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Efficacy of Cross-linking of Biopolymers in Soil Stabilization

M. Ashok Kumar[1][0000-0001-7432-3214], Arif Ali Baig Moghal[2][0000-0001-8623-7102], Jagadeesh Bommisetty[3][0000-0002-2662-2727] and Nuruddin Mohammad[4][0000-0002-2504-5075]

[1] Research Scholar, Department of Civil Engineering, National Institute of Technology Warangal, Telangana, India – 506004.
Assistant Professor, Department of Civil Engineering, CVR College of Engineering, Hyderabad, Telangana, India -501510.
`ma21cerep04@student.nitw.ac.in,m.ashokkumar@cvr.ac.in`
[2] Associate Professor, Department of Civil Engineering, National Institute of Technology Warangal, Telangana, India – 506004.
`baig@nitw.ac.in, reach2arif@gmail.com`
[3] Assistant Professor, Department of Civil Engineering, CVR College of Engineering, Hyderabad, Telangana, India -501510.
`b.jagadeesh@cvr.ac.in`
[4] Research Scholar, Department of Civil Engineering, National Institute of Technology Warangal, Telangana, India – 506004.
`mnce20224@student.nitw.ac.in`

Abstract. Soil stabilization relying on sustainable methods like BPST (Biopolymers-based Soil Treatment) has been gaining attention in the recent past. These biopolymers form a hydrogel between soil and pore water and the durability of hydrogel is affected under varying conditions. Crosslinking of biopolymers addresses this issue by forming hydrogels of enhanced physical and mechanical properties. In this present study, Xanthan gum (XG) and Guar gum (GG) were cross-linked with varying percentages (i.e., 1% GG and 2% XG) to treat clay of high plasticity. The performance indicators include Atterberg limits, Standard proctor compaction test, Unconfined Compressive Strength (UCS) test and Permeability tests. The test results have shown an increase in Atterberg limit values with an increase in the percentage of cross-linked biopolymer dosage. The standard proctor test results reveal that the Maximum Dry Density (MDD) of soil decrease and the UCS test results shows an increase in the UCS value, which is attributed to the suction of the soil specimen. Moreover, the coefficient of permeability (k) values decreased due to the filling of pores spaces with hydrogels.

Keywords: Biopolymer, Xanthan gum, Guar gum, Crosslinking, Hydrogel, Unconfined compressive strength.

1 Introduction

Mechanical, biological, and chemical soil improvement technologies are the three main categories of soil improvement technology. Cement and lime are the two most popular chemical stabilizing substances used to stabilize the soil chemically [1]. Although the traditional techniques are well known for their capability of improving the soil properties, they also result in the emission of Green House gases and recycling costs for cement and concrete. Recently, eco-friendly alternatives to conventional soil improvement techniques in geotechnical engineering have been investigated using biological methodologies including reactive enzymes, microbial polymers like biopolymers, and microbially induced calcite precipitation [2, 3]. Due to their natural origins, biopolymers manufacturing procedures are frequently less damaging to the environment and its biota. They can provide the same level of strengthening at far lower concentrations and are more environmentally benign than many other chemical soil additives. More significant usage of biopolymers could reduce the 1.25 tonnes of carbon dioxide that can be released into the atmosphere for every tonne of cement produced. Liner contaminant sorption and anti-seepage potentials are prime essential in the design of landfill. The clay minerals have high sorption capacity, long-term structural stability, and low permeability, which aids their usage as an efficient landfill liner. Bentonite clay has gained wide attention in the design of landfill liner systems due to its low hydraulic conductivity, high swelling capacity, and adsorption properties. According to the researchers, the soil stabilized with biopolymers has gotten industrial attention as a competent landfill liner due to its low permeability [4, 5].

Muhammad and Marri [6] observed from their investigations that adding stabilizing agents like lime and wheat straw to the clayey soil helps in enhancing the shrinkage and swelling properties. The nanomaterials were also used as stabilizing agents that showed an improvement in the shrinkage properties of the soil [7]. Imane et al. [8] investigated the effect of wheat straw addition on the swelling nature of clay soil. Ob- tained results of the investigation have shown that there is a considerable decrease in compressibility index and swelling index with an increase in the wheat straw content.

Researchers mentioned that the locally available soil could be used as a low-cost landfill liner material if it is stabilized by adding biopolymers [4, 5, 9]. By evaluating the parameters like unconfined compressive strength and hydraulic conductivity, they have assessed the suitability of a soil as a liner in landfill construction. Two biopolymers namely xanthan and guar gum, were added to the expansive soil in different dosages and their effect on hydraulic conductivity and unconfined compressive strength was evaluated. The results showed that the values of hydraulic conductivity decreased with an increase in consolidation pressure and biopolymer content. Reliability-based design optimization methodology was used to assess the performance of the soils. Their investigations focused mainly on the efficacy of soil modified by biopolymer as a substitute liner material for MSW. Appreciable improvement in anti-seepage has been observed in the soil after blending it with guar and xanthan gums. Dosages of the biopolymers needed to modify the cohesive soils at different curing periods were done by using target reliability-based design optimization and deterministic design. The results of these methods showed that when the guar gum concentration rises from 0.5% to 4%, the reliability index and factor of safety against failure increase drastically. On the other side, the dependability index and factor of safety continued to rise notably when the cohesive soils were blended with guar gum at a dose of 0.5% to 2.9%. Although the reliability index and element of safety are significantly decreased when guar gum is added to more than 2.9%, results show that it is the optimum dosage [5]. Studies like Fourier-transform infrared spectroscopy and electron microscopy on unamended and biopolymer-treated soils revealed that crosslinking of soil particles with gum strands has improved the strength properties of soil [9].

Chang and Cho [10] studied to check the suitability of using environment-friendly biopolymers for soil stabilization. A commercial β-1,3/1,6-glucan polymer product was used to stabilize the hwangtoh, a Korean residual soil. The residual soil was mixed with liquid type β -1,3/1,6-glucan polymer solutions and cured at different temperatures. Time-dependent compressive strength was determined to assess the strengthening process. A gain in the compressive strength of soil was observed and it is due to the particle surface sorption of biopolymer. However, the gain in strength was very high at a curing temperature of 60^0C. From a quick environmental/economic study, it was proved that the biopolymer treatment is more beneficial compared to conventional methods like cement stabilization and reinforcement. Chang et al. [11] investigated the usage of microbial polysaccharides called gellan gum to strengthen sandy soil. The effect of gellan gum on sandy soil was evaluated by performing different tests under various moisture conditions. They observed an enhancement of bonding between the sand particles with hydrogel condensation, which is due to the development of artificial cohesion by the microbial agent. Three different pore fluids, namely deionized water, kerosene, and 2M-NaCl brine were used to obtain the liquid limit values of sand and biopolymer-treated clay mixture. Adding xanthan gum to the soil can decrease the liquid limit attributed to particle aggregation or increase the liquid limit due to hydrogel formation [12].

Variation of adhesion and friction angle in the sand treated by xanthan gum due to the construction of subsequent structural members was explained by Lee et al. [13]. From the results, they concluded that a solid intergranular bonding was observed due to condensed biopolymer biofilm. They also stated that physical condition through the surface affects the interfacial shear. However, the rise of moisture content results in the reduction of intergranular bonding. Kwon et al. [14] investigated the significance of exocultered biopolymers in controlling the erodibility coefficient and critical shear stress of soil with different particle size distribution using an erosion functioning apparatus and ultrasonic P-wave reflection monitoring device. Chen et al. [15] performed UC tests to assess the possibility of replacing cement stabilization with the combined action of biopolymer and fiber inclusion in the soil. Results from the UC tests revealed that the combination of biopolymer and fibre inclusion was ineffective in managing the compressive strength and ductility of soil. Biopolymers were found effective in increas- ing the unconfined compressive strength, and fiber inclusion helped increase the soil ductility [15].

Vydehi et al. [16] mentioned that biopolymers could be used as an effective soil stabilizer in place of cement and fly ash to reduce the negative impact on the environment. By adding xanthan and guar gum biopolymers at different dosages to the soil, they evaluated shrinkage characteristics along with curling and cracking. Possible mechanisms behind the cracking phenomenon, particle arrangement, and curling state were explained.

Muguda et al. [17] mentioned that the hydrogels are responsible for the strength improvement of the soil. The mechanical properties and physical integrity of hydrogel depend on the properties of the biopolymer used and the time taken for the dilution of a hydrogel. They have concluded that crosslinking of biopolymer can be done to delay or avoid the dilution of hydrogels. He also mentioned that biopolymers xanthan and guar gum can instantly react and form crosslinks without any initiation.

With the benefits of biopolymers and their crosslinking, it becomes a prospective area for the study of biopolymers and their effects on various soil characteristics. The main goal of the present work is to study the efficacy of crosslinking of select biopolymers in enhancing the geotechnical properties. The targeted geotechnical properties include Atterberg limit, Standard proctor compaction test, Unconfined compression, and Hydraulic conductivity. Results are then compared and interpreted to better understand the effect of crosslinking of biopolymers on the geotechnical properties.

2 Materials and Methods

To determine the effectiveness of cross-linking of biopolymers for stabilizing the soil, Black cotton soil passing through a 4.75 mm sieve was used. Two biopolymers namely, Xanthan gum and Guar gum were added in different mix proportions to the soil for cross-linking.

2.1 Black Cotton Soil

Black cotton soil collected from the Ibrahimpatnam lake located beside Hyderabad-Nagarjuna Sagar Road (17.19^0 N, 78.63^0 E) is used for investigation. The physical properties of the soil such as Atterberg limits and compaction characteristics were determined according to IS 2720(Part V) and IS 2720(Part VII) respectively. Using the plasticity chart as a reference and based on the values of Atterberg limits, the soil was classified as clay with high compressibility (CH). Table 1 presents the physical properties of the soil used for investigation.

Table 1. Properties of unamended soil.

S.No	Property	Value
1	Liquid Limit	63.5%
2	Plastic Limit	30.5%
3	Compressive Strength	1.48 Kg/cm^2
4	Optimum Moisture Content	26%
5	Max. Dry Density	1.47 g/cc
6	Hydraulic Conductivity	5.24 x 10^{-3} cm/s

2.2 Biopolymers

The biopolymers used in this investigation namely Xanthan gum and Guar gum were purchased online from Nature’s velvet lifecare, Hyderabad. Basically, Xanthan gum comes under the category of anionic-based polysaccharide, which is a microorganism based and can be produced by fermentation of Xanthomonas campestris bacterium. Xanthan gum is being used widely in the oil, cosmetics, and paper industries as a thickening agent. Galactose and mannose are the two sugars we find in guar gum and it is extracted from the guar plant. It is available in both the cationic and anionic states and helps in hydrogel formation among all the particles of soil through bonds of hydrogen.

2.3 Crosslinking of Biopolymers

The hydrogels formed in the soil after adding biopolymers are responsible for improving soil strength. Hydrogel formations connected with the soil particles change their nature from a glassy to a rubbery state. The mechanical properties and integrity of the hydrogel depend on the properties of biopolymers added to the soil [5]. The outer chains of biopolymer absorb and holds water which results in the dilution of the hydrogel. The hydrogels formed start to dissolve in the water after desiccation and the time required for dissolving depends on the chemical properties of the biopolymer. To improve the mechanical properties and physical integrity of hydrogels, crosslinking of biopolymers is done where the outer chains of biopolymers react with the polymeric chains of another biopolymer [17]. The literature recommends that polysaccharide galactomannans like guar gum can generate cross links instantaneously with helix-forming polysaccharides like xanthan with no need for any initiation.

Crosslinking of biopolymers can be done in various methods such as physical, chemical, and enzymatic methods. Even though the properties of biopolymers can be improved by crosslinking, most of the crosslinkers may end up with unwanted changes in functionality or may lead to cytotoxicity. Physical crosslinking is used in this investigation as potential toxicity can be avoided and biomedically safe [4].

Biopolymers were mixed into the soil in different combinations as shown in Table 2. M0 refers to the unamended soil, M1 refers to 1% XG (Xanthan Gum) + 2% GG (Guar Gum), and M2 refers to 2% XG (Xanthan Gum) + 1% GG (Guar Gum) to the dry weight of soil.

Table 2. Combinations of biopolymers in soil.

S.No	Soil description	Dosage of Biopolymers	
		Guar-gum	Xanthan gum
1	M0	0	0
2	M1	2.0	1.0
3	M2	1.0	2.0

2.4 Tests Conducted

Atterberg Limits. The unamended soil mixture was sieved using a 425-micron sieve and kept in an oven for 24 hours at a temperature of 100±55^0 C [18]. Oven-dried soil was used for conducting the Atterberg limit tests using Casagrande liquid limit apparatus (Fig. 1).

Fig. 1. Atterberg limit tests.

Compaction Tests. Compaction characteristics of unamended and biopolymer-treated soil were determined using the test procedure in IS 2720-7 [19]. Biopolymers were added to the soil in the amounts mentioned in Table 3 before adding the water and thoroughly mixed to obtain a uniform mixture. The soil was compacted into a light-weight compaction apparatus and the values of optimum moisture content (OMC) and maximum dry density (MDD) were determined (Fig. 2).

Fig. 2. Standard proctor compaction test setup.

Compression Strength Tests. Unconfined compression strength (UCS) tests were conducted for all the soil mixes M0, M1, and M2 as per IS 2720-part10 [20]. Three cylindrical specimens of size 38 mm in diameter and 76 mm in length (l/d ratio=2) were prepared for each trial mix by adding water content equal to optimum moisture content (OMC). Specimens were tested in the compression testing machine and sheared at a rate of 0.6 mm/min, and the values of peak stresses were noted (Fig. 3).

Fig. 3. Unconfined compression test setup.

Hydraulic conductivity test. The soil was compacted into the permeameter mould by adding water equal to OMC and compacted it to the required density. Water was allowed to pass through the soil compacted in the permeameter to make it saturated [21]. The variable head permeability method was used in this investigation, and the hydraulic conductivity was calculated using the appropriate formula (Fig. 4).

Fig. 4. Permeability test setup

3 Results and Discussions

3.1 Variation of Atterberg limits

Table 3 shows the values of Atterberg limits of unamended and biopolymer stabilized soil. Values of liquid and plastic limits for the soil mix M0 were 63.5% and 30.5%, respectively. After the stabilization of soil by crosslinking the biopolymers, the liquid limit, and plastic limit values were increased. For the soil mix M1, the liquid limit value increased to 111.7% and the plastic limit increased to 41.93%. For the soil mix M2, the liquid and plastic limit values were increased to 144% and 54.6%, respectively. From the values of plastic and liquid limits of soil after crosslinking with biopolymers, it can be noted that the effect of crosslinking on the plastic limit and liquid limit is considerable.

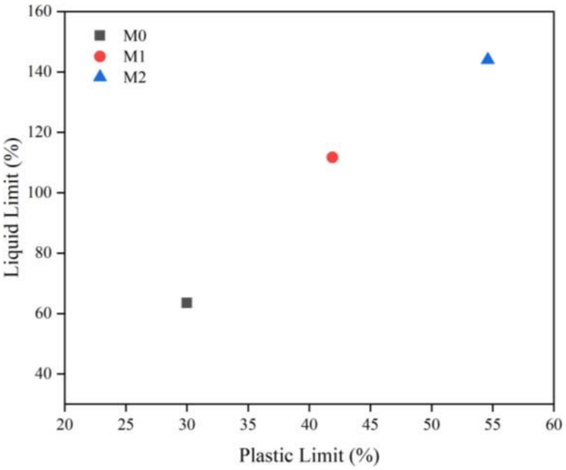

Fig. 5. Variation of Atterberg limits at different biopolymer combinations.

By observing the values of Atterberg limits for unamended soil and modified soil, it can be noted that the plasticity index is drastically increased. The increase in plasticity index of stabilized soil for the soil mix M1 is around 110%, and for the soil mix M2 is 170%. Increment of GG content in the soil resulted in the rise of the plasticity index. From Fig. 5, it can be observed that there is an effective change in the values of plastic and liquid limit after adding biopolymers to the soil and crosslinking them.

Table 3. Variation of Atterberg limits.

S.No.	Soil Description	Liquid limit	Plastic Limit
1.	M0	63.5%	30%
2.	M1	111.7%	41.9%
3	M2	144%	54.6%

The rise in values of liquid limit is a result of the chemical properties of biopolymers and the chemical reaction they undergo with the clay particles. Added to the soil matrix and mixed with it, hydroxyl ions in guar gum interacts in two essential ways. Initially, the pore water in the soil interacts with hydroxyl ions of guar gum and its viscosity gets increases. Due to this, the liquid limit of the soil also increases. Secondly, soil agglomerations occur when biopolymer chains interact with clay particles and is due to the reduction of soil particle surface area. Soil's liquid limit is determined by the combination of these two interactions. Being a neutral polysaccharide, guar gum interacts with clay particles in soil to form hydrogen bonds. Thus, the soil with higher guar gum has a higher liquid limit than soils with other stabilizing agents [5].

3.2 Variation of compaction characteristics

Table 4 shows the variation of Maximum dry density (MDD) and optimum moisture content (OMC) for unamended and modified soil. There is an increase in optimum moisture content and a decrease in dry density values for the soil mix M1.

Table 4. Variation of compaction characteristics.

S.No.	Soil combination	Max. dry density (g/cc)	Optimum moisture content (%)
1.	M0	1.47	26%
2.	M1	1.25	28%
3	M2	1.23	29%

A slight increment in the value of optimum moisture content and fall in the dry density of soil was observed after increasing the amount of Xanthan gum in the soil to 2% in the soil mix M2. The reason for the reduction of MDD after adding biopolymers to soil is attributed to the increase of biopolymers filling the void spaces and adhering to soil particles. This improves the resistance of the resultant soil-biopolymer matrix against applied compaction energy [9]. An increase in optimum moisture content is due to the adsorption of water which helps to dissolve the biopolymer content [9]. It may also be due to the higher affinity towards the water and the viscous nature of xanthan gum. As shown in Fig. 6, considerable change was observed in both optimum moisture content and maximum dry density after adding biopolymers to stabilize the soil.

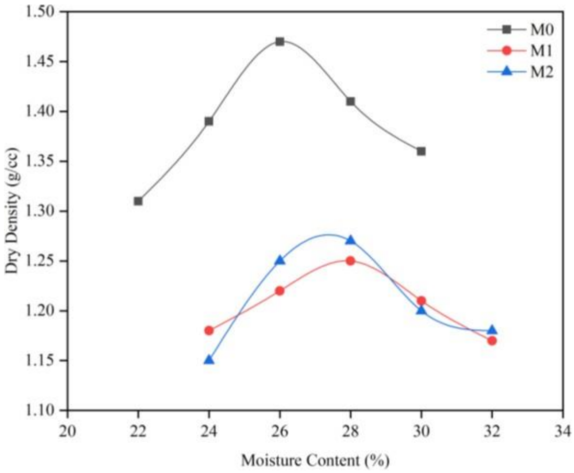

Fig. 6. Variation of MDD and OMC for different combinations of biopolymers.

3.3 Variation of Unconfined Compressive strength

Table 5 shows the variation of compressive strength of soil for the unamended and soil modified by adding biopolymers.

Table 5. Compressive strength characteristics of soil.

S.No	Soil combination	Compressive strength (Kg/cm^2)
1	M0	1.48
2	M1	1.862
3	M2	1.815

The average compressive strength of unamended soil is 1.48 kg/cm^2. By the inclusion of biopolymers in the soil as per the mix M1, the compressive strength of the soil was increased to 1.862 kg/cm^2, and it may be due to the formation of hydrogel and soil suction. Guar gum added to the soil helps transform the hydrogels to a glassy state on drying and is also a reason for the improvement of compressive strength. No considerable change in the compressive strength of soil is observed after increasing the xanthan gum and decreasing the guar gum to 2% and 1%, respectively (Fig. 7).

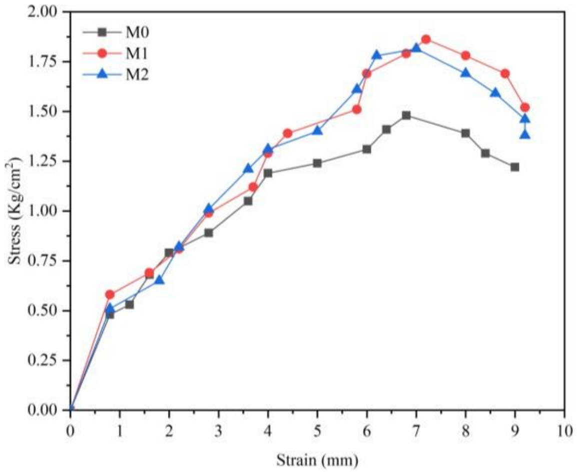

Fig. 7. Variation of stress and strain in UCS test for different combinations of Biopolymers.

3.4 Variation of hydraulic conductivity

Table 6 shows the values of the coefficient of permeability for unamended and amended soils. A considerable decrease in the value of the hydraulic conductivity is seen after adding the biopolymers to the soil.

Table 6. Permeability characteristics of soil.

S.No	Soil combination	Coefficient of permeability (cm/s)
1	M0	5.24×10^{-3}
2	M1	1.25×10^{-3}
3	M2	1.23×10^{-3}

The hydrogels formed in the soil after adding biopolymers to the soil fill the pore spaces available in the soil and thus decrease the tendency of water to flow between the soil particles. The biopolymer added to the soil reacts with water and turns it into leachate and decreases the permeability of the soil. The clay particles surrounded by water molecules will create a narrow flow path to the water and result in a decrement in the soil's hydraulic conductivity [22-23].

4 Conclusions

In this study, variation of strength and permeability characteristics of high compressible clay after adding biopolymers has been investigated. Both guar gum and xanthan gum instantly interact with soil particles and form cross-links without adding any initiating agents. Both Guar and Xanthan gum were added to the soil at different dosages and tests like Atterberg limits, standard proctor compaction, Unconfined compression, and permeability were conducted. Following were the conclusions drawn from the investigation.

- The addition of biopolymers to soil was found to increase in both liquid and plastic limits. For the soil mix M1, the liquid limit was 111.7% and it is 75% more than the soil mix M0. The plastic limit was 41.9% and it is 40% more than the soil mix M0.
- Both liquid and plastic limits of soil were increased when the biopolymers were mixed as per the soil mix M2. The liquid limit was 144% and the plastic limit was 54.6%. Rise in the liquid and plastic limits was 126% and 82% respectively.
- The rise in plasticity index of soil mix M1 is around 110% and for the soil mix M2 is around 170%.
- MDD of unamended soil M0 is 1.47 g/cc. Inclusion of the biopolymers in the soil has shown a fall in the values of soil MDD. For the soil mix M1 and M2, values of MDD were 1.25g/cc and 1.23 g/cc respectively. This could be due to the resistance offered by the soil-biopolymer mix to the applied compaction energy.
- The inclusion of biopolymers in the soil mix has shown an increase in compressive strength. For unamended soil mix M0, compressive strength was 1.48kg/cm^2. For the soil mix M1 & M2, compressive strength was 1.862 kg/cm^2 and 1.815 kg/cm^2 respectively. The rise in compressive strength of soil mix M1 after adding biopolymers was around 25%.
- No appreciable change in compressive strength was observed for the soil mix M2 when compared to the soil mix M1.
- Hydraulic conductivity of unamended soil (M0) is 5.24 x 10^{-3} cm/s. Crosslinking of biopolymers in the soil to the dosage of M1 has reduced the hydraulic conductivity to 1.25 x 10^{-3} cm/s and no change was observed when the dosage of both guar gum and xanthan gum were interchanged in the soil mix M2. For this reason, higher dosages of xanthan gum are not required to improve the compressive strength and permeability of the soil.

By analyzing the results from this investigation and available literature on methods of stabilization, it can be concluded that cross-linking of biopolymers is more effective in improving the geotechnical properties and is environmentally sustainable. More research needs to be done on crosslinking of biopolymers to understand the mechanism involved in it and to check the durability of biopolymers in the long run to replace the existing biopolymers.

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