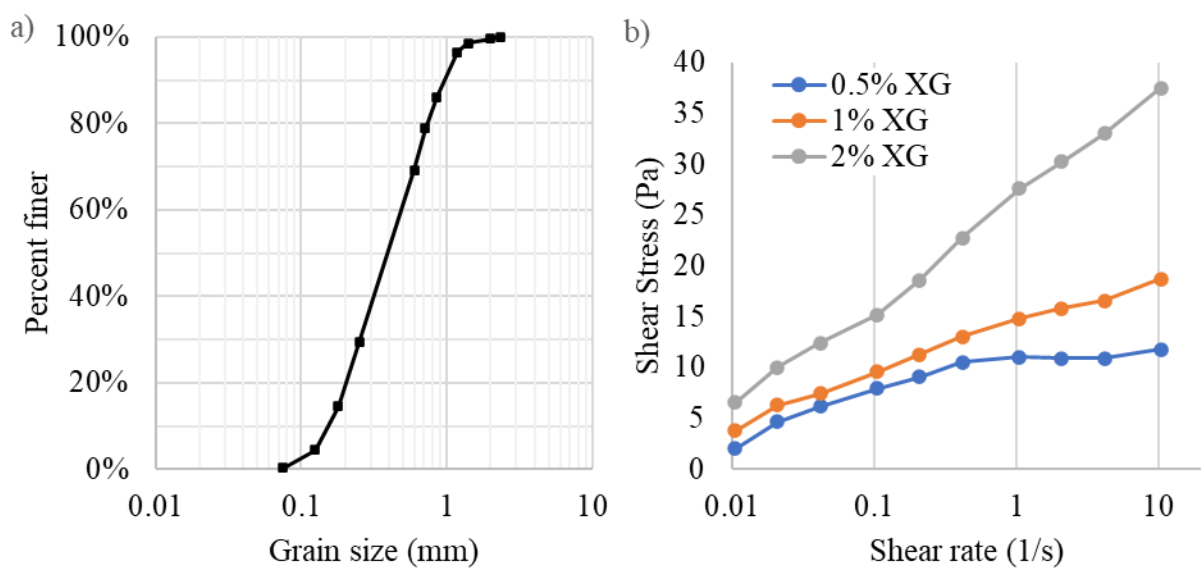

Figure 1. a) sand grain size distribution, b) rheology of xanthan gum-water mixtures

Rheological Properties of Xanthan Gum

To compare materials used in these experiments to those used in earlier studies (Casas and García-Ochoa, 1999, Morris et al., 1977, Mrokowska and Krztoń-Maziopa, 2019), the viscosity of the water-xanthan gum mixtures was measured using a DV Next Rheometer. Various concentrations of xanthan gum solutions were prepared, and rheological curves were generated for different water contents. A plot of shear rate (1/sec) against shear stress (Pa) is presented in Figure 1b, clearly indicating that higher xanthan gum concentrations, based on the mass of xanthan gum to mass of water, correspond to an increase in yield strength and viscosity, in agreement with previous studies with lower concentrations (Mrokowska and Krztoń-Maziopa, 2019).

Preparation of biopolymer-treated samples

Samples of sand and xanthan gum were prepared at the optimal water content to allow the comparison across experiments conducted with different xanthan gum mass concentration and shear stress. The optimal water content for each mixture was determined using the Standard Energy Proctor test (ASTM, 2021). The wet mixing technique outlined in Abdelaziz et al. (2019) was used, as this method ensures efficient polymerization of the xanthan gum and promotes uniform distribution of both the biopolymer and water within the mixture. To obtain the optimal water content, the required amount of water for each mixture was previously measured. This volume of water was gradually added and mixes with xanthan gum. The mixture was then stirred with a hand drill for about 45 seconds until a viscous gel-like mixture formed. This gel-like mixture was then added and mixed to the sand until a uniform mixture is obtained (Kotey 2024).

Experimental Setup

Figure 2 shows a schematic of the erodibility flume used in the experiments. The flume consisted of two modified 1.32 m³ tanks connected by a 4.9 m long and 26 cm wide channel. A sediment box with dimensions of 22 cm by 22 cm was positioned 2.8 m from the flume entrance. The sediment box, constructed from plexiglass, had a vertically adjustable platform connected to a cylindrical rod and jack. The jack, calibrated for precision, allowed the platform height to be adjusted at 3 mm increments for each quarter-turn. As sediment was eroded, the platform was incrementally raised to maintain the sample position relative to the flow.

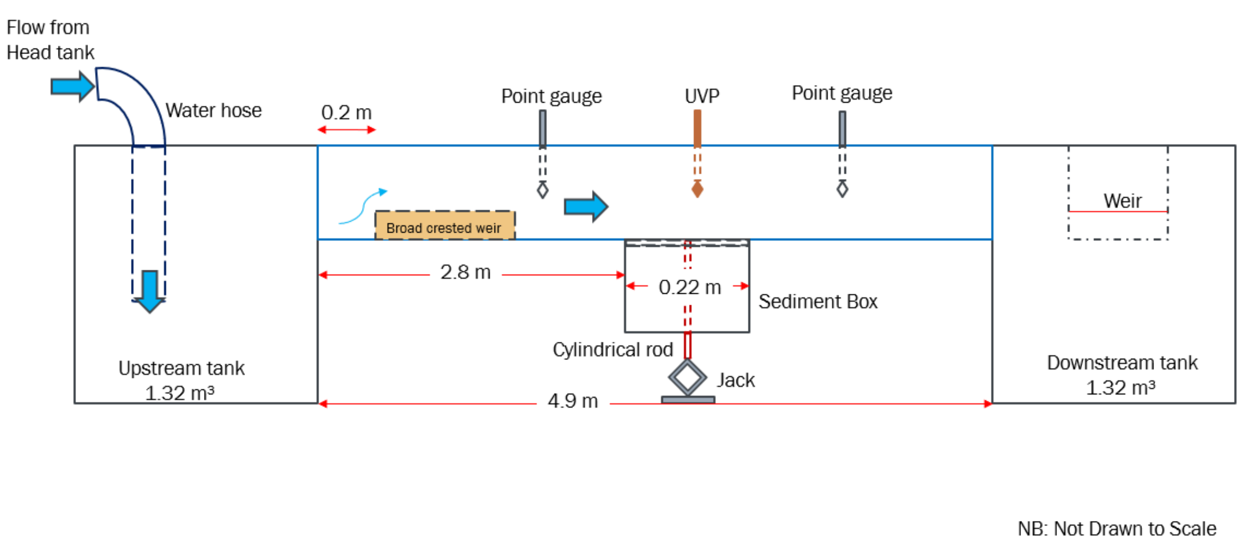

Figure 2: Schematic of the laboratory flume used for the experiment.

Water was supplied from a constant head tank to the upstream reservoir. Discharge was measured using a manometer attached to an orifice plate, and the water inlet into the flume was controlled by a weir system located in the upstream section. A tail weir at the downstream end regulated water levels and facilitated the return of water to the laboratory sump. Flow conditions during the erosion tests were characterized in terms of bed shear stress τ_b, as indicated in Table 1 with measured erosion rates.

Erosion Test

To prepare for the erosion tests, a compacted layer of highly concentrated xanthan gum-treated sand (1% xanthan gum) was placed on the movable platform in the sediment box. This layer served as an impermeable barrier preventing water seepage through the main sample. The primary soil sample was placed on top of the treated sand and compacted to minimize loose packing, which would have led to premature erosion. The top of the compacted sample was aligned with the channel surface and covered with a plastic lid to maintain its integrity during flume filling. Once the flume was filled with water, the lid was carefully removed, and the sample was raised to 3 mm above the channel bed to initiate the erosion test. Each experimental run lasted 30 minutes, consistent with previous erosion test protocols (Chen, 2006). As the sample surface was eroded, the jack was raised to maintain the sample surface at a relatively constant level above the channel bed. This process was repeated until the time for each run (30 minutes) has elapsed and then a new sample is prepared and placed in to begin another run. At the end of the experiment, the number of cranks, is then divided by the total time to attain the erosion rate:

$$erosion\ rate = \frac{\text{number of cranks x 0.3}}{\text{total duration of experiment}}$$

RESULTS

Measured erosion rates are provided in Table 1 for xanthan gum concentrations of 0.05%, 0.1%, and 0.15%, relative to the mass of sand. At higher xanthan gum concentrations and low shear stress, soil erosion was too low to be accurately measured in the experimental flume shown in Figure 2.

Table 1. Erosion rates in millimeters per minute of xanthan gum treated sand

	XG concentration		
τ_b (Pa)	0.05%	0.10%	0.15%
1.27	0	0	0
2.00	0	0	0
5.95	0.4	0	0
9.3	0.8	0.2	0.3
9.50	1.8	0.7	0.5
11.70	3.5	2	0.9

The data demonstrate a clear trend that as xanthan gum concentration increases, erosion rate decreases for a given shear velocity. This is attributed to the water absorption and swelling of xanthan gum within the soil pores, which forms a strong matrix that binds individual soil grains together, thereby resisting erosion.

Figure 3 illustrates the variation in erosion rate with bed shear stress for the different xanthan gum concentrations. As expected, erosion rate increases with bed shear stress at a constant xanthan gum concentration.

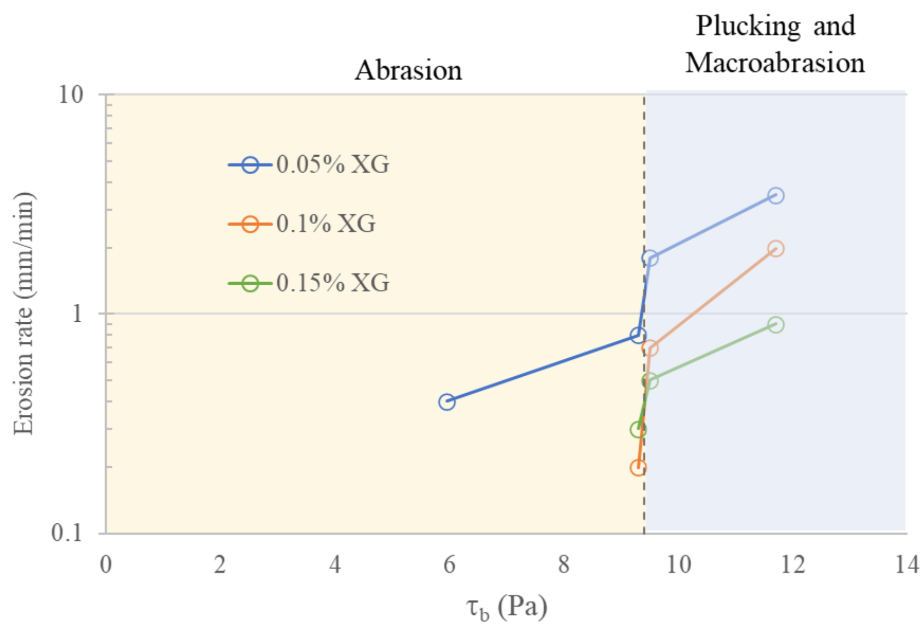

Figure 3. Erosion rate of xanthan gum treated sand for different xanthan gum concentrations. Shaded areas indicate the preferential mode of erosion, grain-grain abrasion when τ_b <= 9.3 Pa and plucking and macroabrasion when τ_b > 9.3 Pa

Notably, when the bed shear stress exceeds 9.3 Pa, there is an abrupt increase in erosion rate. This corresponds to a shift in the erosion mechanism, from grain entrainment typical of loose alluvium and abrasion, to plucking and macroabrasion, where soil lumps are dislodged and transported downstream. Lump size increases with xanthan gum concentration and shear stress. We can surmise that erosion rate will continue to increase as shear stress is increased, but it is not clear how much more erosion is to be expected. Given that higher shear stresses are common during embankment breaching at the field scale, more studies will be required to evaluate the erodibility of xanthan gum sands at such conditions.

CONCLUSIONS

Erosion tests on xanthan gum treated sand revealed that as xanthan gum concentration increases, erosion rate of treated sand decreases. Furthermore, at xanthan gum concentration as low as 0.05% and low shear stress the mode of sediment detachment is similar to abrasion with grain erosion that is typical of loose alluvium. As the shear stress increases, the mode of erosion transitions to plucking and macroabrasion with lumps detached and transported downstream. At xanthan gum concentrations of 0.1% and 0.15% grain-grain erosion is observed close to the initiation of significant motion and a slight increase in shear stress initiates plucking with removal of lumps. Further research is indeed necessary to fully characterize erosion and transport of xanthan gum-treated sand and to fully assess the applicability of xanthan gum as a soil additive in real-world scenarios.

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