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Review

The Mode of Formation, Nature and Geotechnical characteristics of Black Cotton Soils - A Review

***Gidigasu S. S. R and Gawu S. K. Y**

Department of Geological Engineering,
Kwame Nkrumah University of Science and Technology, Kumasi-Ghana

***Corresponding author** E-mail: ssrgidigasu@yahoo.com

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Abstract

Black clay soils or tropical black earth or black cotton soils are known to be potentially expansive soils. They classify in pedological parlance as Vertisols and have been subject of considerable agricultural and engineering research especially in India and some African countries. The black cotton soils are considered "problematic" and sometimes as "potential natural hazard" because they cause extensive damage to light structures founded on them due to excessive seasonal volumetric changes (swell and shrinkage). Considering the widespread prevalence of black cotton soils around the world and the geomechanical challenges they pose to structures founded on them, we need to understand the peculiar characteristics and behaviours to enable effective utilization of these soils for engineering purposes. As a first step there is a need to assemble, correlate and integrate useful information on the genesis, nature and distribution as well as some basic geotechnical characteristics of the black cotton soils useful for civil engineering purposes scattered in various journal papers, proceedings of conferences, symposia, workshops, etc. Secondly, there is also the need to add value to existing knowledge in terms of technical information relating to geology and geomechanics of the black cotton soils occurring in Ghana through laboratory and field studies. The paper attempts to review the literature on the state of the art. The review relates to the raw soils and has not discussed improvement and stabilisation aspects.

Keywords: Weathering, classification, problematic, potentially expansive, black cotton soil

INTRODUCTION

Black cotton soils are major problematic soils of some tropical countries especially in Africa and India. They are poor materials by temperate zone standards and difficult to use for road and air field construction because they are often expansive due to the presence of large percentages of expansive clay minerals, i.e. montmorillonite. These soils swell when in contact with water and shrink on drying. The soil deposits are usually extensive making it impossible to avoid or by pass during construction of engineering projects. Many roads and foundations of light buildings have been reported distressed due to the seasonal volume change (i.e. swell and shrinkage) of these soils (Chen, 1988). These soils have reportedly inflicted billions of dollars in damages and repairs annually to earth structures and facilities. Table1 presents some estimated cost of damages due to heave on facilities of some countries. Some works have been done on the black cotton soils locally and internationally, however, this rather useful information are scattered in various publications and the need to bring these scattered information together has long been felt. This paper therefore seeks to address this problem. The work is augmented with results from a current research on Ghanaian black cotton soils. The black cotton soils used in the study were collected from depths between 0.3-1.0m below ground level from Tsopoli and Doryumu in the Accra Plains of Ghana. The geographical location of the test pits were N 05^{o}53'55.0"; E 00^{o}01'05.40" and N 05^{o}53'55.0"; E 00^{o}01'05.40" respectively. The sites are underlain by the garnetiferous hornblende gneiss of the Dahomeyan formation.

Table 1. Estimated cost of damages due to undesirable heave/swell of expansive soils

Country	Amount	References
Britain	£3 billion (2001)	Bell and Culshaw, 2001
China	¥100 million	Ng et al., 2003
France	€3.3 billion (2002)	Zemienu et.al., 2009
India	several lakhs of rupees	Gourley et. al.,1993
Saudi Arabia	>US$ 300 million (1977 and 1987)	Ruwaih, 1987
Sudan	>US$ 6 million (1983)	Osman and Charlie, 1983
USA	US $2 billion annually	Nelson and Miller, 1992

Definition and Nomenclature

Black clays or tropical black earth or black cottons are known to be potentially expansive soils which are "black" or "greyish black" or in their eroded phase "greyish white" heavy loam or clay (usually 50%), with predominant clay mineral of the smectite group, rich in alkali earth elements and the horizons sometimes contain calcium carbonate or magnesium oxide concretions. Many other terms have been applied locally, such as *"regur"* soils in India, *"margalitic"* soils in Indonesia, *"black turf"* in Africa and *"tirs"* in Morocco. Although there are several names, the term "black cotton soil" is adopted in this paper because of its extensive use in literature. The term "black cotton" is believed to have originated from India where the locations of these soils favour cotton growth. Pedologically, the black cotton soils classify as Vertisols (Table 2) and both terms are used interchangeably in this paper.

Black cotton soils have been defined differently by different authors, for instance Mohr and Van Baren (1959) proposed the term "margalitic soils" which they defined as "black or greyish black, grey or in the eroded phase greyish-white" heavy loam or clays; which crack when dry and swell when moistened, they are mostly rich in alkaline earths; horizons of calcium concretions develop sometimes or lime concretions are found scattered throughout the profile; they are characterized by montmorillonite or other minerals of the smectite group as clay compound. USAID/BRRI (1971) also defined the tropical black cotton clay to be dark grey to black soil with a high content of clay usually over 50%, in which montmorillonite is the principal clay mineral and are commonly expansive. Morin (1971) defined black cotton soil as dark grey to black soil which has high clay content usually over 50% and are potentially expansive. Bucher and Sailie (1984) described black cotton soil as rich in montmorillonite and therefore prone to high volume change in the presence of water.

The main characteristics of black cotton soils among others are:

1. Black or darkish grey to brown colour
2. High content of expansive clay mineral montmorillonite
3. Poses the tendency to shrink and swell with change in moisture condition
4. Exhibits heave and crack as geo-environmental phenomena.

Table 2. Pedological classification of black clays (Wesley, 1988)

Commonly Used Names	Rigoros Pedological Names			Dominant Clay Minerals
	FAO	US Soil Taxonomy	French	
Black cotton soil, Black clays, Tropical black earths, Grumusols	Vertisols	Vertisols	Vertisols	Smectite (Montmorillonite)

FAO- Food and Agriculture Organisation

Weathering

Weathering is a pedogenic process by which soils are formed as a result of disintegration or decomposition of rocks. This process causes changes in rocks at and near the earth's surface by interaction between the rocks and the chemically active components of the earth's atmosphere, principally water, carbon dioxide and oxygen. The effects of weathering extend below the earth's surface by ground-water movement through or around grains or along joints and fissures. The depth of weathering is largely controlled by topography and the availability of channels of flow for surface water. In some regions where climatic, topographic, and structural conditions are appropriate, weathering caused by circulation of groundwater of surface origin extends tens to hundreds of meters underground and causes notable changes in originally fresh rocks.

Within a given area on the earth's surface and at a given geologic time, the particular effects of weathering are assessed in terms of at least five variables: (1) climate, (2) biological activity, (3) topography, as it affects underground movement of water, or contributes to erosional removal of weathered material (4) parent material (rocks) and (5) time.

A great variety of physical, chemical, and biological processes act to breakdown rock masses. Physical processes reduce particle size, increase surface area, and increase bulk volume. Chemical and biological processes may cause complete changes in physical, chemical and mineralogical composition of the end products. Robinson (1949) recognized two main stages in chemical weathering. The first stage has to do with the destruction of mineral phases, and the second stage the formation of secondary products. These two stages involve the operation of various processes resulting in two main types of materials of morphogenic interest i.e., (i) weathering residues and secondary materials that occur insitu (residual soils), and (ii) materials which are transported before deposition (transported soils).

The first process of physical or mechanical weathering is also designated as disintegration while the second stage– chemical weathering is designated as decomposition. Disintegration results in a decrease in size of rocks and minerals without appreciably affecting their composition. By decomposition, however, definite chemical and physico-chemical changes take place, soluble materials are released, and new minerals are synthesized or are left as resistant end products.

The formation of black cotton soils with respect to soil forming factors

Climate of formation of black cotton soils

It was first thought that black cotton soils occur only in monsoonal type of climates with distinct annual wet and dry seasons in the tropics and subtropics, because of earlier recognition of their associations with these climates. However, they are now known to occur in almost every major climatic zone of the world and their classification has developed (Ahmed 1996). Annual rainfall between 300-900mm per year favours the formation of the soils (Katti et. al., 2002), however, higher rainfall values of 1270mm/year have also been recorded.

Parent material

Black cotton soils have been identified on igneous, sedimentary and metamorphic rocks. They are formed mainly by the chemical weathering of mafic (basic) igneous rocks such as basalt, norite, andesites, diabases, dolerites, gabbros and volcanic rocks and their metamorphic derivatives (e.g. gneisses) which are made up calcium rich feldspars and dark minerals which are high in the weathering order, in poorly drained areas with well defined wet and dry seasons. All constituents weather to form amorphous hydrous oxides and under suitable conditions clay minerals develop. The absence of quartz leads to the formation of fine grained, mostly clay size, plastic soils which are highly impermeable and easily becomes waterlogged. In addition abundant magnesium and calcium present in the rock adds to the possibility of formation of black cotton soil with its attendant swelling problem (Ola, 1983). The black cotton soils have also formed over sedimentary materials such as shales, limestones, slates etc.

Table 3 shows typical parent rocks that have formed black cotton soils. Ahmad (1983) found that although the parent materials are diverse, one striking feature which is common to all is the fact that the parent materials are rich in feldspar and ferromagnesian minerals which yield clay residue on weathering. He also noted that where the parent rock is not mafic (basic), alkali earth elements can be added through seepage or by flooding waters.

Topography

Katti et al., (2002) reported that the black cotton soil deposits are formed under conditions where the slope of the terrain is less than 3^{o}. The most frequent physiographic position of black cotton soils is flat, alluvial plains (Dudal and Eswaran, 1988; Eswaran et al., 1988) such as those found in Sudan, Texas in the USA, Darling Downs in Australia, the Accra plains, Ho-Keta plains and the Winneba plains in Ghana (USAID/BRRI, 1971; Building and Road Research Institute, 1985). Other fewer occurrences are the Lufina valley of Zaire, the Kafue Flats of Zambia and the Panamalenga plains and the Springbok flats in Botswana, and South Africa respectively. However, black cotton soils also occur in surfaces with greater slopes (Ahmad, 1983).

Age

Clemente et al., (1996) reported that time of formation of vertisols are usually inferred from the age of the underlying parent material from which the soil has developed. Furthermore, they realised that most vertisols are derived from cenozoic era materials including Tertiary and Quaternary. Some sediments of Cretaceous age have also formed vertisols. They indicated however, that the age of the parent material gives information only on the maximum chronological point, the age of the geomorphic surface and the soils would be much younger.

Distribution of Black cotton soils

Black cotton soils (vertisols) have been reported all over the world and have been found to occupy about 2% (257 million hectares) of the total ice-free land area of the earth with 72million hectares occurring in India, 71million hectares in Australia (Swindale, 1988) and 43million hectares is in Africa(Virmani, 1988). Countries reported to have black cotton soils are Australia (Aitchison, et. al., 1962; Ingles and Metcalf, 1972), Algeria (Afes and Didier, 2000), Botswana, Ethiopia (Mgangira and Paige-Green, 2008), Bulgaria, Hungry, Italy (Dudal and Eswaran, 1985), Togo (Oscar et al., 1977), Nigeria (Ola, 1976, 1983; Osinubi, 2006), South Africa (Van Der Merwe, 1964), Morocco, Chad, Cameroon, Kenya, Zambia, (USAID/BRRI, 1971), Tanzania (Bucher and Sailie, 1984), Sudan (Charlie et al., 1984), India (Michael, 2006; Rao et al., 2001), Ghana (Building and Road Research Institute, 1985; USAID/BRRI, 1971) etc. Figure 1 shows the major distribution of black cotton soils in the world.

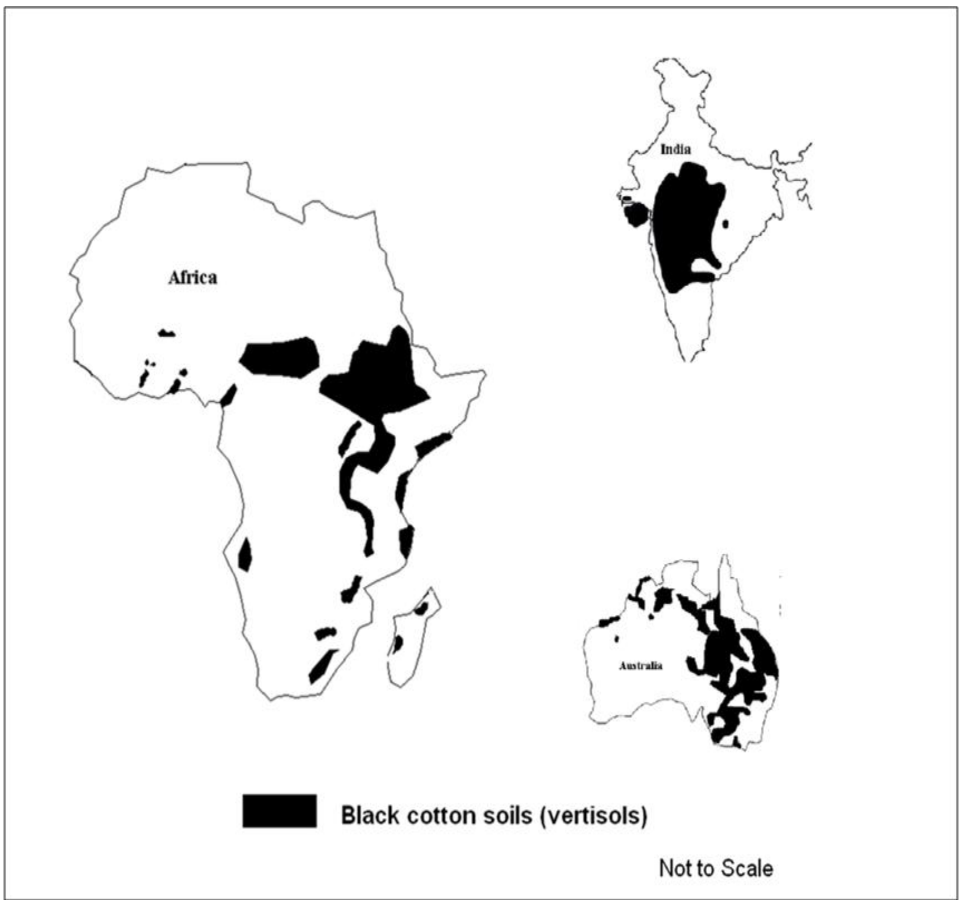

Figure 1. Distribution of black cotton soils (Vertisols) with special reference to areas of major concentrations (redrawn from Swindale, 1988, USAID/BRRI, 1971 and Soils and Land Resource Division, USA (undated)

Profile characteristics of black cotton soils

The black cotton soils (vertisols) have been found to develop on varied topography from the summit to the valley bottom of the terrain (Cobbina, 1988; Ahmad, 1983; Clemente et al., 1996) and in different climatic zones.

General profile characteristics of black cotton soils vary with parent rock, topography, climate, time etc. Vertisols lack the horizon development diagnostic of other horizons. They have “vertic horizon” which is a clayey subsurface horizon with slickensides or edge shape or parallelepiped structure aggregates and are characterised by argillipedoturbation (disruption and mixing) caused by swell- shrink of the soil mass. These characteristics are diagnostic features of the black cotton soils. Anon (2009) reported that the swell and shrinkage causes self mulching where these soil materials consistently mixes itself causing vertisol to have extremely deep A-horizon and no B-horizon. Usually the soils are called A/C soils. The heaving of the underlying material to the surface often creates micro-relief known as gilgai.

Cobbina (1988) recognised that the depth of the soil profiles are variable ranging from a few to 180 cm or even more, and also they lack distinct horizons in the profiles with only the "A" and "C" horizons being discernable for Ghanaian black cotton soils. Some typical profile characteristics of the soils are shown in Figure 2.

The colour of the upper horizons is usually dark grey to black whilst the bottom varies from grey brown, reddish brown to whitish colour.

The soil profiles may contain spherical hard, dark coloured ironstone concretions, magnesium oxides, calcium carbonate concretions and sometimes quartz gravels or pebbles at varying depths (Cobbina, 1988; Michael, 2006). The calcium carbonates may be in diffused or segregated form.

Studies by Brammer (1967) indicated that the black cotton soils are neutral to slightly acidic in reaction in the upper horizon whereas the lower layers are moderately alkaline in nature.

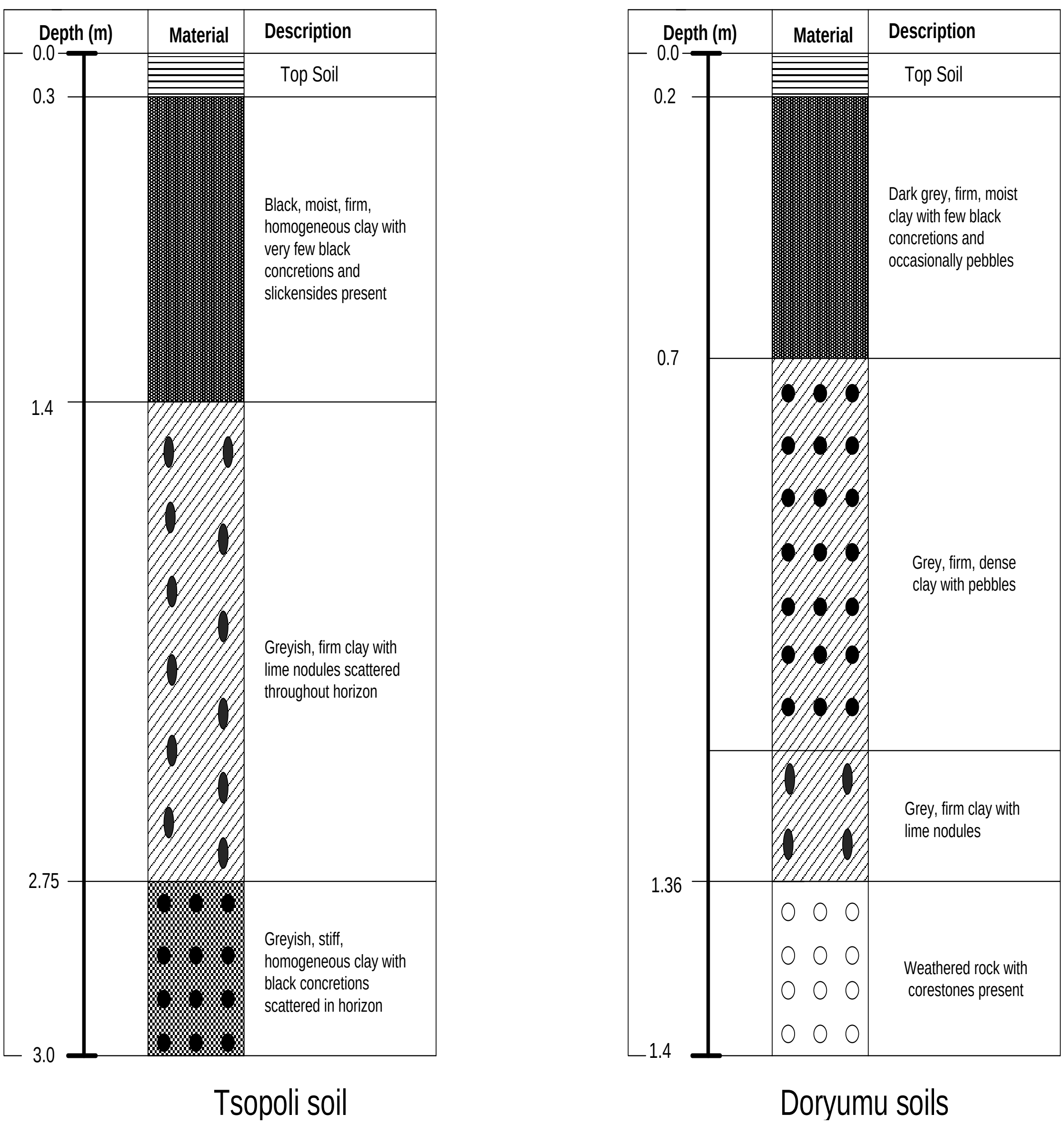

Figure 2a. Profile characteristics of the black cotton soils from Ghana

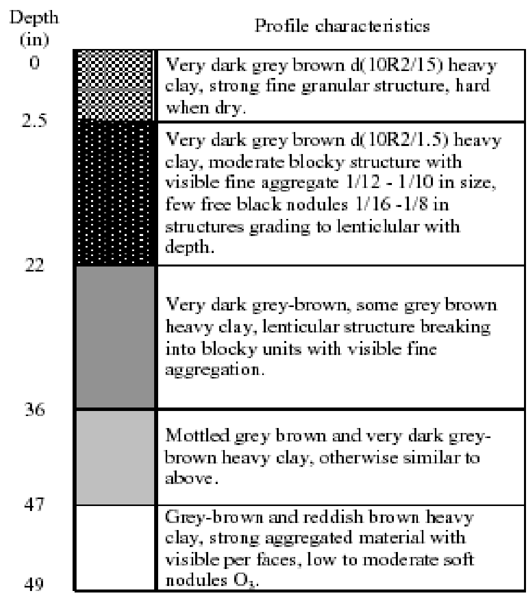

Figure 2b. Typical Black cotton soil profile from Australia (Aitchison et al., 1962)

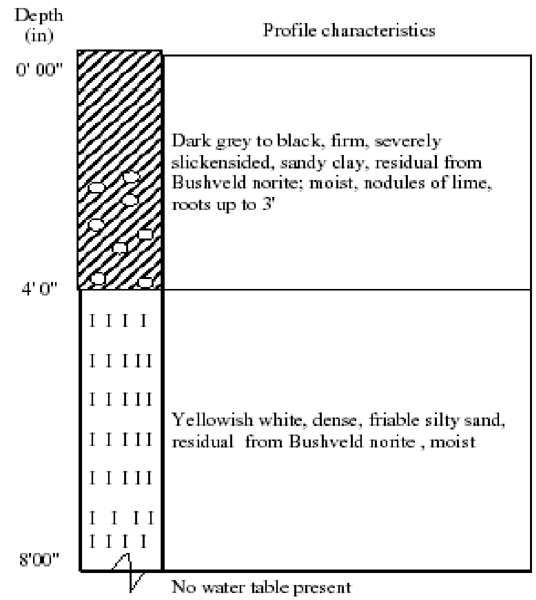

Figure 2c. Profile of black clay from South Africa (Weinert, 1980)

Table 3. The origin and characteristics of some black cotton soils

Location	Parent material	Soil Type	Clay Mineralogy	Rainfall (mm/yr)	drainage	Reference
Nigeria	Olivine basaltic rocks.	Residual	Montmorillonite, Kaolinite	<1270	poor	Ola,1983; Nwaiwu and Nuhu,2006, USAID/BRRI, 1971
Nigeria	Calcareous materials such as ancient alluvium; clayey and shaly sediments or lagoonal clays	Transported	Montmorillonite	<1270	Poor	Nwaiwu and Nuhu,2006
South Africa	Norites of the Bushveld igneous complex	Residual	Montmorillonite	609.6		Van Der Merwe, 1964
Ghana	Garnetiferous Hornblende Gneiss	Residual	Montmorillonite (tr. of Kaolinite)	<1270	Poor	Brammer,1955;Stephen, 1953
India	Granites, granite-gneiss, Basalt, etc	-	-	-	-	Michael, 2006
Sudan	Alluvium from basalt	-	Montmorillonite, Illite, Kaolinite, Chlorite	-	-	USAID/BRRI, 1971
Horn of Africa	Cenozoic basalt	Residual andTransported	Montmorillonite, Kaolinite, Halloysite	-	-	Mgangira and Paige-Green, 2008
Australia	Alluvial deposits derived from carboniferous shale, slate and clay	Transported	--	-	-	Hosking, 1935
Chad Basin	Alluvium	-	Kaolinite, illite and Montmorillonite	-	-	USAID/BRRI, 1971
Kenya	Basalt	-	Montmorillonite, Kaolinite	-	-	USAID/BRRI, 1971
West Cameroon	Basalt	-	Vermiculite, metahalloysite	-	-	USAID/BRRI, 1971
Honduras	Chalk or Marl	-	Montmorillonite	-	poor	USAID/BRRI, 1971

Chemical and clay mineralogical status of black cotton soils

Chemistry

Chemical weathering is the main soil forming process of the black cotton soils. In this process, the minerals in the rocks are decomposed, resulting in chemical alteration. It is therefore important to indicate the chemical composition of the soils which will vary with such factors as parent rock, genetic characteristics of soil (transported or residual), degree of weathering, etc. Typical oxide composition of some typical black cotton soils from some countries are presented in Table 4.

The black cotton soils are rich in silica, lime, iron, magnesia and alumina. Titanium oxide also occurs in very small concentrations; however, its presence is believed to give the soil the characteristic black colour (Building and Road Research Institute, 1985). In spite of its black colour, low organic matter contents (less than 5%) have been recorded for these soils. USAID/BRRI (1971) found that silica-sesquioxides ratios of the black cotton soils are greater than 2.50 indicating that they are non-lateritic soils.

Table 4. Chemical composition of black cotton soils from some countries

Major Oxides	Concentration weight percent (%)					
	India[1]	Nigeria[2]	Togo [3]	Ghana*		Indonesia[4]
SiO_2	49.3	31.01	46.32	54.26[D]	62.18[T]	42.80
TiO_2	1.9	1.34	0.85	1.42	1.09	0.02
Al_2O_3	13.7	16.19	22.04	20.29	18.23	19.03
Fe_2O_3	14.8	4.74	12.83	10.22	6.7	8.68
MnO		0.13	-	0.29	0.07	0.05
MgO	4.8	-	2.2	2.78	2.45	1.81
CaO	6.9	-	0.37	1.6	0.7	1.73
Na_2O	-	-	0.18	1.12	2.07	0.75
K_2O	-	-	0.2	0.05	0.11	0.08
P_2O_5	-	-	-	0.004	0.05	0.06
SO_3	1.6	-	-	0.04	0.1	-

[1.] Katti et. al., 2002, [2.] Osinuobi and Iiimdiva, 2008, [3] Oscar et. al., 1977; [4] Mohr and Van Baren, 1959, *Current study (D-Doryumu; T – Tsopoli)

Clay mineralogy

The main clay mineral reported in black cotton soil is the smectite group of clay minerals of which montmorillonite is the predominant. Accessory minerals may be kaolinite, illites, etc. Figure 3 shows typical mineralogical composition of the black cotton soils from X-Ray diffractogram. According to Sudharkar (2006), low rainfall has hindered the weathering of the active montmorillonite minerals into low active clay mineral such as illite and kaolinite.

Mermut et al., (1996) recognised that the formation and stability of the smectite are dependent on the Si activity as well as pH. At high pH, in the presence of high potentials of Si as well as Mg, smectite develops (a process which is also favoured by poor drainage). Transformation of some primary or secondary minerals into smectite have been reported (Eswaran et. al., 1988). The micro-environmental condition for this transformation is well established as essentially a pH of 7 or higher. If leaching occurs in the upper part of the soil with the generation of an acid environment, montmorillonite tends to be destroyed and other soil forming processes initiate. The environment of formation of montmorillonite (smectite), illite and kaolinite is shown in Figure 4.

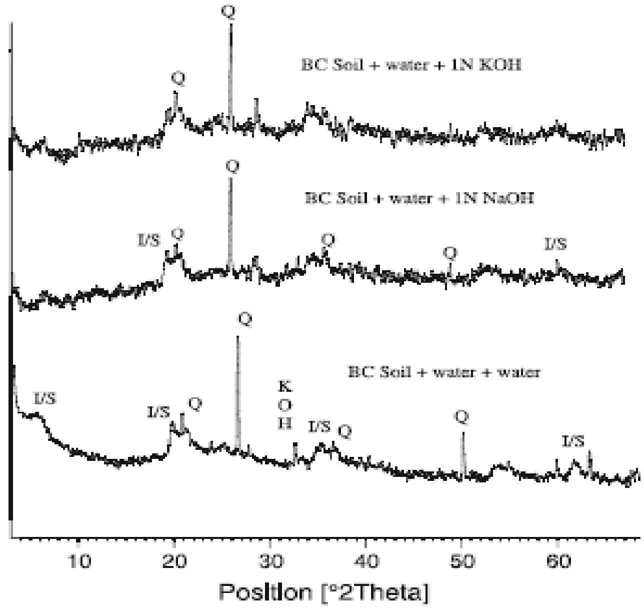

Figure 3. Typical X-ray diffractogram of Black cotton soils (from Sivapullaiah and Reddy, 2010)

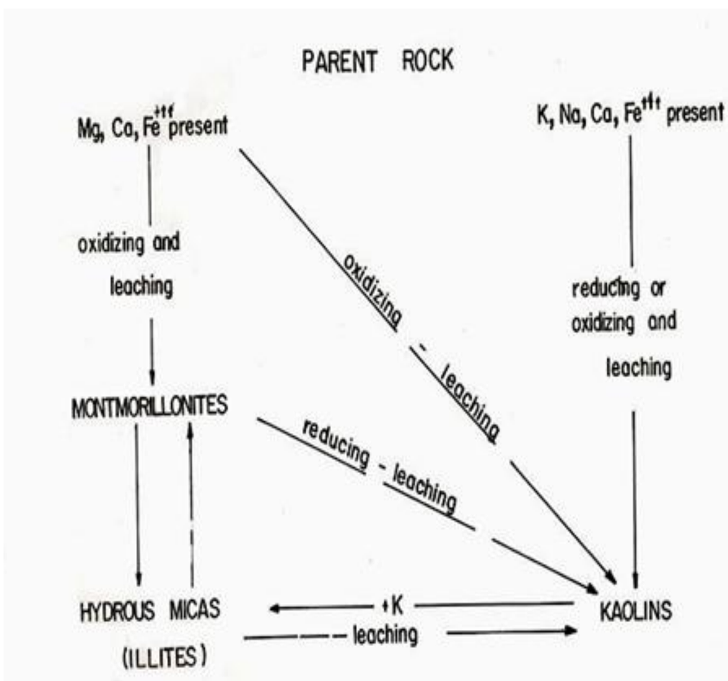

Figure 4. The environment of formation of illite, kaolinite and montmorillonite (Frederickson, 1952)

Basic Geotechnical characteristics of black cotton soils

Introduction

Table 5 presents a compilation of some available geotechnical characteristics of black cotton soils and are discussed in this section. This is then supplemented by a study of geomechanical characteristics black cotton soil from the Accra plains of Ghana.

Table 5. Summary of Geotechnical characteristics of black cotton soils

Location	Grading (%)			SG	LL (%)	PL (%)	PI (%)	Activity	SL	Soil Group		MDD (Kg/m^3)	OMC (%)	Free Swell (%)	References
	Sand	Silt	Clay							ASTM	ASSHTO				
	6	54	40		82	35	47		10.0	CH		1290	35		Sivapullaiah, 2010
	2	37	61	2.6	86	32	54			CL		1400	36.3		Rao et al 2008
	16	29	55		84	23	61		10.0	CH					Mishra et al , 2008
	7	41	52	2.68	85	38	47		12.0			1320	28		Sahoo & Pradhan 2010
	31	28	41		63	24	39		10.0					132	Shankar et al (1987)
	11	28	61	2.7	77	31	46		10.0	CH		1410	30		Rao&Shivananda, 2005
	3	28	69	2.6	190	45	145		15.3	CH				690	Ameta et al 2007
	6	54	40		82	35	47		10.0	CH		1290	35		Sivapullaiah, 2010
India				2.74	56	23	33		10.3			1510	27.76		Sivapullaiah et al, 2007
	28	32	40		65	19	46					1730	20		Rao et al 2001
	20	29	51		55	25	30					1690	21		
				2.36	28	14	24			CL		1440	21.04		Gosavi et al., 2004
	2	37	61	2.65	86	32	54			CH		1400	36.3	180	Rao & Rao, 2008
	2	79	19	2.7	85	44	41		23.7	CH				75	Ameta et al 2007
	30	34	36		45	23	22		11.0		A-7-6(13)				
	15	29	56		82	23	59		10.0			1240	28		
	17	30	53		69	34	35		10.0		A-7-5(20)				
Honduras	2	23	75	2.64	126	58	68		25.0		A-7-5(20)				BRRI/USAID 1971
Rodesia	34	11	55		72	24	48		11.0		A-7-6(17)				
	10	40	50		99	29	70		11.0		A-7-6(20				
Ghana					60-100		30-60				A-7-5 (10-20)	1601-1762	18-16		Gidigasu & Appiagyei 1980
	19.72	18	63.3	2.37	91.72	29.6	62.12	0.98		CH	A-7-6	1680	19.48	140	current study
	38.3	15.2	46.5	2.3	74.68	26.55	48.13	1.03		CH	A-7-7	1820	17.54	73	
Horn of Africa	3-12	25-70	18-73	2.43-2.45	43-103	17-49	26-54	0.6-1.11				1108-1278	22-49		Mgangira & Green,2008
	14	32	54		56	24	32	0.59			A-7-6				
	19	25	56		59	31	28	0.5			A-7-5				USAID/BRRI, 1971
Moroco	5	25	70		60	20	40		10.0						
	12.4	17.5	70.1	2.5	65.5	30.5	35		10.2	CH	A-7-6			90	
	12.58	12.47	74.95	2.48	63.9	31.25	32.65		11.2	CH	A-7-6			110	
	12.47	12.49	75.05	2.56	65.6	32.3	33.3		11.0	CH	A-7-6			105	
	11.54	31.91	56.55	2.58	62	31.85	30.15		10.4	CH	A-7-6			70	Nwaiwu and Nuhu, 2006
Nigeria	12.18	32.04	56.78	2.57	63.3	27.5	35.8		11.7	CH	A-7-6			60	
	13.7	29.55	56.75	2.55	64.1	33.15	30.95		11.9	CH	A-7-6			60	
	12.39	14.99	72.56	2.34	62.3	24.2	38.1		18.6	CL	A-7-6(24)	1710	18	76.25	Osinubi, 2000
	20	5	75	2.66	65	19	46		13.0	CL	A-7-6(6)	1630	19.2	70	Osinubi & Iiimdiva, 2008
	51	23	28		70	27	43		20.7			1417.6	28.7		Ola, 1983
Nigeria				2.5	93	21	72				A-7-6	1410	24.3		Oriola et al., 2010
				2.56	78	31	47					1413	27	50	Ola.1978
	10	20	70		58	16	42	0.61	12.0			2970	20.2	70	
Chad Basin	19	28	53		44	14	30	0.59	9.0			2162	13	55	
	10	30	60		52	19	33	0.82		CL	A-7-6			50	
Chad Basin	14	34	52		56	30	26	0.4	15.0			1650	18.6	50	USAID/BRRI, 1971
Kenya	30	8	62	2.28	104	34	70	1.15						92	
	8	37	55	2.47	72	24	48	0.88			A-7-5			87	
Ethiopia	4	38	56		109	28	81	1.36	14.0			1485	23	88	
					35	21	14		7.0						Van der Merwe, 1964
South Africa					78	32*	46		18.0						Van der Merwe, 1964
	19	31	48		60	30	30					1730	18.7	65	USAID/BRRI, 1971
	15	43	42		57	29	28	0.7				1660	10.2	660	
	6	34	60		79.8	34.9	44.9	1				1400	28.5	220	
	12	38	50		84	32.6	51.4	0.8							
	35	38	27		60	25.9	34.1	1.3							
Tanzania	28	37	35		79.8	29.9	49.9	1.4							
	45	20	35		55.4	21	34.4	1				1560	22		Bucher&Sailie, 1984
	32	41	27		59.2	18	41.2	1.5							
	8	27	65		90.4	38	52.4	0.8				1580	17		
	48	30	22		51	19.2	31.8	1.5							
	25	37	38		73.2	29.5	43.7	1.2			A-7-6(20	1260	36		
Palistine	16	26	58	2.79	69		42		10.0						
Zambia	14	35	51	2.58	49	16	33	0.65	16.0			1802	16	57	
	30	20	50	2.61	50	17	33		15.0					58	USAID/BRRI, 1971
Cameroon	42	58	0		64	37	27	1.7			A-7-5				
	19	43	38		62	35	27	0.71			A-7-6				
Algeria	8	28	62		47.7	24	23	0.37							Afes and Didier, 2000
	11	22	67	2.83	88	34	54		22.0	CH	A-7-5(20)	1538	21		
	3	26	71	2.84	91	31	60		24.0	CH	A-7-5(20)	1562	25.5		
Australia	14	18	68	2.86	101	36	65		22.0	CH	A-7-5(20)	1554	27		Ingles and Metcalf, 1972 Aitchison at al 1962
	20	23	57	2.93	102	29	73		24.0	CH	A-7-6(20)	1554	28		
	1	29	70	2.87	100	27	73		23.0	CH	A-7-6(20)	1514	29		
Botswana			47-58	2.58-2.69	53-55	24-28	27-29					1236	22		Abadjieva, 2001

Natural Moisture content

The natural moisture content of a black cotton soil in a profile is variable, for instance, the Building and Road Research Institute (1985) reported natural moisture contents for Ghanaian black cotton soils to be between 20% and 45%; Mgangira and Paige-Green (2008) reported that the moisture contents of subgrade black cotton soils in the Horn region of Africa range between 24% and 54%. A typical monthly variation of natural moisture content with depth of a Ghanaian black cotton soil is shown in Figure 5.

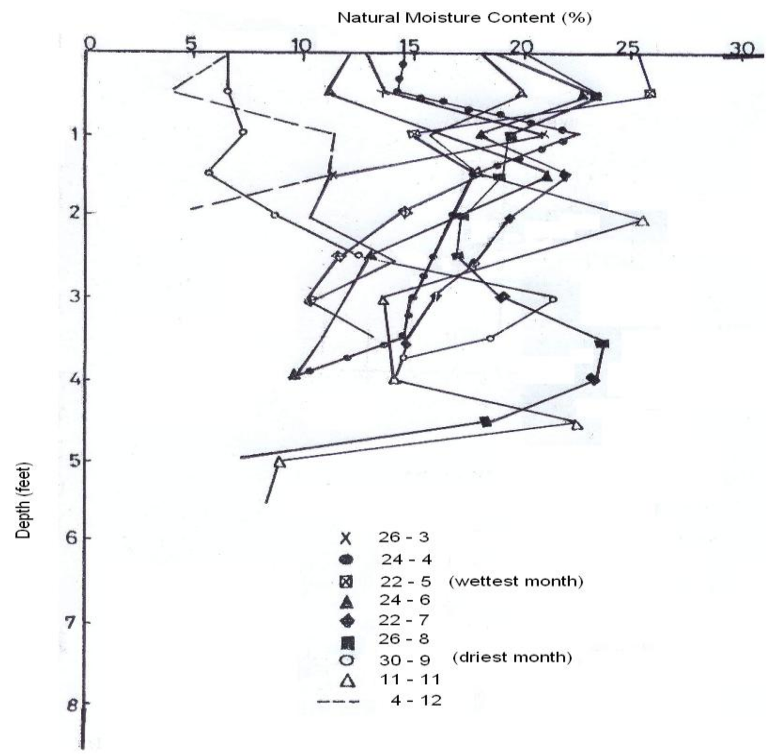

Figure 5. Variation of natural moisture content with depth of typical Ghana black cotton soil profile (Building and Road Research Institute, 1985)

Grading and textural classification

The gradation of the black cotton soils varies considerably. There are little or no gravels size in most black cotton soils and those that have show percentages of less than 8% (USAID/BRRI, 1971). The amount of sand varies between 2% and 50 % and silt 11% to 58%. The clay size contents also range from 40% to 75%. Low clay size contents (22%) have been reported for some Tanzania black cotton soils (Bucher and Sailie, 1984). The soils classify as clay, sandy-clay and silty-clay on the U.S. Engineers textural classification chart (Figure 6).

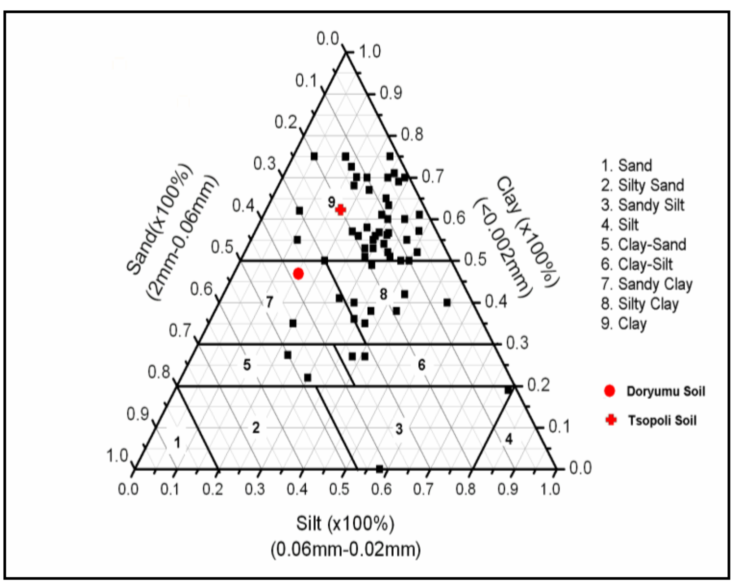

Figure 6. Textural classification of black cotton soils based on US Engineers soil classification System (53 data sets)

Plasticity characteristics and Activity

The Liquid Limit of the black cotton soils are variable and range from 28% to190%, and the Plasticity Index range between 14% and 145%. The black cotton soils normally plot above the A-line and classify as inorganic clay of low to very high plasticity on the Casagrande's chart (Figure 7). The location of the black cotton soils on the Casagrande's chart gives an indication of its mineralogy (Wesley, 1988), however, from studies by Sridharan and Prakash (2000) indicate that both kaolinitic and montmorillonitic soils lie above and below the A-line. Hence, nothing can be inferred regarding their expansive nature just by their position on the plasticity chart. . The shrinkage limits range between 7% and 26%.

Most black cotton soils classify as A-7-5 and A-7-6 by the AASHTO Classification System (AASHTO, 1986) with group index values varying from 13-89 (USAID/BRRI, 1971) and CH and CL on the Unified Soil Classification System (ASTM, 1992).

The activity of the black cotton soils from the data collected (Table 5) was found to range between 0.37-1.70 thus indicating that the soils have low to high expansion potential based on the criteria proposed by Skempton (1953).

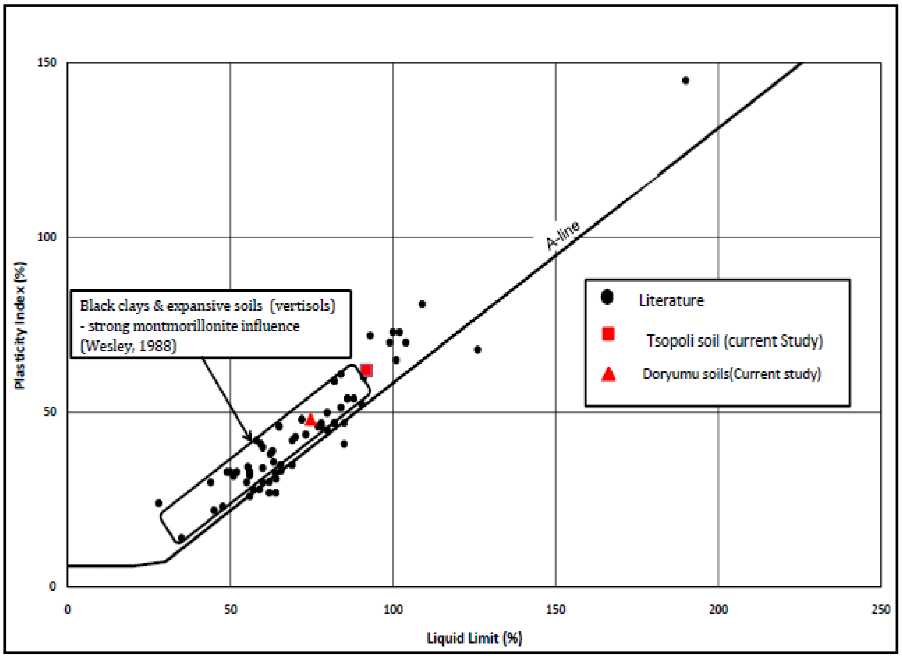

Figure 7. Plasticity classification of Black cotton soils using Casagrande Chart

Free swell and permeability characteristics

Generally, free swell of black cotton soils varies between 50% and 220%. However, values of 660%have been reported for a Tanzanian black cotton soil (Bucher and Sailie, 1984) and 690% for an Indian black cotton soil (Ameta et. al. 2007). Ola (1978) found the permeability of typical black cotton soil from oedometer test to be of the order of 10^{-10} cm/sec, very similar to those reported by Ranganathan (1961) for Indian black cotton soils.

Compaction characteristics

The Maximum Dry Density (MDD) and Optimum Moisture Contents range from 2970kg/m^3 to 1108kg/m^3 and 10%-49% respectively. The correlation between MDD and OMC (Figure 8) shows $\boldsymbol{MDD} = \mathbf{1971.7} - \mathbf{18.59}\boldsymbol{OMC}$and a coefficient of correlation approximately **0.7.**

Unsoaked California Bearing Ratio (CBR) values of black cotton soils are generally high but soaking reduces them greatly. According to the Building and Road Research Institute (1985) the CBR of typical Ghanaian black cotton soils compacted at West African Standard and Modified ASSHTO standard were 35% and 40% respectively but due to the sensitivity of the soils to water, the 96-hour soaked CBR values reduced drastically to between 0.5% and 2%. CBR values of 0.003 and 0.007 were recorded for Tsopoli and Doryum soils respectively compacted at Modified AASHTO compaction and soaked for 96hours.

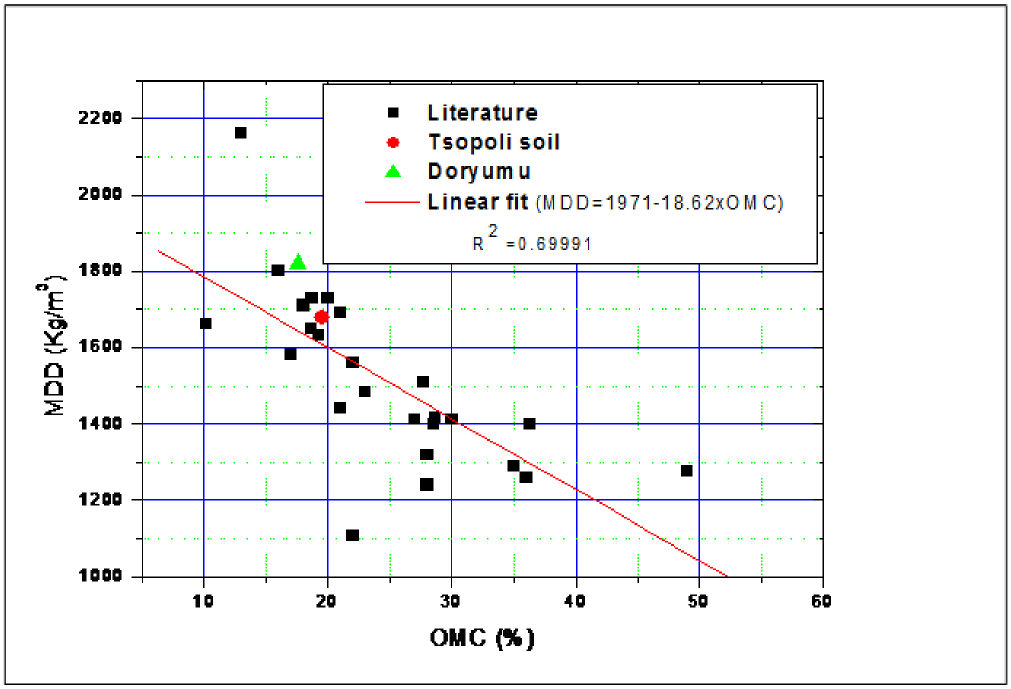

Figure 8. The relationship between MDD and OMC

SUMMARY OF CONCLUSIONS

The literature sources reviewed show that, the black cotton soils occur in almost every major climatic zone worldwide predominantly over mafic (basic) igneous rocks as well as some sedimentary and metamorphic rocks. The parent rocks are reported to be usually rich in feldspar and ferromagnesian minerals which yield clay residue on weathering and where rocks are not mafic (basic), alkali earth elements are added through seepage or by flooding waters. The environmental conditions that favour the formation of black cotton soils are low rainfall, high temperature, flat topography, mafic igneous rocks, and poor drainage. The main clay mineral reported is montmorillonite of the smectite group. The chemistry of black cotton soils is variable with the most abundant oxides being silica and Aluminium and Iron.

The natural moisture content of the black cotton soils is variable. The soils generally classify as sandy-clay and silty-clay. The Liquid Limit of the black cotton soils are also variable but range between 28% and 190%, whereas the Plasticity Index vary between 14% and 145%. Free swell varies between 50% and 220%. Based on the AASHTO Classification System the soils classify as A-7-5 and A-7-6 with group index values varying from 13-89 and they classify as CH and CL on the Unified Soil Classification System. The black cotton soils normally plot above the A-line and classify as inorganic clay of low to very high plasticity on the Casagrande's chart. The permeability of typical black cotton soil from oedometer test were found to be in the order of $x10^{-10}$ cm/sec. The Maximum Dry Density (MDD) and Optimum Moisture Contents range from 2970kg/m3 to 1108kg/m3 and 10%-49% respectively. The correlation between MDD and OMC shows $\boldsymbol{MDD}=1971.7-18.59\boldsymbol{OMC}$. The information available also indicates that the CBR values of unsoaked samples are relatively high but soaking reduces the value drastically.

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