Influence of mineralogical composition on geotechnical properties

Influence de la composition mineralogique sur les proprietes geotechniques

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ABSTRACT

To evaluate the geotechnical properties of a soil mass, different soil specimens were prepared in the lab by mixing various proportions of quartz, smectite, and illite. Liquid limit, plastic limit, and volume change behavior in terms of compression and swelling indices were measured according to the procedure mentioned in the respective ASTM methods. Those minerals are considered as the most common minerals that are found in expansive soils that include mudstone/clay stone, marl and shale. Such expansive soils are always considered as problematic soils in geotechnical engineering. The results show that plasticity index and liquid limit depend on the proportion of smectite and total clay content. A parabolic relationship could be observed between the liquid limit and proportion of smectite. Smectite is mainly controlling the plasticity characteristics. Likewise, volume change properties also depend on the proportion of smectite and liquid limit. A parabolic relationship was observed between the compression index and proportion of smectite, whereas a linear relationship was observed between the liquid limit and compression index. The results clearly show that we can estimate the coefficient of consolidation, and compression and swelling indices of a soil mass with reasonable accuracy with liquid limit and proportion of dominant clay mineral. This finding has a great significance in the geotechnical engineering because with a small amount of soil that can be collected from a boring core, we will be able to evaluate liquid limit, mineralogical composition, and clay content. Those parameters can be used to estimate the compressibility and hydraulic conductivity of a soil mass. They are very important in numerical simulation, foundation design, and many other applications in geotechnical engineering.

RÉSUMÉ

Afin d'évaluer les propriétés géotechniques d'un sol, différents échantillons ont été prépares en laboratoire en mélangeant différentes proportions de quartz, de smaltite et d'illite. La limite de liquidité, la limite de plasticité, et le potentiel de retrait et de gonflement du sol en termes d'indices de retrait et de gonflement ont été mesurés selon la procédure décrite dans la méthode standard de l'organisation internationale ASTM (American Society for Testing and Materials). Ces minéraux sont considérés comme les minéraux les plus couramment trouvent dans les sols expansifs, y compris l'argilite, la marne et le schiste argileux. De tels sols expansifs sont toujours problématiques en ingénierie géotechnique. Les résultats montrent que les indices de plasticité et de liquidité dépendent de la proportion de smectite et de la teneur totale en d'argile de l'échantillon. Une relation parabolique a pu être observée entre la limite de liquidité et la proportion de smectite dans l'échantillon. La smectite controle principalement les propriétés plastiques du sol. De même, les propriétés de retrait et de gonflement dépendent de la proportion en smectite et de la limite de liquidité. Une relation parabolique a été observée entre l'indice de compression et la proportion en smectite, tandis qu'une relation linéaire a été observée entre la limite de liquidité et l'indice de compression. Les résultats montrent clairement que le coefficient de consolidation, et les indices de retrait et de gonflement d'un sol peuvent être détermines avec une précision raisonnable, a partir de la limite de liquidité et la proportion du composant argileux dominant. Cette découverte a une importance considérable pour l'ingénierie géotechnique puisqu'a partir d'une petite quantité de sol provenant d'un prélèvement géologique, la limite de liquidité, la composition minéralogique, et la teneur en argile pourront être évaluées. Ces paramètres peuvent être utilisés pour évaluer la compressibilité et la conductivité hydraulique des sols. L'usage de ces données est très important pour la simulation numérique, le calcul de fondations, ainsi que pour de nombreuses autres applications dans le domaine de l'ingénierie géotechnique.

Keywords : liquid limit, plasticity index, compression index, swelling index, hydraulic conductivity

1 BACKGROUND

Fundamental physical properties of a rock mass depend on the mineralogical composition of the rock. Likewise, geotechnical properties of a soil mass depend on those fundamental properties of the parent rocks. Index properties, coefficient of consolidation, and compression index of a soil specimen primarily depend on the proportion of minerals in the mixture. Effect of mineralogical composition in a soil mass can be roughly assessed through activity. Therefore, if effect of mineralogical composition in the geotechnical properties of a soil mass is assessed, that will help a geotechnical engineer to estimate baseline geotechnical properties of soil in the field.

Volume change behavior of a soil specimen is very important in various designs pertinent to geotechnical engineering that include but not limited to the design of foundation, landfill liner, and embankment structures. Volume change behavior is primarily explained with compression and swelling indices. Because of an extensive use of bentonite in landfill designs, we can get several literature focused on the volume change behavior of bentonite-sand mixture. Stewart et al. (2003) conducted research to evaluate the volume change behavior of bentonite enhanced sand. The literature briefly explained the findings of previous researchers. Later, Di Maio et al. (2004) did further work to evaluate the compressibility of bentonite-kaolinite mixture in different pore fluid – distilled water,

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-68

saline water, and non-polar water. Yeo et al. (2005) also conducted measured the volume change behavior of different clay-bentonite mixture. All of those literature showed that higher percentage of bentonite increases the compressibility characteristics of soil. If the specimen is treated with salt water, compression index reduces considerably. However, those researches were mainly concentrated on the application in landfill design and for the two phase mixtures such as sand-bentonite or kaolinite-bentonite. It is known that a considerable percentage of the land in USA lies on expansive soil/rocks that include shale. Study of the compressibility of soil made from shale is important not only for the design of foundation but also for the design of embankment structures. Constituent clay minerals in most of the shale are smectite, kaolinite, chloride, and illite. Proportion of illite and smectite are also considered to be dominant within clay minerals of shale. Likewise, there is a significant amount of quartz in shale. Therefore, study pertinent to the geotechnical properties of quartz-illite-smectite mixture will be beneficial not only in the landfill designs but also in the design of various geotechnical structures designed on or from shale and shale products. To evaluate the geotechnical properties of a soil mass, different soil specimens were prepared in the lab by mixing various proportions of quartz, smectite, and illite. First, liquid limit, plastic limit, and plasticity index of those specimens were measured. Then a number of soil specimens were selected out of them to measure the compressibility and permeability properties of those mineral mixtures. Tiwari and Marui (2005) showed that residual shear strength of a soil specimen varies with liquid limit, plasticity index, and mineralogical composition. Therefore, this research can be further extended to estimate the strength characteristics of soil for different composition of natural minerals. This paper deals in detail with the experimental research results pertinent to plasticity and volume change characteristics.

2 SAMPLE PREPARATION

First, commercially available quartz, smectite, and illite were pulverized. Then, those minerals were mixed in different proportions based on the dry weight of each specimen. Mixing was done thoroughly to avoid particle segregation. Sufficient amount of mixtures were taken from the batches and were hydrated with distilled water for more than 72 hours to let the mixture soak water appropriately. Atterberg's limit tests were conducted on those specimens to measure liquid limit, plastic limit, and plasticity index. Procedures mentioned in the ASTM D4318 were strictly followed to measure those parameters. Then, 24 different mixtures were identified to measure volume change characteristics of those mixtures. Those mineral mixtures were first mixed with distilled water, approximately 120% of the liquid limit by weight, to make slurry. After letting the mixture hydrate for more than 72 hours, the hydrated mineral mixture was mixed thoroughly in a batch mixer to avoid particle segregation while wet mixing. Then, the soil specimen was loaded into a one-dimensional consolidometer to measure compression index, swelling index, void ratios, coefficient of consolidation, and hydraulic conductivity. While measuring those properties, procedure mentioned in the ASTM D-2435-04 was strictly followed. The specimens were subjected to normal stress of 3.5 psi, 7 psi, 14 psi, 28 psi, 56 psi, 112 psi, and 224 psi for stage-consolidation and were then allowed to swell by reducing the normal stress back to 112 psi, 56 psi, 28 psi, 14 psi, 7 psi, and 3.5 psi. The deformation data was used to calculate void ratio, compression index, swelling index, coefficient of consolidation, and hydraulic conductivity.

3 SOIL TEST RESULTS

Shown in figure 1 is the plasticity information of the tested soil specimens. Most of the soil specimens were plotted above A-line with liquid limit higher than 50 and were classified as fat clays according to USCS, while a few specimens were lean clays. Shown in figure 2 is the variation of liquid limit with proportion of smectite. There is an excellent relationship between liquid limit and proportion of smectite as can be seen in the proposed parabolic equation shown in figure 2. Shown in figure 3 is the variation of liquid limit with the proportion of illite. The relationship shows that liquid limit varies with the proportion of illite. However, it also depends on the total clay content (sum of the proportion of smectite and illite) at the same time. Shown in figures 4 and 5 are the variations of plasticity index with proportion of smectite and illite, respectively. Plasticity index also showed similar relationship with smectite and illite as that with liquid limit. These facts clearly demonstrate the possibility of variation of other geotechnical parameters with the proportion of smectite, illite, and clay content.

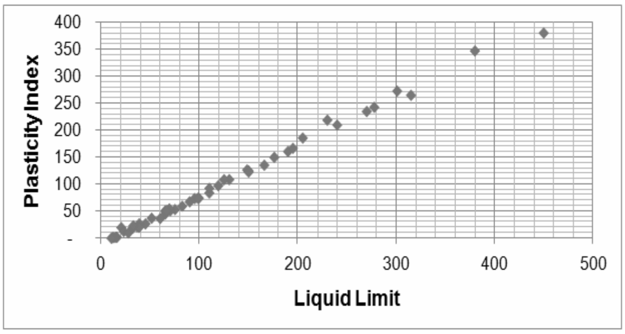

Figure 1. Relationship between plasticity index and liquid limit of the tested mineral mixtures

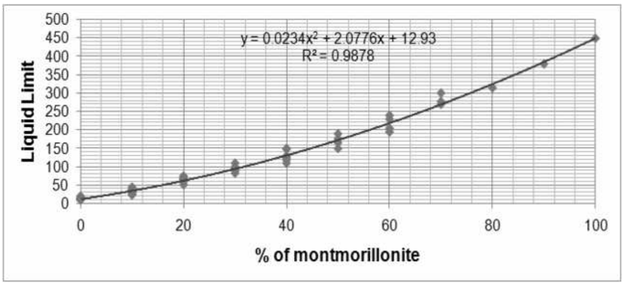

Figure 2. Variation of liquid limit of the mixture of quartz, iliite, and smectite (montmorillonite) with the proportion of smectite

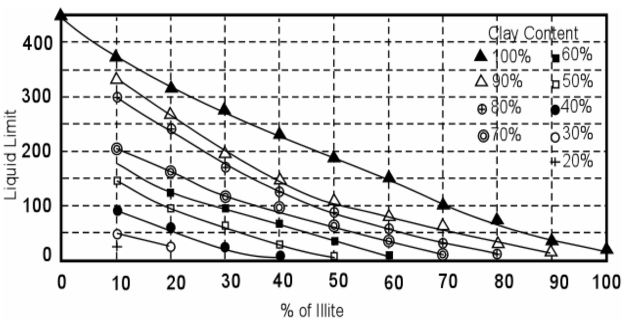

Figure 3. Variation of liquid limit of the mixture of quartz, iliite, and montmorillonite with the proportion of illite

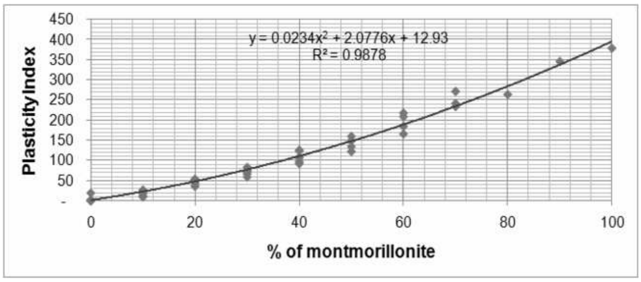

Figure 4. Variation of plasticity index of the mixture of quartz, iliite, and smectite with the proportion of smectite

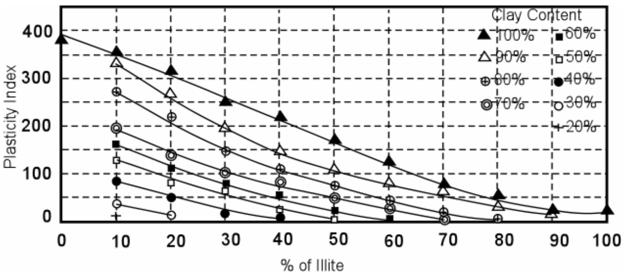

Figure 5. Variation of plasticity index of the mixture of quartz, iliite, and smectite with the proportion of illite

Shown in figure 6 is the variation of compression index (Cc) with percentage of smectite in the mixture. There exists an excellent relationship between the proportion of smectite and compression index and the relationship can be fitted with a parabolic regression function, as seen for the liquid limit in figure 2. As shown in figure 7, there is a good linear relationship between liquid limit and compression index. Shown in figure 8 is the relationship between activity and compression index. Although there was a qualitative relationship, it was hard to fit a good regression curve that illustrates the relationship between activity and compression index.

Shown in table 1 are the values of swelling index of various mixtures of quartz, illite, and smectite. The swelling index ranged from 0.008 to 0.251. The ratio of compression index and swelling index ranged from 3 to 65 with an average value of 17. Although it is believed that swelling index ranges from one sixth to one-tenth of the compression index, the ratio is found to be considerably high for the quartz-smectite-illite mixture, especially for the high plasticity soil. Qualitatively, swelling index could be related to uniformity coefficient and liquid limit. However, it was difficult to get exact relationship with the available data. It is expected that with further research data, it may be possible to define such relationships.

Shown in table 2 is the coefficient of consolidation for the mixtures. Coefficients of consolidation were measured with both Casagrande's deformation – log of time method and Taylor's deformation – square root of time method. The data presented in table 2 are the values obtained with the Casagrande's methods. Value of coefficient of consolidation ranged from 0.3 x 10^{-6} to 479 x 10^{-6} in^2/sec. Although quantitative relationship could not be developed, coefficient of consolidation decreased with an increase in smectite content. Likewise, coefficient of consolidation decreased with the increase in liquid limit. Moreover, coefficient of consolidation also decreased with the increase in uniformity coefficient. It is expected that if sufficient data is available, it is possible to show a good relationship between coefficient of consolidation and liquid limit.

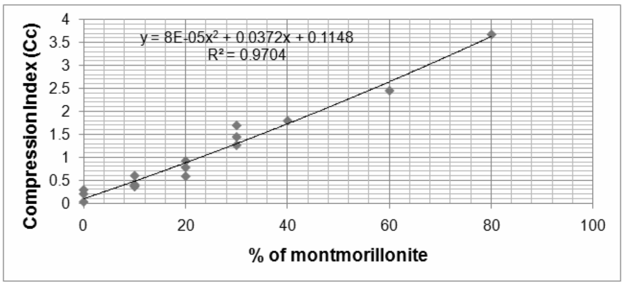

Figure 6. Variation of compression index of the mixture of quartz, iliite, and smectite with the proportion of smectite in 1-D consolidation test

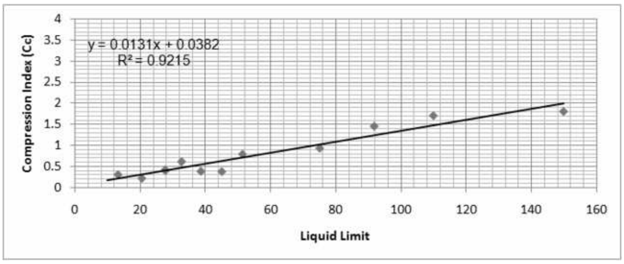

Figure 7. Variation of compression index of the mixture of quartz, iliite, and montmorillonite with the liquid limit in 1-D consolidation test

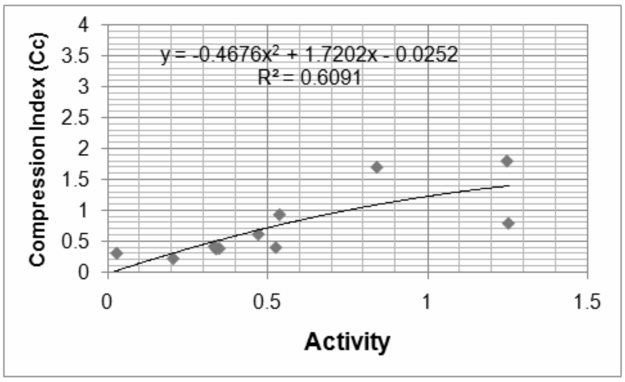

Figure 8. Variation of compression index of the mixture of quartz, iliite, and montmorillonite with the activity in 1-D consolidation test

Shown in table 3 is the hydraulic conductivity of the mineral mixtures. Hydraulic conductivity of the mixtures were calculated based on the average change in void ratio for the net stress increase. Hydraulic conductivity was very low for higher clay content and higher smectite content. All of the specimens exhibited a very low hydraulic conductivity than the value that we generally consider for clays.

It is to be noted that it took more than 3 weeks to have 100% consolidation of soil mixture that has higher smectite proportion. Several tests were repeated because extremely high moisture content in the highly plastic soil frequently caused the top platen to tilt.

Table 1. Compression and swelling indices of various mineral mixtures measured at 1-D consolidation test

Proportion of			Swelling Index (C_s)
Quartz	Illite	smectite	
30	70	0	0.020
80	10	10	0.008
70	20	10	0.069
50	40	10	0.021
20	70	10	0.048
80	0	20	0.040
0	80	20	0.17
70	0	30	0.251
60	10	30	0.147
0	60	40	0.06
40	0	60	0.203
20	0	80	0.134

Table 2. Coefficient of Consolidation of various mineral mixtures measured at 1-D consolidation test

Proportion of			Coefficient of Consolidation (C_v) ($x10^{-6}$ in^2/sec)
Quartz	Illite	smectite	
30	70	0	479
80	10	10	27
70	20	10	4.5
50	40	10	131
20	70	10	4.3
80	0	20	346
0	80	20	12
70	0	30	2.5
60	10	30	0.8
0	60	40	1.2
40	0	60	2.2
20	0	80	0.3

Table 3. Hydraulic conductivity of various mineral mixtures measured at 1-D consolidation test

Proportion of			Hydraulic conductivity (K) ($x\ 10^{-10}$ cm/s)
Quartz	Illite	Montmorillonite	
30	70	0	8530
80	10	10	10
70	20	10	43
50	40	10	92
20	70	10	4
80	0	20	508
0	80	20	9
70	0	30	29
60	10	30	15
0	60	40	0.6
40	0	60	9
20	0	80	4

4 CONCLUSION

Research on volume compressibility of various minerals and two phase mixture of sand-bentonite or kaolin-bentonite has been done in the past and it has been observed that compression index increases with the increase in bentonite and reduces with the increase in sodium concentration in the solution. Compressibility characteristics of soil is very important in the design of geotechnical structures that include but not limited to foundation, retaining wall, dams, and landfill liner. Considerable portion of USA shows the existence of expansive rocks such as shale. Those rocks are composed of quartz, feldspar, illite, kaolinite, calcite, and smectite. Major clay minerals available in shale are smectite and illite. Therefore, liquid limit and plasticity index of more than 50 different mixtures of quartz, illite, and smectite were measured. Liquid limit increased with the increase in smectite proportion and a parabolic regression curve could be fitted. However, liquid limit decreased with the proportion of illite for the same clay content value. However, for the same amount of illite, liquid limit increased with clay content. One dimensional consolidation test data showed that compression index increases with the proportion of smectite and a parabolic regression curve can be fitted. There was a good linear relationship between liquid limit and compression index. Swelling index was 3 to 65 times lower than the compression index – higher for higher proportion of smectite and higher uniformity coefficient. Coefficient of consolidation and hydraulic conductivity were also low for higher proportion of smectite and higher uniformity coefficient.

ACKNOWLEDGEMENT

Students involved in the research were supported by "California State University, Fullerton, out of state tuition waiver", "Dwight David Eisenhower Transportation Graduate fellowship" and "Dwight David Eisenhower Transportation Undergraduate fellowship". The authors would like to appreciate the Federal Highway Department and California State University, Fullerton for those supports.

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