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Effect of Using Xanthan Gum on Properties of Fine-Grained Soils

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ABSTRACT

This paper presents the results of a laboratory testing program that was undertaken to investigate the effects of mixing fine-grained soils with xanthan gum on soil properties. The tests performed included liquid and plastic limits, incremental stress consolidation tests (done as part of the direct shear tests), fully softened direct shear tests, and ring shear tests to measure the residual shear strength. All these tests were performed on untreated specimens and specimens treated with 1% xanthan gum (by mass). The specimens were prepared remolded and mixed at a water content close to the liquid limit for shear strength measurements. The results show that mixing soils with 1% xanthan gum can change the liquid limit, plastic limit and plasticity index of fine-grained soils, sometimes enough to change the USCS classification. The direct shear tests results showed a significant decrease in the coefficient of consolidation of fine-grained soils mixed with 1% xanthan gum but not a significant effect on the fully softened shear strength measured. The residual ring shear tests showed a significant increase in the residual strength for VBC but not for Colorado Clay. The strength tests for Colorado Clay will be redone as these were performed on samples that were processed twice which appear to have altered the results.

INTRODUCTION

The fully softened shear strength was defined by Skempton (1970) as the peak drained strength of fine-grained soils in their normally consolidated state. Based on back-analysis of failed slopes, this shear strength has been shown to be the controlling shear strength of cuts in stiff clays (Skempton 1970) and embankments constructed using compacted high-plastic fine-grained soils that are exposed to significant seasonal variation in moisture content (Kayyal and Wright 1991). Failures associated with fully softened shear strength on compacted embankments are usually shallow, less than 10 ft (Castellanos et al. 2016). Although generally treated as maintenance repairs by most agencies/owners, these slides represent a significant expense. Some preventative measures include treating the soils with chemical additives such as cement and lime to improve the soil's strength and reduce the shrink-swell potential (Barman and Dash 2022). Cement production is a significant source of CO_2 emissions globally, it accounts for approximately 8% of global CO_2 emissions (Andrew 2018). One other issue is the significant dust produced during manufacturing of these materials and the environmental impact of using either lime or cement as a soil stabilizer

(Moghadam 2014; Mohamad et al. 2022). Biopolymer-based stabilizers are being studied as eco-friendly alternatives to traditional stabilizers. Several studies have been conducted on improving soil strength using different biopolymers (Ayeldeen et al. 2017; Bagheri et al. 2023). In addition to being environmentally friendly, these biopolymers are required at low concentrations and can act as soil binders, thickening, and stabilizing agents (Mudgil et al. 2014; Abdl Aali and Al-Sahlany 2024). Among the researched biopolymers, xanthan gum is currently the most widely used. This is due to its availability in the market, it is used in multiple industries such as medical and the petroleum industry as a thickening agent (Akpan et al. 2020).

Bagheri et al. (2023) investigated the effects of xanthan gum on soil index properties for low plasticity silts. They found that adding xanthan gum significantly increased the plasticity index (PI) and the liquid limit but showed little change in the plastic limit. Vydehi and Moghal (2022) conducted research for plastic soils and found out that the liquid and plastic limit increased slightly for xanthan gum concentrations of 1% but for concentrations of 2% and 4% there was considerable increase in liquid limit and plastic limit.

Chen et al. (2024) showed that xanthan gum-treated soils remained intact when submerged in water, showing increased resistance to disintegration. Also, xanthan-gum-treated soils exhibited greater shear strength than untreated soils even after several wetting and drying cycles (Chen et al. 2024). Xanthan gum changes the consolidation behavior of fine-grained soils by absorbing water (as much as 25 times its weight), which results in slow consolidation and clogging of the pores with its swollen structure (Kwon et al. 2023). Because of its ability to fill up the pores, bond with clay particles, hold water, and swell, xanthan gum reduces the soil's hydraulic conductivity (Venkata Vydehi et al. 2022; Kwon et al. 2023).

Kwon et al. (2023) performed consolidation tests on xanthan gum-treated Kaolinite with water content of 80% and observed that compression index (C_c) increase with increase in the amount of xanthan gum. Venkata Vydehi et al. (2022) performed one-dimensional consolidation tests and measured a decrease in the coefficient of consolidation of the soil caused by mixing the soil with xanthan gum, which was attributed to the hydrophilic nature of xanthan gum. gum Chang et al. (2015) found that the amount of xanthan gum required to achieve the same compressive strength for a red yellow soil is less than the amount of cement needed. After 28 days of mixing, the unconfined compressive strength of a red yellow soil mixed with 1% xanthan gum was about 1.9 times greater than soil mixed with 10% cement. (Chang et al. 2015).

Ayeldeen et al. (2017) conducted a series of direct shear tests on collapsible soil mixed with xanthan gum, cured for 1 week using ASTM D3080, and observed an increase in effective stress cohesion and friction angle. Ayeldeen et al. (2016) mixed xanthan gum with water to get xanthan gum gel of the required consistency before mixing it with collapsible soil from Egypt to study its effects. Modified Proctor test (ASTM D1557), direct shear test (ASTM D3080), and a single odometer test (ASTM D5333) to estimate the collapsible potential of the soil-polymer mixture with biopolymer content of 0.25, 0.5, 1, 2 & 4% were performed. The results showed a decrease in maximum dry unit weight and collapsible potential whereas an increase in optimum moisture and shear strength for the soil-xanthan-gum mixtures. According to Chang et al. (2015), for sandy soil, xanthan gum coats the sand grains increasing the contact area and creating a bridge between those particles that were previously not in contact. In the case of fine-grained soils, xanthan gum creates a network and sticks to the soil particles through interactions like hydrostatic or electrostatic attraction (Chang et al. 2015). Chang et al. (2015) observed these characteristics by performing a scanning electron microscopic analysis of the treated soils.

Even though the addition of xanthan gum for changing the soil properties has shown good results, the biodegradability of xanthan gum needs to be studied well as the hydrophilic nature of the gum may result in ineffectiveness as a strengthening agent (Lee et al. 2023). According to Hiraishi and Taguchi (2009), the physical and chemical degradations of biopolymers with time limits their use as long-term soil-strengthening agents. Chen et al.(2024) and Lee et al. (2022) found that the strength of hydrated (initially wet or resubmerged) xanthan gum-treated soil was significantly lower than that of dry xanthan gum-treated soil.

SOILS USED

The purpose of this laboratory testing program was to investigate the effect of mixing fine-grained soils with xanthan gum on soil properties. For this purpose, soils with different plasticity and mineralogy were tested. Thus far, three different soils have been tested: Brabston Soil, Colorado Clay, and Vicksburg Buckshot Clay (VBC). The Brabston soil is light brown elastic silt, the Colorado clay is brown lean clay, whereas VBC clay is brown fat clay. The index properties of the soils tested are presented in Table 1.

Table 1 Soil index properties

Sample	USCS		Atterberg Limits			Clay-sized fraction (<2μm)
	Symbol	Group Name	LL	PL	PI	
Brabston Soil	MH	Elastic Silt	54	33	21	NA
Colorado Clay	CL	Lean Clay	42	22	20	24
VBC	CH	Fat Clay	78	26	52	69

LABORATORY TESTING PROGRAM

The laboratory testing program undertaken for this investigation was used to evaluate the effect of mixing different soils with xanthan gum at different concentrations and curing times. Thus far, only three soils have been tested at a concentration of xanthan gum of 1% and with no curing time.

Sample Preparation

Soil samples were processed by washing the soil at the as-received water content through a No. 40 sieve. After washing, samples were air dried to a water content close to the soil's liquid limit. A Casagrande liquid limit cup was used to infer the soil's liquid limit water content. The soil was deemed at the right water content when 23-27 blows were required to close the groove in a regular liquid limit test.

Mixing the soil with xanthan gum could be performed using the dry or wet technique suggested by Chang et al. (2015) and Ayeldeen et al. (2017) For the dry technique, the soil was mixed to the desired concentration with the xanthan gum in powder form. For the wet technique, the xanthan gum was first mixed with water to the desired consistency, and the resulting gel was then mixed with the soil. This research used the wet method as it provided a more consistent and homogenous mixture.

When using the wet-mixing technique, the consistency of the gel is very important in creating a homogenous soil-biopolymer mixture. As the viscosity of the xanthan gum gel increases, it gets harder to mix it well with the soil to create a homogenous mixture. For this research, a ratio of the weight of the water to the weight of dry xanthan gum of 15:1 was used as it provided an excellent viscosity to create a homogenous soil-biopolymer mixture. A viscometer was used to characterize the gel. The xanthan gum gel was prepared at room temperature, which was kept constant near 68 °F because viscosity is highly dependent on temperature. Same spindle with same revolution rate was used to measure the viscosity to ensure no effect of the geometry and speed of the spindle. Amex Brookfield DV Next rheometer was used for this purpose. At last, the viscosity measurement given by the device was observed and if the gel varied in value from the previous one, a new xanthan gum gel was prepared.

The concentration of xanthan gum for each soil mixture was calculated using the dry weight of the soil to calculate the dry weight of the xanthan gum needed. To mix the soil with the right proportion, the water content of the soil was measured and used to calculate the amount of dry soil used in the mix. The percentage used to reference every mix is the percentage of dry xanthan gum as a proportion of the total weight of dry soil used. For example, if the mixture is at 1%, 1 g of xanthan gum was mixed for every 100 g of dry soil. After preparing the gel, it was mixed with the soil manually to ensure a uniform mix. The results presented in this paper are for soil-biopolymer mixtures prepared at 1% concentration by mass of xanthan gum.

Tests performed

The laboratory testing program presented in this research investigates the effect of mixing fine-grained soils with xanthan gum on the liquid limit, plastic limit, plasticity index, coefficient of consolidation, fully softened shear strength, and residual shear strength. The tests performed in this testing program were Atterberg limits (ASTM D4318), direct shear tests (ASTM D3080), and ring shear tests (ASTM D6467). The direct shear tests were used to measure the fully softened shear strength, whereas the ring shear tests were performed to measure the residual shear strength.

Direct Shear Specimen Preparation

There are multiple different methods used to form test specimens for fully softened shear strength testing. The method described by Castellanos (2014) was initially adopted in this research. This method produces test specimens that are 1.4 inches tall. Due to the drastic decrease in the coefficient of consolidation caused by the xanthan gum, as will be shown later, specimens this tall would have taken months to test. For this reason, a new specimen preparation method that produces specimens that are 1 inch tall was implemented. This method consisted of forming test specimens inside a consolidation ring and transferring them to the direct shear box. For this purpose, a plastic sheet was put under the consolidation ring to prevent the soil from sticking to the table and allowing the specimen to be handled after it was formed. The specimens were formed similarly as described by Castellanos (2014) Using a spatula, the soil was placed from the outside towards the inside, applying a small pressure to prevent air bubbles from being entrapped in the specimen. When the specimen was formed inside the consolidation ring, a straight edge was used to level the top and the bottom with the consolidation ring. The specimens were then carefully transferred to the direct shear box to be tested following ASTM D3080-23.

Ring Shear Specimen Preparation

The ring shear test specimens were formed in a similar fashion as described by Castellanos (2014). Using a spatula, the soil was placed inside the specimen container from the outside towards the center. Pressure was applied with the spatula during the soil placement to prevent air bubbles from being trapped inside the test specimen. The specimen was then leveled and transferred to the ring shear device to be tested following ASTM D6467-21e1.

RESULTS AND DISCUSSION

Atterberg Limits

The Atterberg limits measured on the standard soils and soils mixed at 1% xanthan gum are summarized in Table 2 and plotted on a plasticity chart in Figure 1. As seen from this table and figures, mixing soils with xanthan gum changed the liquid limit, plastic limit, and plasticity index of the soils. The changes in the index properties were more pronounced for Brabston Soil and VBC than for Colorado Clay. For the Brabston Soil, the liquid limit increased from 54 to 63, the plastic limit from 33 to 35, and the plasticity index from 21 to 28. For Colorado Clay, the liquid changed from 42 to 44, the plastic limit from 22 to 25, and the plasticity index decreased from 20 to 19. For VBC, the liquid limit increased from 78 to 90, and the plastic limit increased from 26 to 41, but the plasticity index decreased from 52 to 49. As can be seen in Figure 1, the change in Atterberg limits for VBC changed the USCS from CH to MH. The results of the Colorado Clay aligned well with the result from the study conducted by Vydehi and Moghal (2022), where a slight increase in liquid and plastic limit was observed for soil treated with 1% xanthan gum by mass.

Direct Shear Test Results

The direct shear tests performed during this investigation started with an incremental stress consolidation from an initial stress of 100 psf to a final consolidation stress using a load increment ratio of approximately one (i.e., the consolidation stress was doubled). Each intermediate stress up to the final consolidation stress was applied for 24 hrs., and the final stress applied until the end of primary consolidation was obtained as required by ASTM D3080-23. The first set of tests performed on treated specimen showed that the time needed to reach the end of primary consolidation was much higher compared to untreated specimen. The first soil tested was Colorado Clay at 1% concentration of xanthan gum by mass. Because the specimens were formed using the technique presented in the Direct Shear Specimen Preparation Section that produced specimens around 1.4 inches tall before consolidation and it would take months to shear the specimens. For this reason, the tests were dismantled, the specimens were mixed and sieved through a No.40 sieve again and mixed to a water content close to the liquid limit. This time, specimens were formed using the new technique described above, forming specimens 1-inch tall, thus reducing the time required to consolidate and shear the specimens. That is why Figure 2 shows Colorado Clay 1 (taller specimens and fresh mixture) and Colorado Clay 2 (reconditioned soil).

Table 2. Atterberg limits of standard soils and soils mixed with 1% xanthan gumby mass.

Sample	Atterberg Limits		
	LL	PL	PI
Brabston Soil	54	33	21
Brabston Soil with 1% XG	63	35	28
Colorado Clay	42	22	20
Colorado Clay with 1% XG	44	25	19
VBC	78	26	52
VBC with 1% XG	90	41	49

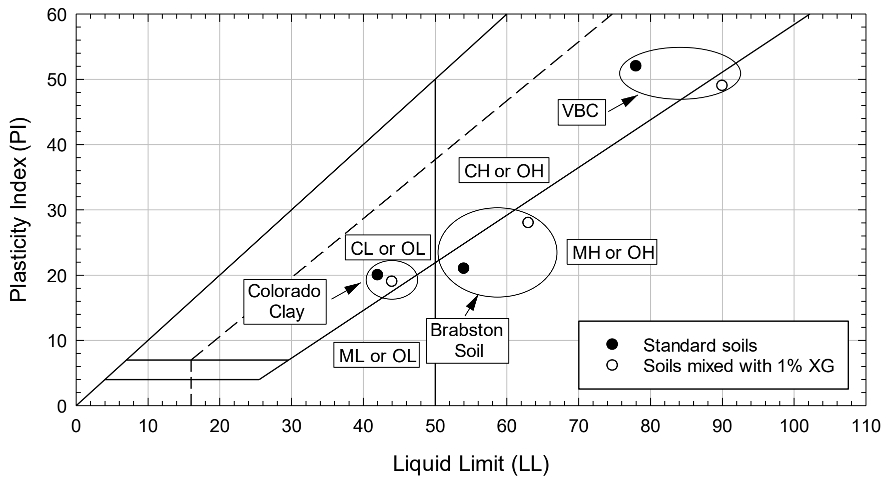

Figure 1. Plasticity chart showing the change in index properties for soils mixed at 1% xanthan gum

The coefficient of consolidation was determined from the results of the consolidation stage of the direct shear tests for the standard soils and the soils mixed with 1% xanthan gum. The results of this comparison, shown in Figure 2, show that the coefficient of consolidation is significantly reduced by mixing the soils with xanthan gum. For Brabston soil, the coefficient of consolidation measured on untreated soils ranged between 14 and 32 times that of the treated soils. For Colorado Clay, a reduction in the coefficient of consolidation was observed when Colorado Clay was tested for the first time, but after being re-sieved, mixed, and retested, the coefficient of consolidation was near that of the untreated soil. It is not yet clear what caused that difference, and more research will be performed to clarify this. For VBC, the ratio was between 6 and 13 times larger than that of the VBC mixed with xanthan gum. The coefficient of consolidation controls the time required to reach the end of primary consolidation and the time needed to shear the specimens. The consolidation coefficient could also indicate the permeability of the soil, as these two are linearly related. These results are in agreement with the results presented by Venkata Vydehi et al. (2022b) and Vydehi and Moghal (2022).

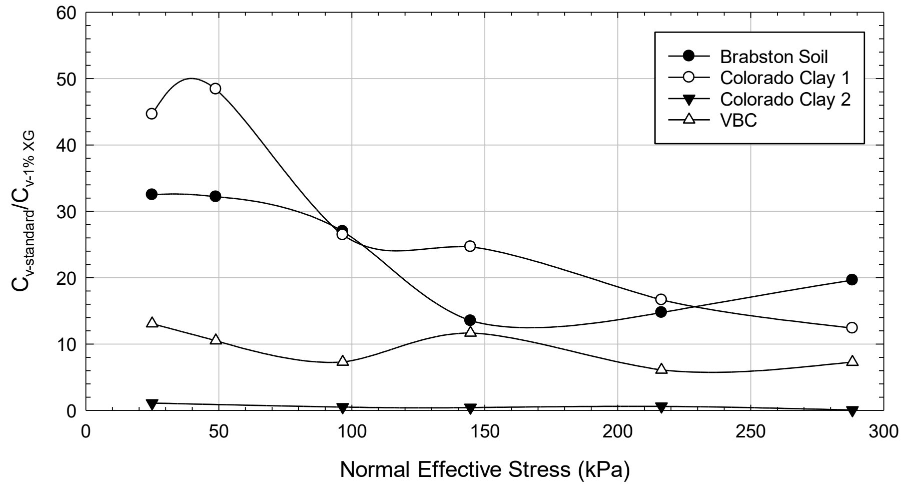

Figure 2. Variation of coefficient of consolidation for samples mixed with 1% XG

The strength results from the direct shear tests were interpreted using three shear strength interpretations: (1) linear envelope, (2) linear envelope assuming the effective cohesion intercept (c') is equal to zero, and (3) non-linear envelope. The equation used to fit the non-linear envelope is presented in Equation 1.

$$s = aP_a\left(\frac{\sigma'_n}{P_a}\right)^b \qquad (1)$$

Where s is the shear strength of the soil, a and b are curve-fitting parameters, σ'_n is the normal effective stress on the failure plane, and P_a is the atmospheric pressure in the same units as σ'_n. The results obtained from the three interpretations are summarized in Table 3 and plotted in Figures 3 and 4. The figures show that the fully softened failure envelope measured on samples mixed at 1% XG tends to be lower than that of the unmixed soil. The difference is more pronounced for Colorado Clay, whereas in VBC, it can be considered standard scatter in the measurements. Brabston soil is currently being tested. The results obtained from Colorado Clay mixed at 1% xanthan gum will be reran using a freshly batch of Colorado Clay mixed at the same concentration.

Table 3. Summary of the strength parameters obtained from the direct shear tests

Sample	c'-ϕ'		c' = 0	Power Function	
	c' (kPa)	ϕ' (deg)	ϕ' (deg)	a	b
Colorado Clay	3.35	29	30	0.6097	0.9269
Colorado Clay with 1% XG	0.77	27	27	0.5330	0.9138
VBC	12.35	17	20	0.4573	0.7231
VBC with 1% XG	7.09	18	19	0.4023	0.7806

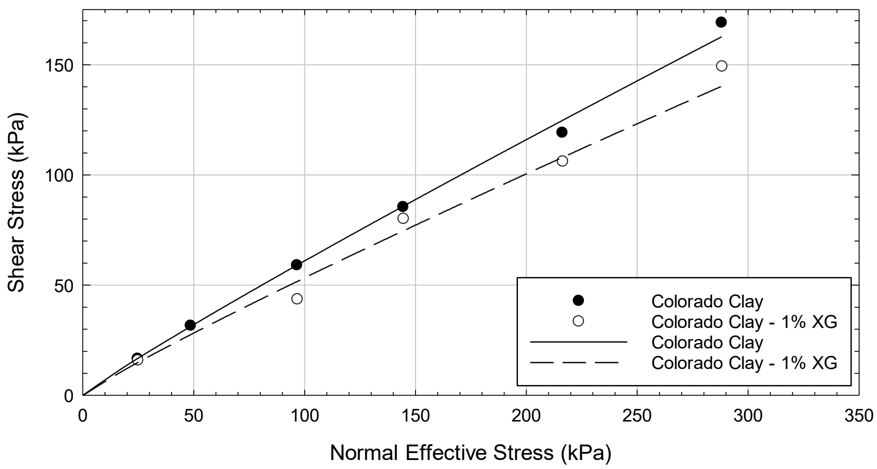

Figure 3. Fully softened shear strength results from Colorado Clay

Ring Shear Test Results

Ring shear tests were performed as part of this investigation to assess the effect of xanthan gum on the residual shear strength of soils. Thus far, only Colorado Clay and VBC have been tested with untreated and treated specimens. The residual shear strength was interpreted using the same three methods as was done for the fully softened direct shear tests. The results of the residual shear strength tests performed are presented in Table 4 and Figures 5 and 6. For Colorado Clay, the measured residual shear strength was not affected by mixing it with 1% xanthan gum. For VBC, a significant increase in the residual strength was observed for specimen mixed with 1% xanthan gum. For Colorado Clay, since these tests were performed after the specimen was mixed at 1% xanthan gum, re-sieved and reconditioned and there is some discrepancy in the consolidation behavior of the before and after reconditioned, the ring shear test results presented here for Colorado clay will be redone with a fresh batch on Colorado Clay mixed at 1% xanthan gum.

CONCLUSIONS

The results presented in this paper shows that xanthan gum can influence the behavior of soils. The Atterberg limits measurements show that mixing soils with xanthan gum can change the liquid limit, plastic limit and plasticity index of the soils sometimes enough to even change the USCS classification. The fully softened direct shear tests results showed that the coefficient of consolidation is greatly reduced by mixing soil with xanthan gum. This can also be seen as a reduction in permeability as these two are linearly related. The fully softened shear strength was found not to be greatly affected by mixing soils at 1% xanthan gum. The results from the ring shear tests performed to measure the residual shear strength showed that for VBC, mixing the soil with xanthan gum caused a significant increase in the residual shear strength. For Colorado Clay, the results did not show any effect on the residual shear strength from mixing the soil at 1% xanthan gum. The strength results for Colorado Clay will be verified as these were performed on a sample that was processed twice which appears to have had some influence in the results.

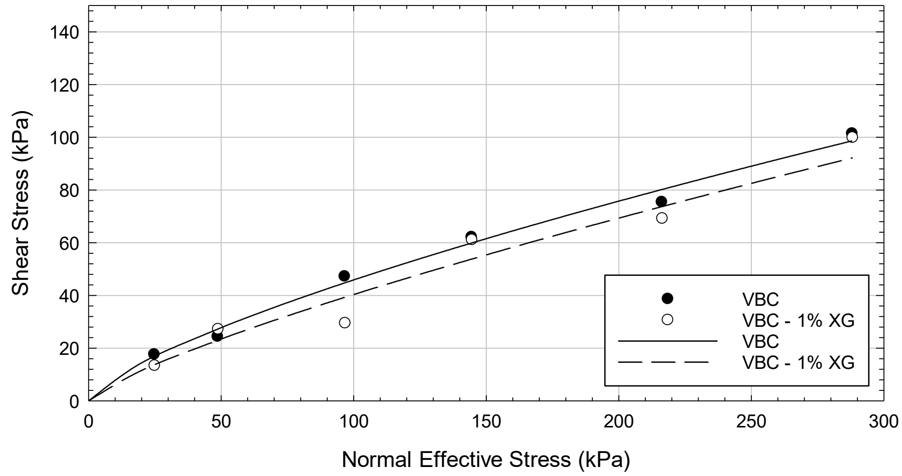

Figure 4. Fully softened shear strength results from VBC

Table 4. Summary of the strength parameters obtained from the ring shear tests

Sample	c'- ϕ'		c' = 0	Power Function	
	c'(kPa)	ϕ'(deg)	ϕ' (deg)	a	b
Colorado Clay	2.44	19	19	0.3735	0.9617
Colorado Clay with 1% XG	2.63	18	18	0.3571	0.9412
VBC	1.24	9	9	0.8218	0.1692
VBC with 1% XG	7.80	15	17	0.3821	0.7455

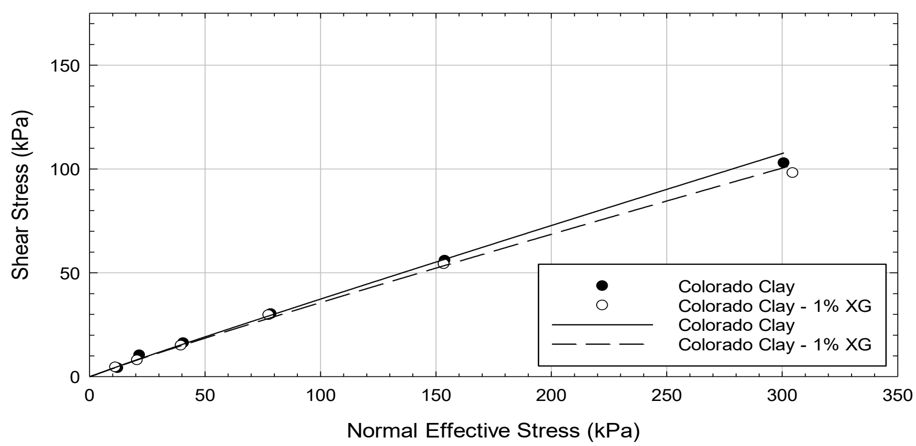

Figure 5. Residual shear strength results from Colorado Clay

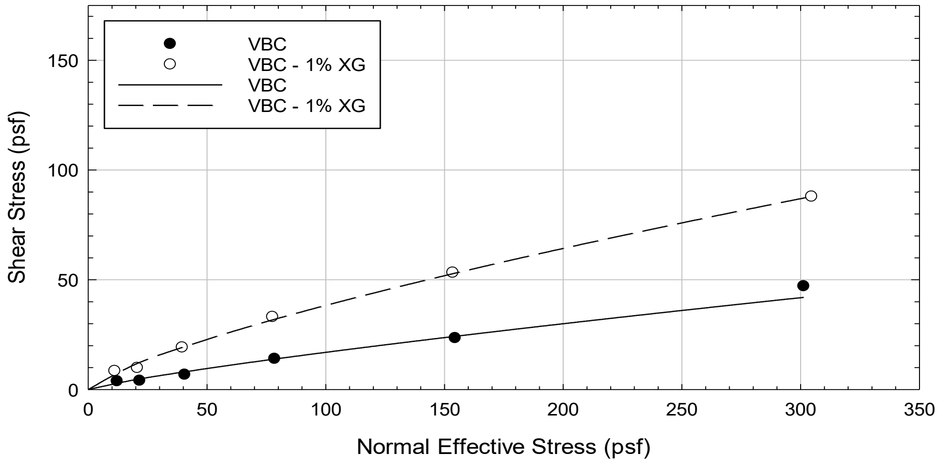

Figure 6 Residual shear strength results from VBC

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