

Debris flow mitigation by using biopolymers as a soil stabilizer

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Abstract. Towards rising the attention to the use of green materials in geotechnical applications, this study aims to introduce carrageenan as a new environment-friendly polymer for slope surface stabilization. A set of experiments were conducted to evaluate the performance of the biopolymer-treated soil to form a resistant surface against the surface erosion and debris flow. Samples were tested by changing a variety of effective parameters including biopolymer content, moisture content, curing time, soil type, and durability under wet-dry cycles. Kaolinite soil along with river sand in different combinations were employed and treated by various biopolymer proportions to optimize the biopolymer and soil parameters. Subsequently, the optimum mixture of each biopolymer-treated soil was subjected to 5 cycles of wetting and drying. A broad microstructural study by performing FTIR analysis and scanning electron microscopy (SEM) images was conducted and an analytical model was developed to clarify how biopolymer stabilize the slope surface. The results confirm the successful performance of carrageenan in connecting soil grains, increasing mechanical strength and durability of soil against surface erosion. It can be concluded that carrageenan can be considered as a sustainable alternative to conventional materials such as cement and lime.

1 Introduction

Whereas conventional materials enhance the engineering properties such as strength, stability, workability as well as the hydraulic features, they adversely affect the surrounding environment [1]. Cement is responsible for approximately 5% of global CO₂ emissions, causing detrimental damages to biodiversity and environment [2]. Among several methods and materials which have been developed to minimize the impacts of cement, biopolymer have shown to have a significant impact on soil improvement and reducing harm to the environment. Biopolymers are a type of natural polymer produced by living organisms. They can be divided into three major types: polynucleotides, polypeptides, and polysaccharides [3]. Sustainability, low carbon emission, renewable resource, and being biodegradable are the benefits of using biopolymers towards reaching a greener planet [4].

An annual cost of eight billion dollars is incurred by the global economy due to soil erosion caused by water. Biopolymer have been utilized for a variety of geotechnical applications including erosion prevention, hydraulic barriers, slope stability, and subgrade improvement [5]. The governing parameters that control the behaviour of the biopolymer-treated soils are biopolymer content, biopolymer concentration, curing time, soil type, and temperature. It has been shown that incorporating biopolymer into soil enhances its resilience to erosion and critical shear strength. Its strong erosion resistance is the result of boosting soil cohesion and decreasing soil permeability and void ratio [6].

Carrageenan is a biopolymer produced from natural linear sulphated polysaccharides [7]. Addition of a small quantity of Carrageenan reduced the soil loss imposed by water flow and wind by creating a resistant layer on the surface of soil [8].

In this study, carrageenan is introduced as a novel biopolymer to improve the slope surface stabilization. A set of laboratory tests were used to evaluate the characteristics of carrageenan treated soil. Durability under wetting and drying cycles were studied. Soil and biopolymer interactions were explained by providing SEM pictures and a schematic model.

2 Materials and methods

2.1 Soil

Kaolinite silt and sand were employed in this study. Kaolinite main chemical component is aluminum silicate. The soil is classified as high-plasticity kaolinite silt based with Skempton activity of 0.77%. A poorly-graded sand was the other soil used in this study.

2.2 Carrageenan

Carrageenan is a linear polysaccharide comprising long chains of sugar molecules. It is typically produced from red seaweed and utilized as thickener and stabilizer in food products. The biopolymer used in this work was Kappa-Carrageenan manufactured by the Tokyo Chemical Industry (TCI).

2.3 Experimental Program

Unconfined compressive strength test was used to assess the effect of biopolymer content, dehydration time, and soil type in slope surface stability. Durability of the treated samples was tested after 5 cycles of wetting and drying. SEM images were taken to visually express the interaction of the biopolymer and soil through a chemical model.

A labelling pattern was used to name different samples. K as kaolinite, S as sand, a number from 0 to 4 for kaolinite-sand mixture. For example, K1S3 shows a mix of 25% kaolinite and 75% sand.

3 Results

3.1 Biopolymer content

Figure 1 displays the compressive strength values for untreated and treated soils with varying quantities of carrageenan and xanthan (0, 0.25, 0.5, 1, and 1.5% by weight to dry soil). The treated samples were stored for 14 days in a controlled environment with a temperature of 23 °C and a relative humidity of 50-60%. On the basis of compaction test, the initial moisture content of K4S0 and K1S3 samples was estimated to be 35% and 15%, respectively.

As seen in Fig. 1, carrageenan increased the strength and stiffness of samples up to 0.5%, after which a reduction was observed. The highest improvement in terms of the soil type was for K1S3 due to its higher relative density and better soil particle size distribution.

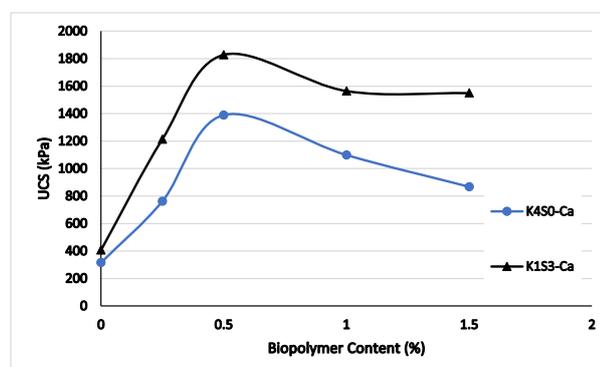


Fig. 1. UCS of untreated and carrageenan-treated soil by different biopolymer contents

3.2 Time

The effect of curing time on the compressive strength of carrageenan-treated soil was studied after 0, 1, 3, 7, 14, and 28 days of curing in a controlled environment. As per Fig. 2, after 24h from preparation, a growing trend in strength was started. More than 90% of the compressive strength was attained within the first 7 days from preparation, and the strength of the treated samples reached their maximum on day 14 and remained almost constant until the day 28. Therefore, in subsequent phases, 14 days was deemed to be the optimal duration.

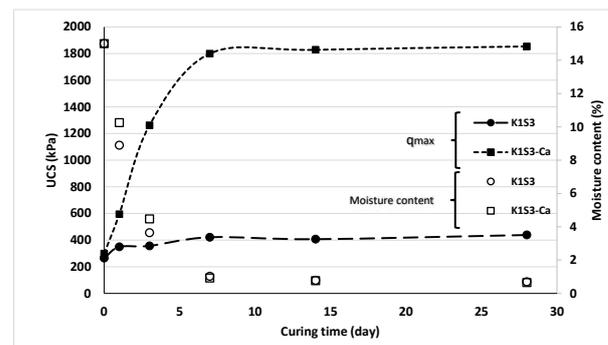


Fig. 2. UCS and moisture content variation with time

3.3 Soil type

Fig. 3 depicts the UCS test results for several sand-kaolinite combinations treated with 0.5% carrageenan and kept for 14 days. In sand-kaolinite combinations, the quantity of sand varies by 0, 25, 50, 75, and 100 percent. All samples had a moisture level of less than 1%, hence the impact of moisture may be disregarded.

As expected, the soil combination with 25% kaolinite and 75% sand (K1S3) provided the maximum strength. The small particles of kaolinite were distributed throughout the sand spaces to produce a dense soil mass, allowing K1S3 to reach the maximum dry density of all soil combinations.

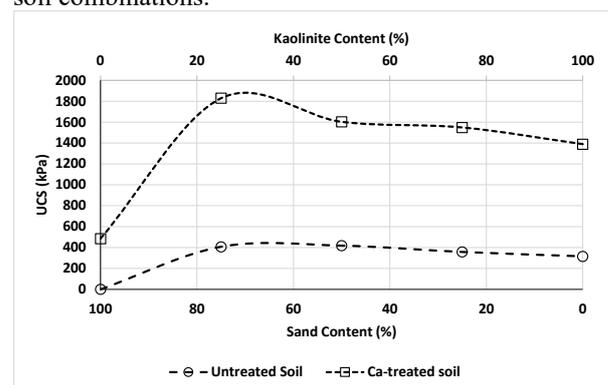


Fig. 3. UCS value by different soil type

3.4 Leaching capacity under wetting and drying

Figure 4 depicts the change in compressive strength and stiffness of untreated soil and carrageenan-treated soil (0.5% biopolymer) after cyclic wetting and drying operations. It reduces the strength and elasticity modulus of both untreated and treated soils. The reduction rate in UCS values was significant for untreated soil, with almost 50% after 3 and 80% after 5 wetting and drying cycles, whereas carrageenan maintained a viable level of strength after five cycles of wetting and drying, with carrageenan retaining 19.3% of the strength reduction. This suggests that, despite the fact that soaking in water adversely effect the strength, most of the bonds and interactions rebound substantially after drying.

The mass loss of the biopolymer lowered the amount of soil washed during the process of wetting and drying. Figure 5 indicates the shape of sample over the wet-dry cycles. Mass loss was reduced from around 80% for

untreated soil to 19% for carrageenan treated soil after 5 cycles.

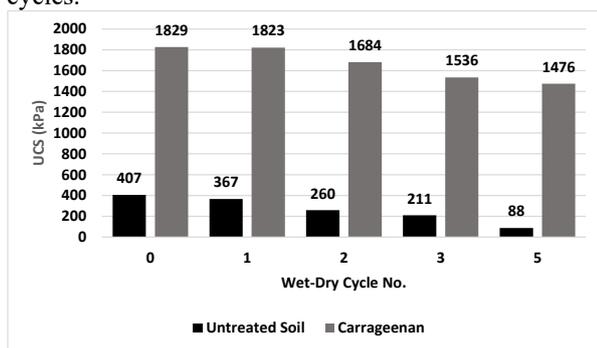


Fig. 4. Durability over wetting and drying cycles

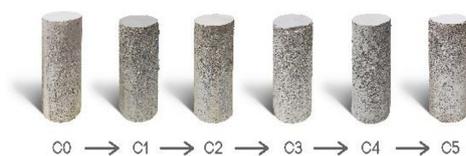


Fig. 5. Stability under cycle of wetting and drying

3.5 Microstructural Analysis

Figure 4 shows how carrageenan bind the soil particles through complex physiochemical interactions. There are several strong hydrogen interactions between oxygen atoms of tetrahedral silicate sheets and hydroxyl groups of octahedral aluminium hydroxide sheets in the interlayer region of kaolinite. Intermolecular hydrogen bonding is an interaction in kaolinite/k-carrageenan composite formation due to the presence of abundant hydroxyl functional groups on the surface of kaolinite (inner surface -OH) and organic functional groups, namely -OH and -SO₄, in the structure of k-carrageenan. A schematic figure of the existing interactions is provided in Figure 7.

The interfacial mechanical contact of the sand/k-carrageenan polymeric chain is the major driving factor for the production of the sand/k-carrageenan composite. The second driving factor in the composite structure is hydrophobic bonding between the uncharged surface of sand and the carbon chain of k-carrageenan.

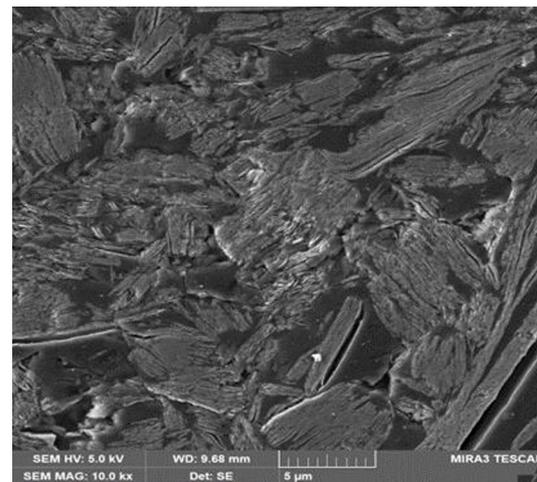


Fig. 6. SEM of carrageenan treated K1S3

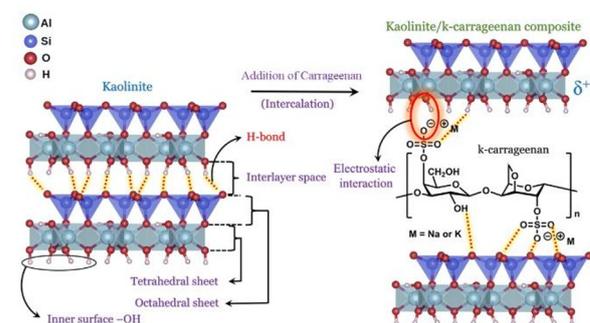


Fig. 7. Schematic figure of the biopolymer-kaolinite interaction

4 Conclusions

This study introduces carrageenan as a new source of sustainable material with the aim of soil improvement. Detailed research was performed to present the performance of the biopolymer. Carrageenan indicated a significant growth in the compressive strength in terms of biopolymer content, moisture content, and durability. Therefore, more research is encouraged to be done using carrageenan combined with various soil types.

References

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