Gellan Gum for Strengthening Bentonite-Sand Slurry

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ABSTRACT: The strengthening ability associated with adding a gellan gum as an additive to bentonite slurry for use in coating soil surfaces was studied. Bentonite powder was mixed with hot gellan gum hydrogel (i.e., at 200 °C) to different gellan gum concentrations (i.e., 0, 3, 4, 5, 6, and 7% of the mass of distilled water). A series of unconfined compressive strength tests were conducted on gellan gum-bentonite mixtures subjected to various thermal curing conditions. The shrinkage behavior was observed during the thermal curing process. The research also studied the sand size particle effect on the strength and volume change of the dried gellan gum-modified bentonite. The test results showed the soil strengthening effect of adding gellan gum to bentonite slurry which was then added it to bentonite/silica sand mixtures.

KEYWORDS: Gellan gum, Bentonite, Silica sand, Unconfined compressive strength, Thermal curing process.

1. INTRODUCTION

The past decade has witnessed significant growth in research related to biopolymers-based soil improvement techniques. Many studies have shown that biopolymers such as agar, starch, betaglucan, xanthan gum, gellan gum can enhance the inter-particle cohesion of soils and improve their strength characteristics (Chang et al., 2020; Smitha et al., 2016). Biopolymers have also been shown to increase the hydraulic conductivity of soils (Aminpour et al., 2015; Chang et al., 2016). Along with these mentioned engineering properties, biopolymers have been shown to produce effective dust control (Chen et al., 2015), anti-desertification, and erosion resistance (Chang et al., 2020). Using biopolymers can significantly reduce the CO_2 emissions associated with conventional methods, such as cement which contributes 5% or more to global greenhouse gases (Hendriks et al., 1998). Chang et al. (2015) also found that soils treated with 1% xanthan gum and 1% gellan gum show higher compressive strengths than cement-mixed soils. Consequently, biopolymers are recognized as a viable alternative to conventional chemical polymers because of their potential cost savings, low environmental impact, non-toxicity, and non-secondary pollution (Aminpour and O'Kelly, 2015).

At a microscopic level, biopolymers indirectly interact with sand particles by coating sand surfaces with a hydrogel film. Meanwhile, clay soils tend to directly interact with biopolymer particles via different electrostatic interactions such as hydrogen bonding, ionic bonds, and van der Waals bonds (Chang and Cho, 2019; Fatehi et al., 2021). Bentonite, which is widely used as drilling slurry and excavation slurry material, has also been known to result in serious environmental concerns because of the harmful discharged waste (Paschoalin Filho et al., 2013). Therefore, numerous studies have been carried out on the enhancement of bentonite slurry using hydrogel polymer. The intent of the studies was to improve properties such as pumpability (Dai et al., 2020), permeability (Wang et al., 2015), adsorption (Yang et al., 2018), chemical resistance (Di Emidio et al., 2017) and strength (Tran and Katsumi, 2021). Recently, there have been many studies on the effect of biopolymers such as xanthan gum, guar gum, chitosan on the volume change and strength enhancement of expansive soil (Keshav et al., 2021; Singh et al., 2020). The current study focuses on the effect that biopolymers bring to the stability of bentonite slurry which is widely used as an excavation slurry or a hydraulic barrier material.

Gellan gum has thermal gelation properties that have proven to show improved hydraulic conductivities (Chang, Tran, et al., 2019), improved strength under wetting/drying cycles (Chang et al., 2017), heavy metal adsorbability from a contaminated slurry (Tran, Cho, et al., 2021) and enhanced stability for hydraulic barrier systems (Tran et al., 2022). Tran and Takeshi (2021) showed that gellan gum can improve the unconfined compressive strength of bentonite slurry. Thermal curing for 1 to 3 days at 30 °C also significantly enhances the strength of gellan gum-treated bentonite (Tran and Katsumi, 2021). Furthermore, the study showed that the addition of 2% gellan gum had no effect on strengthening bentonite slurry (Tran and Katsumi, 2021). The research shows the effects of adding gellan gum as a binder on the strength and stability of bentonite slurry.

The objective of the present study was to quantify the effect of adding gellan gum to bentonite. A series of laboratory unconfined compression experiments were performed on gellan gum-treated bentonite with different gellan gum concentrations and various thermal curing conditions. The shrinkage of the specimens was also measured during thermal curing. The study also evaluated the strength and volume change of gellan gum-treated bentonite/sand mixtures. The scope is limited to the investigation of one modified bentonite slurry.

2. MATERIALS AND EXPERIMENTAL PROCEDURES

2.1 Materials

2.1.1 Bentonite

Bentonite API, known as drilling mud when constructing Barrette piles and diaphragm walls, was used. The product is manufactured according to standards set by the American Petroleum Institute. Bentonite API has the following soil properties; PL = 105 %, LL = 350 %, Gs = 2.73.

2.1.2 Sand

Silica sand collected from the Phong Dien District, Vietnam was used in this study. The sand was sieved using Sieve No. 40 and No. 60 (ASTM, 2001). Sand passing No. 40 and above No. 60 was collected to obtain homogenous sand. This avoided the effect of sand particle size on the unconfined compression strength of the modified bentonite.

2.1.3 Gellan Gum Biopolymer

Gellan was produced by the bacteria Sphingomonas (formerly Pseudomonas) elodea (Bajaj et al., 2007). Gellan was discovered in 1978 and has been commercially distributed in the USA and Japan. Gellan gum is a linear, anionic exopolysaccharide with the repeating unit consisting of α-L-rhammose, β-D-glucuronate, in the molar ratio 1:2:1 (Osmałek et al., 2014). The preparation of gellan gum gels is a temperature-dependent process. Gellan gum solutions need to be heated to a temperature of higher than 95 °C to obtain a clear hydrogel solution with low viscosity (Imeson, 2011). This is followed by a cooling process at room temperature which allows changes in biopolymer chains to form a coil-to-helix transition (Morris et al., 2012). Low acyl gellan gum biopolymer was supplied for this study by Sigma Aldrich (CAS No. 71010-52-1).

2.1.4 Specimen Preparation

The following procedure was used to prepare thermo-gelated gellan gum-treated bentonite mixtures. Dry gellan gum powder was first dissolved and hydrated in distilled water heated up to 200 °C. Varying gellan gum concentrations were then prepared having a mass of gum to mass of water (mG/mw) ratio of 0, 3, 4, 5, 6, and 7%. It was observed that gellan gum concentrations greater than 7% could not form a homogenous mixture with bentonite. Therefore, 7% was considered the maximum concentration that could be prepared. The bentonite powder was dried to 105 °C and heated until it reached a constant value. The dry bentonite powder and the boiled gellan gum solution were uniformly mixed at an initial gravimetric water content, w, of 500% to form a uniform gellan gum-bentonite slurry.

After thorough mixing, the hot gellan gum-bentonite was immediately placed into cubic molds made of stainless steel. The molds had an inner width dimension of 35 mm, a length of 35 mm, and a depth of 35 mm. A sample of the unconfined compression test specimens are shown in Figure 1. The dry density of the gellan gum-treated bentonite specimens were 0.327 ± 0.03 g/cm^3. After cooling for 6 hours, the specimens were dried in the oven at 30 °C for 7 and 28 days; at 40 °C and 50 °C for 1, 3, 7, and 28 days. This constituted the overall study conducted by Tran and Takeshi (2021).

Furthermore, to prepare gellan gum-treated bentonite/sand mixes, dry sand and bentonite were mixed and then combined with the boiled gellan gum solution. The mixed soil specimens with varying bentonite and sand ratios (m_b:m_s) are shown in Table 1. The study was designed to determine the effect of adding sand and then measuring the strength and volume change of gellan gum-modified bentonite. Specimens with a gellan gum concentration of 3% were used for these tests. The specimens were cured at a temperature of 40 °C for 7 days. This was the protocol decided upon based on the results from gellan gum-treated bentonite cured at 40 °C. The effect of water content on the unconfined compressive strength of the bentonite/sand mixtures was measured while the water content was changed (e.g., 500%, 250% and 100%). The dry density of the specimens is tabulated in Table 1.

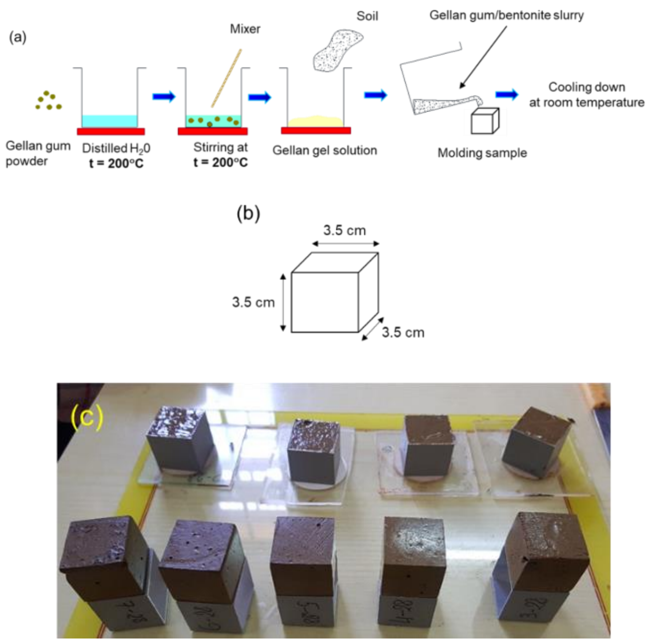

Figure 1 Gellan gum-treated soil specimen preparation: (a) Scheme of specimen preparation, (b) specimen mold, and (c) gellan gum-treated bentonite

Table 1 Information on the soil mixture of bentonite powder and silica sand

m_b:m_s	Symbol				
100:0	B10	**w [%]**	100	**Dry density [g/cm^3]**	0.97 ± 0.02
90:10	B9S1				
80:20	B8S2				
70:30	B7S3		250		0.46 ± 0.03
60:40	B6S4				
50:50	B5S5				
40:60	B4S6		500		0.35 ± 0.03
30:70	B3S7				
20:80	B2S8				

2.2 Experimental Procedure

2.2.1 Unconfined Compression Test

Unconfined uniaxial compressive strength (UCS) testing was performed using an unconfined compressive apparatus (Figure 2). The strength tests were conducted on the cubic specimens prepared at two initial conditions (i.e., after 6 hours cooling down, at a room temperature of 20 ± 1 °C) and dry conditions. For dry conditions, the specimens were left in the oven for 1, 3, 7, and 28 days at 30, 40 and 50 °C; conditions that might be encountered in the outdoors in an emergency situation. The axial strain was controlled at a medium rate of 1.7 %/min (ASTM, 2016; Das et al., 2020). Generally, the UCS is taken as the peak of the axial stress versus strain curve; however, if any specimen did not show a peak value, the stress level recorded at 15% strain was taken as the UCS (ASTM, 2016). The maximum strengths and stress-strain behaviors were averaged over three test specimens.

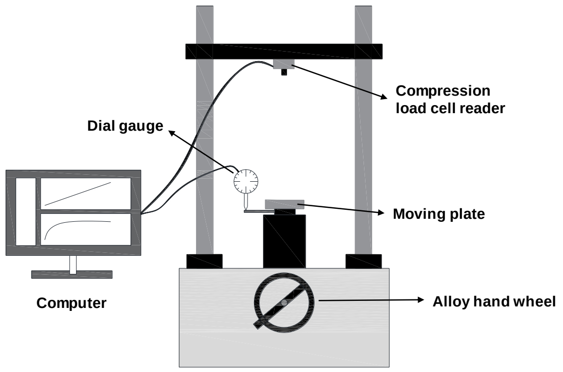

Figure 2 Scheme of Unconfined compression apparatus (Tran and Katsumi, 2021)

2.2.2 Shrinkage Observation

The shrinkage behavior of specimens was observed by recording changes in volume and mass of specimens with time during the thermal curing process.

The reduction rate in mass, Rm, was calculated as followed:

$$R_m = \frac{M_o - M_i}{M_o} * 100 \tag{1}$$

where M_o is the mass of soil at initial condition (i.e., after cooling down); and Mi is the mass of soil as it was cured at day ith.

The change in volume was calculated as follows:

$$R_V = \frac{V_o - V_i}{V_o} * 100 \tag{2}$$

where V_o is the mass of soil under initial conditions (i.e., after cooling down); and V_i is the mass of soil as it was cured at day ith.

3. RESULTS AND ANALYSIS

3.1 Strengthening Effect of Gellan Gum on Bentonite Slurry

Figures 3, 4, and 5 show the UCS (stress) versus strain curves of bentonite when tested with and without treatment with gellan gum. All the soil specimens did not show a peak for the stress versus strain curve. In these cases the strength was taken as corresponding to 15% strain. This behavior was also obtained in the study conducted by Tran and Takeshi 2021 (Tran and Katsumi, 2021).

Figure 3(a) shows the UCS of the specimens after being cured 7 days at 30 °C. The UCS behavior of the gellan gum-treated bentonite is consistent for varying concentrations of gellan gum biopolymer in bentonite. The higher gellan gum concentration resulted in higher values of UCS. The UCS of bentonite increases approximately 10, 12, 22, and up to 56 times as 3, 4, 5, and 6% gellan gum, respectively, were added. The UCS with 7% treated bentonite (1429 kPa) was 94 times higher than that of the untreated (15.2 kPa), showing the most significant improvement in the strength of the bentonite slurry (Figures 3(a) and 6). The order in strengthening effect referred to gellan gum concentration was obtained for bentonite cured at 40° for 1 and 3 days (Figures 4(a) and (b)) and 50 °C for 1 day (Figure 5). The strength of modified bentonite increases with gellan gum concentration due to the direct interaction between bentonite clay and gellan gum biopolymer particles (Chang and Cho, 2019; Dai et al., 2020). The interaction creates a mixture which has a higher compressive strength than when untreated.

Figure 3(b) shows the UCS of all the specimens cured for 28 days. The results show a dramatic increase in strength in comparison to results obtained for the case of curing for 7 days (Figure 3(a)). However, the increase in the strength of the soil with time (Figure 3(b)) did not correspond to the rise in gellan gum concentration as shown in Figure 3(a). The strengthening effect versus gellan gum concentration was not observed for the case when the specimens were cured at 40 °C for 7 days (Figure 4(c)). The specimens cured at 50 °C for more than 3 days were not consistent due to the fracture system formed during the thermal curing process. This effect will be further presented in the following section.

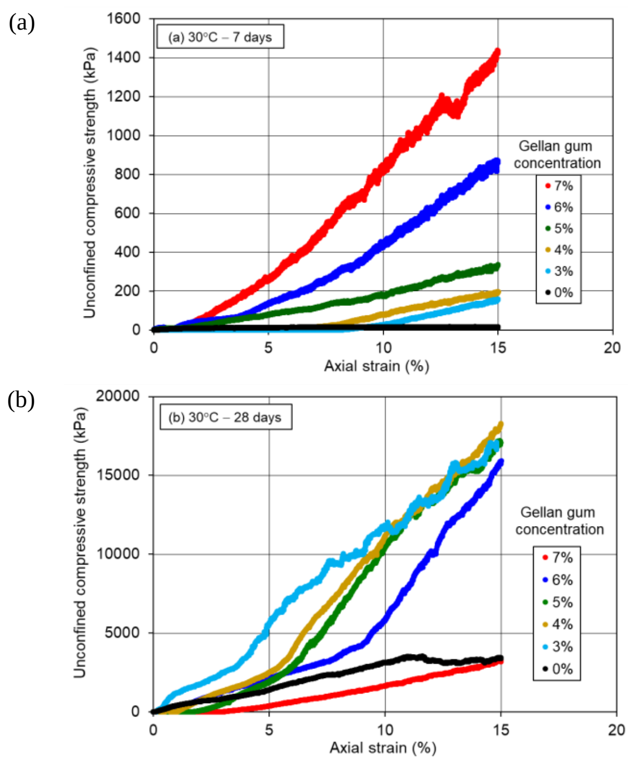

Figure 3 Unconfined compressive strength up to 15% strain of gellan gum-treated bentonite slurry after curing of: (a) 7 days and (b) 28 days at 30 °C

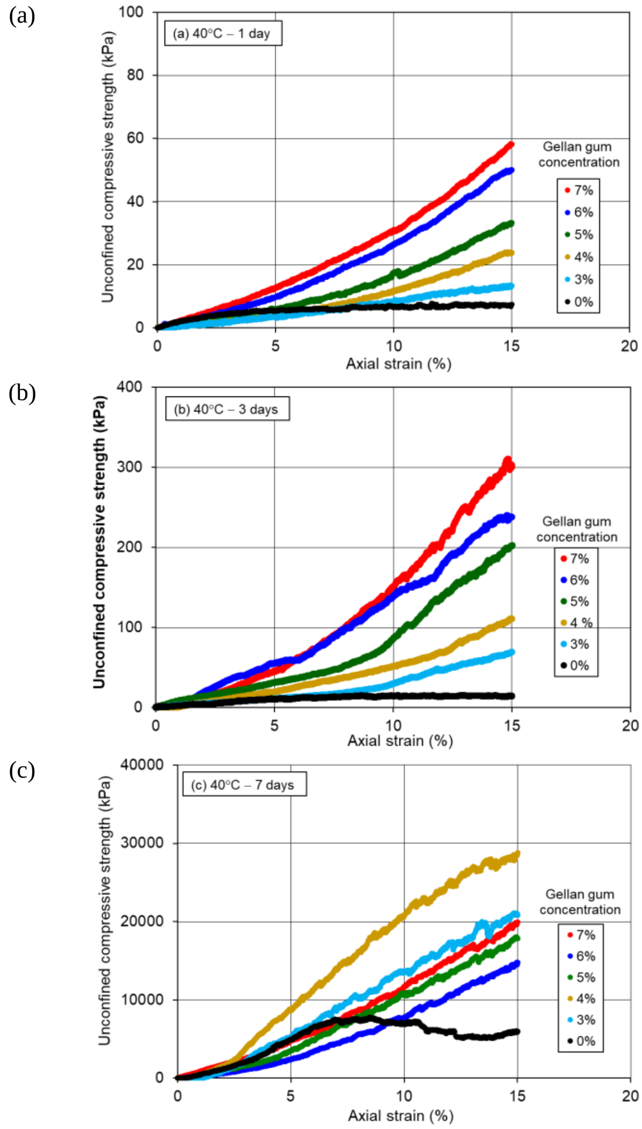

Figure 4 Unconfined compressive strength up to 15% strain of gellan gum-treated bentonite slurry after curing: (a) 1 day, (b) 3 days, and (c) 7 days at 40 °C

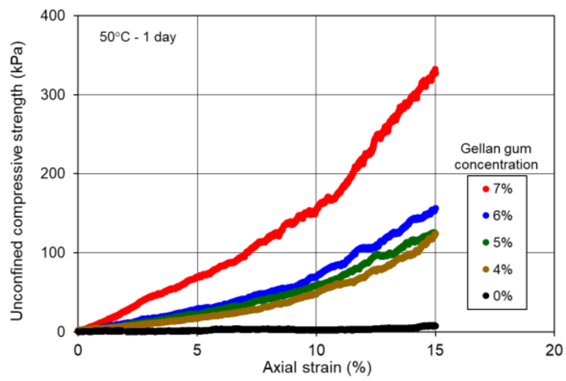

Figure 5 Unconfined compressive strength up to 15% strain of gellan gum-treated bentonite slurry after curing 1 day at 50 °C

The modified bentonite increased in strength with thermal curing time. Figure 6 summarised the change of USC of the soil that had not shown a crack system in specimens with varying duration and temperature values of the thermal curing process. The more extended the curing period applied, the higher UCS values were obtained for all temperature cases. As seen for the 30 °C curing case, the UCS of untreated bentonite went from zero at an initial and 1 day of curing to a slight increase of 3.88 kPa and 15.2 kPa after 1 and 7 days of curing (Figure 6). This phenomenon can be observed for all cases of modified bentonite. For instance, the UCS of 7% gellan gum-treated bentonite significantly increased from 55.6 kPa at initial up to 1429 kPa after 7 days of curing (Figure 6). However, the remarkable increase rate in strength can be seen for the case of 3% gellan gum treated. Compared to the initial condition, the UCS of 3% treated bentonite increased approximately 162 times after 7 days of curing, followed by 48 times for 4%, 20 times for 5, 6% and 25 times for 7% (Figure 7(a)).

The results showed that the higher the gellan gum concentration used, the lower the increase in strength. This was also observed for other curing periods and temperatures (Figure 7). The reduction in the rate of strength improvement under thermal curing occurred because of the different types of water within gellan gum hydrogel. There are three types of water in hydrogel, namely strongly bound water, weakly bound water and free water (Gun'ko et al., 2017). At low gellan gum concetration, gellan gum hydrogel contains more free or weakly bound water which can be easily removed by temperature increase. This resulted in the significant effect on the state of dried gellan gum and the UCS of clay. Gellan gum contents of 5, 6 and 7% left the specimens with more strongly bounded water which left the specimens less affected by temperature.

Figures 6 and 7 also show the role of curing temperature in strengthening bentonite slurry with gellan gum. For 1 day of curing, the untreated bentonite at 30 °C was not strong enough to stand under its own weight; however, the UCS increased to 6.85 kPa and 7.6 kPa at 40 °C and 50 °C, respectively. The UCS values of treated bentonite, under the same curing period, increased with the temperature applied, except for the case of 3% gellan gum treatment. For instance, the UCS of 7% gellan gum-treated bentonite slightly increased from 55.6 kPa at the initial state to approximately 60 kPa at 30°C and 40°C, and then at 50 °C reached a value of 6 times as great as initial condition (Figure 6). The higher strength with curing temperature can be explained by the formation of gellan gum hydrogel film during the thermal process. Water in gellan gum loses sharply with time and temperature applied (Roy et al., 2013), which forms dried gellan gum matrix within clay particles (Chang and Cho, 2019; Chang et al., 2015). Along with the loss of water within the bentonite slurry, dried gellan gum matrix formed a more stable and more rigid mixture with curing temperature. Furthermore, the higher gellan gum concentration, the thicker hydrogel threads (Korzhikov-Vlakh et al., 2016), and in turn, resulted in higher UCS values.

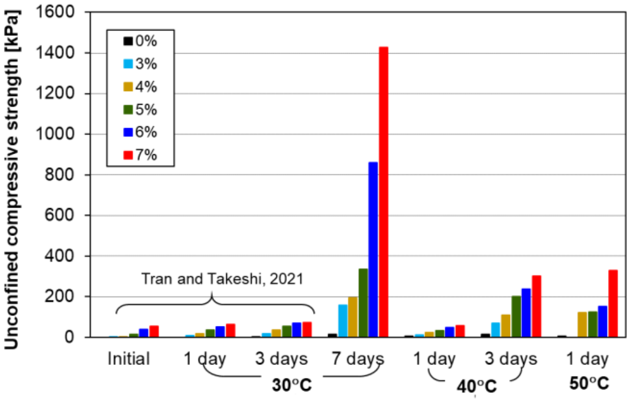

Figure 6 Unconfined compressive strength at 15% strain of gellan gum-treated bentonite slurry

3.2 Cracking on Gellan Gum-Modified Bentonite

Crack formations in bentonite were the result of soil shrinkage due to loss of water by evaporation. The crack formations on the soil surface was also temperature-dependent (Tang et al., 2010). The water removal from the hydrogel network was due to weight reduction, structural and volume changes (Łabowska et al., 2021). Cracking was also observed on the surface of gellan gum-modified bentonite. The shrinkage of the modified bentonite was triggered by a complex shrinkage mechanism induced by the hydrogel and the bentonite. The shrinkage phenomenon resulted in a change in volume and mass of the specimens.

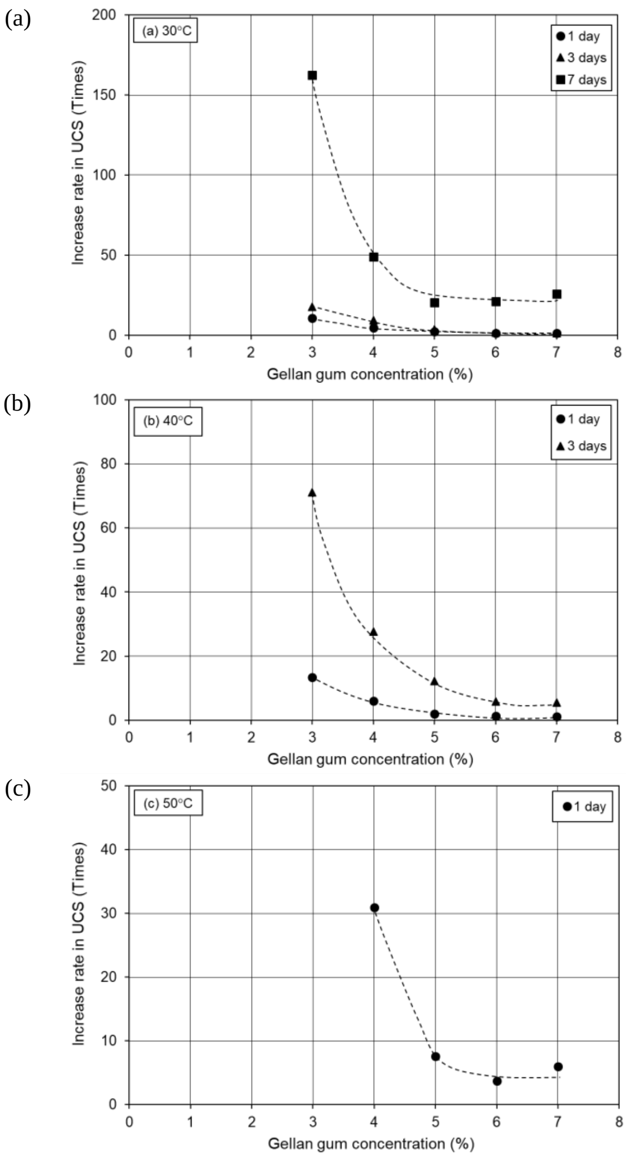

Figure 7 Increase rate in unconfined compressive strength with curing period for different gellan gum concentration at: (a) 30 °C, (b) 40 °C, and (c) 50°C

Figure 8 shows the change in soil structure with thermal curing time and temperature. The cracking was categorized into four levels: none, mild, major, and severe cracks. The severity level of cracking was related to the gellan gum concentration, curing period, and curing temperature. None-cracked specimens have a smooth surface, marked in green in Figure 8. As crack appeared unclearly and disconnected without a mouth opening on the specimen surface, the specimens experienced the formation of mild cracking, which is marked in orange. Next, the mouth-opening became wider up to 1 mm, and the severity level was classified as major cracking (Figure 8). Finally, the crack-mouth opening increased to 3 mm and even formed connected crack systems within some specimens and was classified as severe level using a dark orange (Figure 8).

No crack appears on the gellan gum specimen surfaces after being cured at 30 °C for 7 days. After 28 days of curing, major cracks were formed on all specimens. As the specimens were cured at 40 °C, mild cracks appeared for the case of untreated bentonite, and major cracks came earlier, (i.e., 7 days), compared to cases cured at 30 °C. The specimens cured for 28 days experienced severe cracking. The specimens cured at 50 °C were severely cracked after 3 days. The 3% treated specimens were deformed when treated after 1 day at 50 °C. Generally, higher temperatures caused severe cracks to appear earlier. In general, longer curing times triggered crack appearance.

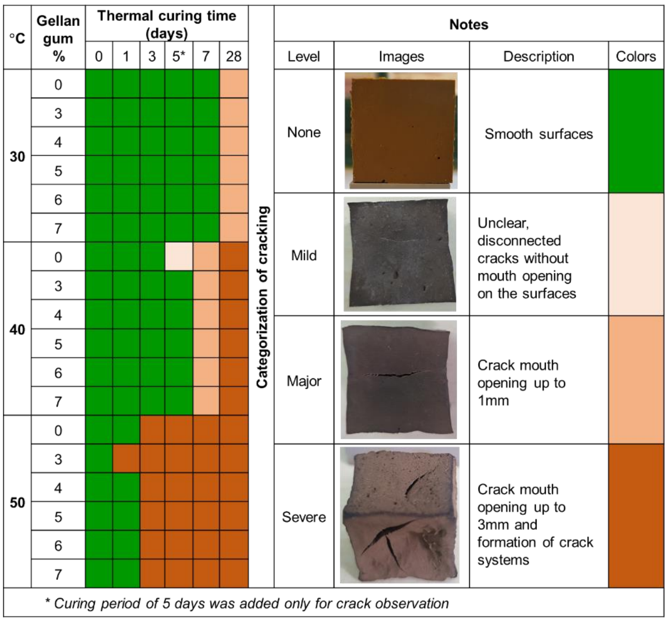

Figure 8 Description of crack formation in soil during thermal study

Cracks appeared due to shrinkage associated with reductions in volume and mass changes. Figures 9, 10, and 11 show the change in volume and mass of the specimens for thermal curing temperatures of 30, 40, and 50 °C. The results shown were for specimens for which unconfined compression tests could be performed. The reduction in mass of the specimens was due to the water loss during thermal curing.

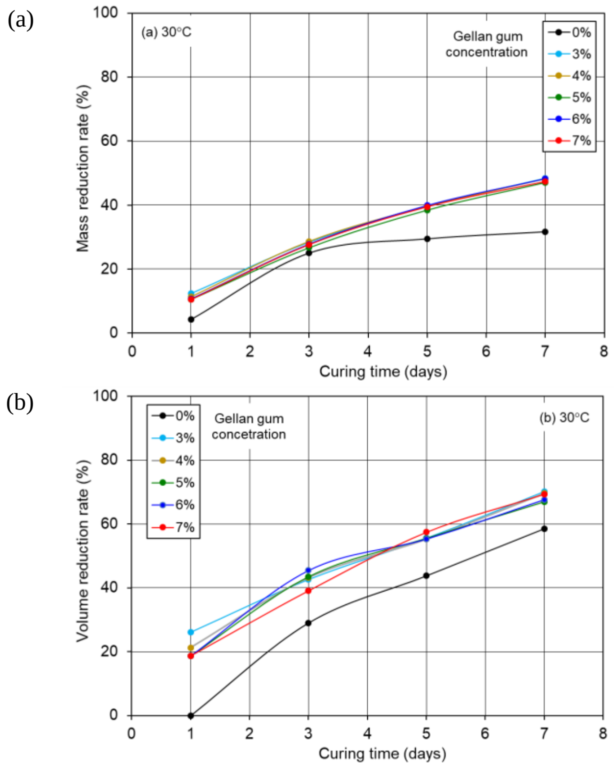

Figure 9 Reduction rate in: (a) mass and (b) volume of specimens cured at 30 °C *(*Curing time of 5 days was added for observation of mass and volume reduction)*

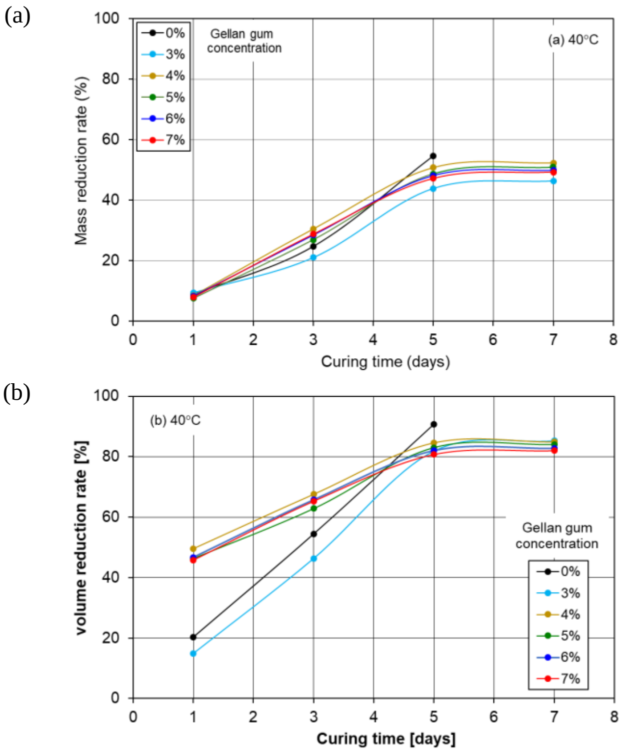

Figure 10 Reduction rate in: (a) mass and (b) volume of specimens cured at 40 °C *(*Curing time of 5 days was added for observation of mass and volume reduction)*

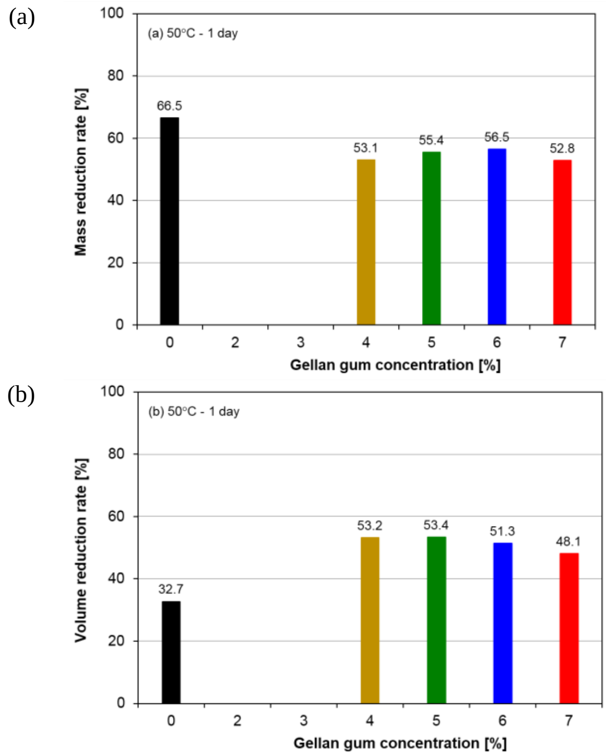

Figure 11 Reduction rate in (a) mass and (b) volume of specimens cured at 50°C

The soil mass continued increasing with curing time for the case of 30 °C (Figure 9(a)) regardless of the gellan gum concentration. The mass change of the modified soil leveled off after 5 days of curing at 40 °C, while the unmodified soil mass kept increasing until day 5 before the specimen became thermally distorted (Figure 10(a)). The trend could be seen for changes in volume for soils cured at 30 and 40 °C (Figures 9(b) and 10(b)). The phenomenon occurred because at low temperatures (i.e., 30 °C), the loss of water occurred more slowly than at higher temperatures (40 °C). The reduction rate in mass and volume followed an increasing trend with curing time. At higher temperatures, the water loss occurred more rapidly and reached its maximum value after 5 days with a reduction rate in mass and volume of approximately 50% (Figure 10(a)) and 80% (Figure 10(b)), respectively.

The mass reduction rate after 1 day of curing at 30 and 40 °C was 10 ± 2% (Figures 9(a) and 10(a)). The mass rate increased significantly up to 66% for the unmodified soil and became 54 ± 2% for modified soils cured at 50 °C (Figure 11(a)). The observed behavior was related to the role of temperature on water loss within the soil. The reduction in mass and volume of soil cured for 1 day at 50 °C is shown in Figure 11. The mass reduction rate of unmodified bentonite was higher than for other modified specimens (Figure 11(a)). The volume of unmodified bentonite decreased at a higher rate as shown in Figure 11(b).

3.3 Strengthening Effect of Gellan Gum on Bentonite/Sand Mixture

The UCS results of gellan gum-treated clay and sand mixture varied with sand and bentonite content and water contents. Figure 12 shows the relationship between UCS and axial strain of the specimen having no fractures, distortion or layering between sand and clay. In general, the UCS stress increased with strain. For the specimens having 500% water content, only mixtures of bentonite and sand, mb:ms, of 60:40 and 70:30 reached the USC strength values (Figure 12(a)). As the soils were thermally cured at 40 °C for 7 days, a similar reduction in mass (82%) and volume (86%) occurred (Figures 13(a) and 13(b)); however, the UCS at 15% strain of specimen B7S3 was 19692 kPa which was higher than that of specimen B6S4 (15606 kPa) (Figure 13(c)).

Soils with a m_b:m_s ratio of 20:80 were not able to be tested for strength when the water content was 250%. This behavior was due to there being an insufficient amount of sand to thoroughly mix with bentonite (Figure 14). The highest UCS was observed for mb:ms ratios of 80:20 with a value of 20928 kPa, followed by the strength of soils with mb:ms of 90:10 (20175 kPa) and 70:30 (19779 kPa). As the sand content increased, the soil strength decreased and went to the lowest UCS for mb:ms of 30:70 (7653 kPa). The reduction rate in volume and mass of specimens slightly decreased with the amount of sand in specimen (Figures 13(a) and 13(b)).

For the specimens with water content of 100%, the lowest UCS was for mb:ms of 70:30 with a value of 1607 kPa and the highest UCS was for the case of mb:ms of 50:50 (Figure 14). Similar to the case of a water content of 250%, the reduction rate followed a slight decrease with sand content in the specimen.

4. CONCLUSIONS

The UCS tests on bentonite samples and bentonite/silica sand mixture were carried out with different gellan gum-treated concentrations, thermal curing temperatures and elapsed time periods The test results were analyzed and the following conclusions were arrived at:

1) Results of UCS tests show that the strength values of gellan gum-treated soils depend on type of soil, water content, gellan gum content, and curing process (i.e., time and temperature).
2) The UCS properties of bentonite can be effectively improved by using various gellan gum concentrations. The curing temperature and treatment period are important factors influencing the behavior of the mixtures. A significant soil reinforcement effect was observed when using a temperature of 30 °C and a curing time of 7 days. Seven percent gellan gum results in a 94 times increase in the UCS when compared to soil mixtures without any thermal treatment. An extension of the curing time of up to 28 days results in severe distortion with cracking of the specimens. Higher curing temperatures (40 and 50 °C) enhance the strength of treated bentonite; however, cracking occurs earlier when the same curing time is considered. It can conclude that gellan gum cannot significantly improve the shrinkage and cracking phenomenon associated with adding bentonite. With these findings, we can suggest using gellan gum/bentonite mixture for emergent or short-term stabilization of excavation walls and slope surfaces.
3) The presence of silica sand within bentonite/gellan gum mixtures enhances the UCS and reduces the cracking phenomenon. Three percent gellan gum treatment for the bentonite/sand mixture with ratio of 80:20 and water content of 250% emphasized the best combination of bentonite, sand and gellan gum for strengthening improvement.

This study showed that benefits can be accrued in using gellan gum as a friendly environmental soil binder. The gellan gum can be used as an effective tool for engineers working in the field of soil improvement. Practical application areas could be in the area of slope stability and landfill liner design. This study is limited to investigating the strength of the suggested material. More studies on hydraulic conductivity and heavy metal adsorption should be conducted in the future to earn more evidence of the workability of the material for hydraulic barriers, landfill covers and liners.

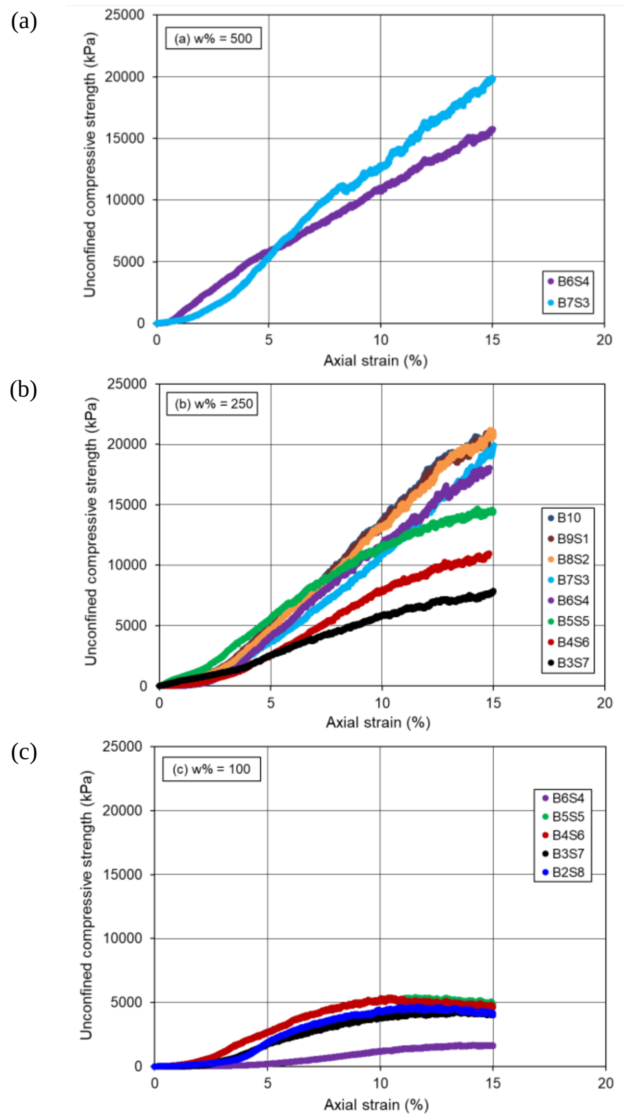

Figure 12 Unconfined compressive strength up to 15% strain of gellan gum-treated bentonite/sand mixture with: (a) 500%, (b) 250%, and (c) 100% initial water content curing for 7 days at 40 °C

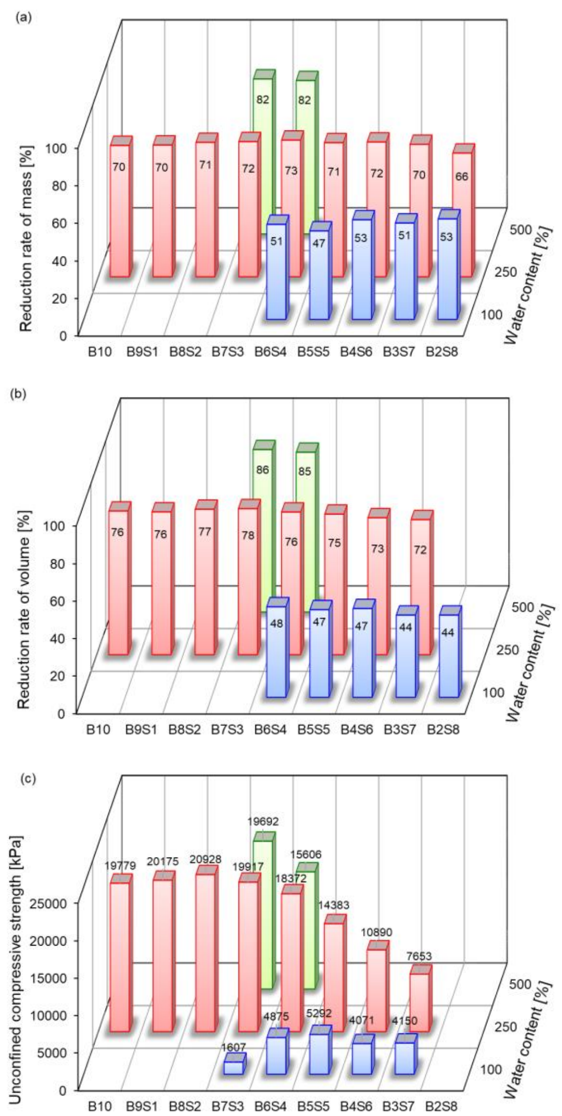

Figure 13 Changes in: (a) mass, (b) volume, and (c) unconfined compressive strength of gellan gum-treated bentonite/sand mixture with different initial water contents

Figure 14 Layer formation of soil with varying sand content

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Aminpour, M., and O'Kelly, B.C. (2015) "Applications of biopolymers in dam construction and operation activities", Proceedings of the 2nd International Dam World Conference, Lisbon, Portugal, pp937-946.

ASTM (2001) Standard sieves ASTM Specification E-11, Nominal Dimensions, Permissible Variations for Wirecloth of Standard Test Sieves, U.S.A.

ASTM (2016) D2166 Standard test method for unconfined compressive strength of cohesive soil. In: ASTM international West Conshohocken, PA.

Bajaj, I.B., Survase, S.A., Saudagar, P.S., and Singhal, R.S. (2007) "Gellan gum: fermentative production, downstream processing and applications", Food Technology and Biotechnology, 45, Issue 4, pp341-354.

Chang, I., and Cho, G.-C. (2019) "Shear strength behavior and parameters of microbial gellan gum-treated soils: from sand to clay", Acta Geotechnica, 14, Issue 2, pp361-375.

Chang, I., Im, J., and Cho, G.-C. (2016) "Geotechnical engineering behaviors of gellan gum biopolymer treated sand", Canadian Geotechnical Journal, 53, Issue 10, pp1658-1670. https://doi.org/10.1139/cgj-2015-0475

Chang, I., Im, J., Lee, S.-W., and Cho, G.-C. (2017) "Strength durability of gellan gum biopolymer-treated Korean sand with cyclic wetting and drying", Construction and Building Materials, 143, Issue, pp210-221. https://doi.org/10.1016/j.conbuildmat.2017.02.061

Chang, I., Im, J., Prasidhi, A.K., and Cho, G.-C. J.A.G. (2015) "Effects of Xanthan gum biopolymer on soil strengthening", Construction and Building Materials, 74, Issue, pp65-72. https://doi.org/10.1016/j.conbuildmat.2014.10.026

Chang, I., Lee, M., Tran, A. T. P., Lee, S., Kwon, Y.-M., Im, J., and Cho, G.-C. (2020) "Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices", Transportation Geotechnics, 24, Issue, pp100385. https://doi.org/10.1016/j.trgeo.2020.100385

Chang, I., Tran, A., and Cho, G.-C. (2019) "Introduction of biopolymer-based materials for ground hydraulic conductivity control",T unnels and Underground Cities: Engineering and Innovation meet Archaeology, Architecture and Art (p 277-283): CRC Press.

Chen, R., Lee, I., and Zhang, L. (2015) "Biopolymer stabilization of mine tailings for dust control", Journal of Geotechnical and Geoenvironmental Engineering, 141, Issue 2, pp04014100. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001240

Dai, G., Sheng, Y., Pan, Y., Shi, G., and Li, S. (2020) "Application of a bentonite slurry modified by polyvinyl alcohol in the cutoff of a landfill", Advances in Civil Engineering, 2020, Issue. https://doi.org/10.1155/2020/7409520

Das, D., Kalita, T., and Chetia, M. (2020) "Influence of strain rate on unconfined compressive strength of bentonite and sand mixes", Geotechnical Characterization and Modelling (pp195-204): Springer.

Di Emidio, G., Verastegui-Flores, R. D., Mazzieri, F., and Dominijanni, A. (2017) "Modified clays for barriers: a review", Innovative Infrastructure Solutions, 2, Issue 1, pp1-13. https://doi.org/10.1007/s41062-017-0073-8

Fatehi, H., Ong, D. E., Yu, J., and Chang, I. (2021) "Biopolymers as Green Binders for Soil Improvement in Geotechnical Applications: A Review", Geosciences, 11, Issue 7, pp291.

Gun'ko, V. M., Savina, I. N., and Mikhalovsky, S. V. (2017) "Properties of water bound in hydrogels", Gels, 3, Issue 4, pp37.

Hendriks, C. A., Worrell, E., De Jager, D., Blok, K., and Riemer, P. (1998) "Emission reduction of greenhouse gases from the cement industry", Proceedings of the fourth international conference on greenhouse gas control technologies, pp939-944.

Imeson, A. (2011) Food stabilisers, thickeners and gelling agents: John Wiley & Sons.

Keshav, N., Prabhu, A., Kattimani, A., Dharwad, A., Kallatti, C., and Mahalank, S. (2021) "Enhancing the Properties of Expansive Soil Using Biopolymers—Xanthan Gum and Guar Gum", Proceedings of the Indian Geotechnical Conference 2019, pp129-135.

Korzhikov-Vlakh, V., Krylova, M., Sinitsyna, E., Ivankova, E., Averianov, I., and Tennikova, T. B. (2016) "Hydrogel layers on the surface of polyester-based materials for improvement of their biointeractions and controlled release of proteins", Polymers, 8, Issue 12, pp418. https://doi.org/10.3390/polym8120418

Łabowska, M. B., Jankowska, A. M., Michalak, I., and Detyna, J. (2021) "Shrinkage of Alginate Hydrogel Bioinks Potentially Used in 3D Bioprinting Technology", Key Engineering Materials, pp39-45.

Morris, E. R., Nishinari, K., and Rinaudo, M. (2012) "Gelation of gellan–a review", Food Hydrocolloids, 28, Issue 2, pp373-411.

Osmałek, T., Froelich, A., and Tasarek, S. (2014) "Application of gellan gum in pharmacy and medicine", International journal of pharmaceutics, 466, Issue 1-2, pp328-340.

Paschoalin Filho, J., Alexandre, Dias, A. J. G., and de Lima Duarte, E. B. (2013) "The use of polymer slurry as an economic and sustainable way to build diaphragm walls–a case study of a construction work in São Paulo/Brazil", Exacta, 11, Issue 3, pp299-306.

Roy, N., Saha, N., and Saha, P. (2013) "Stability study of novel medicated hydrogel wound dressings", International Journal of Polymeric Materials, 62, Issue 3, pp150-156. https://doi.org/10.1080/00914037.2011.641697

Singh, S. P., and Das, R. (2020) "Geo-engineering properties of expansive soil treated with xanthan gum biopolymer", Geomechanics and Geoengineering, 15, Issue 2, pp107-122. https://doi.org/10.1080/17486025.2019.1632495

Smitha, S., and Sachan, A. (2016) "Use of agar biopolymer to improve the shear strength behavior of sabarmati sand", International Journal of Geotechnical Engineering, 10, Issue 4, pp387-400. https://doi.org/10.1080/19386362.2016.1152674

Tang, C.-S., Cui, Y.-J., Tang, A.-M., and Shi, B. (2010) "Experiment evidence on the temperature dependence of desiccation cracking behavior of clayey soils", Engineering Geology, 114, Issue 3-4, pp261-266. https://doi.org/10.1016/j.enggeo.2010.05.003

Tran, T. P. A., Cho, H., Cho, G.-C., Han, J.-I., and Chang, I. (2021) "Nickel (Ni2+) Removal from Water Using Gellan Gum–Sand Mixture as a Filter Material", Applied Sciences, 11, Issue 17, pp7884.

Tran, T. P. A., and Katsumi, T. (2021) "Improving the stability of bentonite slurry using gellan gum for an emergent hydraulic barrier", Hue University Journal of Science: Earth Science and Environment, 130, Issue 4A.

Tran, T. P. A., Katsumi, T., Nguyen, T. T., and Lê, T. C. T. (2022) "Gellan Gum-Bentonite Mixture as a New Vertical Hydraulic Barrier", CIGOS 2021, Emerging Technologies and Applications for Green Infrastructure (pp1085-1093): Springer.

Wang, Y., Dai, G., Jiang, X., and Shi, G. (2015) "Research on performance of impervious grouting based on modified bentonite", Water Resource and Power, 33, Issue 6, pp123-125.

Yang, Y.-L., Reddy, K. R., Du, Y.-J., and Fan, R.-D. (2018) "Sodium hexametaphosphate (SHMP)-amended calcium bentonite for slurry trench cutoff walls: workability and microstructure characteristics", Canadian Geotechnical Journal, 55, Issue 4, pp528-537.