INFLUENCE OF COMPACTION CONDITION ON THE MICROSTRUCTURE OF A NON-PLASTIC GLACIAL TILL

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Abstract The influence of compaction water content on the structure has been well known for clayey soils, but has never been studied for granular materials. In this paper the structure of a non-plastic till and the effect of compaction moisture is investigated by means of water retention curve study, scanning electron microscopy and mercury intrusion porosimetry tests. The results show that when compacted on the dry side of the optimum water content, the porous system is characterized by a relatively uniform medium pores, while in case of compaction on the wet side, pores size is very diversified and the numerous small pores dominate the porous system. The difference in the structure was also approved by measuring the rigidity and the coefficient of permeability showing a less rigidity and permeability in case of compaction on the wet side.

Key Words Microstructure, Pore Size, Compressibility, Settlement, Permeability, Saturation Degree, Granular Soils

چکیده تاثیر درصد رطوبت در هنگام تراکم بر ساختمان خاکهای رسی از مدتها قبل شناخته شده است. اما در مورد خاکهای غیر چسبنده، تا کنون تحقیقی صورت نگرفته است. در این مقاله ساختمان خاک غیر پلاستیک تیل تحت تأثیر رطوبت تراکم از طرق آزمایشهای تخلخل سنجی جیوه‌ای، میکروسکوپ الکترونی و منحنی مشخصه رطوبت خاک بررسی می‌شود. نتایج نشان می‌دهد که ساختمان خاک‌های دانه‌ای نیز همانند خاکهای چسبنده از شرایط رطوبتی تراکم تاثیر می‌پذیرد. چنانچه خاک در رطوبتهای کمتر از رطوبت بهینه متراکم شود، اندازه حفرات آن نسبتاً یکنواخت می‌شود. در حالی که در رطوبتهای بیشتر از مقادیر بهینه، اندازه حفرات متنوع بوده و حفرات ریز، عملکرد هیدرولیکی سیستم تخلخل خاک را تحت الشعاع قرار می‌دهند. این تفاوت توسط آزمایشهای نفوذ پذیری و تراکم پذیری نیز تایید شده است؛ به نحوی که تراکم در رطوبتهای بیشتر از مقدار بهینه، موجب کاهش نفوذ پذیری و افزایش تراکم پذیری خاک می‌گردد.

1. INTRODUCTION

Compaction is the densification of soil by the application of mechanical energy to expel air from the soil-water-air system and to produce particle packing. Compaction water content has been known for many years to influence the microstructure and behavior of compacted clayey materials: Cabot and Le Bihan [1], Prapaharan et al. [2], Daniel and Benson [3] and Mitchell et al. [4]. With increasing water content, the soil fabric of clays becomes increasingly oriented, while dry of optimum compacted clayey soils are rather flocculated. At the optimum water content, an intermediate fabric exists: Lamb [5]. Garcia-Bengochea et al. [6] reported pore size distribution of a silt-kaolin mixture containing 90% silt and 10% kaolin was also influenced by compaction condition. For fine-grained soils, in general, the compaction energy is used to overcome the inter particle forces resulted from electrochemical bounds, cohesion and suction. For a given compact

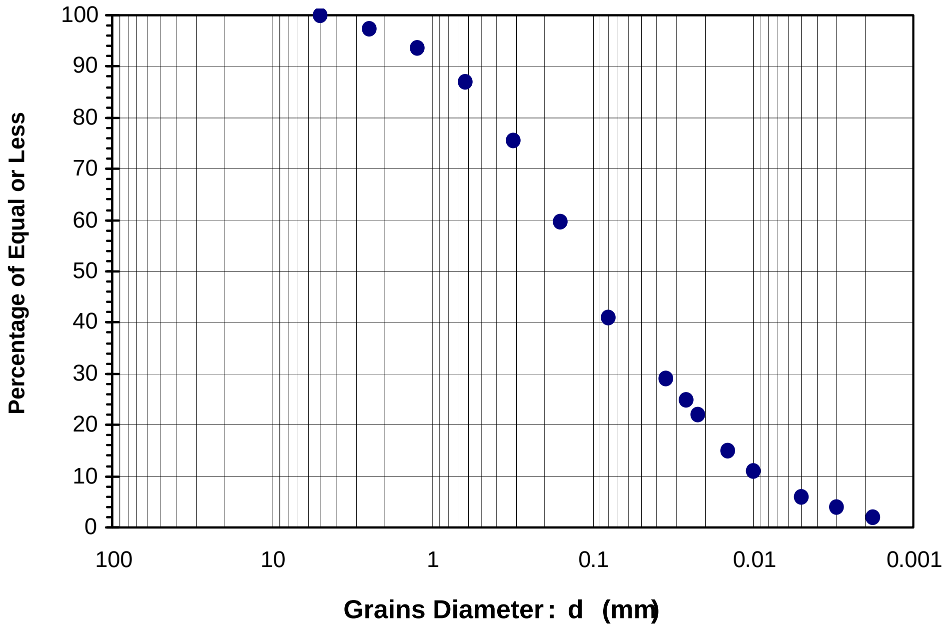

Figure 1. Particle size distribution curve for Till LG-4 (The portion passing from sieve 5 mm).

effort, the coefficient of permeability is generally much higher when clayey materials are compacted dry of optimum than when compacted wet of optimum due to a difference in the arrangement of clay particles [7].

For granular materials, most of researches have been performed to study the influence of compaction methods on the microstructure (Chapuis et al. [8]) and less attention has been paid to the influence of compaction water content. The single-grained nature of the structure of cohesionless soils depends on grain-to-grain contact forces arising from gravity for its stability. Compaction energy disturbs these contacts and a new more stable and denser configuration is produced. Since application of a steady force results in an increase in the grain-to-grain force with little permanent densification, the cohesionless soils are most efficiently compacted by vibration: Schroeder and Dickenson [9].

In this research, the question is whether the microstructure of glacial tills (a granular material composed of gravel and sand with a relatively low percentage of cobble and silt) is influenced by compaction water content.

2. METHOD AND MATERIAL USED

Series of tests were carried out on the passing portion of a 5 mm opening sieve of a glacial till which is a well-graded silty sand, containing 57% sand, 41% silt and 2% colloidal particles. The material, designated as LG-4 Till, was obtained from James Bay in northwestern Quebec, Canada. The standard proctor test showed a maximum dry density of 2050 kg/m³ is achieved at optimum water content of 7%, at which the degree of saturation (*S*) is 58% (Davoudi [10]). The other characteristics of material are as follows: $c_c = 1.2$, $c_u = 16.7$, as revealed in Figure 1.

As the microstructure, the pore size distribution, the coefficient of permeability and the solid-water characteristic of a soil are obviously related together: Vanapalli et al. [11], Mitchell et al. [4], Fredlund et al. [12]. The investigation was

TABLE 1. Characteristics of Specimens of Water Retention Tests and the Results.

Test No	End of Compaction (Before Submergence)				End of Submergence		Air Entry Value (AEV)		Micropore Suction Point (MSP)	
	Comp. Degree(%)	Void Ratio	*w* (%)	*S* (%)	*S* (%)	*u* (cm)	*S* (%)	*u* (cm)	*S* (%)	*u* (cm)
t-w2-5	97.6	0.3458	5.19	40.4	85.8	0.0	79	50	46	122
t-w1-6	96.8	0.3573	6.3	47.5	85.6	0.0	81	69	55	129
t-w3-8	97.6	0.3461	8.63	67.2	84.4	0.0	77	74	62	134

TABLE 2. Characteristics of Mercury Intrusion Porosimetry Test Samples.

Specimen	Compaction Water Content w_c (%)	Deg. of Satur. At the End of Compaction S_c (%)	Void Ratio *e*	Dry Density ρ_d (Kg/m^3)	Porosity *n* (%)	Dry Mass of Specimen M_s (gr.)
PR4-8	8.5	72.95	0.3138	2049.8	23.89	4.6208
PR7-7	6.87	53.79	0.3439	2003.9	25.59	4.3371
PR6-6	5.97	47.81	0.3363	2015.3	25.17	6.0392

done using the results of three series of tests: Mercury Intrusion Porosimetry, Scanning Electron Microscopy and water retention curves. All tests were carried out on two groups of specimens, dry and wet, and their results were compared. Dry group are specimens being compacted on the dry side of the optimum water content, and the wet group on the maximum workable moisture, 9%. All specimens were compacted to 96-100% of maximum dry density.

3. WATER RETENTION CURVE (WRC) TESTS

Vanapalli et al. [11] reported that the solid-water-air interaction of soil is influenced by its structure. Miller et al. [13] used the WRC for studying the effect of compaction moisture on the characteristics of compacted soils. It is known that at a given moisture content, the magnitude of soil matric suction is inversely related to the largest radii of meniscus which in turn, is a function of the microstructure. The WRC was investigated for three specimens compacted at three different moistures, Table 1. All the tests were run in drainage process based on ASTM Standard D2325-68.

The water retention curve of specimen t-w1-6 compacted near the optimum water content, Figure 2, is considered as the reference. Its initial degree of saturation was 47.5% and after submergence, rose to 85.6%. The curve shown has two breaking points. The first one corresponds to a 67 cm water suction, at which degree of saturation is 81%, and is considered as the *air entry value* of the specimen (AEV). At this pressure, air starts to enter the largest pores (macropores) and pushes out a portion of pore water: Fredlund and Rahardjo [14].

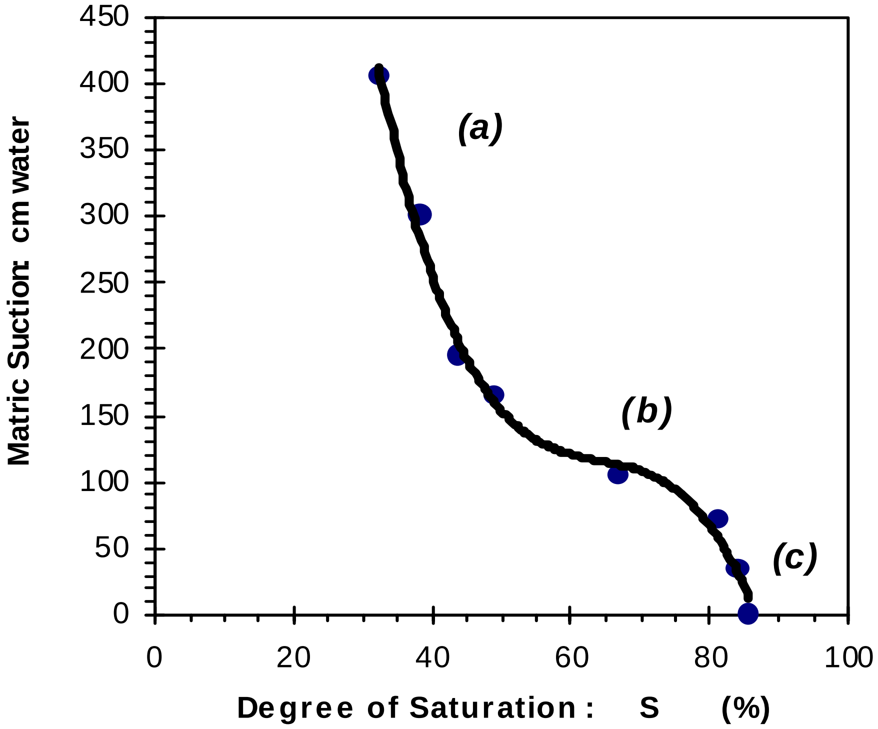

Figure 2. Water retention curve for specimen t-w1-6.

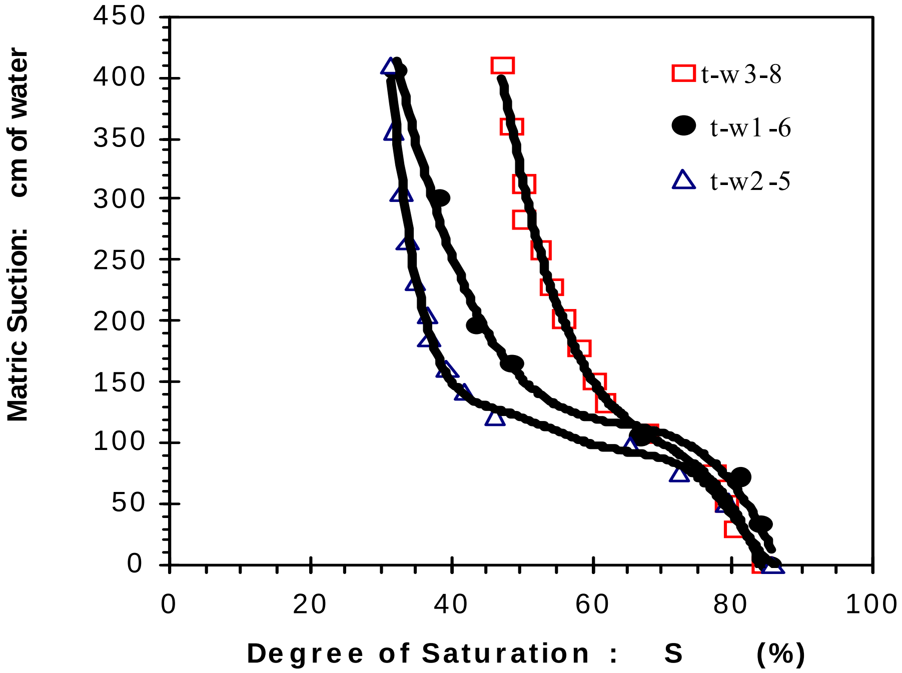

Figure 3. Comparison of breaking points of specimens compacted at different moistures.

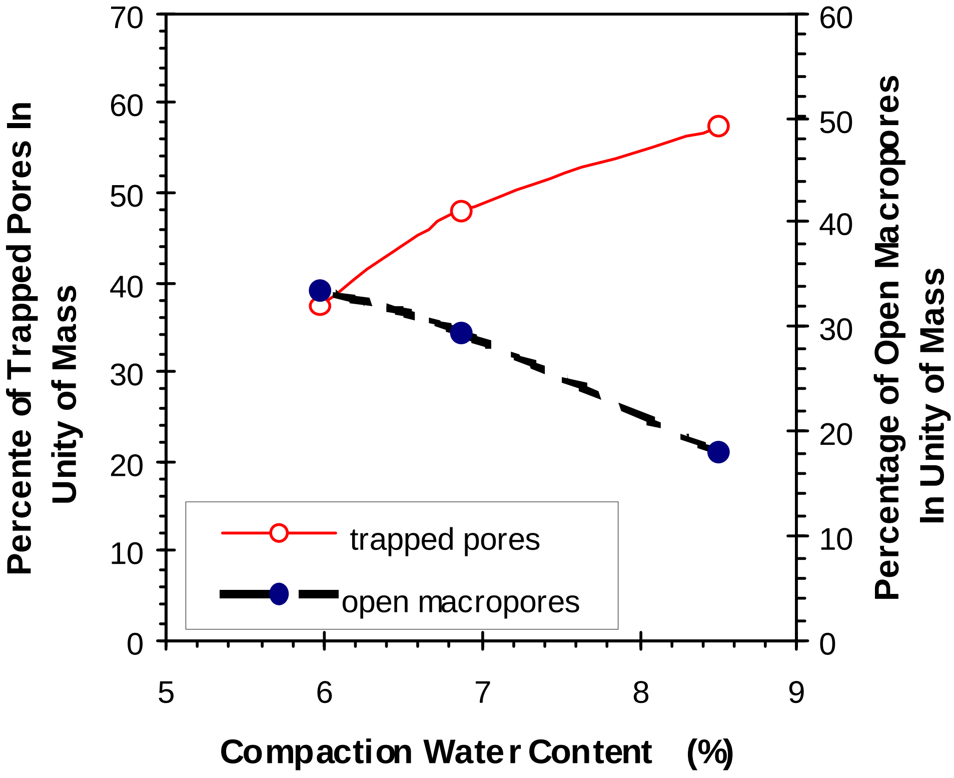

Figure 4. Volumetric percentage of open micropores and all trapped pores as a function of compaction water content.

As the air pressure is increased, smaller pores start losing water, on one hand, and simultaneously more water is removed from the macropores. At the second breaking point, at a suction of 130 cm of water, degree of saturation has decreased to 55% and the rate of water removal drops sharply. This point is referred to as the *micropore suction point* (MSP). The number and the diameter of undrained micropores decrease as suction increases, and the remaining water within drained pores approaches the *residual water content*. One can indeed consider that the segment "*b*" of the curve, between the two breaking points, reflects mainly the desaturation of macropores, while segment "*a*", beyond the second breaking point, reflects the desaturation of micropores. For each pore, however, there is a certain quantity of water, which cannot be removed under low suctions.

The results of two other specimens, t-w2-5 compacted dry of optimum water content, and t-w 3-8 compacted wet of the optimum, are compared in Figure 3. The specimens showed quite different behaviors. The main difference is related to part "*b*" by the figure, is inversely proportional to the compaction moisture content.

Table 1 shows AEV is proportional to the compaction water content and increases from 50 to 74 cm. Comparison of the saturation degree of specimens at MSP, also reveals the volume occupied by micropores is directly proportional to the compaction moisture.

4. MERCURY INTRUSION POROSIMETRY (MIP) TESTS

Lawrence [15], Kenny [16] and Reed et al. [17]

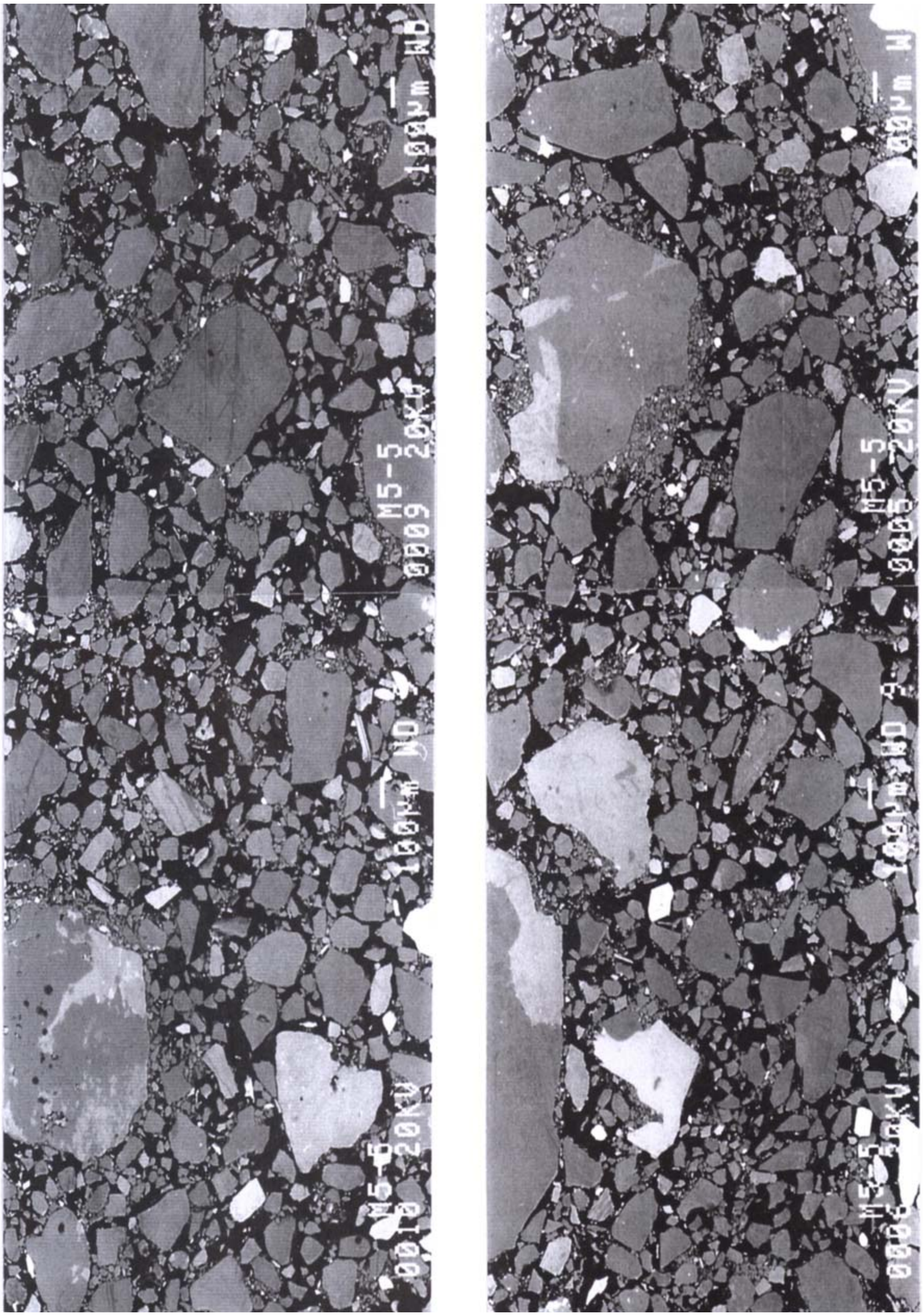

Figure 5. Microphotographs of sample No M5-5 compacted at 4.76% water content.

found that mercury intrusion doesn't disturb soil fabric, and can be thus used as a reliable technique for the study of soil structure. Three specimens compacted at different water contents, Table 2, were prepared and tested based on standard ASTM D4404-84.

A complete cycle of ascending and descending pressure was applied to the mercury and at each pressure step the volume of the intruded and extruded mercury was measured. It should be noted that with the equipment used, a standard test procedure detects only the pores having a radius smaller than 6.3 μm, since all pores having a radius larger than 6.3 μm are filled once the sample is submerged in the mercury without any pressure.

The results showed that the percentage of micropores (<6.3 μm) decreases from 61.9% to 49.8% and 47.7% as the compaction water content decreases from 8.5% to 6.9% and 6%, respectively. Contrarily, the percentage of the trapped micropore increases from 39% to 54.7% and 60.1% as the compaction moisture increases from 6% to 6.9% and 8.5%, respectively.

Macropores were studied by a series of mercury intrusion tests without applying any pressure. The chamber containing new samples was just filled with mercury without any pressure, and the samples were then taken out. The difference between the mass of a sample before and after submergence corresponds to its trapped macropores volume.

The volume of free macropores was then calculated and found to be inversely proportional to the compaction moisture. The variation of open macropore volume in terms of percentage of total porous volume is illustrated in Figure 4 showing an increase of 15.6% with a decrease of 2.5% in compaction water content. It raises from 18% to 29.7% and 33.6% in samples PR4-8, PR7-7 and PR6-6, respectively.

Contrarily, the percentage of trapped porous volume is directly related to the compaction water content, particularly for water contents less than the optimum. It increases as much as 20% with an increase of 2.5% in compaction moisture. In sample PR4-8, 57.3% of the pores are of trapped kind, while in PR6-6 compacted on the dry side, it is only 37.4%.

5. SCANNING ELECTRON MICROSCOPY (SEM) TESTS

Two samples were compacted in a cylindrical mold 2.36 cm in height and 2.66 cm in diameter at water contents of 4.76% and 8.71% to almost identical porosity of 26.7% and 26.2%, respectively. Once dried, were intruded by proxy resin, and after being hardened were cut, finished and prepared for scanning.

The specimens were scanned by means of backscattered electrons in a 1.5 mm wide strip along their diameter. Two representative images (scale 1:50) are presented in Figures 5 and 6. Based on this scale, grains of 0.25 to 3.75 mm diameter represent silt particles and therefore make up a large proportion of the sample, as do sand particles. The micropore family is detected at 0.3 mm and smaller, and cannot be analyzed by these images. The global porous system and the structure of the mass can nevertheless be investigated and evaluated.

In sample M5-5, compacted 2.24% dry of optimum (Figure 5), silt particles are well distributed between the sand grains such that each of them contributes individually in the skeleton of the mass. The void space thus is well distributed between the grains and eventually between the tiny aggregates formed by the fine silts. This arrangement results in a porous system composed of relatively uniform macropores, as well as of micropores. Most of the macropores have a radius of the order of 25 μm with a maximum measured of the order of 50 μm. Macropores appear to be fairly well interconnected, which results in a high contribution to water flow. It seems that most of the porous volume belongs to the macropore family, as was found during the mercury intrusion porosimetry tests.

Figure 6 shows that, in sample M8-8 compacted wet of optimum, silt particles gather around the sand grains and form coarse aggregates. This arrangement results in the formation of a few large macropores and several smaller macropores. A wide range of macropore radii is observed, the largest being in the vicinity of 130 μm, while most of them are surrounded by micropores. This phenomenon creates two effects. It either increases the tortuosity within the macropore system, or

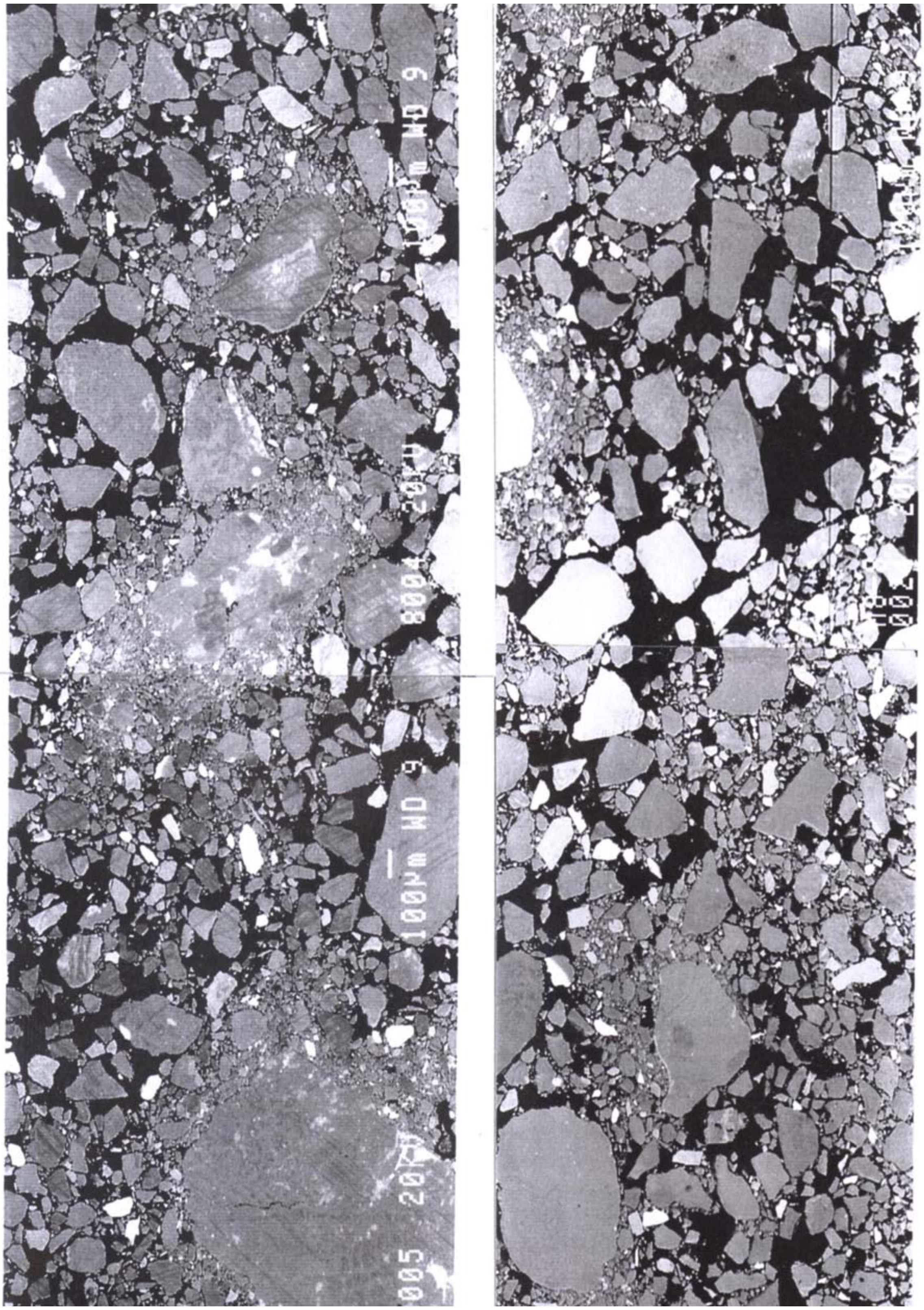

Figure 6. Microphotographs of sample No M8-8 compacted at 8.71% water content.

isolates the macropores, preventing them from contributing substantially to water flow.

6. PERMEABILITY AND COMPRESSIBILITY OF MATERIAL

It is well known that for a given soil the hydraulic and mechanical behavior is a function of its structure. The results of permeability tests done by Davoudi [10] on the same material approve the results of this research. Carrying out six tests on two groups of specimens compacted on the dry and wet side of the optimum water content to an identical degree of compaction of 96% to 99% and a void ratio of 0.32 to 0.36, he found that the coefficient of saturated permeability of the dry group is at least two times of the wet group.

The average of permeability for the first group was 1.3×10^{-4} cm/s, while for the second group it was much lower, 6.2×10^{-5} cm/s. Considering the similarity in void ratio, the difference in coefficient of permeability of the two groups indicates a remarkable difference in their porous system, i.e. tortuosity, pore size distribution, percentage and distribution of isolated pores.

The consolidation and settlement-submergence tests of the same specimens, reported by Davoudi [10], also are in good coincidence with the results of this research. In general, the deformation during consolidation under 900 kPa was very low due to the high density; however, it was 1.7% for the wet specimens, while the dry specimens showed much higher rigidity and had a deformation less than 0.60%.

The same specimens were submerged by water and after 24 hours the settlement was measured. The submergence settlement under 900 kPa was also very small, however the wet specimens showed a lesser deformation. The maximum deformation was 0.03% for this group, and 0.09% for the dry specimens. In general, the total compression (consolidation plus settlement) is directly proportional to compaction water content and varies by 0.6% for water content of 5%, and by 1.7% for water content of 8%. In spite the absolute values are very small, the difference is more than three times. Ben Belfadhel found the same trend, too [18].

7. CONCLUSION

The scanning electron microscopy and the mercury intrusion porosimetry tests show that the microstructure of LG-4 till is significantly affected by the moisture content at which it is compacted. When compacted on the wet side of the optimum, the silt particles gather around the sand grains and form coarse aggregates, which can be easily deformed and pushed into large interaggregate pores under any applied pressure.

A larger proportion of the porous volume is composed of micropores surrounding the fewer large macropores resulting in either a considerable degree of tortuosity within the macropore system, or prevents macropores from fully contributing the water flow. Furthermore, macropores and particularly well-interconnected macropores occupy less volume compared to the samples compacted on the dry side of the optimum.

If compacted on the dry side, the particle arrangement is much more uniform with little aggregation of particles. The void space is well distributed between particles, relatively uniform macropores are formed, and most of the porous volume is composed of macropores. These arrangement results either the saturated coefficient of permeability to be two times higher than wet specimens, and in case of loading the applied force to be distributed between all grains and consequently a lesser deformation is produced.

Due to the dominance of micropores in specimens compacted wet of optimum; the matric suction corresponding to given moisture content is much higher than that for a soil compacted on the dry side of optimum. Similarly, its air entry value and matric suction corresponding to the residual moisture is higher.

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