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ENGINEERING GEOLOGICAL CHARACTERISTICS OF THE CLAY SOILS OF BOLE AREA, THEIR DISTRIBUTION AND PRACTICAL IMPORTANCE

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Engineering geological characterstics of the clay soils of Bole area, their distribution and practical importance

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Abstract

On the basis of the demand to construct new engineering objects, an engineering geological study was carried out in Bole and the surrounding area.

Basic igneous rocks (basalts) are exposed along river valleys and pyroclastic sediments (welded tuffs) outcrop as a form of isolated ridges in many places of the area. Most part however, is covered by thick (5-6 m) accumulations of clay and sandy clay soils. Except for those present in river valleys, all the rest clay and sandy clays are found as residual soils.

The area is generally flat with some undulations and control moisture migrating from the surrounding high lands. The annual mean evapotranspiration is higher than the annual mean precipitation and this condition exercises an influence on the formation of clay soils of the area.

Field investigations of the area on the basis of test pits, dug holes and bore holes indicate that both the clay and sandy clay soils grade with depth to sands, gravels and boulders of bed rocks.

The following types of laboratory analyses were carried out on soil samples: organic matter, calcium carbonate and clay mineral content, bulk and dry densities, porosity, void ratio, consistency limits, free swell and swelling pressure determinations. The results obtained indicate varying degrees of interdependence.

Grain size distribution indicate the presence of greater proportion of clay fraction compared with silt and sand. Mineralogical analysis of the fraction less than 0.075 mm

showed high percentages of montmorillonite in all lithological type of soils with smaller amount of illite and kaolinite. Consistency limits were determined and index values calculated for all soils and it is observed that the clay soils of the area have the highest plasticity relative to sandy clays and hard to be crushed. Swelling pressure values of clay soils indicate a considerable degree of swelling which poses structural failures.

Based on field investigations and laboratory analyses an engineering geological classification of soils and rocks was hierarchically constructed. The clay soils are classified as inorganic and organic clays of high plasticity where as all the sandy clays are of low to medium plasticity and divided into two in terms of their origin (those which are in situ weathering products and those of alluvial origin). The rocks on the other hand, are classified in to three units according to their lithology and weathering grade.

The results of the classification system are presented in the form of an engineering geological map.

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1. Introduction

Soils which are weathering products of volcanic rocks are the most widely spread types of soils, that cover the Bole and surrounding area. Many engineering structures were constructed on these soils for the past few decades and some site investigations had been carried out delivering fundamental geotechnical data for the construction at hand. Due to the increase in the interest of people to build up many new engineering objects on this area, it was desired to study the engineering geological properties of the soils so as to prepare an engineering geological map. The later presents the distribution of different kinds of soils, their lithology, thickness and properties. A special emphasize was given to the swelling properties of the soils on the bases of the demand for to solve construction failures. All these data should be relevant to different stages of planning and constructions of some engineering structures.

The study area comprises the southeastern part of Addis Ababa bounded by latitudes $8^{0}57'43"$N and $9^{0}00'50"$N, and longitudes $38^{0}45'55"$E and $38^{0}49'04"$E (Fig.1.1), and is located at the western margin of the Main Ethiopian Rift. The area belongs to somewhat moderate humid condition in which the average annual total of evapotranspiration exceeds the mean annual total of precipitation. Big trees and bushes are generally scarce except in the northern part where abundant vegetation types are present. Asphalts and unpaved roads are widely distributed in the area and makes it easily accessible

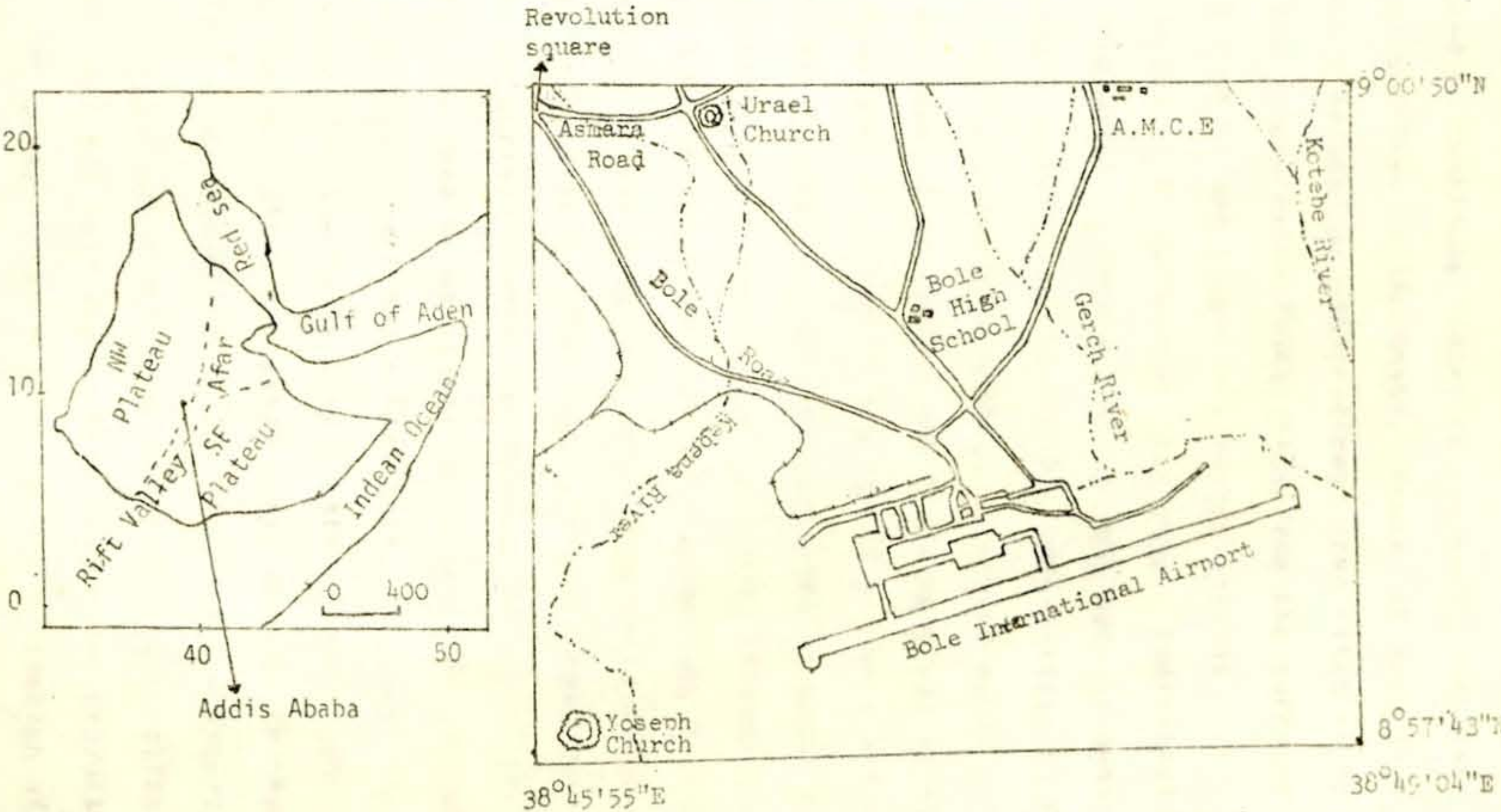


Fig.1.1. Location map of the study area (Scale 1: 59000).

on foot and by any kind of vehicle. The area is nearly flat, surrounded by continous ridges to the north side and is open with gentle slopes to the south. Hence, it acts as a receptacle of moisture induced by either direct precipitation or surface runoff and ground water fluctuation from the surrounding areas.

The surface and subsurface investigations of the area was conducted with the help of test pits. Additional informations were obtained from dug holes (DH) made by owners for construction purposes and bore holes (BH) drilled by Ethiopian Building Design Enterprise (EBDE). Detailed photo interpretation was carried out before the field work was started to be familiar with the general geology of the area and mainly to estimate the general location of test pits to be carried out. The orginal proposed location of test pits however, was modified due to artificial and natural problems and mainly due to the presence of dug holes and bore holes which would provide adequate informations. (See App.1, field methdology).

During surface mapping and sample logging of the existing test pits and bore holes it was found possible to recognize two rock units: Basalt and Welded tuff, and three soil units: Clay, Silty Clay and Sandy Clay. Later however, the silty clays bulge into clays and sandy clays when their physical properties were determined in the laboratory. Except for some of sandy clays which cover the main river valleys of the area, all the rest are in situ weathering products. The absence of quartz in the basalt and the collection of minute particles of volcanic glass in the welded tuff lead to the formation of a fine grained mostly clay size, plastic soil which can easily become water logged (Ola, 1981). Environmental factors such as climate and topography have a significant influence on the genesis and engineering geologic properties of those soils since they affect the degree of weathering and exercise a selective control on the types of clay minerals which can form from weathering processes.

The influence of geological factors on the physical properties of soils of the study area might increase since the early stages of soil formations. The different weathering grades observed in the study area introduced important variations in particle size, mineralogy and structure of soils and therefore influence the soil properties. In this study, it is tried to formulate the effect of organic matter, clay minerals and particle size in governing the engineering geological property of soils.

For determination of soil units on the basis of engineering geological properties various laboratory tests were carried out and jointed with informations obtained from the field analysis. Grain size distribution and plasticity are properties examined for the classification of soils. Each soil unit has a definite genetic relation and engineering geological characterstics, and can be considered as a definite and uniform type of medium. The resulting classification is presented in the form of an engineering geological map which reflects clearly and accurately the site conditions and is convenient in application for engineering design and

and construction. The map also gives general ideas about the surface conditions and provides existing test pit and bore hole locations and graphic presentations of the subsurface conditions along the cross section.

In order to find a working solution to the problems created by the soils of the study area, various attemnts were carried out on the basis of geotechnical studies. In 1975, the Ministry of Public Works and Housing proposed remedials for the damaged buildings of the study area. Later, Solomon (1982) presented M.Sc. thesis on case studies of building damages in Addis Ababa area. Geologists from Ethiopian Institute of Geological Survey (EIGS), are currently conducting a research to prepare an engineering geological map of the Addis Ababa area. The present work will provide additional informations on the engineering geological properties of the soils and rocks of the study area.

2. The geology and geomorphology of the study area

2.1. The geology of the study area and its surroundings

2.1.1. Regional geology

The Addis Ababa region is located at the western margin of the Main Ethiopian Rift Valley. The geology of this region and the surrounding areas had been studied by several researches both locally and in regional scale. The stratigraphy given by Morton et al. (1979) and Haile Selassie and Getaneh (1989), is shown below.

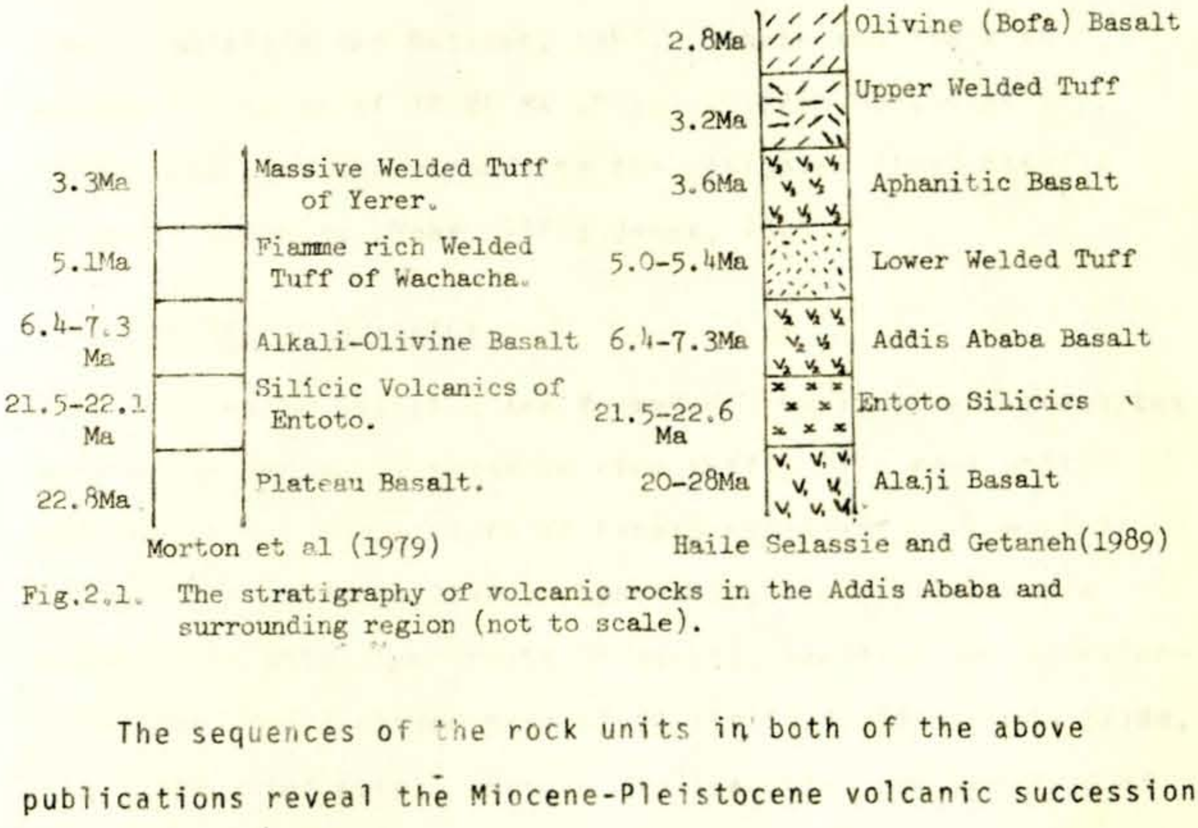


Fig.2.1. The stratigraphy of volcanic rocks in the Addis Ababa and surrounding region (not to scale).

The sequences of the rock units in both of the above publications reveal the Miocene-Pleistocene volcanic succession ranging from older plateau volcanics to younger rift volcanics. The rock units are described below according to their stratigraphic order from bottom to top. The description is mainly based on Haile Selassie and Getaneh (1989) and all therminologies of rock units are kept the same.

The Alaji Basalts

The Alaji Basalts have got their name from a village called "Alaji" located 426 kms from Addis Ababa on the Addis Ababa-Asmara road (latitudes 8°33'N, longitudes 39°26'E). In the surrounding area of Addis Ababa, these rock units are exposed at the crest of Entoto hills (which bounds the northern limit of Addis Ababa) and across the Sululta plain (15 km to the north of Addis Ababa). The basalts showed variations in texture from porphyritic with phenocrysts of labradorite, andesine, pyroxene and magnetite to aphyric. (Haile Selassie and Getaneh, 1989). Their age limit is within the range of 20-28 Ma (Morton, 1974; Morton et al., 1979), and this corresponds to the Ethiopian flood basalts of early Tertiary (Mohr, 1964; Jones, 1976).

The Entoto Silicics

The Entoto silicics are formed of rhyolites and trachytes with minor amount of obsidian rich tuffs. The rock units outcrop at the upper parts of Entoto hills and on the plain to the east of Addis Ababa. Generally, the rhyolites are porphyritic with phenocrysts of quartz, sanidine and andesine-oligoclase and a ground mass of divitrified glass, iron oxide, plagioclase and quartz whereas the trachytes are composed of phenocrysts of anorthoclase, sandidine, oligoclase and magnetite and a ground mass of divitrified glass and plagioclase (Haile Selassie and Getaneh, 1989). These rock units are 21.5-22.6 Ma old (Morton, 1974; Morton et al., 1979).

At the southern flanks of Entoto they are overlain by alkali-olivine basalts.

The Addis Ababa Basalt

This rock unit mainly outcrops at the northern and north-western part of Addis Ababa extending from the southern flanks of Entoto hills to the Filwoha region. It is composed of olivine-rich and plagioclase-rich subunits. These subunits are porphyritic in texture with phenocrysts of labradorite-bytownite and olivine and augite respectively. The ground mass is made of andesine, labradorite, olivine and magnetite (Haile Selassie and Getaneh, 1989). This alkali-olivine basalt rock unit is 6.4-7.3 Ma old (Zanettin and Justin-Visentin, 1974; Morton, 1974; Morton et al., 1979), which places it in Oligocene. The Addis Ababa basalt is overlain by welded tuffs to the south of the Filwoha region.

The Lower Welded Tuff

This rock unit is exposed mainly in the central and south-western part of Addis Ababa. It is strongly welded, composed of glass with abundant fiamme. Absolute age determinations of samples taken from Kebena river (near Aboware) by Morton (1974), and Sululta area by Morton et al. (1979) put its age in the range of 5-5.4 Ma. This age corresponds to the Wachacha volcanism dated to be 4.5 Ma by Miller and Mohr (1966). It may thus be derived from this volcano (Haile Selassie and Getaneh, 1989).

The Aphanitic Basalt

The type locality of this rock unit is mainly around the Bole International Airport and in the upper reaches of Akaki river valley. This basalt is vesicular in texture and the vesicules are filled by calcite. It is composed of fine grains of plagioclase, clinopyroxene and magnetite (Haile Selassie and Getaneh, 1989). The K-Ar age determination of Morton (1974) and Morton et al. (1979), in the tributary of Akaki river valley near Lideta airfield (at the southwest part of Addis Ababa) indicates that the basalt is 3.6 Ma old. This age corresponds to Yerer volcanism whose age is 3.5 Ma (Morton and Rex, 1975) which is assumed to be the parent source of this basalt.

The Upper Welded Tuff

This rock unit is the youngest of all volcanic rocks outcropping in the Addis Ababa region. It covers the south and southwestern part of Addis Ababa and extends to the Akaki town (15 km to the southeast of Addis Ababa). It is composed of sanidine, anorthoclase, riebekite, quartz, pumice and unidentified volcanic rock fragments (Haile Selassie and Getaneh, 1989). As determined from a sample near Kebena river around Asmara road, the age of this welded tuff is 3.2 Ma (Morton, 1974). It is overlain by olivine basalt at Akaki river near Akaki town (Fig. 2.2).

2.1.2. Local geology of the study area

The study area constitutes the southeastern part of Addis Ababa. The area is composed of two relatively younger rock units namely:

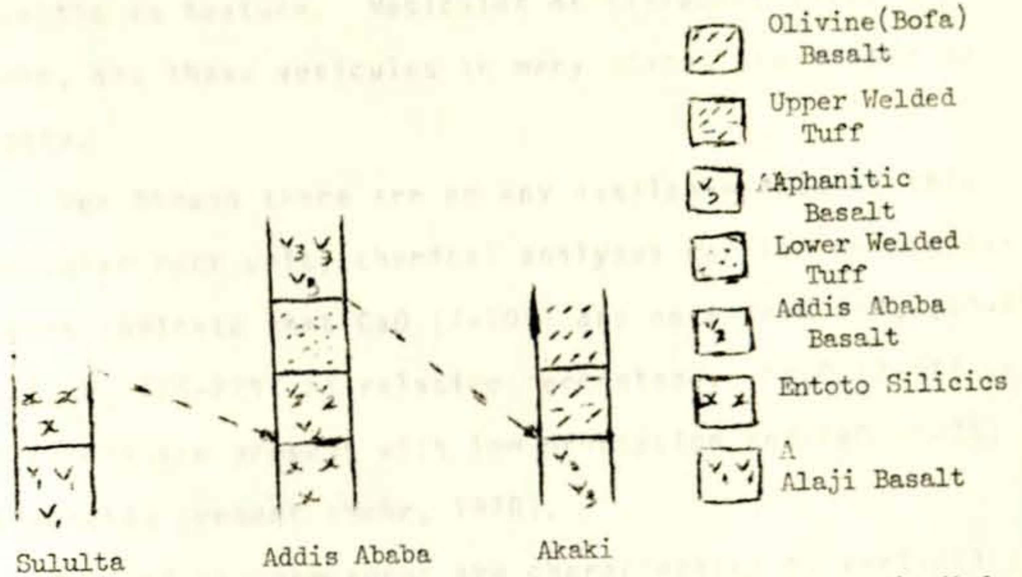


Fig. 2.2. Stratigraphic correlation of rock units in the Addis Ababa and surrounding region (not to scale). After Haile Selassie and Getaneh (1989).

- The Aphanitic Basalt
- The Upper Welded Tuff

As described in the Regional geology section, the Aphanitic basalt is older than the upper welded tuff and the following description is according to this stratigraphic order.

The Aphanitic Basalt

This basaltic unit is exposed in the south and south-eastern part of the study area mainly in Gerch and Kebena river valleys around Bole International Airport (Fig.2.3).

Mineralogical analyses of this basalt indicated that plagioclase and augite are the dominant components with minor amount of olivine and magnetite (Haile Selassie and Getaneh, 1989). Big phenocrysts are lacking and the rock unit is aphanitic in texture. Vesicules of different sizes are common, and these vesicules in many places are filled by calcite.

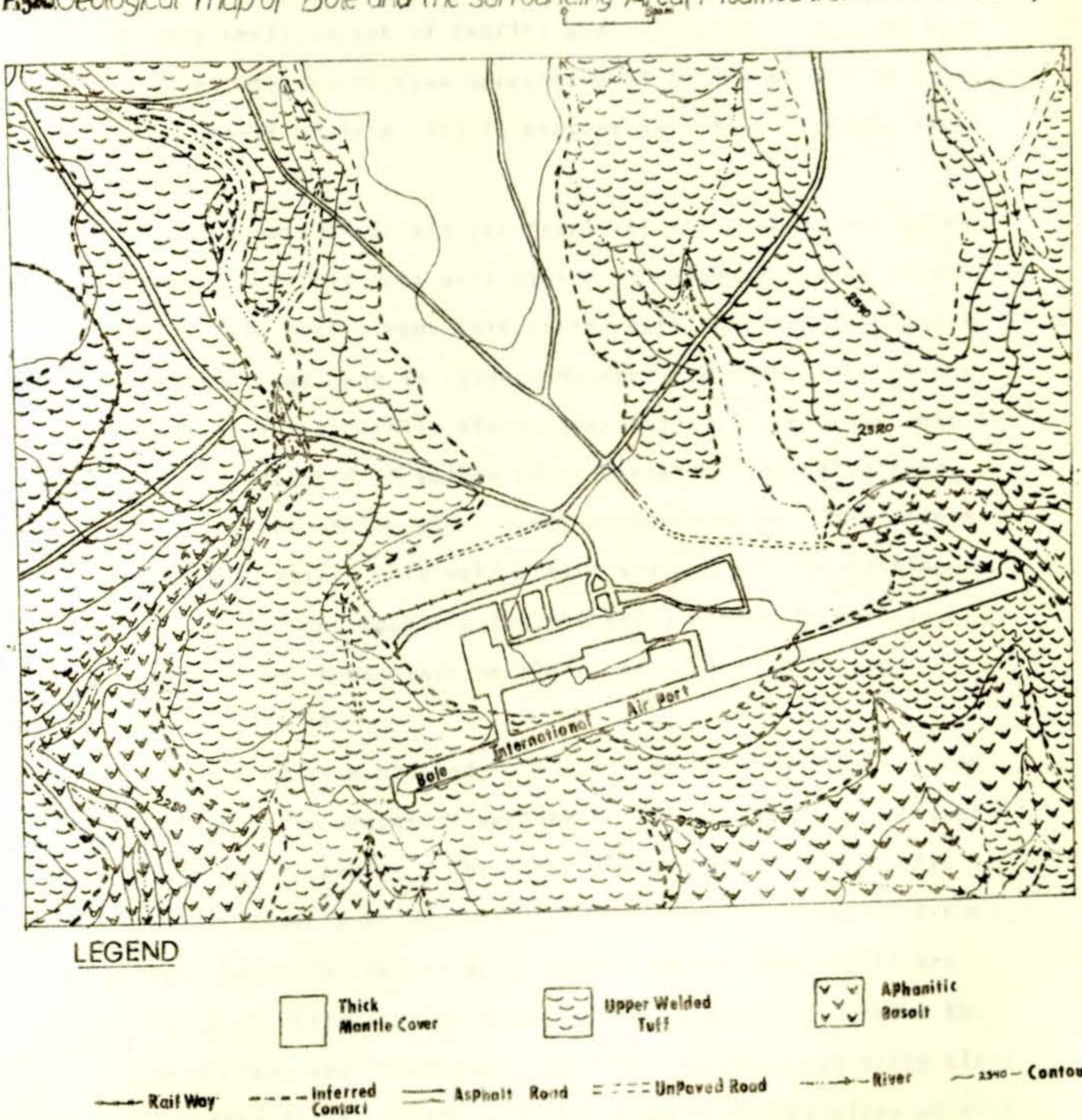
Even though there are no any available data on this particular rock unit, chemical analyses carried on similar basalts indicate that CaO (7-10%) are next from SiO_2 (40-45%) and Al_2O_3 (15-22%) in relative percentage. Na_2O (2-5%) and K_2O (2-4%) are present with low proportion and FeO (5-7%) is appreciably present (Mohr, 1970).

Most of the exposures are characterized by vertical and horizontal joints with the later crossing the former in some places and flow bands of NE direction are commonly observed. In most consequent streams it is spheroidally weathered along two sets of joints and in some places it is exteremely disintegrated grading to heavy crusts. In river valleys and quarries its thickness ranges from 3-16 m and as is discussed before it is dated to be 3.5 Ma in age (Morton and Rex, 1975).

The Upper Welded Tuff

This rock unit is the relatively younger rock unit exposed in the study area. It is dominantly present in the eastern and southwestern part as a form of isolated ridges (Fig. 2.3). It is composed of sanidine, anorthoclase,

Fig.2.5. Geological map of Bole and the surrounding Area (Modified from Morton, 1974).



riebekite, pumice and some unidentified volcanic rock fragments (Haile Selassie and Getaneh, 1989).

Chemical analyses of this rock unit indicate the presence of a relatively high amount of SiO_2(72%) and Al_2O_3(10%) and a very small amount of CaO(1%) and MgO(0.5%). Na_2O and K_2O present with respective percentage of 3% and 5% and an apprciable amount of iron (4%) is present as a form of Fe_2O_3 (Mohr, 1970).

Two sets of joints (vertical and horizontal) are characterstics of this rock unit giving it columnar blocks of various sizes. In most places this welded tuff is fresh to slightly weathered and grey in color. However, in some parts of the study area (especially along river valleys), the rock unit is globally altered to yellow color variaties (pantelerized). In any place of the study area, there is no any clear contact observed between this welded tuff and the basalts mentioned above. In some quarries its thickness ranges from 10-15 m and K/Ar age determination places it to be 3.2 Ma old (Morton, 1974).

The above mentioned rock units of the study area grade both to heavy crusts of weathering and directly to soils of different thickness. The late pliocene-recent clay soils largely cover most part of the area to a thickness of 2-6 m. The relatively flat areas (central and northern part) are places of thick (5-6 m) deposits of these clays whereas the sandy clays are localized along river valleys and silty clays with gravels and bounders distributed in places close to rock exposures. The present work gave more emphasize to the engineering geological characterstics of these soils and hence a brief description and classification of the soils of the study area is given in Chapter 4 and Chapter 6.

2.2. The Geomorphology of the study area and its surroundings

The Addis Ababa area and its surroundings is quite rugged with many typical volcanic topographic features. Among these volcanic features the most important are: Entoto Ridge (elv. 3200 m), Mt Yerer (3100 m), Mt Furi (2839 m) and Mt. Wachacha (3385 m).

The steep slopes of Entoto Ridge surround the city on its northern sides, whereas to the south it is open to gently south sloping surface which extends to the Ethiopian Rift. In the Addis Ababa region elevation varies from about 3100 m in the north to 2500 m in the south. The slope decreases sharply from north (the area from foot of Entoto hills to Filwoha region) to the south from Inclination of 30^0-35^0 to 5^0-7^0 respectively.

The Addis Ababa region has been an active zone of sliding even though the degree of movement varies from place to place. The northern morphounit (with a slope of 30^0-35^0) is characterized by rock slides. In the morphounit to the south, since the topography slopes gently with an inclination of 5^0-7^0, the area seems to be affected by slow mass movements (creeping). Slumping is suggested to be the main way of mass movement in the middle sector of the two extremes the degree of movement being governed by the lithology and geologic setting of the rocks and climate of the area.

The topographic features of the study area are the results of the youngest volcanism. The basalt flows and welded tuffs cover most of the area and govern the macro and micro-relief condition. As discussed before, the area is generally flat with an undulating microrelief. The undulating surfaces

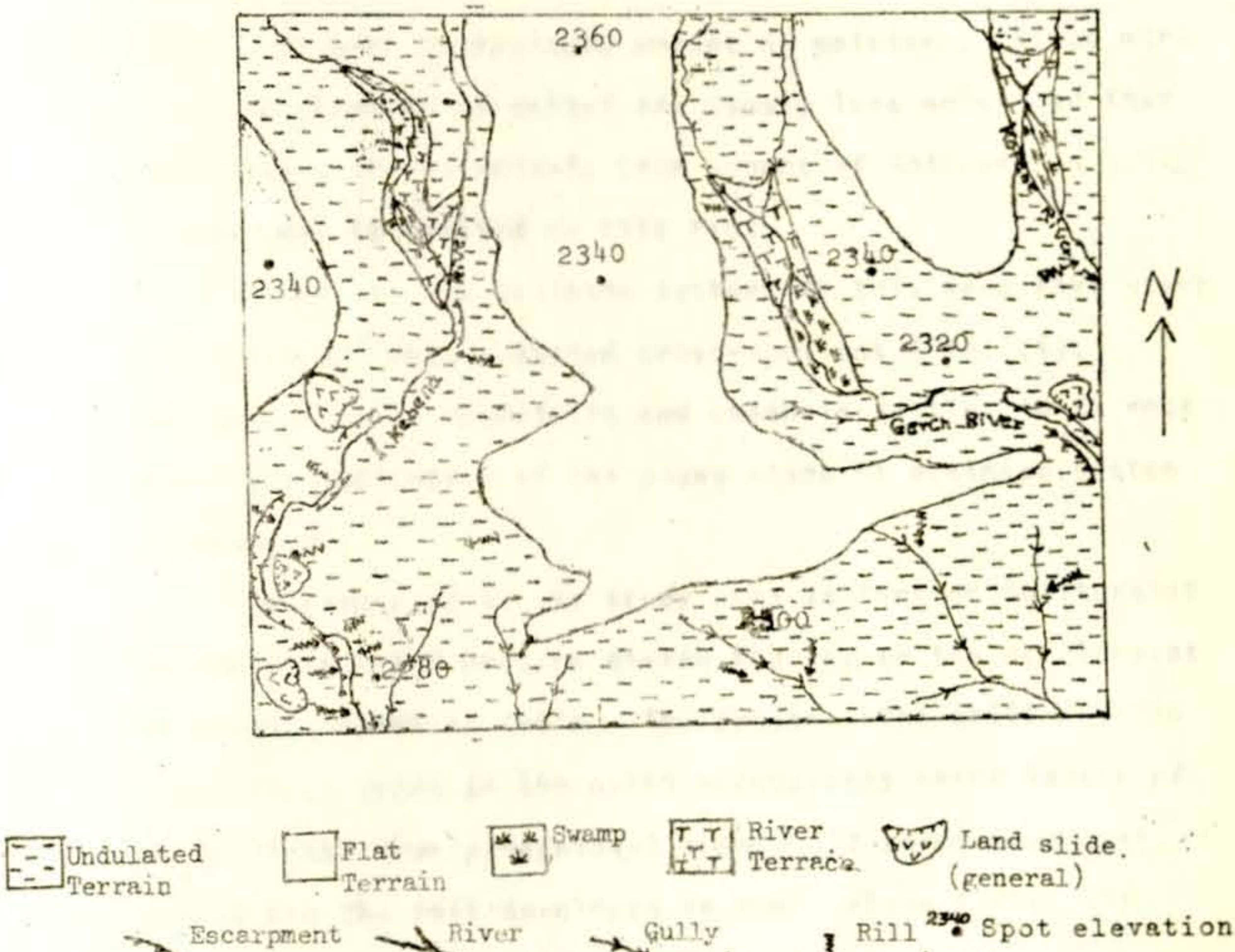


Fig. 2.4 Geomorphological map of Bole and the surrounding area (scale 1:50000)

result from the existing isolated ridges of welded tuff and basalt (Fig.2.4). Hence, within the area there are no dominant morphologic directions with the exception of the southern part. From general consideration the area seems to be flat with a slope of 1^0-3^0 and in the southern part however; the value increases to 5^0-7^0 with southward inclination.

A very interesting thing related to the difference in the slope of the study area and its surroundings and the resulting undulating surface is that most of the soils are associated with appreciable amount of moisture. Since more elevated elements of relief are usualy less moistened than lower ones, the relatively high amount of moisture in soils of the area is related to this fact.

Almost all the drainage systems in this area have steep sided valleys with v-shaped cross-sections (Fig.2.4). Frequent rapids, waterfalls and channels cutting in to rock units are indicative of the young stage of drainage system development.

The landscape of the study area is further obliterated by weathering and erosion giving the way to the development of various kinds of soils. The erosion that still acts in mountainous areas to the north accumulates thick layers of soils in the low-lying(study) areas. It seems true that, except for the soil developed in some valley fills, all the rest are residual.

3. The climate and hydrogeology of the study area

3.1. The climate of the study area

The climatic condition of the Addis Ababa region is some what variable ranging from subhumid to dry. In most cases, the Addis Ababa climate belongs to somewhat moderate humid, the total rainfall being appreciably lower than the total evapotranspiration. The monthly total rainfall and the corresponding maximum and minimum temperature of the study area in the year 1988 is given in Table 3.1.

The precipitation occurrence in the study area and its surroundings has a seasonal distribution over a year with a marked difference in the amount of total rainfall. Most of the annual total of precipitation mainly coming in spring and summer. In the year 1988, from the total of 1023. 9 mm, 543 mm (50%) was precipitated in summer and 244.6 mm (25%) in spring. In some other years the summer rainfall mainly comes in sharp thunder storms and has a high intensity.

Table 3.1 Average maximum and minimum temperature and monthly total rainfall for year 1988 (Ethiopian National Metrological Service)

ELEMENT	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEP.	OCT.	NOV.	DEC.
Ave.Max Temp. °C	24.7	24.9	27.3	25.2	25.9	22.0	20.1	21.2	22.2	22.0	22.0	22.9
Ave.Min Tem. °C	7.4	10.9	9.4	11.1	10.4	10.4	12.1	11.2	10.4	8.1	3.9	4.5
Monthly total rainfall	4.7	33.4	6.0	157.9	34.9	93.0	147.7	301.9	137.3	57.3	0.0	0.0

the average value in this season. The difference between the evapotranspiration and the precipitation is higher in winter and autmun than in summer and spring. Generally speaking, the mean annual evapotranspiration exceeds the mean annual total rainfall in most of the years.

3.2. The hydrogeology of the study area

The study area is highly disected by three main rivers. The Kebena river flows in the west, the Gerch river in central position and the Kotebe river in the eastern part of the area. In addition to these rivers, small consequent streams overflow the study area. Except for the consequent streams, all the main rivers orginate in areas of highest elevation (mainly the Entoto ridge) and flow to the south and southeast direction. Based on the topography and the structure of bed rocks, it is suggested that these rivers are fed by recharges coming from the surrounding aquifers. The average discharge generally vary throughout the year with the highest value in summer and lowest value in winter and autmun.

Water wells had been dug in the surroundings of the study area in the last few years. Six water wells were examined thoroughly and the data obtained from these wells are summarized in Table 3.2.

The estimation of data on aquifer discharge of these wells leads to the suggestion that the source of recharge for the deeper aquifers is mainly the precipitation falling in areas of higher elevation. An overall estimation of the discharge of the continuous aquifers present in the area is 10 mm/yr

Table 3.2. Ground water chemistry and static water level in six water wells in Bole and the surrounding area (acc. Ethiopian Water Wells Drilling Agency).

Ground water Chemistry		Location of Well					
		Anbassa Garage	Addis Ababa edible oil factory	Socialist Ethiopia Military Orphanage	Ethioplastic (Asmara road)	Wöllo Sefer	National Road Tran. Crop.
Cation meq/100g	NH_4^+	Nil	0.11	0.14	345.5	0.06	Nil
	K^+	29.5	20.4	78.2	-	26	91.8
	Na^+	5.3	4.6	2	-	3.6	3.3
	Ca^{2+}	40.1	46.5	4.8	12.8	40	16.0
	Mg^{2+}	9.7	10.2	1	5.8	14	1.6
	Fe (Total)	0.02	0.10	0.44	1.15	0.2	0.3
	Al^{3+}	Nil	Nil	Nil	-	-	-
Anion meq/100g	HCO_3^-	249.6	231.8	183.0	05.2	244	219
	CO_3^{2-}	Nil	Nil	Nil	48.8	Nil	24
	SO_4^{2-}	Nil	Nil	Nil	Nil	Nil	16.5
	NO_3^-	9.4	3.54	0.4	0.4	1.5	0.7
Total SiO_2		58.2	84	43.8	46.6	67.4	85
Total hardness as $CaCO_3$		140.0	58	16	56	160	48
PH		7.6	8.1	8.1	8.7	7.6	8.6
s.w.l(m)		91.98	101.65	23.84	86.65	89.2	27.84

(Tesfaye, 1988). The static water level (S.w.l) given in Table 3.2 corresponds to the position of water table and as naturally expected it fluctuates seasonally being near the surface in summer and far deep in winter. Two other static water levels 3.9 m and 39.6 m obtained in wells dug at Kotebe Security Training Center during summer and at Misrak Flour factory during winter respectively assured this suggestion. This fluctuation of the water table affect the degree of saturation of subsurface materials and this accordingly influence the swelling and shrinkage property of clay soils present in the study area. Even though it is difficult to say definitely, the correlation of the static water level in the six water wells enables to suggest that the ground water table generally slopes to the south and southeast following the topography of the area. Hence, moisture can easily be accumulated on the flat areas (most part of the study area) and causing the soils to be relatively wet.

The ground water chemistry of the study area and its surroundings have been investigated in the six of the already mentioned wells. As shown in Table 3.2, the variation in water chemistry is diversified.

Data analyses of the six water wells attests that the $Na^{+}$and Ca^{2+} are the relatively most abundant cations with high anomalous value of NH_4^{+} in one of the wells. The concentration of K^{+} and Fe(total) is relatively constant and large amount of Mg^{2+} is observed where Ca^{2+} is the dominant cation. In the case of anions, the HCO_3^{-} is highly distributed in all of the wells and when the PH value is above 8.2 (Davis and De Weist, 1966), it is observed that the content of the CO_3^{-2} increases. The nitrates are almost exist in all of the wells and silica is present in every case with considerable amount.

The large concentration of Na^{+}ion in some wells and C_a^{2+} ions in others is connected to the release of these ions from clay minerals of the study area during cation exchange reactions under certain conditions. Depending on the relative concentration, Ca-bicarbonate waters may convert to Na-bicarbonate waters or vice versa, leaving the clay minerals rich in either Na^{+} and Ca^{2+} respectively. Since most commonly clays will exchange sodium if available, for both calcium and magnesium ions, exceptionally low values of magnesium and calcium are found in some waters which have undergone natural softening by cation exchange.

The relative immobility of potassium as is observed from Table 3.2. may be due to two cases. Potassium might enter mainly into the structure of illite or it might not be sufficiently released since potassium-containing minerals are highly resistant to weathering. The rare occurrence of nitrate may be owing to leaching of subsurface materials which contain organic matter. The relatively less amount of silica means a fairly less degree of leaching of clay minerals, quartz and feldspars.

4. The lithological description of soils and their classification

Most of the places in the study area are covered by thick (2-6 m) accumulations of soils. The distinction of such soils relative to rocks out croping in the area is based on Annon (1972). According to this author, "Soil is an aggregate of mineral grains that can be separated by such gentle means as agitation in water. Rock, on the other hand is a natural aggregate of minerals connected by strong and permanent cohesive forces."

Since the present work mainly aims at the engineering geological characterstics of the soils of the study area, basic site investigation and detailed field analyses was carried out. On the basis of such field investigations and accompanying arial photointerpretation, the soils of this area are virtually described (see Appendix 2), and are lithologically classified into the following types.

- Clay soils (C)
- Silty clay soils (CM)
- Sandy clay soils (CS)

4.1. Clay soils (c)

These type of soils cover the central, the northeastern, and the northwestern part of the study area. They are characterstically found in the relatively low-lying areas (with a slope of 0-3^{o}) to a thickness of as much as 5-6 mts. The common occurrence of thick layers of such soils may be related to paleomorphology of the area in relation to the surrounding regions. Commonly, they are composed of the following three distinct clay layers.

a) The black clay layer (C_b

This layer is the uppermost of all clay layers in areas were there exists a thick clay soil accumulation. Its thickness ranges from 0 to 1 m. It is invariably cracked, the cracks being disposed in a manner of polygonal network giving the soil peds[*1] an angular blocky structure[*2]. The cracks are very close with each other and often the opening of the cracks reach 10 cm and their depth goes as much as the lower clay layers (2 to 2.5 m). It is hard in consistency. Roots of grasses and big trees are common in this layer and in some places, the roots penetrated down to great depths.

b) The dark grey clay layer (C_{dg})

This clay layer is found in the succession next from the overlying black clay layer. It ranges in thickness from 0.8 to 1.4 m and are normally present at a depth of 0.2 to 2.2 m. In an area where it is found close to the surface, it is highly cracked and usually is firm to stiff. It is suggested that this clay layer possesses a characterstics which lie in between the overlying black clay layer and the underlying grey clay layer. Due to such fact most of a time

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*1 Soil peds are aggregates of individual soil particles.

*2 According to the description of the structure of soil (Mathewson, 1981).

it is difficult to be recognized and as such is considered to be the overlying black clay layer.

c) The grey clay layer (C_g)

As the name describes, this clay layer is generally grey in color and in most places it is observed to be mottled with black. The effect of mottling generally increases with depth and it indicates poor leaching characterstics. The grey clay layer is 1-3 m in thickness and is commonly found at a depth of 2-6 m. It is firm to stiff and appear to be highly compacted. In some places it is composed of appreciable amount silts.

Generally, the clay soils are underlain by light grey and light yellowish brown gravelly sands and boulders of bedrocks which normally grade to their overlying clay soils. The fact that these clay soils are underlain by gravel size rock fragments and boulders of bed rocks (see Appendix 2).testifies the suggestion that they are in situ products of weathering of the parent rock. The basic igneous rocks (the basalts), which are made up of calcium rich feldspars and dark minerals which are high in the weathering order (i.e unstable) and the pyroclastic sediments (the tuffs and ashes) which are made up of volcanic glasses, under suitable conditions grades to form clay minerals. The retention of magnesium and calcium from parent rocks, the degree of evaporation which exceeds the precipitation in this area, and the poor leaching conditions, all prevail the formation of such type of clay soils.

The clay soils of the study area which are composed of the three distinct clay layers mentioned above are subdivided into two subtypes:

- non-carbonaceous clay soils (C_{-c})
- carbonaceous clay soils (C_{+c})

4.1.1. Non-Carbonaceous clay soils (C_{-c})

This subtype is widely distributed and is commonly observed in areas where there are no signs of basic igneous rocks (the basalts). It commonly covers the northwestern, the northeastern and the central (including the western part of Bole International Airport) portion of the study area. The absence of calcium carbonate as a form of concretions in this subtype might be due mainly to the composition of its parant material, which in this case is assumed to be the pyroclastic sediments (the tuffs and ashes).

4.1.2. Carbonaceous clay soils (C_{+c})

This subtype covers the eastern part of the Bole International Airport and the nearest surrounding areas where basaltic rock units outcrop. It usually possesses similar features as the first subtype except for the presence of calcium carbonate, which is randomly distributed in the three distinct clay layers as a form of concretions.

Test pit data collected during field investigations and archive materials prepared at the time when the Bole International Airport was first constructed (Archives of Ministry of Public Works and Communication, 1960) indicates that, the concentration of the calcite concretions in the first black clay layer is up to 5%, in the second dark grey clay layer 10-15%, and in the third grey-clay layer it becomes 5-10%. It is clear from this observation that the highest concentration of the calcite concretions is at a depth of 1.-3 m. The gravelly sands and boulders of bedrocks which are underlying the clay soils contain small amount of calcite concretions and generally the concentration gradually decrease downward until total elimination near the bedrock.

These calcite concretions which are commonly observed are of various sizes ranging from 0.5 mm to 1 or 2 cm in diameter. Concretions of such sizes are known as inactive forms of calcite (Zonn, 1966) and hence they do not easily interact with HCO_3 to form soluble bicarbonates as finely crystalline calcites do.

It seems true that these calcite concretions might be derived from the parent material (the basalt) itself. Their concentration at different depths is related to varying degrees of leaching; poor leaching being accomplished in places where their exists highest degree of accumulation.

4.2. <u>The silty clay soils (CM)</u>

The silty clays cover some parts of the eastern and western and most part of the southern portion of the study area. They are generally present at those areas where the bedrocks are at a depth of 0.5-2.5 m. Hence, they are characteristically found at relatively high lands bounding the clay soils of relatively low-lying areas.

They are mostly black and dark grey in color and in some places where they are assumed to be products of loose welded tuff and ashes, light yellowish brown, light grey and red varieties are common. Shrinkage cracks of shallow depths are frequently observed in the upper layer of these soils and the resulting soil peds are sub-angular blocky to granular in structure. They are 0.5-1 m in thickness and hard to stiff. Roots of grasses, thorns and bushes are common, and in the southern portion of the study area they are highly cultivated.

Usually they are underlain by light yellowish brown gravelly sands and light grey boulders of welded tuff. From this observation, it is possible to suggest that they may be a gradational boundary between the rocks (the parent materials) and the clay soils (the weathering products). Hence, these type of soils might be more recent as compared to clay soils of relatively low-lying areas.

4.3. <u>The sandy clay soils (CS)</u>

This type of soils is commonly found in the upper reaches of the Kebena, Gerch and Kotebe river valleys. Their thickness varies from 1-3 m and are commonly interstratified with sand layers. Quartz is the most common mineral which is observed in the sand layers and sometimes feldspars are also present.

They are black in color and in some old river terraces red and light red colors are observed (along Kebena river, 100-150 m from Asmara road). At their contact with the highly weathered rocks, they seem to be interstratified with the residual soils and form distinct layers. In areas where this

Table 4.1. Lithological description and classification of soils.

General lithological description	Symbol of lithological types	Soil subtypes		Description of litholo-gical sub-types	Symbol of litholo-gical subtypes
Clay Soils; black, dark grey and grey. Hard to firm, Cracked in the upper part and mottled in the lower part. 5.6 m in thickness. Grass roots are common in the upper zone.	C	Non-carbonaceous clay soils (C_{-c})	Carbonaceous clay soils (C_{+c})	Black clay. Hard to stiff. V.closely cracked and grass roots are common.	C_b
				Dark grey clay. Stiff to firm. in some places cracked	C_{dg}
				Grey clay. Stiff to firm. Mottled with black	C_g
Silty Clay Soils; black and in some places red, light grey, light yellowish brown and dark grey. Cracked up to a depth of 1 m, sands, gravels and boulders are common. Hard to stiff and grass roots are observed.	CM	-		-	-
Sandy Clay Soils; black and sometimes red and light red. They are alluvial in origin. Swamps and bogs are common. Interstratified with sand layers.	CS	-		-	-

type of soils is present, swamps and bogs are common which are totally grassed. Since they are deposited along river terraces, they are used for crop plantation.

The following table (Table 4.1) summarizes the brief description and classification of soils of the study area on the basis of field analyses and interpretation.

5. The result of laboratory studies of different lithological types of soils

5.1. General

Field investigation of soils of the study area was carried out on the basis of 23 test pits (P) together with 14 dug holes*1 (DH) and bore holes*2 (BH). The locations of test pits were first assumed to be at every 1 km in a form of rectangular network. However, the distribution was later modified due to natural and artificial problems, and mainly on the basis of availability of data from dug holes and bore holes.

During field investigation, about 60 soil samples which were estimated to be the more representatives of each soil type and subtype were selected for laboratory studies. Among these, 43 were further selected for different analyses on the basis of visual discrimination. Table 5.1 and 5.2 summarize the correlation of each soil sample with lithological types and subtypes in-accordance to the depth of investigation in different bore holes and test pits respectively. Soil samples with a sample No.of 1s-16s were taken from bore holes (BH) and from 17s-43s from test pits (P).

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*1 Holes dug by owners for construction purposes

*2 Drilled by Ethiopian Building Design Enterprise, project Addis Ababa Stadium, Central Bole, Addis Ababa, 1989.

Table 5.1. Correlation of soil samples taken from Bore holes with lithological types and subtypes.

Sample No	Bole hole No	Depth in m.	Lithological type	Lithological subtype
1s	1	1.9	C	C_{dg}
2s	1	2.0	C	C_g
3s	1	3.5	C	C_g
4s	1	8.1	C	C_r
5s	1	10.0	SG	-
6s	2	1.25	C	C_{dg}
7s	3	2.2	S	-
8s	3	4.2	SG	-
9s	3	6.6	SG	-
10s	6	3.6	C	C_g
11s	9	4.9	SG	C_g
12s	11	0.6	CM	-
13s	11	1.8	SG	-
14s	11	2.4	SG	-
15s	13	9.6	CM	-
16s	14	3.4	C	C_g

5.2. Basic Chemical Studies

5.2.1. Organic matter content

The presence of organic matter in the soils of the study area is tested and the results which were obtained for soils of the study area are presented in Table 5.3. The black clays (C_b) have an orgnic content of 4.5 - 5.5%, the dark grey clays (C_{dg}) have 0 - 5% and the grey clays (C_g) contain 0 - 35%. The organic

Table 5.2. Correlation of soil samples taken from test pits with lithological types and subtypes.

Sample No	Pit No	Depth in m	Lithological type	Lithological Subtype
17s	1	0.5	CM	-
18s	2	1.1	CM	-
19s	3	0.9	C	C_{dg}
20s	3	2.2	c	C_{dg}
21s	5	0.5	C	C_b
22s	5	2.2	C	C_{dg}
23s	5	3.0	C	C_d
24s	7	0.7	CM	-
25s	9	1.4	C	C_{dg}
26s	11	0.4	CM	-
27s	13	0.5	CS	-
28s	15	0.55	CM	-
29s	15	0.9	S	-
30s	15	1.6	S	-
31s	16	1.2	C	C_{dg}
32s	16	1.75	C	C_g
33s	18	0.45	C	C_b
34s	18	1.25	C	C_{dg}
35s	19	1.2	C	C_{dg}
36s	19	2.8	C	C_{dg}
37s	20	0.32	CM	C_g
38s	21	0.46	CM	-
39s	21	1.24	S	-
40s	21	2.9	S	-
41s	22	0.8	SM	-
42s	23	0.7	C	C_b
43s	23	2.2	C	C_g

Table 5.3. Percentage of organic matter for soils taken from Bole and surrounding area.

Sample No	Litho-logical type	Litholo-logical subtype	% Organic matter (M_o)	Sample No	Litho-logical type	Litho-logical subtype	% Organic matter (M_o)
1s	C	C_{dg}	5.0	22s	C	C_{dg}	2.5
2s	C	C_g	2.5	23s	C	Cg	2.0
3s	C	C_g	0	24s	CM	-	4.5
4s	C	C_r	0	25s	C	C_{dg}	3.5
5s	SG	-	0	26s	CM	-	5.0
6s	C	C_{dg}	0	27s	CS	-	5.0
7s	S	-	5	28s	CM	-	2.5
8s	SG	-	0	29s	S	-	4.5
9s	SG	-	0	30s	S	-	4.0
10s	C	C_g	0	31s	C	C_{dg}	4.0
11s	SG	-	0	32s	C	C_g	3.5
12s	CM	-	2.5	33s	C	C_b	4.5
13s	SG	-	0	34s	C	C_{dg}	3.5
14s	SG	-	0	35s	C	C_{dg}	4.0
15s	CM	-	0	36s	C	C_g	2.5
16s	C	C_g	0	37s	CM	-	0
17s	CM	-	5.0	38s	CM	-	0
18s	CM	-	2.5	39s	S	-	0
19s	C	C_{dg}	2.5	40s	S	-	0
20s	C	C_{dg}	0	41s	SG	-	0
21s	C	C_b	5.0	42s	C	C_b	5.0
				43s	C	C_g	2.5

content in the silty clays (CM) is in the range of 0-5% and that of sandy clays (CS) is 5%. The black clays have a higher amount of organic matter compare to other clays and the silty clays have an average value. Sandy clays are more organic since they are areas of crop plantation and generally the percentage decreases with depth without any dependence on lithology.

5.2.2. Calcium carbonate content

Soil samples are normally tested in the laboratory for the presence of calcium carbonate ($CaCO_3$) if they show an effervescence reaction with hydrochloric acid (HCI). Higher percentage of calcium carbonate gives more intensive reactions.

Soils of the study area showed no reaction with HCl except those that are present around the eastern part of Bole International Airport. Clay soils found in this portion of the study area however contain calcium carbonate as a form of concretions to a field estimated percentage of 5-15%.

The calcite concretions that are present in samples of such clay soils (C_b, C_{dg} and C_g) were selected out by hand in the laboratory and further tests were carried out. But, there was no visible reaction observed. Hence, it is possible to suggest that all soil units which cover the study area are devoid of finely crystalline calcite. The calcium ions(C_a2+) that are leached from the basic rocks (basalts) might be taken into the structure of clay minerals which compose the clay soils of the study area.

5.3. Basic physical studies

5.3.1 Moisture content (w)

The moisture content determination was carried out on a dry month (December) and the corresponding moisture content of 43 soil samples is given in Table 5.4.

The black clay soils (C_b) have a moisture content of 28.1-33%, the dark grey clay soils (C_{dg}) have 31.3-41.4% and the grey clay soils (C_g) have 29.5-39.9%. The moisture content of the silty clays (CM) is in the range of 20.2-39% and that of sandy clays (CS) is 36.5%.

The highest value is obtained for clay soils (C) especially for the dark grey clays (C_{dg}) which corresponds to highest capacity of holding water due to greater amount of clay fraction. Within the same lithological type and subtype, the moisture content decreases with depth. Correlations of moisture content values of soil samples of the same lithological type and subtype taken from different test pits (P) and bore holes (BM) enables to suggest that the moisture content is almost constant (about 30%) at a depth of 2-2.5 m in places where shrinkage cracks terminate.

5.3.2. The bulk density (ρ)

Bulk density was determined for those undisturbed soil samples which had been taken with undisturbed soil condition from bore holes.

The bulk density for 10 soil samples is given in Table 5.4. The highest value is obtained for clay soils (C) compare

Table 5.4. Laboratory results of moisture content (w), bulk density (ρ), specific gravity (Gs), dry density (ρ_d), void ratio (e) and porosity (n) for soils taken from Bole and the surrounding area.

Sample No	Litho-logical type	Litho-logical subtype	Moisture content (w) %	Bulk density (ρ) Mg/m^3	Specific gravity (Gs)	Dry density (ρ_d) Mg/m^3	Void ratio (e)	Porosity (n) %
1s	C	Cdg	31.8	-	-	-	-	-
2s	C	Cg	34	1.66	2.73	1.19	1.29	56.3
3s	C	Cg	29.5	1.94	2.76	1.49	0.84	45.7
4s	C	Cr	30.5	1.92	2.75	1.47	0.87	46.5
5s	SG	-	29.5	1.95	2.69	1.50	0.77	44.0
6s	C	Cdg	34	-	-	-	-	-
7s	S	-	37.3	1.57	2.64	1.14	1.31	56.7
8s	SG	-	32	1.66	2.67	1.26	1.12	52.9
9s	SG	-	31.8	1.16	2.62	0.88	1.97	66.4
10s	C	Cg	31	-	-	-	-	-
11s	SG	-	28	-	-	-	-	-
12s	CM	-	39	1.53	2.73	1.10	1.48	59.7
13s	SG	-	20	1.67	2.67	1.34	1.00	50.0
14s	SG	-	17.7	1.38	2.65	1.17	1.26	55.8
15s	CM	-	34	-	2.75	-	-	-
16s	C	Cg	30	-	2.73	-	-	-
17s	CM	-	32	-	-	-	-	-
18s	CM	-	33	-	-	-	-	-
19s	C	Cdg	38	-	-	-	-	-
20s	C	Cdg	32	-	-	-	-	-
21s	C	Cb	33	-	-	-	-	-
22s	C	Cdg	39	-	-	-	-	-
23s	C	Cg	31.1	-	-	-	-	-
24s	CM	-	21.4	-	2.69	-	-	-
25s	C	Cdg	43.7	-	-	-	-	-
26s	CM	-	32.5	-	-	-	-	-
27s	CS	-	36.5	-	-	-	-	-
28s	CM	-	20.2	-	-	-	-	-
29s	S	-	17.5	-	-	-	-	-
30s	S	-	18.5	-	-	-	-	-
31s	C	Cdg	41.4	-	-	-	-	-
32s	C	Cg	39.9	-	-	-	-	-
33s	C	Cb	28.1	-	-	-	-	-
34s	C	Cdg	31.3	-	-	-	-	-
35s	C	Cdg	-	-	-	-	-	-
36s	C	Cg	-	-	-	-	-	-
37s	CM	-	38.1	-	-	-	-	-
38s	CM	-	25.8	-	2.66	-	-	-
39s	S	-	20.9	-	-	-	-	-
40s	S	-	19	-	-	-	-	-
41s	SM	-	30	-	-	-	-	-
42s	C	Cb	30.7	-	2.72	-	-	-
43s	C	Cg	30.2	-				

to silty clays (CM) and even sands (S) and gravelly sands (SG) have a much lower value. For the same lithological types the bulk density increases with depth.

5.3.3. The specific gravity (G_s)

The specific gravity determination was restricted for those soil samples which were assumed to be the more representative of each soil unit. The results obtained are reported in Table 5.4.

Generally the specific gravity of the soil samples correlates with theoretical values. The specific gravity of the clay soils (C) is in the range of 2.72-2.76 and that of sands (S) and gravelly sands (SG) is from 2.65-2.69. This ranges are expected since the soils contain small amount of organic matter and clays mainly govern the whole mass propeerty.

. 5.3.4. The dry density (ρ_d), void ration (e) and Porosity(n)

The moisture content (W), bulk density (ρ) and specific gravity (G_s) which are determined above are useful to calculate the three other important parameters such as the dry density (ρ_d), the void ratio (e) and the porosity (n).

Values of dry density, void ratio and porosity for 10 soil samples taken from bore holes is given in Table 6.4.

The dry density of clays (C) generally increase with depth and this corresponds to an increase in strength of the soils. The sands(S) and gravelly sands (SG) have a lower value of dry density compare to the clays of the area.

Clay soils (C) have lower values of void ratio and porosity as compared to the sands (S) and gravelly sands (SG) and within the same lithology both values decrease with depth as naturally expected.

The relative density of the sands and gravelly sands which underly the clay soils was determined in the field using SPT values (Archives of Ethiopian Building Design Enterprise, 1989) and generally it is described that the soils become denser with depth. This corresponds to the value of void ratio obtained in the laboratory.

5.3.5. Grain size analyses

Grain size analyses provide a usefull way of classification system for soils. Under such circumstances, 22 soil samples were selected from each soil type at different depths and analyses were carried out to determine the range of sizes in which the soil samples fall and their relative proportions.

Sieve analysis was carried out on the basis of dry and wet sieving. Dry sieving was preferred for 2 of the soil samples since they were discribed to be sands and gravelly sands on the basis of visual discrimination. Wet sieving on the other hand was used for composite analyses of both sieve and hydrometer and for preparing of soil samples which phass No.200 (0.075 mm) sieve for hydrometer analyses only.

After complete size analysis, the relative proportion of different size groups in each soil sample is given in

Table 5.5 and Fig. 5.1 (a,b). The size range of each group was adopted from ASTM (4.75 mm - gravel, 4.75-0.75 mm - sand, 0.075-0.002 mm - silt and 0.002 mm — clay).

All soil samples are composed of a relative proportion of different size groups as naturally expected, altHough one group dominates the others in relative percentage. Clays for example are present in percentage range of 28-85% (see Table 5.5) and govern the propoerty of the soils in most of the study area. Silts are appreciablly low in abundance and sands and gravelly sands increase in proportion with depth.

As shown in Table 5.5, the clay fractions make up abount 74% in black clays (C_b), from 73.7-34.7% in dark grey clays (C_{dg}), 65.8-84.4% in grey clays (C_g). 46.4-75.2% in silty clays (CM) and 35.0% in sandy clays (C_s). Silts and sands make up the rest proportion. Comparison of these data revealed that a high percentage of clays is present in the dark grey (C_{dg}) and grey (C_g) clays. The silty clays (CM) contain an average value and that of sandy clays (CS) have a relatively lower percentage of clays since sands make up the greater proportion in these type of soils.

Using a Triangular Classification Chart proposed by U.S Bureau of Reclamation, soils which were described as clays, silty clays and sandy clays during field investigation fall in the field of clays. Those soil samples taken from bore holes (7s and 11s) indicate that sands(S) and gravelly sands (SG) underly the clay soils wich respective uniformity of narrow (uniform) and well graded.

Table 5.5. Results of grain size analysis of soils taken from Bole and the surrounding area

Sample No	Litholo-gical type	Litho-logical-subtype	Soil fractions: Gravelly >4.75mm %	Sandy 4.75-0.075 mm %	Fines: silty 0.075-0.002mm	clayey <0.002 mm %	C_u	C_c	Soil class acc. to Triangular classification Chart
7s	S	-	-	97.5	2.5		2	1.7	sand (uniformlly graded)
10s	C	C_g	-	5.9	22.9	71.2	-	-	clay
11s	SG	-	16.3	79.0	4.7		1.9	0.66	sand with gravels)
12s	CM	-	-	7.3	17.5	75.2	-	-	clay
15s	CM	-	-	11.4	20.6	67.6	-	-	clay
16s	C	C_g	-	10.0	2.42	65.8	-	-	clay
17s	CM	-	-	8.6	18.4	73.0	-	-	clay
19s	C	C_{dg}	-	8.6	17.7	73.7	-	-	clay
20s	C	C_{dg}	-	1	17.8	81.2	-	-	clay
21s	C	C_b	-	9.4	15.2	75.4	-	-	clay
24s	CM	-	-	35.2	12.8	50.1	-	-	clay
25s	C	C_{dg}	-	3.3	22.7	74.0	-	-	clay
27s	Cs	-	-	47.5	17.5	35.0	-	-	clay
28s	CM	-	-	11.4	28.9	59.7	-	-	clay
30s	S	-	-	55.6	19.9	24.5	-	-	clay
34s	C	C_{dg}	-	6.7	22.3	70.0	-	-	clay
35s	C	C_{dg}	-	5.4	9.0	84.7	-	-	clay
36s	C	C_{dg}	-	3.7	11.9	84.4	-	-	clay
37s	CM	-	-	11.4	39.0	49.6	-	-	clay
38s	CM	-	-	14.3	39.3	46.4	-	-	clay
39s	S	-	-	46.1	15.7	38.2	-	-	clay
40s	S	-	-	52.7	18.5	28.5	-	-	clay

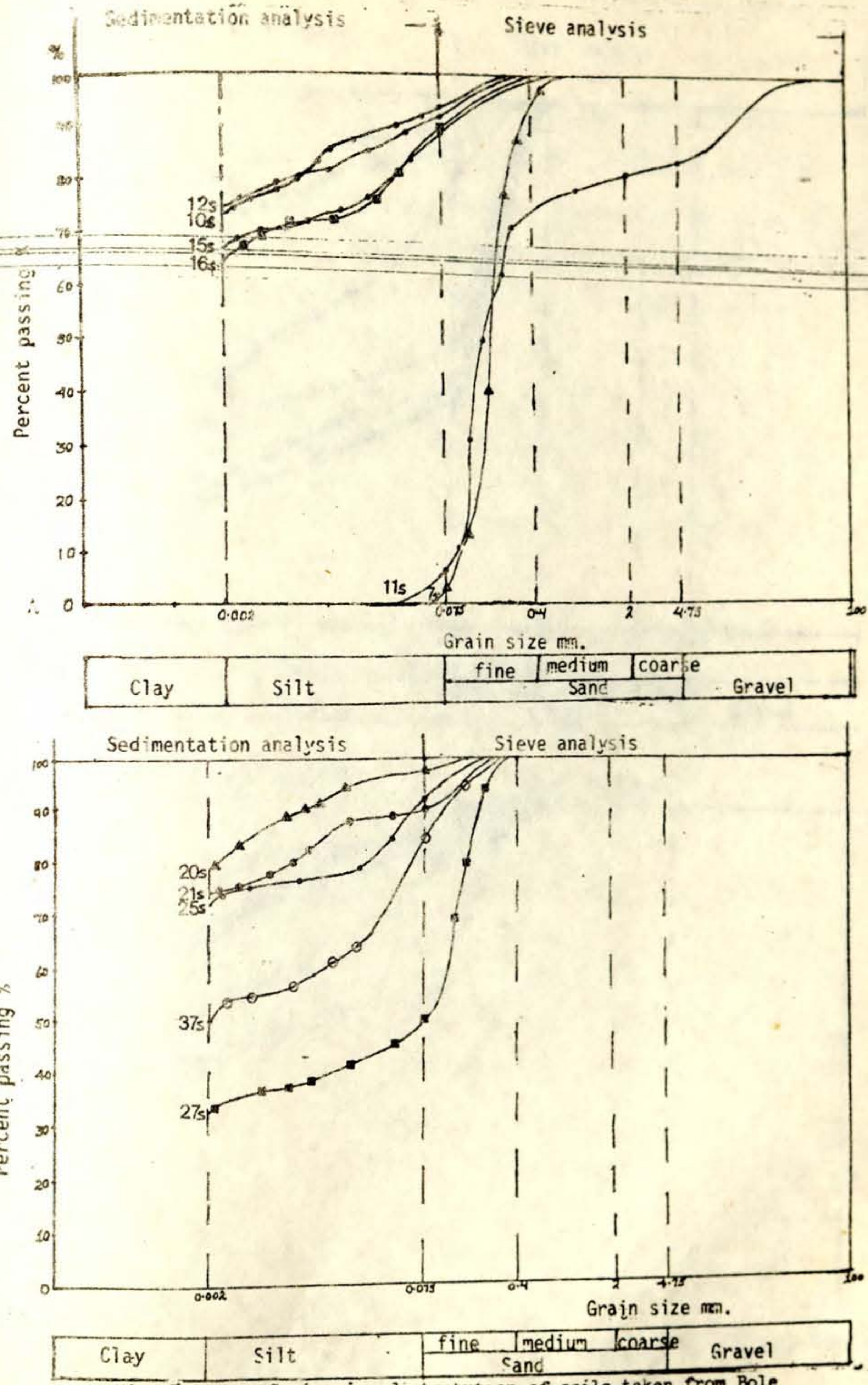


Fig. 5.1. a. Grain size distribution of soils taken from Bole and the surrounding area

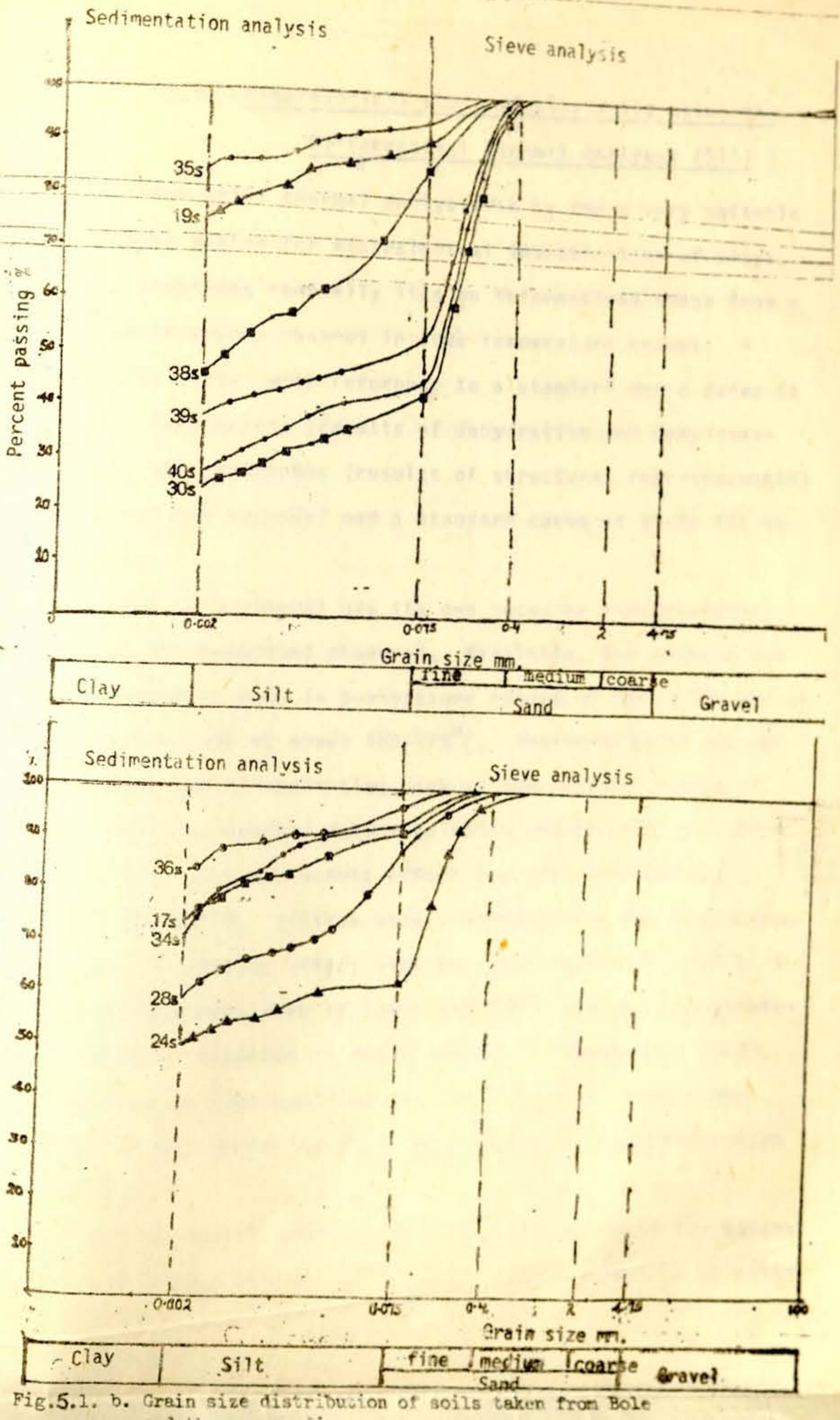


Fig.5.1. b. Grain size distribution of soils taken from Bole and the surrounding area.

5.4. Mineralogical study of clay soils using the Differrential Thermal Analyses (DTA)

Differential thermal analysis is by far a very suitable and simple method for mineralogical investigation of clays. Its applications generally lies on informations taken from a measurable energy changes in some temperature ranges. A sample is heated with reference to a standard and a curve is drawn. Endothermic (results of dehydration and dehydroxylation) and exothermic (results of structural rearrangements) reactions are recorded and a standard curve of their fit is searched.

Each clay mineral has its own peculiar characterstics towards the reactions observed. Kaolinite, for example has an endothermic peak in temperature ranges of 500-660^{0}C and an exothermic peak at about 900-975^{0}C. Montmorillonite on the otherhand has a dehydration peak at temperature ranges of 100-300^{0}C and another dehydroxylation endothermic peak from 500-900^{0}C. The exothermic effect for montmorillonites is from 800-1000^{0}C. Illites show a moderately-sized low temperature endothermic effect with the peak from 130^{0}C-225^{0}C, a main endothermic peak at about 550-720^{0}C and an endothermic-exothermic inversion at about 800-950^{0}C (Mackenzie, 1957). some factors like humidity and organic matter affect the position and intensity of peaks and make the interpretation difficult.

Differential thermal analysis (DTA) was used for mineralogical investigations of 15 representative samples of silty clay (CM and clay (C_h+ C_{dg}+ C_g+ C_r) soils taken at different depths in bore holes and test pits. The instrument used for this purpose was Netzch DTA 404 EP and the following test depths in bore holes and test pits. The instrument used for this purpose was Netzch DTA 404 EP and the test procedure for the whole analysis is given in Appendix 1.

The 5.6 DTA temperature reactions for soils taken from Bole and the surrounding area

Sample	Litho-logical type	Litho-logical subtype	Endothermic peaks Tst °C	2nd °C	3rd °C	Exothermic peak °C
2s	C	C_g	196	580	-	905
4s	C	C_r	170	590	-	915
10s	C	C_g	175	370	-	900
12s	CM	-	188	555	-	895
16s	C	C_g	185	576	-	905
17s	CM	-	190	593	-	900
20s	C	C_{dg}	200	550	848	880
21s	C	C_d	196	565	785	898
23s	C	C_g	175	575	-	906
25s	C	C_{dg}	200	580	-	900
28s	CM	-	194	582	-	910
34s	C	C_{dg}	175	580	-	900
35s	C	C_{dg}	185	560	-	880
36s	C	C_g	178	576	-	90£
37s	CM	-	180	570	-	896

Generally two types of DTA curves are obtained for the investigated soil samples. The first type corresponds to all lithological types and subtypes and contain two endothermic peaks (with

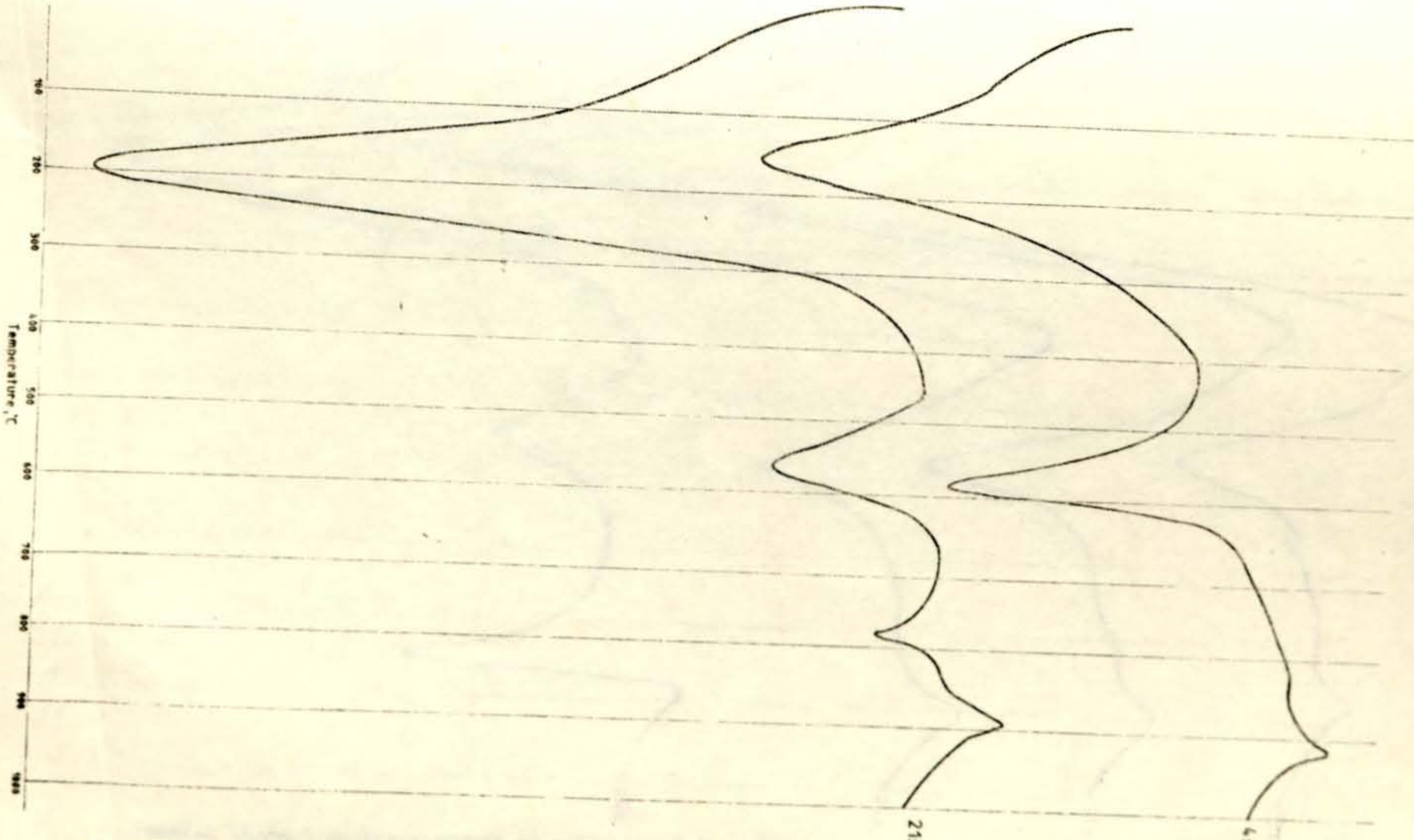
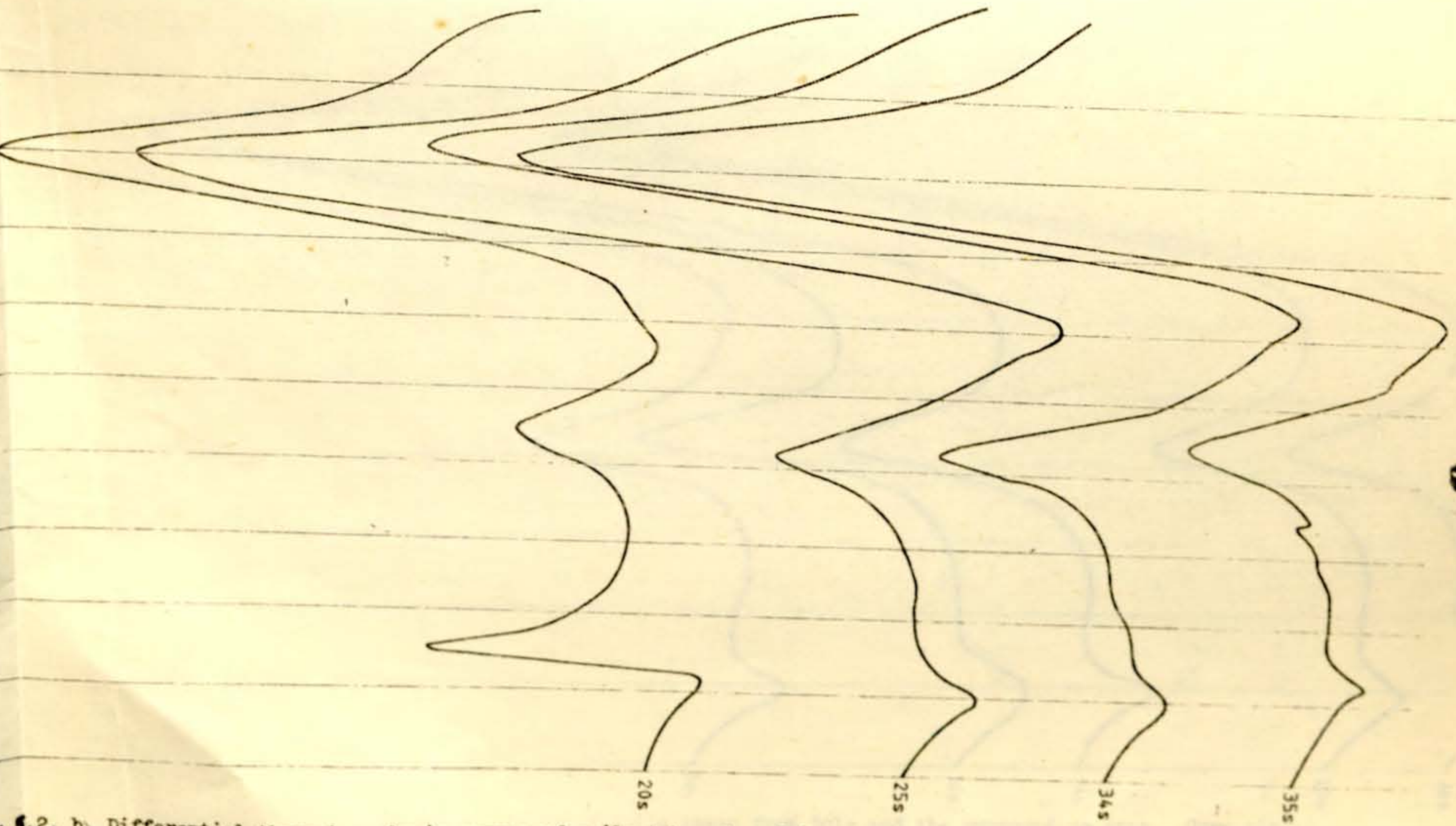


Fig. 5.2. a. Differential thermal analysis curves of soils taken from Bole and the surrounding area. 4s Red clays. 21s Black clays.



g.5.2. b. Differential thermal analysis curves of soils taken from Bole and the surrounding area. Dark grey clays.

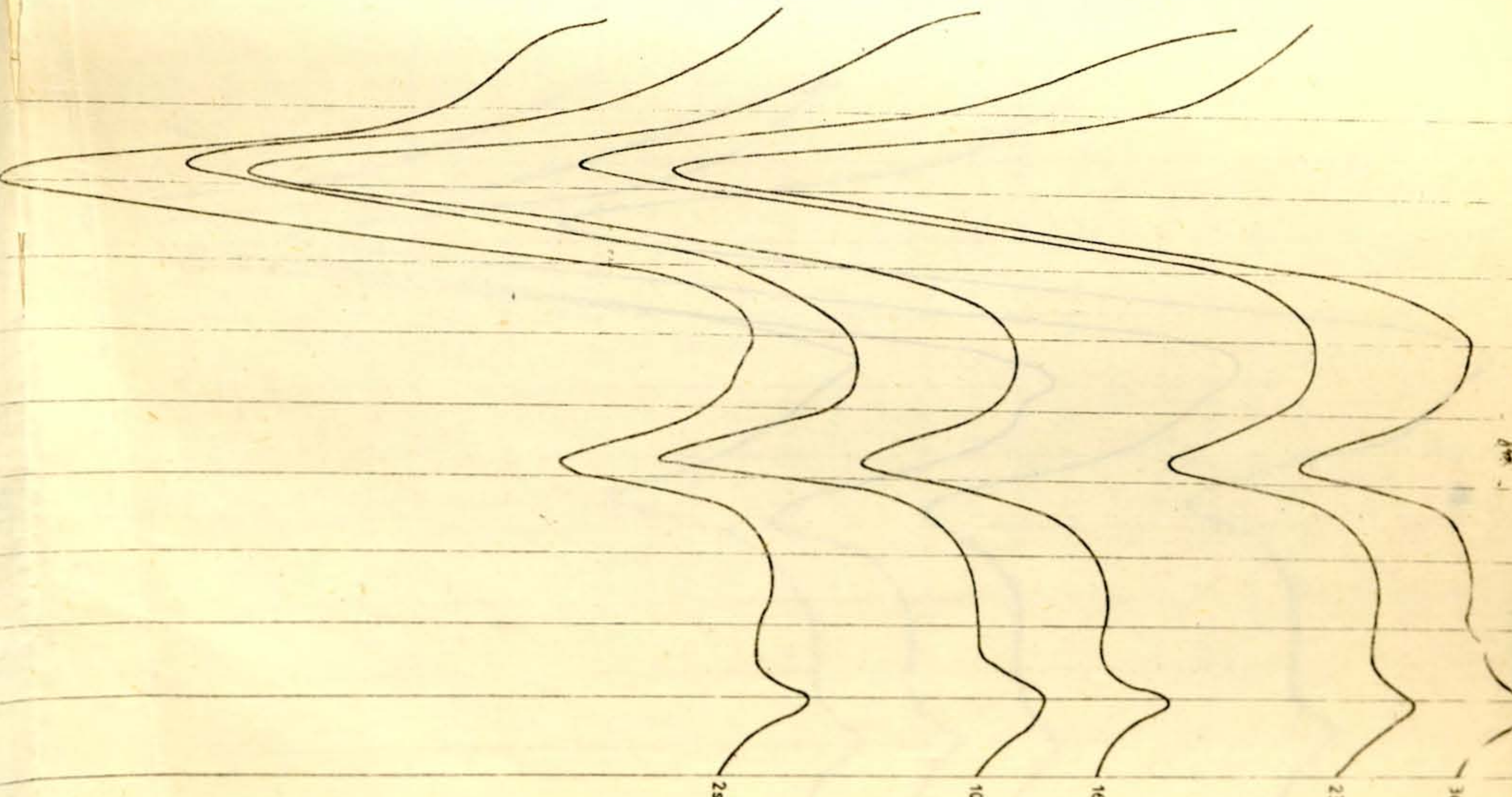


Fig. 5.2. c. Differential thermal analysis curves of soils taken from Bole and the surrounding area. Grey clays.

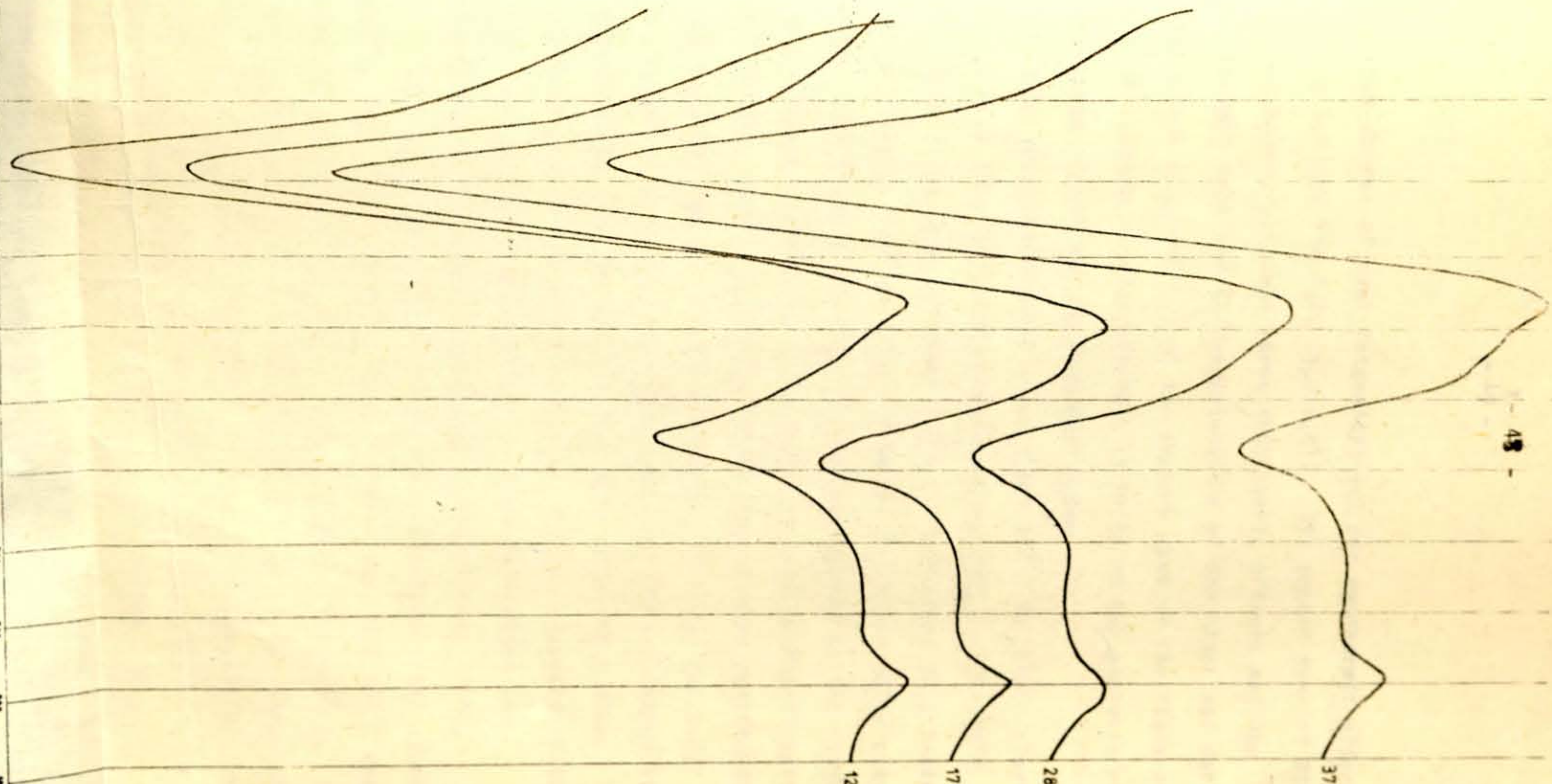


Fig. 5.2. d. Differential thermal analysis curves of soils taken from Bole and the surrounding area. Silty clays.

various degree of peak intensity) and one exothermic effect (Table 5.6 and Fig.5.2. (a,b,c,d)). The second type of DTA curves however contain three endothermic effects and one exothermic peak and is characterstics of the black and dark gray clays (C_{dg} and C_b) of the eastern part of the study area. Identification of clay minerals is based on the analysis of the curve itself and is discussed below.

The dehydration peak is at about 196°C for black clays (C_b), from 175-200°C for dark grey clays (C_{dg}), 175-196°C for grey clays (C_g) at about 170°C for red clays (C_r) taken at relatively great depth and from 180-194°C for silty clays (CM). All these temperature values correspond to the range of the first endothermic peak values of both montmorillonite and illite. But, a narrow and long size of this endothermic peak system observed in all DTA curves (Fig.5.2. a,b,c,d) indicates a great loss of sorbed water which by no means is characterstics of montmorillonites with divalent cation. The dehydration peak system of red clays (C_r) is exceptional to this idea since it is broad and shallow indicating the characterstics of monovalent cations (Mackenzie, 1957).

The black clays (C_b) have a 2nd endothermic peak at about 565°C, the dark grey clays (C_{dg}) in the range 550-580°C whereas that of grey clays (C_g) have a narrow range (570-580°C). The 2nd endothermic peak of silty clays (CM) is in the range of 555-593°C and that of red clays (C_r) is at about 590°C. These dehydroxylation peaks are characterstics of the three clay minerals: kaolinite, montmorillonite and illite. Hence, identification of each clay mineral using these endothermic peaks is difficult. But, comparison of the area of the dehydroxylation peak with those curves of standard mixtures given by Mackenzie (1957) revealed the presence of a greater proportion of montmorillonite, and an appericiable amount of kaolinite with small amount of illite.

Two of the investigated soil samples (20s and 21s) both of which were taken from the eastern part of the study area near Bole International Airport show a third endothmic peak with an immediate inversion of exothermic effect. The black clays (C_b) and the dark grey clays (C_{dg}) of this portion of the study area have a respective 3rd endothermic effect at about a temperature of 785°C and 848°C. The grey clays (C_g) and silty clays have no any sign of this further dehydroxylation effect. These third endothermic peaks of the black and dark grey clays with their exothermic inversions generally correspond with standard curves of mixtures of montmorillonite and illite (Grim, 1968; Mackenzie, 1957). The intensity of the peak is generally governed by the amount of illite and hence, the dark grey clays (C_{dg}) have greater amount of illite as compared to the black clays (C_b).

The exothermic peak for black clays (C_b) is at about 890°C, for dark grey clays (C_{dg}) is in the range of 880-900°C and for that of grey clays (C_g) is from 900-906°C. The silty clays have a relatively wide range (895-910°C) and that of red clays (C_r) is at about 915°C. Comparison of these exothermic peaks with curves given by Netzch DTA Instruction Manual (1985) and 21s, all the rest contain a greater proportion of montmorillonite than illite. Sample No. 20s and 21s contain a relatively good amount of illite as compared to other samples. The relatively high temperature peak of the red clays may be due to the presence of kaolinite.

Identification of each clay mineral (kaolinite, montmorillonite and illite) with accurate quantitative estimation by differential thermal analysis is not easy. But, it is possible to give an average estimation based on "finger-print" curves.

Matching of the DTA curves shown in Fig. 5.2 with standard mixture, given by Netzch DTA Instruction Manual (1985) and Mackenzie (1957) leads to the following general estimation of percentage of clay minerals in each lithological type and subtype of clay soils.

The BLACK CLAYS (C_b) contain a percentage of : 70-80% montmorillonite, 10-15% illite & 10-15% kaolinite. In the eastern part of the study area the proportion of illite increases to 20-25% with corresponding decrease of montmorillonite and kaolinite.

The DARK GREY CLAYS (C_{dg}) contain a percentage of: 80-90% montmorillonite, 5-10% illite, and 5-10% kaolinite. In contrast to these values, the darkgrey clay soils of the eastern part of the study area have a greater amount of illite (25-30%) with 70-75% of montmorillonite and no kaolinite. The GREY CLAYS (C_g) have: 80-85% montmorillonite, 5-10% illite and 5-10% kaolinite. The RED CLAYS (C_r) contain: 60-75% montmorillonite 5-10% illite and 20-30% kaolinite.

The SILTY CLAY soils (CM) have: 80-85% montmorillonite, 5-10% illite and 5-10% kaolinite.

Generally the dehydration and dehydroxylation (1st and 2nd endothermic) temperature reactions enables to give a higher percentage of montmorillonite in all the soils in comparison to illite and kaolinite. These estimations in many sides coincide with the data given by Ola (1978) for black cotton soils of northeastern Nigeria hence are of a good approximations.

5.5. Consistency limits and Index values

The degree of coherence between particles (consistency) of the soils in the study area was roughly determined in the field as soft, firm, stiff and hard using field identification tests. To prove these determinations a laboratory analysis was carried out on the basis of two limit tests; the liquid limit and plastic limit. From these limits index values were calculated and strength characterstics determined.

The liquid limit and plastic limit

The liquid limit and plastic limit of soil samples analyzed in the laboratory is summarized in Table 5.7. Comparison of the plastic limit with the moisture content of the soils indicates that the clay soils (C_b, C_{dg}, C_g) and the silty clays (CM) were below their plastic state when they were sampled out whereas the sandy clays (CS) were almost at their plastic state.

The liquid limit of the black clays (C_b) is from 79-98% and that of dark grey clays (C_{dg}) from 101-125% and the grey clays (C_g) have 97.5-117%. The silty clay (CM) have a lower value (48.5-96%) and the sandy clays (CS) even have a much lower value (48.5%).

Description of plasticity of fine soils in terms of their range of liquid limit is given in Appendix 1. Comparison of the liquid limit of soils of the study area with ranges given in this table enables to describe the clay soils (C_b, C_{dg}, C_g) as being of very high to extremely high plasticity whereas the silty and sandy clays (CM and CS) are of very high plasticity. This is due to the fact that in clay soils (C) of the study area the clay fraction ranges from 65.8-84.7% (Table 5.5) and contain a greater proportion of montmorillonites (a clay mineral capable of holding a greater amount of water) with an average percentage of 70-90% (see page 50-51). Hence, the clay soils of this area are likely to have lower permeability, to be more compressible and to consolidate over a longer period of time.

Index values

The determination of a liquid limit and plastic limit mainly focuses at determining of the corresponding indices: plasticity index, consistency index and liquidity index.

Plasticity index

As shown in Table 5.7, the black clay (C_b) soils have a plasticity index of 40.6-61.5%, the dark grey clays (C_{dg}) have 63.8-80.1% and the grey clays (C_g) have 63-79.5%. The plasticity index of the silty clays (CM) is in the range of 26.6-54% and that of sandy clays (CM) 38.0%. From comparison of these date with those ranges given in Appendix 1, it is

Table 5.7. Consistency limits and index values for soils taken from Bole and the surrounding area.

Sample No	Lithological type	Lithological subtype	Moisture content W%	Liquid limit LL%	Plastic limit PL%	Plasticity index PI %	Consistency index CI	Liquidity Index LI %
1s	C	Cdg	31.8	110	40	75.0	1.11	-11
2s	C	Cg	34	117	37.5	79.5	1.04	- 4
3s	C	Cg	29.5	98	32.1	65.9	1.04	- 4
4s	C	Cr	30.5	78	29.5	49.5	0.96	4
5s	CM	-	29.5	70.5	27.2	43.3	0.95	5
6s	C	Cdg	34	101	37.2	63.8	0.05	- 5
7s	S	-	37.3	48	32.4	15.6	0.69	31
8s	SG	-	32	47	30.7	16.3	0.92	8
9s	SG	-	31.8	42	29.5	12.5	0.82	18
10s	C	Cg	31	105	31.9	73.1	1.01	- 1
11s	SG	-	28	36	-	-	-	-
12s	CM	-	39	96	42	54.0	1.06	- 6
13s	SG	-	20	32.5	14.5	18.0	0.69	31
14s	SG	-	17.7	26.5	-	-	-	-
15s	CM	-	34	75	32.1	42.9	0.96	4
16s	C	Cg	30	99	32.4	66.6	1.04	- 4
17s	CM	-	32	85	36.3	48.7	1.09	- 9
18s	CM	-	33	91.5	37.7	53.8	1.09	- 9
19s	C	Cdg	38	110	42.6	67.4	1.07	- 7
20s	C	Cdg	32	105	36.6	68.4	1.07	- 7
21s	C	Cb	33	98	36.4	61.6	1.06	- 6
22s	C	Cdg	39	120	43.5	76.5	1.06	- 6
23s	C	Cg	31.1	110	33.1	76.9	1.03	- 3
24s	CM	-	18.0	48.5	21.9	26.6	0.91	9
25s	C	Cdg	43.7	125	44.9	80.1	1.01	- 1
26s	CM	-	32.5	88.5	34.5	54.0	1.04	- 4
27s	CS	-	18.5	48	16.0	32.0	0.92	8
28s	CM	-	20.2	86.5	36.7	49.8	1.33	-33
29s	S	-	18.5	46	16.3	29.7	0.93	7
30s	S	-	17.5	40	16.0	24	0.94	6
31s	C	Cdg	41.4	116.5	44.1	72.4	1.04	- 4
32s	C	Cg	39.9	115	40.3	74.7	1.01	- 1
33s	C	Cb	28.1	74	33.4	40.6	1.13	-13
34s	C	Cdg	31.3	103	34	69	1.04	- 4
35s	C	Cdg	-	106	38.9	67.1	-	-
36s	C	Cg	- -	107.5	37.3	70.2	-	-
37s	CM	-	38.1	94	41.4	52.6	1.06	- 6
38s	CM	-	25.8	83	38	45	1.27	-27
39s	S	-	20.9	48	19.2	28.8	0.94	6
40s	S	-	19	44	16.0	28	0.89	11
41s	SM	-	30	40	32	8	1.25	-25
42s	C	Cb	30.7	79	36.4	42.6	1.13	-13
43s	C	Cg	30.2	97.5	34.5	63	1.07	- 7

possible to conclude that all clays and silty clays are extremely plastic while the sandy clays are highly plastic. The dark grey and grey clay remain at their plastic state for a greater and wide range of water content compared to the silty and sandy clays.

<u>The consistency index</u>

The consistency of soils is classified according to their range of consistency index values and is given in Appendix 1.

The consistency index of the black clay soils (C_b) is in the range of 1.06-1.13 and that of the dark grey clays (C_{dg}) is 1.04-1.11 and the grey clays (C_g) have 1.01-1.07. Silty clays (CM) have a wide range (0.91-1.33) and the consistency index of the sandy clays (CS) is 0.92. Except for the sandy clays, all the clays and silty clays are classified as hard soils. This in most cases coincides with the field description of consistency of the soils. The sandy clays are stiff and generally the consistency of soils grades to firm and soft with depth.

<u>The liquidity index</u>

In Table 5.7 the black clay soils (C_b) have a liquidity index of -13% to -6%, the dark grey clays (C_{dg}) have -11% to -4% and that of grey clays (C_g) have -7% to -1%. The silty clay (CM) have a wide range and smallest negative value (-35% to 9%) and the sandy clays (CS) have only a positive value (8%) of liquidity index. From this observation, it is safe to say that the clay and silty clay soils are highly dessicated and have a greater shear strength compare to the sandy clays and the degree of dessication decreases with depth for all cases.

Activity of clay soils

The plasticity of a clay soil is influenced by the amount of its clay fraction since clay minerals greatly influence the amount of attracted water in the soil.

On the basis of "activity", clays can be classified in to four groups as shown in Appendix 1.

Activity is calculated for those soil samples which are classified as clay using the triangular classification chart. As shown in Table 5.8 the dark grey clay soils (C_{dg}) have an activity of 0.79-1.08 while the grey clays (C_g) have 0.83-1.03. The activity of silty clays (CM) is in the range of 0.53-1.06. The dark grey clays are more active than the rest and have a relatively high water holding capacity. Their properties are largely influenced by the clay fraction and that is why they do have a greater amount of moisture content compare to the others.

Comparison of the activity of the soils with the activity ranges given in Appendix 1 testifies that the dark grey and grey clays are normal to active clays and the silty clays grade from inactive to normal. On the basis of an Activity Chart Solomon (1982) classified all these lithological types as bad clays.

Table 5.8. Activity of clay soils taken from Bole and the surrounding area.

Sample No	Litho-logical type	Litho-logical subtype	Plasticity index %	Clay-fraction %	Activity
10s	C	C_g	73.1	71.2	1.03
12s	CM	-	54	75.2	0.72
15s	CM	-	42.9	67.6	0.64
16s	C	C_{dg}	66.6	65.8	1.01
17s	CM	-	48.7	73.0	0.67
19s	C	C_{dg}	67.4	73.7	0.91
20s	C	Cdg	68.4	81.2	0.84
24s	C	CM	26.6	50.1	0.53
25s	CM	C_{dg}	80.1	74.0	1.08
28s	C	-	49.8	59.7	0.83
34s	C	C_{dg}	69.0	70.0	0.99
36s	CM	Cg	70.2	84.4	0.83
37s	CM	-	52.6	49.6	1.06
38s			45.0	46.4	0.97

5.6. The free swell and swelling pressure of clay so

a) Free swell

According to Head(1984) soils with free swell values than 5% are not likely to show expansive properties. Valu of 100% or more are associated with clays which could swe considerably when wetted.

The free swell value for 43 soil samples is given in 5.9.

- The Black Clays (C_b) have a free swell of 98-105%
- The Dark Gray Clays (C_{dg}) have 75-130%
- The Grey Clays (C_g) have 75-102% and

- The Silty Clays (CM) have 55-75% and
- The Sandy Clays (CS) have 65%.

All the clay soils (C_b, C_{dg} and C_g) swell considerably, the dark grey clay soils (C_{dg}) being more expansive as compare

Table 5.9. Free swell values for soils taken from Bole and the surrounding area.

Sample No	Litho-logical type	Litho-logical subtype	Free swell %
1s	C	[illegible]	[illegible]
2s	C	C_g	100
3s	C	C_g	75
4s	C	C_r	65
5s	SG	-	32
6s	C	C_{dg}	75
7s	S	-	20
8s	SG	-	20
9s	SG	-	8
10s	C	[illegible]	[illegible]
12s	CM	-	55
13s	SG	-	25
15s	CM	-	65
16s	C	C_g	100
17s	CM	-	75
18s	CM	-	70
19s	C	C_{dg}	113
20s	C	C_{dg}	125
21s	C	C_b	105
22s	C	C_{dg}	130
23s	C	C_{dg}	115

Sample No	Litho-logical type	Litho-logical subtype	Free swell %
24s	CM	-	40
25s	C	C_{dg}	125
26s	CM	-	75
27s	CS	-	55
28s	CM	-	75
29s	S	-	40
30s	S	-	35
31s	C	C_{dg}	110
32s	C	C_g	100
33s	C	C_b	98
[illegible]	C	C_{dg}	85
35s	C	C_{dg}	125
36s	C	C_g	95
37s	CM	-	70
38s	S	-	75
39s	S	-	42
40s	S	-	40
41s	SM	-	45
42s	C	C_b	105
43s	C	C_g	102

to the others. The silty clays (CM) are less expansive and the sandy clays (CS) are even much less expansive. Since the clay soils (C_h, C_{dg} and C_g) contain a greater amount of clay fraction with dominant proportion of montmorillonite compared to other lithological types they are susceptible to high degree of expansibility. The swell and shrinkage problem present in the area is then largely associated with the clay soils covering it.

b) Swelling pressure (P_S)

Swelling in soils is a widely occuring natural process caused by the wetting of clay and the consequent increase in its volume. Its recognition in times when any kind of engineering structure is under construction is rather difficult. The development period may take several months or weaks. As time went on however, its magnitude increases at higher rate until a constant value is obtained at the final stage. Structures constructed before this limit are prone to considerable magnitude of damage.

The swelling of clay soils can be prevented, in the laboratory as well as in the field, by the application of a counter pressure. For the purpose of laboratory measurements, the maximum pressure which is required to prevent any volume increase of the sample at the final stage of swelling process is referred to as Swelling Pressure (Madsen and Muller-Vonmoos, 1989). The experimental determination of swelling pressure provides a laboratory value only and may not coincide with the true field value since preparatory works required will bring about some stress relief and will have an effect on natural water conditions. Hence, test results are used with an approximation to determine the depth (weight) of cover material required to prevent determintal expansion of the soil when used in a pavement structure.

Swelling pressure determination in soils of the study area was based on expanded and loaded method using the Geonor Swelling Device. 15 soil samples were selected in each lithological type and subtype according to their depth and distribution and on the basis of their clay fraction and free swell in all range of values. Each soil is then described as medium swelling and high swelling with a respective rating of 145-240 Kpa and greater than 240 Kpa (Ola, 1980).

The test procedure used for complete analysis was adopted from the laboratory manual written by Grabowska-Olszewska (1989) and is given in Appendix 1.

Swelling pressure values corresponding to each lithological type and subtype of clay soils are given in Table 5.10 and Fig. 5.3 (a,b,c). The values depend on the depth, amount of clay fraction, percentage of montmorillonite in clays and the type of solution used for the analysis.

- The Black Clays (C_b) have a swelling pressure, (P_S) of 0.32-0.34MPa.
- The Dark Grey Clays (C_{dg}) have 0.30-0-36 MPa
- The Grey clays (C_{dg}) have 0.30-0.36 MPa
- The Silty Clays (CM) have 0.21-0.23 MPa and
- The Red Clays (C_r) have the lowest value (0.18 MPa).

The swelling pressure of black clays (C_b), in contrast to their relatively small amount of clay fraction and percentage of montmorillonite, is high in magnitude since the

Table 5.10 Swelling pressure values for soils taken from Bole and the surrounding area.

Sample No	Depth m	Litho-logical type	Litho-logical subtype	Clay fraction %	Percentage of montmorillonite %	Solution used	Swelling Pressure MPa
2s	2	C	C_g	71.2	80-25	Distilled Water	0.32
4s	8.1	C	C_r	67.6	60-75	Distilled Water	0.18
10s	3.6	C	C_g	71.2	80-85	Distilled Water	0.31
12s	0.6	CM	-	75.2	80-85	Distilled Water	0.26
16s	3.4	C	C_g	65.8	80-85	Distilled Water	0.32
16s	3.4	C	C_g	65.8	80.85	NaCl(0.001N)	0.30
16s	3.4	C	C_g	65.8	80.85	NaCl(0.01N)	0.26
16s	3.4	C	C_g	65.8	80-85	NaCl(0.1N)	0.22
16s	3.4	C	C_g	65.8	80-85	$CaCl_2$(0.1N)	0.20
20s	2.2	C	C_{dg}	81.2	70-75	Distilled Water	0.35
21s	0.5	C	C_b	75.4	60-70	Distilled Water	0.34
21s	0.5	C	C_b	75.4	60-70	NaCl(0.1N)	0.31
21s	0.5	C	C_b	75.4	60-70	$CaCl_2$(0.1N)	0.29
23s	3.0	C	C_g	75.0	80-85	Distilled Water	0.32
25s	1.4	C	C_{dg}	74.0	80-90	Distilled Water	0.36
25s	1.4	C	C_{dg}	74.0	80-90	NaCl(0.1N)	0.31
25s	1.4	C	C_{dg}	74.0	80-90	$NaCl_2$(0.001N	0.30
25s	1.4	C	C_{dg}	74.0	80-90	$CaCl_2$(0.01N)	0.27
25s	1.4	C	C_{dg}	74.0	80-90	$CaCl_2$(0.1N)	
28s	0.55	CM	-	59.7	80-85	Distilled Water	0.23
31s	1.2	C	C_{dg}	75.0	80-90	Distilled Water	0.34
34s	2.8	C	C_g	70.0	80-90	Distilled Water	0.30
35s	1.2	C	C_{dg}	84.7	80.85	Distilled Water	0.36
36s	2.8	C	C_g	84.4	80-85	Distilled Water	0.32
42s	0.7	C	C_b	70.4	70-80	Distilled Water	0.32

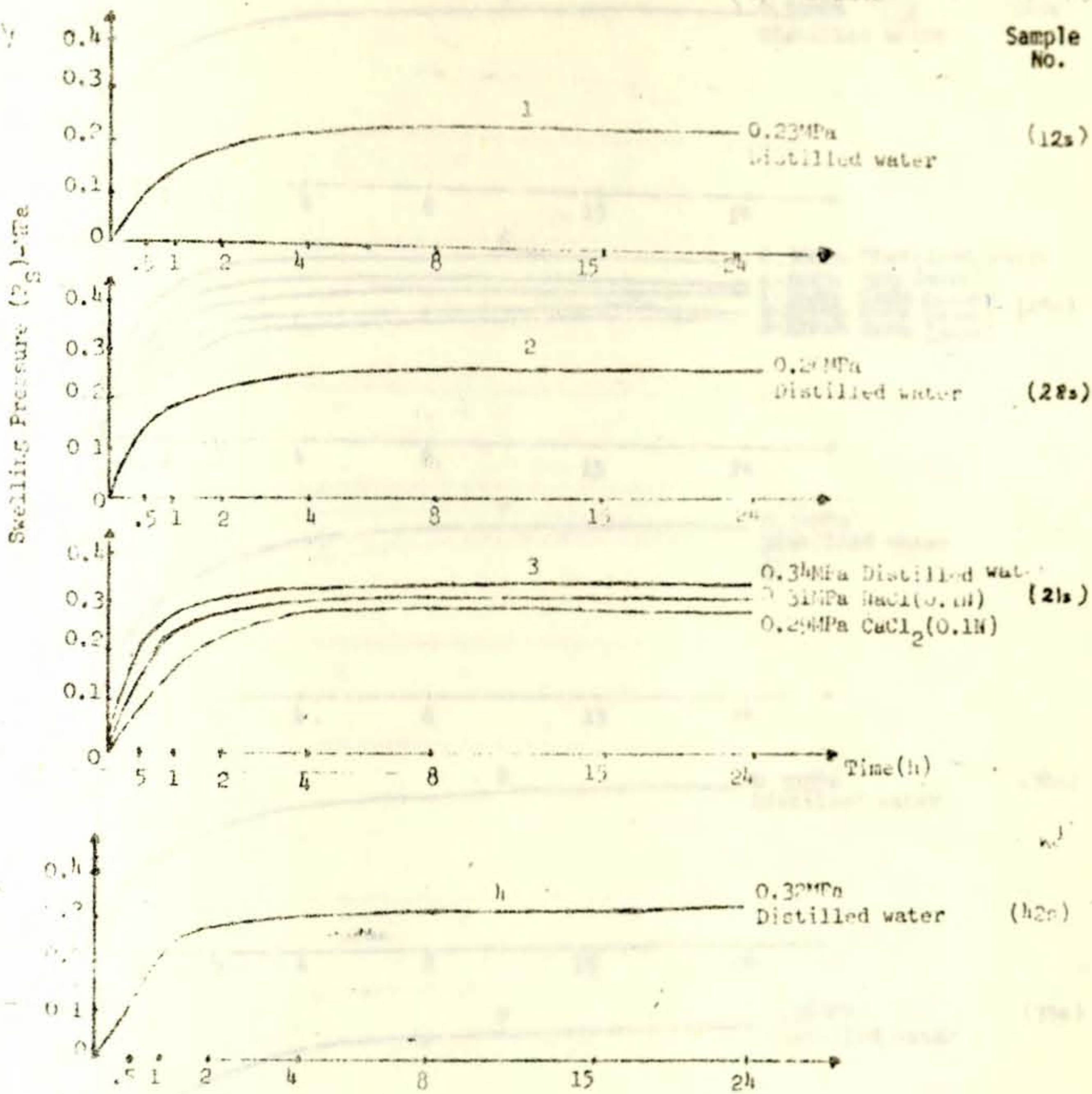


Fig. 5 .3. a. Swelling pressure (P_s) of soils taken from Bole and the surrounding area. 1 and 2 Silty clays. 3 and 4 Black clays.

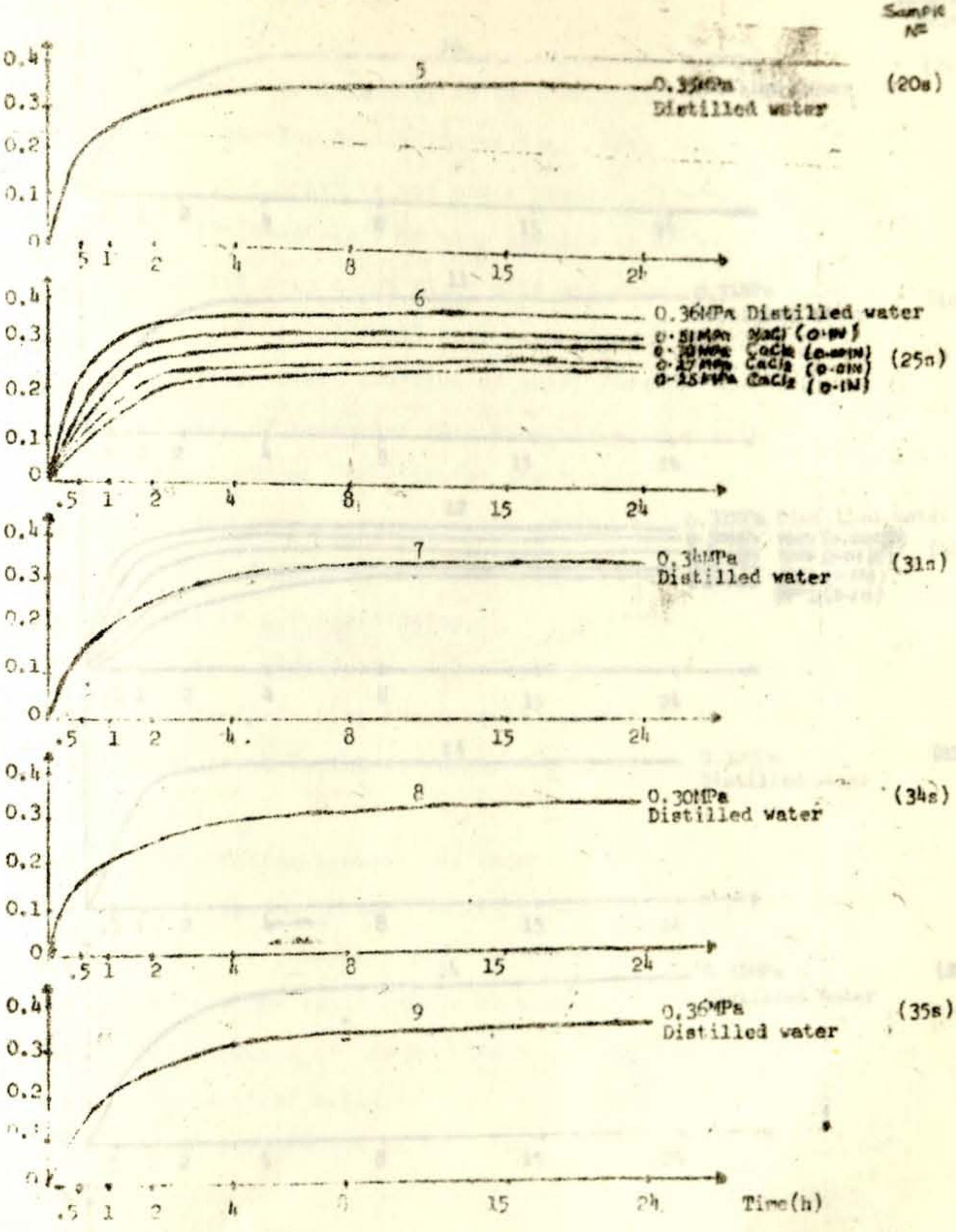
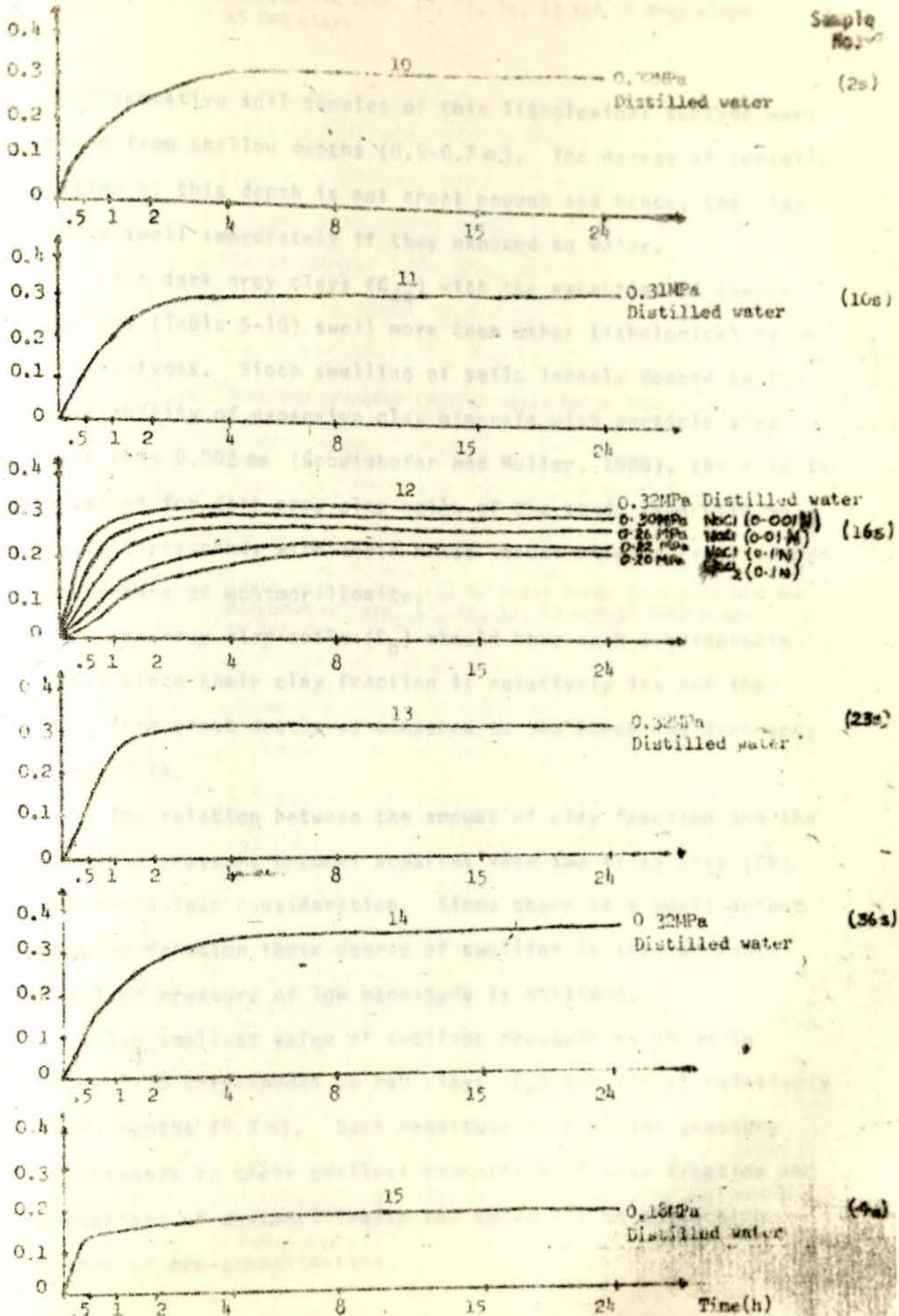


Fig. 5.3. b. Swelling pressure (P_S) of soils taken from Bole and the surrounding area. 5, 6, 7, 8 and 9 Dark grey clays.



Sample No.
10
0.32MPa
Distilled water
(2s)
11
0.31MPa
Distilled water
(16s)
12
0.32MPa Distilled water
0.30MPa NaCl (0.001N)
0.26 MPa NaCl (0.01N)
0.22 MPa NaCl (0.1N)
0.20 MPa CaCl2 (0.1N)
(16s)
13
0.32MPa
Distilled water
(23s)
14
0.32MPa
Distilled water
(36s)
15
0.18MPa
Distilled water
(4s)
0 0.1 0.2 0.3 0.4
.5 1 2 4 8 15 24
Time(h)

representative soil samples of this lithological subtype were taken from shallow depths (0.5-0.7 m). The degree of consolidation at this depth is not great enough and hence, the clay soils swell immediately if they exposed to water.

The dark grey clays (C_{dg}) with the exception of sample No. 34s (Table 5-10) swell more than other lithological types and subtypes. Since swelling of soils largely depend on the availability of expansive clay minerals with particle size less than 0.002 mm (Schwighofer and Muller, 1988), the results obtained for dark grey clay soils of the study area with no doubt corresponds with their great amount of clay fraction and percentage of montmorillonite.

The grey clay soils (C_g) should have such considerable value since their clay fraction is relatively low and they came from great depths as compared to the black and dark grey clay soils.

The relation between the amount of clay fraction and the swelling pressure becomes apparent when the silty clay (CM) are taken into consideration. Since there is a small amount of clay fraction their degree of swelling is low and hence swelling pressure of low magnitude is obtained.

The smallest value of swelling pressure as shown in Table 5-10 corresponds to red clays (C_r) sampled at relatively great depths (8.3 m). Such magnitude of swelling pressure corresponds to their smallest proportion of clay fraction and percentage of montmorillonite and above all tbctheir high degree of pre-consolidation.

The swelling pressure values given in Table 5.10 are the maximum possible vertical magnitudes since the samples were treaten at their driest state. In actual case however the values are lower than these since in nature the moisture content of soils is higher than what was taken during analysis and clay soils swell in large magnitude at their dry condition than if they are associated with considerable moisture.

The swelling behavior of three soil samples (16s, 21s, 25s) taken from different clay lithological subtypes is examined by saturating them with NaCl and $CaCl_2$ salt solutions of variable concentration. Comparison of the swelling pressure values of these cases with those obtained for the same samples saturated with distilled water (Table 5.10 and Fig. 5.3. (a,b,c)) revealed a marked decrease in magnitudes. An inevitable reduction is occurred in case of NaCl being higher for greater concentrations. Hence, samples saturated with 0.1N NaCl salt sn-itopm gave a greater reduction than samples saturated with 0.001N NaCl relative to data obtained in case of distilled water. The greatest reduction however is in those samples saturated with $CaCl_2$ salt solution. Here also, the decrease in magnitude of swelling pressure depend on the concentration, the highest being in the case of 0.1N $CaCl_2$ and the lowest in 0.001N $CaCl_2$ in comparison with values obtained for the same samples using distilled water.

The decrease in swelling pressure values using different salt solutions is attributed due to the fact that there exists an increase in the strength of bonds due to reduction of the thickness of double layer which causes greater attraxtion of the clay particles. Therefore the solutions may not penetrate so easily as in case of distilled water.

The same relation was obtained by Schwaighofer and Muller (1988) for pelitic rocks.

Generally, it is suggested that there should have been a load (pressure) which will counterpart such magnitude of swelling if structures are proposed to be constructed in the study area. Ola (1980) went on to state after noted an average swelling pressure of 0.12 MPa and a maximum of about 0.24 MPa for black cotton soils of northeastern Nigeria with moisture content of 25% that the dead load of buildings should be at least 0.08 Mpa to counteract the exerted pressures. After estimating that the swelling pressure values obtained for soils of study area will be comparable with those given by Ola (1980) with possible moisture content corrections, it can be proposed to use a dead load of greater than 0.08Mpa at least to decrease the magnitude of possible failures. In addition to this, stablization of soils with chemicals rich in calcium as mentioned above reduces the magnitude of swelling pressure estimated to be present.

6. Engineering geological classification of soils and rocks

Engineering geological classification involves grouping of different soil and rock types into categories which possess similar properties so as to provide a systematic method of description. Most of the time the classification takes into consideration both the field and laboratory results then with a joint guidance it is possible to identify and interprete rock and soil types.

Classification of soils and rocks for engineering geological mapping should be based on the principle of their physical or engineering geological properties in its present state which are dependent on the combined effects of age, mode of origin, subsequent diagentic, and many post-genetic processes including weathering. The principle of classification makes it possible not only to determine the reasons for the lithological and physical characteristics of soils and rocks, but also for their spatial distribution. The following classification, based on lithology and mode of origin is suggested: (a) engineering geological type (ET); (b) lithological type (LT); (C) lithological complex (LC); (d) lithological suite (LS) (Bulletin of IAEG No 24, 1981).

- The Engineering Geological type (ET) has the highest degree of physical homogeneity. It should be uniform in lithological character and physical state. These units can be characterized by statistically determined values derived from individual determinations of physical and mechanical properties and are generally show only on large-scale maps.

- The Lithological Type (LT) is homogeneous throughout in composition, texture and structure, but usually is not uniform in physical state. Usually only a general idea of engineering properties, with a range of values, can be presented. These units are used on large-scale, and where possible, on medium-scale maps.

- The Lithological Complex(LC) comprises a set of genetically related lithological types developed under specific paleogeographical and geotectonic conditions. Within a lithological complex the spatial arrangement of lithological types is uniform and distinctive for that complex, but a lithological complex is not necessarily uniform in either lithological character or physical state. The lithological complex is used as a mapping unit on medium-scale and same small-scale maps.
- The Lithological Suite(LS) comprises many lithological complexes that developed under generally similar palaeogeographical and tectonic conditions. These units are only used on small-scale maps.

6.1. Engineering geological classification of soils

The domain of the engineering geologists is in most cases within the top few metres of the earth's surface. Therefore, surficial deposits are of critical importance in an engineering geological map. Soil is mapped only when its thickness exceeds one meter; when it is less thick, the underlying rock is mapped (Soeters and Rengers, 1980). In the study area however, the top 50 cm thick soil is only discarded for mapping purposes since people in most cases excavate to a depth of this much level.

Eeven though several soil classification systems are in use the Unified Soil Classification System (USCS) proposed by the U.S. Bureau of Reclamation and Corps of Engineers (Appendix1) modified by IAEG (1981) is employed for classification of soils of the study area. The classification method used is based on grading of the constituent particles and plasticity of that fraction of the material consisting of particles finer than 0.425 mm.

For the purpose of laboratory classification of soils using USCS, 20 soil samples were selected from each lithological type and subtype with even distribution throughout the study area. The corresponding soil fractions, the liquid limit and plasticity index are taken from Sections 5.3 and 5.5. and given in Table 6.1. The percentage of fines (materials smaller than

Table 6.1. Classification of soils taken from Bole and the surrounding area according to USCS.

Sample No	Litho-logical type	Litho-logical subtype	Depth m	Soil fractions: Gravely >4.75mm %	Sandy 4.75 0.075 mm	Fines <0.075mm: silty 0.075-0.002 mm	clayey <0.002 mm %	Liquid limit (LL) %	Plasticity index (PI) %	Soil class acc. to USCS
21s	C	C_b	0.5	-	9.4	15.2	75.4	98	61.6	CH
33s	C	C_b	0.45	-	10.0	15.0	75.0	74	40.6	CH
42s	C	C_b	0.7	-	10.0	20.0	70.0	79	42.6	OH
1s	C	C_{dg}	1.9	-	8.6	17.7	73.7	115	75.0	CH
22s	C	C_{dg}	2.2	-	1.0	17.8	81.2	120	76.5	CH
31s	C	C_{dg}	1.2	-	6.7	22.3	70.0	116.5	72.4	CH
35s	C	C_{dg}	1.2	-	5.4	9.0	84.7	106	67.1	CH
3s	C	C_g	3.5	-	6.5	19.7	73.8	98	65.9	CH
23s	C	C_g	3.0	-	11.0	17.8	71.2	110	76.9	CH
36s	C	C_g	2.8	-	3.7	11.9	84.4	107.5	70.2	CH
43s	C	C_g	2.2	-	3.7	11.9	84.4	97.5	63	CH
12s	CM	-	0.6	-	7.3	17.5	75.2	96.0	54.0	OH
17s	CM	-	0.5	-	8.6	17.7	73.7	85.0	48.7	CH
24s	CM	-	0.7	-	35.2	12.8	50.1	48.5	26.6	CLS
28s	CM	-	0.55	-	11.4	28.9	59.1	86.5	49.8	CH
37s	CM	-	0.32	-	11.4	39.0	49.6	94.0	52.6	OH
38s	CM	-	0.45	-	14.3	39.3	46.4	83.0	45.0	OH
27s	CS	-	0.5	-	47.5	17.5	35.0	48	32	CLS
11s	SG	-	4.9	16.3	79.0	4.7	-	36	-	SP
39s	S	-	1.24	-	46.1	15.7	38.2	48	28.8	CLS

0.075 mm) is more than half in relative proportion in almost all lithological types. Due to this fact the classification of soils of the study area is mainly based on their liquid limit and plasticity index by using the plasticity chart given by Casagrande. The plots of plasticity index versus liquid limit for the 20 soil

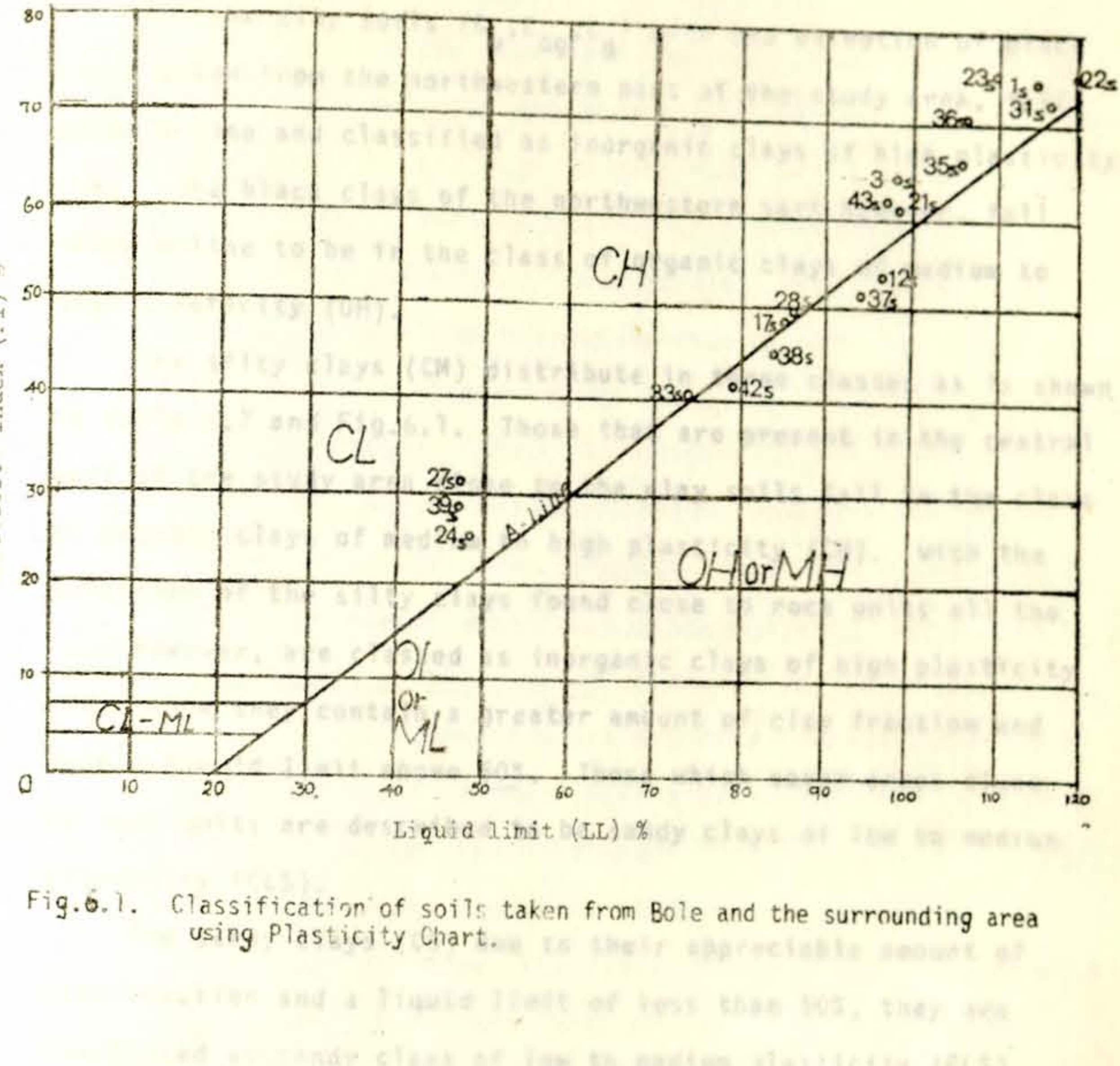


Fig.6.1. Classification of soils taken from Bole and the surrounding area using Plasticity Chart.

samples are shown in Fig 6.1 and the corresponding class for each sample is given in Table 6.2.

All the clay soils (C_b,C_{dg},C_g) with the exception of black clays taken from the northwestern part of the study area, fall above A-line and classified as inorganic clays of high plasticity (CH). The black clays of the northwestern part however, fall below A-line to be in the class of organic clays of medium to high plasticity (OH).

The silty clays (CM) distribute in three classes as is shown in Table 6.2 and Fig.6.1. Those that are present in the central part of the study area close to the clay soils fall in the class of organic clays of medium to high plasticity (CH). With the exception of the silty clays found close to rock units all the rest however, are classed as inorganic clays of high plasticity (CH) since they contain a greater amount of clay fraction and have a liquid limit above 50%. Those which cover areas close to rock units are described to be sandy clays of low to medium plasticity (CLS).

The sandy clays (CS) due to their appreciable amount of sand fraction and a liquid limit of less than 50%, they are classified as sandy clays of low to medium plasticity (CLS). The gravelly sands (SG) and sands (S) which underlie the clays, and sand clays as is described in Chapter 4 are designated to be poorly graded sands (SP) with gravels and sandy clays of low to medium plasticity (CLS) respectively. The characterstics of each soil group is discussed on the basis of both field observations and laboratory results hereunder.

a) Inorganic clays of high plasticity (CH)

These type of clay soils cover the central, the northeastern and some of the eastern part of the study area. In this group, the black clays are the uppermost representative lithological subtype with the dark grey and grey clays underlying them. This group of clay soils are high to very high in dry strength and severely cracked. They are hard to be crushed with very high extremely high plasticity. Their general property including their use as foundations for engineering structures is largely determined by their clay fraction and above all by the mineralogy of the clay fractions. Since the clay fraction in these soils is greater than 70% and montmorillonites amount a percentage range of 70-90% in this clay fraction, they have an ability to hold large quantity of water. This characterstic has a determinetal influence on their shear strength, shrinkage and swelling property. When they are saturated enough their shear strength becomes poor and fail easily while they are compacted. In dry months however, their strength increases due to loss of moisture and shrinkage cracks of various dimensions appear. During the onset of summer they again absorb water and swell to a greater degree. These processes of swelling and shrinkage results in failures of engineering structures in the study area. Hence, this group of soils by far are the most known foundations in which cracked buildings and fences are observed.

For the purpose of engineering geological mapping, this soil group is already divided into two subunits on the basis of field identification: those clays without calcite concretions (CH) and those with calcite concretions (CHc) (for a better discussion see chapter 4). The physical properties of these subunits are the same except for the presence of more illite (20-25%) in those clays with calcite concretions. This might be attributed to the poor leaching of Ca^{2+} from the parent material so as to enter into the clay structure and substitute K^+.

b) <u>Organic clays of medium to high plasticity (OH).</u>

The group of clay soils dominantly present in the north-eastern part of the study area and distributed in some other places as a form of isolated patches. In most of the cases they are foundations of preconstructed houses and buildings. Due to this fact big trees are largely present which accounts for their organic character. They are medium to high in dry strength and hard enough. Due to their organic content they fall in a group of medium to high plasticity. They are composed of the three clay layers (C_b, C_{dg}, C_g) with a comparable amount of clay fraction and montmorillonite as CH group. So, they possess the same soil properties mentioned above. Cracked buildings and fences are commonly observed and hence they will lie side by side with inorganic clays of high plasticity (CH) in terms of possible structural failures.

Both inorganic clays of high plasticity (CH) and organic clays of medium to high plasticity (OH) fall in areas close to the A line and elongated parallel to it. This implies that they all came from the same possible source. Generally, it is possible to suggest on the basis of the global properties of both CH and OH groups for engineering use that they are relatively impermeable, very poor subgrade and base course material, of high compressibility, poor workability as construction material and are poor foundations as compared to unified coarse grained groups (Truitt, 1983).

c) Sandy clays of low to medium plasticity (CLS).

These type of soils cover the upper reaches of the main river valleys and those areas close to the rock exposures. They are mostly black and in some places light yellowish brown, light red and red varieties are common. They normally graded to poorly graded sands with gravels (SP) and boulders of bed rocks. These sandy clays are medium to high in dry strength and associated with shrinkage cracks of shallow depth. They are firm to stiff with low to medium plasticity. In terms of origin these types of soils are divided into two subunite: Those sandy clays of in situ weathering products and those of alluvial origin.

The sandy clays of in situ weathering products (CLSi) cover the western and most part of the southern portion of the study area. They were first described to be silty clays before laborarartory analyses. The depth to the bedrock in these particular soils is 0.5-2.5 m. Hence, the degree of cracking as compared to those of CH and OH groups is partially reduced. Foundations are relatively stable and adequate stablization of these soils will not consume great effort and money.

The second subunit of sandy clays (CLSa) is soils that are transported by rivers and deposited along river valleys. The bedrock in these type of soils is at a depth of greater than 2.5 m. Since they contain comparable amount of clay fraction and montmorillonite as the first sub-units their soil properties are almost the same. But, they are not suitable places for foundation purposes since they are areas of swamps and bogs and occasionally associated with flooding.

The engineering aspects of the above subunits (CLS and CLSa) of sandy clays is that they are low permeable, poor subgrade and base course materials, of medium compressibility when compacted and saturated, good to fair workability as a construction material and are poor foundations as compared to unified coarse grained groups (Lambe and Whitman, 1969; Truitt, 1983).

d) Poorly graded sands with gravels (SP)

This group of soils found at a depth of greater than 1m. When they are underlying the clay soils, they are present at great depth but, if they underlie the sandy clays, they are relatively shallow. They never exposed in the study area hence are not shown in the engineering geological map. They are known to be permeable, low compressible, fair subgrade or base course, fair workability as construction material and fair to good foundation if seepage is not a factor (Truitt, 1983). So, if special type of structures are planned to be constructed in the study area, it is recommend to install the base of foundation at such type of soils at least in places where they are found at shallow depths.

6.2. Engineering geological classification of rocks

The base for the classification of rock units in the study area is restricted on their lithology and degree of weathering. As discussed in chapter 2 there are two rock units exposed in the area: Welded Tuff and Basalt. The descrimination of the properties of these two rocks is on the basis of visual observation in the field.

a) Welded Tuff (WT)

This unit cover most part of the eastern and south-western part of the study area and in many other places it is present as a form of isolated ridges. Its color usually is grey with yellow varieties in some places. It is fine grained with some unidentified volcanic rock fragments. This rock unit is massive and columnarly jointed with two sets of joints (vertical and horizontal) giving it columnar blocks of various sizes. These discontinuites are closely to very closely spaced (less than 100 mm) and are left without any infilling. In most places it is fresh to slightly weathered but in some cases it is globally altered to yellow varieties (pantelerized). Its strength characterstics were tested in the field using a "rock hammer" test[*1] which relates the sound, rebound and impact marks of a hammer blow to the general strength of the rock material. The observation obtained are thud, slight mark, and sometimes no rebound and fractures. Hence, it is estimated to possess moderate to high strength characterstics. Using K/Ar age determination, it is described to be late Pliocene in age (Morton, 1974).

b) Basalt (B)

This rock unit is exposed in the south and southeastern part of the study area mainly along Gerch and Kebena river

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[*1] According to the description of rock strength for classification purposes, Mathewson (1981).

valleys around Bole International Airport. It is black in color as usual and aphanitic in texture. In most places it is massive and columnarly jointed with columnar blocks of various sizes. In some cases however, it is flow banded and seems to be affected by posttectonic movements. It is further subdivided in to two subunites according to the degree of weathering: that which is fresh to slightly weathered (B_F) and that which is extremely weathered (B_W).

The first subunit (BF) is the most popular and dominantly present. Two discontinuities (vertical and horizontal joint sets) of very closely spaced (less than 60 mm) are observed and in some places these discontinuities are filled by calcite. it is spheroidally weathered along the two joint sets somewhere along the rivers. It gives clear rebound, solid ring and no mark with a hammer and hence described to have very high strength

The second subunit (B_W) is present in one locality along the upper reaches of Kebena river. It is extremely disintegrated and grading to heavy crusts. While hammering it, the hammer left its imprints indicating its low strength.

The age of both subunits (B_F and B_W) is dated to be 3.5 Ma (Morton and Rex, 1975) which places them in early Pliocene.

7. Foundation movements in the study area and Remedial measures recommended to be used

Soils of the study area for a long time have been notified to be associated with cracking of buildings which are thought to be the first sign of foundation movements. In most cases the cracks are much larger than 30 mm and pass through the foundations, the walls and lintels. From the investigation of the cracked buildings, it was obvious that the major problems are those of swelling and shrinkage. Typical cracks that are wide at the top and narrow at the bottom developed in the walls and diagonal cracks below exterior windows both indicate heaving of structures (Chen, 1979). Some examples of cracked buildings and fences are shown in Fig. 7.1 - 7.5.

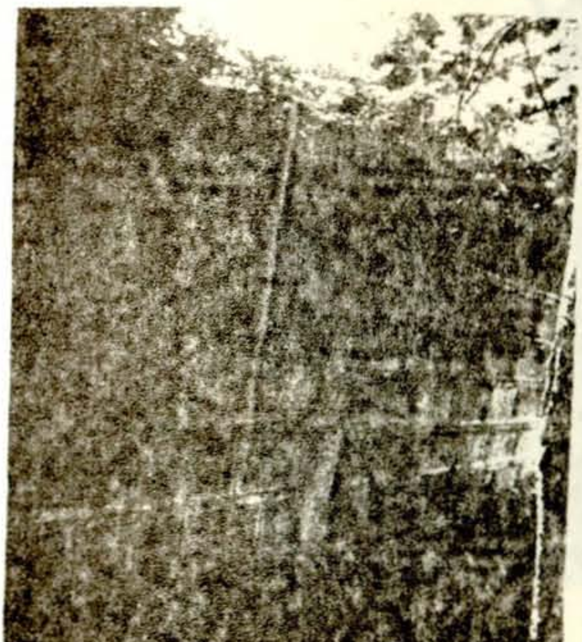

Fig. 7.1 Tilting of a fence. Higher 17, Kebele 20, House No 2009

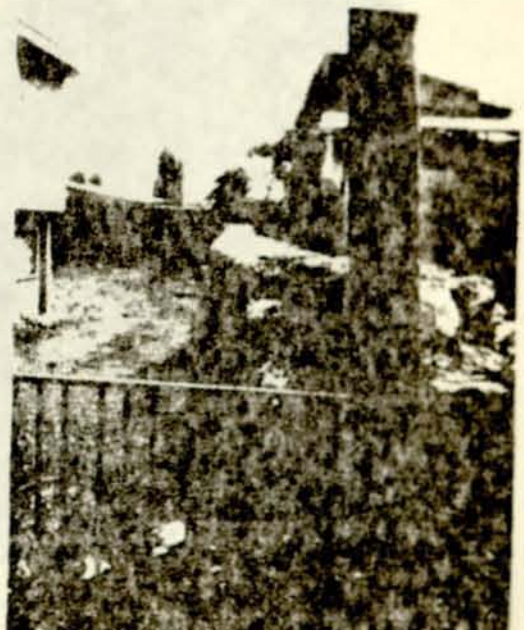

Fig. 7.2 Bending of a fence. Higher 17, Kebele 23, House No 2213

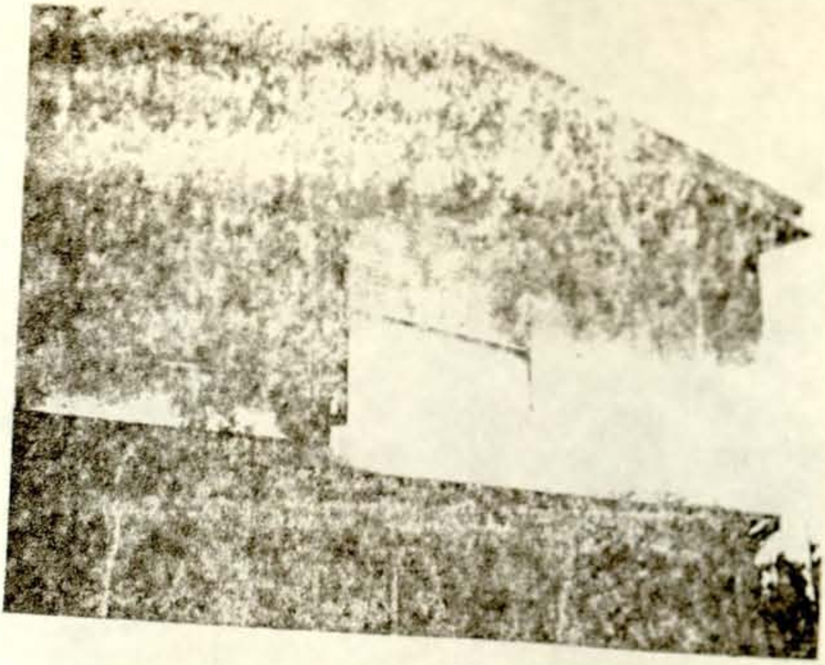

Fig. 7.3 Diagonal cracks along exterior walls and Windows; Higher 17, Kebele 23, House No.2213.

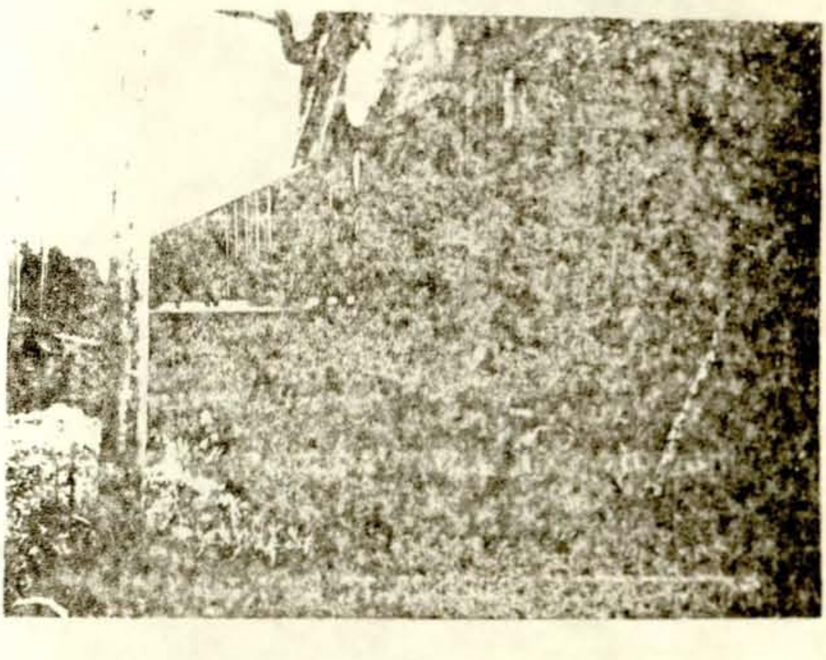

Fig. 7.4 Sinking and cracking of a fence, Higher 17, Kebele 23, House No. 2213.

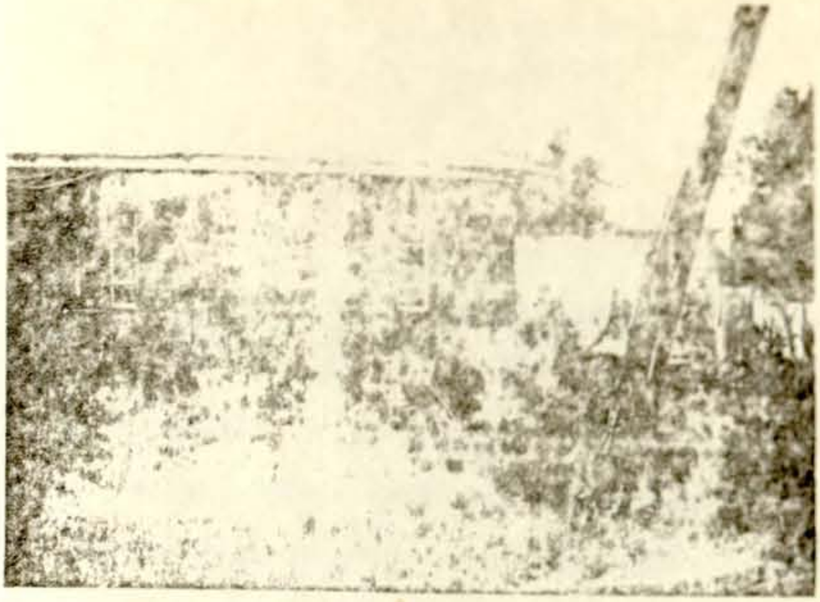

Fig. 7.5. Cracks along the exterior walls and windows. Higher 18, Kebele 35, House No. 691.

It is relatively easy to recommend the necessary remedial construction for a cracked building when the cause of foundation has been determined. The most known remedial measures used in many damaged structures are moisture control, type of foundation proposed to be built and soil stablization.

a) Moisture Control

It is relatively simple undertaking to remove free water which may seep into a building foundation by providing adequate surface drainage and properly installed subsurface drainage systems. The provision of proper drainage system plays an important role in reducing damage due to heaving. Even though it is not widely known, retardation of moisture migration by means of surface drainage is used by some owners of buildings in the study area. What will be recommended however is that, the ground surface around a building should be graded so that surface water will drain away from the structure in all directions.

b) Type of foundation

The type of foundation selected to be erected on expansive soils largely depend on the property of the soils and the economy available based on world-wide considerations. Chen (1979) recommend to use both drilled pier and footing foundation systems with suggested requirements.

The use of a drilled piers is to provide a relatively inexpensive way of transferring the structural loads to a stable zone (active zone) where moisture changes are improbable. After moisture content determinations in chapter 5, it is proposed that the active zone in most of the study area is at a depth of 2.5-3 m. Hence the piers should be founded to a depth of this much level at least to reduce possible failures.

Chen (1979) continued on to state that footing foundations can be successfully placed on expansive soils provided that sufficient dead load pressure is exerted on the foundation and if the swelling potential of the foundation soils can be reduced by other methods. It is also recommended to use stiffened mat foundations in areas where the active zone is deep (Solomon, 1982).

Generally, in any type of foundation, it is possible to suggest that by loading the soil with a pressure greater than the swelling pressure values given in section 5.6, heaving movement can be prevented in the study area.

c) Soil stabilization

The chief objectives of soil stablization are to improve soil strength, to decrease permeability and water absorption and to improve bearing capacity and durability under cyclical conditions such as varying moisture content. There are two ways of stabilization of soils: mechanical and chemical stabilizations.

Mechanical stabilization involves a removal of natural expansive soils and their replacement with nonexpansive soils with accompanying compaction and densification. This method however fails to apply in most cases in the study area since the expansive material of the study area extends to great depths and hence removal to such depth needs great cost.

Chemical stabilization involves inorganic chemicals, the most known of which are lime and cement. Lime flocculates the clay minerals due to base exchange and its application causes soils to become more workable and less plastic. It can also appreciably reduce swelling and shrinkage due to gain or loss of moisture. Cement on the other hand increases the soil strength and decreases its permeability. The type of clay minerals in a cohesive soil influence the case with which it can be stabilized with lime or cement. Despite this, the requirements for stablization of different soils have to be determined by laboratory tests such soil properties as consistency limits. Results presented by Ola (1978) for stablization of road bases for heavy wheel loads indicated that a combination of 6% lime and 8% cement is recommended to restrain the high swelling and to substantially increase the strength of black cotton soils of northeastern Nigeria. Hence at the present knowledge, it is suggested to use these combinations in the study area for field trial in the first instance at least to minimize the possible structural failures.

8. CONCLUSION

Based on the existing demands of peoples to construct new engineering objects, an engineering geological study was carried out in Bole and the surrounding area. More emphasize was given to determination of the engineering geological parameters of soils since the area is covered by thick unconsolidated clayey sediments.

The area is composed of two relatively young rock units. Early Pliocene basalt is exposed along river valleys in the southern part of the area whereas Late Pliocene welded tuff is distributed throughout the area as isolated ridges.

Recognition of geomorphological conditions of the area is presented on a Geomorphological Map. The topography of the area is the result of the youngest volcanism and subsequent weathering and erosion processes. It is possible to conclude from general considerations that the area is relatively flat. Except in the southern part where slow soil movements are encountered along river scarps, the area is relatively stable in terms of the geodynamic processes.

The annual mean evapotranspiration in the area generally exceeds the annual mean precipitation. The ground water conditions are complex because of the rare occurrence of water wells around the area. But, based on the available data, it is proposed that the ground water table is inclined to the south following the topography and its level fluctuates in relation to the climate. The effect of this fluctuation on inducing of moisture to soils of the area however, is less intensive since in most cases the static water level is found to be very deep (greater than 20 m). Even though the chemical analyses of the ground water table in the investigated water wells refer to samples taken at a depth beneath the normal range of engineering activities, the general chemical composition indicate variable degrees of leaching of the surrounding rock units and soils.

During field investigations it was possible to classify the soils into three types (Clay, Silty Clay and Sandy Clay). The clay soils contain three different distinct layers: the black clay, the dark grey clay and the grey clay grading from top to bottom. Both the silty clay are sandy clays are underlain by poorly graded sands, gravels and boulders of the bed rocks. The depth to the bed rocks beneath the silty and sandy clays is smaller than the depth to the same rock below clay soils. The clay soils present in the eastern part of the study area near Bole International Airport contain calcite concretions of greater than 0.5 mm in size.

Except for some sandy clays found along the upper reaches of main rivers all soils are residual. The basic igneous rocks (the basalts) that are made up of calcium rich-feldspars which are high in the weathering order (i.e unstable) and the pyroclastic sediments (the tuffs) which are made up of volcanic glasses, under suitable conditions lead to the formation of a fine grained, mostly clay size, soil. The degree of evaporation which exceeds precipitation in the area and the poor leaching conditions have a significant influence on the genesis and engineering geological properties of the soils since they affect the degree of weathering and exercise a selective control on the types of clay minerals which can form from weathering processes.

Laboratory determination of organic matter content of soils of the area was carried out and it was observed that the clay and silty clay soils of the northern part of the study area are more organic compare to other types of soils.

In all lithological type of soils, an average moisture content value of 35% was obtained. Since the area is relatively flat, the soils can hold aboundant moisture migrating from the surrounding area. Correlation of data of the same lithological types and subtypes in different test pits and bore holes indicate that the value of the moisture content was almost similar (30%) and kept constant at a depth of 2.5-3 m. This depth might correspond to the active zone of the area.

Values of specific gravity, bulk density, dry density, void ratio and porosity are discussed and they are invariably related to the lithology of the soils.

The particle size distribution of soils is characterized by very high clay fraction with respect to silt and sand. The percentage of coarse fraction increases with depth until the bed rock.

Mineralogical analysis of soils finer than 0.075 mm using differential thermal analysis (DTA) gave two types of curves. The first type corresponds to all lithological types of clay soils and has two endothermic effects and one exothermic peak. Interpretation of this type of curves with respect to standard curves indicate the presence of a greater proportion of montmorillonite (70-90%) and small percentage of illite (5-15%) and koolinite (5-20%). The second type however, has three endothermic peaks with an immediate inversion of an exothermic peak. It is characterstic of the black and dark grey clays of the eastern part of the area close to Bole International Airport. It is interpreted to contain 70-80% of montmorillonite and 20-30% illite

Consistency limits determination of all soils indicate that the clay soils are characterized by high values of liquid and plastic limits relative to the silty and sandy clays. Hence, they are described to be highly plastic and hard enough to be crushed on the basis of their indices. The less plastic silty and sandy clays grade from stiff to hard in consistency.

The swelling pressure values of clay soils revealed that all the three lithological subtypes of clays swell considerably. A maximum value of 0.36 MPa was obtained for dark grey clays found at a depth of 1-2 m. The value generally decrease with depth corresponding to the consolidation effect of the clays and a minimum value of 0.18 MPa was observed for red clays taken at a depth of 8-10 m. The dead load of engineering objects founded on these soils should be either equal or greater than the values obtained at least to reduce possible structural failures.

Based on field observations and laboratory results, an engineering geological classification of soils and rocks of the area was conducted.

The soils are classified into different unites on the basis of the Unified Soil Classification System.

Since soils of the area are largely dominated by fine fractions, the plasticity chart was taken into consideration for grouping purpose.

The clay soils fall below and above the A-line in the Plasticity chart and are grouped into two units: inorganic clays of high plasticity (CH) and organic clays of high plasticity (OH). The inorganic clays of high plasticity are further subdivided into two: those which contain calcite concretions (CHc) and those which do not contain calcite concretions (CH). Since both CH and OH groups fall within an area extended parallel to the A-line they are proved to be derived from the same origin.

The sandy clays fall above A-line in an area of low to medium plasticity. They are divided into two units in terms of their origin: those which are in situ products of weathering (CLS*i*) and those of alluvial origin (CLS**a**).

The silty clays are classified as clays or sandy clays since they were found to possess similar engineering geological properties of either of the later when they were examined in the laboratory.

The rocks are divided into different units in terms of their lithology and weathering state. The first unit comprises the welded tuffs that are distributed throughout the area as a form of isolated ridges (WT). The basalts are classified to be the second and third rock units on the basis of their degree of weathering. Those which are fresh to slightly weathered are assigned to be B_F and those which are extremely weathered are considered as BW.

The use of each soil and rock unit for engineering purpose is discussed and the result of classification is presented in the form of an Engineering Geological Map. The later might give informations which are relevant to the early planning stages of engineering objects.

Appendix 1

Field methdology and Laboratory test procedures

Field methdology (4)

Field investigation of soils of the study area was carried out on the basis of 23 test pits (P) together with 14 dug holes (DH) and bore holes (BH). The locations of test pits were first assumed to be at every 1 km in a form of rectangular network. However the distribution was later modified due to the following reasons.

1. Most part of the study area was already occupied by houses, buildings and large engineering structures which made impossible to carry out test pits.

2. The occasional undulating nature of the area did not permit to follow such a rectangular pattern of distribution of test pits.

3. Since it was obtained adequate informations from bore holes and dug holes in some areas, there had not been a need to carry out test pits in such localities.

on the basis of these reasons the number of test pits carried out in the study area was restricted to such a number (23) and the description of such pits is given in Appendix 2

Laboratory test procedures

- Laboratory test procedures for basic physical studies (moisture content, bulk density, specific gravity, grain size analysis) was taken from Head (1984).

- The determination of consistency limits (liquid limit and plastic limit) is according to ASTM and the test procedure was adopted from Head (1984).

Terms for the description of fine soils (Bulletin of IAEG, No. 24, 1981)

Term	Range of liquid limits
of low plasticity	under 35
of intermediate plasticity	50-70
of high plasticity	50-70
of very high plasticity	70-90
of extremely high plasticity	over 90

Terms for the description of plasticity index (Bulletin of IAEG, No.24,1981)

Term	Plasticity index
Non-plastic	under 1
Slightly plastic	1-7
Moderately plastic	7-17
Highly plastic	17-35
Extremely plastic	over 35

ssification of the soils in terms of consistency index (Bulletin of IAEG, No.24, 1981)

Term	Consistency index
Very soft	less than 0.05
Soft	0.05 - 0.25
Firm	0.25 - 0.75
Stiff	0.75 - 1.00
Very stiff or hard	over 1.00

Activity of clays (Head, 1984)

Description	Activity
Inactive clays	0.75
Normal clays	0.75 - 1.25
Active clays	1.25 - 2
Highly active clays	2

ree swell determination of soils of the study area

as based in the test procedure given by Head (1984).

procedures for Differential Thermal Analysis (DTA)

test procedure used for differential thermal analysis

s of the study area is described below.

- A sample of 200 mg which passed the No 200 (0.075 mm) sieve was prepared without any pretreatment and placed in a crucible.

- A preheated kaolin was used as a reference substance.

- The sample was heated under normal laboratory atmospheric conditions and temperature reactions were recorded.

- Measuring ranges of temperature was from 20-1000°C with chart speed 150 mm/h and heating rate of 10k/min.

- A DTA curve was prepared together with the temperature curve. Fig.6.2 (a-d) show the 15 DTA curves for 15 soil samples.

Test procedures for determination of Swelling Pressure

The following test procedure was used to determine the Swelling Pressure of soils of the study area.

- An air-dried (with moisture content of 5-10%) soil sample was ground and then 20g was selected without any pretreatment*1.

- The sample was placed properly in a sample cylinder with a set of paper and stone filters below and above it and all adjustment of the device were carried out so as to measure the vertical swelling pressure (a component which approximates the exact field values).

- The sample was first axially loaded with a pressure of 2MPa (this limit is defined by equipment constriants) to consolidate it to equilibrium conditions.

- The pressure was released to zero and the sample was allowed to expand freely to constant height.

- At this time, distilled water or various salt sollutions was filled into the cylinder with the same level as to the sample height and the dry sample adsorb water through the filter.

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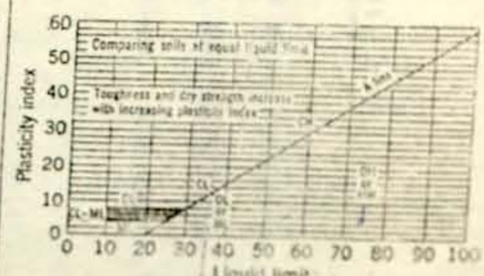
*1 Removal of organic matter and treating of the sample with salt solutions so as to concentrate it with specific cations was not carried out.

- The pressure exerted by the sample at the time of expansion within a given period of time (30 sec., 1 min. 2 min, ... 24 h) was measured by means of a calibrated restraining pressure gauge and recorded.

- Pressure values were plotted on a swelling pressure-time log diagram and the pressure at the end of the test is taken as the swelling pressure for the sample.

Table 7.1 Unified Soil Classification.

Major divisions		Field Identification Procedures (Excluding particles larger than 3 in. and basing fractions on estimated weights)			Group Symbols[a]	Typical Names	Information Required for Describing Soils	Laboratory Classification Criteria	
Coarse-grained soils. More than half of material is *larger* than No. 200 sieve size[b] (The No. 200 sieve size is about the smallest particle visible to naked eye)	Gravels. More than half of coarse fraction is larger than No. 4 sieve size (For visual classification, the ¼ in. size may be used as equivalent to the No. 4 sieve size)	Clean gravels (little or no fines)	Wide range in grain size and substantial amounts of all intermediate particle sizes		*GW*	Well graded gravels, gravel-sand mixtures, little or no fines	Give typical name; indicate approximate percentages of sand and gravel; maximum size; angularity, surface condition, and hardness of the coarse grains; local or geologic name and other pertinent descriptive information; and symbols in parentheses	Determine percentages of gravel and sand from grain size curve. Depending on percentage of fines (fraction smaller than No. 200 sieve size) coarse grained soils are classified as follows: Less than 5% *GW, GP, SW, SP*; More than 12% *GM, GC, SM, SC*; 5% to 12% *Borderline* cases requiring use of dual symbols	$C_U = \frac{D_{60}}{D_{10}}$ Greater than 4; $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			Predominantly one size or a range of sizes with some intermediate sizes missing		*GP*	Poorly graded gravels, gravel-sand mixtures, little or no fines			Not meeting all gradation requirements for *GW*
		Gravels with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures see *ML* below)		*GM*	Silty gravels, poorly graded gravel-sand-silt mixtures	For undisturbed soils add information on stratification, degree of compactness, cementation, moisture conditions and drainage characteristics		Atterberg limits below "A" line, or *PI* less than 4 — Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)		*GC*	Clayey gravels, poorly graded gravel-sand-clay mixtures			Atterberg limits above "A" line, with *PI* greater than 7
	Sands. More than half of coarse fraction is smaller than No. 4 sieve size	Clean sands (little or no fines)	Wide range in grain sizes and substantial amounts of all intermediate particle sizes		*SW*	Well graded sands, gravelly sands, little or no fines	Example: *Silty sand, gravelly;* about 20% hard, angular gravel particles ½-in. maximum size; rounded and subangular sand grains coarse to fine, about 15% non-plastic fines with low dry strength; well compacted and moist in place; alluvial sand; (*SM*)		$C_U = \frac{D_{60}}{D_{10}}$ Greater than 6; $C_C = \frac{(D_{30})^2}{D_{10} \times D_{60}}$ Between 1 and 3
			Predominantly one size or a range of sizes with some intermediate sizes missing		*SP*	Poorly graded sands, gravelly sands, little or no fines			Not meeting all gradation requirements for *SW*
		Sands with fines (appreciable amount of fines)	Nonplastic fines (for identification procedures, see *ML* below)		*SM*	Silty sands, poorly graded sand-silt mixtures			Atterberg limits below "A" line or *PI* less than 5 — Above "A" line with *PI* between 4 and 7 are *borderline* cases requiring use of dual symbols
			Plastic fines (for identification procedures, see *CL* below)		*SC*	Clayey sands, poorly graded sand-clay mixtures			Atterberg limits below "A" line with *PI* greater than 7
		Identification Procedures on Fraction Smaller than No. 40 Sieve Size						Use grain size curve in identifying the fractions as given under field identification	
		Dry Strength (crushing characteristics)	Dilatancy (reaction to shaking)	Toughness (consistency near plastic limit)					
Fine-grained soils. More than half of material is *smaller* than No. 200 sieve size (The No. 200 sieve size is about the smallest particle visible to naked eye)	Silts and clays, liquid limit less than 50	None to slight	Quick to slow	None	*ML*	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity	Give typical name; indicate degree and character of plasticity, amount and maximum size of coarse grains; colour in wet condition, odour if any, local or geologic name, and other pertinent descriptive information, and symbol in parentheses		
		Medium to high	None to very slow	Medium	*CL*	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays			
		Slight to medium	Slow	Slight	*OL*	Organic silts and organic silt-clays of low plasticity	For undisturbed soils add information on structure, stratification, consistency in undisturbed and remoulded states, moisture and drainage conditions		
	Silts and clays, liquid limit greater than 50	Slight to medium	Slow to none	Slight to medium	*MH*	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts			
		High to very high	None	High	*CH*	Inorganic clays of high plasticity, fat clays	Example: *Clayey silt,* brown; slightly plastic; small percentage of fine sand; numerous vertical root holes; firm and dry in place; loess; (*ML*)		
		Medium to high	None to very slow	Slight to medium	*OH*	Organic clays of medium to high plasticity			
Highly Organic Soils		Readily identified by colour, odour, spongy feel and frequently by fibrous texture			*Pt*	Peat and other highly organic soils			



Plasticity chart
for laboratory classification of fine grained soils

From Wagner, 1957
[a] *Boundary classifications.* Soils possessing characteristics of two groups are designated by combinations of group symbols. For example *GW-GC*, well graded gravel-sand mixture with clay binder.
[b] All sieve sizes on this chart are U.S. standard.

Appendix 2

The description of the more representative soil profiles of test pits (P), dug holes (DH) and bore holes (BH) along preferred directions is given below. All the following sketches are not to scale.

DH-3

1	Clay, black, hard, v.closely cracked, fresh.
2	Sandy Clay, light yellowish brown, firm, dry, fresh.
3	Gravelly Sand, light grey, loose, dry, slightly weathered.

DH-2

1	Clay, black, hard, dry, v. closely cracked, fresh.
2	Clay, dark grey, hard, dry, fresh.
3	Clay, grey mottled with black, stiff, dry, fresh.

P-21

Layer	Description
1	Silty clay, black, hard, v. closely cracked, dry, fresh.
2	Sand, light grey, loose, dry fresh.
3	Ash, light yellow, loose, discoloured, dry, slightly weathered.

BH-1

Layer	Description
1	Clay, black, hard, v. closely craked, dry, fresh
2	Clay, dark grey, hard, dry, fresh.
3	Clay, grey mottled with black, stiff, dry, fresh
4	Gravelly Sand, light yellowish brown, loose dry, slightly weathered.
5	Sand with gravels, yellowish red, loose, dry, slightly weathered.
6	Clay, red, stiff, dry, fresh.
7	Gravelly Sand with Boulders of Welded Tuff and Pumice fragments, dense, dry, light grey, slightly weathered.
8	Welded Tuff, dark grey, densely compacted, extremely disintegrated and highly decomposed, pumaceous, loosely welded.

Layer	P-5	P-11	P-8
1	Clay, black, firm, V.closely cracked, moist, fresh, (2-3% $CaCO_3$ concretions), with grass roots.	Silty Clay, black, hard, slightly wet, v.closely cracked, fresh with grass roots.	Silty Clay, black, hard, slightly wet, v.closely cracked, fresh, with grass roots.
2	Clay, dark grey, stiff, v.closely cracked, slightly wet, fresh, (10-15% $CaCO_3$ concretions).	Silty Clay, light yellowish brown, stiff, dry, fresh.	Silty sand, light grey, loose, dry fresh.
3	Clay, grey mottled with black, stiff, dry, fresh, (2-7% $CaCO_3$ concretions).	Gravelly Sand with Boulders of Welded Tuff, light grey, dry, slightly weathered.	Welded Tuff, light grey, globally altered, massive, rough, v.wide joint sets in two orthogonal planes giving columnar blacks, strongly welded, slightly weathered.

P-13

1 Sandy Clay, black, firm, dry, fresh.

2 Sandy clay, red, firm, dry, fresh, interstratified with sand.

3 Ash, light yellow, loose, discoloured, dry, slightly weathered.

P-15

1 Clay, black, firm, v.closely cracked, wet, fresh with grass roots.

2 Sandy clay, red, hard, v.closely cracked, dry, fresh.

3 Sand, light red, loose, dry, fresh.

4 Gravelly Sand with Boulders of Welded Tuff, light grey, loose, dry, fresh.

Layer	P-9	DH-4	P-4
1	Clay, black, firm, v.closely cracked, wet, fresh with grass roots.	Clay, black, hard, dry, v.closely cracked, fresh.	Sandy Clay, black, firm, dry, fresh.
2	Clay, dark grey, stiff, slightly wet, fresh.	Clay, dark grey, stiff, dry, fresh, (with 2-5% $CaCO_3$ concretions).	Gravelly Sand, light grey, loose, dry, slightly weathered.
3	Clay, gray mottled with black, stiff, dry, fresh.	Clay, grey mottled with black, stiff dry, fresh, (with 2.5% $CaCO_3$ concretions).	Gravelly Sand with Boulders of Welded Tuff and Pumice fragments, dense, dry, light grey, slightly weathered.

Appendix 3

1. Correlation of Soil Profiles.
2. Engineering Geological Map of Bole and the Surrounding area. Scale 1: 10,000.
3. Engineering Geological Cross-section.

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree in any other university. All sources of material used for the thesis have been duly acknowledged.

Name: Lulseged Ayalew

Signature: ____________

Place and date of submission: School of Grauduate Studies, June, 1990.