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An experimental study on improvement of cohesive soil with eco-friendly guar gum

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Article

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Curing effect
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Abstract

Recently, the demand for environmentally friendly products has been increasing worldwide. In this study, the improvement of cohesive soil with a biopolymer material (Guar Gum), which is a type of additive and organic, environmentally friendly, is investigated. For this purpose, various laboratory tests have been conducted on the biopolymer-added soils, including the compaction test, the Atterberg limits test, and the unconfined compressive strength test. The samples for tests have been prepared that the biopolymer has been mixed with the soil in three different proportions to determine the optimum mixing ratio. Also, in the biopolymer-added soils, some samples have been cured at varying times to determine the effect of curing periods on their strength. For comparison, the tests performed on improved soils have been also carried out on the untreated cohesive soil. For a comprehensive evaluation, scanning electron microscopy analyses (SEM analyses) was carried out on some samples. On the other hand, X-ray fluorescence analysis (XRF analysis) was performed to have an idea about the composition of the cohesive soil. Consequently, the biopolymer additive material has improved the geotechnical properties of the cohesive soil in all mixing ratios and curing times. Moreover, the optimum mixing ratio has been obtained at 1% according to the results of tests.

1. Introduction

The soil is the outer layer that covers the globe and contains crushed rocks, water, mineral materials, and organic matter inside. The soil containing the silt and natural particles is the result of the loss of bonding elements due to the weathering and temperature difference in different seasons with time. Soils can be insufficient for construction requirements due to inadequate of its geotechnical properties such as shear strength and consolidation. Particularly, loose or soft soils can be unable to resist the loads imposed on them. These weak soils need to improve their geotechnical properties to be ready for various engineering projects. Generally, geotechnical properties of weak soils are improved by using compressive mechanisms, or by adding additives to it (Kumar & Kumar, 2020). In previous studies, some additive materials such as cement, lime, fly ash, slag, polymers, glass water, acid, epoxy etc. were used to improve the soil (Marto et al., 2014; Kampala et al., 2014; Arulrajah et al., 2016; Dash & Hussain, 2012; Cristelo et al., 2013; Du et al., 2014; Tingle & Santoni, 2003; Sarici, 2019; Najah et al., 2013; Oliveira Júnior et al., 2019; Menezes et al., 2019). However, these additives can cause serious damage to the environment although they can improve the soil. A few studies have stated some environmental problems and pollutions formed by the use of these additives (Worrell et al., 2001; Afolabi et al., 2012; Chang et al., 2016; Mascarenha et al., 2018). Today in the construction industry as in many fields, environmentally friendly materials are encouraged to be used due to various environmental concerns. Therefore, it is very significant in terms of reducing the damage to the environment of additives and the sustainability of resources to investigate environmentally friendly additives, which do not cause environmental damage, such as biopolymers, in soil improvement. Accordingly, many researchers continue to study these additives (Chang & Cho, 2011; Chang et al., 2015, 2016; Khatami & O'Kelly, 2013; Ayeldeen et al., 2016; Im et al., 2017; Lee et al., 2019; Cabalar et al., 2017; Cole et al., 2012; Ivanov & Chu, 2008; Mitchell & Santamarina, 2005; Fatehi et al., 2018; Soldo et al., 2020).

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Biopolymers are polymers produced from biological organisms by biodegradation such as fungi, algae, and bacteria. They consist of polysaccharides, which are mixtures consisting of monosaccharides linked at identified positions. Ultimately, biopolymers are non-toxic and biodegradable due to their structures owned. Hence, they can be accepted as environmentally friendly additives (Cole et al., 2012; Ivanov & Chu, 2008; Mitchell & Santamarina, 2005).

The use of various biopolymers such as natural bitumen, straw, and sticky rice in civil engineering applications goes back to ancient times. For example, sticky rice mortar was used as a binder in the Great Wall of China which still stands nowadays (Chang et al., 2016). In the literature, there are some studies related to the usability of biopolymers to develop the geotechnical properties of soil. In these studies, it is stated that biopolymers can be used as an additive (Chang & Cho, 2011; Chang et al., 2015, 2016; Khatami & O'Kelly, 2013; Ayeldeen et al., 2016; Im et al., 2017; Lee et al., 2019; Cabalar et al., 2017; Fatehi et al., 2018; Soldo et al., 2020). However, these studies are generally on improving loose sandy soil. At the same time, the sandy soil used in a few studies had some fine particles. For example, Soldo et al. (2020) performed a study on a soil, SW-SM (well-graded sand with silt), which has fine particles classified as silt with low plasticity. In their study, they stated that biopolymers can significantly increase the strength of the soil. However, the rate of sand in the soil was higher than cohesive soil even if some parts of the soil used in this study contained cohesion. Although biopolymers have grand potential as additives, a remarkable study on cohesive soils related to this topic has not been found. Therefore, the improvement by biopolymers of cohesive soils is still well-unknown.

In this study, the improvement of cohesive soil by the Guar Gum (GG), which is a type of biopolymer and can be used as an additive material, was investigated. Test samples were prepared by mixing the soil with the GG at three different ratios as 1%, 2%, and 3%, and then some samples were cured during six different periods as 1 day, 7 days, 14 days, 21 days, 56 days and 196 days. Subsequently, laboratory tests such as the compaction test, the Atterberg limits test, and the unconfined compressive strength (UCS) test have been conducted on the prepared samples and untreated samples. Also, scanning electron microscopy analyses (SEM analyses) and X-ray fluorescence analysis (XRF analysis) carried out on some prepared samples and cohesive soil, respectively.

2. Materials and methods

2.1 Natural soil

The soil used in the study was collected in Adana, Turkey. The chemical composition and geotechnical properties of this soil have been specified by the laboratory tests. As the result of Atterberg limits tests conducted out on this soil, the liquid limit and plastic limit values of the soil have been determined as 42% and 24%, respectively, according to the Standard ASTM D 4318-00 (ASTM, 2003). Moreover, the particle-size distribution of the soil obtained as a result of hydrometer and sieve analysis is shown in Figure 1. As a result of these tests, the soil has been classified according to ASTM D 2487-06 (ASTM, 2006) as low plasticity clay (CL).

As a result of the pycnometer test, the particle unit weight of the soil has been determined as 27kN/m3 (ASTM, 2018). On the other hand, the optimum moisture content and the maximum dry unit weight, obtained by Proctor test (ASTM, 2009a), were found as 18.1% and 17.40 kN/m^3, respectively. In the result of the unconfined compressive strength (UCS) tests performed on the clay soil (ASTM, 2009b), the UCS value of the clay soil was 128.48 kPa (Kahiyah, 2020). The compaction and unconfined compressive curves of the clay soil are shown in Figure 2. Finally, the chemical composition of this soil has been determined by performing the X-ray fluorescence analysis (XRF analysis), as per ASTM E 2809 (ASTM, 2013). According to the result of the XRF analysis, the soil consists of MgO (6.1%), Al2O3 (18.4%), SiO2 (50.6%), P2O5 (0.65%), K2O (3.1%), CaO (3.2%), MnO (3.1%), Fe2O3 (8.7%), Na2O (2.5%) and LL (3.15%). Accordingly, the soil possesses alumina and silicate in high ratios. Moreover, calcite, quartz and a few groups of clay minerals such as smectite, kaolinite and vermiculite have been detected in the soil.

2.2 Guar Gum (GG)

GG is a biopolymer appropriated in different fields of the industry, mostly due to its structural characteristics, which

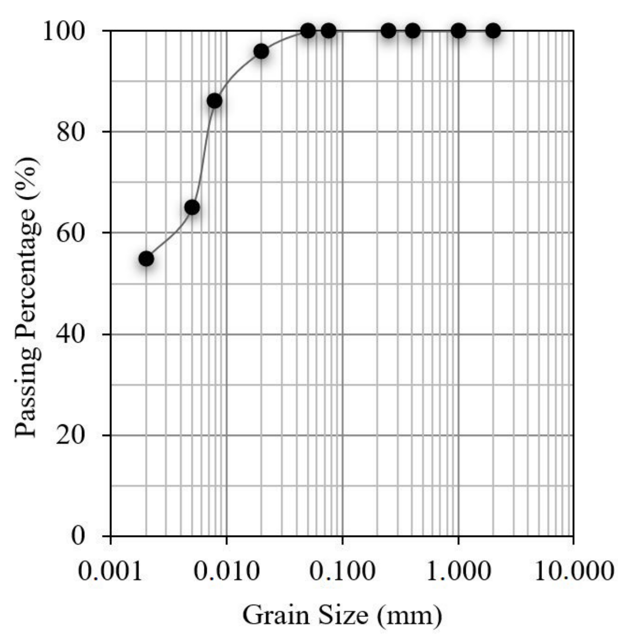

Figure 1. Particle-size distribution of the clay soil (Kahiyah, 2020).

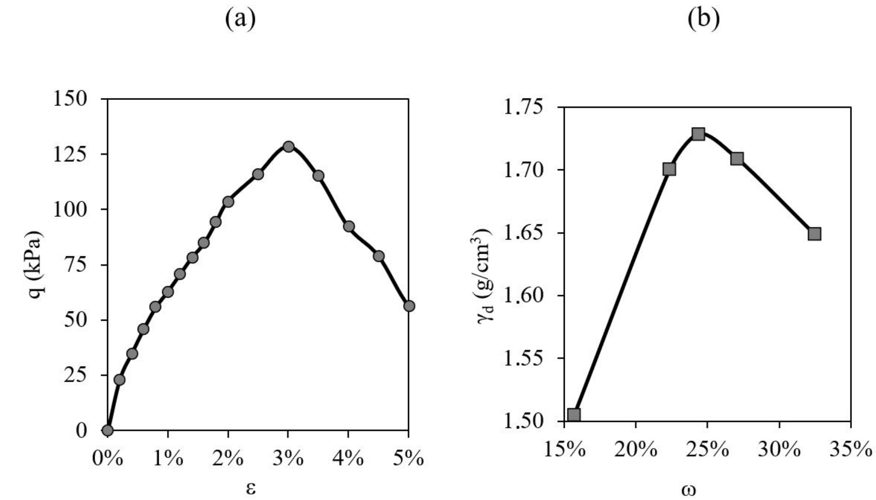

Figure 2. Curves of (a) unconfined compression and (b) compaction tests of the clay soil.

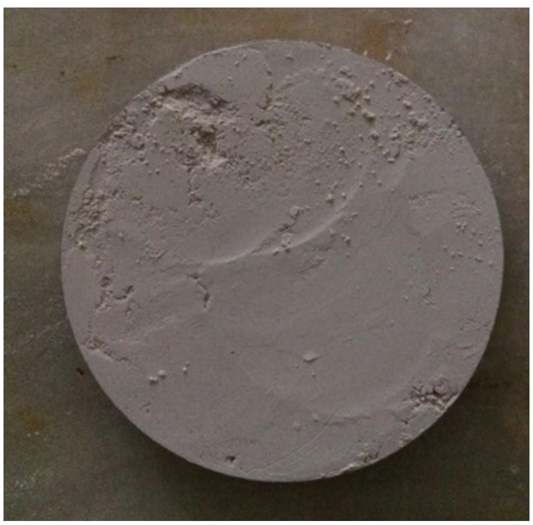

Figure 3. The GG powder.

Figure 4. The wet mixing method (Kahiyah, 2020).

form greatly viscous suspensions at low concentrations. It is a typical non-ionic polysaccharide and composes of mannose and galactose. Commonly-known properties of guar gum can be listed that (1) GG has a pH range of about 1.0 to 10.5 due to its non-ionic and its viscosity also is not affected by the pH, (2) GG can swell and or dissolve in a polar solvent, and also it can form strong hydrogen bonds. It is cheap, easily produced, and available from chemical companies (Whistler & Hymowitz, 1980; Risica et al., 2010; Sharma et al., 2015; Kahiyah, 2020). The GG used in this study was obtained from a chemical company (Figure 3).

2.3 Sample preparation

In this study, GG has been mixed to the soil at three different ratios as 1%, 2%, and 3% by wet mixing method. Accordingly, the quantity of the GG calculated according to the amount of the soil was mixed with a specific quantity of water, which is required for tests, using a mixer. The mixing process was continued until GG soluble in water (Figure 4). Subsequently, the prepared mixture was mixed with the dry soil (Fatehi et al., 2018; Chang et al., 2015; Kahiyah, 2020).

For UCS tests, firstly, soils were placed by tamping in the proctor mold to provide their maximum unit weights and optimum moisture contents obtained from the proctor test. Subsequently, samples, which have a diameter of 50 mm and a length of 100 mm, were removed from this mold with the help of a sampler. Finally, the samples were cured during six different periods. For this, samples, which are obtained mixing soil with GG, were held in isolation bags inside the desiccators at varying times as 1 day, 7 days, 14 days, 21 days, 56 days and 196 days. Then, sequentially, UCS tests were performed on the cured samples. Sujatha & Saisree (2019) stated that after forming gel-like structures (hydrogels) due to the GG, these gels wraps soil grains and form hydrogen bonds. Subsequently, they mentioned that in order to strengthen these hydrogen bonds formed, they should be dehydrated. For this reason, they suggested dry curing at room temperature. Similarly, some researchers stated in their studies that dry curing is more effective (Lee et al., 2019; Chang et al., 2015).

In addition, Sujatha & Saisree (2019) recommended the curing is carried out in an airtight environment to prevent oxidation of the GG. For these reasons, a similar curing method has been carried out in this study.

2.4 Test procedure

Firstly, the Atterberg limits test according to ASTM D 4318-00 (ASTM, 2003) and compaction tests according to ASTM D 698-00 (ASTM, 2009a) has been carried out on samples, mixed with the GG in different ratios. Then, according to ASTM D 2166 (ASTM, 2009b), the UCS test has been performed on the cured samples, which have optimum moisture content. Finally, the Scanning Electron Microscope images (SEM images) of samples obtained from the only GG and the soil-the GG mixture, which contains 1% the GG and is cured for 21 days, have been taken to determine their microstructures (Figure 5). Besides, the Energy Dispersive Spectroscopy (EDS) to specify the elemental composition of samples imaged in the scanning electron microscope has been used. Most elements with concentrations of 0.1% in the sample can be detected with this technique (Moretti et al., 2020). Subsequently, SEM/EDS analyses have been performed by using obtained images.

3. Results and discussion

3.1 Atterberg limits

The liquid limit, plastic limit, and the plasticity index of untreated soil and the soils, which are mixed with the GG, are shown in Figure 6. Increasing the liquid limit value of soil means that it decreases the range where the soil acts like a liquid. Hence, the soil can be more rigid at certain water contents. Furthermore, it has determined from SEM analyses that the GG has been gel-like form after it is mixed with water and this the gel-like structure formed some bonds between the clay soil particles. After adding the GG to the clay soil, the change in consistency limits is thought to be caused by this mechanism.

3.2 Compaction tests

Compaction curves of untreated soil and the soils, which are mixed with the GG, are shown in Figure 7. It is seen in the curves that as the percentage of GG in the soil-GG mixture has increased, the optimum water content has increased and the maximum dry unit weight has decreased. Based on the observation in the tests, it can be said that the GG is a very water-absorbent material. The high water absorption of the GG has been thought to negatively affect the compaction parameters of the soil-GG mixture. Therefore, in fillings by using the GG-soil mixture water consumption might be a

Figure 5. SEM device.

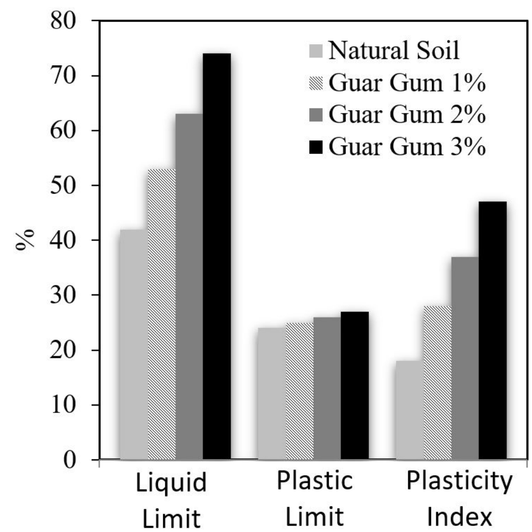

Figure 6. Liquid limit, plastic limit, plasticity index values of the soils.

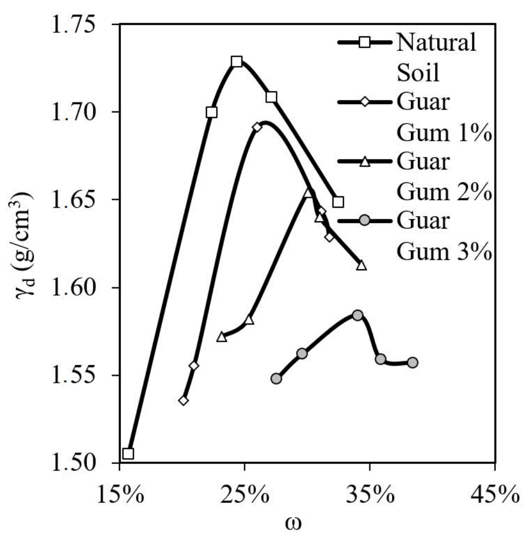

Figure 7. Compaction curves of the soils.

little too much than that of other fillings. In fact, it is thought that this case does not prevent building a filling by using the GG-soil mixture. Nevertheless, water consumption should be taken into account when constructing a filling.

3.3 Unconfined compressive strength (UCS) tests

Results of UCS tests performed on soils that are cured during 1 day and contained 1%, 2%, and 3% GG are presented by comparing with that of untreated soil in Figures 8. As can be seen from the figure, the highest strength was obtained for the soil having 1% GG. This percentage of GG has been accepted as the optimum ratio. As similar to the result in this study, Soldo et al. (2020) determined the optimum percentage of GG in the soil-GG mixture as 1% in their study, which performed on a soil containing a part of silt with low plasticity. Results of UCS tests at different curing periods such as 1 day, 7 days, 14 days, and 21 days in the optimum percentage of the GG are shown in Figure 9. As seen in this figure, the strength of the soil-GG mixture increased as the curing period increased. While the strength of the soil increased approximately 6 times than untreated soil after 1-day of curing, it increased about 9 times after 21 days of curing. It is thought that this increase in strength of the soil-GG mixture occurs in a few steps as the curing time increases. Initially, when the GG is mixed with water, hydrogels start to form due to hydration. Subsequently, when this is mixed with the soil, hydrogels formation continues by absorbing the water in the soil. After that, these hydrogels form hydrogen bonds by coating soil particles. Finally, these bonds become thicker and stronger when the hydrogels are

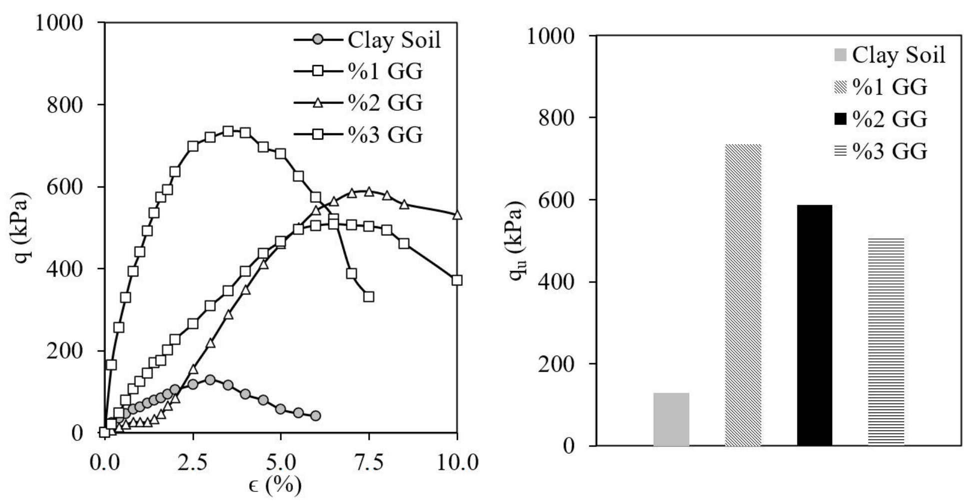

Figure 8. Results of UCS tests for different ratios of GG (the samples were cured during 1 day).

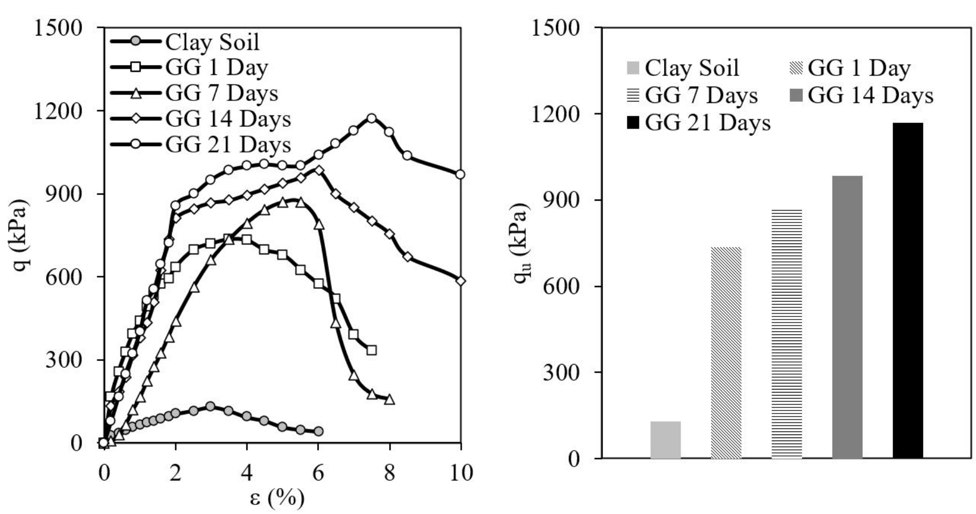

Figure 9. Results of UCS tests for 1% GG at different cure periods.

dehydrated (Sujatha & Saisree, 2019). On the other hands, in the literature, higher increases than this study were obtained at a similar cure period and percentage of biopolymer. However, these studies, unlike this study, performed on the sandy soil as mentioned previously.

3.4 The long-term assessment

The UCS tests have been performed on the soil-GG mixture that is cured for 56 days and 196 days and contained 1% of GG to evaluate the long-term improvement effects of the GG. The results of these tests are given in Figure 10 in comparison with other results of tests. The UCS values of samples which are cured for 56 days and 196 days have been measured as 2.02 and 2.06 times that of sample cured for 1 day, respectively. Therefore, it has been deduced that

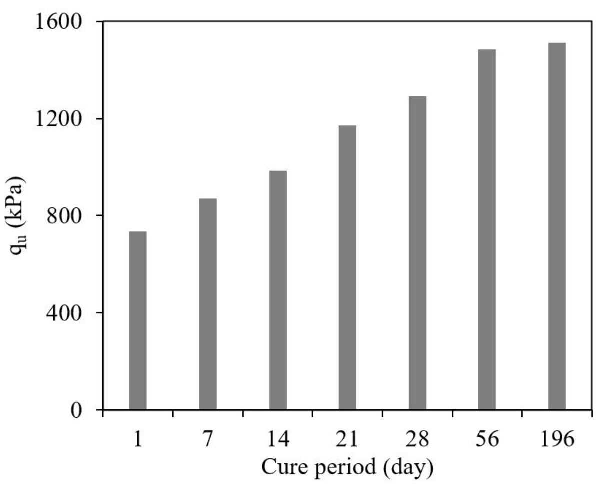

Figure 10. The effects in the long-term of the GG improvement (1% GG).

the UCS value remained approximately constant after the cure period of 56 days.

3.5 Scanning electron microscope analyses

In this study, the dry GG has been mixed with water and then the wet GG has been mixed with soil. SEM images obtained from samples of the dry GG and the soil-the GG mixture, which contains 1% GG and is cured for 21 days, has been used to determine their microstructures. The dry GG has a dispersed form as seen in its SEM image (Figure 11). However, the GG has been gel-like form after it is mixed with water (Figure 4). From the SEM image of soil-the GG mixture, it has been observed that the gel-like structure of wet GG formed some bonds between the clay soil particles (Figure 11). Chang et al. (2016) stated that in clay-biopolymer mixtures, hydrogen and ionic bonds occur between clay particles, which have electrical charges, and biopolymers. Sujatha & Saisree (2019) the increase in strength of guar gum soil mixture correlated with the formation of hydrogen bonds. Besides, they stated that the guar gum coats the soil particles and bridges between them by forming hydrogels. Ultimately, they put forward that the dehydration of the gel with the thickness and strength of the gel bounds increases with age. On the other hand, Ayeldeen et al. (2016) mentioned that guar gum gels fill the voids more than other biopolymers due to being their bonds are thicker and wider. According to the EDS results, it has been thought that the mentioned bonds and hydrogels have occurred as the result of a chemical reaction due to the fact that the peak values of compounds, namely their amount, in dry GG and soil-the GG mixture have changed (Figure 12). Consequently, it is predicted that those bonds and hydrogels have increased the strength of the clay soil.

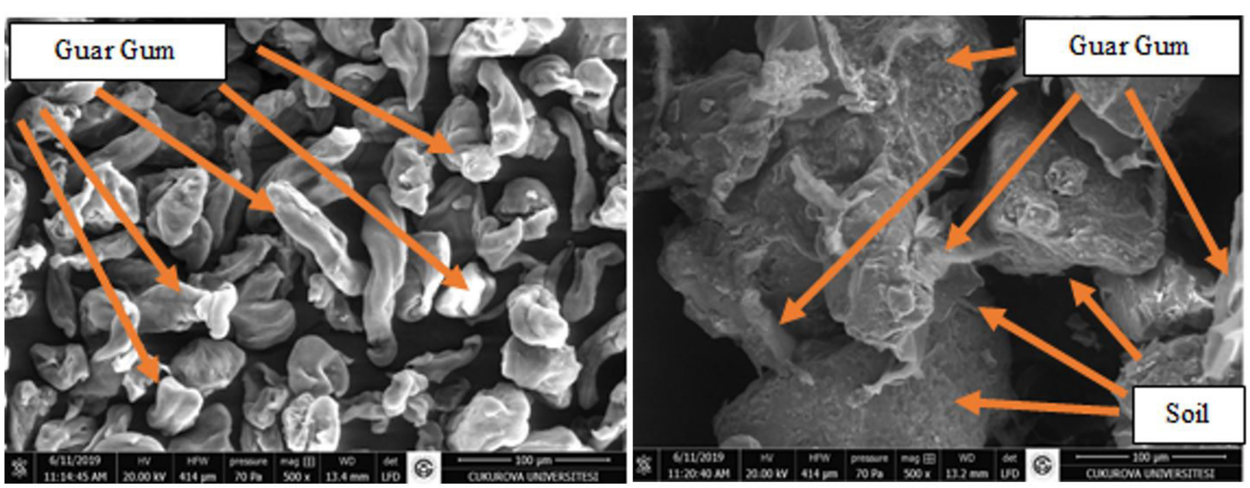

Figure 11. SEM images of the dry GG and soil-the GG mixture.

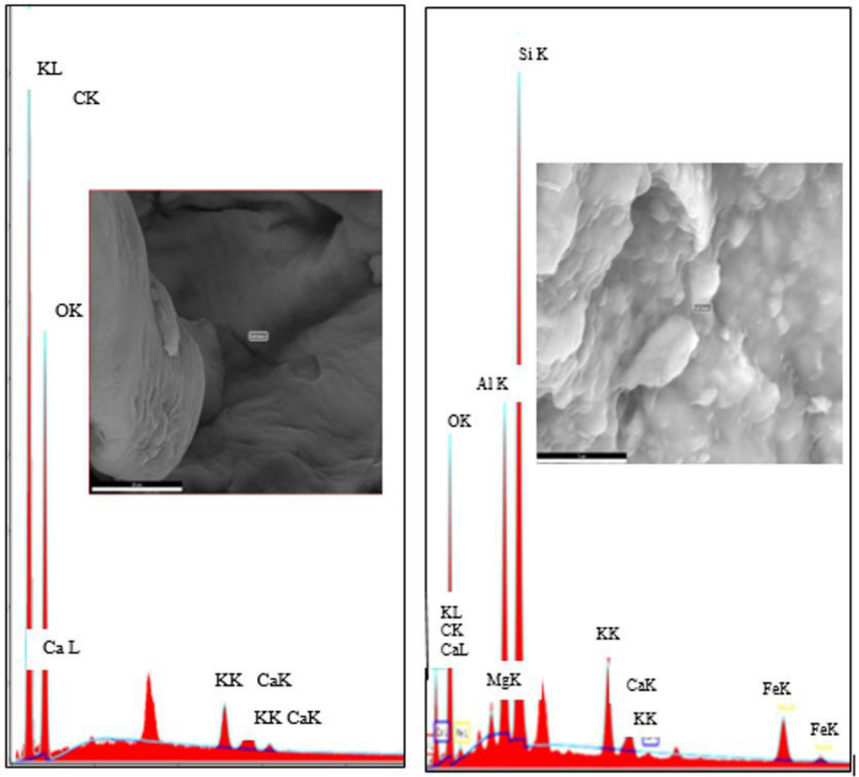

Figure 12. EDS results of the dry GG and soil-the GG mixture.

4. Conclusions

In this study, the improvement of clay soil by using the environmentally friendly GG, which is a type of biopolymer material, has been investigated by laboratory tests, SEM, and XRF analyses. The examined parameters in this research are cure periods and ratios of GG. On the other hand, the mechanism by which the GG improvements the clay soil has been explained with SEM and XRF analyses. The results obtained are presented below.

- It has been determined that in SEM analyses, when the GG is mixed with water, it formed a gel-like structure. Also, in the EDS study, the changes of compound amounts have been thought of as proof of this gel-like structure. In addition, it has been detected that this structure has formed bonds between the clay particles. Therefore, the strength and rigidity of the soil have increased as obtained in the results of the consistency and UCS tests;
- Although the strength of the soil has increased in all percentages of GG, the maximum strength has been obtained when the percentage of the GG is 1%. In this case, the strength of the soil has increased approximately 6 times. Moreover, at this percentage of GG, as the curing time has increased, the rate of improvement has increased. The strength of the soil has determined as approximately 9 times more than untreated soil after 21 days of curing;
- Due to the high water absorption by GG, it has been observed that as the percentage of GG in the soil-GG mixture increased, the compaction parameters of the mixture are negatively affected. During filling construction, it is recommended not to use an excessive amount of GG since the workability can be reduced by affecting the consistency of the soil and the water requirement can be increased;
- According to the results of tests, it is determined as the optimum percentage of GG in the soil-GG mixture in terms of both strength and compressibility for low plasticity clay in this study is 1%;
- According to the results of tests samples that have a long-term curing period, the optimum curing period has been obtained as 56 days;
- It is put forward that the GG can be an alternative to other additives in the soil improvement since it is an environmentally friendly material and the strength of clay soil can be increased even when used at a low percentage;
- The guar gum-soil slurry has the potential to stabilize the walls of trench excavations. Besides, guar gum-soil mixture can provide stability against shallow slope failures and can use in the compacted covers or biopolymer grouts.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Author's contributions

Baki Bagriacik: conceptualization, data curation, methodology, visualization, supervision, project administration, formal analysis, writing – original draft. Bahadir Ok: conceptualization, data curation, methodology, validation, writing – original draft, writing – review & editing. Mustafa Tahseen Mohamed Ali Kahiyah: investigation, methodology, resources.

List of symbols

q Unconfined compressive stress of the soil
q_u Unconfined compressive strength of the soil
γ_d Dry unit weight of the soil
ω Water content of the soil
ε Strain of the soil sample

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