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Civil Engineering Journal

Vol. 5, No. 9, September, 2019

Sustainable Improvement of Expansive Clays Using Xanthan Gum as a Biopolymer

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Received 31 May 2019; Accepted 17 August 2019

Abstract

In this study, Biopolymers are used as an attempt to create sustainable environment by eliminating the negative environmental impacts of using traditional admixtures in soil stabilization. Xanthan Gum is used as a biopolymer to treat expansive soil. A series of tests like, Standard Proctor Test, Unconfined Compressive Strength (UCS), One-Dimensional Consolidation and Standard Direct Shear tests were conducted on virgin soil and biopolymer (0, 0.5, 1, 1.5, 2, 2.5%) treated soils. The results revels that by addition of biopolymer content Maximum Dry Density (MDD) of soil decreases and Optimum Water Content (OMC) increases. The UCS value is increased by 4 times for the addition of 1% xanthan gum to soil for 28 day curing period. Compressibility of soil is deceased by 65% for 28day curing period. Shear parameters of treated soil shows improvement with addition of xanthan gum content. For further examination, SEM analyses were conducted on the tested samples and revealed that the soil fabric had white lumps and pores in the soil structure were filled with cementitious gel. Moreover, the resistance towards shear and compressibility of treated samples increased with curing times. Therefore, use of Xanthan Gum for soil stabilization is a solution for eco-friendly soil stabilizing material.

Keywords: Xanthan Gum; Natural Biopolymer; Sustainable Improvement; Soil Fabrics; Microstructure Analysis.

1. Introduction

The soil treatment processes are used to modify different properties of soil for instance strength, stability, and permeability and erosion resistance. Soil stabilization process includes biological, chemical, electrical, and mechanical mechanisms of soil improvement [1-3]. Cement, fly ash and/or lime are commonly used in improving the Geotechnical properties of soil; however, the principles of sustainable development state that there should be limited use of water and non-renewable energies, so as to reduce the emission of greenhouse gas like CO_2 (Carbon dioxide) and NOx (Nitrogen oxides) and suspension of particulate matter in air [4]. The cement used in soil treatment can remain in the soil for extremely long durations due to the low degradability of cement mixtures. The presence of cement in the soil can disturb the ecosystem by raising pH level and increase desertification effects [5]. Thus, it is necessary to determine eco-friendly materials for the treatment of soil [6]. Most of the eco-friendly additives, such as acids, enzymes, ions, lignin derivatives, polymers, resins, and silicates, are in powder or liquid form and are naturally happening or may be organized through a natural method [7, 8]. Similarly, water-insoluble gel-forming microbial biopolymers that are industrially produced can be used in the treatment of soil as it encloses a bioremediation zone and mitigates soil liquefaction. Some of these biopolymers are chitosan, polyhydroxybutyrate, polyglutamic acid, sodium alginate, and xanthan gum [9, 10]. Many research works have demonstrated the potential applications of bio polymeric treatments in

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http://dx.doi.org/10.28991/cej-2019-03091380

the construction industry. Use of biopolymer in Geotechnical applications reduces permeability of sands and silty sands by void filling [11, 12]. It increases shear parameters of soil and used as a soil binder by forming gel - clayey matrix via strong hydrogen bonding [13]. Application of biopolymer to fine grain soil decreases compressibility and increases shear strength, in case of water scarcity it directly reacts with clay particles and form hydrogen bonding or it accelerated by alkalis metals present in earth soil [14]. Furthermore, as biopolymers are easily available in nature and known for its eco-friendliness; researchers are showing interest in application of biopolymers. Many polysaccharide group biopolymers have been examined recently for civil and geotechnical applications.

The main goal of this study is to use biopolymer based stabilizing material to reduce the environmental effects and move towards sustainable development, in the present study Xanthan Gum as a biopolymer have been examined for their geotechnical properties of high-plasticity clays. The Xanthan Gum is a biodegradable polysaccharide generated by organisms such as algae, bacteria and fungi. In general, expansive soils are more problematic in geotechnical applications due to their swelling, low strength and high compressibility. For this reason, the authors performed an extensive study on the characteristics of clay improved by xanthan gum biopolymer. For comparing the behaviours of untreated and stabilized clays, multiple Direct Shear (DS) tests, Unconfined Compression Strength (UCS) tests, and 1-D consolidation tests were performed. The obtained results and the related discussion can help researchers to gain an insight into clay stabilization by xanthan gum biopolymer.

2. Material and Methods

Figure 1 explains the experimental test procedure and the analysis of test results which are investigated in the present study.

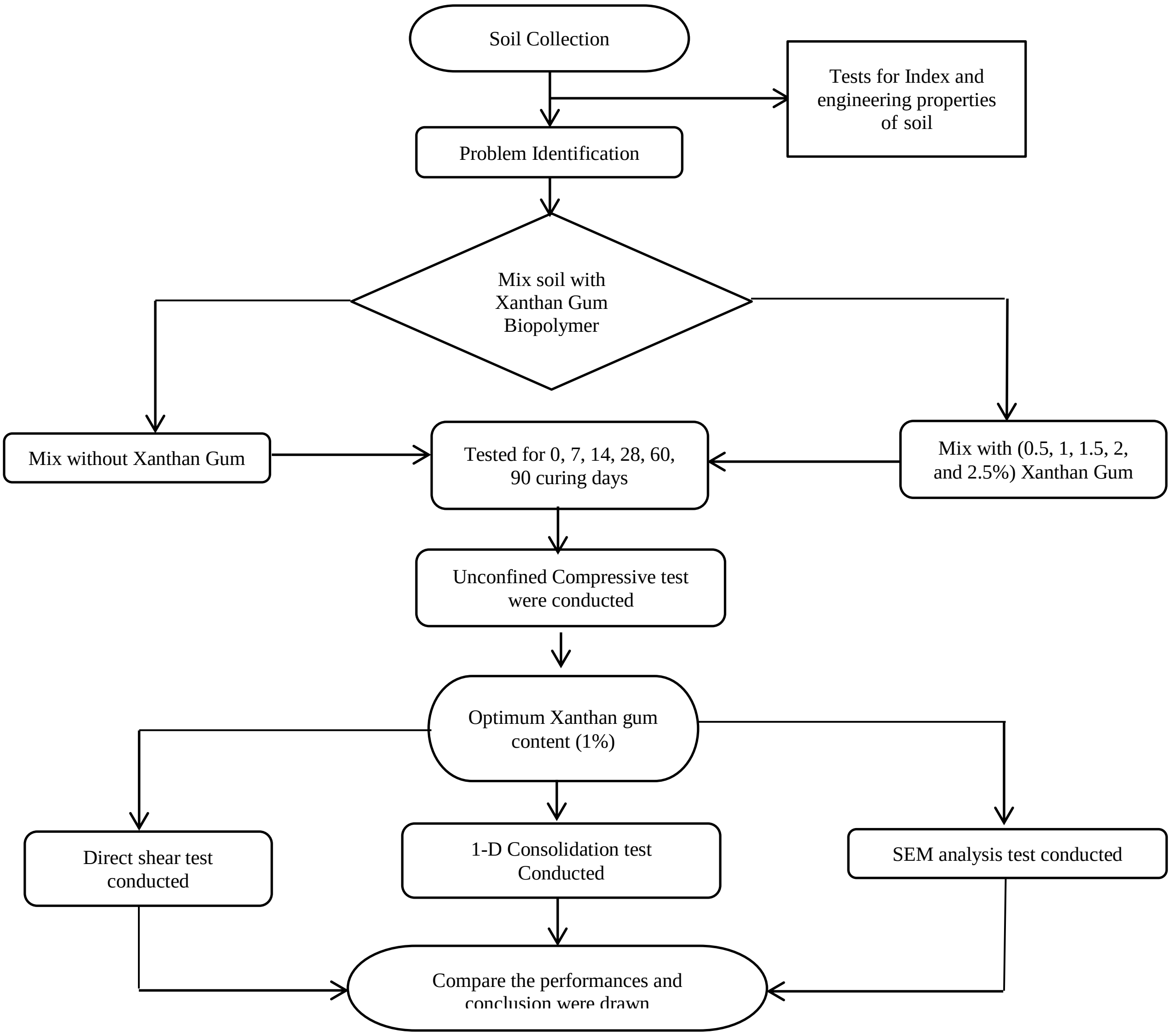


Figure 1. Flow chart of Experimental test procedure and results analysis

2.1. Soil

For this study, the clay samples having a 91 % liquid limit and 39% plastic limit were collected from Kurnool, Andhra Pradesh, India. The clay grains had a specific gravity of 2.56. According to the Indian Standard Soil Classification, the collected clay samples have been classified as high-plasticity clay; the free swell index of clay is approximately 160% and the soil is classified as expansive soil.

2.2. Xanthan Gum

When sugar is aerobically fermented by the bacterium Xanthomonas campestris, it produces an anionic polysaccharide known as xanthan gum. This polysaccharide contains a linear 1,4-linked β- D-glucose chain in which every two elements is paired with a charged trisaccharide side chain that is collected by a D-glucuronic acid element-linked between two D-mannose elements [15]. Since it is an anionic biopolymer, xanthan gum can absorb water molecules by forming hydrogen bonds and forms viscous hydrogels [16]. Due to its high viscosity, xanthan gum is generally utilized as an additive for drilling muds in the petroleum and mining industries and as fluid thickeners in the food industry [17]. Also, its anionic and hydrophilic surface facilitates interactions with cations [18, 19] and other polysaccharides such as acetate, glucose mannose, potassium gluconate, and pyruvate. This results in the formation of stronger hydro gelation [20].

2.3. Sample Preparation

The soil samples were first collected from 2 meters below the ground level by hand and dried under the sun for a week and then sieved. After being air dried, the soil samples had a water content of around 2%. In this study, we used the wet mix method to prepare all the samples. In this method, the processed soil sample was mixed with the biopolymer solution of different concentrations to increase the moisture content of the samples to 8% ±0.1. The concentration of the solution was measured by dividing the weight of the biopolymer powder by the overall weight of the solution in percentage. In this study 0.5%, 1%, 1.5%. 2% and 2.5% concentrations of biopolymer solution were used. For preparing the solution, the biopolymer additive was added tenderly to the water to ensure no clumps are formed, and then the mixture was stirred till a homogenous solution was obtained.

2.4. Test Procedure

The standard Proctor soil compaction test was performed in accordance with IS: 2720 (Part 7) to measure the soil’s Maximum Dry Density (MDD) and its corresponding Optimal Moisture Content (OMC) with biopolymer at different concentrations. Both treated and untreated soil samples were arranged at their optimum water content for performing strength, durability and compressibility tests.

For both treated and untreated soil specimens, the UCS test was performed according to the guidelines mentioned in IS: 2720 (Part 10). For preparing homogeneous UCS specimens, the stabilizing additive and distilled water were added to the tested clay soils at their optimum water content by means of hand-mixing with palette knives. The mixture was then compacted in a split rounded mould measuring 3.8 cm in diameter and 7.6cm in height to produce specimens having the Standard Proctor maximum dry unit weight. The specimens were then extruded in an air tied film and cured for the different interval at different temperature settings. The untreated specimens were cured for 0 days while the stabilized specimens were cured at 7, 14, 28, 60 and 90 days within a room having controlled temperature of 20°C, an oven temperature at 40°C, and in submerged conditions. For the determination of accurate results, three specimens were prepared for each additive contents, and curing periods. For UCS testing, the strain rate considered was 1.5mm/min. In addition, the axial load and axial deformation were recorded using an automated data acquisition unit, in which the failure point was considered as the peak stress in an axial direction. After UCS testing, the samples that failed were the first oven dried and then weighed for its water content.

For untreated and stabilized specimens, the direct shear test was performed according to IS: 2720 (Part 13). Based on the results of the UCS test, the optimum additive content of 1% was maintained in the stabilized specimens. Then, appropriate proportions of xanthan gum, clay soil and distilled water were thoroughly mixed with the specimens. The resultant additive was compacted into the shear box of length 6 cm, width 6 cm, and height 2 cm so as to obtain the OMC and MDD by standard Proctor test [21]. The obtained specimens were cured for 7, 14, 28, 60 and 90 curing days in ambient temperature at 20°C. This value of maximum displacement was determined according to the capability of the apparatus used for the Direct Shear Testing machine. Normal stresses of 28, 56, and 112 kPa were applied to the specimens obtained after direct shear testing [22]. The values of normal and shear stress at failure point were taken to get Mohr-Coulomb failure envelopes for both stabilized and unstabilized samples.

For both the untreated and untreated samples, 1-D consolidation tests were performed according to IS: 2720 (Part 15) at the optimum percentage of admixture is taken from the results of UCS tests. For the consolidation test, appropriate proportions of xanthan gum, clay soil, and distilled water (at the target OMC value) were first added to the specimens. Then the resultant mixture was compressed statically into an odometer ring measuring 5 cm in diameter and 2 cm in height taken by Standard Proctor test results. Before conducting the test, treated specimens were immersed in water for complete saturation. While testing, by increasing vertical loads from 12.5 to 800 kPa were imposed on each specimen such that each load was twice as the previous load. After achieving 800 kPa, similar increments from 800 to 1000 kPa was applied to the specimens for unloading. For every loading and unloading, the vertical load applied on the specimen was kept constant for 1 day, and the values corresponding to settlements were noted for every time periods.

3. Results and Discussion

3.1. Compaction Characterization

Under Standard Proctor test, the soil is compacted to a particular level of density after it is mixed with a stabilizing material. This process is used for enhancing the surface soil layer. The newly achieved density also influences mechanical characteristics such as settlement and bearing capacity and shear strength. Thus, the compaction behavior of clay soil was studied with respect to different concentrations of biopolymer. It was observed that when the concentration of xanthan gum biopolymer was increased from 0 to 2.5%, the value of maximum dry density reduced from 16 to 13.7 kPa. This could be because of the physical categorization of the biopolymer solution, particularly its viscosity, and partial weight of soil. Due to viscosity, the soil particles are dispersed randomly because of their lightweight, resulting in the overall reduction in soil density as shown in Figure.2. Moreover, this viscosity is increased with increase in the concentration of the solution, resulting in a further reduction in the soil density [23]. Increasing concentration of solution also increased the optimum moisture content from 32% to 37.3% due to the increased absorption of water used in dissolving the biopolymer.

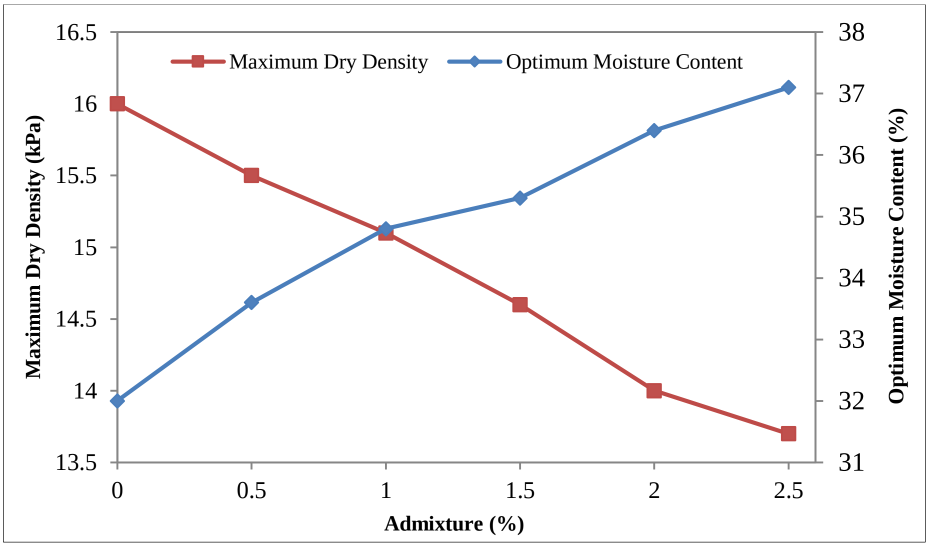
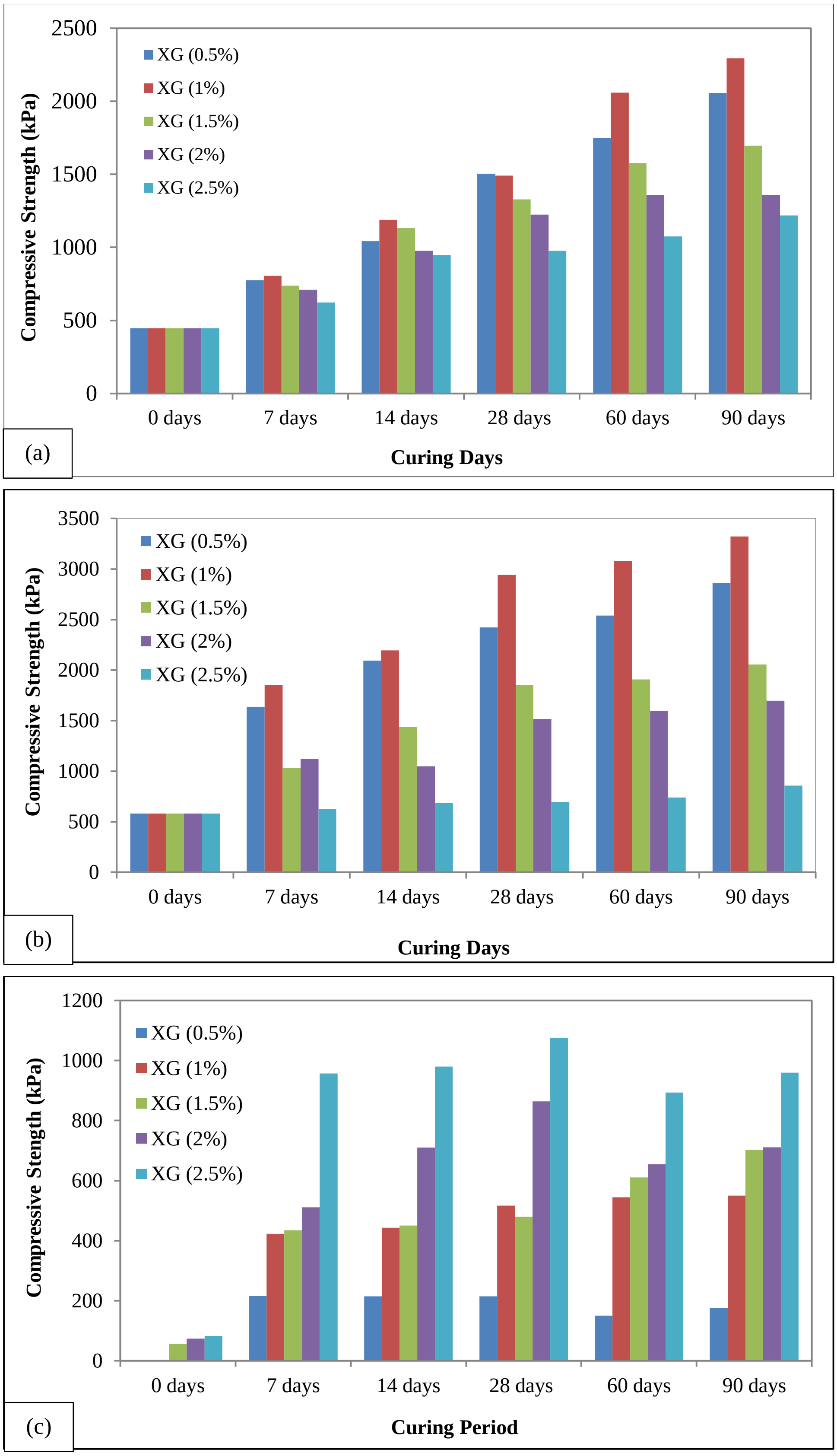


Figure 2. Compaction characterizations for soil biopolymer mixtures

3.2. Unconfined Compressive Strength

Figure.3 shows that the stabilized soils had much higher UCS value than the untreated virgin soils. In addition, the strength increased with curing period and an increase in additive content. Moreover, it was showed that the UCS values of treated clay have significant increase within the initial curing periods (28 days), whereas an increase in strength observed thereafter is minimum (up to 90 days). This indicates that about 80% or more chemical reaction occurred within the first 28 day curing period. With the increase in xanthan gum content up to 1%, the UCS value of treated clay increased significantly, as shown in Figure 3(a, b). But with further increase in the xanthan gum content, the UCS value continued to increase, but at a slower rate than the previous loading percentage of xanthan gum. As a result, it was found that the optimum xanthan gum content required for ambient curing and oven curing (at 40°) of the soils tested was 1%. For soil cured under submerged condition, the optimum value of xanthan gum was 2.5%, as shown in Figure 3(c). When mixed with xanthan gum having a concentration of 1%, the UCS value of 28 day blended sample increased to 1,504 kPa, which is about four times the UCS value of untreated clay of 447kPa. Similarly, in submerged condition xanthan gum clay mixture having a concentration of 2.5%, the 28 day curing period UCS test value is increased to 1,075 kPa, which is about 12 times the corresponding value for untreated clay (i.e., 83 kPa). Moreover, when xanthan gum of 1% concentration was mixed with treated clay, the 28 day UCS value under dry condition increased to 2,941 kPa, which is about five times the corresponding value for untreated clay (i.e., 580kPa).

Figure 3 shows the difference in values of the optimum content of xanthan gum with respect to oven curing (1%), ambient curing, and under submersion curing (wet curing) (2.5%). This difference in content values attributes to the different lattice linkage characteristics at the microstructure level. Figure 3(d) shows the values of optimum xanthan gum content for the treated sample under different curing conditions and different days. In general, the increase in strength is due to the formation of cementations materials that bind the soil particles and blocks the void spaces in the xanthan gum-clayey framework. It is known that clay and polysaccharides have strong microstructure interactions with each other [17, 22]. Through cation interactions and bonding between the hydroxyl (–OH) groups and carboxyl group (–COOH) of xanthan gum and due to electrically charged surfaces of clay particles, the monomers of xanthan gum can directly bond with clayey particles [24, 25]. Treatments of clayey soils with xanthan gum for the different curing periods at a lower additive contents gets higher UCS values compared to treatment with lime at a higher level of additive content. These findings indicate the superior mechanical results of xanthan gum compared to lime stabilization, taking into consideration that xanthan gum is an edible, non-toxic and eco-friendly stabilization alternative



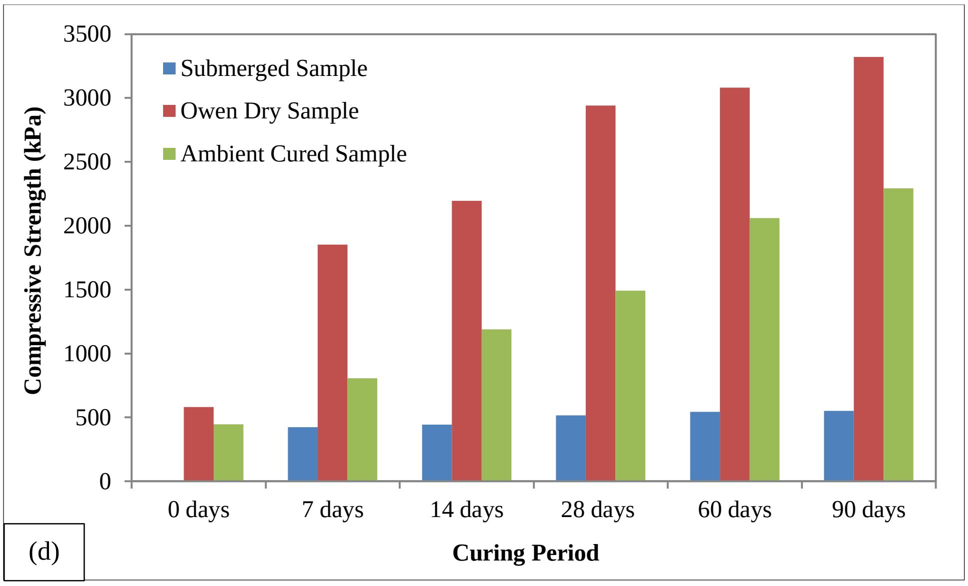
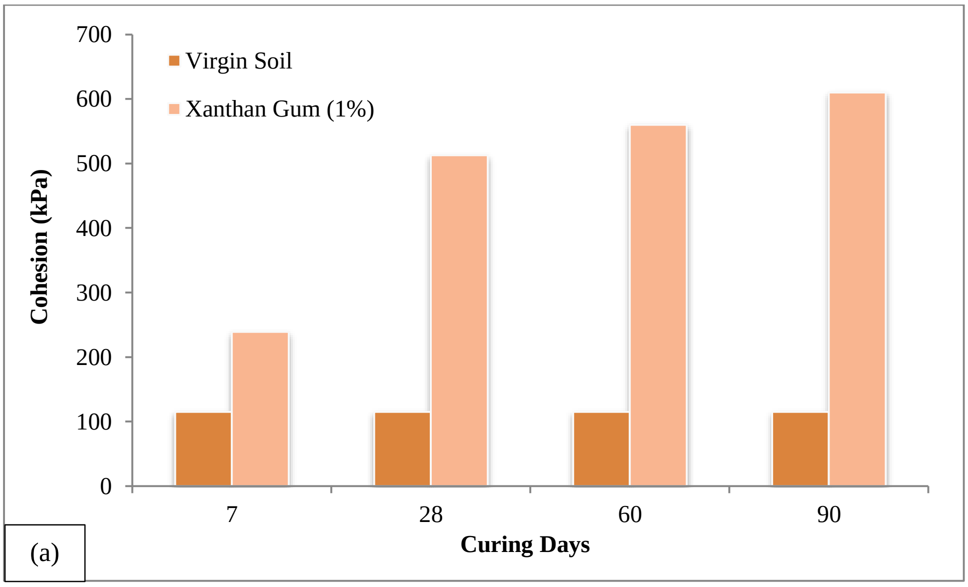


Figure 3. Unconfined compressive strength of treated sample for different curing days (a) for ambient curing condition (b) for oven dry curing (40 degrees) (c) for the submerged condition (d) optimum percentage of xanthan gum for different curing periods

3.3. Direct Shear Strength

In geotechnical engineering structures, adequate shear strength is more vital for determining the probability of failures in shallow foundations, earth retained structures, earth dams, pavements, natural slopes, cuts, and earth fills. In other words, under expected maximum loading condition, shear strength is essential to every structure for its overall stability and performance. In our study, Direct Shear Tests were performed to measure the different shear parameters of xanthan gum blended and unblended samples at various curing periods. Figure.4. shows the shear parameters for stabilized soils and virgin soil. Untreated specimens refer to those specimens cured for 0 days before examine, while the treated samples are those cured for 7, 14, 28, 60 and 90 days before testing. It was found that the cohesion values of the treated specimens significantly increased and the values of internal friction angle minorly increased with increasing curing periods. This behavior is similar to that observed for cement-treated clays as reported in a previous study [26]. The angle of internal friction value increased from 18.6° to 22.3° after 28 days curing period and increased to 24.4° after 90 day curing period. The cohesion for 28 days cured soil was 513 kPa, which is 5 times higher compared to untreated soil (114 kPa). The cohesion was increased to 610 kPa for 90 day curing period. Which indicates that major enhancement occurs in shear parameters within the short curing days than longer curing days.



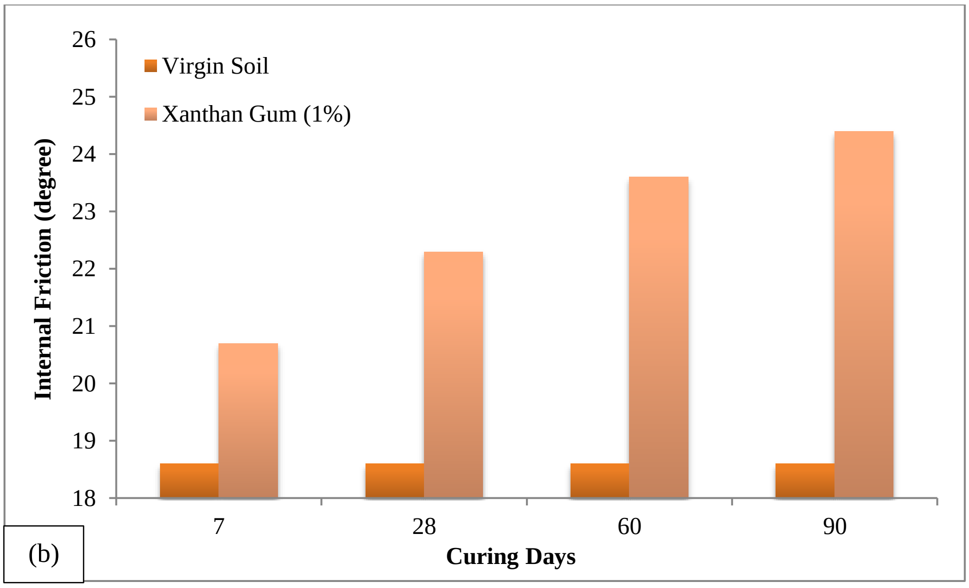
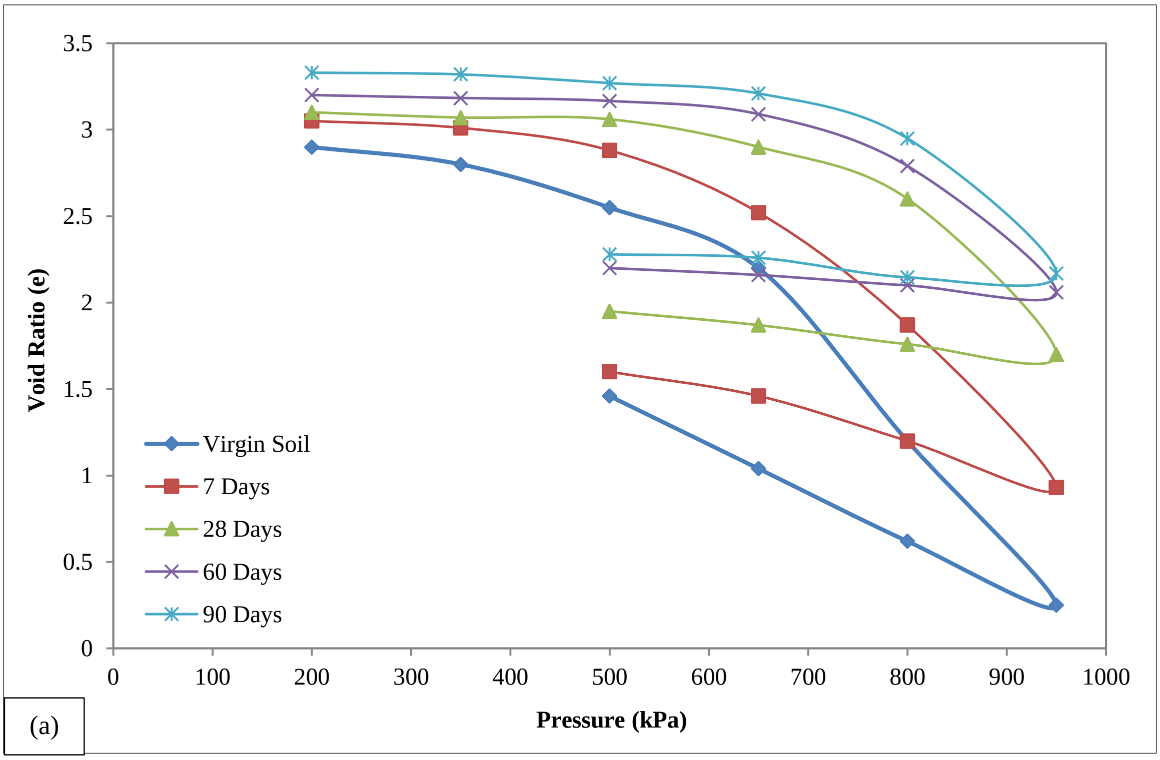


Figure 4. Shear parameters by direct shear test for different curing days on treated and untreated samples; (a) cohesion values for different curing days (b) friction angle values for different curing days

3.4. Compressibility

For predicting the settlement in clays, it is required to determine the compressibility indices and pre-consolidation pressure. One-dimensional consolidation tests were performed on both treated and untreated samples to determine the compressibility properties of soil. The results were presented in Figure 5 (a) as void ratio (e) versus pressure (p); which represents the results for soil specimens treated with 1% Xanthan Gum and treated soils for different curing periods. The compression curve was absorbed well below the treated specimens. The compressibility of the stabilized soil samples improved with the increase in curing days, and the compression curve decreased with the increase in curing time. At 90 days, the compression curve of treated soil specimens showed higher yield stress, which indicates the small strain at large portions. In accordance with the UCS test results, it was observed that the changes in specimen behavior were the major during the initial days of curing and relatively insignificant from 28 days curing period to 90 days curing period.



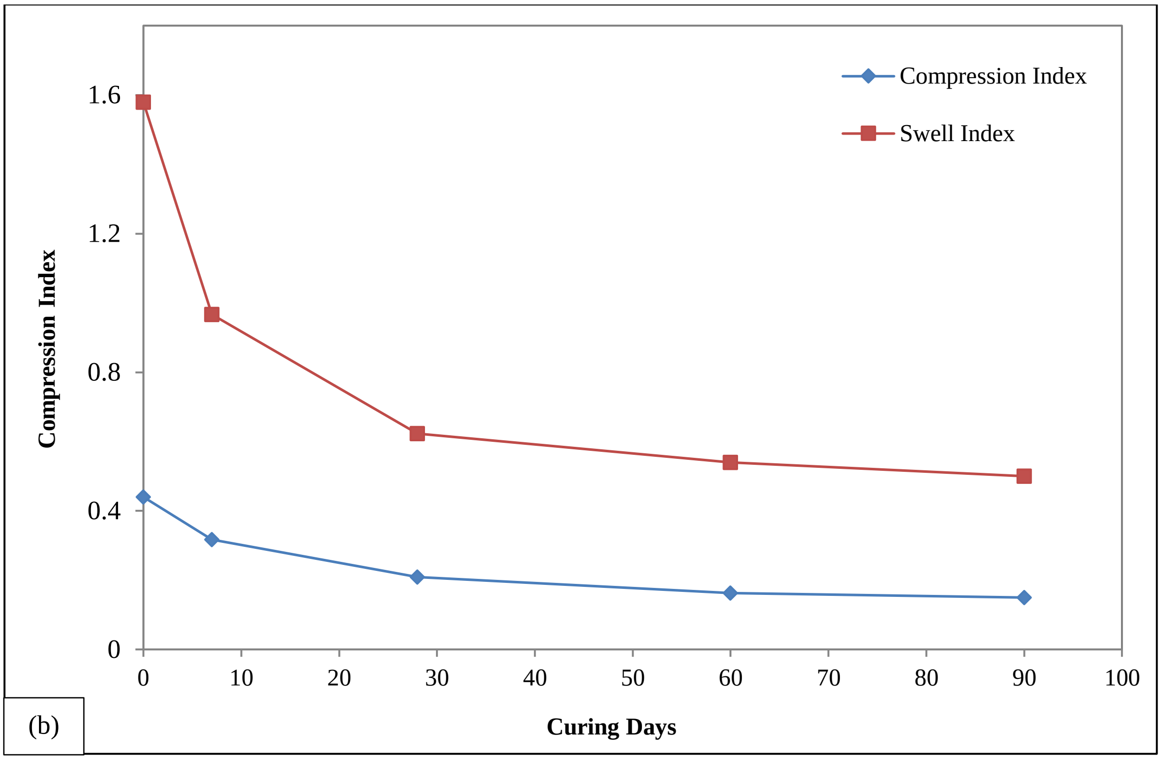
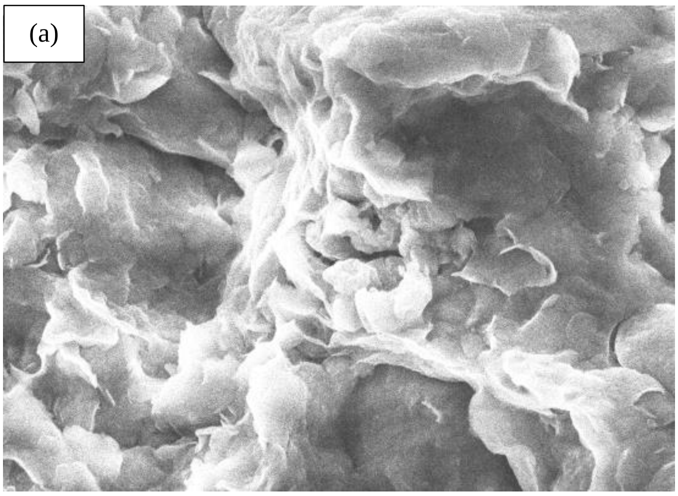


Figure 5. 1-D Consolidation test outcomes for different curing days at different admixture percentages: (a) Compression Curves while loading and unloading; (b) Swell and Compression Indices variations

Figure 5(b) shows the Compression Index (Cc) and swell index (Cs) versus curing periods in days; After 28 days of the curing period, the compression index of the treated sample was 0.623, which is 62.6% less than that of untreated soil. After 90 curing period, the compression index of the treated sample was 0.5, which is less by 76% compared to untreated soil. This behavior is observed for a less change i.e. 1% even after long curing periods of 60 periods. A similar trend was continued in the swelling index of treated soil after 28 days curing period of 0.44 to 0.16 (approximately 63.5% reduction) same trend of results were observed [27].

3.5. Scanning Electronic Microscope (SEM) Analysis

Figure. 6 shows the SEM images of clayey soils treated with xanthan gum. There is a direct linkage bridge between xanthan gum and fine clay particles by hydrogen bonding it is because of the electrically charged clay particles. In addition, bridges are formed between distant particles in xanthan gum, enhancing particle alignment and improving strength (Figure 6a).



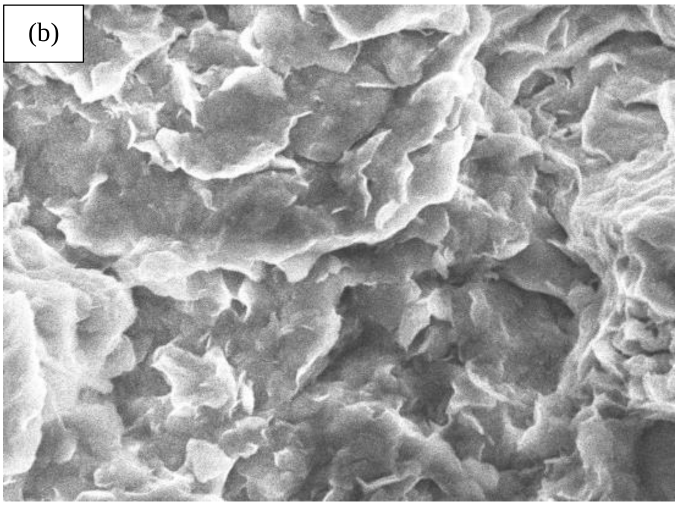


Figure. 6. SEM analysis of 1% treated soil at various curing periods: (a) 7 days; (b) 28 days

Thus, the direct interaction is accelerated in the presence of clayey particles because of the hydrogen and ionic bonding between clay particles and biopolymers; here, it should be noted that the clay particles have electrical charges of the xanthan gum matrix (e.g., threads or textiles). Firm xanthan gum-fine soil matrices are formed by the hydrogen bonding characteristics between both of them [13]. Figure 6(a) denotes a 7 day cured specimen that indicates cementitious material in the form of white cooler lumps among the clay particles. The cementitious material filled most of the voids in the clay framework after 7 days of curing [28]. Figure 6(b) shows 28 days of curing in which the clay particles were bind strongly and the new cementation products occupy the large voids. This resulted in significant changes in clay particle visibility.

4. Conclusion

In our study, the improvements in stiffness and strength of xanthan gum-treated clay were quantified using different laboratory macro- and micro-structural experiments. In addition, an attempt was made to identify the micro-level mechanisms involved in stabilization of treated specimens. The results of the UCS tests revealed that 1% (ambient curing and oven curing samples) and 2.5% (submerged condition) xanthan gum additive levels achieved the most favorable percentages for stabilization. For stabilized specimens, the UCS tests and Direct Shear tests revealed that an increase in shear strength values with increase in curing time. Similarly, one-dimensional tests showed that increased additive levels and curing times resulted in increased yield stress and decreased in compressibility. The mechanical properties of the stabilized specimens showed the most significant changes during the initial curing period of 28 days and they showed a minor increase from 28 days to 90 days of curing period. In general, the engineering properties showed significant improvements even after only 7 days of curing in treated clays at lower additive levels. These interpretations imply that Xanthan Gum can be potentially used as an effective and eco-friendly stabilizer for expansive soils. The results also indicate the chemical interactions between stabilized soil particles and xanthan gum resulted in the formation of new cementations products. These newly formed cementations products welded the soil particles together, by reducing the outer surface area of soil particles, and block the void gaps in between soil particles by particle agglomerations (particle clusters). These findings provide an insight into the mechanisms involved in the treatment of fine-grained soils using Xanthan Gum biopolymer. Based on our findings, it is recommended to use xanthan gum as an alternative to traditional soil stabilization methods.

5. Acknowledgements

The authors would sincerely like to thank the management of G Pulla Reddy Engineering College (Autonomous), Kurnool for providing the testing facilities and their constant support.

6. Conflict of Interest

The authors declare no conflict of interest.

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