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ORIGINAL PAPER

Effect of fines content and plasticity on undrained shear strength of quartz-clay mixtures

Eyyüb Karakan [1] · Süleyman Demir [1]

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Abstract

Data obtained from previous soil borings revealed that, natural soils free of fines are rarely encountered in the field. On this basis, the aim of this study is to investigate the effects of plastic fines on mechanical behavior of sand (quartz)-clay mixtures. Two types (bentonite and kaolinite) of clay were mixed with quartz at rates ranging among 0% to 100% by dry weight. Evaluations were made based on changes in threshold fines content (FC_t) with clay type and mechanical properties, consistency limits, and compaction characteristics. The results indicate that undrained shear strength (s_u) decreased up to 30% kaolinite content while increased with bentonite content from 0 to 100% which is an evidence of the effect of clay type on FC_t. Furthermore, quartz-kaolinite mixtures have greater maximum dry unit weight that quartz-bentonite mixtures. On the contrary, the undrained shear strength of quartz-bentonite mixtures was greater than quartz-kaolinite mixtures.

Keywords Quartz-clay mixtures · Threshold fines content · Fall cone test · Plastic fines

Introduction

There are numerous studies concerning engineering behavior of sand-clay mixtures, which are utilized in many field applications including nuclear waste containment, earth fill dams, and road pavement structures. In the literature, sand-clay mixtures were investigated by analyzing effects of fines content on several geotechical properties such as liquefaction (Karim and Alam 2014), matric suction (Shayea 2001), void ratio (Cubrinovski and Ishihara 2002), undrained shear strength (Thevanayagam 2000), and compressibility (Cabalar and Hasan 2013). In addition, effects of plasticity on several geotechnical properties are well documented in the literature (Vucetic and Dobry 1991; Albrecht and Benson 2001; Jafari et al. 2002; Stark et al. 2005; Bray and Sancio 2006). For instance, Vucetic and Dobry (1991) emphasized that plasticity index caused increase in shear modulus ratio and a corresponding decrease in damping ratio. Albrecht and Benson (2001) studied the volume change during desiccation by applying drying and wetting cycles on soils and results showed that soils of high clay content with large plasticity are likely exposed to volumetric shrinkage strain. Tiwari and Ajmera (2011) experimentally obtained the effects of plasticity, liquid limit and clay content on fully softened and residual shear strength values. The researchers well documented differences between fully softened and residual strength as a function of soil plasticity. Naeini and Jahanfar (2011) investigated the effect of varying soil plasticity on results obtained from direct shear test tests. As the plasticity values were increased up to a value of (16.7%) increase in undrained shear strength is followed with a decrease by increasing plasticity. Sudjianto et al. (2011) performed swelling tests on clays of different plasticities and concluded that one-dimension swelling is increased by increasing soil plasticity. Jafari et al. (2002) performed resonant column tests on clays of different plasticities. The results showed that the medium plastic clay has the highest maximum shear modulus value and the lowest damping ratio. Sridharan and Gurtug (2004) carried out swelling tests on five soils of different plastic values and concluded that volumetric change in montmorillonitic soils is higher than those of other types of clays. They

✉ Eyyüb Karakan
eyyubkarakan@kilis.edu.tr

Süleyman Demir
suleymandemir@kilis.edu.tr

[1] Department of Civil Engineering, Geotechnical Division, Kilis 7 Aralik University, Kilis, Turkey

Table 1 Chemical analyses of materials used during experimental study

Minerals	Bentonite (%)	Quartz (%)	Kaolinite (%)
A.Z	7.5	0.2	0
$SİO_2$	71	99.2	47
AL_2O_3	14	0.5	32
FE_2O_3	0.7	0.03	0.6
$TİO_2$	0.05	0.02	0.8
CAO	1.1	0.02	0.6
MGO	3.2	0.02	0
NA_2O	0.25	0.1	0
K_2O	1	0.02	0
LoI	0	0	13
SO_3	0	0	0.3

showed that sand-clay mixtures of different fines content and plasticities have different swelling and compaction properties. Bayat et al. (2014) review effects of fines and its plasticity on undrained shear strength and pore water pressure. They concluded that increasing fines content caused a decrease in pore water pressure and rate of this decrease is higher for the mixtures with high plastic bentonite. Stark et al. (2005) indicated that highly plastic clay gains additional shear strength during healing. They concluded that highly plastic clay has greater shear strength in comparison with lowly plastic clay. Bray and Sancio (2006) carried out cyclic triaxial test on four soils of different plasticities showing that cyclic resistance increased regularly when PI > 12. Sawangsuriya et al. (2009) investigated and modeled maximum shear modulus values for various soils based on matric suction changes. The *A* and *C* parameters used in this model decreased with the clay content and plasticity values.

In this study, two types (bentonite and kaolinite) of clay were added to the quartz at the contents ranging from 0 to 100%, by dry weight. In this scope, 11 mixtures were used for each type of quartz-clay mixtures. Consistency limits, compaction, and Fall cone tests were performed on different mixtures to evaluate effects of clay content and its plasticity of on maximum dry density (MDD), optimum water content (ω_{opt}), Atterberg limits, and undrained shear strength (s_u).

Materials and methods

Bentonite and kaolinite were mixed with quartz to obtain mixtures of different clay contents and plasticities. The chemical analysis of these commercially available materials is given in Table 1. Specific gravity of quartz was found to be 2.65 while MDD and ω_{opt} values were found to be 10.27 and 19.50, respectively. Some geotechnical properties of quartz along with its sieve analysis are given Fig. 1.

The specific gravity of the kaolinite and bentonite were found to be 2.45 and 2.35, respectively. Standart compaction, Casagrande, plastic limit, and Fall cone experiments were performed on the mixtures. The mixtures were oven dried for 24 h at 105 °C before mixing. The dry mixtures were prepared by mixing clay and quartz in dry state until a homogeneous quartz-clay distribution was observed. ASTM D698 was followed during standart proctor experiment. The mixtures were compacted in three layers and each layer was densified using freely falling rammer from 0.305 m, applying 25 blows per layer. The MDD and corresponding water contents were obtained for each mixture. In Casagrande test, according to ASTM D4318, the samples were completely dried and a sample was taken from all the mixtures and sieved

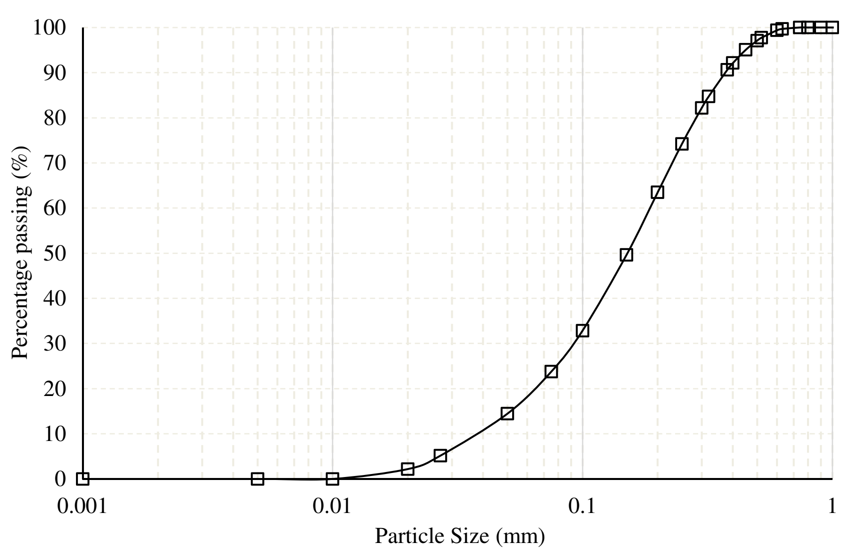


Fig. 1 Particle size distribution of quartz used during experimental study

Table 2 Summary of test results

Clay content (%)	Clay type	MDD (Mg/m^3)	ω_{opt} (%)	Casagrande LL	FCT LL	PL	Casagrande PI	FCT PI
10% clay	Bentonite	1.120	21.56	34.19	36.51	25.23	8.96	11.28
	Kaolinite	1.580	18.89	27.46	28.00	18.33	9.13	9.67
20% clay	Bentonite	1.260	21.59	38.59	43.72	26.27	12.32	17.45
	Kaolinite	1.641	17.46	29.74	30.77	19.07	10.67	11.70
30% clay	Bentonite	1374	25.32	47.53	55.26	32.08	15.45	23.18
	Kaolinite	1.625	19.00	31.84	31.02	22.40	9.44	8.62
40% clay	Bentonite	1.374	30.25	62.13	66.33	35.41	26.72	30.92
	Kaolinite	1.583	20.97	37.59	35.29	24.25	13.34	11.04
50% clay	Bentonite	14.00	30.50	85.57	73.84	47.00	38.57	26.84
	Kaolinite	1.518	22.92	37.35	35.19	29.16	8.19	6.03
60% clay	Bentonite	1.417	32.50	97.89	83.67	54.03	43.86	29.64
	Kaolinite	1.448	24.36	37.42	39.03	33.33	4.09	5.70
70% clay	Bentonite	1.357	33.36	117.26	101.03	56.66	60.6	44.37
	Kaolinite	1.393	27.33	38.58	46.49	31.11	7.47	5.38
80% clay	Bentonite	1.498	40.61	120.53	112.46	58.37	62.16	54.09
	Kaolinite	1.374	28.43	40.05	43.97	30.66	9.39	13.31
90% clay	Bentonite	1.490	41.25	132.54	119.25	58.92	73.62	60.33
	Kaolinite	1.367	30.20	52.97	51.64	32.24	20.73	30.91
100% clay	Bentonite	1.463	47.17	158.21	139.75	66.46	91.75	73.29
	Kaolinite	1.334	31.50	60.79	59.10	32.83	27.96	26.27

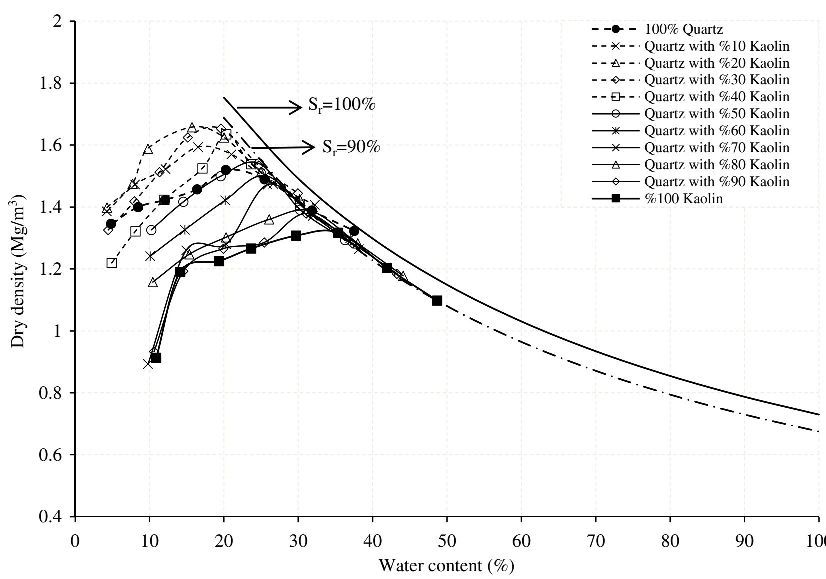
MDD maximum dry density; ω_{opt} optimum water content; *LL* liquid limit; *PL* plastic limit: *PI* plastisite ındex; *FCT* Fall cone test

through No.40 sieve (0.425 mm). The liquid limit of the mixtures was determined as the water content corresponding to 25 strokes. Fall cone tests were carried out according to BS 1377 using a British Fall cone apparatus. The Fall cone apparatus includes a specimen cup of 55 mm in diameter and 45 mm in height. Water content corresponding to 20 mm of penetration is recorded as the liquid limit of specimen.

Results and discussion

The results of compaction, consistency limits experiments on quartz-clay mixtures were given in Table 1. Initially, compaction properties of the mixtures were determined. It should be noted that, repeatability of test results were ensured by carrying out three consecutive tests (Table 2). Figure 2 shows the results of the quartz-kaolinite mixtures. As kaolinite content

Fig. 2 Compaction curves of quartz-kaolinite mixtures



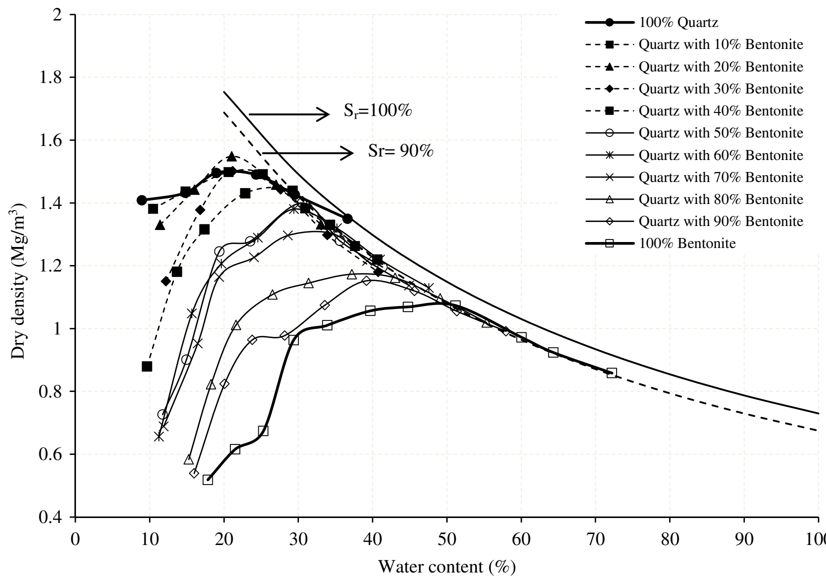


Fig. 3 Compaction curves of quartz-bentonite mixtures

was increased, MDD was increased up to 20% clay content then decreased. On the other hand, optimum water content decreased up to 20% clay content and then increased. Such behavior could be related to existence of a threshold fines content (FC_t). Numerous studies emphasize that there is a specific fines content that control the mechanical behavior of sand-clay mixtures (Thevanayagam 2000; Xenaki and Athanasopoulos 2003). The researchers explained that below a certain $FC_{t,}$ coarse particles govern mechanical behavior of coarse-fine mixtures. Beyond FC_t, fines control the mechanical behavior. Such behavior in MDD and ω_{opt} of kaolinite quartz mixtures revealed that, FC_t is around 20% fines content. The reason of such behavior could also be attributed to fill voids between the quartz sand particles by kaolinite up to a content of 20%. Similar results were reported by De Magistris et al. 1998 Chiu and Shackelford (1998), Komine (2004), and Purvana et al. (2012). De Magistris et al. (1998) mixed different sand types with bentonite and the compaction tests were carried out. The addition of bentonite increased the MDD up to certain FC_t and then decreased. Optimum water content, on the other hand, increased continuously or decreased up to FC_t (depending on sand type) then increased. Figure 3 shows the compaction values of the bentonite with quartz. The maximum dry density increased with the 10% bentonite content and then decreased. Optimum water content showed a steady increase with bentonite content. Compaction curves of different clay contents in Fig. 4 show (20%, 50%, 80%) the effects of plasticity on compaction results. The results of MDD and ω_{opt} of different mixtures were compared in Figs. 5 and 6, respectively. The MDD results showed an increase up to the

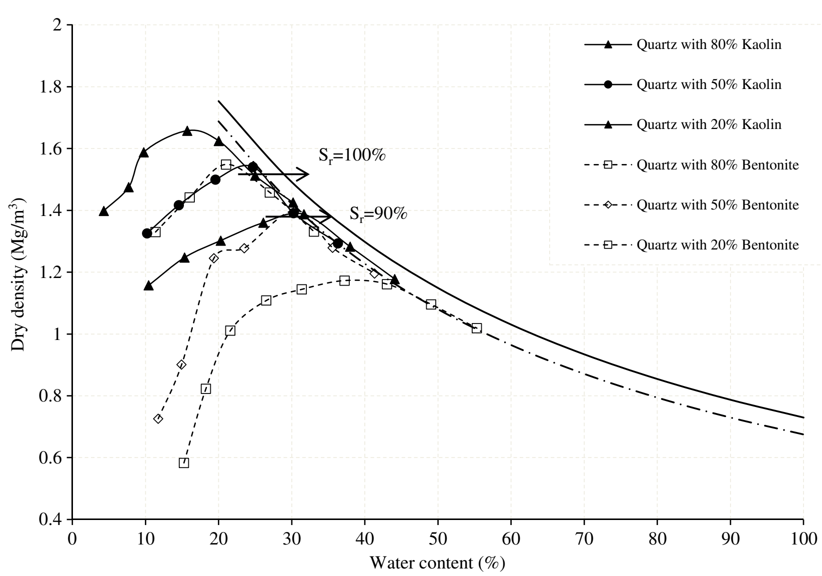


Fig. 4 Compaction curves for quartz with different clay types

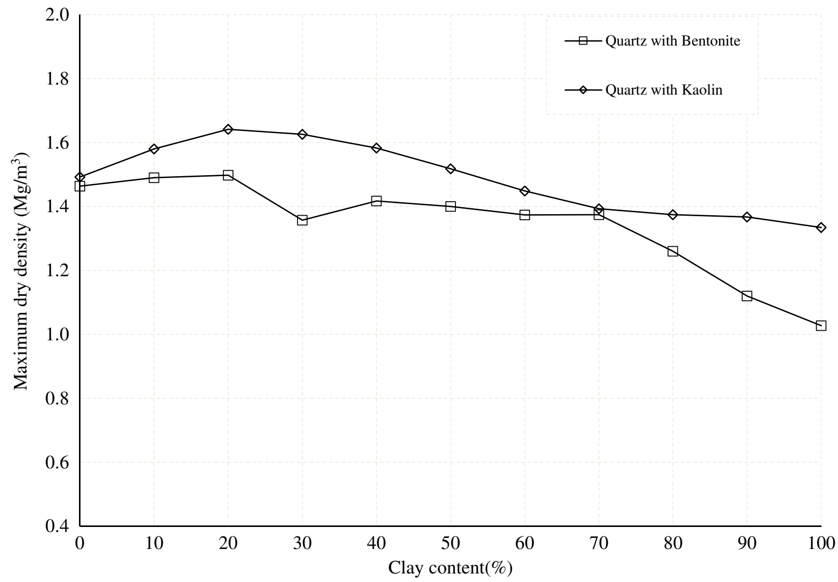


Fig. 5 Variation of MDD of quartz with different clay types

addition of 10% bentonite while it was found to be 20% for kaolinite, after a decrease was observed. The main difference between the two clay types is thought to be plasticity, compressibility, and matric suction. It was previously stated that the increases up to a certain FC_t means clay particles have filled the voids of quartz particles. At this point, it was considered that bentonite filled voids between quartz particles with 10% bentonite content while in quartz-kaolinite mixtures this ratio was found to be 20%. In addition, compressibility of materials could be reason of such behavior. Simpson and Evans (2015) stressed that compressibility of sand-clay mixtures decrease up to 10% then increased. The authors attributed changes in MDD behavior to compressibility of mixtures. Compressibility of mixtures could decrease up to 20% therefore MDD could also be increased. As for bentonite, compressibility of mixtures could decrease up to 10% then increased. Furthermore, Park and Santamarina (2017) stated that plasticity of fines affect the control behavior of course-fines in compression index so different plasticity between kaolinite and bentonite might be reason that different FC_t. In Fig. 5, mixtures prepared with kaolinite have greater MDD than those with bentonite at a given quartz content. Similar results were found by Kolay and Ramesh (2016). They mixed kaolinite and bentonite with sand and fly ash. Their results

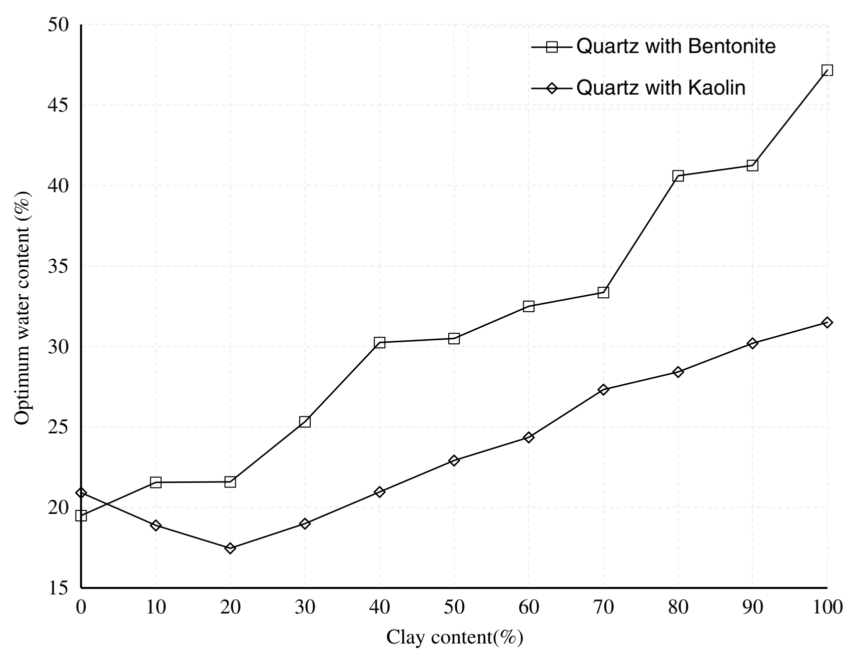


Fig. 6 Variation of OMC of quartz with different clay types

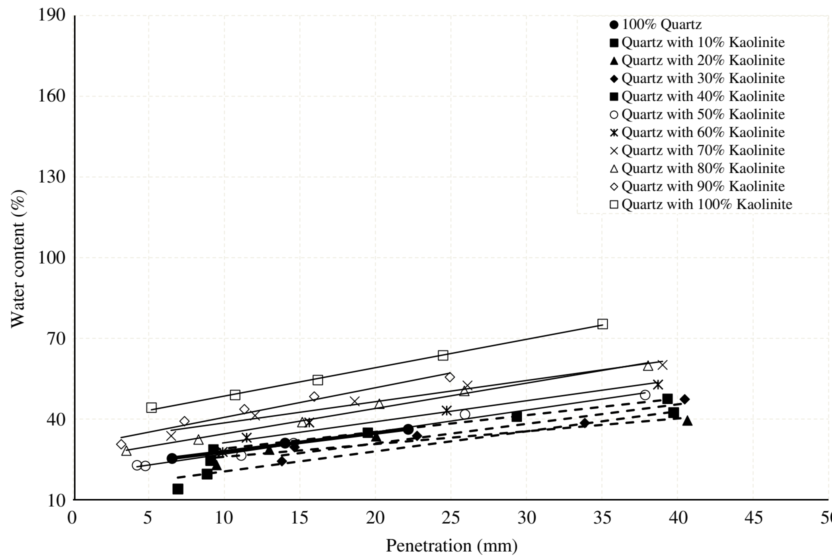


Fig. 7 Variation of penetration with water content for the quartz-kaolinite mixtures

showed that at a given sand content or fly ash MDD of mixtures with kaolinite was higher than those with bentonite. The reason also could be higher void ratio of bentonite clay compared to kaolinite clay. Maio et al. (2004) and Jacobs et al. (2007) found similar results denoting that bentonite has a greater void ratio compared to kaolinite. In addition, the reason could be difference of compressibility properties between bentonite and kaolinite. Bentonite compressibility might be higher than kaolin; therefore, MDD of mixtures with bentonite is higher than that of kaolinite. Kolay and Ramesh (2016) concluded that bentonite has higher compressibility than kaolinite. They found that mixtures with kaolinite have higher MDD those of bentonite. The reason for this behavior might be that the bentonite has higher suction due to its higher surface area. Such an approach is also pointed out studies carried out by Murray (2000) and Shayea (2001).

Fall cone test used for estimating several geotechnical properties such as liquid limit, plastic limit, sensitivity, compressibility, and undrained shear strength of fine grained soil (Kumar and Wood 1999; Feng 2001). Figure 7 presents the cone penetration-water content relationship of the quartz-kaolinite mixtures. Figure 7 clearly shows that, as the water content increases, the penetration increases. In addition, the penetration values increased up to 30% with the kaolinite at a given water content. Beyond 30%, the penetration values decreased. Penetration-water content relationship of bentonite and quartz mixtures are given in Fig. 8. As the bentonite content increases, the penetration value decreases at a given

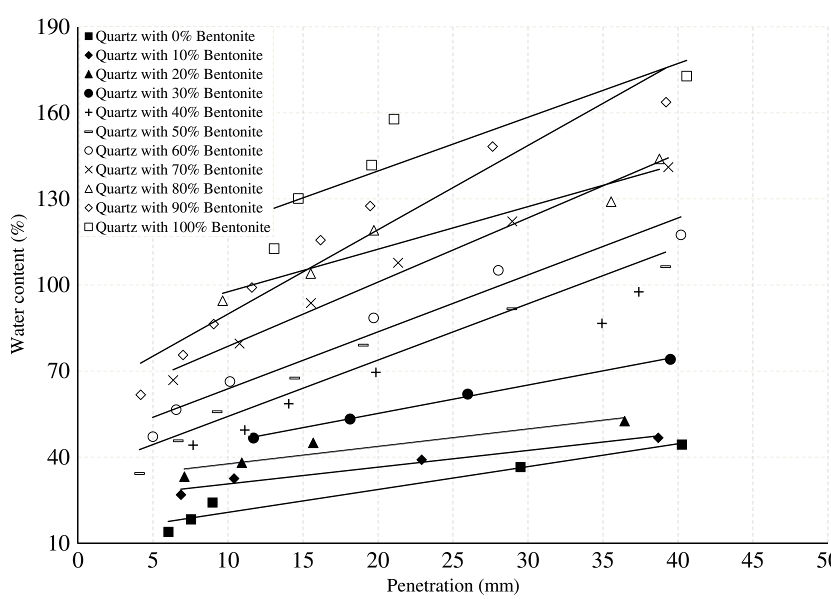


Fig. 8 Variation of penetration with water content for the quartz-bentonite mixtures

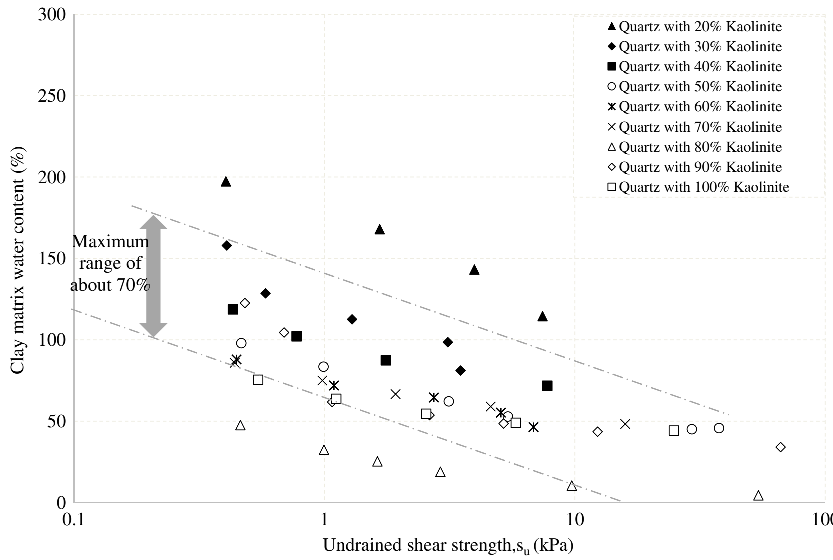


Fig. 9 Variation of penetration with clay matrix water content for the quartz-kaolinite mixtures

water content. Contrary to quartz-kaolinite mixtures, the penetration value was stable up to a FC_t of 20%; however, it was continuously decreased for rest of the samples tested. This behavior indicated that the mixtures gain strength against decreasing penetration all addition of bentonite. This could be attributed to the differences in the plasticity of the different clays. The penetration-water content relations could be interpreted by using clay matrix water content penetration relations. Kumar and Wood (1999), Cabalar and Mustafa (2015) indicated that clay matrix water content governed Fall cone penetration. The authors used Eq. 1;

$$w_c = \frac{m_w}{m_c} \tag{1}$$

where w_c is water content of clay matrix, m_w, and m_c is masses of water and clay, respectively. Clay matrix water content-s_u relationships are present in Figs. 9 and 10. It was clearly seen that above 20% clay content penetration values were governed by clay matrix.

It has been indicated that the Fall cone testing is also a strength measuring device. Hansbo (1957) suggested that undrained s_u can be found by using Eq. 2.

$$s_u = k \times \frac{mg}{d^2} \tag{2}$$

where, m is the mass of cone, g is the gravitational acceleration, k is a constant, which changes based on the angle of the cone and it is found to be 0.85 for the 30° British cone (Wood 1985), d is the penetration of cone. The s_u values found using Eq. 1 are shown in Fig. 11 for quartz-kaolinite mixtures. Figure 11 clearly shows that the undrained shear strength has decreased by up to 30% kaolinite then increased. This

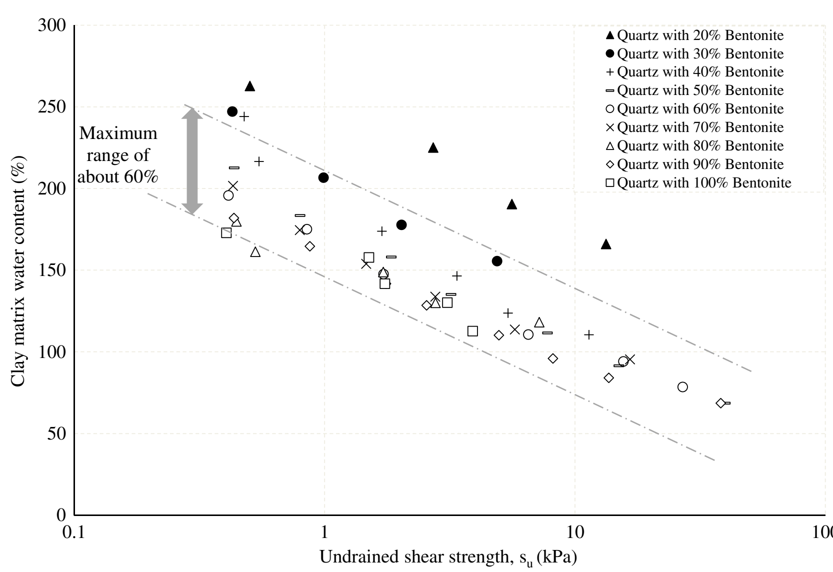


Fig. 10 Variation of penetration with clay matrix water content for the quartz-bentonite mixtures

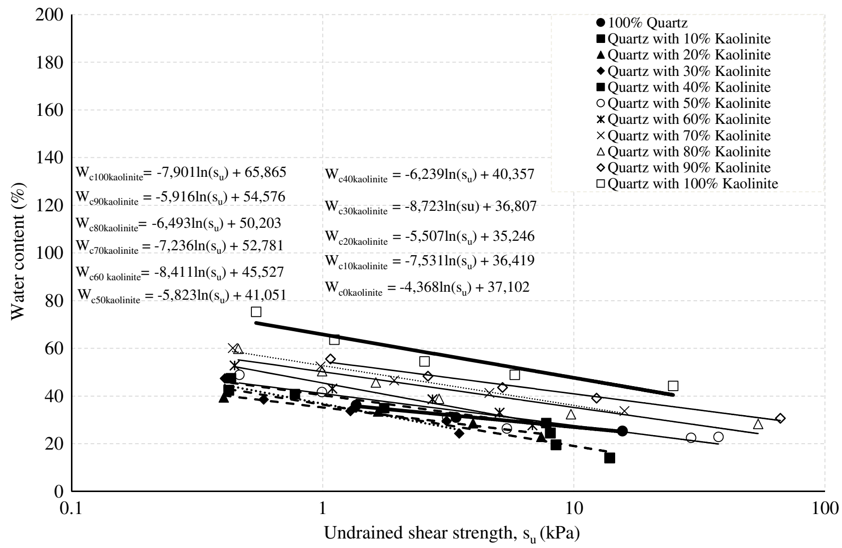


Fig. 11 Variation of undrained shear strength with water content for the quartz-kaolinite mixtures

behavior is consistent with intergranular void ratio approach (Thevanayagam 2000). The researcher used the concept of intergranular void ratio (e_g) and interfines void ratio (e_f) instead of global void ratio (e) to clarify behavior of sand-clay mixtures. According to this approach, the mixture is considered to consisting of coarse grains, fine grains, and voids. Fines content less than FC_t (%), the fine grains floats in the voids of coarse graines and decrease number of contact points between coarse grains and the mechanical behavior is mainly governed by the contact points of coarse grains. The mechanical behavior of the soil is reduced with addition of fines in this part due to contact points. Then fine grains fill voids between coarse grains, so the fine grains govern the main behavior of soil the case that fines content exceeds FC_t. In this part, the concept of e_f is used as a indicator of sand-clay mixtures behavior. Therefore penetration decrease up to 30% kaolinite content could be explained by theory of Thevanayagam (2000). In addition, Vallejo and Mawby (2000) concluded that porosity controls the shear strength of mixtures. It is reasonable that the values of the undrained shear strength values and the MDD values with kaolinite content behavior interchange same FC_t. Besides, various formulas between water content and s_u were suggested. According to the critical state concept, slope of these curves could be related to compression behavior (Wood 1990). In this context, it is evident that as the kaolinite ratio increases, the slope of line is increased. This behavior shows that compressibility generally increases with kaolinite addition, which is similar to outcomes reported in literature (De Magistris et al., 1998; Kolay and Ramesh 2016). Figure 12 shows s_u values of quartz-bentonite mixtures. It was evident that undrained shear strength is controlled by water content of soil matrix. However, as bentonite content is increased, the s_u values were increased unlike kaolinite, there is no decrease in up to 30% (FC_t) was observed. As a

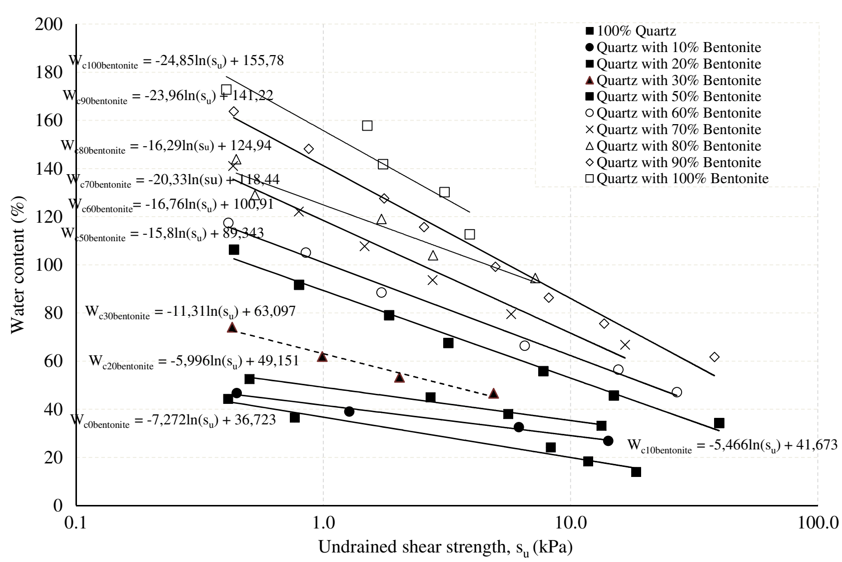


Fig. 12 Variation of undrained shear strength with water content for the quartz-bentonite mixtures

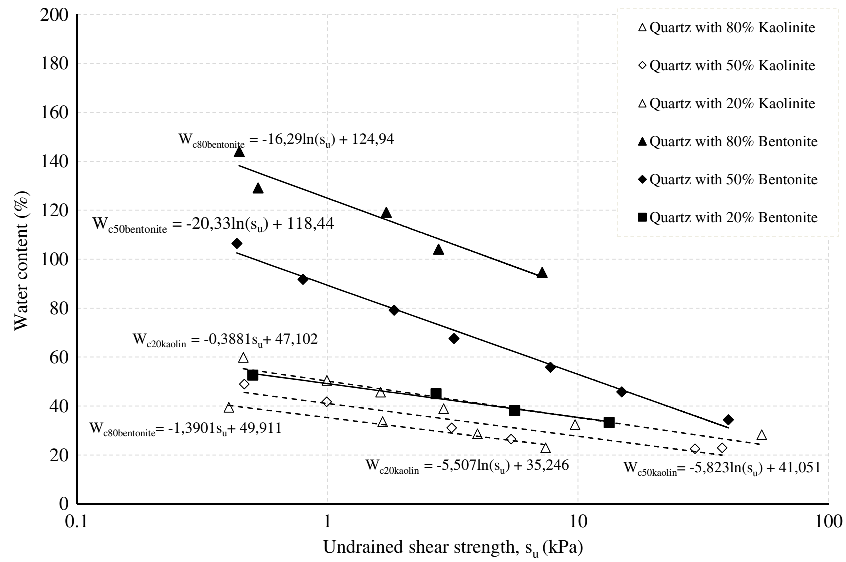


Fig. 13 Variation of undrained shear strength with water content for the quartz with different clay types

result of these different behaviors of bentonite and kaolinite clay, the undrained shear strength behavior of bentonite was controlled by viscous shear stress and viscous double layer water as Sridharan and Prakash (1999a) concluded, s_u decrease up to FC_t was not observed. Since the particle arrangement forces control the undrained shear behavior, there might be decrease in contact points of quartz particles with the kaolinite additions therefore s_u values be decrease up to FC_t. Water content—undrained s_u are proposed for each mixtures in Fig. 12. The compressibility, which is the slope of the curves, is clearly increases as the bentonite content increases. Since different clays of plasticity added plasticity values are different, it is desired to investigate the effect of these values on s_u values. Figure 13 includes variation of strength of quartz including different amounts of bentonite and kaolinite. It is evident that quartz with bentonite mixtures has greater s_u values than those including kaolinite for a constant water content. The plasticity and liquid limit difference between kaolinite and bentonite could be given as the reason behind this. Sridharan and Prakash (1999b) stated that liquid limit and the undrained shear strength parameter are consistent with each other in a consistent manner. Greater the liquidity of bentonite mixtures, higher the s_u values. Furthermore, additional shear stresses due to the suction forces (Kochmanová and Tanaka 2011; Vanapalli 2009; Likos and Jaafar 2014) could be evaluated as the reason of different behaviors. Bentonite has greater effective stress since it has more suction stress than kaolinite. This behavior could also be attributed to different plasticity of bentonite and kaolinite (Fig. 16). A similar interpretation was performed by Blatz et al. (2002) who made a review of strength and stiffness behavior of bentonite quartz mixtures. They found that as plasticity of mixtures

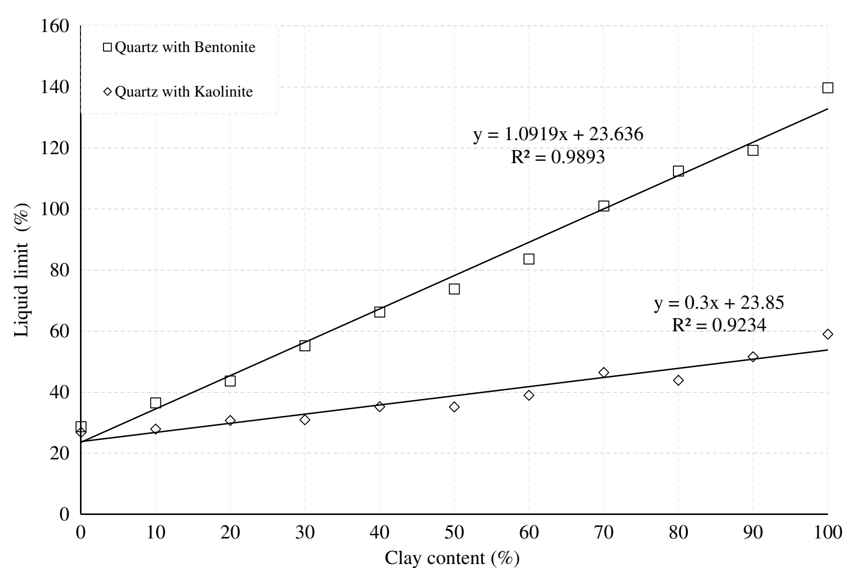


Fig. 14 Liquid limit values as a function of clay content

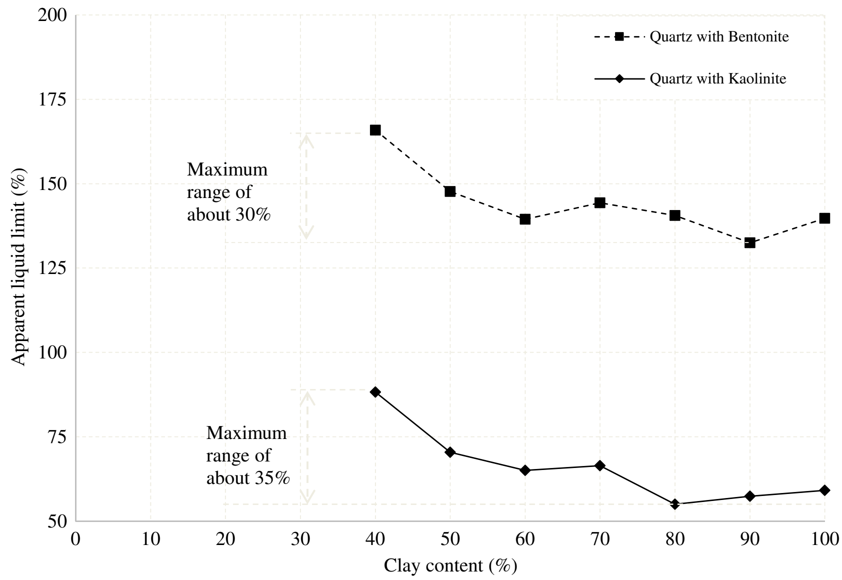


Fig. 15 Apparent liquid limit values as a function of clay content

increased s_u values also increased. Besides, at a given water content, it was clearly shown that the slope of the mixtures with bentonite is much higher than that of kaoline. This indicates that bentonite has a higher compressibility values than kaolinite. Similar results found by Kolay and Ramesh (2016). Liquid limit from fall cone, plastic limit values of quartz with clay additions are shown in Figs. 14 and 16, respectively. These figures indicated that the liquid limit values were increased with clay additives and it is obvious that bentonite has greater liquid limit value than kaolinite at a given clay content (Fig. 15). Similar behaviors were observed by Sridharan and Prakash (1999b), Tiwari and Marui (2003), and Shayea (2001). In addition, Fig. 16 clearly indicated mixtures with bentonite have higher plasticity than those with kaolinite. In addition, apparent liquid limit values are shown in Fig.15. Apparent liquid limit defines liquid limit properties for only clay matrix (Cabalar and Mustafa 2015). Comparision of liquid limit values (Fig. 14) and apparent liquid limit values (Fig. 15) clearly indicated that difference between maximum and minimum values of mixtures are clearly decrease in Fig. 15. It proves that liquid limit of mixtures are governed by clay particles as Cabalar and Mustafa (2015) concluded (Fig. 17). Comparison of the liquid limit values found in the Fall cone test with the liquid limit values found in the Casagrande test show in Fig. 18. Different formulas with R^2 correlation between Fall cone and Casagrande liquid limit values have been proposed for quartz-kaolinite and quartz-bentonite mixtures.

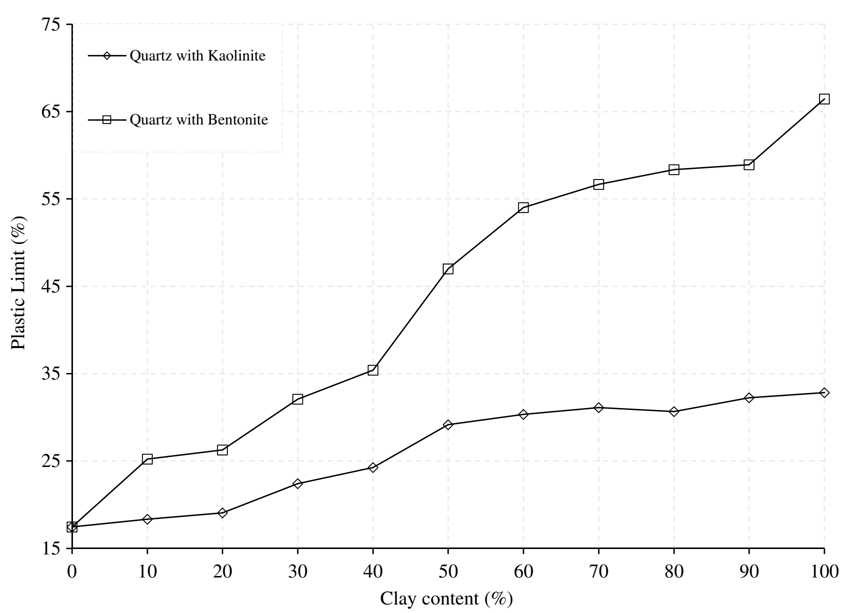


Fig. 16 Plastic limit values as a function of clay content

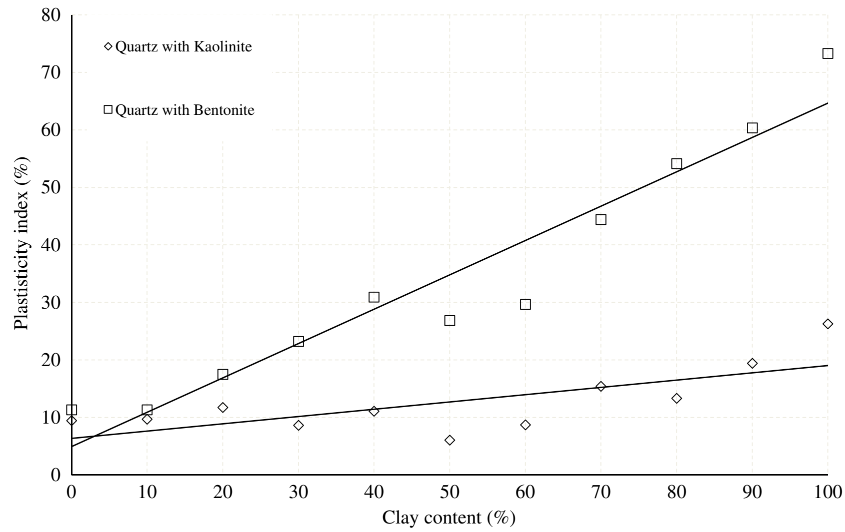


Fig. 17 Plasticity index values as a function of clay content

Conclusions

An experimental study is carried out to evaluate the liquid limit, plastic limit, plasticity index, and undrained shear strength properties of two types of clay (kaolinite and bentonite)-quartz mixtures regarding to clay content, plasticity effect of clay contents. Experimental results indicated that liquid limit, plastic limit, and plasticity index values are increased with both kaolinite and bentonite content. Consistency limits of bentonite-quartz mixtures were greater than those including kaolinite. Compaction tests revealed that MDD of mixtures increase with clay content up to FC_t then decreased. This ratio is determined to be 20% for mixtures with kaolinite while 10% for bentonite. Optimum water content on the other hand, increased with 20% kaolinite content then decreased while it was increased continuously for bentonite content ranging among 0% to 100%. Fall cone results indicated that clay inclusion increased the resistance aganist penetration. Undrained shear strength values obtained from the Fall cone test governed by water content of clay matrix. Undrained shear strength results indicated that s_u values decreased up to 20% kaolinite content then increased whereas bentonite additions increased s_u values continuously. Furthermore, quartz-kaolinite mixtures has greater maximum dry density that those with bentonite whereas quartz-bentonite mixtures has greater undrained shear strength than those with kaolinite.

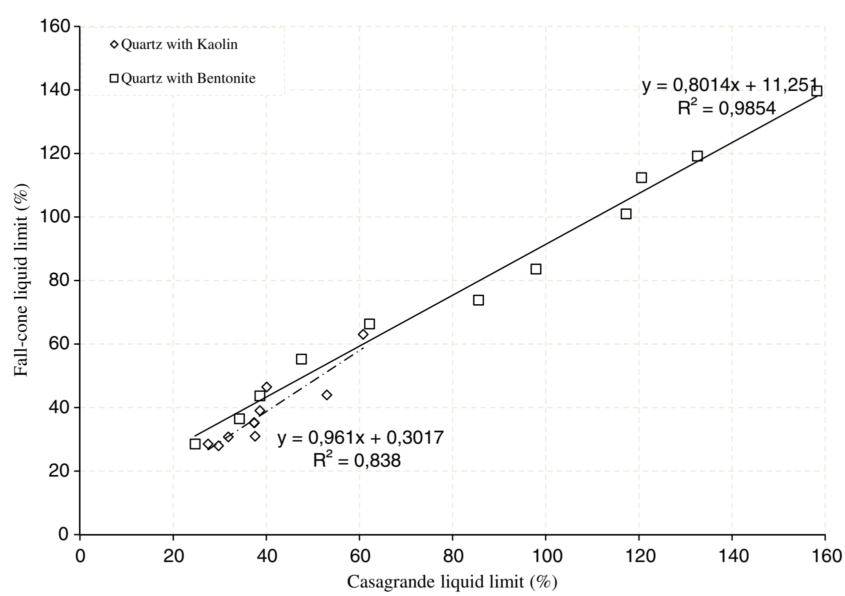


Fig. 18 Comparision of Casagrande and Fall cone liquid limit values

References

Albrecht A, Benson C (2001) Effect of desiccation on compacted natural clays. J Geotech Geoenviron 127(1):67–75

Bayat M, Bayat E, Aminpour H, Salarpour A (2014) Shear strength and pore-water pressure characteristics of sandy soil mixed with plastic fine. Arab J Geosci 7(3):1049–1057

Blatz JA, Graham J, Chandler NA (2002) Influence of suction on the strength and stiffness of compacted sand bentonite. Can Geotech J 39(5):1005–1015

Bray JD, Sancio RB (2006) Assessment of the liquefaction susceptibility of fine-grained soils. J Geotech Geoenviron 132(9):1165–1177

Cabalar AF, Hasan RA (2013) Compressional behaviour of various size/shape sand–clay mixtures with different pore fluids. Eng Geol 164:36–49

Cabalar AF, Mustafa WS (2015) Fall cone tests on clay–sand mixtures. Eng Geol 192:154–165

Chiu TF, Shackelford CD (1998) Unsaturated hydraulic conductivity of compacted sand-kaolin mixtures. J Geotech Geoenviron 124(2):160–170

Cubrinovski M, Ishihara K (2002) Maximum and minimum void ratio characteristics of sands. Soils Found 42(6):65–78

De Magistris FS, Silvestri F, Vinale F (1998) Physical and mechanical properties of a compacted silty sand with low bentonite fraction. Can Geotech J 35(6):909–925

Feng TW (2001) A linear log d log w model for the determination of consistency limits of soils. Can Geotech J 38(6):1335–1342

Hansbo S (1957) A new approach to the determination of the shear strength of clay by the fall-cone test. In: Royal Swedish Geotechnical Institute, 14. Stockholm

Jacobs W, Van Kesteren WGM, Winterwerp JC (2007) Permeability and consolidation of sediment mixtures as function of sand content and clay mineralogy. Int J Sediment Res 22(3):180–187

Jafari MK, Shafiee A, Razmkhah A (2002) Dynamic properties of fine grained soils in south of Tehran. J Seismol Earthq Eng JSEE 4(1):25

Karim ME, Alam MJ (2014) Effect of non-plastic silt content on the liquefaction behavior of sand–silt mixture. Soil Dyn Earthq Eng 65:142–150

Kochmanová N, Tanaka H (2011) Influence of the soil fabric on the mechanical properties of unsaturated clays. Soils Found 51(2):275–286

Kolay PK, Ramesh KC (2016) Reduction of expansive index, swelling and compression behavior of kaolinite and bentonite clay with sand and class C fly ash. Geotech Geol Eng 34(1):87–101

Komine H (2004) Simplified evaluation on hydraulic conductivities of sand–bentonite mixture backfill. Appl Clay Sci 26(1):13–19

Kumar GV, Wood DM (1999) Fall cone and compression tests on clay ±gravel mixtures. Geotechnique 49(6):727–739

Likos WJ, Jaafar R (2014) Laboratory fall cone testing of unsaturated sand. J Geotech Geoenviron 140(8):04014043

Di Maio C, Santoli L, Schiavone P (2004) Volume change behaviour of clays: the influence of mineral composition, pore fluid composition and stress state. Mech Mater 36:435–451

Murray HH (2000) Traditional and new applications for kaolin, smectite, and palygorskite: a general overview. Appl Clay Sci 17(5):207–221

Naeini SA, Jahanfar MA (2011) Effect of salt solution and plasticity index on undrain shear strength of clays. World Academy of Science. Eng Technol 49:982–986

Park J, Santamarina JC (2017) Revised soil classification system for coarse-fine mixtures. J Geotech Geoenviron 143(8):04017039

Purvana YM, Nikraj H, Jitsangiam P (2012) Experimental study of suction-monitored CBR test on sand-kaolin mixture. Int J Geomate 3(2 (SI.No.6)):419–422

Sawangsuriya A, Edil TB, Bosscher PJ (2009) Modulus-suction-moisture relationship for compacted soils in postcompaction state. J Geotech Geoenviron 135(10):1390–1403

Shayea A (2001) The combined effect of clay and moisture content on the behavior of remolded unsaturated soils. Eng Geol 62(4):319–342

Simpson DC, Evans TM (2015) Behavioral thresholds in mixtures of sand and kaolinite clay. J Geotech Geoenviron 142(2):04015073

Sridharan A, Gurtug Y (2004) Swelling behaviour of compacted fine-grained soils. Eng Geol 72(1):9–18

Sridharan A, Prakash K (1999a) Mechanisms controlling the undrained shear strength behaviour of clays. Can Geotech J 36(6):1030–1038

Sridharan A, Prakash K (1999b) Influence of clay mineralogy and pore-medium chemistry on clay sediment formation. Can Geotech J 36(5):961–966

Stark TD, Choi H, McCone S (2005) Drained shear strength parameters for analysis of landslides. J Geotech Geoenviron 131(5):575–588

Sudjianto AT, Suryolelono KB, Mochtar IB (2011) The effect of variation index plasticity and activity in swelling vertical of expansive soil. International Journal of Engineering & Technology IJET-IJENS 11(6):117–123

Thevanayagam S (2000) Liquefaction potential and undrained fragility of silty soils. 12WCEE 2000: 12th World Conference on Earthquake Engineering, Auckland, New Zealand, Sunday 30 January - Friday 4 February 2000. New Zealand Society for Earthquake Engineering, Upper Hutt

Tiwari B, Ajmera B (2011) A new correlation relating the shear strength of reconstituted soil to the proportions of clay minerals and plasticity characteristics. Appl Clay Sci 53(1):48–57

Tiwari B, Marui H (2003) Estimation of residual shear strength for bentonite-kaolin-Toyoura sand mixture. Journal of the Japan Landslide Society 40(2):124–133. https://doi.org/10.3313/jls.40.124

Vallejo LE, Mawby R (2000) Porosity influence on the shear strength of granular material–clay mixtures. Eng Geol 58(2):125–136

Vanapalli SK (2009) Shear strength of unsaturated soils and its applications in geotechnical engineering practice. Unsaturated Soils – Buzzi, Fityus & Sheng (eds) © 2010. Taylor & Francis Group, London

Vucetic M, Dobry R (1991) Effect of soil plasticity on cyclic response. J Geotech Eng 117(1):89–107

Wood DM (1985) Some fall cone tests. Geotechnique 35(1):64–68

Wood DM (1990) Soil behaviour and critical state soil mechanics. Cambridge University Press, United Kingdom

Xenaki VC, Athanasopoulos GA (2003) Liquefaction resistance of sand–silt mixtures: an experimental investigation of the effect of fines. Soil Dyn Earthq Eng 23(3):1–12