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Effect of Bentonite fine Content on the Triaxial Shear Behavior of Sandy Soils

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ABSTRACT: Addition of fine and plastic clays such as bentonite to sandy soils is one of the methods of reducing soil hydraulic conductivity and making it suitable for seepage barriers. Also, in nature, soil mixtures such as clayey sands, silty sand and clayey silts are found much more than pure soils such as clean sand, clay or silt. Thus, in this paper, the effects of adding bentonite particles on the shear behavior of a sandy soil were studied by performing series of consolidated un-drained triaxial tests. In these experiments, different amounts of weight contents of bentonite such as 0, 5 and 10% were added to a sandy soil named Firoozkooh sand. Generally, obtained results showed that addition of bentonite led to changes in the shear behavior and strength of sand. These changes depend on the relative density of soil, confining stress and bentonite content. As an example, in loose samples of sand, addition of bentonite reduced the maximum deviator stress of the soil; on the other hand, in dense samples, addition of 5% bentonite reduced the deviator stress. However, addition of 10% bentonite increased the deviator stress. Generally, addition of bentonite reduced the secant modulus of elasticity and increased the positive pore water pressure at phase transition point. It is worth noting that, in dense samples, the effectiveness of bentonite content was not as high as that in loose samples and, in some conditions, the results did not follow a specific trend.

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1- Introduction

Synthetic liners as seepage barriers in landfills encounter problems after long term despite their advantages in short term use. Unfortunately, once damage or perforation occurs in synthetic liners, their performance in the prevention of pollution transmission is greatly reduced [1, 2]. Recent studies have shown that compacted clay liners (CCl) together with geo-synthetic clay liners (GCL) can be used as an assurance when perforation occurs in synthetic liners [3]. However, when compacted clay liners are dried, cracking may occur, which results in increase in the hydraulic conductivity. On the other hand, these liners are very sensitive to the thaw-freeze cycles, which are very problematic for them [4]. Also, CCls cannot withstand the overloads which are available in landfills. In order to eliminate the cracking caused by drying and increase the strength and stability of the basis, sand-bentonite mixture is usually used in the bottom liners of industrial and urban landfills [5-7]. It is worth noting that sand enhanced bentonite (SEBs) is less sensitive to freezing or the cracks which are formed by drying [8, 9].

The characteristics of SEBs which make them suitable for use as the bottom liners of landfills are as follows: Their hydraulic conductivity does not exceed 10-9 cm/s, have enough strength for stability and form less shrinkage cracks in the conditions of water content changes [10-12]. In SEB mixtures, sand acts as a skeleton and it keeps the strength and stability of the mixture while bentonite fills the space between the sand particles, which results in less permeability of the mixture. For economic reasons, it is suggested to keep the bentonite content of mixture as low as possible (4-12%) [13]. Studies have demonstrated that adding bentonite to sand, results in increase in the plasticity index (PI), unit weight, compressibility, and coefficient of secondary consolidation as well as reduction in the shear strength of soil [14].

In order to improve the permeability characteristics of soil, sometimes, it is mixed with bentonite which has a low hydraulic conductivity, high specific surface and many holes because of the small size of its particles. Swelling characteristics of clay after water absorption can compensate for the hydraulic weakness caused by shrinkage cracks in wetting-drying cycles [15]. In soils with uniform grading, addition of bentonite, even in small amounts, decreases rapidly, the hydraulic conductivity [16]. For well-graded sand with low permeability, effects of adding bentonite are low because of its high content of fine grains and also low initial porosity of sand [17].

The laboratory test results showed that liquid limit, plastic limit and plasticity index increased linearly with increased amount of bentonite. The addition of bentonite resulted in decreased maximum dry unit weight but the optimum moisture content increased slightly. Unconfined compression strength of compacted clay-bentonite mixtures increased linearly with an increase in the amount of bentonite. Hydraulic

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conductivity of compacted clay-bentonite mixtures decreased nonlinearly with increased amount of bentonite, but a linear relationship was observed between logarithm of hydraulic conductivity and bentonite content [18].

One dimensional consolidation and falling head permeability tests were conducted to evaluate permeability of 2, 4, 6, 8 and 10% bentonite content by weight in dune sand. Some of the findings are: The coefficient of consolidation decreased inversely proportional to lower bentonite/dune sand ratios. The coefficient of volume change was more susceptible to changing stresses and inversely related to it. The permeability of dune sand with bentonite varied significantly and reduced significantly after addition of bentonite [19]. Gueddouda et al. [20] observed that with increase in the sand content in a sand-bentonite mixture, the friction angle, hydraulic conductivity, increases and swelling potential decreases. For a small amount of bentonite, the mixture kept the properties of granular soils, while for higher bentonite contents, there was a gradual transition to the typical mechanical behavior of plastic clays. The interaction between sand and bentonite was investigated using Scanning Electron Microscope (SEM). Compressibility and permeability was measured by one dimensional swelling and compression tests [21].

The geotechnical and geo-environmental characteristics such as hydraulic conductivity, diffusion and shear strength of bentonite-sand mixture were investigated by Badv and Aliashrafi (2015). For study on shear strength parameters of mixture, direct shear and unconfined compression tests were performed. It was shown that addition of bentonite to sand reduces the internal friction angle and increases its cohesion. Also, unconfined compression strength of the mixture increased up to bentonite content of 30%, and decreased afterwards [22].

As shown above, related technical literature demonstrates that shear behavior and strength of sand-bentonite mixture have not received much attention before; therefore, in this paper, shear behavior and strength of sand-bentonite mixtures were studied using common consolidated un-drained triaxial test.

2- Materials used

A sandy soil named Firuzkuh sand was used as the base soil. It is a silica soil and its physical properties and grain size distribution are provided in Table 1 and Figure 1, respectively (ASTM D6913 / D6913M – 17, ASTM D4253-16 and ASTM D4254-00). As shown, this is a uniform and poorly graded sand. Physical characteristics of the used bentonite including, distribution of particle size, Atterberg limits, water content and specific gravity are presented in Table 2 (ASTM D4253-16, ASTM D4318).

Table 1. Physical characteristics of clean sand of Firuzkuh

Sand Type	G_s	e_{max}	e_{min}	D_{50} (mm)	C_u	C_c
Firuzkuh #161	2.685	0.943	0.603	0.29	1.72	0.94

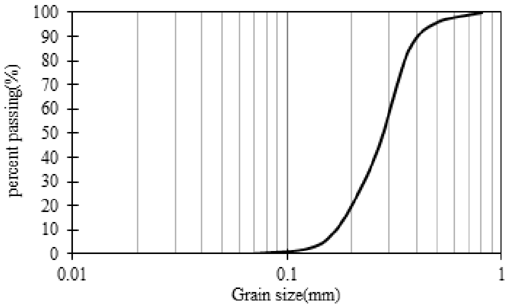

Figure 1. Grain size distribution of Firuzkuh sand

Table 2. Characteristics of bentonite sample

Properties	Measured values
Clay	76%
Silt	23%
Sand	1%
Liquid limit (LL),%	321%
Plastic limit (PL),%	35%
Plasticity index (PI),%	286%
Activity	3.7
Soil classification	CH
Water content (air dried)	7.10%
Gs	2.79

The mentioned sand was mixed with 0, 5 and 10% of bentonite and then tested. Accordingly, the effect of adding bentonite on the minimum and maximum unit weight values of mixed samples is presented in Table 3.

Table 3. Minimum and maximum unit weights for sand and sand with 5 and 10% bentonite

Soil type	γ_{min}	γ_{max}
Sand	1.38	1.67
sand with 5% bentonite	1.44	1.71
sand with 10% bentonite	1.46	1.75

3- Testing program

Totally, 21 consolidated-undrained triaxial tests were performed with confining stresses of 100, 200, 300 and 400 kPa. Test samples were prepared with bentonite percentages of 0, 5 and 10 in loose (D_r=30%) and dense (D_r=80%) states. Test samples were 38 mm in diameter and 76 mm in height. Sand and bentonite were mixed in dry condition and then poured in molds using dry deposition method. The soil was divided into 5 equal parts and each part was poured into mold and correctly placed by slow impacts. In order to saturate the samples, CO_2 gas, at first, and then distilled water, were passed through the sample. Almost all the samples were saturated using a cell and back-pressure of 150 and 140 kPa, respectively, where B parameter reached at least, a value of 95%. Afterwards, all the samples were consolidated and then loaded as strain control with the rate of 1 mm/min (ASTM D4767). Characteristics of the performed tests are presented in Table 4.

Table 4. Characteristics of the performed triaxial tests

Bentonite (%)	D_r (%)	Confining stress (kPa)	Test code
0%	30%	100	SL100
		200	SL200
		300	SL300
	30%	100	SD100
		200	SD200
		300	SD300
		400	SD400
5%	30%	100	5BL100
		200	5BL200
		300	5BL300
	80%	100	5BD100
		200	5BD200
		300	5BD300
		400	5BD400
10%	30%	100	10BL100
		200	10BL200
		300	10BL300
	80%	100	10BD100
		200	10BD200
		300	10BD300
		400	10BD400

4- Results

4- 1- Shear behavior

As an example, variations of deviator stress and pore water pressure versus axial strain of the samples under the confining stress of 200 kPa are illustrated in Figure 2. According to Figure 2a, for loose sands, addition of bentonite varied the sand process of hardening behavior; however, at the end of the experiment, the effect of bentonite was reduced and the three samples reached almost a certain value of strength. Thus, addition of bentonite influences the behavior pattern of sand and reduces its hardening. This process could also be seen in dense samples to some extent; thus, addition of 5% bentonite reduces the strength of sand, however, 10% of bentonite also increases the strength of soil up to clean sand; but, the hardening rate in sand is still low. It can be argued that the presence of bentonite particles between the sand grains reduces the friction between them and creates some cohesion and then reduces the hardening trend of soil as well. The effect of bentonite content on the kind of soil behavior depends on the soil relative density or its void ratio, confining presser and total strain.

Figure 2b demonstrates that, for loose sands, pore water pressure rises at first and negative pore water pressure is generated because sandy soil is uniform and poorly graded. The presence of clay minerals has changed the behavior of sand from dilative to contractive. This behavior pattern could be also seen in dense sample with 5% bentonite; however, addition of more bentonite and obtaining the bentonite percentage of 10 also returned its behavior as clean sand.

This pattern of pore water pressure changes is to some extent complex. Certainly, mixture of sand and bentonite resulted in a gap graded soil sample. Added bentonite filled the voids between the sand grains, coats and lubricates them; therefore, changing the pore water variations against axial strain. Results of the tests (Figure 2b) show that in loose samples, addition of bentonite shifts the dilative behavior gradually to contractive state. In other words, in this state, bentonite lubrication effect reduces the friction and dilation angle between the particles; however, soil particle are in contacts, and the soil show negative pore water pressure. Whereas in dense sample, due to the lower free space between sand grains, 10% bentonite is higher than this free space, therefore, separating the grains from each other and compensating completely for the dilation tendency of soil after 5% axial strain, and soil reach a stable state with no variation in pore water pressure.

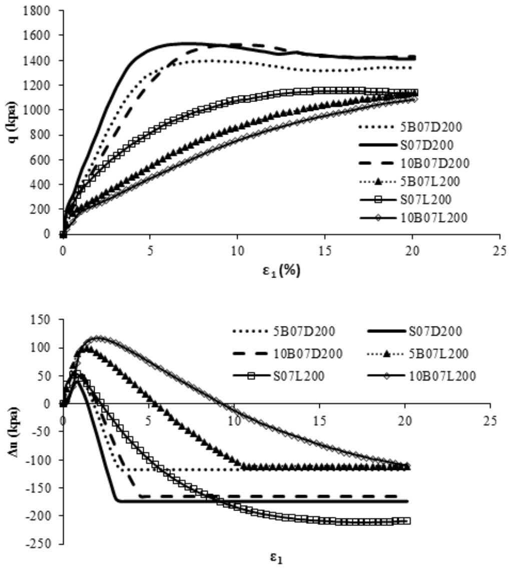

Figure 2. a) Variation of deviator stress. b) Excess pore water pressure under confining stress of 200 kPa

4- 2- Shear strength

Maximum values of mobilized deviator stress on the tested sample versus the amount of bentonite are illustrated in Figure 3. This figure demonstrates that, in loose samples, addition of bentonite led to a reduction in the maximum deviator stress due to reduction in friction between the grains. As an example, in loose sample and under 100 kPa confining stress, addition of 10% bentonite led to 15% reduction of deviator stress. The mentioned trend in loose samples, is also observed to some extent with confining stresses of 200 and 300 kPa.

In dense samples, effect of adding bentonite is different, and addition of 5% bentonite led to a strength reduction, and 10% bentonite also increased the maximum deviator stress or strength. It can be argued that the reduction of friction between sand grains occurs when bentonite content is 5%, and increase of adherence was the reason for strength increase when bentonite content reached a value of 10%.

Related strain at maximum shear strength or peak point versus the bentonite content is illustrated in Figure 4. This figure shows that in loose samples (except one of the samples), the effect of adding bentonite on this strain is negligible, but in dense samples, the presence of bentonite makes shear strength of mixed soil to mobilize at more strains.

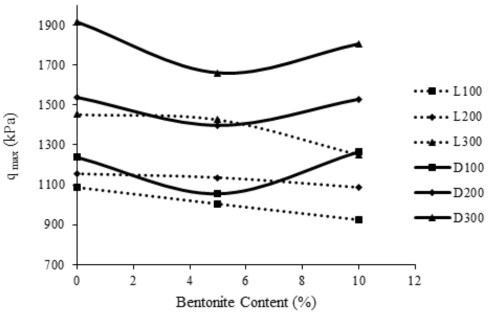

Figure 3. Effect of bentonite content on maximum deviator stress

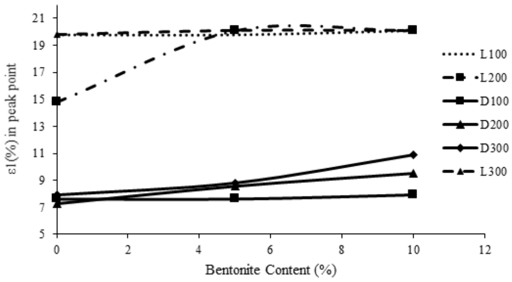

Figure 4. Axial strain at maximum deviator stress

4- 3- Shear failure envelope

Mohr–Coulomb shear failure envelope of soil in both loose and dense conditions is demonstrated in Figure 5. Equations of this envelope are summarized in Table 5. Generally, it is obvious that the presence of bentonite particles leads to reduction in the friction between the sand grains and also formation of an adhesion in sandy soil. It is worth noting that resulting adhesion in loose sample is more than that of dense sample. Also, effect of adding bentonite with different percentages on loose samples is different from that on dense samples. For example, in loose samples, with 5% bentonite, more adhesion is formed than with 10% bentonite. This trend seems to be more accurate in dense samples, meaning that more adhesion is formed for samples with more bentonite contents.

Table 5. Shear failure envelope equations of sand mixed with different percentages of bentonite

Bentonite (%)	Dense state	Loose state
0	τ=1.03σ	τ=0.46σ
5	τ=0.78σ+92.97	τ=0.47σ+212/26
10	τ=0.7σ+138/24	τ=0.49σ+187/76

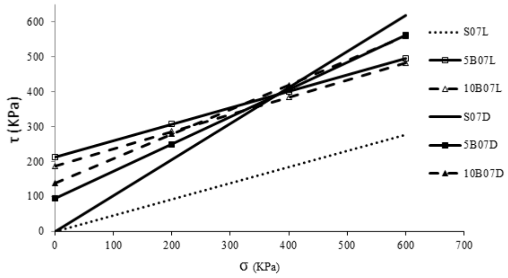

Figure. 5. Mohr–Coulomb shear failure envelope of sand mixed with bentonite

4- 4- Internal friction angle

The amount of internal friction angle at the peak point of deviator stress (ϕ_p) is calculated using Equation. 1:

$$(\sigma_1')/(\sigma_3')=\tan^2(45+\varphi/2) \quad (1)$$

Peak internal friction angle of sand mixed with bentonite versus bentonite content is demonstrated in Figureg. 6. This figure shows that the presence of bentonite has different effects on the internal friction angle of soil. For example, in loose sample and under 100 kPa confining stress, addition of bentonite increased the internal friction angle. Under 200 kPa confining stress, addition of 5% bentonite increased the internal friction angle, and then addition of 10% bentonite reduced it a little bit. The trend of internal friction angle change in loose sample and under 300 kPa confining stress, is the same as that of 200 kPa confining stress, and with 5% bentonite, the internal friction angle increased slightly, and in addition of 10% bentonite, the internal friction angle decreased. The observed behavior in loose sample is similar to that of dense sample, with the exception that under 300 kPa confining stress, with addition of bentonite, the internal friction angle completely decreased. Thus, it is clear that the effect of bentonite on the internal friction angle is a function of relative density and confining stress, which has no explicit pattern.

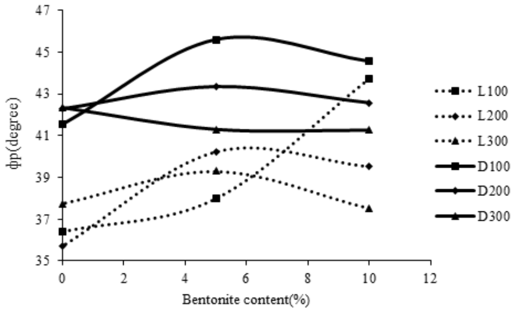

Figure. 6. Total internal friction angle

4- 5- Modulus of elasticity

Among different methods for calculating modulus of elasticity for soils, the secant modulus of elasticity in 50% deviator stress was employed in this study. Figure .7 which illustrates the secant modulus of elasticity versus bentonite content demonstrates that addition of bentonite to sand leads to a decrease in the modulus of elasticity. Also, it seems that decreasing rate is higher in loose samples than dense samples. For example, under 200 kPa confining stress, addition of 10% bentonite to sand leads to 36 and 62% drop in modulus of elasticity for dense and loose samples, respectively. It is noteworthy that the effect of confining stress on the elasticity modulus is decreased by addition of bentonite to sand, and diagrams of secant modulus of elasticity get closer to each other.

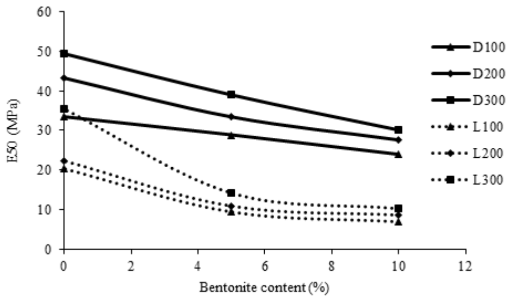

Figure. 7. Bentonite content effect on secant modulus of elasticity

4- 6- Pore water pressure at phase transition point

The pore water pressure diagram at phase transformation (PT) point versus bentonite content is demonstrated in Figure .8. It is evident that, by adding bentonite, there is an increase in the pore water pressure at PT point. It is shown that the effect of bentonite on pore water pressure at PT point is low in dense samples, and significant in loose samples. As an example, under the confining stress of 200 kPa, addition of 10% bentonite to samples led to 57 and 120% increase in pore water pressure for dense and loose samples, respectively. It is concluded that the presence of clay particles between the sand grains changes the behavior of sand from dilative to contractive state.

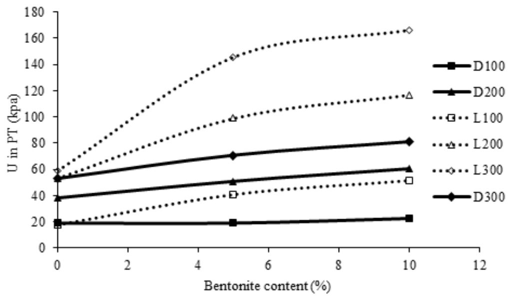

Figure. 8. Pore water pressure at phase transformation point

4- 7- Axial strain at phase transformation point

Axial strain at the phase transformation point versus bentonite content is demonstrated in Figure 9. This figure shows that addition of bentonite to loose samples leads to an increase in strain at PT point with almost a constant rate. In dense samples, the trend is different, and under 100 kPa confining stress and 5% bentonite, a reduction occurred in axial strain of PT point and with 10% bentonite, an increase occurred. This figure shows that for dense samples and under confining stress of 200 kPa, bentonite has no effect and under confining stress of 300 kPa, an increase was observed in axial strain at PT point like loose samples. Therefore, it is concluded that the effect of bentonite minerals on the axial strain at PT point depends on the sample relative density, confining stress and bentonite content.

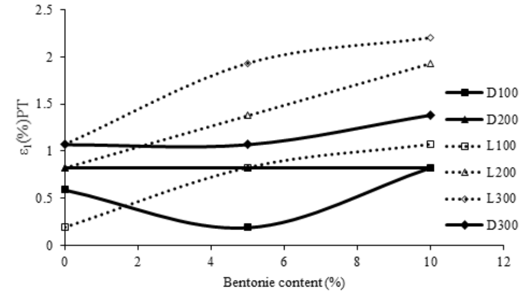

Figure. 9. Axial strain at the phase transition point against bentonite content

5- Conclusion

In this paper, using 21 consolidated un-drained triaxial tests, the effects of adding bentonite clay mineral on the shear behavior of a sandy soil named Firoozkooh sand were studied by using 21 consolidated un-drained triaxial tests. Test sSamples with bentonite contents of 0, 5 and 10% were tested under 100, 200, 300 and 400 kPa confining stresses. Obtained rResults of the tests showed that:

1. Addition of bentonite to a sandy soil changes the stress- - strain behavior of soil considering hardening or softening, shear strength, pore water pressure build up trend and secant elasticity modulus; however, the rate and amount of changes greatly depends on bentonite content, confining stress and relative density of soil.
2. The presence of bentonite particles in loose samples led to reduced maximum deviator stress. For example, at 100 kPa confining stress, addition of 10% bentonite led to 155% reduction in the deviator stress of sand. In the dense samples, addition of 5% bentonite led to a decrease in deviator stress at first; but, addition of 10% bentonite increased the deviator stress.
3. The cohesion from bentonite particles was higher in loose samples in comparison with dense particles. In contrast to what was expected, effect of 5% bentonite was higher as compared to 10%.
4. The presence of bentonite was expected to reduce the effective internal friction angle; nevertheless, the tests results showed that the influence of fine grains of bentonite on the internal friction angle of soil were affected by the relative density of the samples and their confining pressures. For example, addition of bentonite to a loose sample under 100 kPa confining stress led to an increase in the internal friction angle; but, in dense sample, it increased the internal friction angle at first, and addition of more bentonite caused a reduction. It is obvious that this issue was caused by different stress paths and different values of pore water pressure.
5. Presence of bentonite increased the soil positive pore water pressure and axial strain at phase transition point. For example, for loose sample under confining stress of 300 kPa, addition of 10% bentonite led to 183% increase in the positive pore water pressure and 105% increase in the axial strain at phase transition point.
6. With addition of more than 5% bentonite, the 50% secant modulus of elasticity reduced. Also, addition of bentonite to soil reduced the effectiveness of confining

stress on the modulus of elasticity, and reduction in the effect of bentonite on loose samples was more than that of dense samples.

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