Applied Clay Science 135 (2017) 532–537

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Note

Practical charts to identify the predominant clay mineral based on oxide composition of clayey soils

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ARTICLE INFO

Article history:
Received 12 July 2016
Received in revised form 29 September 2016
Accepted 30 September 2016
Available online 11 October 2016

Keywords:
Geotechnical engineering
Soil mechanics
Clay minerals
Oxide composition
Mineral identification

ABSTRACT

This study proposes some useful practical charts representing the relationships between oxide composition and the type of predominant clay mineral present in clay soils. In order to produce the charts, the data set are collected from published literature. Some useful classification schemes for predominant clay mineral type were obtained by using binary and ternary graphs of oxide composition data. The most successful relations indicating the type of clay mineral have been found on SiO_2 versus $Al_2O_3 + Fe_2O_3 + FeO$, SiO_2 versus $MgO + CaO + Na_2O + K_2O$ binary plots, $SiO_2 - Al_2O_3 -$ Others and $SiO_2 - Al_2O_3 - K_2O$ ternary plots.

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1. Introduction

Mineral type is one of the most important properties of fine-grained soils. The colloidal particles of soils are mainly composed of clay minerals that occur in all type of sediments and sedimentary rocks as a result of weathering and hydrothermal alteration. All the clay minerals are layered crystalline hydrous aluminosilicates, and the arrangement and the chemical composition of the layers determine the type of clay mineral (Holtz and Kovacs, 1981; Craig, 1994; Terzaghi et al., 1996; Weaver and Pollard, 1973).

Clays are defined as soils which have particles smaller than 2 μm and cohesive effects. The influence of the electrical forces acting at the surface of each particle is significant. It is very complicated and difficult to classify the mineral types. However, various groups exist based on mineralogical and chemical structures in the literature. In terms of geotechnical engineering, clay minerals are mainly classified as kaolinite group, micalike minerals group and Smectite group (Lambe and Whitman, 1979; Mitchell, 1993). It is so difficult to find pure clay mineral composing of only one mineral on earth. However, it is possible to estimate behavior of clays from geotechnical point of view as the predominant mineral existing in clay is known.

For geotechnical engineers the mineralogical composition of clays may be useful as a notice of their characteristic behavior, and as an indication of the difference from the other materials (Holtz and Kovacs, 1981). Sizes, shapes and surface characteristics of the clay particles as well as their interactions with fluids are governed by the mineralogy. Therefore, mineralogical characterization is essential for understanding of geotechnical properties of clayey soils such as plasticity, swelling, compression, strength, and permeability. It also gives us good estimation about the consistency limits and grain size distribution reflecting both composition and engineering properties (Mitchell, 1993).

The consistency limits are very useful for soil identification and classification. In addition, they are widely used as a means of estimating the plastic properties of clay materials. The liquid limit (w_L) and plastic limit (w_p) are in the order montmorillonite > illite > kaolinite for common clay minerals belonging to smectite group, mikelike minerals group and kaolinite group, respectively (Mitchell, 1993; White, 1949; Bain, 1971). Susceptibility of clays to swelling and shrinking increases with increasing activity (A_c). Therefore, the swelling and shrinking potential is in the order montmorillonite > illite > kaolinite for clay minerals. For clay minerals compared at the same water content, the permeability is in the order montmorillonite < illite < kaolinite. The compressibility of saturated clay minerals decreases in the order montmorillonite > illite > kaolinite (Mitchell, 1993). The angle of shear strength decreases in the order by kaolinite, illite and montmorillonite for clay minerals (Olson, 1974).

One of the most important issues for geotechnical engineers is to estimate behavior of clayey soils, which is mainly governed by the dominant clay type. Although identification of mineralogical composition of clay samples by XRD analysis is an easily applicable technique for clay scientist, the specimen preparation and assessment of XRD patterns to determine the available minerals in clay soils is a complicated methodology for

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http://dx.doi.org/10.1016/j.clay.2016.09.035
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geotechnical engineers. Therefore, assessment of predominant clay type in soils and their engineering properties, by using practical charts prepared based on chemical composition, could be more attractive when compared to sophisticated XRD analyses for geotechnical engineers.

In this study, some practical charts have been prepared for use in estimation of dominant clay type in fine-grained soils from their chemical composition. The general idea presented in this study is to provide practical charts for geotechnical engineers to assess dominant clay type in soils and thus to evaluate their related engineering properties based on their chemical compositions, instead of complicated X-ray diffraction methods utilized by clay scientists.

2. Materials and methods

In this study, it is aimed to produce practical charts that can be used for identification of major type of clay minerals in clay soils based on their oxide composition. For this purpose, the oxide composition data of 40 clay samples for each of three common clay mineral types (kaolinite as a mineral in kaolinite group, illite in micalike group and montmorillonite in smectite group) from published literature are collected. Types of dominant clay mineral in clay soil samples had been reported as determined by powder XRD analyses in published literature. Their chemical compositions had been reported as determined by means of X-ray fluorescence (XRF) or conventional wet chemical method or inductively coupled plasma emission spectrometry (ICP) by fusion/dissolution technique using the bulk or powdered samples which had grain size <20 μm. In order to produce practical charts representing the relations between oxide composition and dominant clay mineral type in clay soils, some binary and ternary graphs were plotted and they are assessed analytically to identify the regions representing each dominant clay mineral type.

3. Results and discussion

3.1. Relationships between SiO_2, Al_2O_3, Fe_2O_3 contents of clays and their type of dominant mineral

The data sets clay soil samples of kaolinite, illite and montmorillonite and their statistical parameters are determined (Table 1, Table 2 and

Table 1

Chemical contents and statistical parameters of kaolinites used in the study.

	Chemical composition (%)												
Data number	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	TiO_2	Na_2O	K_2O	LOI	H_2O^-	Total	References
1	46.20	39.20	0.23		0.06	0.07	0.09	0.09	0.21	13.80		100.0	Jepson and Rowse (1975)
2	45.2	39.2	0.17		0.06	0.08	1.21	0.03	0.02	13.3		99.3	
3	46.40	39.52	0.09		0.23	0.15		0.09	0.01	13.90		100.4	Nemecz (1981)
4	44.06	39.44	0.80		0.06	0.26				14.16	1.06	99.8	
5	45.10	37.70	0.70				1.40			13.90	0.90	99.7	
6	44.59	38.12	1.43		0.10	0.06	1.38	0.12	0.08	13.91	0.71	100.5	
7	44.84	40.36	0.30		0.31					13.99		99.8	
8	44.15	38.99	1.06			0.14	0.62			12.96		97.9	Weaver (1989)
9	46.86	38.22	1.19				0.41			13.59		100.3	Weaver and Pollard (1973)
10	45.84	38.30	1.50		0.06		0.01	0.03	0.31	14.08		100.1	Çelik et al. (1997)
11	46.30	34.80	0.65		2.33			0.45	0.18	14.40		99.1	Karakaya et al. (2001)
12	45.10	37.50	0.60		0.10	0.02	0.03		0.10	14.70		98.2	
13	46.51	39.62			0.11				0.03	13.74		100.0	Bauer and Berger (1998)
14	44.6	38	0.2		0.01	0.02		0.01	0.04			82.9	Heller-Kallai and Lapides (2007)
15	44.1	37.8	1.08		0.02	0.04		0.01	0.04			83.1	
16	47.6	38	1.1		1.1	0.5		<0.1	1			89.3	
17	44.4	37.9	0.68		<0.02	0.11		<0.15	0.29			83.4	
18	42.8	37.2	1		<0.1	<0.1		<0.1	<0,1			81.0	
19	46.7	33.8	2		1.1	0.26		0.28				84.1	Kamiyango et al. (2009)
20	48.15	38.36	0.43		0.09	<0,02	0.5	0.13	0.5	11.5		99.7	Kılıç and Hoşten (2010)
21	48	37	0.75						2.5			88.3	Mergen and Aslanoğlu (2003)
22	47.2	35.75	2.86		0.17		0.9			12.23		99.1	Saikia et al. (2003)
23	47.05	36.98	0.34				0.53	0.12	0.08	14.31		99.4	Suraj et al. (1998)
24	46.01	34.27	1.26				2.2	0.15	1.45	14.4		99.7	
25	45.5	38.1	0.3				1.4			13.8		99.1	Sanchez et al. (2003)
26	51.3	32.6	1.1		0.1	0.3	1.1	0.2	0.3	13		100.0	Jaarsveld et al. (2002)
27	51.4	31.2	3.8				0.6		3.1	10		100.1	Sei et al. (2004)
28	51.8	28.8	4.4				1.7		2.6	10.5		99.8	
29	51.6	31.3	3.5				2.3		0.3	11.1		100.1	
30	47	36	3.08		0.16	0.32		0.42	0.74	12.31		100.0	
31	45	34	7.38		0.23	0.24		0.12	0.5	13.1		100.6	
32	48	33	6.13		0.19	0.19		0.08	0.62	12.41		100.6	
33	49	34	4.13		0.25	0.22		0.19	0.7	10.02		98.5	
34	49.72	33.85	0.96		0.03	0.3	0.04	0	3.02	11.9		99.8	Steudel et al. (2009)
35	44.72	36.34	1.58		0	0.08	1.58	0	0.47	14.2		99.0	
36	45.69	35.98	0.97		0.16	0.33	1.39	0	0.27	15.1		99.9	
37	43.98	38.54	1.12		0.01	0.03	2.34	0.01	0.01			86.0	Volzone and Ortiga (2006)
38	45.5	35.15		1.54	0.06	0.47	0.83	0.63	1.01	12.12	0.63	100.0	Ekosse (2001)
39	44.12	35.71		1.64	0.04	0.46	0.83	0.14	1.15	12.84	0.95	99.9	
40	51.4	34.5	0.45		0.15	0.3	0.41	0.15	0.58	11.9		99.8	Ferrari and Gualtieri (2006)
Statistical parameters													
Max.	51.80	40.36	7.38	1.64	2.33	0.50	2.34	0.63	3.10	15.10	1.06		
Min.	42.80	28.80	0.09	1.54	0.00	0.02	0.01	0.00	0.01	10.00	0.63		
Avrg.	46.59	36.38	1.60	1.59	0.26	0.21	0.99	0.14	0.72	13.04	0.85		
Median	46.11	37.10	1.06	1.59	0.10	0.21	0.87	0.12	0.31	13.45	0.90		
Std dev.	2.39	2.67	1.70	0.07	0.49	0.15	0.71	0.16	0.90	1.36	0.18		

LOI: Loss of ignition from 110° to 1000 °C.

H_2O^-: Ignition loss below 110 °C.

Table 2
Chemical contents and statistical parameters of illites used in the study.

	Chemical composition (%)													
Data number	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	FeO	MnO	TiO_2	Na_2O	K_2O	LOI	H_2O^-	Total	References
1	51.25	23.53	2.02	0.59	3.32	0.33		0.17	0.05	7.61	5.87	5.26	100	Srodon et al. (1986)
2	47.4	35.6	1.5		0.3			0.23	0.53	9.12			94.68	Srodon and Eberl (1984)
3	50.55	26.14	0.67	0.6	4.25	0.65		0.42	0.19	10.29	4.59	0.99	99.34	Weaver (1989)
4	53.63	29.21	4.43	0.03	1.78			0.88	0.22	9.43			99.61	Çelik and Arslan (1994)
5	56.64	26.71	4.32	0.07	1.65			0.15	0.45	10.16			100.15	
6	57.34	28.21	2.91	0.14	2.03			0.14	0.4	8.7			99.87	
7	49.54	32.56	3.11	0.39	0.97			0.33	1.4	6.75	6.14		101.19	Çelik et al. (1999)
8	51.23	31.28	0.78	1.1	0.8			0.24	0.21	7.78	5.88		99.3	
9	46.53	27.48	1.71	0.02	2.34				0.56	7.32			85.96	Inoue et al. (2004)
10	48.03	28.37	1.75	0.01	2.4			0.07	0.6	7.43			88.66	
11	47.00	23.30	7.74	0.17	1.7	3.2		0.66	0.14	6.69	8.24	0.64	99.48	Nemecz (1981)
12	54.09	26.30	1.5	0.49	2	1.49		0.68	0.22	6.87	6.89	1.32	101.85	
13	43.95	21.12	7.9	0.84	1.5	3.42		0.62	0.32	5.9	8.25	2.08	96.6	
14	47.08	28.05	8.16		2.33				0.32	6.48	7.73		100.15	
15	51.26	30.15	2.36		1.37	0.59		0.05	0.13	7.77	6.28		99.96	
16	49.67	27.31	2.96	0.29	1.09		0.1	0.23	0.1	7.26	10.5		99.47	
17	52.87	24.90	0.78	0.69	3.6	1.19		1.62	0.22	7.98	6.73	2.56	103.14	
18	47.56	22.02	7.93	1.46	3.27		0.1	0.08	0	6.82	11.1		100.71	Steudel et al. (2009)
19	47.6	36.04	0.15	0.15	0.25			0.34	0.35	9.32	5.43		99.63	Jiang et al. (2008)
20	56.8	28.8		0.28	0.61	0.93	0	1.1	0.13	3.58	7.96		100.24	Aras (2004)
21	47.78	35.29	1.19	0.14	0.82		0	0.01		8.96	4.51		98.72	Post and Borer (2002)
22	46.51	35.42	1.53	0.08	0.64		0	0.8		9.13	4.52		98.63	
23	46.65	34.5	1.99	0.21	0.89		0.1	0.6		9.58	4.55		99.06	
24	47.95	32.95	2.22	0.07	1.15		0	0.47		9.48	4.52		98.83	
25	48.4	32.21	2.31	0.08	1.2		0	0.54		9.43	4.55		98.72	
26	46.23	34.34	2	0.03	1.57		0	0.55		9.7	4.5		98.95	
27	47.94	33.62	2.21	0.05	0.63		0	0.34		9.8	4.5		99.12	
28	53.28	32.2	2.25	0.38	0.5			1.53	1.48	4.58	5.59		101.94	Baioumy and Gharaie (2008)
29	59.48	29.5	1.99	0.27	0.27			1.3	1.19	3.82	5.26		103.19	
30	56.34	32.32	0.57	0.52	0.12			1.25	1.4	2.97	5.81		101.46	
31	57	27.64	3.77	0.88	0.74			1.34	1.41	3	4.9		100.82	
32	56.38	26.84	5.12	0.87	0.97			1.41	1.43	2.75	5.13		101.12	
33	56.62	28.54	4.49	0.61	0.1			1.08	1.51	2.94	5.3		101.36	
34	50.75	20.04	9.13	1.67	3.45	0.37		0.5	0	6.01	6.74		98.66	Jiang et al. (2008)
35	44.7	25.6	10.47	1.16	2.95	0.42		0.95	0.11	5.1	8.2		99.66	
34	53.3	29.4	0.38	0.38	1.11			0.11	0.28	9.31	5.44		99.71	Ferrari and Gualtieri (2006)
35	57.6	26.3	0.49	0.33	1.16			0.11	0.26	8.47	5.01		99.73	
36	49.6	33.2	0.8	0.2	1.1			0.11	0.06	8.79	5.19		99.05	Drits et al. (1993)
37	50.2	33.7	0.8	0.2	1.5			0.08	0.11	8.59	5.11		100.29	
38	51.74	23.98	4.57	0.97	1.99	1.09		0.68	0.36	5.59			90.97	Brindley and Maksimovic (1980)
39	49.78	26.35	4.3	0.32	2.75	0.61		0.42	0.25	7.02			91.8	
40	58	25.84	4.63	1.52	3.24			0.55	2.21	3.97			99.96	Howard (1981)
Statistical parameters														
Max.	59.48	36.04	10.47	1.67	4.25	3.42	0.10	1.62	2.21	10.29	11.10	5.26		
Min.	43.95	20.04	0.15	0.01	0.10	0.33	0.00	0.01	0.00	2.75	4.50	0.64		
Avrg.	50.88	29.03	3.31	0.47	1.60	1.19	0.03	0.59	0.55	7.11	6.14	2.14		
Median	49.99	28.46	2.25	0.29	1.44	0.79	0.00	0.52	0.32	7.38	5.59	1.70		
Std dev.	4.14	4.29	2.64	0.46	1.09	1.05	0.05	0.46	0.59	2.27	1.75	1.68		

LOI: Loss of ignition from 110° to 1000 °C.
H_2O^-: Ignition loss below 110 °C.

Table 3). The average values of the clay mineral compositions are found to be close to the typical values in the literature given by theoretical SiO_2 and $Al2O_3$ contents respectively as 46.6% and 39.5% for kaolinite; 54.0% and 17.0% for illite; 43.8% and 18.6% for montmorillonite (Mitchell, 1993). The data covers the major mineral type and chemical composition. In this study, the data of the samples including purity or <10% amount of impurity for kaolinite and montmorillonite are taken into consideration. On the other hand, the data of the samples <25% amount of impurity for illite are considered because illite generally exist in impure form.

SiO_2 and Al_2O_3 are the major oxides available in clay minerals. Therefore, the ratio of SiO_2/Al_2O_3 could be accepted as a common parameter for oxide composition of clays in order to distinguish the type of clay minerals. In this study, the average SiO_2/Al_2O_3 ratios for kaolinite, illite, and montmorillonite are found to be 1.28, 1.75 and 2.85, respectively (Tables 1, 2 and 3). The SiO_2/Al_2O_3 ratio of kaolinite (1.28) and montmorillonite (2.85) determined from this study is close to that of their theoretical values of 1.18 and 2.35, respectively. However, average SiO_2/Al_2O_3 ratio for illite (Table 2) is away from the theoretical value of 3.18 probably due to impurities in clay samples.

To identify mineral type of clays based on their oxide compositions, the charts (Fig. 1 and Fig. 2) as for two-axes and ternary graphs are proposed. The relationship between SiO_2 content and $Al_2O_3 + Fe_2O_3$ content is presented (Fig. 1). It is clearly observed that the clays exhibit a distinguished arrangement in the order of kaolinite, illite and montmorillonite from up to down parts of the chart. However, an overlap zone exists between kaolinite and illite zones (Fig. 1). It is revealed that montmorillonite-type clays can be recognized by utilizing Fig. 1 whereas kaolinite and illite type clays could not be distinguished effectively from each other due to the overlap zone.

Fig. 2 presents ternary plot of SiO_2:Al_2O_3:the other oxides. Montmorillonite type clays can be identified noticeably, similarly to Fig. 1, by using a practical ternary chart of SiO_2:Al_2O_3:the other oxides contents of clays (Fig. 2). In addition a small overlap zone again exists

Table 3
Chemical contents and statistical parameters of montmorillonites used in the study.

	Chemical composition (%)													
Data number	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	FeO	MnO	TiO_2	Na_2O	K_2O	LOI	H_2O^-	Total	References
1	49.00	23.00	0.30	1.60	2.90						23.00		99.8	Nemecz (1981)
2	50.95	16.54	1.36	2.26	4.65	0.26		0.32	0.17	0.47	8.28	15.01	100.3	
3	51.69	18.65	4.00	0.24	1.64	0.23		0.16	0.00	0.17	7.89	14.82	99.5	
4	61.47	22.17	4.32	0.14	2.73			0.09	3.18	0.03	6.02		100.2	
5	48.24	20.30	2.29	2.10	2.06	0.11		0.08	0.36	0.05	7.20	17.94	100.7	
6	51.70	20.20	0.77	2.50	3.40				0.09	0.84	7.40	13.00	99.9	
7	64.80	24.54	1.27			0.56	1.60		0.40				93.2	
8	62.00	23.42	3.74	0.68		0.32	0.93		0.72	2.63			94.4	
9	62.30	23.50	3.35	0.31		0.37	1.95		0.40	0.03			92.2	
10	62.70	22.20	4.62	0.58		0.48	2.00		0.01	0.12			92.7	
11	59.73	24.30	5.54			0.37	2.10		0.80	0.22			93.1	
12	60.22	23.67	6.28	0.13			1.46	0.34	0.09	0.19			92.4	
13	60.76	23.08	6.10	0.17			1.44	0.38	0.13	0.21			92.3	
14	59.91	21.97	6.72	0.34			2.15	0.33	0.09	0.11			91.6	
15	58.67	23.34	3.64			0.38	2.00		0.62	0.18			88.8	
16	61.77	19.85	1.95	1.89	5.56			0.24	0.07	0.09			91.4	
17	62.23	21.03	1.75		5.70	0.48			0.65				91.8	
18	63.07	18.46	1.99	0.24	7.38			0.28	0.16	0.16			91.7	
19	61.55	20.44	2.02		6.06	0.38			0.30				90.8	
20	60.90	20.71	2.06	0.30	6.84	0.36			0.23				91.4	
21	60.80	22.15	0.07	3.74	4.44								91.2	
22	65.07	19.10	1.09		4.56	0.76			0.13				90.7	
23	51.34	16.29	2.84	2.59	4.51			0.25	0.15	0.17	21.30		99.4	Çelik et al. (1999)
24	51.25	16.39	2.85	2.36	4.93			0.24	0.37	0.21	21.00		99.6	
25	57.37	20.03	4.70	3.42	4.61			0.21	0.37	0.32	8.98		100.0	
26	57.07	19.88	3.49	3.52	4.23			0.05	0.23	0.12	9.15		97.7	
27	58.12	21.39	4.17	3.16	5.88			0.27		0.22	8.82		102.0	
28	58.50	18.12	6.87	0.56	2.93			0.44	2.62	0.51			90.6	Inoue et al. (2004)
29	57.47	24.29	3.77	0.09	1.95			0.12	0.28	3.33			91.3	
30	60.12	23.00	5.65	0.77	6.51			0.27	1.38	2.26			100.0	Krekeler et al. (2004)
31	53.98	15.97	0.95	2.30	4.47	0.19		0.08	0.13	0.12	9.12	13.06	100.4	Weaver (1989)
32	51.95	18.02	0.21	3.09	5.10			0.02	0.04		7.60	15.60	101.6	
33	53.42	16.40	1.58	0.09	4.33			0.27	2.92	0.07	20.8		99.9	
34	58.10	17.15	1.02	0.15	4.43			0.14	2.8	0.14	16.1		100.0	
35	57.80	16.25	1.1	0.06	6.56			0.16	3.87	0.14	14.1		100.0	
36	60.00	14.73	3.6	0.08	1.68				1.95	0.1	17.9		100.0	
37	56.8	21.32	4.07	0.07	2.31				3.06	0.11	12.7		100.4	
38	54.25	17.6	4.31	1.06	3.88			0.5	2.16	0.12	15.6		99.5	
39	54.9	20.3	3.7	0.17	2.4				2.79	0.08			84.3	
40	55.39	19.2	6.77	0.17	2.25			0.6	2.56	0.42	10.5	12.29	110.2	
Statistical parameters														
Max.	65.07	24.54	6.87	3.74	7.38	0.76	2.15	0.60	3.87	3.33	23.00	17.94		
Min.	48.24	14.73	0.07	0.06	1.64	0.11	0.93	0.02	0.00	0.03	6.02	12.29		
Avrg.	57.68	20.22	3.17	1.20	4.22	0.38	1.74	0.24	0.98	0.44	12.67	14.53		
Median	58.31	20.30	3.42	0.57	4.44	0.37	1.95	0.25	0.37	0.17	9.83	14.82		
Std dev.	4.47	2.74	1.95	1.25	1.63	0.16	0.41	0.14	1.18	0.78	5.59	1.94		

LOI: Loss of ignition from 110° to 1000 °C.
H_2O^-: Ignition loss below 110 °C.

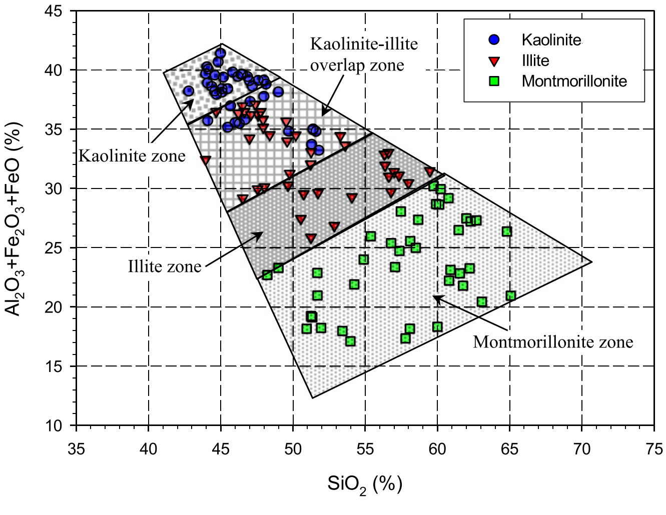

Fig. 1. Relation of SiO_2 to Al_2O_3 + Fe_2O_3 for common clay minerals.

between kaolinite and illite although they mostly distinguish from each other.

3.2. Relationships between SiO_2, alkali/alkali earth metals contents of clays and their type of mineral

It is clear that some additional charts are required to distinguish the type of mineral when the oxide composition corresponds to the kaoline-illite overlap zones (Fig. 1 and Fig. 2). These overlaps could be attributed to low cation exchange capacities and few common substitution types of kaolinite and illite-type clays compared to the montmorillonite-type clays. Thus the content of cations could be more distinctive factor for kaolinite and illite type clays corresponding to the overlap zone. For this purpose, the chart representing relationship between SiO_2 content and summation of MgO + CaO + Na_2O + K_2O contents of clays is proposed (Fig. 3).

Fig. 3 demonstrates a clear clustering for kaolinite and illite type clays. The MgO + CaO + Na_2O + K_2O contents of kaolinite-type clays

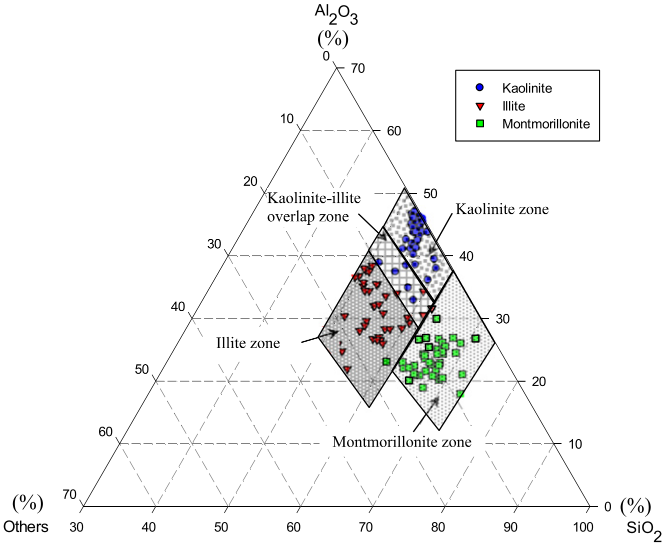

Fig. 2. Ternary plot of SiO_2:Al_2O_3:Other oxides.

is $<4\%$ whereas this value is generally higher than 4% in illite data except for some data. These exceptions could be attributed to impurities up to 25% of illite type clays in the data set. While the overlap zone in Fig. 1 is between kaolinite and illite zones, the overlap zone (Fig. 3) is between illite and montmorillonite zones.

Fig. 2 presents ternary plot of SiO_2:Al_2O_3:the other oxides. Montmorillonite type clays can also be identified noticeably (Fig. 2). In addition a small overlap zone exists between kaolinite and illite although they mostly distinguish from each other. The ternary relationship between SiO_2, Al_2O_3 and K_2O is demonstrated and a clear clustering among the mineral types is observed (Fig. 4). The four exceptional data mentioned above in the kaolinite zone (Fig. 3) are also observed (Fig. 3 and Fig. 4). It appears that Fig. 4 could also help us to clarify the overlap zone between kaolinite and illite. The authors recommend that both Figs. 3 and 4 should be considered together for identification of clay mineral type. Comparing two identification methods proposed by using Figs. 1 and 2 and Figs. 3 and 4, the later are preferable due to narrower overlap zone existing between kaolinite and illite zones when compared to the former.

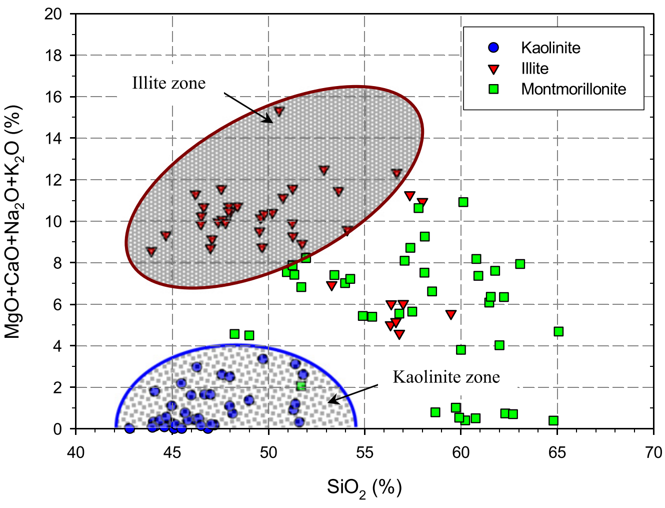

Fig. 3. Relation of SiO_2 to $MgO + CaO + Na_2O + K_2O$ for common clay minerals.

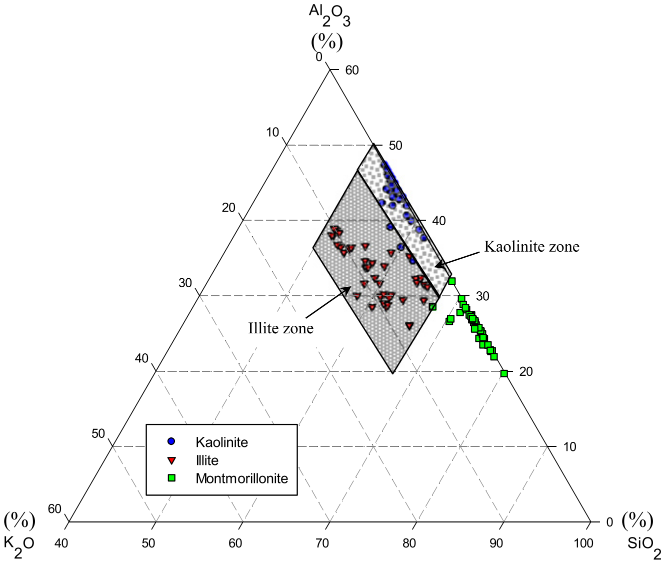

Fig. 4. Ternary plot of SiO_2:Al_2O_3:K_2O.

4. Conclusions

In this study, the data sets were collected from published literature in order to create some practical chart for use in identification of predominant clay mineral in clayey soils based on their oxide compositions. The following conclusions can be drawn in accordance with the practical charts obtained:

- The relationships between chemical composition of clays and their mineral types, which are sufficient to identify the clay minerals, are determined. In this context, the relationships among the different oxides for each type of minerals are shown by using the graphs plotted in two and ternary axes.
- The best relations between both $SiO_2 - Al_2O_3 + Fe_2O_3 + FeO$ and $SiO_2 - MgO + CaO + Na_2O + K_2O$ are found in two-axes plots. In addition, the promising relations between both $SiO_2 - Al_2O_3 -$ Others and $SiO_2 - Al_2O_3 - K_2O$ are found in ternary plots. These relations are observed to be highly decisive in accordance with mineral type of clays.
- The data between mineral type and chemical content show compatibility for kaolinite, illite and montmorillonite which are considered as common clay minerals from kaolinite group, micalike group and smectite group minerals in geotechnical engineering. It is observed that the average chemical content ratios obtained from the data collected are consistent with their theoretical rate.
- It should be noted that the charts proposed in this study are found to be useful for practical purposes, although the type of predominant clay mineral in clays can also be determined by XRD analysis.

Acknowledgments

The authors would like to express sincere thanks to Mr. Ahmet Gurkan Yazici and Miss. Cigdem Yesildag for their helps in the compiling and analyzing data for the paper. They also would like to thank Prof. Dr. Ergun Togrol for his comments and contribution to this paper.

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