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Research Article

Influence of Variation in Moisture Content to Soil Bearing Capacity in Nairobi Area and Its Environs

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Abstract: The increasing human population in cities and urban areas continues to raise the demand for housing and other infrastructure in developing nations. Stability of structures is critical for sustainable development to ensure longer useful life of structures and reduction in the rate at which natural resources for construction purposes are extracted from the environment. Foundation of buildings infrastructure plays a key role of transferring the loading from the structure to the soil underneath. In foundation design, the ultimate bearing capacity of soil under normal circumstances assumes that the water table is located well below the foundation. Variation in soil moisture content during construction and during the structure's lifespan affect the soil bearing capacity. Information on the extent to which variation in soil moisture content affect the soil bearing capacity was lacking. This paper presents findings of a research that sought to establish the extent to which variation in soil moisture content affects the soil bearing capacity. Seven soil samples collected from Nairobi area and its environs were subjected to 30%, 50% and 75% moisture content variation. The soil bearing capacity was tested using Direct Shear method and Undrained Triaxial method in accordance to British Standard 1377 of 1990 Part 7 and Part 8 respectively. Test results determined that the insitu moisture content for the collected 7 soil samples from Nairobi area and its environs varied from 21.9% to 55.4% implying the diverse characteristics of soil samples and sites studied. Increasing the soil moisture content from 30% to 50% and to 75% all other factors held constant contributed to reduction in soil bearing capacity as illustrated by a linear equation $y = -170.89x + 565.64$ using direct shear method. y is the resultant soil bearing capacity (kN/mm^2) while x is the soil moisture content in percentage. This shows that variation in soil moisture content contributes to a significant reduction in soil bearing capacity by a factor of $-170.89x$. To mitigate the negative effect of reduction in soil bearing capacity as a result of changes in soil moisture content, a factor of safety should be applied at design stage by adjusting the allowable soil bearing capacity to take cognisance of the contribution by changes in soil moisture content. This is critical to ensure that all structures are designed to withstand variation in moisture content at the foundation throughout their lifespan and avoid potential structural failure.

Keywords: Foundation, Building Structure, Soil Moisture Content, Bearing Capacity, Construction Technology

1. Introduction

1.1. Building Foundation

The increasing human population in cities and urban areas in developing nations continues to increase the demand for housing and other basic infrastructure such as roads, water and power supply. Stability of structures is critical for sustainable development to ensure their longer useful life and reduce the rate at which natural resources for construction purposes are extracted from the environment. Foundation of buildings play a key role of transferring the loading from the structure to the soil underneath. Properties of soil for foundation work is therefore important at it inform the types of foundations, their geometries and methods of construction. Foundation of a building structure must withstand the loading at ultimate limit state and at serviceability limit state for the structure to be stable (Budhu, 2010). In determining the most economical foundation of a building, the superstructure load, the subsoil conditions, and the desired tolerable settlement are considered.

The ultimate bearing capacity of soil under normal circumstances assumes that the water table is located well below the foundation [2-3]. Moisture content in soil affects its bearing capacity. When the soil gets submerged, its ability to support the load subjected to the soil over a unit area is reduced. The presence of a water table near a building foundation significantly affects the foundation's load bearing capacity as well as settlement. Variation of moisture at building foundations results in differential settlement of foundations and possible structural failure or collapse (Lamb, 1966).

1.2. Buildings Collapse in Kenya

Over the last 15 years, Kenya has witnessed an increase in collapse of buildings that has led to loss of lives, caused injuries as well as loss of properties. The information available in reports and media (television, digital and printed newspapers) indicate that over 27% of the 40 collapsed buildings may be related to foundation challenges as illustrated in the Figure 1 below. These challenges include inadequate foundation, construction in wetland and construction during heavy rains. This implies that presence of water in the soil affects its ability to withstand imposed loading leading to structural failure of buildings.

While past studies show that the soil bearing capacity changes once the soil experiences change in moisture, it was not clear to what extent does the changes in moisture content affects the soil bearing capacity [5-9]. Varying soil moisture content can lead to differential settlement of structures and such settlement can occur during construction or when a building is complete and in use [10-16]. The research paper present findings on the effect of variation of soil moisture content on the soil bearing capacity. The research output is beneficial to structural designers, construction industry practitioners and researchers aimed to enhance safety of building strucutures.

1.3. Research Overview

To achieve this research output, 7 soil samples were collected from Nairobi area and its environs with geographical focus on sites that are susceptible to flooding and those near rivers. Insitu soil moisture content was tested and the corresponding soil bearing capacity determined through direct shear and undrained triaxial laboratory testing as detailed in British Standard 1377 Part 7 and Part 8 [17-18]. Through laboratory testing, the level of soil moisture content was varied from 30%, 50% and to 75% and the corresponding Cohesion (c) and angle of friction (ϕ) determined. The soil bearing capacity was then determined and its relationship with changes in soil moisture content determined. Dynamic Cone Penetration (DCP) testing was carried out to determine the insitu soil bearing capacity.

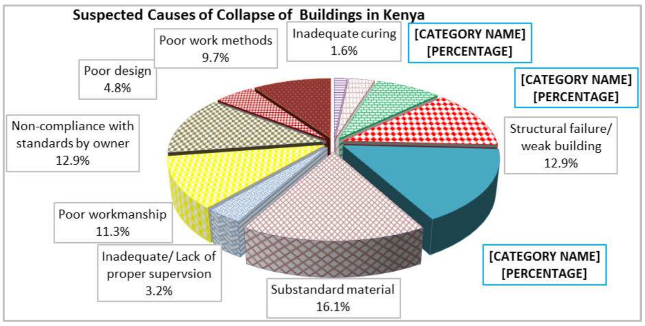

Figure 1. *Main suspected causes of buildings failure in Kenya.*

2. Materials and Methods

2.1. Research Design

The research employed laboratory testing of soil samples to determine the effect of moisture content on soil bearing capacity for structural stability of frame structures. Soil samples were collected from Nairobi areas and its environs.

2.2. Materials

Seven soil samples were collected from four sites within Nairobi County and its environs. Trial pits measuring 2m wide 2m length and target depth of 3m were excavated in sites prone to changes in moisture content specifically near rivers and swamps. Soil samples were collected at a distance of 15m from the river bank out of riparian land. Hoes, folks, ropes, buckets, core cutter steel rings were used for extraction of soil samples in the field. Direct Cone Penetration (DCP) hammer and penetration rods were used for testing insitu soil bearing capacity (Feleke and Araya, 2016). The collected soil samples were put in a samples collection bags labelled, carefully sealed and transported to the laboratory for testing. Direct shear testing equipment was used to determine Cohesion (c) and angle of friction (ϕ) for determination of soil bearing capacity using Terzanghis equation (British Standards Institution, 1990b). Undrained unconsolidated triaxial soil testing equipment was also used to determine soil bearing capacity using Morh Circles method (British Standards Institution, 1990a). Sieve analysis sieves and hydrometer were used for determination of dry and wet sieve analysis to determine particles sizes (British Standards Institution, 1990c). Oven and weighting scale were used to determine the soil moisture content.

2.3. Methods

The research started with sourcing and study of secondary data for Nairobi soils and their characteristics. Potential soil samples sites within Nairobi area and its environs were marked on the survey map and this was followed by reconnaissance survey to physically identify the exact location for trial pits excavation. Attention was paid to areas near rivers or areas subject to water level fluctuations. Accessible sites located about 15m from the river bank were identified for collection of soil samples after obtaining permission by the land owners. They are as follows;

i. Kariobangi site near Mathare river (KMR).
ii. Githurai shopping area near Gatharaini-Ngare river (GGR).
iii. Kiambu near Kiambu Institute of Science and Technology (KIST) near Riara river (KKR).
iv. Kiambu town near Riara river (KTR).

Disturbed and undisturbed soil samples were collected at 1.5m, 2.0m, 2.5m and 3.0m depth based on the ground conditions. After collection of all samples, trial pits were then covered with the soil and site made good.

Onsite testing of soil bearing pressure using Dynamic Cone Penetration method was carried out in accordance with Standard Test Procedures Manual STP 240-20 for Foundation Investigation Using Dynamic Cone Penetrometer by Saskatchewan Highways and Transportation dated 1992 04 16 to determine the insitu soil bearing capacity (Transportation, 1992). DCP testing was carried out on site prior to commencement of trial pit excavation. Number of blows and depth of rod penetration were recorded and analysed. The number of blows as well as the extent of cone penetration was recorded on site. The test was terminated after achieving 5 metres below ground or at refusal when the rod penetrates less than 1/8-inch in 10 drops. Data analysis was undertaken using the DCP Application and the following formulas applied;

$$\text{Log CBR} = 2.465 - 1.12\log(\text{DCI}) \text{ or } \text{CBR} = 292 / (\text{DCI}^{1.12})$$ as recommended by U.S. Army Corps of Engineers (1992) and (Feleke and Araya, 2016) (1)

Where, CBR = California Bearing Ratio
DPI = DCP Penetration Index

$$\text{Log CBR} = 2.628 - 1.273\ \log(\text{DCP}) \quad \text{(Transportation, 1992)} \tag{2}$$

Where, DCP = penetration mm/blow.

$$\text{Bearing capacity} = 26.16 * \text{CBR}^{0.664}/2 \tag{3}$$

Where CBR is in percentage (%).

Laboratory testing carried entailed soil characteristics profiling for particle size distribution using sieve analysis and hydrometer methods depending on particle sizes in accordance with (British Standards Institution, 1990c). Sieve analysis and hydrometer particles size testing were carried out. Soil moisture content testing was carried out in accordance with British Standard for determination of soil moisture content while soil plasticity index testing was carried out in accordance with British Standard for soil classification tests (British Standards Institution, 1990c). This entailed determination of liquid limit, plastic limit and plasticity index and Atterberg Limit state for all the 7 soil samples. Data was analysed and interpretation made.

Direct shear method for determining the soil bearing capacity was carried out in accordance to (British Standards Institution, 1990b) for determination of shear strength by direct shear method using the small shear box apparatus. The relationship between the shear stress at failure and the normal applied stress was obtained. The Cohesion (C), Frictional angle (ϕ) and the subsequent soil bearing capacity determined using Terzaghis equation. Reading the bearing capacity factors from Figure 3 (Tomlinson, 2001) and the bearing capacity values were analysed. Soil bearing capacity was carried out for all samples at insitu moisture content and at variation of moisture content to 30%, 50% and 75%.

DCP testing at KMR site **Soil samples extraction KKR and KKR sites** **Soil samples**

Figure 2. *DCP testing and Extraction of soil samples at various sites.*

Each soil sample was subjected to an axial loading inducing a normal stress of 50kN/m^2, 100kN/m^2, 150kN/m^2, 200kN/m^2,

$300kN/m^2$, $400kN/m^2$ and $500kN/m^2$ on the sample. The induced shear stress was recorded until sample failure. The normal stress was plotted against the shear stress at sample failure. From the graph the values for Cohesion (C) and Angle of friction (ϕ) were computed from the graph constant and tan inverse of slope respectively. Testing was done for none flooded and flooded condition. For flooded condition as soil sample was sequentially loaded up to 4kg loading. The sample was then flooded with water and left for 24 hours. Loading of the flooded soil specimen continued the following day (after 24 hrs) and the induced stress recorded until shear failure occurred of the soil speciment occurred.

Terzaghis equation was used to compute the ultimate and allowable soil bearing capacity in reference to Figure 3. The following equation was applied to analyse the soil bearing capacity results.

$$q_{nf}=cN_cS_cd_ci_cb_c + p_0N_qs_qd_qi_qb_q+ 0.5\gamma BN_\gamma s_\gamma d_\gamma i_\gamma b_\gamma \quad (4)$$

Where;
q_{nf} = ultimate bearing capacity
c= undrained cohesion of soil
p_o = effective pressure of overburden soil at foundation level
γ = density of soil below foundation level
B = Breadth of foundation
N_c, N_q and N_γ=bearing capacity factors
s_c, s_q and s_γ=shape factors
d_c, d_q and d_γ depth factors
l_c, l_q and l_γ=load inclination factors
b_c, b_q and b_γ=base inclination factors
Using;

1. Type of foundation = spread (pad) footing
2. Size of pad = 1.5m x 1.5m
3. Depth of footing = 1.5m

Wedge bearing capacity factors for foundation on rocks Nq, Nc, Nγ are obtained from (Tomlinson, 2001) from Figure 3.

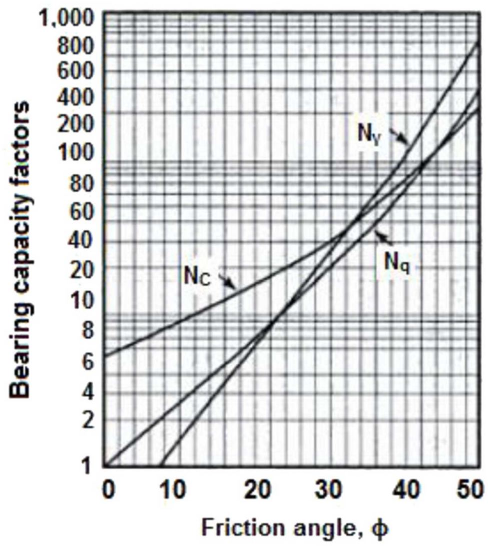

Figure 3. *Bearing Capacity Factors.*

The analysis was simplified and the formula for shallow foundations was used to compute soil bearing capacity as follows;

$$q_f=1.3CN_c+0.5_\gamma BN_\gamma+_\gamma D_fN_q \quad (5)$$

where,
q_{nf} = ultimate bearing capacity
1.3 = factor for square pad foundation
C = undrained cohesion of soil
B = Width of foundation
D = Depth of foundation
p_o = effective pressure of overburden soil at foundation level
γ = density of soil below foundation level
N_c, N_q and N_γ = bearing capacity factors

Undrained triaxial testing method in accordance to British Standard 1377 of 1990 Part 8 (British Standards Institution, 1990a): The cell pressure and principal stress at failure were determined and Cohesion (c) and frictional angle (ϕ) determined using Mohr Cycle method for determination of soil bearing capacity. This was done for soil samples at 30% and 50% moisture content. 75% moisture content was not done under Undrained Triaxial testing due to high water content making the sample unworkable (British Standards Institution, 1990b).

Figure 4. *Plasticity, Shrinkage, Direct Shear and Undrained Triaxial Testing.*

3. Results and Discussion

3.1. Physical Assessment of Collected Soil Samples

Seven soil samples were collected from four sites in Nairobi area and its environs. The collected soil samples were labelled as follows based on the collection site and depth of the sample;

i. Kariobangi site near Mathare river at 1.5m depth (KMR1.5).
ii. Githurai shopping area near Gatharaini-Ngare river at 1.5m depth (GGR1.5).
iii. Githurai shopping area near Gatharaini-Ngare river at 2.0m depth (GGR2.0).
iv. Githurai shopping area near Gatharaini-Ngare river at 2.5m depth (GGR2.5).
v. Kiambu at Kiambu Institute of Science and Technology (KIST) near Riara river at 1.5m depth (KKR1.5).
vi. Kiambu at Kiambu Institute of Science and Technology (KIST) near Riara river at 1.8m depth (KKR1.8).
vii. Kiambu town near Riara river at 1.5m (KTR1.5).

The 4 samples collection sites and the corresponding 7 soil samples collected are mapped out in Figure 5.

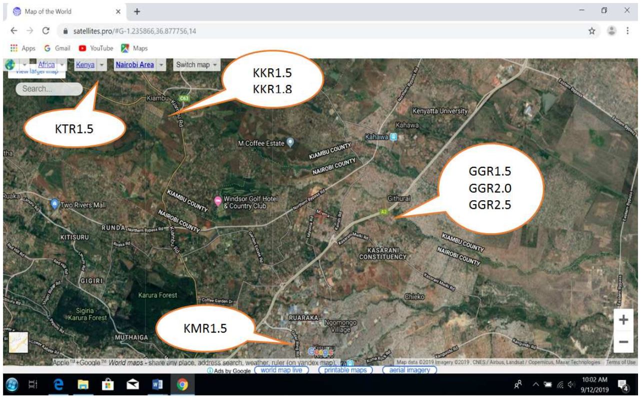

Figure 5. *Map showing soil samples collection sites and samples collected.*

Physical examination was carried out during trial pits excavation and soil samples collection. Soil samples were collected from depth ranging from 1.5m to 2.5m below the ground level. Water seepage was encountered after reaching 1.5m depth below ground level for sites KMR and KTR thus halting further pit excavation. Presence of rocks and boulders was found at KKR site leading to discontinuation of trial pit excavation at 1.8m depth. Site GGR was characterised by presence of dumped materials leading to termination of trial pit excavation at 2.5m depth. Undisturbed samples were collected using 50mm diameter and 75mm long core-cutters and preserved in a water tight polythene bag after samples labelling. Three core cutters steel rings were used to collect undisturbed samples for each of the 7 soil samples collected.

3.2. Dynamic Cone Penetration Test Results for Insitu Soil Bearing Capacity

The field data analysis in term of number of blows and depth of rod penetration was recorded and data analysis carried out. Results on number of blows, depth of penetration, CBR and the corresponding soil bearing capacity for KMR and GGR sites are shown in Table 1 and illustrated in Figure 5.

The insitu soil bearing capacity for site KMR at 1.5m, 2.0m, 2.5m and 3.0m depth are 103kN/m^2, 262kN/m^2, 222kN/m^2 and 159kN/m^2 respectively. This depicts a heterogenous soil profile. Subsequently, the insitu soil bearing capacity for site GGR at 1.5m, 2.0m, 2.5m and 3.0m depth are 49kN/m^2, 75kN/m^2, 99kN/m^2 and 107kN/m^2 respectively using the DCP method. The soil bearing capacity increases with depth in an irregular manner. The soil bearing capacity for GGR site is lower than the typical average of 150kN/m^2 applied for Nairobi area.

As detailed in Table 1 the soil bearing capacity for KMR site recorded the highest soil bearing capacity at 2.0m, 2.5m and 3m depths using DCP method compared to GGR, KKR and KTR sites. KTR site registered the highest soil bearing capacity at 307kN/m^2 at 1.5m depth. KKR and KTR sites were characterised by medium sized rocks and small borders ranging from 50mm – 450mm which hindered penetration of DCP rod beyond 1.8m and 1.5m depths respectively. For purposes of setting up a building foundation in such areas, further mechanical excavation is required to investigate the underlying layer to confirm rock continuity and its compressive strength before a foundation is laid. A summary of the insitu soil bearing capacity using DCP method is illustrated in Figure 6.

Table 1. *Soil Bearing capacity at 1.5m, 2.0m, 2.5m, 3.0m.*

	Site	Bearing Capacity (kPa) at Various Depths			
		1.5m	2.0m	2.5m	3m
1	Kariobangi near Mathare River (KMR)	103	262	222	159
2	Githurai town near Gatharaine river (GGR)	49	76	98.	107
3	Kiambu KIST near Riara river (KKR)	99	146	-	-
4	Kiambu Town near Riara river (KTR)	308	-	-	-

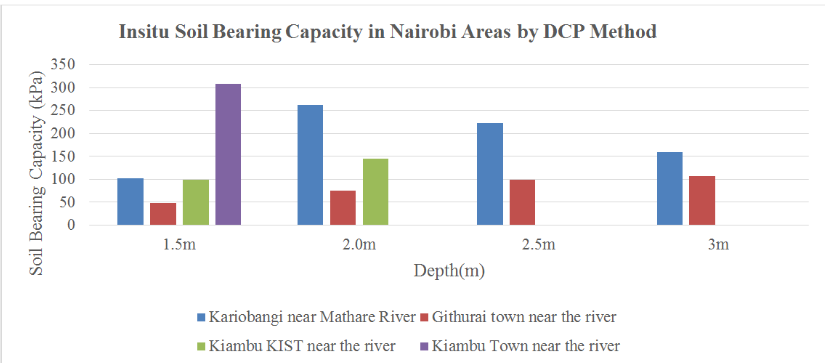

Figure 6. *Insitu Bearing Capacity using DCP method.*

It is observed that soil bearing capacity for the four sites varied widely from 75 kPa to 307kPa. Only 5 test points (33%) out of the 15 test points exceed the typical average of 150kPa usually used for Nairobi area. An overwhelming 10 points (67%) out of 15 points tested had a soil bearing capacity of less than 150kPa. The DCP method established that 4 points (27%) out of 15 points had the soil bearing capacity at less that 100kPa which is critical. The average soil bearing capacity is

148 kPa across the soil profile for all samples combined and the soil profile was heterogenous. This implies that if soil testing was not done for a specific site and the typical average of 150kPa for Nairobi area used for design and construction of a building structure, then the building would collapse due to inadequate soil bearing capacity to withstand structural forces. It critical for structural and geotechnical engineers to carry out sites specific soil samples testing to ensure that the data applied during foundation and structural designs of structures is factual.

3.3. Soil Classification Through Particle Size Distribution Analysis

The results on soil particle distribution and description are shown Figure 6 and Table 2 below.

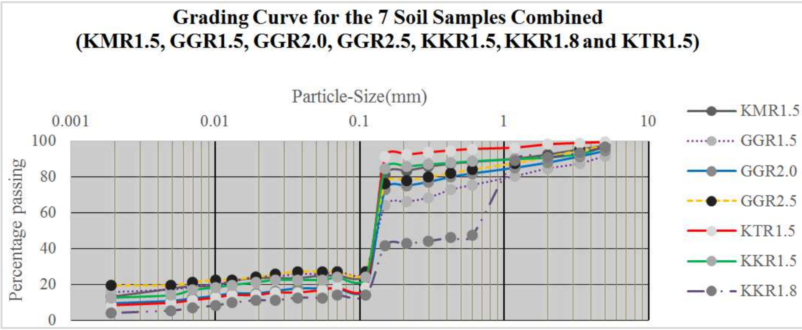

Figure 7. *Grading Curve for the 7 Soil Samples Tested.*

Table 2. *Classification and Description for All Soil Samples.*

	Soil Samples	Soil Description		
		Colour	**Particle shape**	**Particle size distribution**
1	KMR1.5	Dark brown	Sub-angular	Dark Brown Clayey Silty Sand. Traces of gravel were evident.
2	GGR1.5	Dark grey	Irregular	Dark Grey Clayey Gravelly Sand. Traces of silt was present. Gravel was attributed to dumped waste material observed on site. Black cotton soil was also evident.
3	GGR2.0	Dark grey	Irregular	Dark Grey Clayey Gravelly Sand with traces of silt
4	GGR2.5	Dark grey	Irregular	Dark Grey Clayey Sand with traces of gravel and silt. Black cotton characteristic we also observed on site.
5	KKR1.5	Dark brown	Sub-angular	Brown Gravelly Silty Sand with traces of clay. Rock boulders were also evident on site.
6	KKR1.8	Dark brown	Sub-angular	Brown Gravelly Silty Sand with traces of clay. Rock boulders were also evident on site.
7	KTR1.5	Reddish brown	Sub-angular	Reddish Brown Clayey Silty Sand with traces of gravel

Sieve analysis results indicate that sand was the most dominant component in all the 7 soil samples tested. This was followed by silt and then clay. Gravel was present in small quantities while boulders were observed at KKR site. Presence of black cotton soil is known to cause swelling during rainy seasons and shrinkage during dry seasons hence not suitable for building foundation. Gravel on the other hand is preferred for its relatively high soil bearing capacity for foundation works.

3.4. Results on Insitu Moisture Content

Results on insitu moisture content for the soil samples as collected from the field is shown in Table 3 below. It is noted that 4 out of 7 soil samples tested had an insitu moisture content of over 50%. Sample KKR1.8 had the lowest insitu moisture content of 21.9% while sample GGR2.5 had the highest insitu moisture content of 55.4%. This implies that structural and geotechnical engineers should consider soil moisture content of the soil during design of foundations to ensure that adequate factor of safety is allowed at design stage.

Table 3. *Insitu Moisture Content for the 7 Soil Samples.*

	Soil Samples	(a)	(b)	(c) =a-b	(c)
		Weight of wet sample + Tin (g)	**Weight of dry sample + Tin (g)**	**Weight of water (g)**	**Weight of Tin (g)**
1	KMR1.5	70.3	49.6	20.7	9.9
		91.6	63.8	27.8	9.8
2	GGR1.5	71.6	58.1	13.5	22.3
		69.0	56.6	12.4	22.7
3	GGR2.0	78.5	59.3	19.2	24.0
		104.5	75.5	29.0	24.1
4	GGR2.5	76.6	57.3	19.3	22.2
		79.0	59.6	19.4	24.3
5	KKR1.5	89.6	76.1	13.5	24.1
		87.8	74.6	13.2	23.4

	Soil Samples	(a) Weight of wet sample + Tin (g)	(b) Weight of dry sample + Tin (g)	(c) =a-b Weight of water (g)	(c) Weight of Tin (g)
6	KKR1.8	70.9 87.3	62.3 76.0	8.6 11.3	23.4 23.9
7	KTR1.5	73.7 106.6	54.1 76.4	19.6 30.2	18.3 19.3

Table 3. *Continued.*

	Soil Samples	(e)=b-c Weight of dry sample (g)	(f)=c/e Soil Moisture Content (%)	(g) Average Soil Moisture Content (%)
1	KMR1.5	39.7 54.0	52.1% 51.5%	51.8%
2	GGR1.5	35.8 33.9	37.7% 36.6%	37.1%
3	GGR2.0	35.3 51.4	54.4% 56.4%	55.4%
4	GGR2.5	35.1 35.3	55.0% 55.0%	55.0%
5	KKR1.5	52.0 51.2	26.0% 25.8%	25.9%
6	KKR1.8	38.9 52.1	22.1% 21.7%	21.9%
7	KTR1.5	35.8 57.1	54.7% 52.9%	53.8%

3.5. Determination of Plasticity Index

The soil plasticity index was determined using the Atterberg Limits cone penetration method. The results from liquid limit, plastic limit, plastic index and linear shrinkage are shown the Figure 8.

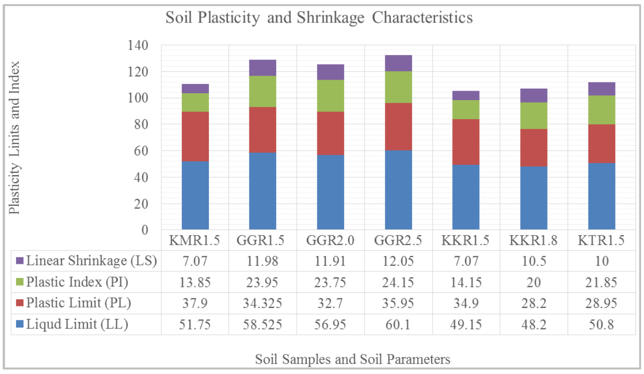

Figure 8. *Soil Plasticity and Shrinkage Characteristics.*

Sample GGR2.5 exhibited the highest liquidity limit of 60.1 while the KKR1.8 exhibited the lowest liquidity index of 48.2. Presence of gravel, small rocks soil and boulders at sample KKR1.8 site correlates with the low liquid limit state for that sample. Sample GGR2.5 exhibited the highest linear shrinkage of 12.05 while sample KKR1.5 had the lowest linear shrinkage of 7.07. Sample GGR2.5 was dark grey in colour with presence of dumped foreign material and traces of black cotton soil which are attributed to cause high linear shrinkage level. Building stability of enhanced by soil with low shrinkage and low plasticity levels.

3.6. Determination of Soil Bearing Capacity by Direct Shear Method

The results for C and ϕ for soil samples at 30% moisture content are shown on Table 4 while results for allowable soil bearing capacity are shown on Table 5 below. It is observed that sample KKR1.5 in non-flooded condition registered the highest Cohesion value of 62.27 while sample KKR1.8 in flooded condition registered the minimum Cohesion value of 0.68. The reduction in Cohesion value in flooded condition is attributed to increased presence of water between soil particles that reduces the ability to withstand the compression forces from the axial load applied during direct shear testing. This results to soil particles displacement and deformation in flooded condition under shear stress. Sample KKR1.8 in non-flooded condition registered the maximum Angle of friction of 33.69 while sample GGR2.0 in flooded registered the minimum angle of friction at 9.11.

Table 4. *Analysis of Cohesion (C) and Angle of friction (ϕ) for Soil Samples at 30% MC.*

	Soil Samples	Flooded/Non-Flooded Conditions	Loading	Failure Load (kN/m^2)		
			Normal Stress (kN/m^2)	50	100	150
1	KMR1.5	Non-flooded	Shear Stress (kN/m^2)	41.43	43.35	84.40
		Flooded	"	38.36	70.97	85.94
2	GGR1.5	Non-flooded	"	46.80	64.83	138.88
		Flooded	"	44.89	70.21	99.75
3	GGR2.0	Non-flooded	"	39.51	57.93	83.25
		Flooded	"	45.27	58.70	78.26

	Soil Samples	Flooded/Non-Flooded Conditions	Loading	Failure Load (kN/m²)		
			Normal Stress (kN/m²)	50	100	150
4	GGR2.5	Non-flooded	"	31.84	45.27	79.80
		Flooded	"	40.67	84.78	99.75
5	KKR1.5	Non-flooded	"	140.03	122.76	141.18
		Flooded	"	80.95	90.54	94.76
6	KKR1.8	Non-flooded	"	32.61	85.17	126.60
		Flooded	"	21.87	63.30	88.24
7	KTR1.5	Non-flooded	"	59.46	74.43	111.26
		Flooded	"	29.92	85.94	95.91

Table 4. *Continued.*

	Soil Samples	Flooded/Non-Flooded Conditions	Failure Load (kN/m²)				Slope	Cohesion (C)	Angle of friction (ϕ)
			200	300	400	500			
1	KMR1.5	Non-flooded	105.50	159.59	183.40	260.11	0.32	20.61	17.61
		Flooded	126.60	147.70	163.05	164.96	0.29	40.97	16.01
2	GGR1.5	Non-flooded	166.88	228.27	268.32	337.99	0.66	15.58	33.35
		Flooded	126.60	145.78	298.09	191.82	0.43	33.06	23.20
3	GGR2.0	Non-flooded	73.28	119.70	168.42	109.72	0.21	41.06	12.10
		Flooded	97.83	105.50	138.11	104.35	0.16	50.79	9.11
4	GGR2.5	Non-flooded	126.60	131.59	168.32	252.43	0.49	6.49	26.19
		Flooded	129.29	178.39	180.31	270.08	0.45	30.80	24.44
5	KKR1.5	Non-flooded	88.24	204.86	263.94	360.62	0.52	62.27	27.52
		Flooded	203.33	173.40	299.24	313.82	0.57	42.28	29.45
6	KKR1.8	Non-flooded	144.25	258.96	253.97	354.87	0.67	15.38	33.69
		Flooded	118.16	164.20	205.25	293.48	0.37	0.68	20.14
7	KTR1.5	Non-flooded	87.47	149.62	203.33	223.66	0.37	37.27	20.32
		Flooded	126.60	163.81	209.08	250.13	0.46	26.27	24.70

Table 5. *Analysis of Ultimate and Allowable Soil Bearing Capacity for Soil Samples at 30% MC.*

	Samples	Flooded/ Non-Flooded	N_c	N_γ	N_q	C (kN/m²)	B (m)	γ (kN/m³)
1	KMR1.5	Non-flooded	15.5	3.85	6.2	20.61	1	16.58
		Flooded	11.2	1.75	3.95	40.97	1	16.72
2	GGR1.5	Non-flooded	42	44	27	15.58	1	14.86
		Flooded	18	7.5	9.5	33.06	1	15.97
3	GGR2.0	Non-flooded	8.8	0	2.8	41.06	1	16.16
		Flooded	9	0	2.8	50.79	1	15.94
4	GGR2.5	Non-flooded	10	10.5	22	6.49	1	13.50
		Flooded	8.8	10	20	30.80	1	16.08
5	KKR1.5	Non-flooded	27	14.5	16	62.27	1	16.12
		Flooded	29	21	17.5	42.28	1	17.43
6	KKR1.8	Non-flooded	14.2	3.7	6	15.38	1	14.51
		Flooded	15.7	3.9	6.1	0.68	1	14.25
7	KTR1.5	Non-flooded	15.5	3.85	6.2	37.27	1	15.85
		Flooded	20	8.5	10	26.27	1	15.93

Table 5. *Continued.*

	Samples	Flooded/Non-Flooded	D_f (m)	q_f (kN/m²)	θ°	Q_{all} (kN/m²)	C (kg/m²)	Bulk Density (kg/m³)	C (kg/cm²)
1	KMR1.5	Non-flooded	1.5	601.50	17.61	240.60	2000	1,690.28	0.2
		Flooded	1.5	710.18	16.01	284.07	2000	1,704.17	0.2
2	GGR1.5	Non-flooded	1.5	1779.78	33.35	711.91	2000	1,515.28	0.2
		Flooded	1.5	1061.06	23.20	424.42	2000	1,627.78	0.2
3	GGR2.0	Non-flooded	1.5	537.63	12.10	215.05	2000	1647.22	0.2
		Flooded	1.5	661.21	9.11	264.48	2000	1625.00	0.2
4	GGR2.5	Non-flooded	1.5	600.70	26.19	240.28	2000	1376.00	0.2
		Flooded	1.5	915.04	24.44	366.02	2000	1638.89	0.2
5	KKR1.5	Non-flooded	1.5	2689.41	27.52	1075.76	2000	1643.06	0.2
		Flooded	1.5	2234.41	29.45	893.77	2000	1776.39	0.2
6	KKR1.8	Non-flooded	1.5	441.41	33.69	176.56	2000	1479.17	0.2
		Flooded	1.5	172.01	20.14	68.80	2000	1452.78	0.2
7	KTR1.5	Non-flooded	1.5	928.94	20.32	371.58	2000	1615.28	0.2
		Flooded	1.5	989.63	24.70	395.85	2000	1623.61	0.2

From Table 5, it is observed that the maximum soil bearing capacity for soil samples at 30% moisture content was recorded at KKR1.5 in non-flooded condition amounting to 1075.76 kN/m². The minimum allowable soil bearing capacity was recorded for sample KKR1.8 in flooded condition and amounts to 68.80kN/m^2 which is much lower than the typical 100kN/m^2 used for Nairobi area and its environs. The soil bearing capacity trend is directly relate to the cohesion level of the soil samples. 3 samples out of the 7 soil samples tested show a higher soil bearing capacity in non-flooded condition compared with flooded condition. These are GGR1.5, KKR1.5 and KKR1.8 soil samples. This is expected because cohesive soils (silt and clay) are bound together by electrochemical bonds between individual soil particles. Increase in soil's moisture content can change the distance between particles thus decreasing the strength of the inter-particle bonds. This then leads to reduction in cohesion between particles and subsequent reduction in the soil bearing capacity to support loading without catastrophic failure. For granular soils such as sand and gravel, the effective unit weight is reduced as moisture content approaches saturation as the intergranular voids are 100 percent filled with water) thus reducing the confining pressure and soil bearing capacity.

Interestingly the remaining 4 out of the 7 soil samples showed a higher soil bearing capacity in flooded condition than in non-flooded condition. The samples are KMR1.5, GGR2.0, GGR2.5 and KTR1.5. This is attributed to other soil properties such as particle sizes, chemical composition, soil hard ness among others. Following the chemical testing the four samples are noted to have a significant amount of Chromium, Magnesium and Titanium chemical element which are responsible to soil hardness hence the high soil bearing capacity in flooded condition. KMR1.5 had the highest level of Chromium and Magnesium and second highest in Titanium. Sample GGR2.0 recorded the highest Cohesion in flooded condition and the lowest in non-flooded condition at 50% moisture content variation. Sample KTR1.5 recorded the highest cohesion value of 32 in non-flooded condition compared with a minimum of 5.36 recorded for sample GGR1.5 in non-flooded condition.

Table 6. *Analysis of Ultimate and Allowable Soil Bearing Capacity for Soil Samples at 50% MC.*

	Samples	Flooded/ Non-Flooded	N_c	N_γ	N_q	C (kN/m^2)	B (m)	γ (kN/m^3)	Df (m)
1	KMR1.5	Non-flooded	15.5	4	6.5	2.06	1	16.58	1.5
		Flooded	16	4.1	6.7	26.19	1	16.26	1.5
2	GGR1.5	Non-flooded	8.5	0	2.4	11.66	1	16.56	1.5
		Flooded	20	8.8	10	30.74	1	15.57	1.5
3	GGR2.0	Non-flooded	6.3	0	6.8	0.09	1	16.02	1.5
		Flooded	6.5	0	1.75	39.41	1	16.16	1.5
4	GGR2.5	Non-flooded	5.2	0	1.3	34.06	1	16.02	1.5
		Flooded	11	2.45	3.8	2.13	1	17.55	1.5
5	KKR1.5	Non-flooded	8.5	0	2.5	20.56	1	18.09	1.5
		Flooded	15.2	3.75	6	22.86	1	17.75	1.5
6	KKR1.8	Non-flooded	15.5	3	5.8	25.00	1	18.76	1.5
		Flooded	30.1	14.2	20.4	0.00	1	19.29	1.5
7	KTR1.5	Non-flooded	20	8.8	10	19.60	1	16.60	1.5
		Flooded	9.9	0	2.9	26.27	1	15.81	1.5

Table 6. *Continued.*

	Samples	Flooded/ Non-Flooded	q_f (kN/m^2)	θ°	Q_{all} (kN/m^2)	C (kg/m^2)	Bulk Density (kg/m^3)	C (kg/cm^2)
1	KMR1.5	Non-flooded	236.38	21.72	94.55	2000	1690.28	0.2
		Flooded	741.50	21.90	296.60	2000	1658.00	0.2
2	GGR1.5	Non-flooded	188.40	10.87	75.36	2000	1688.00	0.2
		Flooded	1101.42	23.99	440.57	2000	1587.50	0.2
3	GGR2.0	Non-flooded	164.20	5.36	65.68	2000	1633.33	0.2
		Flooded	375.41	5.93	150.16	2000	1647.22	0.2
4	GGR2.5	Non-flooded	261.48	2.61	104.59	2000	1633.00	0.2
		Flooded	152.05	15.01	60.82	2000	1788.89	0.2
5	KKR1.5	Non-flooded	295.00	11.38	118.00	2000	1844.44	0.2
		Flooded	644.76	19.96	257.90	2000	1809.72	0.2
6	KKR1.8	Non-flooded	695.20	19.70	278.08	2000	1912.50	0.2
		Flooded	727.35	30.10	290.94	2000	1966.67	0.2
7	KTR1.5	Non-flooded	831.63	32.00	332.65	2000	1691.67	0.2
		Flooded	406.85	24.58	162.74	2000	1611.11	0.2

From Table 6 above, it is observed that the maximum allowable soil bearing capacity for soil samples at 50% moisture content was recorded for GGR1.5 in flooded condition amounting to 440.57kN/m^2. The minimum allowable soil bearing capacity was recorded for sample GGR2.5 in flooded condition and amounts to 60.82 kN/m^2 which is much lower than the typical 100 kN/m^2 used for Nairobi area and its environs. For the 50% moisture variation scenario, five samples namely KMR1.5, GGR1.5, GGR2.0, KKR1.5 and KKR1.8 depicted higher allowable soil bearing capacity at 296.60 kN/m2, 440.57 kN/m^2, 150.16 kN/m^2, 257.90 kN/m^2 and 290.94 kN/m^2 in flooded condition compared with 94.55 kN/m^2, 75.36 kN/m^2, 65.68 kN/m^2, 118.00 kN/m^2 and 278.08 kN/m^2 respectively for non-flooded condition. This is attributed to other soil factors such as mechanical composition and heterogeneous type of soil. Only two samples namely GGR2.5 and KTR1.5 showed reduction in soil bearing capacity for flooded scenario compared to the non-flooded scenario.

Sample GGR1.5 recorded the highest Cohesion of 21.75 in non-flooded condition compared with KKR1.8 that recorded Cohesion of 6.14 in flooded condition being the lowest Cohesion value for samples tested under 75% moisture content variation.

Sample KTR1.5 recorded the highest cohesion value of 32 in non-flooded condition compared with a minimum of 5.36 recorded for sample GGR1.5 in non-flooded condition.

Table 7. *Analysis of Ultimate and Allowable Soil Bearing Capacity for Soil Samples at 75% MC.*

	Samples	Flooded/ Non-Flooded	N_c	N_γ	N_q	C (kN/m^2)	B (m)	γ (kN/m^3)	D_f (m)
1	KMR1.5	Non-flooded	6.5	0	1.7	14.59	1	14.25	1.5
		Flooded	7	0	1.9	7.90	1	14.59	1.5
2	GGR1.5	Non-flooded	5	0	2.8	21.75	1	14.88	1.5
		Flooded	7.8	0	2.3	8.45	1	15.56	1.5
3	GGR2.0	Non-flooded	6.4	0	1.63	21.20	1	16.54	1.5
		Flooded	6.4	0	1.65	16.62	1	15.86	1.5
4	GGR2.5	Non-flooded	6.8	0	1.7	19.02	1	14.16	1.5
		Flooded	6.1	0	1.4	13.59	1	14.82	1.5
5	KKR1.5	Non-flooded	7.2	0	1.85	11.08	1	13.31	1.5
		Flooded	7.8	0	2.2	11.68	1	13.91	1.5
6	KKR1.8	Non-flooded	8.4	0	2.45	12.57	1	16.76	1.5
		Flooded	9.8	0	3	6.14	1	15.18	1.5
7	KTR1.5	Non-flooded	8	0	2.2	14.43	1	15.89	1.5
		Flooded	8.2	0	2.4	9.73	1	13.94	1.5

Table 7. *Continued.*

	Samples	Flooded/Non-Flooded	q_f (kN/m^2)	θ°	Q_{all} (kN/m^2)	C (kg/m^2)	Bulk Density (kg/m^3)	C (kg/cm^2)
1	KMR1.5	Non-flooded	159.60	5.08	63.84	2000	1452.78	0.2
		Flooded	113.49	7.125	45.39	2000	1487.50	0.2
2	GGR1.5	Non-flooded	203.86	12.216	81.54	2000	1517.00	0.2
		Flooded	139.38	8.643	55.75	2000	1586.11	0.2
3	GGR2.0	Non-flooded	216.79	5.11	86.72	2000	1686.00	0.2
		Flooded	177.55	5.2739	71.02	2000	1616.67	0.2
4	GGR2.5	Non-flooded	204.19	5.906	81.68	2000	1443.00	0.2
		Flooded	138.90	4.0897	55.56	2000	1511.00	0.2
5	KKR1.5	Non-flooded	140.65	7.367	56.26	2000	1357.00	0.2
		Flooded	164.30	8.749	65.72	2000	1418.00	0.2
6	KKR1.8	Non-flooded	198.83	11.315	79.53	2000	1708.00	0.2
		Flooded	146.47	12.495	58.59	2000	1547.00	0.2
7	KTR1.5	Non-flooded	202.51	9.866	81.00	2000	1619.44	0.2
		Flooded	153.89	9.46	61.56	2000	1420.83	0.2

From Table 7 above, it is observed that the maximum allowable soil bearing capacity for soil samples at 75% moisture content was recorded for GGR2.0 in non-flooded condition amounting to 86.72 kN/m^2. The minimum allowable soil bearing capacity was recorded for sample KMR1.5 in flooded condition and amounts to 45.39kN/m^2 which is much lower than the typical 100 kN/m^2 used for Nairobi area and its environs.

From the illustration above it is noted that 6 out of the 7 soil samples tested under non-flooded condition registered the highest soil bearing capacity at 30% moisture content compared with the same sample at 50% and 75% moisture content variation. This account to 85.7% of the samples tested. This confirms that increase in soil moisture content contributed towards reduction in the soil bearing capacity.

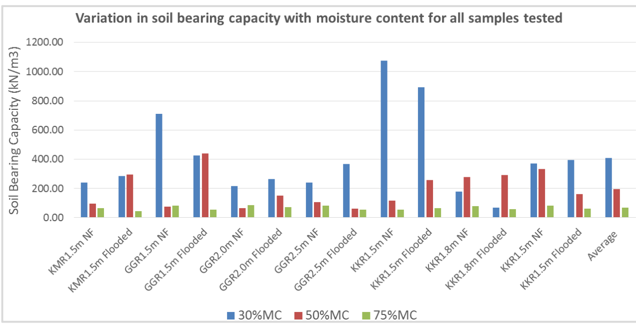

Figure 9. *Variation in allowable soil bearing capacity with moisture content for all soil samples tested.*

For flooded samples, it is noted that 4 out of the 7 tested soil samples exhibited the highest soil bearing capacity at 30% moisture content compared with the same samples at 50% and

75% moisture content variation. Out of all the 7 soil samples tested under flooded and non-flooded condition, it is observed that the soil bearing capacity is highest at 30% moisture content followed by samples at 50% moisture content followed by 75% moisture variation as shown by the average section in Figure 10.

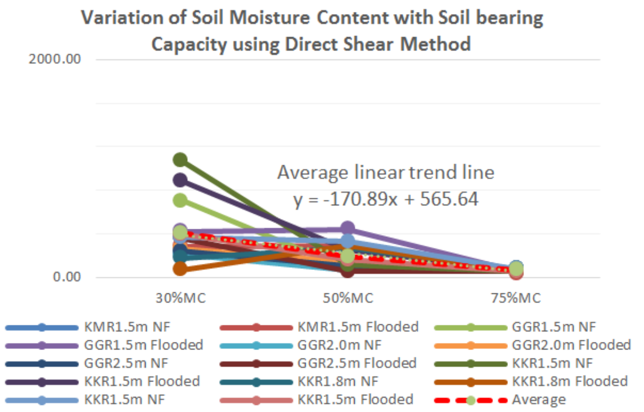

Figure 10. *Variation in soil bearing capacity with moisture content for all samples.*

Figure 10 shows that majority of the soil samples depicted reduction in soil bearing capacity as moisture content increases from 30% to 50% and then to 75%. The negative trend is illustrated by equation $y = -170.89x + 565.64$. The negative gradient in this equation implies that engineers and geotechnical engineers should allow for moisture variation for buildings in areas prone to changes in the level of moisture content such as rainy tropical areas and area near rivers and swamps. Subsequent the soil bearing capacity figures obtained should consider the moisture content in the soil and the appropriate adjustment made to the soil bearing capacity values applied in design of foundations.

3.7. Determination of Soil Bearing Capacity by Triaxial Method

The soil samples were subjected to triaxial shear strength testing method of determining the soil bearing capacity and Cohesion (C) and Angle of friction (ϕ) which were developed through Morh Circle methods. Terzaghis equation was used to compute the soil bearing capacity of soil samples at 30% and 50% moisture variation. It was impossible to carry out triaxial testing of soil samples at 75% moisture content due to high viscosity making the sample difficult to handle and testing unreliable. Normal stress of 50 kN/m^2, 250kN/m^2 and 250kN/m^2 as denoted by Q1, Q2 and Q3 respectively was applied on the sample through the triaxial equipment. The samples were tested in non-flooded condition. The resultants principal stress at failure was plotted against normal stress and Morh Circles developed. The results on soil bearing capacity are shown below.

Table 8. *Determination of Cohesion and Angle of Friction at 30% Moisture Content.*

	Samples	Sample properties				Max. Dry Density (kg/m^3)	Optimum Moisture content
		Mean diameter (mm)	Height (mm)	Weight of Specimen (g)	Volume of Specimen (cm^3)		
1	KMR1.5	62	125	649.1	377.38	1323	23.4%
2	GGR1.5	62	125	659.4	377.38	1344	24.0%
3	GGR2.0	62	125	573.5	377.38	1169	29.6%
4	GGR2.5	62	125	668.2	377.38	1362	25.5%
5	KKR1.5	62	125	658.9	377.38	1343	28.0%
6	KKR1.8	62	125	677.5	377.38	1381	26.1%
7	KTR1.5	62	125	651.5	377.38	1328	23.5%

Table 8. *Continued.*

	Samples	Principal Stress difference at failure (kN/m^2)			Q1			Cohesion (C) (kN/m^2)	Angle (ϕ)	Computed Soil Bearing Capacity
		Cell Pressure = 50 (kN/m^2)	Cell Pressure = 150 (kN/m^2)	Cell Pressure = 250 (kN/m^2)	Q11	Q12	Q13			
1	KMR1.5	134	223	313	184	373	563	38	18	342.60
2	GGR1.5	189	287	363	239	437	613	56	18	481.47
3	GGR2.0	146	208	275	196	358	525	48	15	256.61
4	GGR2.5	202	489	725	252	489	725	50	24	555.14
5	KKR1.5	114	176	287	164	326	537	26	19	254.64
6	KKR1.8	157	267	393	207	417	643	35	27	578.24
7	KTR1.5	190	300	375	240	450	625	54	20	477.74

Table 9. *Determination of Soil Bearing Capacity at 50% Moisture Content.*

	Samples	Sample properties				Max. Dry Density (kg/m^3)	Optimum Moisture content
		Mean diameter (mm)	Height (mm)	Weight of Specimen (g)	Volume of Specimen (cm^3)		
1	KMR1.5	62	125	748.9	377.38	1323	23.4%
2	GGR1.5	62	125	751.7	377.38	1344	24.0%
3	GGR2.0	62	125	661.7	377.38	1169	29.6%
4	GGR2.5	62	125	771	377.38	1362	25.5%

	Samples	Sample properties				Max. Dry Density (kg/m^3)	Optimum Moisture content
		Mean diameter (mm)	Height (mm)	Weight of Specimen (g)	Volume of Specimen (cm^3)		
6	KKR1.5	62	125	760.2	377.38	1343	28.0%
5	KKR1.8	62	125	781.7	377.38	1381	26.1%
7	KTR1.5	62	125	751.7	377.38	1328	23.5%

***Table 9.** Continued.*

	Samples	Principal Stress difference at failure (kN/m^2)			Q1			Cohesion (C) (kN/m^2)	Angle (ϕ)	Computed Soil Bearing Capacity
		Cell Pressure = 50 (kN/m^2)	Cell Pressure = 150 (kN/m^2)	Cell Pressure = 250 (kN/m^2)	Q11	Q12	Q13			
1	KMR1.5	18	32	48	68	182	298	5	4	27.80
2	GGR1.5	20	35	54	70	185	304	7	5	35.95
3	GGR2.0	23	33	50	73	183	300	10	4	42.56
4	GGR2.5	25	52	92	75	202	342	5	8	37.12
6	KKR1.5	19	47	75	69	197	325	2.5	8	26.74
5	KKR1.8	22	47	62	72	197	312	6	6	34.41
7	KTR1.5	30	52	72	80	202	322	7	7	39.55

At 30% MC, samples KKR1.8 recorded the highest soil bearing capacity of 578.24 kN/m^2 while sample KKR1.5 recorded the least soil bearing capacity of 254.64kN/m^2. Sample GGR1.5 had the highest cohesion value while sample GGR2.5 had the highest angle of friction.

At 50% moisture content variation, sample GGR2.0 recorded the highest soil bearing capacity of 42.56 kN/m^2 while sample KKR1.5 recorded the lowest soil bearing capacity of 26.74 kN/m^2.

By increasing the soils' moisture content from the 30% to 50% all other factors held constant, the resultant soil bearing capacity is significantly reduced as illustrated by the following linear equation $y = -386.04x + 806.96$.

This reduction in soil bearing is significant and should be considered in foundation design for all structures to ensure structural integrity of infrastructures is not compromised when soil moisture content is varied from time to time due to effect of weather variation.

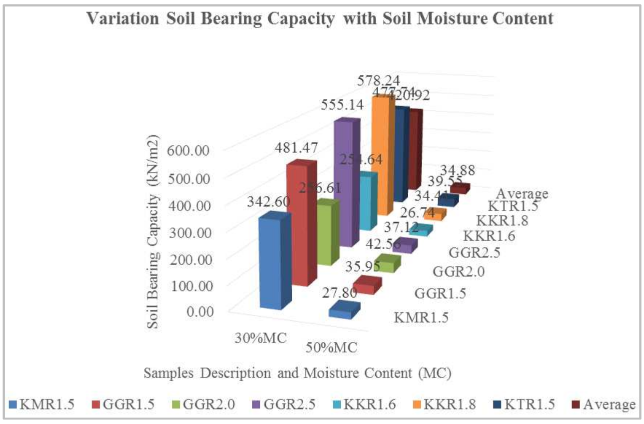

***Figure 11.** Variation of soil bearing capacity with moisture content using Triaxial Method.*

Soil bearing capacity is significantly reduced by up to 10 times as a result of increasing soil moisture content from 30% to 50%.

4. Conclusion, Recommendations and Areas for Further Research

4.1. Conclusion

The findings from this research should be very useful to construction design professional when designing, supervising and constructing building structures in areas susceptible to variation in soil moisture content during the structure's lifespan. The research findings are beneficial to the construction industry stakeholders and will contribute to reduction of collapse of buildings in Nairobi and globally. It is concluded that ground condition are prone to changes in soil moisture content especially for sites near water rivers and swamps. From the insitu soil samples collected the moisture content varied from 21.9% to 55.4%. Increase in soil moisture content reduces the soil bearing capacity as expressed by a linear equation $y = -170.89x + 565.64$ using direct shear method. This is significant reduction in soil resistance strength and would lead to collapse of buildings due to structural failure. Reduction in soil bearing capacity increased when soil moisture content increased. For structures constructed in areas prone to variation in soil moisture content, the variation in soil bearing capacity in a building would contribute to differential settlement of foundation footings.

4.2. Recommendations

This research recommends the soil moisture content should always be tested at planning and design stage for every building construction project. During laboratory testing, variation in soil moisture content should always be undertaken in consideration to the envisaged moisture changes for a particular location during the building's lifespan. This should include consideration for soil moisture changes during rainy and flooding seasons. The amount of soil deformation due to variation of moisture content should be considered and an adequate factor of safety provided at design stage. The factor of safety of *-107x* for direct shear method is recommended.

Policy guidelines should be developed for public review to enforce this recommendation.

Engineers are advised to collect and test soil samples for each construction site to inform foundation and structural design work and thus avoiding the risk of foundation failure emanating from differential settlement arising from variation in soil moisture content during the building's lifecycle.

4.3. Areas for Further Research

The soil samples collection exercise is expensive and time consuming. As a result, only 7 soil samples were collected from Nairobi area and its environs. The 7 samples were drawn from four distinct sites and are deem to be a representative sample of the soil conditions in Nairobi area and its environs. Testing of soil samples from area outside Nairobi area is recommended for further research and for comparison with Nairobi area and its environs case.

Other methods of determining soil bearing capacity and soil moisture content is recommended to compare the research outputs.

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