Surface Area and Engineering Properties of Fine-Grained Soils
De la Surface et des Propriétés d'ingénierie des Sols Fins

A.J. LUTENEGGER & A.B. CERATO, University of Massachusetts, Amherst, MA, USA

ABSTRACT: The engineering characteristics of fine-grained soils is dominated in large part by the physico-chemical interactions present in the clay-electrolyte system and surface phenomena, which is in turn related to both the clay surface area and the clay mineralogy. An investigation was conducted to examine the influence of surface area on the engineering properties of fine-grained soils. Total surface area was measured using the Ethylene Glycol Monoethyl Ether (EGME) method. The influence of surface area on the Activity, Atterberg Limits, and Intrinsic Compression Index was investigated. A description of the test procedures is presented and the results of the study are summarized. The relationships between surface area and clay fraction and engineering properties are presented and described. The results indicate that Specific Surface does exert a significant influence on certain soil properties and may be a more fundamental and convenient basis than mechanical analysis for describing the composition of fine-grained soils.

RÉSUMÉ: Les caractéristiques d'ingénierie des sols fins sont dominées en majeure partie par les interactions physico-chimiques présentes dans le système des argiles-électrolytes et dans les phénomènes de surface, qui sont, en retour, liés aussi bien aux surfaces d'argile qu'à la minéralogie de l'argile. Des recherches ont été menées pour examiner l'influence de la surface sur les propriétés d'ingénierie des sols fins. La surface totale a été mesurée selon la méthode Ethylène Glycol Monoéthyl Ether (EGME). Les recherches ont porté sur l'influence de la surface sur l'Activité, les Limites d'Atterberg et l'Index de Compression Intrinsèque. Nous présentons une description des procédures des expériences ainsi que les résultats de l'étude que nous avons résumés. Les relations entre la surface, les fractions d'argile et les propriétés d'ingénierie sont présentées et décrites. Les résultats montrent que la Surface Spécifique exerce bel et bien une influence sur certaines propriétés des sols et qu'elle peut être une base plus fondamentale et pratique qu'une analyse mécanique quand il s'agit de décrire la composition des sols fins.

1 INTRODUCTION

Physical and chemical properties of fine-grained soils, especially clays, may be greatly influenced by the amount of its surface area. Fine-grained soils differ in surface area predominantly as a result of differences in texture (grain-size distribution) and types and amounts of different clay minerals. The term "Specific Surface Area" (SSA) refers to the area per unit weight of soil and is usually expressed as m^2/g. Clay minerals differ substantially in Specific Surface Area. Nonswelling clays, such as kaolinite, have only external surface, whereas swelling clays like montmorillonite have a great deal of internal a well as external surface. Natural clay deposits can have a wide range of total surface area since the combination of external and internal surface areas may vary simply because of the mixed layer minerals that may exist and the variations in clay mineralogy. Additionally, the clay mineral fraction that is part of the overall grain-size distribution can vary greatly.

A knowledge of the Specific Surface Area is necessary in calculating certain basic soil characteristics, such as the charge density and particle spacing, which in turn may be particularly useful in prediction and rationalization of certain engineering properties. The charge density, σ, is defined as the Cation Exchange Capacity, CEC, divided by the Specific Surface Area. Specific Surface Area may actually be a more fundamental and convenient basis than mechanical analysis for describing the composition of fine-grained soils.

It is not surprising that geotechnical engineers have largely overlooked this area of work. Much of the literature related to the measurement of surface areas of clays appears in various journals related to geology, soil science, ceramics and chemistry.

2 INFLUENCE OF SURFACE AREA ON ENGINEERING CHARACTERISTICS

Table 1 gives a summary of the surface areas of common pure clay minerals, compiled from data given by Mitchell (1993). The range in Specific Surface Area is quite large. For natural soils, which may be composed of a number of different clay minerals and which may also include non-clay minerals, such as carbonates, it would be expected that the variation in surface area would also be large. Several studies have indicated that a number of engineering properties of fine-grained soils are controlled largely by Specific Surface Area.

Table 1. Specific Surface Area of Common Clay Mineral Constituents of Fine-Grained Soils (after Mitchell 1993).

Clay Mineral	Structure	External SSA (m^2/g)	Internal SSA (m^2/g)
Halloysite	1:1	10-20	-
Kaolinite	1:1	35-70	-
Smectites	2:1	50-120	700-850
Illite	2:1	65-100	-
Vermicullite	2:1	40-80	800-900
Chlorite	2:1:1	10-40	-

2.1 *Plasticity*

A number of studies have shown that for some fine-grained soils there is a strong linear relationship between SSA and liquid limit (e.g., Kuzukami et al. 1971; Ohtsubo et al. 1983; Locat et al. 1984; Smith et al. 1985; Morin & Dawe 1986; Churchman & Burke 1991). Other studies (e.g., Sridharan et al. 1986) have shown that for certain soils, especially some montmorillonites, there appears to be almost no relationship between SSA and liquid limit. Muhunthan (1991) used results presented by DeBruyn et al. (1957), Farrar & Coleman (1967), and Sridharan et al. (1988) to show that a linear relationship should exist between 1/SSA and 1/LL.

A review of available data from the literature shows that there is considerable scatter in either a relationship between LL and SSA or 1/LL and 1/SSA. The relationship between surface characteristics and Liquid Limit for natural clays is not a simple one and other variables such as grain-size distribution (specifically clay content), mineral composition (e.g., carbonate content), and mineralogy (cation exchange capacity and surface charge) may need to be considered.

2.2 *Swelling Potential*

The swelling potential of clays has also been related to surface area (e.g., Dos Santos & Castro 1965; Low 1980; Ross 1978; Dasog et al. 1988). Morgenstern & Balasubramanian (1980) have shown that the swelling pressure of some shales may be estimated using double layer theory by calculating repulsive forces of clay particles. In order to do so, the interparticle separation distance is required, which may be estimated by assuming that the particles are of infinite extent and are equidistant throughout the soil as:

$$d = \frac{w(\%)}{SSA(\frac{m^2}{g})} \tag{1}$$

A weighed average SSA is used to account for only the SSA of the clay fraction.

2.3 *Dispersion*

Surface area may also play a significant role in controlling the behavior of dispersive clays through surface charge properties (e.g., Heinzen & Arulanandan 1977; Harmse & Gerber 1988; Sridharan et al. 1992; Bell & Maud 1994).

2.4 *Frost Heave*

A number of studies have shown that surface area is one of the most important parameters influencing frost heave in soils (e.g., Anderson & Tice 1972; Reike et al. 1983; Nixon 1991). The Segregation Potential (SP), which describes the velocity of water arriving at an advancing frost front, has been shown to be directly related to Specific Surface Area.

2.5 *Soil Stabilization*

Surface area may also be significant in evaluating the effectiveness of soil stabilization, for example when treated with lime (Moore & Jones 1971). Clearly, chemical stabilization of clays must consider both SSA and CEC.

3 INVESTIGATION

Tests were performed on a number of reference clay samples obtained from the Clay Minerals Source Clay Project at the University of Missouri and from Ward's Scientific Supply. These clay samples were used to provide a reference framework for evaluating test results on natural clays to be performed at a future date. Laboratory characterization tests included Atterberg Plastic and Liquid Limits, hydrometer analysis to determine % clay (0.002 mm). In addition, intrinsic compressibility of each sample was determined by preparing a soil-water paste at a water content approximately equal to 1.25 times the liquid limit as recommended by Burland (1990). Cation Exchange Capacity was provided for the Source Clays by the University of Missouri; CEC was determined using the NCR-13 Exchangeable Potassium Procedure (Carson 1980) for the other clays.

Specific Surface Area (SSA) was determined on each sample using the Ethylene Glycol Monoethyl Ether (EGME) method described by Carter et al. (1986). This procedure is based on the assumption that a monolayer of EGME (a non-polar fluid) will adsorb to the surface of the soil. In this method, approximately one gram of soil is placed into the bottom of a clean dry aluminum tare. Approximately 3 mL of laboratory grade EGME is added to the soil with a pipette and gently mixed by hand with a swirling motion to create a slurry. The tare is then placed inside of a standard laboratory glass sealed vacuum dessicator. The samples are equilibrated to remove excess EGME, which requires an evacuation time of 24 hours. Surface Area is calculated as:

$$SSA = \frac{W_a}{0.000286W_s} \tag{2}$$

where SSA = Specific Surface Area in m^2/gm; W_a = weight of ethylene glycol monoethey ether (EGME) retained by the sample in grams (final slurry weight – W_s); W_s = weight of soil added initially (gm); 0.000286 = weight of EGME required to form a monomolecular layer on a square meter of surface (gm/m^2).

4 RESULTS

Table 2 presents a summary of the laboratory tests for all samples. Figure 1 shows the location of the samples on the Casagrande plasticity chart. Most of the samples fall along the A-line up to LL = 200%. Montmorillonite samples with LL > 400% fall along the U-line. Activity ranges from 0.2 to 8.0.

Table 2. Properties of Clays Tested.

Soil	SSA (m^2/g)	CEC (meq/100g)	CF (%<2μm)	C^*_c
Kaolinite,well ordered	15	2.0	36.2	0.32
Peerless Clay	23	0.9	76.0	0.33
Kaolinite,poorly ordered	26	3.3	67.6	0.65
Thiele Kaolin	38	2.1	77.3	0.52
Illite, Green Shale	158	17.6	48.0	0.29
Old Hickory Clay	224	24.4	42.8	0.60
Palygorskite	341	19.5	67.3	1.41
NaCa Montmorillonite	381	60.8	47.4	-
Hectorite	387	43.9	53.4	5.32
Ca Montmorillonite	534	84.4	73.3	1.60
Pure Gold Gel	593	23.8	71.2	6.00
Na Montmorillonite	637	76.4	60.4	8.59
PC Southern	675	67.0	49.5	0.78
Montmorillonite	704	47.2	95.8	9.35
Ca Montmorillonite	767	120.0	37.7	1.00

Table 2. (Continued).

Soil	LL (%)	PL (%)	PI (%)	SL (%)	Activity (PI/CF)
Kaolinite,well ordered	42	26	16	26	0.44
Peerless Clay	60	32	28	30	0.37
Kaolinite,poorly ordered	70	30	40	38	0.59
Thiele Kaolin	65	38	27	35	0.35
Illite, Green Shale	33	23	10	17	0.21
Old Hickory Clay	69	37	32	16	0.75
Palygorskite	202	108	94	51	1.40
NaCa Montmorillonite	64	39	25	22	0.53
Hectorite	400	48	352	4	6.59
Ca Montmorillonite	142	44	98	15	1.34
Pure Gold Gel	434	50	384	28	5.39
Na Montmorillonite	519	35	484	14	8.01
PC Southern Bentonite	97	47	50	17	1.01
Montmorillonite	560	52	508	14	5.30
Ca Montmorillonite	130	58	72	12	1.91

4.1 *Plasticity*

The Atterberg Limits have proven to be extremely useful as initial indicators of soil behavior for fine-grained soils. The geotechnical literature is full of examples of correlations between Atterberg Limits and shear strength, sensitivity, compressibility, shrink-swell potential, etc. It is important for geotechnical engineers to have a fundamental understanding of the reasons why Plasticity Index, Liquid Limit, or Liquidity Index are related to other more useful soil properties. Along with grain-size distribution and other constituent related properties such as specific gravity (density of solids), the Atterberg Limits are essentially intrinsic soil characteristics and do not change over the life of a soil, unlike other properties such as voids ratio, strength, stress history, etc., that may change as a result of loading and other external influences. When combined with natural water content, estimates of sensitivity, shear strength, stiffness, compressibility, hydraulic conductivity, etc. can be made.

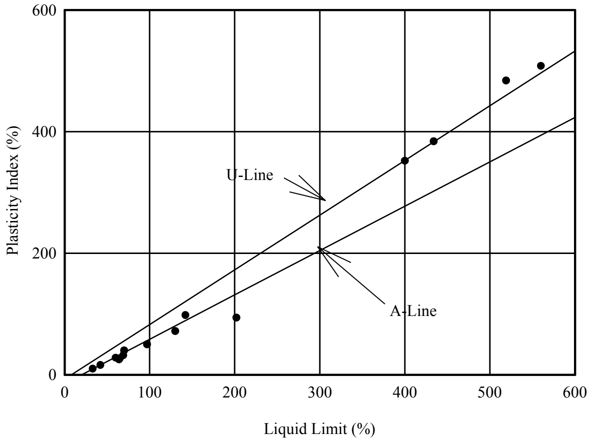

Figure 1. Casagrande Plasticity Chart.

The Atterberg Limits of a fine-grained soil are dependent on a number of soil constituents including: grain-size distribution (clay fraction), clay mineralogy, cation exchange capacity, carbonate content, and surface area. This is a complex system. Basic clay mineralogy has clearly shown that SSA and CEC are directly related for a given clay mineral suite.

Figure 2 shows the relationship between total SSA and Plasticity. It can be seen that this relationship is not unique and is likely influenced by other factors, such as clay content and CEC. Figure 3 shows the relationship between 1/LL and 1/SSA as suggested by Muhunthan (1991) excluding the three montmorillonite clays. This appears to show a better relationship, although it may be stronger for a particular mineral suite.

Intrinsic Compressibility

Figure 4 presents the observed correlation between intrinsic compression index and SSA. Supplemental data from the literature are also shown for comparison. Over the range of SSA tested it can be seen that there is a fairly good correlation as should be expected. Within the range of most natural clays, i.e., SSA < 300 m^2/gm, the correlation is stronger, as shown in Figure 5.

Results of consolidation tests performed on remolded “pure” clays reported in the literature (e.g., Jimenez Salas & Serratosa 1953; Olson & Mesri 1970; Klausner & Shainberg 1971; Kinsky et al 1971; Sridharan & Rao 1973; Sridharan & Jayadeva 1982; Sridharan et al. 1986; Meegoda & Arulanandan 1986) generally support the hypothesis that the compression index should increase as the SSA increases. For example, Sonderman & Quigley (1965) noted that C_c increases as the measured glycol retention (and therefore SSA) increases for several types of clay minerals. The virgin compression of clays is no longer influenced by soil structure and should be related to inherent soil properties and surface properties. This also supports correlations reported in the literature between C_c and Atterberg Limits for remolded clays (e.g., Burland 1990).

5 CONCLUSIONS

The results of laboratory tests on a number of different clays with a wide range of mineralogy indicate that Specific Surface Area is an important factor influencing the engineering characteristics of fine-grained soils. Correlations for a given mineral suite, which for natural clays would be specific to individual geologic deposits, would be expected to be even stronger.

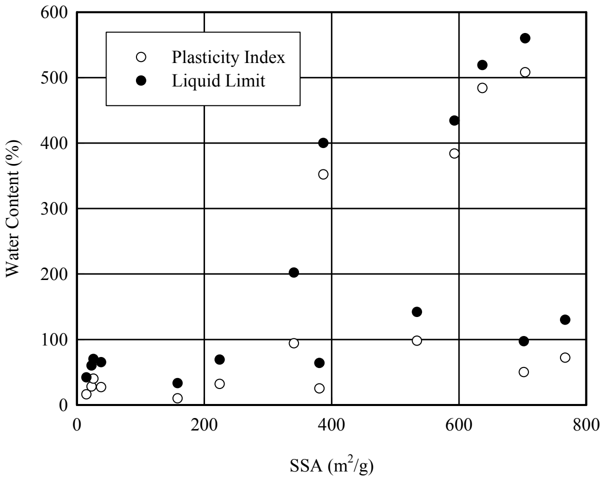

Figure 2. Relationship of SSA and Atterberg Limits.

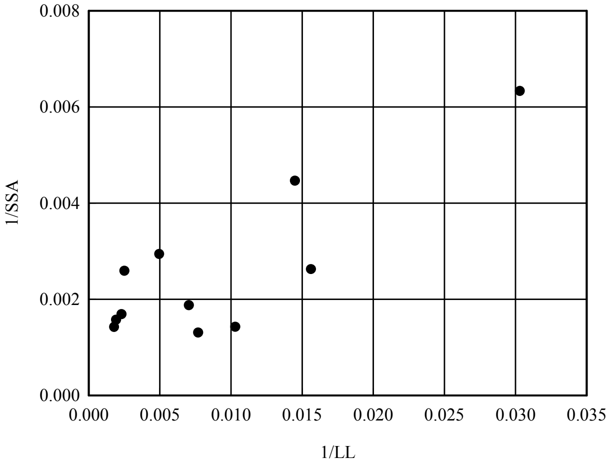

Figure 3. Relationship of SSA and Liquid Limit.

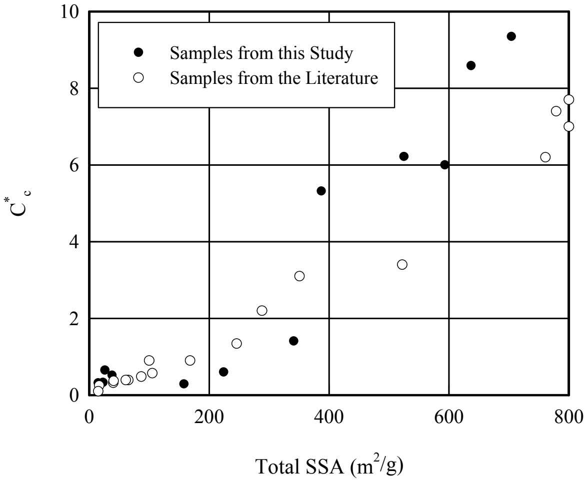

Figure 4. Relationship of Intrinsic Compression Index and SSA.

SSA can be considered an intrinsic soil characteristic property. SSA exerts a strong influence on soil plasticity and intrinsic compression and in the literature has been shown to be related to other behavior of fine-grained soils. 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.

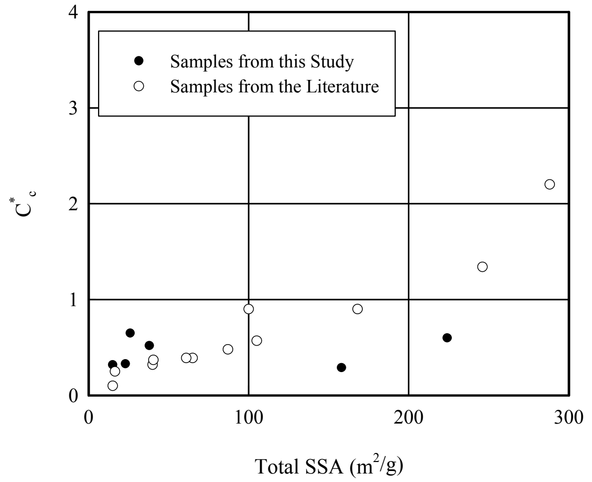

Figure 5. Relationship of Intrinsic Compression Index and SSA.

REFERENCES

Anderson, D.M. & Tice, A.R. 1972. Predicting Unfrozen Water Contents in Frozen Soils from Surface Area Measurements. Highway Research Record No. 393: 12-18.

Bell, F.G. & Maud, R.R. 1994. Dispersive Soils: A Review from a South African Perspective. Quarterly Journal of Engineering Geology, Vol. 27: 195-210.

Burland. J.B. 1990. On the Compressibility and Shear Strength of Natural Clays. Geotechnique, Vol. 40, No. 3: 329-378.

Carter, D.L., Mortland, M.M. & Kemper, W.D. 1986. Specific Surface. Methods of Soil Analysis. Chapter 16, Agronomy No. 9, Part 1, 2nd Ed., American Society of Agronomy.

Carson, P.L. 1980. Recommended potassium test. In W. C. Dahnke, (ed). Recommended Chemical Soil Test Procedures for the North Central Region. North Central Region Publication No. 221 (Revised). North Dakota Agricultural Experiment Station Bulletin 499 (Revised).

Churchman, G.J. & Burke, C.M. 1991. Properties of Subsoils in Relation to Various Measures of Surface Area and Water Content. Journal of Soil Science, Vol. 42: 463-478.

Dasog, G.S., Acton, D.F., Mermut, A.R. & DeJong, E. 1988. Shrink-Swell Potential and Cracking in Clay Soils of Saskatchewan. Canadian Journal of Soil Science, Vol. 68: 251-260.

DeBruyn, C., Collins, L. & Williams, A. 1957. The Specific Surface, Water Affinity, and Potential Expansiveness of Clays. Clay Minerals Bulletin 3: 120-128.

Dos Santos, M.P.P. & DeCastro, E. 1965. Soil Erosion in Roads. Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1: 116-118.

Farrar, D. & Coleman, J. 1967. The Correlation of Surface Area with Other Properties of Nineteen British Clay Soils. Journal of Soil Science, Vol. 18: 118-124.

Harmse, H.J. & Gerber, F.A. 1988. A Proposed Procedure for the Identification of Dispersive Soils. Proceedings of the 2nd International Conference on Case Histories in Geotechnical Engineering, Vol. 1: 411-416.

Heinzen, R.T. & Arulanandan, K. 1977. Factors Influencing Dispersive Clays and Methods of Identification. ASTM STP No. 623: 202-217.

Jimenez Salas, J.A. & Serratosa, J.M. 1953. Compressibility of Clays. Proceedings of the 3rd International Conference of Soil Mechanics and Foundation Engineering, Vol. 1: 192-198.

Kinsky, J., Frydman, S. & Zaslavsky, D. 1971. The Effect of Different Dielectric Liquids on the Engineering Properties of Clay.Proceedings of the 4th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Vol. 1: 369-372.

Klausner, Y. & Shainberg, I. 1971. Consolidation Properties of Na^+ and Ca^{++} Adsorbed Montmorillonites. Proceedings of the 4th Asian Regional Conference on Soil Mechanics and Foundation Engineering, Vol. 1: 373-378.

Kuzukami, H., Ozaki, E. & Nakaya, M., 1971. Relationships Between Specific Surface and Liquid Limit. Transactions of the Japanese Society of Irrigation, Drainage and Reclamation Engineering, Vol. 37: 61-67.

Locat, J. Lefebvre, G. & Ballivy, G. 1984. Mineralogy, Chemistry, and Physical Property Interrelationships of Some Sensitive Clays from Eastern Canada. Canadian Geotechnical Journal, Vol. 21: 530-540.

Low, P.F. 1980. The Swelling of Clay: II. Montmorillonite. Soil Science Society of America Journal, Vol. 44, No. 4: 667-676.

Meegoda, N.J. & Arulanandan, K. 1986. Electrical Method of Predicting In Situ Stress State of Normally Consolidated Clays. Use of In Situ Tests in Geotechnical Engineering, ASCE: 794-808.

Mitchell, J.K. 1960. The Application of Colloidal Theory to the Compressibility of Clays. Proceedings of the Seminar on Interparticle Forces in Clay-Water-Electrolytes Systems: 2.92-2.97.

Mitchell, J.K. 1993. Fundamentals of Soil Behavior. John Wiley & Sons, New York.

Moore, J.C. & Jones, R.L. 1971. Effect of Soil Surface Area and Extractable Silica, Alumina, and Iron on Lime Stabilization Characteristics of Illinois Soils. Highway Research Record No. 351: 97-92.

Morgenstern, N.R. & Balasubramanian, B.I. 1980. Effects of Pore Fluid on the Swelling of Clay-Shale. Proceedings of the 4th International Conference on Expansive Soils, Vol. 1: 190-205.

Morin, P. & Dawe, C.R. 1986. Geotechnical Properties of Two Deep Sea Marine Soils From Labrador Sea Area. Proceedings of the 3rd Canadian Conference on Marine Geotechnical Engineering. Vol. 1: 117-134.

Muhunthan, B. 1991. Liquid Limit and Surface Area of Clays. Geotechnique, Vol. 41, No. 1: 135-138.

Nixon, J.F. 1991. Discrete Ice Lens Theory for Frost Heave in Soils. Canadian Geotechnical Journal, Vol. 28: 843-859.

Ohtsubo, M. Takayama, M. & Egashira, K. 1983. Relationships of Consistency Limits and Activity to Some Physical and Chemical Properties of Ariake Marine Clays. Soils and Foundations, Vol. 23, No. 1: 38-46.

Olson, R.E. & Mesri, G. 1970. Mechanisms Controlling Compressibility of Clays. Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 96, No. SM6: 1863-1878.

Quigley, R.M., Sethis, A.J., Boonsinsuk, P., Sheeren, D.E. & Yong, R.N. 1985. Geologic Controls on Soil Composition and Properties, Lake Ojibway Clay Plain, Matagami, Quebec. Canadian Geotechnical Journal, Vol. 22: 491-500.

Rieke, R.D., Vinson, T.S. & Mageau, D.W. 1983. The Role of Specific Surface Area and Related Index Properties in the Frost Heave Susceptibility of Soils. Proceedings of the 4th International Permafrost Conference: 1066-1071.

Ross, G.J. 1978. Relationships of Specific Surface Area and Clay Content to Shrink-Swell Potential of Soils Having Different Clay Mineralogic Compositions. Canadian Journal of Soil Science, Vol. 58: 159-166.

Smith, C.W., Hadas, A., Dan, J. & Koyumdjisky, H. 1985. Shrinkage and Atterberg Limits Relation to Other Properties of Principle Soil Types in Israel. Geoderma, Vol. 35: 47-65.

Sonderman, L.G. & Quigley, R.M. 1965. Geotechnical Properties of Three Ontario Clays. Canadian Geotechnical Journal, Vol. 11, No. 2: 167-189.

Sridharan, A. & Rao, G. 1973. Mechanisms Controlling Volume Change of Saturated Clays and the Role of the Effective Stress Concept. Geotechnique, Vol 23, No. 3: 359-382.

Sridharan, A. & Jayadeva, M.S. 1982. Discussion of Universal Compression Index Equation. Journal of Geotechnical Engineering, ASCE, Vol. 108, No. GT6: 895-899.

Sridharan, A., Rao, S.M. & Murthy, N.S. 1986. Compressibility Behavior of Homoionized Bentonites. Geotechnique, Vol. 36, No. 4: 551-564.

Sridharan, A., Rao, S. & Murthy, N. 1986. Liquid Limit of Montmorillonite Soils. Geotechnical Testing Journal, Vol. 9, No. 3: 156-159.

Sridharan, A., Rao, S. & Murthy, N. 1988. Liquid Limit of Kaolinitic Soils. Geotechnique, Vol. 38, No. 2: 191-198.

Sridharan, A., Rao, S.M. & Dwarkanath, H.N. 1992. Dispersive Behavior of Nonswelling Clays. Geotechnical Testing Journal, Vol. 15, No. 4: 380-387.