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STRUCTURAL PROPERTIES OF SOILS

EFFECTS OF XANTHAN GUM BIOPOLYMER ON THE PERMEABILITY, ODOMETER, UNCONFINED COMPRESSIVE AND TRIAXIAL SHEAR BEHAVIOR OF A SAND

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A.F. Cabalar[1], M. Wiszniewski[2], Z. Skutnik[3]
[1]University of Gaziantep, Gaziantep, Turkey; [2]Gdansk University of Technology, Gdansk, Poland; [3]Warsaw University of Life Sciences, Warsaw, Poland.

Biopolymers, which are microbially induced polymers, can be used as an alternative material to improve engineering performance of soils. In this paper, a laboratory study of 0.075-1.0 mm size sand and biopolymer (i.e., xanthan gum) mixtures with various mix ratios (0%, 0.5%, 1.0%, and 1.5%) was performed. The materials, specimen preparation, and test methods are described, as are the results of a suite of permeability, odometer, unconfined compressive, and triaxial shear tests. The results suggests that specimen formation in the way used here could reduce permeability and increase compressibility, strength, and deformation characteristics in terms of stiffness.

Introduction

Ground improvement techniques in geotechnical engineering practice are tools applied in order to provide better performance of soils that do not fulfill the requirements of an earthwork project. The major aims of ground improvement can be summarized as follows: to increase bearing capacity, decrease settlement, control shrinking and swelling, control permeability, and reduce susceptibility to liquefaction. The basic principles of these techniques have not changed since the early part of the Twentieth Century. The practices, however, have been changing with time mainly because of the development of innovative materials, advanced machinery, and different technologies [1, 2].

An innovative approach lies in the use of biotechnology to improve the engineering performance of soils. Although biotechnology can be defined in many different ways, the definition used in the present study is that of application of biological organisms, systems, and processes to the production of goods and services. The great promise of the use of biotechnological treatments has already been demonstrated in certain fields. For example, biotechnological methods have been used in the petroleum industry to direct oil flow in the required direction [3, 4], in concrete technology to remediate cracks [5], in development of shields for zonal remediation [6-8], in stabilization of metals [9], and in the stabilization of contaminated soils [10]. Investigations into the influence of biotechnological treatments in soils provide one of the major challenges for geotechnical engineering. Several researchers have investigated the biological treatments in soils using bacteria that can be divided into three groups based on their products (i.e., calcite, biofilm, biogas). For instance, De Jong et al. [11] indicated that microbially cemented specimens exhibit an increase in strength when compared to uncemented specimens. Whiffin et al., [12] observed a decrease of 22-75% in the permeability of the soil tested. Al Qabany and Soga [13] showed that the permeability of the sand is reduced to 20% of its original value. Burbank et al., [14, 15] observed an improvement to resist soil liquefaction. Actually, biopolymers mixed with soil

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allow for the strengthening of the soil (increased cohesion and strength, resistance to erosion, reducing permeability) by acting as a biological binder [16-20]. The direct application of biopolymers to soils overcomes the inconveniences of other approaches, including microbial injection, time for cultivation and precipitation, and the uncertain quality of soil treatment [21]. Furthermore, since the biopolymers are already available in nature and many are known to be harmless and edible, they can be thought of as eco-friendly substitutes for soil treatment [22, 23]. Accordingly, the use of biopolymer provides an alternative technique to improve soil stability at higher depths, beyond the technical limits of other grouting methods [24, 25], because microorganisms that can induce both polymeric and carbonate precipitation (bioclogging, biocementation) live at higher temperatures and much greater depths.

The present study is concerned primarily with the applications of Xanthan gum (XG), a type of biopolymeric material produced by the microorganism Xanthomonas Campestris [26]. The paper presents a systematic experimental investigation into the behavior of various sand- Xanthan gum mixtures by employing a permeability, odometer, unconfined compression, and triaxial compression testing program. The objective of this study was partly scientific curiosity, but also to judge the usefulness of xanthan gum as an alternative cementing agent in soil improvement. The present study will focus on two important aspects of this method for improving soil properties; (i) identifying specific influence of xanthan gum content, namely 0%, 0.5%, 1.0% and 1.5% by dry weight, (ii) assessing testing methods employed in four different ways (permeability, odometer, unconfined compressive, triaxial shear) on the specimens.

Experimental Study

The soil used in this study was Narli Sand, which was quarried in and around Narli River near Gaziantep, southern-central of Turkey. The Narli Sand is widely consumed for earthworks in Gaziantep city and its vicinity. Gradation of the sand falling between 0.075 mm and 1.0 mm was artificially selected to provide uniform specimens for visual classification purposes. D_{10}, D_{30}, and D_{60} sizes were found to be 0.25, 0.35, and 0.54 mm, respectively. Thus, the coefficient of curvature (c_c) and coefficient of uniformity (c_u) have been calculated as 0.91 and 2.16, respectively. The specific gravity of the grains was found to be 2.68. The soil has minimum and maximum void ratios of 0.45 and 0.70, respectively.

The biopolymer used in the present study was Xanthan gum, which is a natural polysaccharide produced by the microorganism Xanthomonas campestris [27-29]. Xanthomonas campestris, which is the most widely employed organism for industrial xanthan gum production, is an aerobic bacterium, and the fermentation is accompanied by a substantial increase in viscosity [29-34].

The experimental work was directed mainly towards an investigation of the influence of Xanthan gum and Narli Sand used in combination as blending materials by weight on water demand. Xanthan gum solutions (0.5%, 1.0%, and 1.5%) were studied by varying the curing times (1, 3, 7, 14, and 28 days). The materials test methods are described, as are the results of a suite of permeability, odometer, unconfined compression, and triaxial compression tests.

A series of constant head permeability tests was performed according to ASTM D2434 [35]. The sand-xanthan gum mixtures were tested at a relative density (R_d) of about 40%. In this stage 42 tests were carried out under the room temperature of 24°C. Consolidation tests were carried out in a series of conventional odometer testing machines (7.5 cm diameter, 2 cm height) equipped with an external linear displacement sensor (ASTM D 2435), which involves daily increments of vertical load to a soil specimen. Loadings were initiated from 25 kPa and were doubled each day, that is, the ratio of load increment to existing load was 1. Following the preparation of specimens in two-part split moulds with a diameter of 38 mm and height of 70 mm, the specimens to be tested in the UC machine were left open to air for drying up at around 24°C temperature. The shear was applied to the specimens at the end of 1, 3, 7, 14, and 28 days of curing times until they fail. Triaxial tests were carried out in a fully automated triaxial loading system, which is a product of GDS (ASTM D2850 and D4767). A specimen was allowed for consolidation until the value reached 0.95. Before axial load is applied, the valve between the chamber and the buret was left open so that the specimen is sheared in a drained condition (*CD*).

TABLE 1

Xanthan gum (%)	Curing (day)	Permeability (m/s) under various hydraulic gradient values					
		5	10	20	30	50	100
0.5	1	$8.65\cdot10^{-10}$	$9.02\cdot10^{-10}$	$1.13\cdot10^{-8}$	$8.71\cdot10^{-8}$	$5.25\cdot10^{-7}$	$1.55\cdot10^{-6}$
	3	$6.26\cdot10^{-10}$	$2.42\cdot10^{-9}$	$5.30\cdot10^{-8}$	$3.76\cdot10^{-7}$	$1.33\cdot10^{-6}$	$1.83\cdot10^{-6}$
	7	$4.25\cdot10^{-9}$	$4.42\cdot10^{-9}$	$9.89\cdot10^{-8}$	$9.75\cdot10^{-7}$	$1.45\cdot10^{-6}$	$2.14\cdot10^{-6}$
	14	$3.12\cdot10^{-9}$	$4.92\cdot10^{-8}$	$2.80\cdot10^{-7}$	$7.49\cdot10^{-7}$	$1.68\cdot10^{-6}$	$2.35\cdot10^{-6}$
	28	$3.14\cdot10^{-8}$	$2.03\cdot10^{-7}$	$9.02\cdot10^{-7}$	$1.53\cdot10^{-6}$	$2.67\cdot10^{-6}$	$2.59\cdot10^{-6}$
1.0	1	$1.18\cdot10^{-10}$	$1.24\cdot10^{-10}$	$4.67\cdot10^{-10}$	$7.23\cdot10^{-10}$	$7.12\cdot10^{-9}$	$1.98\cdot10^{-7}$
	3	$3.68\cdot10^{-10}$	$3.94\cdot10^{-10}$	$7.07\cdot10^{-10}$	$2.75\cdot10^{-9}$	$1.79\cdot10^{-8}$	$9.09\cdot10^{-7}$
	7	$4.98\cdot10^{-10}$	$5.54\cdot10^{-10}$	$6.74\cdot10^{-10}$	$3.81\cdot10^{-9}$	$3.57\cdot10^{-8}$	$1.29\cdot10^{-6}$
	14	$2.12\cdot10^{-9}$	$2.64\cdot10^{-9}$	$1.47\cdot10^{-8}$	$7.17\cdot10^{-8}$	$4.09\cdot10^{-7}$	$1.42\cdot10^{-6}$
	28	$2.69\cdot10^{-9}$	$2.50\cdot10^{-9}$	$5.56\cdot10^{-9}$	$2.00\cdot10^{-7}$	$3.34\cdot10^{-7}$	$1.03\cdot10^{-6}$
1.5	1	$2.84\cdot10^{-11}$	$7.33\cdot10^{-11}$	$1.28\cdot10^{-10}$	$2.20\cdot10^{-10}$	$5.08\cdot10^{-11}$	$9.25\cdot10^{-8}$
	3	$3.40\cdot10^{-11}$	$3.38\cdot10^{-11}$	$1.54\cdot10^{-10}$	$7.53\cdot10^{-11}$	$2.59\cdot10^{-11}$	$7.90\cdot10^{-8}$
	7	$4.39\cdot10^{-11}$	$3.90\cdot10^{-11}$	$7.73\cdot10^{-11}$	$4.91\cdot10^{-11}$	$3.20\cdot10^{-11}$	$1.41\cdot10^{-7}$
	14	$2.18\cdot10^{-11}$	$2.51\cdot10^{-11}$	$1.20\cdot10^{-10}$	$7.98\cdot10^{-10}$	$2.70\cdot10^{-10}$	$6.39\cdot10^{-7}$
	28	$6.84\cdot10^{-11}$	$5.69\cdot10^{-11}$	$2.80\cdot10^{-10}$	$7.27\cdot10^{-10}$	$8.66\cdot10^{-10}$	$1.99\cdot10^{-7}$

Results and Discussion

Grouting of such materials to form soil-polymer columns in the field provides a versatile improvement in cohesionless soils. The use of xanthan gum biopolymer in geotechnical engineering has been examined recently, and its notable findings in geotechnical engineering are as follows.

Permeability

Table 1 gives a summary of the permeability testing results reported here. The testing results on the sand with 0.5, 1.0, and 1.5% xanthan gum indicated that higher xanthan gum concentrations produced lower permeability values in the treated sand under various hydraulic gradient values (i.e., 5, 10, 20, 30, 50, and 100). For example, the test results showed that the permeability of specimens was reduced from $8.46\cdot10^{-5}$ m/s (clean sand) to $8.65\cdot10^{-10}$ m/s by adding 0.5% xanthan gum, for a one day curing time. The permeability of the sand was reduced to $2.84\cdot10^{-11}$ m/s, about a millionfold, by treating it with 1.5% xanthan gum. Permeability of the clean sand was found to be around 8.46·10-5 m/s. It was also realized that permeability values increase as the hydraulic gradient and curing time (1, 3, 7, 14, and 28 days) increase. The authors point out that the change in permeability could be because of binding of the sand grains as well as filling of pores between the grains. Actually, similar results were obtained by Khachatoorian et al. [10], Ivanov and Chu [17], and Bouazza et al. [24], which showed that swelled viscous biopolymer hydrogels fill the pore spaces of soils and induce pore clogging. Then it reduces the hydraulic conductivity of soils by more than 3~4 orders of magnitude. Thus, biopolymers have potential to be applied for hydraulic purposes in geotechnical engineering, such as in slurry walls, temporary seepage barriers, and grouting.

Odometer

A series of one-dimensional consolidation tests was conducted on various sand-xanthan gum mixtures. Variation in void ratio for different samples are presented in Fig. 1. The tests results show that the presence of xanthan gum in the specimens tested had a marked effect on the compressibility of the material under load, on its expansion after release or of pressure. The authors postulate that the presence of xanthan gum helps in binding the grains together. Based on the amount of xanthan gum present, the sand grain are in contact with each other, and the behavior of the samples tested are controlled by the sand grains. When the contacts between the sand grains decrease due to increase in the amount of xanthan gum, the behavior of the samples becomes to claylike. The governing role of either sand grains or xanthan gum on the overall behavior of the sample should be expected to change during one dimensional compression. The interchange of this governing role can be expressed using the amount of

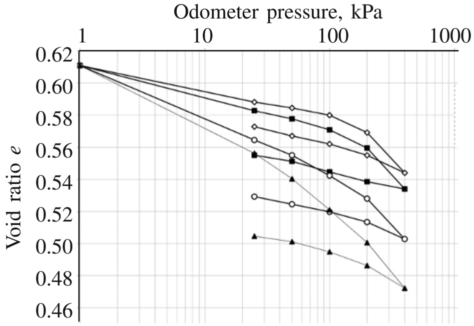

Fig. 1. Odometer testing results: ◇) clean sand; ■) sand with 0.5% xanthan gum; ○) sand with 1.0% xanthan gum; ▲) sand with 1.5% xanthan gum.

TABLE 2

Curing time (day)	UCS (MPa) of specimens with different XG content		
	0.5%	1.0%	1.5%
1	1.13	1.81	1.85
3	1.35	1.85	1.95
7	1.41	1.93	2.04
14	1.45	2.11	2.24
28	1.84	2.19	2.71

biopolymer (i.e., xanthan gum). Change in void ratio also gives an indication of the difference in coefficient of compressibility (m_v, m^2/MN). The results presented here are in a good agreement with the results obtained by Ivanov and Chu [17].

Unconfined compression

Table 2 presents the effect of xanthan gum content on the unconfined compression strength (UCS) of specimens with different mixture ratios (0%, 0.5%, 1.0%, 1.5%). As can be seen, the UCS values increase with increase in xanthan gum content. It was also observed that the UCS values increase as the curing time increases. Similarly, Chang et al. [20] conducted a study to enhance the strength of soil using biopolymer and showed that the use of 3% biopolymer increased the unconfined compressive strength of soil under dried condition.

Triaxial

A series of triaxial compression tests was performed on the fully saturated sand treated with 0.0, 0.5, 1.0, and 1.5% xanthan gum by weight. The data indicated that the maximum deviatoric stress, mobilized for a given confining pressure, increased at higher xanthan gum content. Figure 2 shows deviatoric stress-strain responses of the clean sand and the sand treated with mixtures of 0.5%, 1.0, and 1.5% XG under 100 kPa and 250 kPa confining pressures, respectively. The test specimens failed in compression either by disintegrating into sand clusters or by forming a shear plane. It is postulated that because xanthan gum solution by itself behaves plastically, increasing its concentration introduces some degree of ductility to the treated soil under 250 kPa confining pressure. However, addition of XG had the effect of increasing brittleness of a specimen tested under 100 kPa confining pressure. Shear strength parameters of cohesion (c) and internal friction angle (φ) values for the specimens tested were estimated using nonlinear optimization analysis: for clean sand $c = 0$ kPa and $\varphi = 33^{\circ}$; for sand with 0.5% XG $c = 32$ kPa and $\varphi = 28^{\circ}$; for sand with 1.0% XG $c = 58$ kPa and $\varphi = 30^{\circ}$; for sand with 1.5% XG $c = 91$ kPa and $\varphi = 29^{\circ}$. In the light of the studies [20, 25, and 26], the authors have considered that the strengthening mechanism of biopolymers and soils can be explained as a combination of the formation of biopolymer-soil matrices (cohesion enhancement) and friction improvement by sand particles. Interparticle cohesion enhancement

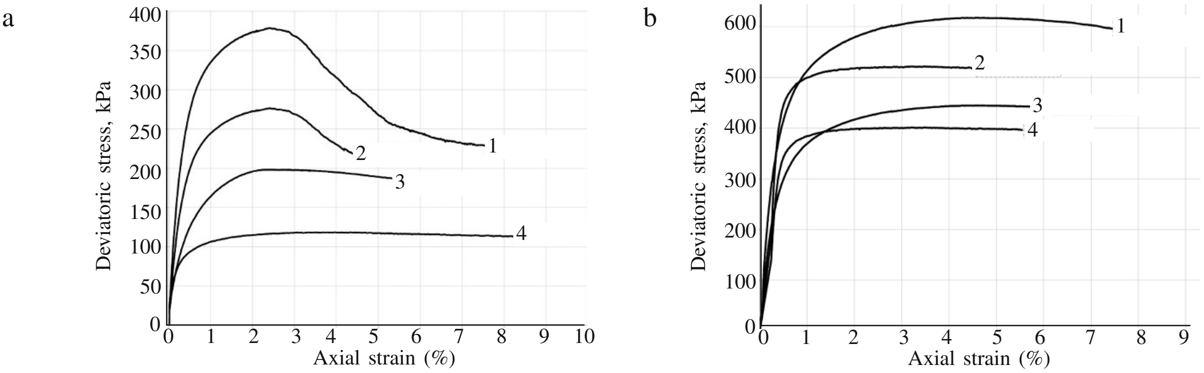

Fig. 2. Triaxial testing of sand treated with xanthan gum tested under 100 kPa (a) and 250 kPa (b) confining stresses: 1) sand with 1.5% xanthan gum; 2) sand with 1.0% xanthan gum; 3) sand with 0.5 xanthan gum; 4) clean sand.

depends on the strength of the biopolymer-soil matrices, which increases with lower water content. The internal friction angles of the soil increase with biopolymer treatment due to improved particle contact. Particularly at lower water content, the stiffer dried gels add a substantial amount of strength with a small increase in the contact radius, as opposed to the softer wet gels with barely any increase in strength with a small increase in contact radius. Therefore, for site implementation, specific in-situ characterization must be implemented beforehand to understand the soil composition, which is important to decide proper quantities and utilization methods of biopolymers for geotechnical engineering purposes.

Conclusions

Xanthan gum as a type of biopolymer affects the permeability, compressibility, and strength characteristics of a sand without causing environmental toxicity. The improvement in permeability and unconfined compressive strength of sand treated with xanthan gum was found to be directly dependent on the content of xanthan gum and curing time. Addition of xanthan gum was observed to significantly decrease the compressibility and also to enhance stiffness. A 1.5% xanthan gum content in sand increased the permeability and strength by more than twice, while it decreased the compressibility by about half. It was concluded that biopolymer treatment provides promise as a technique to engineer soil behavior in order to have specific permeability, compressibility, strength and deformation characteristics in terms of ductility or stiffness. The results of this approach may open up the way for a microorganism-mediated process for improving some engineering properties of subsurface soil formations. Grouting of such materials to form soil-polymer columns in the field provides a versatile improvement in cohesionless soils.

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