SOIL MOISTURE SUCTION OF ALLOPHANIC AND HALLOYSITIC SOILS

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ABSTRACT

Soil moisture-suction relationship of allophanic and halloysitic soils were investigated by conducting laboratory test. In comparison with other soil types which did not contain allophane and halloysite, the residual volumetric water content was high. This was due to the water retained inside the micropores in allophanic soil and the intra lattice water in halloysitic soil. In addition, the high amount of organic content in allophanic soil, which was reflected by its dark colour, was also responsible for the high water holding.

INTRODUCTION

This paper deals with experimental work on allophanic and halloysitic soils to enable determination of the soil moisture-suction relationships, which are required to simulate the infiltration proces through unsaturated soil zone. Discussion on problems arising during laboratory testing are also addressed. The clay mineralogy was investigated by X-ray diffraction analysis.

ORIGIN OF ALLOPHANE AND HALLOYSITE

Both soil types tested in this study, i.e. red allophanic soil and halloysitic soil, are classified as residual soils, formed by the chemical weathering of volcanic rocks under high ambient temperature and high rainfall conditions. High temperature and year-round rainfall favour the formation of low activity (Skempton's activity 0.3 to 0.5) kaolin and Al and Fe oxides (Mitchell and Sitar, 1982). The temperature controls the rate of weathering, while the rainfall affects the availability of moisture which controls the activity of the clay minerals formed. A typical profile through a tropical residual soil is illustrated in the Figure 1.

According to Wesley (1973) the weathering process leading to the formation of allophanic soil is :

volcanic ash --->allophane B ---> allophane AB ---> allophane A ---> meta halloysite ---> kaolinite

Meanwhile, Gichaga et al (1987) sugested the weathering sequence leading to the formation of halloysitic soil as follow :

volcanic ash ---> montmorillonite ----> halloysite ---> kaolinite

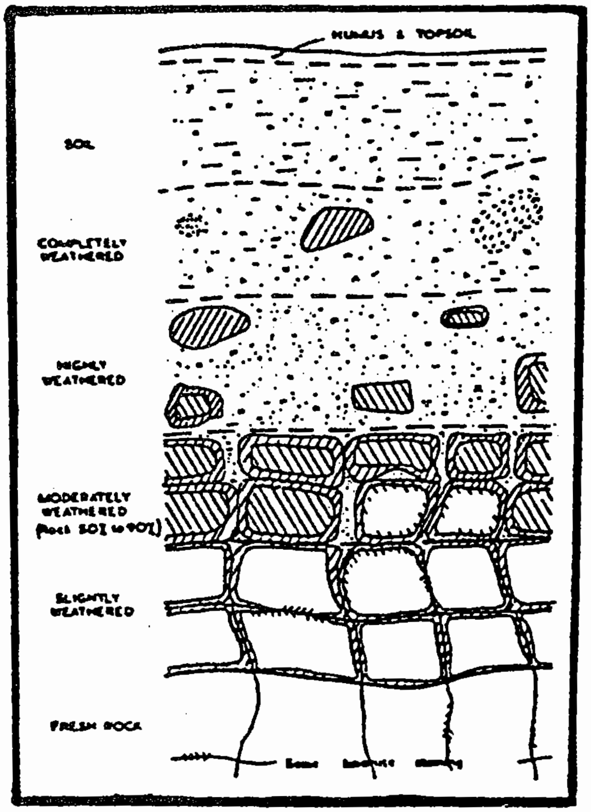

Figure 1. Typical profile through tropical residual soils (Little, 1969, taken from Mitchell and Sitar, 1982)

The weathering process on halloysitic soils has developed further than that on allophanic soil. The parent material of allophanic soil is volcanic ash of Quaternary or Recent age (Tan, 1965). It can attain maturity within 5000 years (Wada and Aomine,1973 after Tan,1965). Yamada (1977) after Tan (1965)

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suggested that allophanic soils can be developed within five hundred to fifteen hundred years, depending on soil formation factors, for instance the type of volcanic ash. Despite the different degree of weathering maturity, the weathering process leading to formation of both soil types involves the leaching out of silica and bases which increases the concentration of iron and aluminium oxides (in their hydrated forms).

SAMPLING AND LABORATORY TEST PROCEDURE

Field samples were taken from 20 - 40 cm depth in 20 sites, selected at random on the failed slope. They were kept in cold storage and then returned to the United Kingdom for testing.

The test was conducted on a core sample of 5 cm diameter and 3 cm thickness (Figure 2). The sample should be fully saturated prior to the test (Figure 3.a). During testing the sample was placed on ceramic disc inside a sealed testing cell (Figure 3.b and c). A controlled pressure was applied into the cell to drain out the water from the saturated soil sample. The saturation of the sample was recorded until the equilibrium was reached; this was repeated for a range of pressures. The applied pressure was equal to the soil suction required to retain this particular water saturation in the soil. Once equilibrium had been reached, the applied pressure is increased and the procedure repeated. The test was stopped when there was no further saturation reduction in response to increased applied pressure.

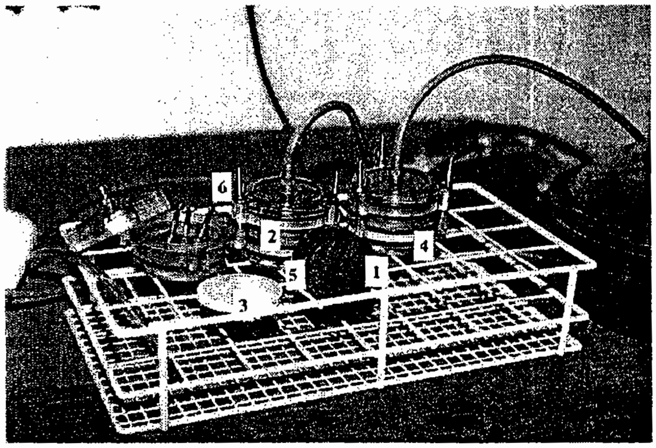

Figure 2. Soil sample and test cell: 1) soil sample held in the ring, 2) sample cell, 3) ceramic disc, 4) rubber ring to seal the cell , 5) metal ring to hold the sample, 6) screw to tighten the cell

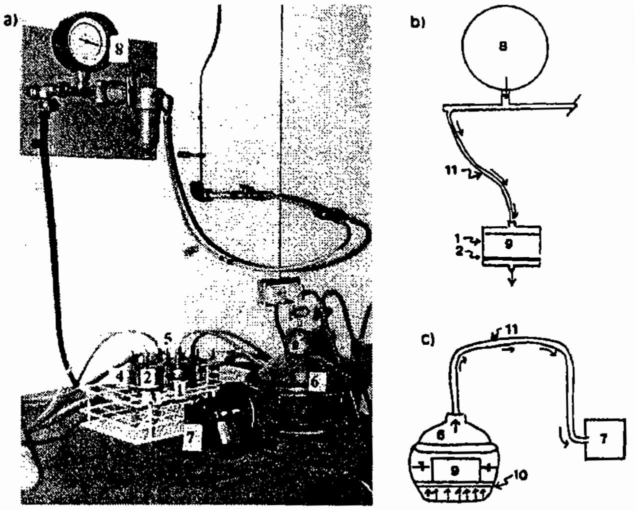

Figure 3. a. Test equipment, b. schematic test equipment, c. schematic equipment for saturating core sample : 1) cell to place the sample, 2) ceramic disc, 3) sealed ring , 4) metal ring to hold the sample, 5) screw to tighten the cell, 6) vacuum desiccator, 7) pump to saturate the sample, 8) pressure gauge, 9) core sample, 10) fine mesh, 11) plastic tubes. ⟶ air flow, ········> water flow.

Soil description

The allophanic soil was dark brown and slightly soft when moist but became firm and gritty when dried. The dry density was in the range of 0.57 to 0.93 g/cm^3 and the void ratio was 2.5 to 4.0. Sugalang (1989) reported that the soil had high plasticity and consists of 4 % to 11 % (by weight) clay size, 26 % to 49 % silt size, 37 % to 43 % fine sand size, 2 % to 8.5 % medium sand size and 0.5 % to 1 % coarse sand size particles. Thus, the silt and fine sand size dominate the soil material.

An example of the X-ray diffraction pattern of allophane is illustrated in Figure 5. The allophane diffraction pattern typically does not show any distinct peak (Brindley and Brown, 1980). This is because the allophane has poorly crystalline or amorphous structure.

The halloysitic soil was reddish brown. When it was fully saturated it was soft and it became firm and gritty when it was dried. The natural moisture content was 46 % to 67 %, the dry density was 1.17 to 1.26 g/cm^3 and the void ratio was in the range of 2.6 to 2.8.

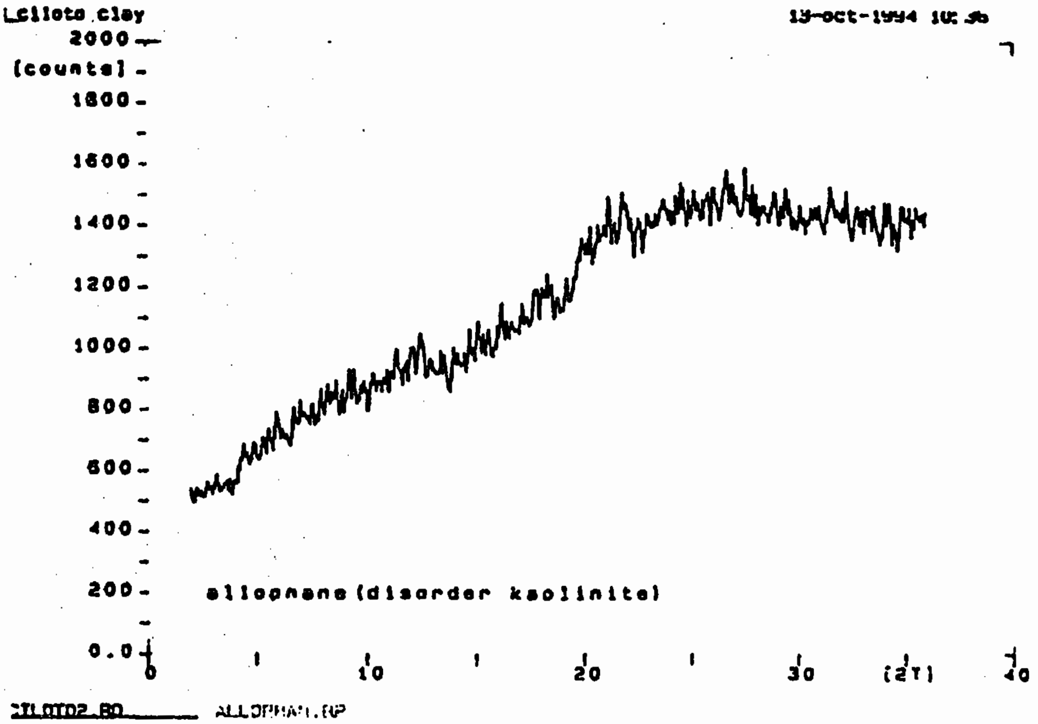

Figure 4. X-ray diffraction pattern of allophane

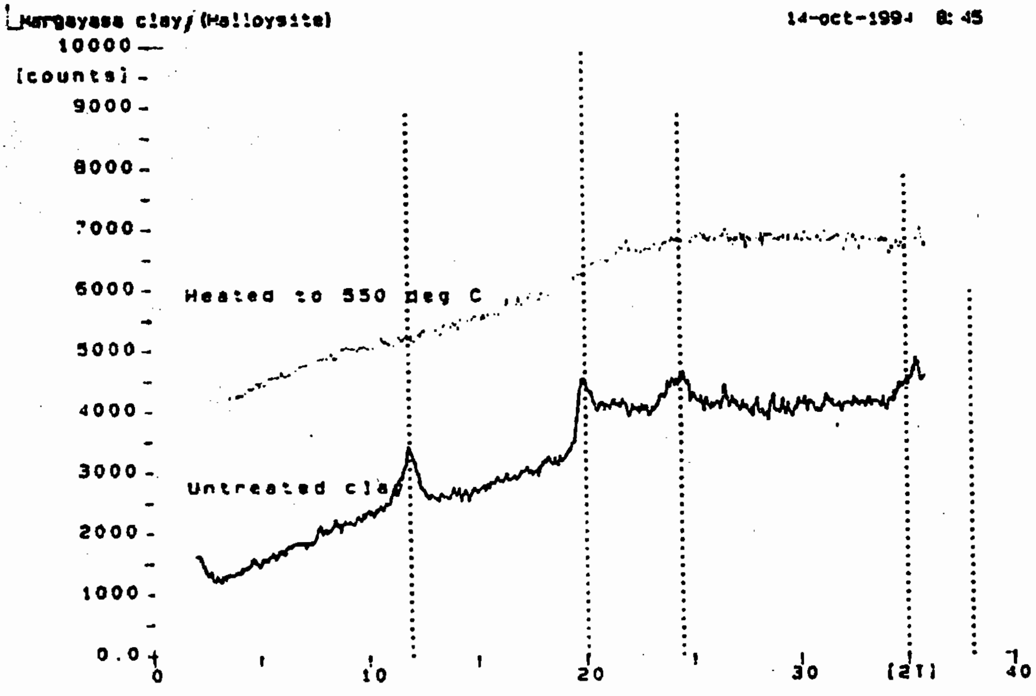

Figure 5. X-ray diffraction pattern of halloysite

The Ministry of Public Works (1989) reported the soil had a liquid limit of 52% to 86.5%, a plastic limit of 36.6% to 62% and an plasticity index of 10% to 42%. This soil consisted mainly of silt.

An example of the X-ray diffraction pattern for the halloysite ($Al_2O_3.SiO_2.nH_2O$) is illustrated in Figure 5 This pattern shows three distinct peaks in which the inter-planar spacing (d) is about 10 Å (redgraph). When the sample was heated to 550° the peaks disappeared (green-graph), as is typical for halloysite (Bridley and Brown, 1980).

Both allophanic and halloysitic soils are sensitive to shrinkage. According to Karnawati (1992) the shrinkage limits for allophanic soil from Indonesia with dry density of 0.9 gr/cm^3, and halloysitic soils from Kenya with dry density of 1.20 gr/cm^3 can exceed 40 %. The shrinkage ratio of the former is 0.45 to 1.12 and of the latter is 1.13 to 2.70.

SOIL MOISTURE - SUCTION RELATIONSHIP OF ALLOPHANIC AND HALLOYSITIC SOILS

A total of 16 cores were tested of which 6 held tension to 100 kPa. The remaining cores had problems of air entry or failure of the ceramic disc during the test runs.

The soil moisture-suction relationships for the allophanic and halloysitic soils respectively are illustrated in Figure 6. In the allophanic soil the initial saturated volumetric water content is about 0.85 cm^3/cm^3 and in halloysitic soils it is initially about 0.72 cm^3/cm^3. There was no drainage occurring under suctions up to 1 kPa (0.1 m suction head) for the allophanic soil and 0.5 kPa (0.05 m suction head) for the halloysitic soil. The air entry suction value (ψ_a) of allophanic soil was therefore about 1 kPa and of halloysitic soil was about 0.5 kPa.

As the suction increased, drainage water became more effective. The volumetric water content in allophanic soil decreased to 0.66 cm^3/cm^3 in response to suction of 20 kPa (2 m of suction head), whilst that in halloysitic soils decreased to 0.56 cm^3/cm^3 in response to suction of 20 kPa (2 m of suction head). However, further suction rose up to 100 kPa (10 m of suction head) had little effect. It only reduced the volumetric water content to 0.64 cm^3/cm^3 (further 0.02 cm^3/cm^3 reduction) for allophanic soil and to 0.5 cm^3/cm^3 (further 0.06 cm^3/cm^3 reduction) for halloysitic soil. These were thought as the residual volumetric water content values of both soil types as there was no further significant change in the volumetric water content when the suction increased from 100 to 120 kPa.

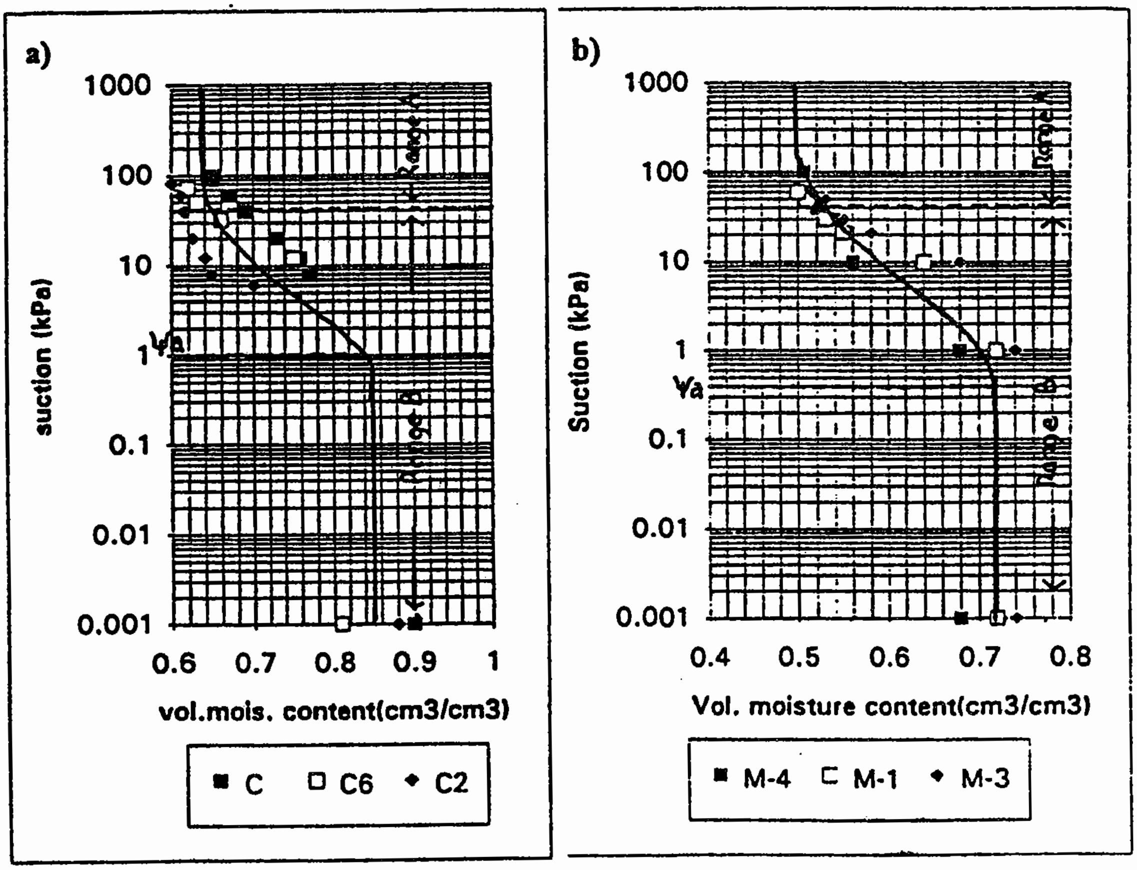

Figure 6. Characteristics of soil moisture-suction relationship,
a) allophanic soil and b) halloysitic soil

ANALYSIS AND DISCUSSION

According to Hoggentogler (1937) there are several types of soil moisture contained in the clay soil (Figure 7). These are free water that has the freezing point, boiling point, surface tension and the viscosity of ordinary water as well as adsorbed or hydrated water that has higher boiling point, lower freezing point, greater surface tension, and is more viscous than the free water.

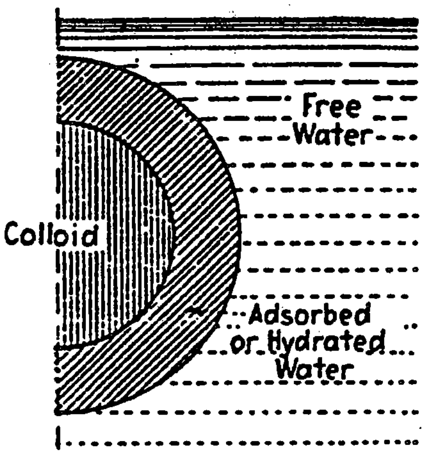

Figure 7. Types of soil moisture (Hoegentogler, 1937)

The free water is contained inside the voids between the clay particles. In physical terms it is gravitational or capillary water, which can be drained by gravity. The adsorbed or hydrated water occurs due to the strong affinity of the clay minerals (allophane or halloysite) for water, which in turn arises from the hydroxyl groups existing on the surface of the mineral particles (Wada, 1966; Wada, 1977). This water can only be drained by very large suctions.

Allophane and halloysite have characteristic structures that cause them to contain water other than those types mentioned above. Allophane is amorphous clay which consists of peds or aggregates within which there are micropores (Rousseaux and Warkentin, 1976 after Tan, 1965). Typical unit particles are spherical with diameters of 30 - 50 Å. Allophane of Andosol from Indonesia is shown in Figure 8. The micropores are too small to be seen in the photograph. The water contained in the micropores can only be removed by oven drying and therefore contributes to the residual saturation (Rousseaux and Warkentin, 1976 after Tan, 1965).

Halloysite crystals consist of clay lattices which have a tabular shape (Figure 9). There is also intra lattice water (Brindley and Goodyear, 1948) which can be removed by oven drying.

AG = AUGITE MG/IL = MAGNETITE OR ILMENITE BRW = BURROW STRUCTURE (ROOT CHANNEL)
AL = ALLOPHANE IO = IRON OXIDESM = SHRINKAGE MICROCRAK

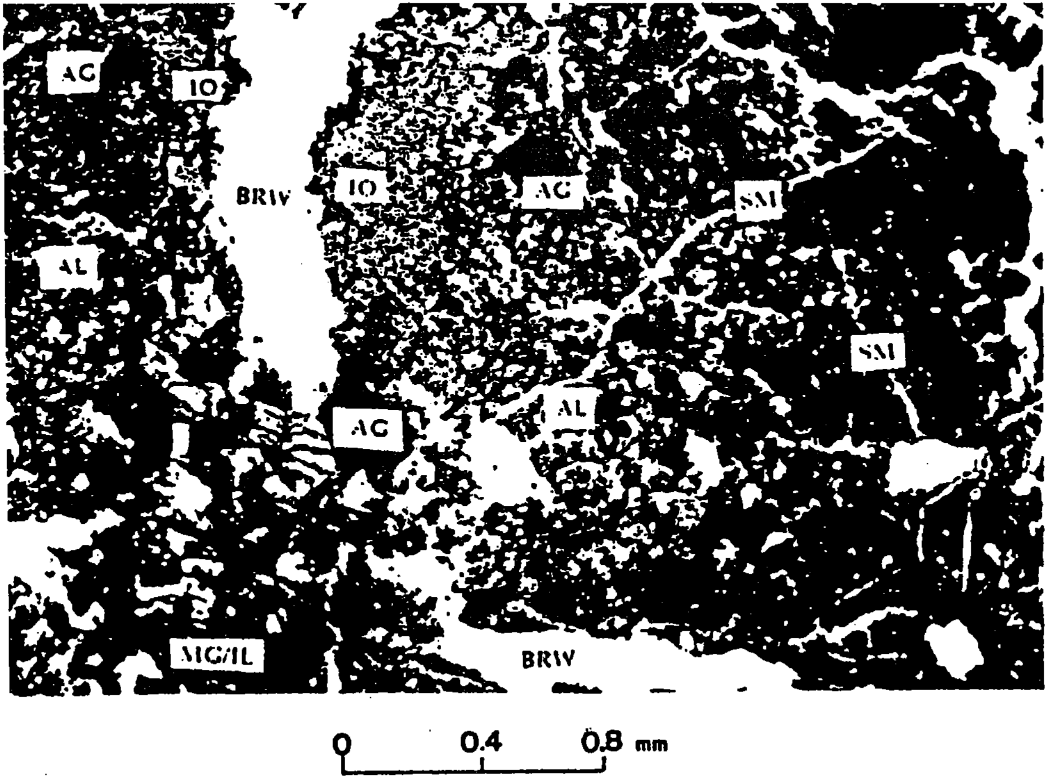

Figure 8. Allophane in Indonesian Andosol (photo courtesy of British Geological Survey)

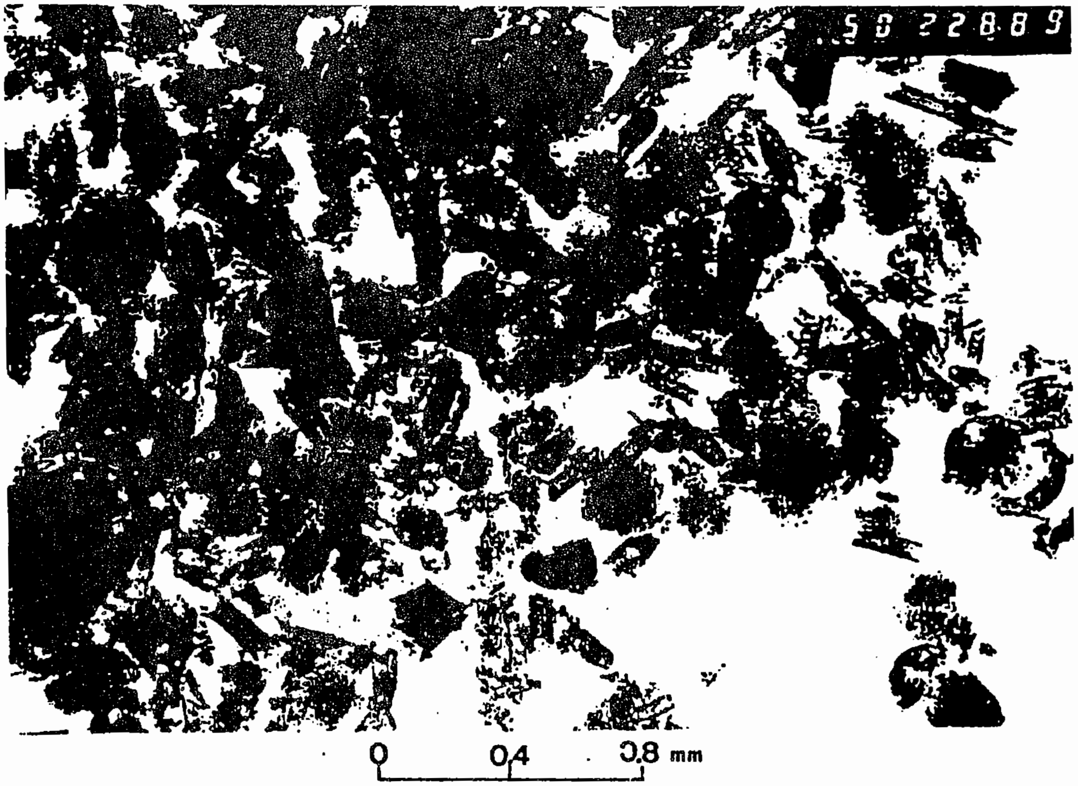

Figure 9. Halloysite structure with tabular lattices (photo courtesy of British Geological Survey)

When suction is applied to the soil samples, only free water can initially drain from the voids. When suctions lower than 5 kPa are applied, no water drains. When the suction is increased so that the air entry suction is exceeded, the water inside the larger voids is drained first. This is because the larger the void diameter, the lower the capillary force. As the suction is further increased, more water is drained out from progressively smaller voids. This process is represented by the gentle gradient portion of the curve in Figure 6. Once the free water has emptied from the voids, the adsorbed water begins to be drained out. The draining rate of this type of water is slower than that of the free water because the free water has been replaced by air, which prevents the movement of the remaining water. It is also probable that the affinity of the clay minerals for this adsorbed water plays a significant role here. When the applied pressure is increased beyond 100 kPa, there is little further draining of water. The volumetric water content has reached equilibrium and is termed the residual volumetric water content. The water is now a discontinuous phase in the soil.

In comparison with other soil types which do not contain allophane and halloysite, the residual volumetric water content is high. This is due to the water retained inside the micropores in allophanic soil and the intra lattice water in halloysitic soil (Brindley and Goodyear, 1948).The high amount of organic content in allophanic soil, which is reflected by the dark colour, is also responsible for the high water holding capacity (Tan, 1965). Such waters can only be removed by oven drying.

In the allophanic compared with the halloysitic soil, the presence of micropores with diameters of up to 20 Å (Rousseoux and Warkentin, 1976) as well as the high organic content are also responsible for the higher volumetric water content, the higher void ratio and the lower soil dry density

Indeed, in the A horizon of the allophanic soil in which organic matter is abundant, the soil dry density is in the range of 0.3 to 0.8 g/cm^3 (Maeda and Warkentin, 1975), which is below typical values for other soil types.

Problems

Problems arose in this investigation which were associated with the duration of test and the effects of oven drying.

Because of the fine size of the soil particles and the strong affinity of the clay minerals (allophane or halloysite) for water, it takes a long time to reach equilibrium. For each applied pressure stage, about 2 weeks to 3 weeks were required. At least 5 pressure levels were applied in each test.

In order to find the volumetric water content, the samples were oven dried. This procedure is not usually problematic for soils unless they have water associated with the organic matter, micropores and intra lattice water in which case the oven dry weight may not be representative. This can be explained as follows :

The rate of infiltration is calculated based on the rate of soil moisture changing with time. The soil moisture concerned here is the free water, called the effective water content, that can be drained out by applied suction, not including the water contained in the micropores or intra lattice spaces. On the other hand, the volumetric water content obtained from the laboratory test includes the water contained in the micropores and intra lattice spaces. In terms of the rate of soil moisture changing with time, there is no difference between the effective volumetric water content changing and the tested volumetric water content changing in response to the applied suction. It is therefore considered that the volumetric water content tested in the laboratory does not cause any problem with the simulation of the rate of infiltration.

SUMMARY AND CONCLUSION

The characteristics of the soil moisture-suction relationship for allophanic and halloysitic soils differs significantly from those of other clay soil types. Relatively high volumetric water contents are maintained under suction exceeding 100 kPa. The rate of drainage is also very low. The unusual/a typical structures of allophane and halloysite clays as well as the fine particle size are responsible for these characteristics. Indeed, the existence of water associated with the organic matter, micropores and intra lattice water in these clay types significantly controls their unique behavior.

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