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Geotechnical Characterization of the Manyana Black Cotton Soils in Botswana

Mompoloki Ndala Marumo, **Gabatsoswe Lebitsa**, and **Goitseone Malumbela**

Botswana International University of Science and Technology, P/Bag 16, Palapye, Botswana

Corresponding author's Email: darriesmorule@gmail.com

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ABSTRACT

The Manyana Village is divided into two types of soils. The center of the village is covered with sand that overlays clays from weathered dolerite whilst the eastern side is covered with exposed clays. Houses constructed on the eastern side of the village are prone to severe cracking attributed to the black cotton soils. The paper hints at shrink-swell mechanism of black cotton soils as a possible explanation for the cracking observed on the houses. Three laboratory methods of identifying and characterizing expansive soils are discussed followed by use of Dynamic Cone Penetration (DCP) in field-testing as well as use of indicator tests and particle sizing in the laboratory. The experimental results have shown a high field moisture content of (18 to 27%) in the eastern part of the village which was three times larger than moisture content at the village center. The clays had a plasticity index range of 12% to 30% with a clay content of 21% to 47% whilst the sandy areas were non-plastic with a clay content of at most 4%. The clay minerals identified from the samples tested were vermiculite, illite, kaolinite and montmorillonite. The soil samples from the village had low potential expansiveness whilst most samples on black cotton soil had a medium to high potential of expansiveness. The bearing capacity estimated from DCP data at depths of 1m throughout the village were 72 kPa to 275 kPa under dry conditions. A draft plasticity index map of Manyana village was produced based on the results of the investigation, the next step is to investigate the effectiveness of different soil stabilization methods for this area and taking in to consideration cost, durability and environmental impact.

Keywords: Black cotton soil, Cracking, Moisture content, Plasticity index, Bearing capacity.

INTRODUCTION

Manyana village occupies 6.57 km^2 of land of which 30% is covered with expansive soils (black cotton soil) and the other 70% is covered with silty sands. The area is relatively flat with the altitude above mean sea level varying from 1121 m on the north to 1142 m on the south (Figure 1). This flat land is surrounded by relatively low-lying hill range to the south, west and northwest.

Dolerite outcrops are exposed in the eastern part of Manyana area as in Figure 2. Fresh hand specimen of the dolerite is dark grey, medium to coarse grained with abundant plagioclase and 30% to 40% quartz content. Weathered parts of the dolerite were observed as greyish brown to light grey with dark brown to grey spots. Reddish brown weathered dolerite also does occur in the southern part of the area. There are no exposures of the dolerite in the village built up area.

Alteration of the dolerite resulted in the formation of clay deposits (Key, 1983). The alteration process of dolerite into clays is greater in the village centre where the dolerite is in contact with the Manyelanong Hill formation, resulting in thicker clayey profiles. These clays are covered by transported sandy deposits from the nearby sandstone ridges, but clays are predominantly exposed in the eastern part of the village

Many structures at Manyana Village experience extensive cracking of walls, flooring and all their respective masonry as shown in Figure 3. These cracks propagate from the ground to the roof levels, on the floors extending from wall end to wall end. The cracks range from hairline to aperture widths of as much as 50 mm and more. Manyana Village elders have called for assistance from various Government Organs. One such organ is the Department of Geological Survey who through a report by Ngonidzashe et al. (2014) attributed cracking of houses in the Manyana Village to the presence of clays associated with the weathering of dolerite. This was however, not substantiated by research and as such residents continued to experience the problem of cracking. It is therefore essential that substantive research be carried out to establish the cause of cracking of houses in the Manyana Village and develop a strategy to mitigate the problem on existing structures and how best to avoid it in future developments.

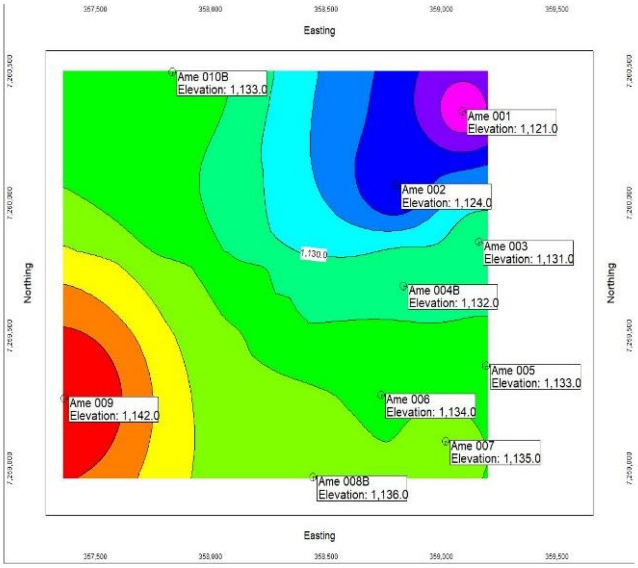

Figure 1. Altitude of the study area

Figure 2. location of the village and outcrops around the village. Source: Google earth map

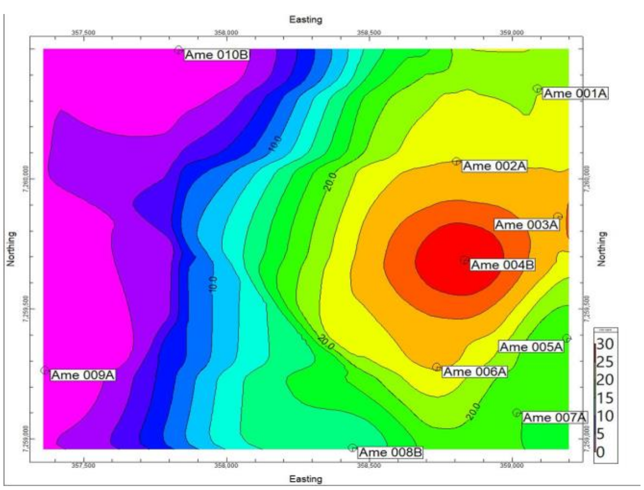

Figure 3a. Plasticity Index map from the observed results

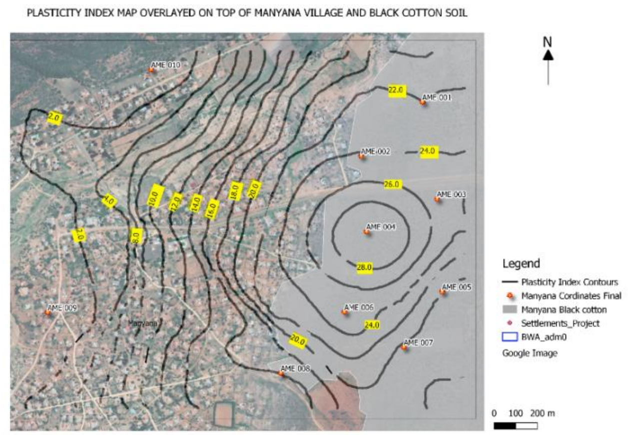

Figure 3b. Overlaying of plasticity Index map on top of Manyana village

Regarding clays in other parts of the world, Zornberg et al. (2008) characterised Eagle Ford clay for the design of and remediation of roadways constructed on poor subgrade materials. Zornberg et al. (2008) found that the clays have a Plasticity index of 47% and clay content was 97%. They found that 24 hrs was necessary for 1 cm specimen of compacted clay to swell to an equilibrium height in the centrifuge permeameter.

MATERIALS AND METHODS

The study intends to establish the cause of cracking of houses in the Manyana Village and develop a strategy to mitigate the problem on existing structures and how best to avoid it in future developments. The tests were done in order to determine the characteristics of black cotton soil and to establish the geotechnical properties of black cotton soil prior construction. The first part of this work which is covered by this paper is characterization of black cotton soil in the area using field and laboratory tests as indicated in Table 1. The in-situ testing was carried out using a Dynamic Cone Penetration (DCP) apparatus whose values were used to predict the California Bearing Ratio (CBR) of the soil. During trial pitting the moisture condition, colour, consistency, structure, soil texture and origin of each layer of the soil profile (MCCSSO) as proposed by Jennings et al. (1973) was used.

Table 1. Activities done at the field and tests done at the lab

Field Work	Laboratory Tests
In-situ testing (Using DCP)	Grain Size Analysis Hydrometer Atterberg Limits
Trial pitting and profile According to MCCSSO	Moisture Content
Use DCP to predict CBR	Specific Gravity

Selection of sampling sites

An area to be sampled was delineated into triangles and all the triangles were sampled in the centre as a representative of the delineated triangle. Figure 3a shows the sampling points. As shown in the figure, most sampling points were within the area covered with black cotton soil with two additional points within the village chosen as controls (AME 009 and AME 010). Quality assurance and quality control (QA/QC) of the results was carried out in the laboratory during analysis as where some of the tests were repeated to check the validity of the results.

Field work

Fieldwork entailed carrying out DCP tests at selected points and manually excavating test pits to depths of between 1 m and 1.5 m to obtain samples for laboratory testing. The DCP test was used to obtain a direct and rapid in-situ evaluation of the structural strength of the layers whilst the samples were to be used in the laboratory to determine pedological conditions and the possible presence of perched ground water bodies.

Thirteen disturbed samples were taken from individual horizons from the test pits for geotechnical and mineralogical determinations and when it was found that different profiles were found within the same pit, samples were separated and labelled A and B as it can be seen at Ame 004, Ame 008 and Ame 010.

The DCP test apparatus was assembled and placed at the test location with the initial penetration of the rod recorded to provide a zeroing scale. While holding the rod vertically, the weight was raised to the top of the rod 575 mm above the anvil and dropped. The penetration of the rod was measured after each drop which was later plotted to give penetration in millimeters per blow (mm/blow).

Sampling

Disturbed soil sampling was used to sample as the horizons of the pit were critical in observing change in horizons inside the pit. These samples were labelled and sent to the laboratory for testing. The field observation of moisture condition, colour, consistency, structure, soil texture and origin (MCCSSO) of each layer of the soil profile was used as proposed by Jennings et al. (1973).

Sample preparation

Samples were prepared in accordance with AASHTO T87-86. As per the AASHTO method, the samples were air dried for a minimum of 24 hrs then soil boulders were pulverized using rubber covered mallet. A riffle box was then used to get representative samples.

Standard laboratory tests on black cotton soil

All the tests that were carried out are summarized in Table 2.

Table 2. Activities or tests that were done

Test	Standard
Moisture Content	ASTM D 4643-08
Particle Size	ASTM D 422-63 (2007)
Hydrometer	ASTM D 422-63 (2007)
Specific Gravity	ASTM D 854-14
Atterberg Limits	ASTM D 4318

RESULTS

This section presents and discusses results from the experimental work.

Moisture content

Moisture Content was conducted as per ASTM D4643 – 08. Table 3 shows the moisture content of all sample pits from Ame 001 to Ame 010. The table shows sample pits that were sited on top of black cotton soil had high moisture content ranging from 10.6% to 27% with the lowest at Ame 008B and the highest at Ame 003 as compared to samples outside the black cotton soil region with moisture content ranging between 5.7% and 6.1% with the lowest at Ame 009 and the highest at Ame 0010A. It is likely that the samples located within the Black cotton soils contained more clay minerals than the samples located closer to the village as clay will absorb more water and take time to release it. The clay minerals by virtue of their relatively large surface area coupled with their net negative charge attract and retain more water (Knappett and Craig, 2012) hence the higher moisture content at sample pits that were sited on top of black cotton soil being three times higher than those located in sandy areas.

Dynamic Cone Penetrometer (DCP)

A total of ten DCP tests were conducted in the study area to complement information obtained from trial pits. The DCP penetration rates (mm/blow) allowed for estimation of the bearing capacity of in-situ soil horizons up to a depth of 1m. Figure 6 shows results for DCP tests in terms of variation of penetration rates (mm/blow) with depth. The average penetration rates in most pits ranged between 24mm/blow and 17mm/ blow indicating soft to firm consistencies. This translates to the presumed allowable bearing capacities ranging between 72 kPa and 275 kPa within the first 1m of the pits. At depths of below 900 mm, almost all the samples had similar penetration rates that ranged between 16 and 18 mm/blow.

Higher values of load bearing capacity are attributed to the presence some ferricrete nodules in some soils such as at Ame 008 and dense clayey materials with some weakly developed cementation in others such as at Ame 001 Soils at Ame 010 contained loose aeolian deposits and therefore exhibited lower values of load baring capacity of below 60 kPa and penetration values that averaged below 38 mm/blow.

Grain Size Analysis

Grain size test analysis was conducted as per ASTM D 422- 63 (2007). Figure 4 shows results of the particle size distribution of all the samples. The figure shows that at particle sizes of below 0.002, which is clay content, samples located on a region with black cotton soils had different percentages of clay content ranging from 21.4 % at Ame 008B and 46.8% at Ame 003A. At Ame 10A, Ame 10B and Ame 9 which were within the village, the samples showed clay contents of 0, 0.2 and 4.2 respectively. It needs to be noted that AME 9 and 10 which are located at the village comprise about 80% of particle sizes between silty sand and clayey silt as observed from Figure 7. However the low content of clay sized particles (-2μm size) means a low content of clay minerals and reduced likelihood to shrink and swell with moisture variations. Therefore, where these samples were found there were no signs of cracking to houses that were close, which can be attributed to low values of clay content. The results have also been summarized in Table 5.

Atterberg limits

Atterberg Limit tests were carried out as per TMH 1 - A1 to A3 testing procedures and the results are shown in Table 5. The liquid limit ranged between 33% at Ame 005 and 59% at Ame 003A. The highest plastic limit of 33% was obtained at Ame 002 and Ame 005 whilst the highest plasticity index of 30% was obtained at Ame 004A and Ame 004B. The lowest plasticity Index were found at Ame 008B at a value of 12%. Linear shrinkage ranged between 6% at Ame 008B and 12.2% at Ame 003.

Figure 3a shows a plasticity map from the results. The figure clearly shows that the plasticity index increases from the village towards the region with black cotton soil. The highest plasticity index is at Ame 004 with a value of 30% and is represented by red colour.

After calculating all the plasticity index of all the samples, the map for plasticity index values was overlayed on top of the Manyana Village as shown in figure 3b. From the figure, it can be observed that the black cotton covers close to 30 % of the village. Plasticity Index increases as one moves from the village towards the black cotton soil and the highest Plasticity Index was found at Ame 004, which is at the centre of the Black Cotton soil area. The two points (Ame 009 and Ame 010) that were within the village were at plasticity Index of 0 that showed the soil within the village is slightly plastic to non-plastic. At the boundary between the village and the black cotton soil area, it was observed that the plasticity index was ranging from 18% to 26%. It was also apparent that even houses close to the boundary had cracked because of the high plasticity index values.

Specific gravity (G_s)

Table 6 shows tests results for specific gravity. It ranged from 2.32 for Ame 001A to 2.66 for Ame 010B. From the results, soils with high G_s values had low clay content while those with high clay content had low G_s values. It was noted that some samples with high G_s values had some nodules of ferricrete which probably contributed to the high G_s values.

Mineralogy

The XRD test results in Table 7 show that all samples contained at least one clay mineral (Montmorillonite, Kaolinite, Illite, Vermicullite and Nacrite). The specific gravity of the minerals (Deer et. al, 1992) are also given in the table. Montmorillonite as an expansive mineral was found more on Ame 001 at a value of 23% followed by Ame 007 at a value of 6% and traces of it was found in Ame 004 up to Ame 006. Clay minerals present in the samples which are overly expansive can lead to cracking of overlying structures. When all the clay minerals were grouped together it was observed that Ame 001 had a high concentration at a value of 77% followed by Ame 002 with a value of 76%. Samples within the village were found to have clay content ranging from 0 to 3%. From the clay minerals that were identified, it is concluded that the clay mineralogy could have led to cracking on houses that are constructed on top of soils containing the expansive minerals especially given the wetting and drying cycle.

Van der Merwe's empirical method for the estimation of potential ground heave

In order to classify samples using Van Der Merwe's empirical methods, plasticity index was plotted against percentage of clay particles in Figure 9 to give a classification of heave potential curve (*Van der Merwe, 1964)*. The figure shows that samples fell in areas of possible high potential heave to areas of low potential heave. Ame 004A and Ame 004B samples plotted on high potential heave whereas Ame 008B plotted on the margin between low and medium potential heave. A further examination of the figure shows that the Van Der Merwe classification method relies on results from other tests such as the use of the results from Atterberg limits (plasticity index (PI)) and results from grain size for clay content. It follows then that any inherent weaknesses in those test results are transferred to the Van Der Merwe classification.

Table 3. Moisture content of all the samples

Sample No	Ame 001	Ame 002	Ame 003	Ame 004A	Ame 004B	Ame 005	Ame 006	Ame 007	Ame 008A	Ame 008B	Ame 009	Ame 0010A	Ame 0010B
Moisture (%)	21.8	22.8	27.0	22.7	21.2	22.5	23.6	17.8	14.1	10.6	5.7	6.1	5.8

Table 4. Particle size distribution of all the samples and USC System

Sample No	Ame 001	Ame 002	Ame 003	Ame 004A	Ame 004B	Ame 005	Ame 006	Ame 007	Ame 008A	Ame 008B	Ame 009	Ame 0010A	Ame 0010B
Gravel	0.9	0.7	0.0	2.4	2.0	0.6	0.1	0.4	0.6	0.2	0.00	0.0	0.0
Sand	37.0	45.8	37.7	33.1	33.3	27.9	21.8	28.3	33.8	51.1	82.1	98.4	98.4
Silt	28.9	21.3	15.5	29.2	29.5	27.4	37.2	32.5	35.1	27.3	13.7	16.0	14.0
Clay	32.2	33.2	46.8	35.3	35.2	44.1	40.9	38.8	30.5	21.4	4.20	0.0	0.2
USCS	CL	MH	CH	CH	CH	MH	CH	ML	CL	SC	SM	SP	SP

Table 5. Atterberg Limits results of all the samples

Sample No	Ame 001	Ame 002	Ame 003	Ame 004A	Ame 004B	Ame 005	Ame 006	Ame 007	Ame 008A	Ame 008B	Ame 009	Ame 0010A	Ame 0010B
Liquid Limit (LL)	48	57	59	58	57	51	51	46	36	33	NV	NV	NV
Plastic Limit (PL)	26	33	31	28	27	33	26	28	21	21	NP	NP	NP
Plasticity Index (PI)	22	24	28	30	30	18	25	18	15	12	NP	NP	NP
Shrinkage	8.4	10.9	12.2	10.0	8.8	8.7	6.5	8.9	7.7	6.0	NP	NP	NP

Table 6. Observed values or Specific Gravity of all the samples

Sample No	Ame 001	Ame 002	Ame 003	Ame 004A	Ame 004B	Ame 005	Ame 006	Ame 007	Ame 008A	Ame 008B	Ame 009	Ame 0010A	Ame 0010B
Specific gravity (g/cm^3)	2.32	2.37	2.34	2.45	2.34	2.43	2.40	2.41	2.62	2.54	2.62	2.52	2.66

Table 7. Mineralogy of all the samples

	Specific Garivity	Ame 001	Ame 002	Ame 003	Ame 004A	Ame 004B	Ame 005	Ame 006	Ame 007	Ame 008A	Ame 008B	Ame 009	Ame 0010A	Ame 0010B
Quartz	2.65	15	11	43	7	6	40	44	45	30	30	84	80	85
Albite	2.62	-	6	-	-	-	-	-	-	-	-	3	-	-
Actinolite	3.00	-	5	19	-	-	-	3	3		3	-	-	2
Kaolinite	2.65	-	32	-	-	-	-	-	-	-	-	-	1	1
Montmorillonite	2.5	23	-	1	Traces	Traces	Traces	Traces	6	3	3	-	-	-
Illite	2.75	-	32		-	-	-	-	-	-	-	-	2	-
Vermiculite	2.30	54	12	2	-	-	-	13	6	11	15	-	-	-
Nacrite	2.60	-	-	-	9	10	8	7	9	14	9	-	-	2
Calcite	2.72	8	2	35	4	2	-	-	-	-	-	-	3	-
Phlogopite	2.82	-	-	-	80	82	52	27	18	29	40	5	14	10
Annite	3.30	-	-	-	-	-	-	6	13	13	-	8	-	-

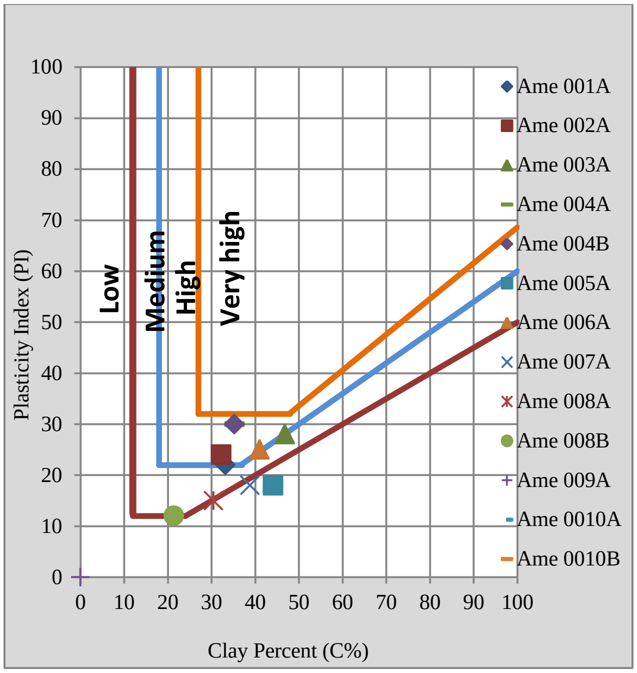

Figure 4. Van Der Merwe classification of all the samples

RESULTS AND DISCUSSION

The results of the field work and laboratory tests carried out under this study have shown that at the centre of the Manyana village where weathered dolerite derived clays are covered with sand the soils provide a better foundation for houses. The soils at the centre of Manyana village are non-plastic with a clay content of up to 4% and they have a low potential expansiveness and a relatively high bearing capacity. The soils on the eastern side of the village on the contrary are clays with plasticity index range of 12 to 30% and clay content of 21 to 47%. The soils exhibit a medium to high potential of expansiveness, a low bearing capacity as well as a high field moisture content (18 to 27%). The bearing capacity range based on DCP correlations was 72kPa to 275kPa under dry conditions. A plasticity index map of Manyana village depicting these conditions has been compiled and it showed that Black cotton soils cover approximately 30% of the village from the eastern side of the village. One of the constraints of the study was sampling during the wet season where it was difficult to move within the study area due to the slippery nature of clay when wet.

Overall it is suggested that the village growth avoid eastern Manyana (which could be reserved for agricultural use) where the heavy clays predominate. It would also be advisable to carry out more tests to adequately delineate the area to be avoided.

DECLARATIONS

Corresponding Author

Correspondence and requests for materials should be addressed to Mompoloki Ndala Marumo; E-mail: darriesmorule@gmail.com; ORCID: 0000-0000-0000-0000

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Authors' contribution

First Author performed the experiments, analysed the data obtained and wrote the manuscript. Second and Third Author designed the experimental process and revised the manuscript. Both authors read and approved the final manuscript

Competing interests

The authors declare no competing interests in this research and publication.

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