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Activity, relative activity and Specific Surface Area of fine-grained soils

Activité, activité relative et superficie spécifique de sols granuleux fins

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ABSTRACT

Activity, as introduced in 1953 by Skempton, was defined as the ratio of plasticity index (PI) to the clay fraction (CF) of a soil and was used by Skempton to help distinguish mineralogic differences in fine-grained soils. While activity (A) provides an approximate method of delineating fine-grained soils by mineralogy, PI is not really a fundamental soil property. Conversely, Specific Surface Area (SSA) and Cation Exchange Capacity (CEC) are more fundamental soil properties that dominate engineering behavior of fine-grained soils. SSA and CEC are "inherent" soil parameters and may be combined with the clay fraction in order to help classify mineralogic composition of fine-grained soils. Two parameters are examined: 1. Specific Surface Area Activity (S_c), which is defined as the ratio of surface area to the clay content, and 2. Cation Exchange Capacity Activity (CECA), defined as the ratio of cation exchange capacity to the clay content. These two parameters show clear groupings of low, medium and high "activity" when used in relationship with other index parameters that may help explain fundamental clay behavior. The relationships between S_c and CECA and engineering properties are presented and described. The results indicate that Specific Surface Area Activity and Cation Exchange Capacity Activity may be a more fundamental and convenient basis for describing the mineralogic composition of fine-grained soils.

RÉSUMÉ

Activité, comme présenté en 1953 par Skempton, a été défini comme rapport de l'index de plasticité (PI) à lafraction d'argile (CF) d'un sol et a été employé par Skempton pouraider à distinguer des différences mineralogic en sols fins. Tandis que l'activité (A) fournit une méthode approximative detracer les sols fins par la minéralogie, Pi n'est pas vraiment une propriété fondamentale de sol. Réciproquement, La superficie spécifique (SSA) et la capacité d'échange cationique(CEC) sont des propriétés plus fondamentales de sol qui dominent lecomportement de technologie des sols fins. SSA et CEC sont des paramètres "inhérents" de sol et peuvent êtrecombinés avec la fraction d'argile afin d'aider à classifier lacomposition mineralogic des sols fins. Deux paramètres sont examinés : 1. Activité Spécifique De Superficie (S_c), ce qui est défini comme rapport de la superficie au contenud'argile, et 2. Activité De Capacité D'Échange Cationique (CECA), défini comme rapport de la capacité d'échange cationique au contenud'argile. Ces deux paramètres montrent des groupements clairs du bas, "activité" moyenne et élevée une fois utilisé dans le rapport avecd'autres paramètres d'index qui peuvent aider à expliquer lecomportement fondamental d'argile. Les rapports entre le S_c et les CECA et des propriétés detechnologie sont présentés et décrits. Les résultats indiquent que l'activité de capacité d'activitéspécifique de superficie et d'échange cationique peut servir de baseplus fondamentale et plus commode à décrire la compositionmineralogic des sols fins.

1 INTRODUCTION

Skempton (1953) defined activity (A) as the ratio of plasticity index (PI) to < 0.002 mm clay fraction (CF) and showed that activity could be related to the mineralogy and geotechnical history of the sediment. He classified clays into three groups; "inactive," "normal" and "active" clays. Skempton (1953) showed that for four clay deposits, an approximately linear relationship existed between PI and CF, defined as activity. The involvement of the clay fraction in the expression for activity is an indication of the variation of the physicochemical potential of soil in terms of the PI as CF increases and the variation of plasticity along the line is expected to reflect the effect of both the amount and type of clay. While for a given clay species, PI is one way of describing the amount and type of clay, Specific Surface Area (SSA) and Cation Exchange Capacity (CEC) are more fundamental soil properties that dominate fine-grained soil behavior. SSA refers to the area per unit weight of soil and is usually expressed as m^2/g. CEC refers to the amount of cations in the double layer that can be easily replaced or exchanged by other cations introduced into the solution and is traditionally reported in milliequivalents of cations per 100 grams of soil. Both of these parameters may be used in combination with clay fraction in defining new "activity" values. Since PI is the range in water content over which a soil exhibits "plastic" behavior, it would be expected that for two soils with the same CF, the more active mineral soil, e.g., montmorillonite, would show a higher PI.

One way to incorporate SSA was suggested by Quigley et al. (1985) who defined the term "relative activity" as the ratio of PI to SSA. Relative activity thus defines the role that SSA has on plasticity. That is, for two soils with the same PI, but different amounts of clay, one would expect different SSA, depending on the clay mineralogy. Whereas CF does not identify in any way the species of clay minerals present, SSA gives some insight into mineralogy, especially when used in combination with CF.

More recently, Locat et al. (2003) suggested that Clay Specific Surface Area (S_c = SSA/CF) be used in conjunction with PI to help identify mineralogy of clays. However, even though it may be convenient, since both A and S_c are normalized by the CF, a linear plot of A vs. S_c, as shown by Locat et al. (2003) simply suggests that a plot of PI vs SSA should be linear, i.e., the water content range from liquid limit (LL) to plastic limit (PL) is essentially controlled by SSA. This is largely because LL itself has been shown to be related to SSA. For a variety of marine clays from around the world Locat et al. (2003) noted that approximately A = 0.005 S_c. They denoted this as the "C-Line."

SSA varies greatly between soils because of differences in mineralogy, organic composition and particle-size distribution.

Clays contribute the greatest amount of surface area of any of the mineral constituents of soil, but may also differ a great deal in SSA. For example, swelling clays such as montmorillonites, have SSAs up to 810 m^2/g. Non-expanding soils such as kaolinites typically have SSAs ranging from 10 to 40 m^2/g (Mitchell 1976). Consequently, the type of clay mineral present in soil is of major importance in determining the effect of specific surface area on soil properties. Since the surface area of a soil is controlled by the grain-size distribution and clay mineralogy, it can be considered an "inherent" soil property.

CEC ranges from 0 in sands to 100 meq/100 g or even more in clays and organic soils. Under chemically neutral conditions, the total number of exchangeable cation charges, expressed in terms of chemical equivalents per unit mass of soil particles, is nearly constant and independent of the species of cations present. Both the SSA and the CEC of a soil are considered "inherent" soil properties that do not change with water content, pore fluid chemistry, and time, etc., and therefore are more fundamental in describing fine-grained soil behavior.

This paper presents results of laboratory tests to determine the SSA and CEC along with other soil index properties for a group of fine-grained soils and compares these different mineralogical indicator parameters. Tests were conducted on both pure clay minerals and natural fine-grained soils.

2 INVESTIGATION

Two general approaches have been used to determine SSA of clays; (1) the measurement of external surface areas by the adsorption of simple molecules, such as nitrogen at low temperatures, with surface areas being derived from adsorption isotherm data and the application of BET theory (Brunauer et al. 1938); and (2) the measurement of total surface area by the adsorption of polar liquids as a means of describing the behavior of expanding clay minerals, whose inner surfaces are inaccessible to nitrogen. In this study, the measurement of total surface area was conducted using the polar liquid ethylene glycol monoethyl ether (EGME) method (Cerato and Lutenegger 2002) and the measurement of external surface area was performed using the BET method. CEC was determined by Harris Laboratory, Inc., using a 1 N ammonium acetate extraction method (Rhoades 1982).

Tests were performed on a number of reference clay samples obtained from the Clay Minerals Source Clay Project at the University of Missouri. These clays were used to provide a reference framework for evaluating test results on natural clays. Additional tests were performed on profiles of natural clays from three different geologic deposits: 1.) Marine Deposit - Boston Blue Clay, Boston, Massachusetts: (4.6 m – 25 m); and Leda Clay, St. Lawrence Co., New York: (1.5 m – 18.3 m); 2.) Lacustrine Deposit - Salt Lake City, Utah: (1.6 m – 23 m) and 3.) Alluvial Deposit - Houston, Texas: (0.84 m – 13.9 m). Laboratory characterization tests included Atterberg PL and LL, shrinkage limit (SL), and hydrometer analysis to determine % clay (< 0.002 mm).

3 RESULTS

Table 1 provides the data from the tests performed on the pure clays.

Table 1. Laboratory Results of Pure Clays.

Soil Description	SSA (m^2/g)	CF (%)	CEC (meq/100 g)	LL (%)	PL (%)	SL (%)
Kaolinite, well-ordered	15	36.2	2.0	42	26	26
Kaolinite, poorly-ordered	26	67.6	3.3	70	40	38
Illite, Green Shale	158	48.0	17.6	33	23	17
Attapulgite	341	67.3	19.5	202	108	51
Hectorite	387	53.4	43.9	400	48	4
Ca-Montmorillonite	534	73.3	84.4	142	44	15
Ca-Montmorillonite	767	37.7	120.0	130	58	12
Na-Montmorillonite	637	60.4	76.4	519	35	14

Table 1. (Continued)

Soil Description	Activity (PI/CF)	Relative Activity (PI/SSA)	SSA Activity (S_c) (SSA/CF)	CEC Activity (CEC/CF)	A/S_c (PI/SSA)
Kaolinite, well-ordered	0.44	1.07	0.41	0.06	1.07
Kaolinite, poorly-ordered	0.44	1.15	0.38	0.05	1.15
Illite, Green Shale	0.21	0.06	3.29	0.37	0.06
Attapulgite	1.40	0.28	5.07	0.29	0.28
Hectorite	6.60	0.91	7.25	0.82	0.91
Ca-Montmorillonite	1.34	0.18	7.29	1.15	0.18
Ca-Montmorillonite	1.91	0.09	20.34	3.18	0.09
Na-Montmorillonite	8.01	0.76	10.55	1.26	0.76

The kaolinite surface areas ranged from 15 to 26 m^2/g and the montmorillonite surface areas spanned a much larger range from 341 to 767 m^2/g. Activity of the pure clays ranged from 0.44 to 8. S_c ranges from 0.4 to 20.3. Cation Exchange Capacity Activity (CECA) ranged from 0.05 to 3.2. There is a clear distinction between the montmorillonitic samples and the kaolinites using the parameter S_c. All five montmorillonites have values of 5 and above. CECA also showed a clear distinction. The kaolinite samples have values less than 0.1, while the rest of the montmorillonite samples fall between 0.82 and 3.2. Activity values, on the other hand, do not show as distinct a pattern between the samples of different mineralogies. Although both kaolinitic samples show low activity values, as suggested by Skempton (1953), the montmorillonitic samples have a wide range of activity, many falling well below reported values. The Skempton (1953) activity values for kaolinite, illite and Na-montmorillonite are 0.38, 0.9 and 7.2 respectively. Most natural soils, which are typically composed of mixed layer minerals, would fall somewhere between those values.

Locat et. al (2003) suggested the parameter A/S_c be used to delineate mineralogy. As can be seen in Table 1, this parameter is simply another way to define relative activity (PI/SSA). With the exception of illite, the pure clays do not follow the reported relationship of $A = 0.005\ S_c$. It is believed that this relationship may only be applicable to Marine Clays.

In order to provide a comparison with previously reported data from the literature, natural clays from three different geologic deposits were studied. The Marine samples all have similar LL values clustered around 50 %, while the Lacustrine and Alluvial samples show much larger range in LL spanning from 20 to 46 % and 27 to 80 % respectively. The alluvial profile tested at Houston, TX, shows two distinct soil layers with samples of high LL, SSA, CEC, CF and Carbonates between 4 and 8 meters. If this layer were left out, the range of LL shown would be much smaller.

Locat et al. (2003) presented the relationship between A and S_c for several Marine Clays from around the world and defined the C-line (C for clays) as A = 0.005 S_c. Activity versus S_c is presented for the clays in this study in Figure 1. As can be seen, only the results from the Marine Clays fall around the "C-line," and the Alluvial and Lacustrine samples fall well below the "C-line" at around A = 0.002 S_c and A = 0.0025 S_c, respectively. The "C-Line" varies for different geologies. It must be noted again that this relationship of A and S_c simplifies to relative activity (PI/SSA), which Quigley et al. (1985) defined. Since this particular relationship did not adequately describe the behavior of the fine-grained soils from various geologic deposits, other parameters were investigated.

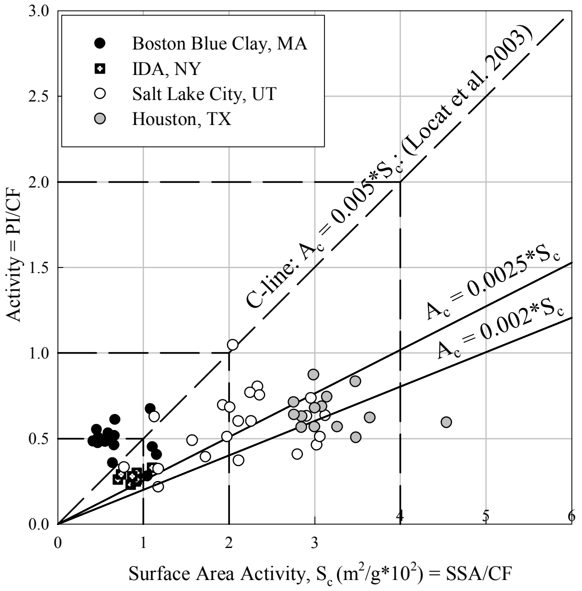

Figure 1. Relationship between Activity and Surface Area Activity.

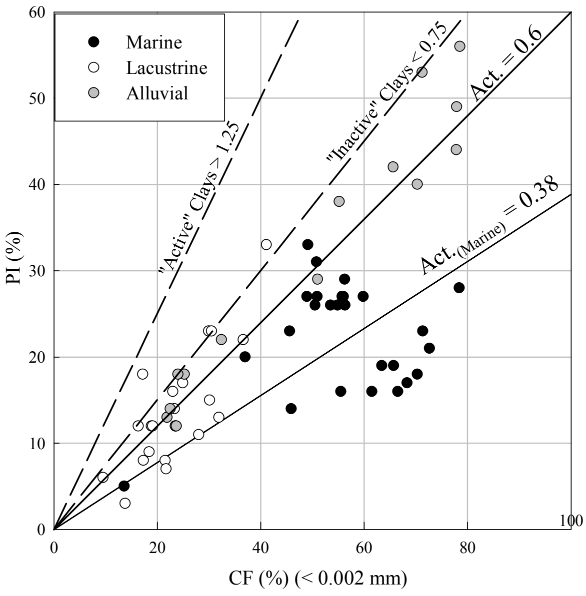

Figure 2. Activity of Natural Clays.

Activity of the natural clays is presented in Figure 2. The Lacustrine, Alluvial and the Boston Blue Clay Marine samples all have activity around 0.6. The Marine Clay from New York, has an activity value closer to 0.25. The average activity for the Marine Clays is 0.38. Activity for the three different geologic deposits is the same (except for the NY deposit), therefore, for many clays it is difficult to delineate mineralogy using activity alone. Skempton's (1953) definitions of "active," "normal," and "inactive" clays are shown as well. Clays which have activity less than 0.75 are "inactive" clays, greater than 1.25 are "active" clays and between the two is classified as "normal" clays.

Relative activity (PI/SSA) for the three geologic deposits is presented in Figure 3. There are three different values of relative activity depending on geology. Marine Clays have a relative activity of around 0.4, Lacustrine samples fall around 0.3 and Alluvial samples fall around 0.2.

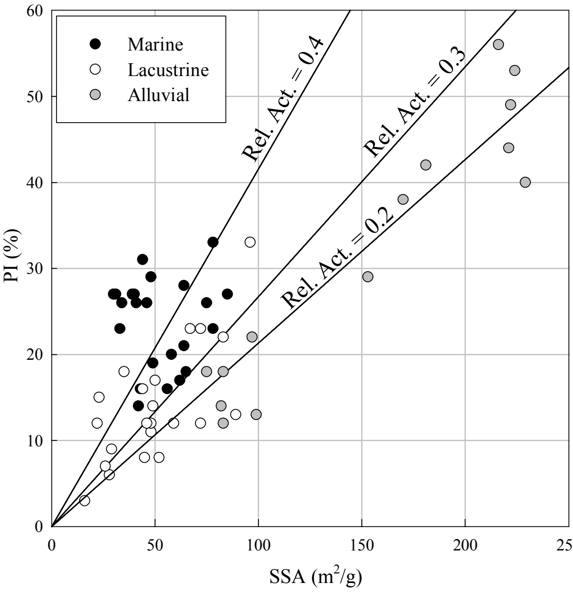

Figure 3. Relative Activity of Natural Clays.

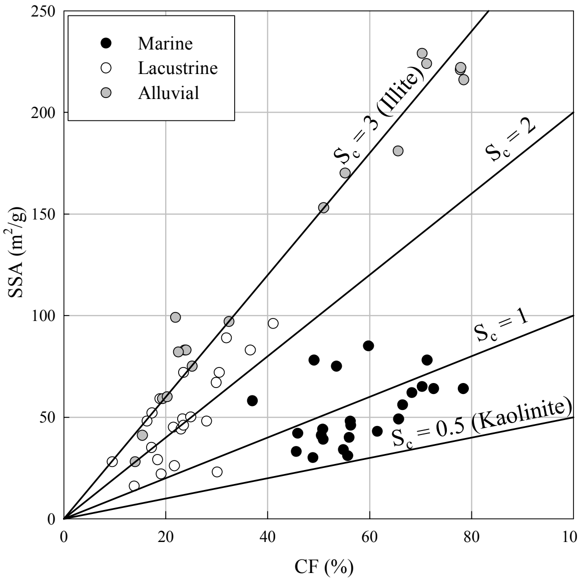

Figure 4. Surface Area Activity of Natural Clays.

Surface Area Activity (S_c) is presented in Figure 4. The Alluvial samples have a S_c of around 3, the Lacustrine samples have a S_c of around 2 and the majority of Marine samples fall between S_c values of 0.5 and 1. S_c shows distinct delineations between the geologic deposits. The range in S_c is much larger than the other parameters. The Marine Clays presented in Locat et al. (2003) have a much wider S_c range, from 0.5 to 10, however, this was expected as there were Marine Clays from a wider geographic area than presented herein. These results illustrate that mineralogy can be clearly distinguished using SSA alone. For a given CF, SSA increases according to mineralogy in the following order: kaolinite < illite < montmorillonite. Surface Area Activities of the pure clays tested and presented in Table 1 show that kaolinite would have a S_c around 0.4, illite would be approximately 3.3 and montmorillonites would have S_c values above 5.

CEC activity is presented in Figure 5. These data do not show such distinct zones as was shown with S_c. Lacustrine samples have the highest CECA at approximately 1, the Alluvial samples have a CECA of around 0.55 and the Marine Clays have a CECA of approximately 0.25. The CECA range presented in Locat et al. (2003) for Marine Clays was 0.1 to 2. Using the pure clays tested as reference presented in Table 1, a CECA of above 1 should indicate montmorillonite, whereas a CECA around 0.3 would indicate illite. The pure kaolinite samples tested had CECA values of 0.05.

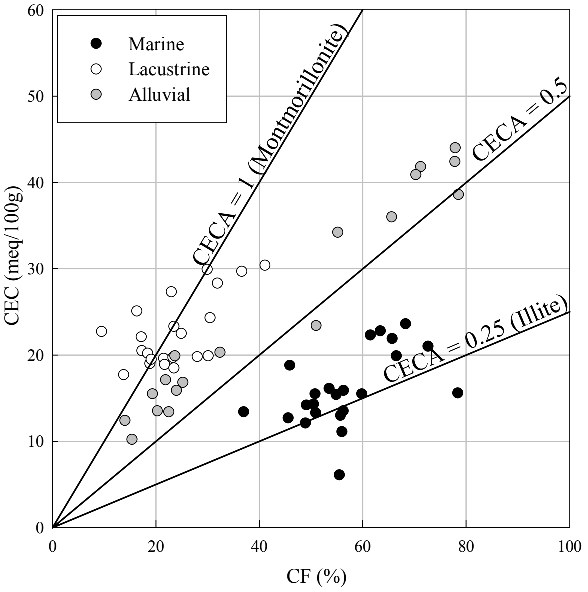

Figure 5. Cation Exchange Capacity Activity of Natural Clays.

If SSA vs. CF is linear and CEC vs. CF is linear then SSA vs. CEC must be linear. This relationship is linear within each geologic deposit. The lacustrine clays show the strongest linear trend while the Marine Clays show the most variability (CEC = 0.93 SSA, 0.71 SSA and 0.29 SSA for Alluvial, Lacustrine and Marine Clays, respectively.

4 CONCLUSIONS

The results of laboratory tests on clays with a wide range of mineralogy indicate that the activity as defined originally by Skempton (1953) may not be adequate in delineating mineralogies, let alone entire geologic deposits. For the samples tested in this study, the activity value was constant for three different geologic deposits. The incorporation of SSA, however, in the relative activity term defined by Quigley et al. (1985), shows distinct delineations in geologic deposits.

Surface area activity, (S_c) defined by Locat et al. (2003) also shows some distinct delineations between geologic deposits, as does the CECA. However, the relationship between activity and S_c, as Locat et al. (2003) presented, simplifies to relative activity (PI/SSA), and thus does not explain fine-grained soil behavior any more then the relative activity. Also, the C-Line, defined as A = 0.005 S_c, appears to be valid only for some Marine Clays, and other geologic deposits do not fall along the same line. The C-Line appears to be geologically and mineralogically dependent and therefore may not be a good indicator of mineralogical composition. Essentially the C-Line proposed by Locat et al. (2003) suggests that Marine Clays, which likely have a similar mineralogy, (mostly illitic), show a linear relationship between PI and SSA. The slope of this relationship, however, does not appear to be a constant for all clays.

SSA and CEC are important factors influencing the engineering characteristics of fine-grained soils. Both SSA and CEC can be considered "inherent" soil characteristic properties. They exert a strong influence on soil plasticity and in the literature have been shown to be related to other behavior of fine-grained soils. The one drawback to introducing a parameter to delineate mineralogy including SSA and CEC is that they need to be measured. The test procedure to measure SSA is relatively simple and therefore it may be advantageous to include SSA in routine soil characterization of fine-grained soils.

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