PARTICULARITY OF PLASTICITY CHARACTERISTICS OF FINE GLACIAL MATERIALS (NORTH CHICAGO AREA)

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Abstract. The representation of plasticity characteristics on Casagrande plasticity chart of glacial material samples, from an investigated area north of Chicago, IL, USA, confirmed the known alignment along the T line (Boulton and Paul, 1976) for the category of glacial materials. The goal of the present study was to identify the factors responsible for the plastic behavior of the glacial materials. We consider that this particular characteristic of plasticity is the result of grain size distribution with a minimum inter-granular space created by genetic glacio-clastic processes. Synergetic association between the minimum inter-granular void grain ratio, and the minimum efficient content of clay pallets around bigger grains, have an impact over plasticity behavior, lowering both liquid limits LL, and plasticity limit PL, but increasing the gap between these limits (the plasticity index).

Key words: Plasticity chart, Atterberg limits, Boulton T line, glacio-clastic processes, minimum void ratio, minimum efficient clay ratio

1. INTRODUCTION

The general geology of northeastern Illinois is glacially derived deposits overlying bedrock. Transportation ways, airports as well as large industrial and commercial buildings, are build on soil that is rich in fine fraction (clay and silty-clay soils).

Glacially derived deposits are among the most complicated of all geological environments, due to the fact that the motion of ice mixed together a large variety of materials. In general, the glacial materials have an overall appearance similar to the regular sedimentary materials, and are even labeled with the same terminology used for sedimentary deposits: gravel, sand, silt, clay, etc. However, it is important to note from the beginning that the genetic mechanism imposed by movement of solid ice has little to no correlation to genetics processes of water based erosion, transport and deposition.

The data for this investigation is derived from the soil samples collected along Tri State I-94, North of Chicago metropolitan area, on the ice-distal slope of the Deerfield Moraine. Field data, laboratory tests results, and additional data were made available by Wang Engineering Company, from Lombard, IL. The same data was used as the basis of the Doctoral Thesis, *"Specific geotechnical problems for transportation ways on glacial deposits area associated with lacustrine deposits" (Constantinescu, 2010)*.

In the case of fine materials, plastic behavior represents an important characteristic. The change in the behavior of different types of soils, based upon the content of water, lead to the creation of standardized procedures of testing and classifying plasticity characteristics.

2. MATERIALS AND METHODS

2.1 Study area and materials

Almost the entire upper part of the subsoil found in the State of Illinois and in Chicago area, in particular, was deposited during the continental glaciations that covered 80 to 85 percent of the area of the current state of Illinois, over the course of the Pleistocene (Wiggers, 1997; Willman, *et al.*, 1975).

The Pleistocene glaciations, with at least four major glacial episodes (Nebraskan, Kansan, Illinoisan, and Wisconsian), overrode the entire Chicago Area. The most recent one, the Wisconsin sheet, left large deposits, during local advances and retreats of the glacier. One aspect of the subsoil in the Chicago area is the presence of large volumes of fine glacial materials (clay and silt–clay), named "*the Wadsworth till* "of the Wedron formation (Fig 1).

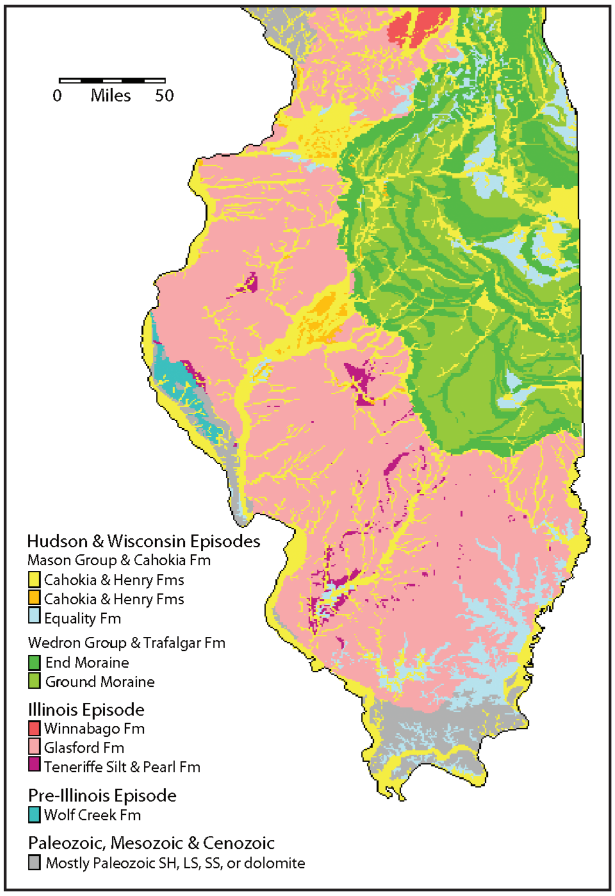

Fig. 1 Illinois Quaternary Deposits

The Quaternary materials are predominantly glacial diamictons related to the main glacial episodes, but also include glaciofluvial (sand and gravel), glacio-lacustrine (silt and clay), as well as materials deposited and formed during interglacial episodes (loess and soils), and the present post-glacial episode (Hansel *et al.*, 1999).

From an engineering viewpoint, the Wadsworth till includes low plasticity clay to silty clay with medium to low water content, with medium to very stiff consistency, poor permeability, and low compressibility. Wadsworth till is a classical example of fine material formed in subglacial conditions (lodgment till).

2.2 Methods of investigation

Over 100 samples collected from geotechnical investigation borings, drilled within a distance of 10 km along the expressway in the investigated area, have been analyzed during the present study. The borings drilled in this area revealed that native sediments consist mainly of brown to gray clay basal diamicton (till).

Soil sampling was performed according to the standardized test of *American Association of State Highway and Transportation Officials (*AASHTO T 206 - Penetration Test and Split Barrel Sampling of Soils). For the roadway borings, the soil was sampled continuously to the projected boring termination depths. The embankment borings were sampled at 0.75m intervals. Samples collected from each sampling interval were placed in sealed jars and analyzed in the lab.

Measurements of unconfined compressive strength (Qu) (using a Pocket penetrometer and a Rimac apparatus) were used in the field to determine an initial set of characteristics of collected samples.

The laboratory testing program included water content determination, particle size gradation, complete grain-size analysis and Atterberg limits, shrinkage limit, specific gravity and compressibility tests of selected samples. Tested samples were classified according to the AASHTO system.

The particle size analysis was conducted using both sieve and hydrometer analysis.

The Atterberg limits tests allow us to investigate the maximum and minimum water content that would define the interval for which the studied material will behave as a solid plastic. The Liquid Limit (LL) and the Plasticity Limit (PL), known as Atterberg limits, are used to calculate the index of plasticity (PI=LL-PL), The PI and LL are then used to characterize and identify the plasticity of soil sampled from the study area.

Currently there are two main methods for measuring the liquid limit, the classical Casagrande method, and the Cone Pentrometer method.

The Casagrande method was used during our investigation due to the fact that in the US it is the standardized procedure for determining the plasticity limit. Four tests were run to determine the liquid limit, and four tests to measure the plastic limit for each collected sample. We plotted the number of blows *vs.* moisture content, and determined the Liquid Limit (LL) (moisture content at 25 blows).

3. RESULTS AND DISCUSSIONS

3.1 Results

3.1.1 Grain-size

Ternary representation of particle-size ratios of sand-silt-clay, based on samples collected from I-94 Reconstruction Area showed similar results as those found in geotechnical literature (Chung and Finno ,1992; Sladen and Wrigley,1983) That is, basal tills samples fall inside of an envelope extended from coarse material corner (sand or sand plus gravel) to silt-clay edge (Fig. 2).

We can observe that our samples are grouped towards finer sizes in two, very well defined, groups:

1. Around 35% clay; 35% silt and 30% sand, at the edge boundary/ region of clay to loam-clay composition.
2. Around 40% clay; 45% silt and 15% sand, at the edge boundary/ region of clay to silty-clay and silty-clay loam.

We can consider that our samples had an average content in clay with a satisfactory value of 35% to 45%.

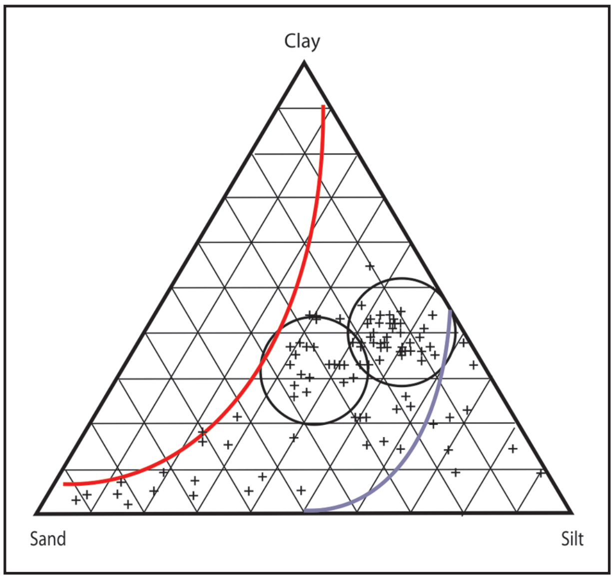

Fig. 2 Ternary representation of samples from the investigated area.

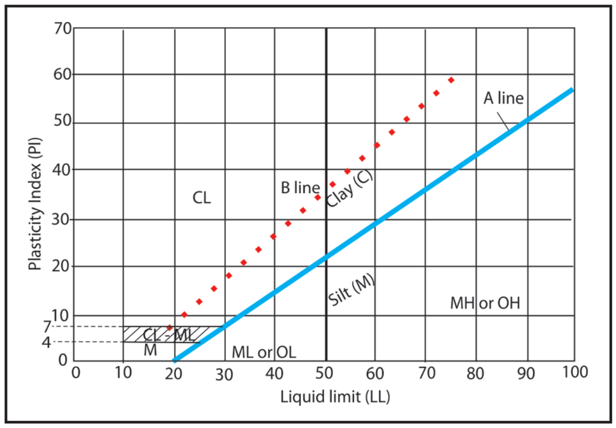

Fig. 3 Casagrande plasticity chart. Points plotted above A-line indicate clay soils. Points below the A-line indicate silt.

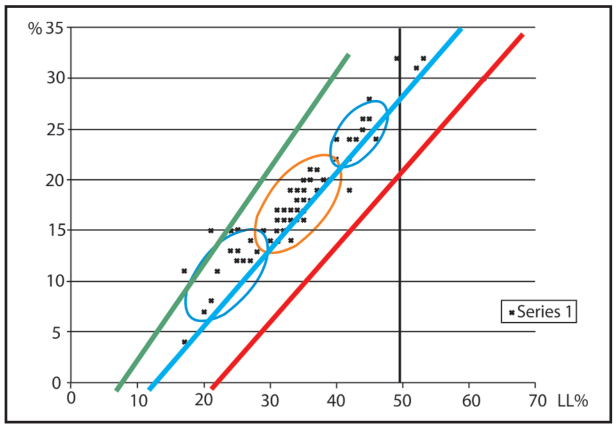

Fig. 4 Representation of plasticity values from research area

3.1.2. Atterberg limits

A common representation of the Atterberg limits is "Casagrande plasticity diagram" representing the plasticity index *PI* (%) plotted *versus* the value of liquid limit *LL* (%) with few reference lines for convenience:

$PI \approx 0.73\ (LL\text{-}20)$ **A** line

$PI \approx 0.90\ (LL\text{-}8)$ **U** line (also call **B** line)

Based on laboratory data (empirical data), Casagrande established that the plasticity range of soils is limited to the representation area situated between line **A** and **U**, where **A** line is the separation between clay area and silt area, and **U** line is the upper limit for currently known soils. Additionally, at *LL* = 50% a line divides silt and clay of high plasticity (*LL* > 50%) from low and medium plasticity category (*LL* < 50%), while *LL*< 20% defines an area of cohesion-less materials (Fig 3).

Boulton and Paul (1976) defined the linear relationship between the plastic and the liquid limits of glacial materials as „**T** line" placed between line **A** and **B** of classical Casagrande diagram representation:

$PI \approx 0.73\ (LL\text{-}\ 11)$ **T** line

A representation of laboratory tests results of Atterberg limits shows that our samples are placed between line **A** and **B**, close to Boulton **T** line, in accordance to the glacial origin of the material. Secondly, we can observe that the data is clustered, forming three well-defined groups (Fig.4).

Around a point situated at *LL*=45% and *PI*=24%, we can identify a group of values that represents clay with an intermediate plasticity index.

The main group of values of plasticity, situated around a point at *LL*=36% and *PI*=17%, represents a transition material with an index of plasticity from intermediate to low values.

The values of low plasticity, around *LL*=24% and *PI*=12%, define a group that has the tendency to move away from the Boulton line in the direction of the **U** line.

In general, the studied samples show a moderate plasticity and a low activity. Some of the values have the tendency to be situated above the T line, closer to the area reserved to smectic clay. This was a particularity of our samples which required an explanation and the identification of the control factors of plasticity in the specific case of glacial fine material.

3.1.3. X-ray diffraction tests

In order to explain the placement of our samples in the smectic clay area, we had to identify the clay mineral composition. For this purpose, nine samples, showing the lowest unconfined compression strength and higher natural water content, were investigated using X-ray diffraction (Fig.5). Samples were run with the X-ray diffraction spectroscope from Geography - Geology department of University of Wisconsin-Whitewater, with the help of Professor Dr. Peter Jacobs.

The silt fraction content for these analyzed samples is high (Table 1).

Table 1 Particle size distribution for x-ray analysis samples. Principle granulometric classes from research area

Particle size Analysis by Pipette and Sieve				
Sample ID	**Sand %**	**Silt %**	**Clay %**	**Cumulative silt and sand %**
Sample 3	7.4	50.5	42.1	57.9
Sample 4	6.8	48.7	44.5	55.5
Sample 5	20.7	52.3	27.0	73.0
Sample 9	8.6	50.8	40.8	59.2
Sample 10	8.7	51.0	40.4	59.6
Sample 11	11.6	52.1	36.4	63.6
Sample 12	8.4	50.8	40.7	59.3
Sample 13	7.8	49.2	43.0	57.0

X-ray diffraction tests showed that the samples contained illite and kaolinite, plus fine powder of quartz and dolomite, but montmorillonite was not found.

Out of the clay minerals, illite shows the highest percentage, between 63% and 68%, while kaolinite plus calcite range between 25% and 31% (Table 2).

Table 2 Clay Mineral Composition of samples from research area

Sample	Illite %	Kaolinite + calcite %
Sample 3	65.0	25.2
Sample 4	65.2	25.1
Sample 5	67.6	27.5
Sample 9	64.1	29.7
Sample 10	63.7	31.2
Sample 11	64.4	28.6
Sample 12	65.8	28.7
Sample 13	63.3	30.8

3.2 Discussion

The mineralogical composition determined through X-ray diffraction is consistent with information found in the literature (Chung and Finno, 1992) and with the glacial origin of our samples, but it is definitely not able to explain the arrangements of the tested samples on the plasticity chart.

A material with this type of consistency (such as illite and kaolinite, fine quartz, calcite and dolomite powder, and a larger amount of silt) should be situated along the Casagrande **A** line (Fig. 6).

The placement along the **T** line, or even above this line, is a discrepancy. To try to explain this behavior, we will review the factors that controlled the plasticity.

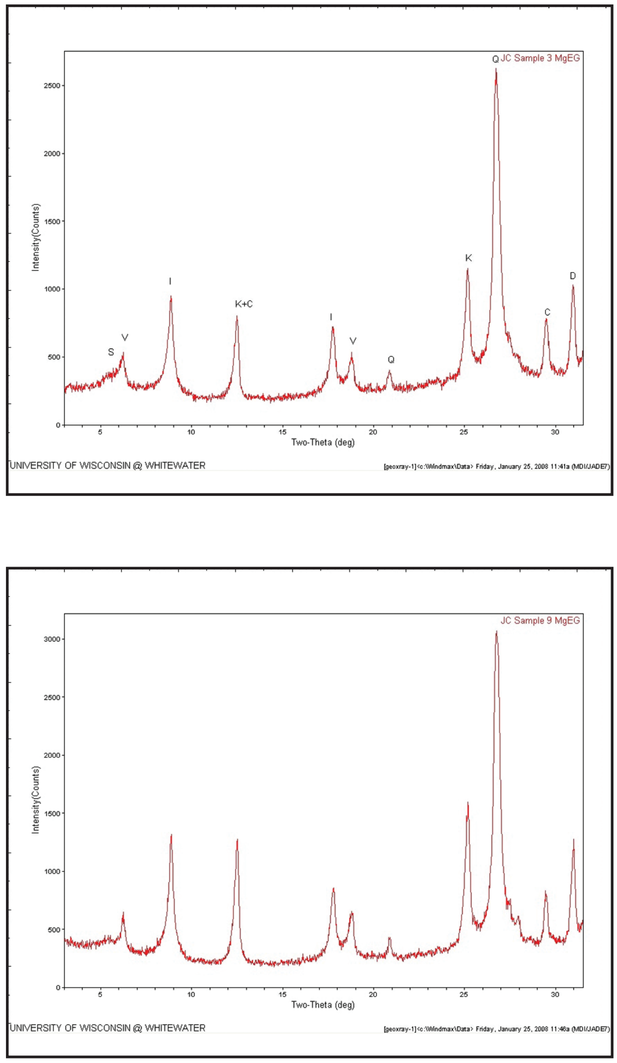

Fig. 5 X-ray results (sample 3 & 9)

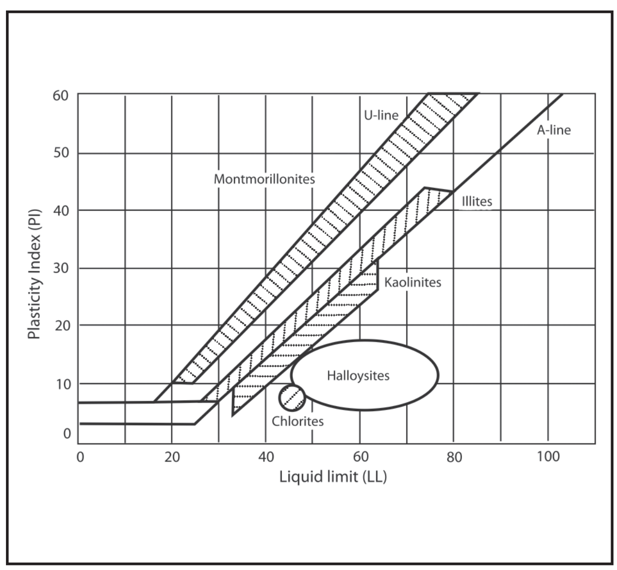

Fig. 6 Distribution of clay minerals on Plasticity chart

3.2.1 Main factors

The ratio of clay content

The clay content is a significant factor, equally important to regular detrital sedimentary materials, as well as to the material of glacial origin. An increased clay percent would also increase the value of the Liquid Limit (LL), as well as increase the Plasticity Index (PI), changing from low plasticity behavior to high plasticity behavior. Large clay minerals content gives a relatively high cohesion, low permeability, and a relatively small angle of internal friction. A large content of silt and sand increases the coefficient of consolidation and decreases the cohesion, as well as increasing the angle of internal friction (Das, B. M., 1998; Lambe and Whitman, 1969). The ratio of clay content could explain approximately 65% to 95% of the variability for LL and PI values (Seybold *et al.,* 2008).

Size and shapes of grains

The difference between the regular detrital sedimentary and the glacial material is related to the genetic process. The selection action during sedimentary processes can generate dominant grain-size classes. In opposition, the glacial processes would create a large spectrum of grain-sizes. An additional characteristic for glacial materials is the preservation of the angular grain shape.

In literature (Sladen, Wrigley, 1983) sand and gravel content is considered to have a small impact on the plasticity characteristics of glacial materials. The silt size particles could influence the plasticity due to the increase of the specific area. The particles that are smaller than 2 microns (clay-size) have the largest effect on the plasticity behavior of materials.

The large specific area of the small grain particles increase the effect of electrochemical forces (both attractive and repulsive) as well as the effect of capillary forces caused by dipolar water molecules present around smaller size grains. The glacial debris shows a wide range of grain sizes, progressively transported and comminuted, and many grains preserve an angular shape. The electrochemical forces are amplified around regions with sharp curvature. In addition, the elongate grain shape increases the internal frictional forces (Santamarina, C. J., 2001; Seybold *et al.*, 2008).

The mineralogical composition of clay

Usually, on a plasticity chart, the presence of illite and kaolinite minerals in clay composition would place the clay along and close to line A, while the presence of montmorillonite mineral would place the clay along line B (Fig. 6).

3.2.2 Specific factors for glacial material

The main factors presented above cannot explain the positioning of glacial materials along the line **T** on a classical Casagrande diagram.

The plastic properties of clay soils are directly related with the interaction of the soil particles. When soil is deformed plastically, particles move relative to each other, creating new equilibrium positions. The inter-particle forces involved depend upon size, shape, type of clay and silt particles present, as well as on the interstitial water amount. The cohesion between particles must be sufficiently low to allow the movement and yet, high enough, to allow the particles to obtain and maintain a new equilibrium position. In achieving the maxim values of the Liquid Limit (LL), the distance between particles is such that the forces of interaction between the clay particles become sufficiently weak to allow easy movement of particles relative to each other (Yong *et al.*, 1966). For the specific case of materials of glacial origin we wanted to identify the unique characteristics that could impact these inter-granular forces.

The presence of fine powders

By comparison with regular detrital sedimentary materials, the glacial soils have a higher ratio of fine or very fine powder (rock flour), as well as relatively inert clay minerals (kaolinite) which decreases the plastic behavior. At the same time, the intergranular forces of capillary nature play a very important role increasing the cohesivity of the material.

The intergranular pores

The type of grain-size dictates the characteristics of intergranular spaces, defines the existing type of pores (closed or free to communicate), and most significantly, the proportion of different size of pores.

The existence of "closed pores filled with water", together with the open pores divides the water content in two categories: one that is trapped inside these pores and one that migrates. When we determine the plasticity limit, the captured water remains present in the structure, acting similarly to water bond to clay palets, maintaining the cohesivity of the material. However, the capacity of retention of water inside closed pores is limited to ratio of these pores vs the open pores.

The grain-size distribution

The origin of sub-glacial clay is related to the clastic processes developed in a restrictive spatial framework and under high pressure. The detritus found under the glacier is exposed to two antagonistic processes: continuous mixing and dilating of material, with a dispersive effect and a selective tendency towards super compact granular arrangement. The cumulative grain-size representation of glacial soil sample usually shows the effect of dispersive processes by low slope segments (regular for larger particles) or the effect of selective processes by high slope segments (regular for smaller particles).

The subglacial mechanism of crushing and grinding imposes a spatial grain distribution that has a tendency to eliminate the empty inter-granular spaces, creating a compact material.

In industry, in order to create a compact material, the formula Fuller –Thompson is used to find the best mixture of granulometric classes:

$$P = 100\left(\frac{D}{D_{\max}}\right)^n$$

P – percent of fraction with grain diameter D
$D_{\max}$ – diameter for maximum size grain fraction
n – index found by experiments:

- n = 0.2 to 0.4 in case of crushed stone;
- n = 0.3 to 0.5 in case of regular gravel

We have found that the grain-size cumulative diagrams, based on values of test laboratory for our samples, resemble the graphs that can be calculated using Fuller-Thompson formula. For our fine grain material the index has values between 0.2 to 0.4.

The efficient arrangement of clay pallets

The smallest size particles are represented by clay pallets with their water envelope. Spaces available for these pallets are constrained to the left-over intergranular space if grain size distribution obeys the Fuller –Thompson formula.

The rolling process of grains that takes place during the motion of ice enables the formation of a clay envelope around larger grains. From a plasticity point of view, this can be considered a very efficient arrangement of slippery material between larger grains.

The importance of the efficient arrangement of clay pallets is emphasized by the concept of "minimum clay content limit," representing the clay ratio necessary for the transition of non-plastic granular material to cohesive material with very low plasticity. For example, for clean sand, an additional small quantity of clay will completely change the granular material from non-cohesive to cohesive, with a very low plastic behavior.

3.2.3 Synergetic association of factors

All fine glacial materials can be found along the **T** line on the Casagrande-Boulton diagram, regardless of their location and the geological characteristics of initial source of the material. Attempting to find one factor responsible for this placement on the plasticity chart is difficult. This general behavior cannot be explained by considering a single factor and it is necessary to consider a synergetic association of factors.

For fine glacial materials, the minimum clay mineral content is associated with the efficient placement of clay minerals, which implies the presence of palets at the contact points between larger size grains.

In our oppinion, due to the efficient placement of the clay minerals associated with specific grain-size distribution, the plastic behavior is likely present at a lower value of natural water content. For a reduced quantity of water, the lubricating properties of clay are preserved due to the fact that water remains bounded to the clay pallets. The immediate result is a lower value of the Plastic Limit (PL).

Low volume of intergranular spaces correlated to the grain -size distribution (as predicted by the Fuller-Thompson formula) require a low amount of water to be filed and oversaturated; this implies small values of Liquid Limit (LL).

The synergetic association between "the efficient content of clay pallets," covering non-plastic grains, with "the minimum intergranular voids" specific to glacio-clastic material, could generate this particular plasticity behavior,by lowering the water content for both the Liquid Limit (LL), and the Plastic Limit (PL). However, the value of the Plasticity Index (PI) remains larger. Under the influence of the above factors, the Plasticity Limit (PL) decreases more than Liquid Limit (LL).

The volume of intergranular spaces is also dependent on the compactation of material. The placement of the plasticity values for fine glacial soil in the area of smectic materials is a result of the non-linearity of plasticity.

4. CONCLUSIONS

In general, the samples collected from our study area can be categorized as a fine-grained material (lean clay to silty-clay) with very small amount of gravel and sand. The ternary representation of ratios of sand-silt-clay shows that the content in clay and in silt is on average, between 35% and 45%. The main mineralogical component of clay is illite (63% to 68%) with additional small percents of kaolinite, plus non-clay powder material (dolomite and quartz).

The plasticity values of our samples are placed on the LL/PI plasticity chart along the **T** line (even a little bit above this line), as expected from glacial deposits but in contradiction with the characterisitcs described above.The position of the samples on the ternary diagram at the edge between clay and silty clay and the presence of illite and fine powders should place them along the **A** line on the plasticity chart.

In general, placement of plasticity values for fine glacial soil in area of smectic materials is the result of non-linearity of plasticity phenomenon and it is not related to the presence of smectic clay minerals. This was a particularity of our samples which required the identification of the factors that control the plasticity, in the specific case of glacial fine material. We propose an explanation of this contradiction based on the synergetic association between grain-size distribution that obeys the Fuller-Thompson mixture formula and an efficient arrangement of clay pallets around larger grains.

Fuller and Thomson (1907) followed by others, were trying to find a formula of agregate gradation in order to obtaine a maximum compact Portland concrete with minimum intergranular void.

Similarly, the subglacial mechanism of crushing and grinding, developed in a restrictive spatial framework and under high pressure has a tendency to eliminate the empty inter-granular spaces and create a compact material. From a genetic process point of view, this law of "compact granular arangement" probably represents for glacial detritus what Stokes' law represents for a normal sedimentary process, introducing order to a process commonly view as chaotic.

The rolling process of glacial detritus imposed by the motion of ice enables the formation of the clay envelope around larger grains in very efficient arrangements of slippery material (clay pallets). For the situation when the content of water is reduced, the placement of clay pallets could preserve the plastic behavior of the material. As a direct result the plasticity limit PL drops to smaler values. In the same time, the low volume of intergranular space (conform with grain-size distribution) implies that a low volume of water is necesary to fill the intergranular pores. As an immediate effect, the liquid limit (LL) would have low values and, on the plasticity diagram values PI vs LL would migrate to area of lower plasticity.

Changing of mechanical strenght of soil materials in relation to the water content represents an important aspect of geotechnical research. The fine glacial materials, with low plasticity characteristics, can create dense materials during a compaction processes. Even though this material is consider to be properly consolidated, under a dynamic load, it can allow the development of local pockets of weak materials, oversaturated with water. Our research showed, the importance of understading of complexity of factors that control the plasticity behavior of materials.

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