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Soil characterisation for suitability for construction work: A Case Study of Rehoboth and Acacia (Windhoek), Namibia

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Abstract :- The populations of Windhoek and Rehoboth, located some 90 km south of the capital, are growing rapidly, leading to major construction to meet people's needs. Due to this rapid increase of the urban population and the resulting demand for housing and facilities in the limited space available, adequate groundwork, necessary for the safety and stability of the planned development, is often lacking. At three sites where construction for residential use was taking place, i. e. Rehoboth South, Rehoboth North and the suburb of Acacia in Windhoek, pertinent soil characteristics were investigated. Soil samples were tested for moisture content, grain size distribution and gradation as these factors, among others, determine the suitability of a building site and the foundation type to be adopted. Failure to ascertain carrying capacity and other essential aspects of the proposed site prior to construction start can have a significant impact on stability and – subsequently – on cost for later modifications. This study, carried out as a B. Sc. (Hons) project at the University of Namibia, provides basic information for construction work, emphasising the need of adequate building ground investigation both for reasons of safety and economy. It presents the findings from the investigation of three construction sites, which encompassed general site reconnaissance and geotechnical field and laboratory tests.

Keywords :- Soil characteristics, Foundation type, Moisture content, Bearing capacity, Gradation analysis, Trace elements

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Introduction

Soil is one of the most important yet the most frequently overlooked factor in construction projects, such as housing, roads, bridges and dams. Soil is the natural foundation that supports all structures and infrastructure investment. Although a thorough soil investigation averages less than one percent of the total construction cost, it is often neglected during the conceptual project phase, and its importance underestimated (Kunkolienkar, 2016). Some contractors base their design on an assumed bearing capacity and rate of settlement (Fame, 2013). However, as the physical and chemical characteristics of soil can vary even within the limits of a proposed construction site, such assumptions cannot substitute for a thorough on-site investigation. Also, climatic influences, site management and a host of other natural and anthropogenic factors can affect the bearing capacity of soil, and, consequently, require foundations designed in accordance with local conditions and the proposed usage to avoid failure of the structure (Arya and Agarwal, 2007). To forestall uncontrolled development of urban areas, with deleterious effects on the environment in the long and short term, obtaining accurate information about the physical properties of the soil underlying a proposed construction site must form the basis for planning, designing and, eventually, building.

To establish the suitability of a particular soil as foundation material, various physical, chemical and mechanical tests are employed (Das, 1990):

a) Atterberg Limits Test to determine plasticity of the soil (includes tests for liquid limit, plastic limit and shrinkage limit);
b) Sieve analysis to determine grain size distribution, which affects soil strength and stability;
c) Proctor Compaction Test to determine the maximum dry density and optimum moisture content of the soil, which affects its ability to resist deformation and support loads;

d) California Bearing Ratio (CBR) test to determine load-bearing capacity;
e) pH test to determine acidity or alkalinity, and the potential for chemical reactions, which may affect strength and stability;
f) Organic Matter Content test to determine the proportion of organic material in the soil, which also may affect strength and stability;
g) Shear Strength test to determine ability of the soil to withstand stress and strain;
h) Cone Penetration test (CPT) to determine the bearing capacity of granular soils (sand, gravel) and estimate the strength of cohesive soils (clay, silt);
i) Natural Moisture Content test to determine the amount of water present in the soil, which affects stability.

The objectives of this site investigation were (a) to define the type, grading and nature of the soil at the proposed building sites in Rehoboth and Windhoek (Figs 1, 2, 3), (b) to determine the bearing capacity of the soil and identify potential problems, and (c) to select the type and depth of foundation required for the planned construction work of single-storey buildings for residential use. For the three sites, geotechnical tests b), h) and i) above were chosen as they encompass the essential soil properties that are crucial for this type of development. Other work carried out in the course of the investigation was soil profiling - a visual assessment of the soil layers - at each location, X-ray fluorescence analyses to determine elemental composition and X-ray diffraction analyses for mineralogical composition.

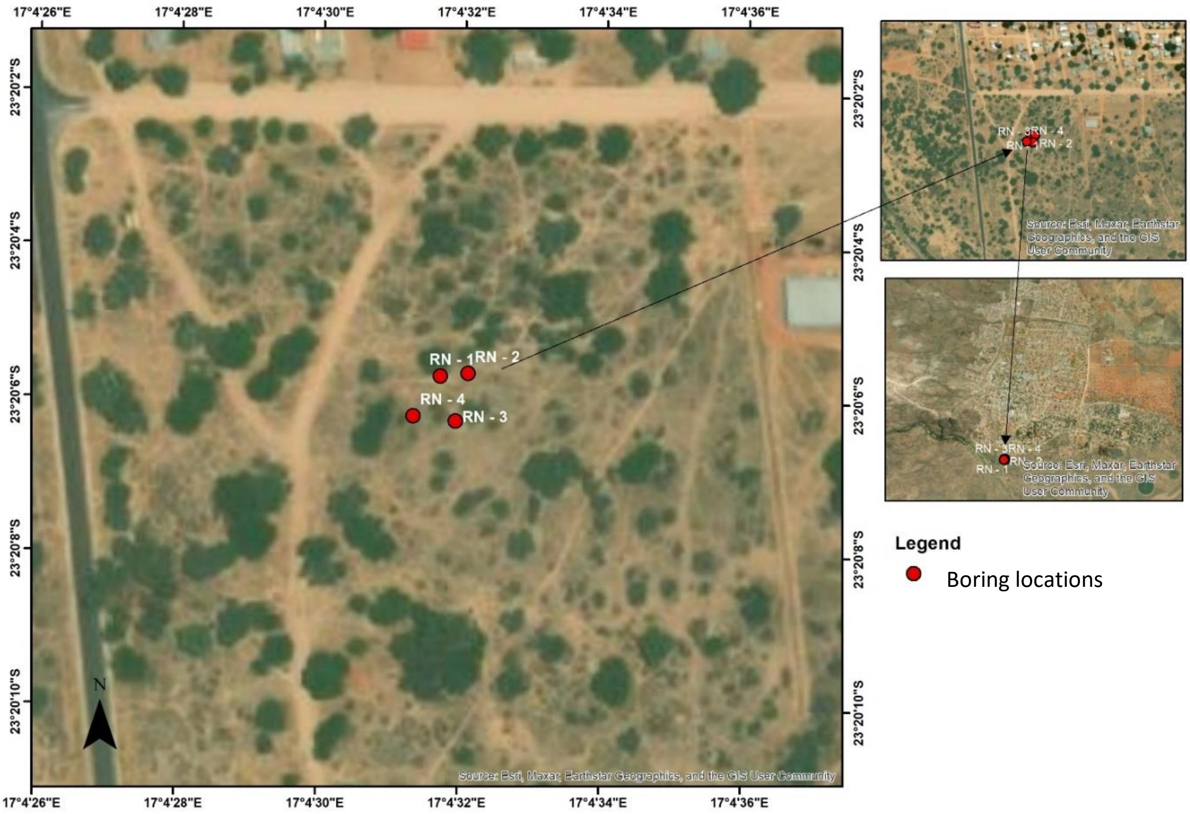


Figure 1. Satellite image (Google Earth) showing construction site at Rehoboth North and boring locations

Due to rapid increase of the urban population during the last 12 years (Windhoek: 33 %; Rehoboth: 29.3 %; NSA, 2024) - pressure is put on development projects, which often leads to adequate site investigation prior to construction start being neglected. To make matters worse, the high demand for building ground, allied to the local topography, has resulted in the allocation of land in sloping areas, which are prone to landslides, erosion and soil movement, for construction. In order to prevent or minimise damage to buildings and their foundations from these causes, full geotechnical investigations and drainage control are especially important.

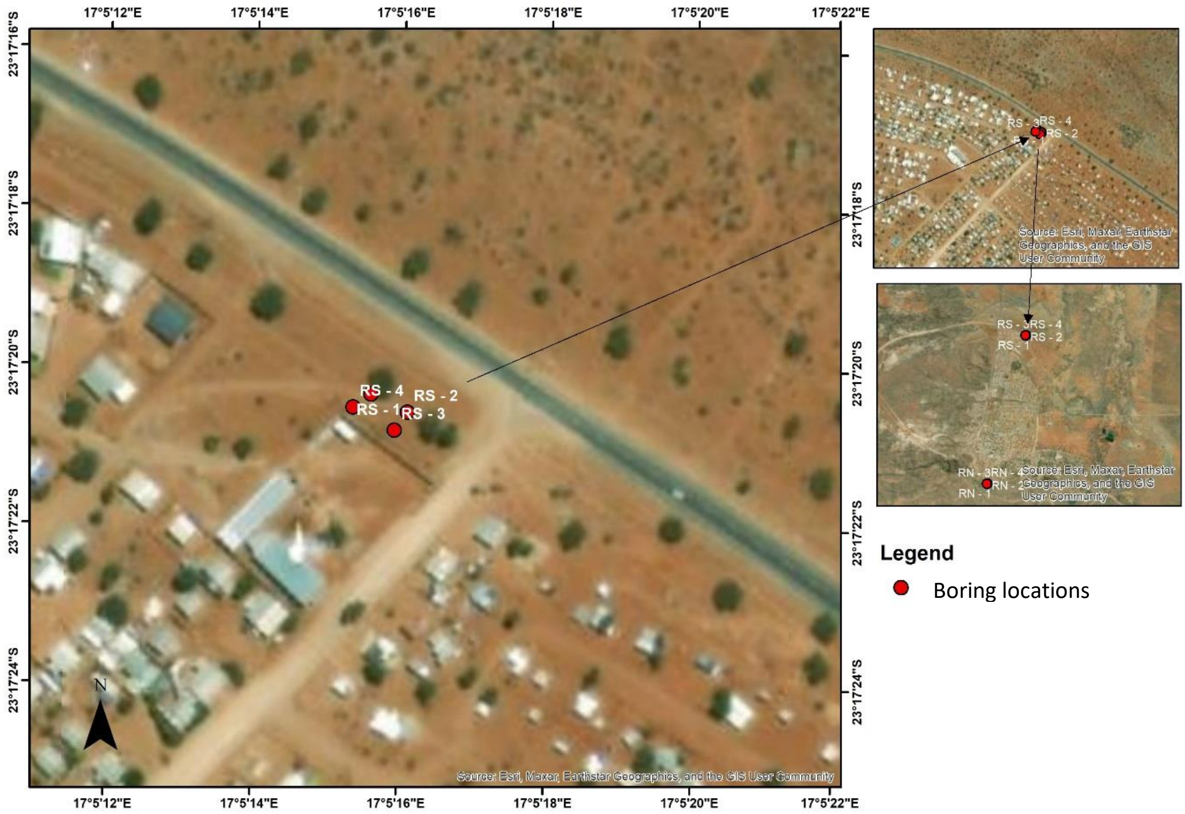


Figure 2. Satellite image (Google Earth) showing construction site at Rehoboth South and boring locations

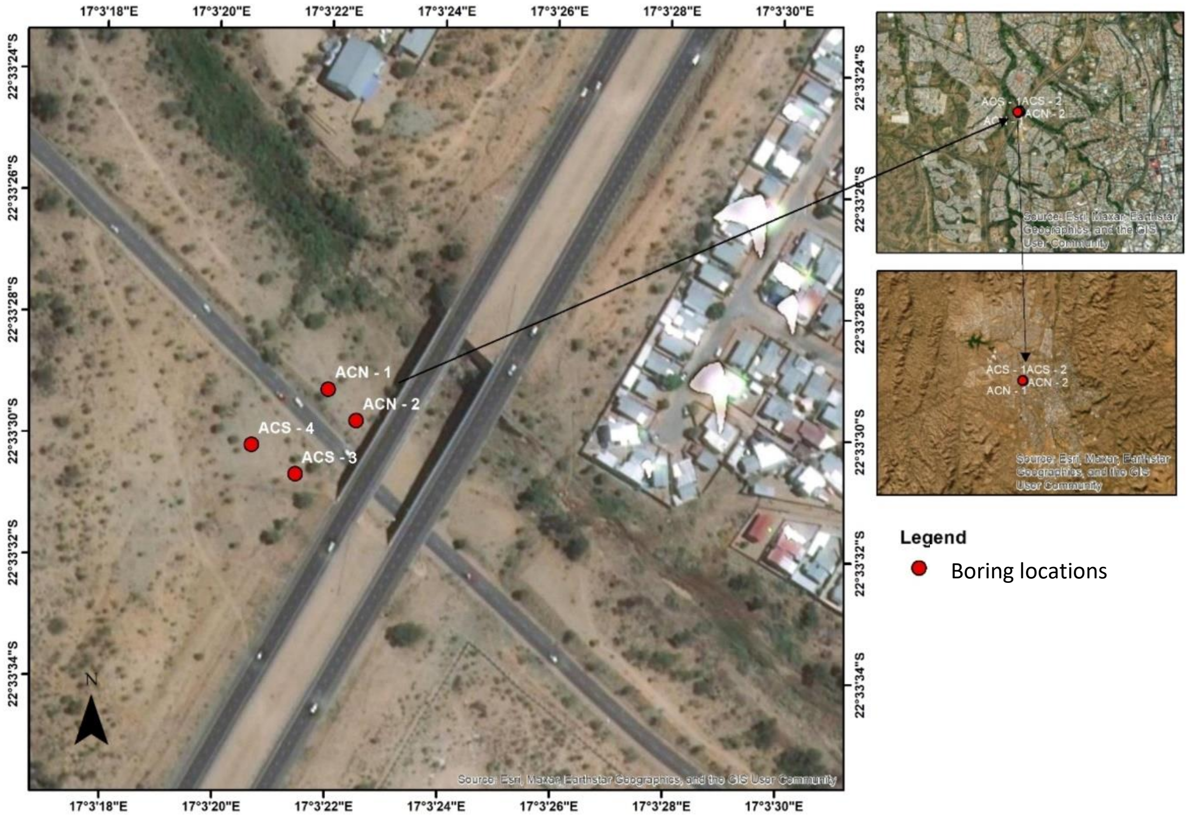


Figure 3. Satellite image (Google Earth) showing construction site at Acacia (Windhoek) and boring locations

Location of the study area

The soil investigations for this study were carried out at three construction sites in Rehoboth, some 93 km south of Windhoek, and Acacia, a suburb of Windhoek between Dorado Park and Dorado Valley (Figs 1, 2, and 3) during the dry season of 2016 (June to September). The soils at each site were observed and tested to determine the soil profile and to decide its suitability for the planned construction work (Fig. 4). The two Rehoboth sites are underlain by sandy soil, while at Acacia the proposed building ground consists of mica schist and quartz gravel, with hardly any soil development.

Figure 4. Site images: (a) Boring at Rehoboth North; (b) Acacia sampling site; (c) Location of housing construction at Rehoboth South; (d) Boring location in Acacia underlain by mica schist and quartz

Regional geology of the investigated sites

The area of interest around Rehoboth North and South is underlain by rocks of Mesoproterozoic age (Fig. 5). Cross-bedded orthoquartzite of the Billstein Formation, with a maximum thickness of approximately 100 m, rests unconformably on Palaeoproterozoic basement gneisses (Kangas Metamorphic Complex). A transitional contact exists between the quartzite and overlying intercalated, locally sericitic, schist and conglomerate, which have a combined thickness of at least 2000 m. Conglomerate clasts consist of granite, vein quartz and quartzite. The Billstein rocks are overlain by the mostly rhyolitic Langberg Formation along a sheared contact; this unit starts with a polymict, ill-sorted, clast-supported conglomerate, followed by a succession of felsic volcanic rocks several hundred metres thick. Basal ignimbrite layers, up to 20 m thick, are intercalated with crystal-rich tuff beds, while reddish quartzite and schist form the top of the succession. The uppermost Opdam Formation rests unconformably upon the Langberg Formation or transgresses the Billstein Formation. It is composed of amygdaloidal basaltic lavas with flow-top breccias, interbedded with polymict conglomerate, slate, phyllite and greyish quartzite. Minor pillow structures have been observed within the basaltic flows. Locally the Mesoproterozoic rocks are covered by the calcrete-cemented Weissrand conglomerate of Palaeogene age. To the east exposures are scarce, with most of the bedrock buried under unconsolidated sediments (sand, gravel, scree and calcrete) of the Kalahari Group. Alluvial sediments occur along river courses.

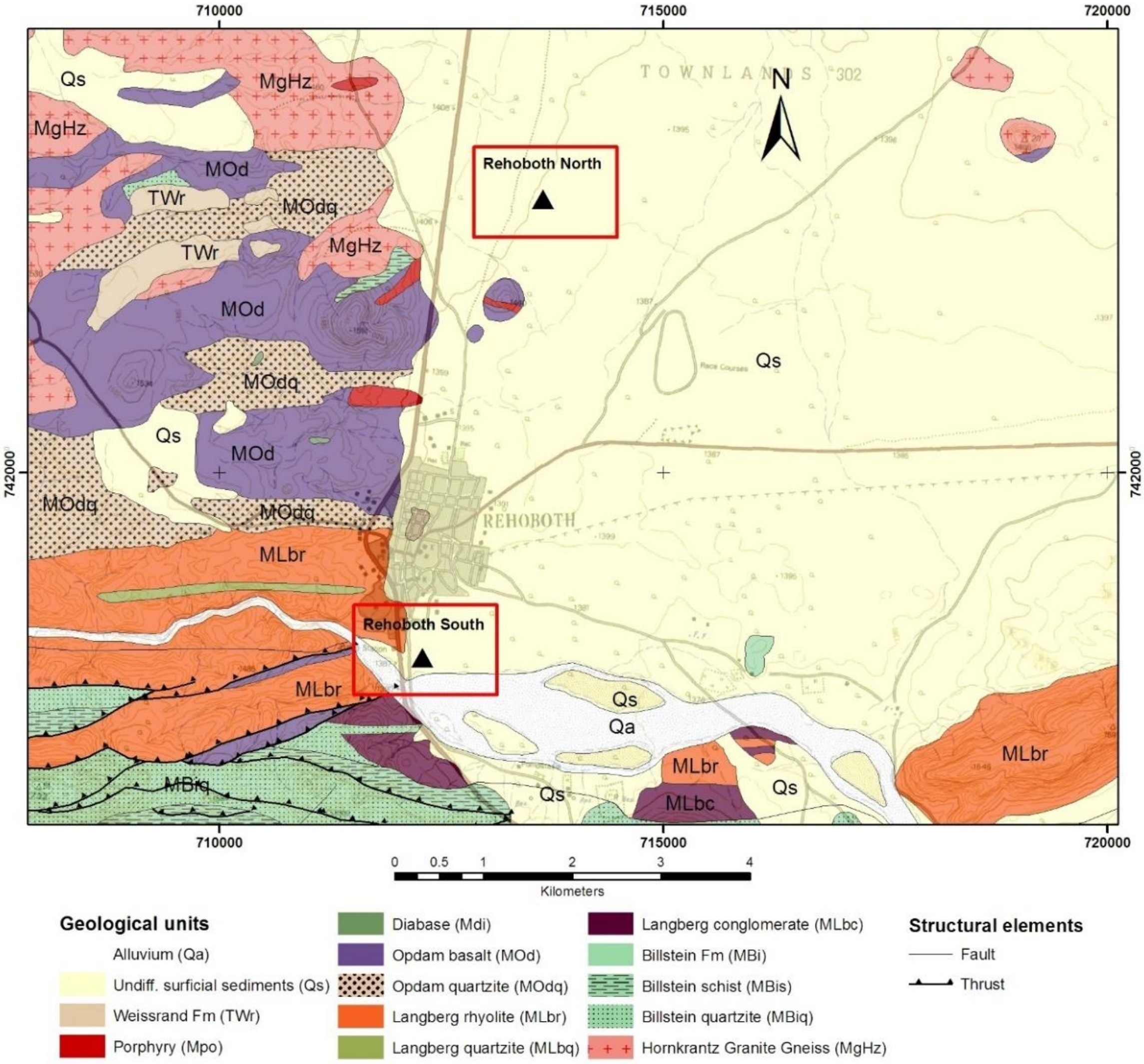


Figure 5. Regional geology of Rehoboth and environs indicating the investigated sites (after Schalk *et al*., 2006)

The regional geology of Windhoek and surroundings (Fig. 6) is characterised by Neoproterozoic metamorphic rocks of the Khomas Complex, consisting of mica schists of the Kuiseb Formation intercalated with Kleine Kuppe quartzites. Also interlayered with the schists are the mafic metavolcanic rocks (amphibolites) of the Matchless Suite, which are both in tectonic and intrusive contact with the Kuiseb schists. Parts of the area are covered by alluvium, sand, gravel or scree.

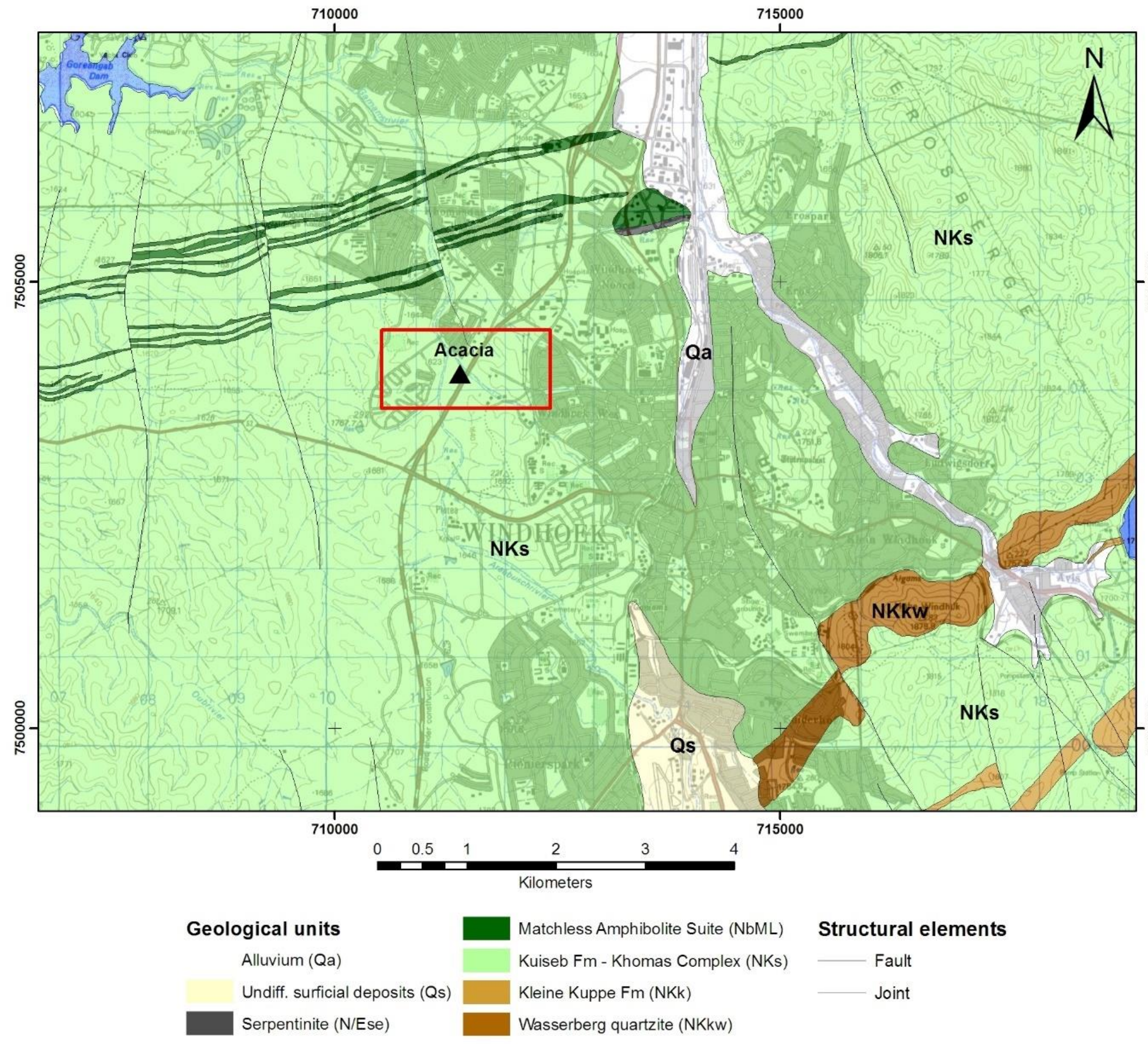


Figure 6. Regional Geology of Windhoek and environs indicating location of investigated site (after Hälbich *et al*., 2006)

Methodology

A total of twelve holes were dug to a depth of ca 50 cm, and the soil profiles described. Seventy-two soil samples, collected from the three construction sites, underwent various laboratory tests, including grain size distribution analysis and determination of elemental and mineralogical composition. A cone penetrometer was used to establish the bearing capacity of the soils; note was taken also of local topography, geological features, vegetation cover, and other relevant environmental data at the three sites.

Field investigation and sampling

Digging and sampling at Rehoboth (North and South) consisted of eight soil borings labelled RN-1 to 4 and RS-1 to 4, respectively, while in Windhoek (Acacia) four soil borings labelled ACN-1 & 2 and ACS-3 & 4 were dug (Table 1). All borings extended to a depth of approximately 50 cm below the surface. This depth was chosen as the soil profile in the investigated areas is relatively consistent, with similar soil properties throughout, and because the planned light construction work does not require deeper penetration. Boring locations at the proposed sites were selected based on accessibility. At each boring locality cone penetration tests (CPT) were carried out to determine the strength, i. e. resistance to penetration, of the soil using a hand-pushed (portable) penetrometer with a cone base area of 2 cm^2.

Area Name	**Boring No**	**Easting (m)**	**Northing (m)**	**UTM Zone**
Rehoboth North	RN - 1	712200	7417882	WGS84_33S
Rehoboth North	RN - 2	712211	7417883	WGS84_33S
Rehoboth North	RN - 3	712206	7417864	WGS84_33S
Rehoboth North	RN - 4	712189	7417866	WGS84_33S
Rehoboth South	RS - 1	713519	7422951	WGS84_33S
Rehoboth South	RS - 2	713533	7422944	WGS84_33S
Rehoboth South	RS - 3	713528	7422937	WGS84_33S
Rehoboth South	RS - 4	713512	7422946	WGS84_33S
Acacia North	ACN - 1	711420	7503939	WGS84_33S
Acacia North	ACN - 2	711434	7503923	WGS84_33S
Acacia South	ACS - 3	711403	7503896	WGS84_33S
Acacia South	ACS - 4	711381	7503911	WGS84_33S

Table 1. Boring locations of the investigated construction sites

Relatively disturbed soil samples were collected at each boring from surface (0 cm) to 25 cm depth, from 25 to 35 cm depth and from 35 to 50 cm depth to establish soil type, gradation, classification, consistency, density and stratification. At each depth two samples were taken, one for sieve analysis and one for X-ray fluorescence (XRF) and X-ray diffraction (XRD) analysis. Samples are considered “disturbed” as the sampling process itself modifies their natural structure (Munfakh *et al*., 1997). A total of seventy-two samples were obtained in the course of field investigations from the three sites.

American Society of Testing and Materials (ASTM) Standard References	
Soil Properties	**Specification**
Classification	ASTM D 2487 - 17: Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
Particle-Size Analysis of Soils (Sieve Analysis)	ASTM D 422 - 63: Standard Test Method for Particle-Size Analysis of Soils
Water (Moisture) Content of Soil	ASTM D 2216 - 19: Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures
Soil Strength (Penetration Test)	ASTM D 3441 - 16: Standard Test Method for Mechanical Cone Penetration Tests of Soil

Table 2. Standard laboratory tests for the determination of soil properties in geotechnical engineering (ASTM)

Laboratory Testing

After an on-site description of the soil samples, their physical and mechanical properties were determined at the laboratories of the Geological Survey of Namibia and the UNAM (University of Namibia) Geology Department. Tests included grain size analysis, determination of water content, X-Ray Fluorescence and X-Ray Diffraction analysis. A total of thirty-six soil samples was prepared for grain size (sieve) analysis and water content determination in accordance with the requirements of the American Society of Testing and Materials (ASTM; Table 2). Twelve samples were submitted for examination by XRF (Niton Portable XRF XL3t GOLDD+950) to determine the elemental composition of the soil, and five for XRD analysis (D8 Advance XRD Instrument C79249-A3054-A21) to establish its mineral components. XRF analysis was performed on pressed powder pellets of the dried, pulverised and homogenised soil samples; for XRD analysis coarser particles of the dried soil sample were selected. To determine grain size distribution in the investigated soils, the dried samples were passed through a stack of sieves of diminishing aperture (Fig. 7).

Figure 7. Sieve analysis at the University of Namibia's Geology Laboratory: (a) Weighing unsieved samples from different depths; (b) and (c) Sieves stacked according to diminishing aperture; (d) Weighing each size fraction for classification of the soil

Results

Results of the above tests and analyses are presented as:

- Soil profiles with soil descriptions (Tables 3, 4)
- Water content determination (Table 5)
- Cone Penetration Test (CPT) results from various depths relating to the strength of the tested soils and their bearing capacity for foundations (Tables 6 to 11; Figs 8, 9, 10).
- Geochemical compositions as determined by portable X-ray fluorescence spectrometer (Table 13)
- Mineralogical composition as determined by X-ray diffraction (Table 14; Figs 11 to 15)
- Sieve analysis results (Tables 4, 15; Figs 17, 18, 19)

Soil profiling

Table 3 shows the soil profiles, i. e. the overall soil types present at various depths, at the three investigated sites. Detailed soil descriptions for each boring depth are given in Table 4. Grain size distribution curves of selected representative soil samples from different depths (from surface to 50 cm) are presented in figures 17, 18 and 19. Parameters defining the grain size distribution curves for each soil sample are listed in Table 4.

Water Content

During the site investigation the soil samples were collected without any interruption in the sampling process; most of the soil samples appeared to be quite dry. Table 5 shows the measured water content of all soil samples, which was determined by the Oven Dry Method (ASTM D 422 - 63) at a temperature of 105 to 110 degrees Celsius. The low percentages of water found in the soils from the three sites (on average < 1 wt %) confirmed field observations; only one sample from Acacia showed a significant water content (ACN-2; 20.2 wt %). The generally low water content of the examined samples is attributed to the absorption of moisture by underlying porous and/or fractured rocks, such as sandstones and schists, which allow the water to drain away, combined with evaporation occasioned by dry weather.

Cone Penetration Test

Cone Penetration Tests (CPT) offer a valuable tool for discovering the nature of the ground beneath our feet. At the three sites, CPTs were conducted to establish soil strength and its variation with depth, as well as overall bearing capacity. The process involved taking manometer readings, which represent the force needed to push a cone-shaped penetrometer steadily downward into the soil. These readings, expressed in Newtons (N; Tables 6, 7 and 8), are transformed into cone resistance (qc) values through division by the cone's base area (2 cm²); results are expressed in Megapascals (MPa; Tables 9, 10 and 11). Based on cone resistance, the Begemann Penetration Resistance (BPR; Libric *et al*., 2017) soil strength classification divides soils into six categories with distinct behavioural properties (Table 12). Relationships between cone resistance (MPa) and depth (cm) are displayed by the curves plotted in figures 8, 9 and 10.

Site Name	Depth (cm)	Soil Description
Rehoboth South	0-25	Dry, light brown, loose, granular sandy soil with dead plant roots
	25-35	Dry, light brown, firm, massive sandy soil
	35-50	Dry to moderately moist, light brown, firm, massive sandy soil with plant roots
Rehoboth North	0-25	Dry, reddish-brown, loose, massive sandy soil
	25-35	Dry, reddish-brown, firm, massive sandy soil with plant roots
	35-50	Dry, reddish, firm, massive sandy soil with plant roots
Acacia, Windhoek	0-25	Dry, brown-greyish, loose, granular sandy gravel soil with plant roots and rock fragments approximately 5 cm in diameter
	25-35	Dry, brown-greyish, hard, granular gravel sandy soil with pebbles
	35-50	Dry, brown-greyish, hard, granular gravel sandy soil with pebbles

Table 3. On-site description of the soil profiles at Rehoboth South, Rehoboth North and Acacia

Sample	Depth (cm)	Soil Description	% Gravel	% Sand	% Fines	D_{10}	D_{25}	D_{30}	D_{50}	D_{60}	D_{75}	C_C	C_U	S_0
RN-1	0 - 25	Dry, reddish-brown, loose, massive sandy soil	1.46	94.41	4.13	0.09	0.18	0.21	0.28	0.30	0.34	1.63	3.33	1.37
RN-1	25 - 35	Dry, reddish-brown, firm, massive sandy soil with plant roots	1.34	95.15	3.51	0.08	0.14	0.16	0.23	0.28	0.34	1.14	3.50	1.56
RN-1	35 - 50	Dry, reddish, firm, massive sandy soil with plant roots	1.36	94.18	4.46	0.08	0.14	0.15	0.23	0.27	0.33	1.04	3.38	1.54
RN-2	0 - 25	Dry, reddish-brown, loose, massive sandy soil	2.35	93.10	4.55	0.09	0.16	0.19	0.28	0.30	0.39	1.34	3.33	1.56
RN-2	25 - 35	Dry, reddish-brown, firm, massive sandy soil with plant roots	1.88	94.87	3.25	0.16	0.23	0.25	0.30	0.33	0.40	1.18	2.06	1.32
RN-2	35 - 50	Dry, reddish-brown, firm, massive sandy soil with plant roots	1.71	94.27	4.02	0.13	0.22	0.24	0.30	0.32	0.40	1.38	2.46	1.35
RN-3	0 - 25	Dry, reddish-brown, loose, massive sandy soil	1.54	95.47	2.99	0.10	0.19	0.21	0.28	0.31	0.38	1.42	3.10	1.41
RN-3	25 - 35	Dry, reddish, firm, massive sandy soil with plant roots	1.56	95.24	3.20	0.15	0.18	0.21	0.30	0.32	0.39	0.92	2.13	1.47
RN-3	35 - 50	Dry, reddish, firm, massive sandy soil with plant roots	2.83	92.11	5.06	0.08	0.16	0.18	0.27	0.30	0.37	1.35	3.75	1.52
RN-4	0 - 25	Dry, reddish-brown, loose, massive sandy soil	2.55	94.14	3.31	0.13	0.21	0.23	0.30	0.31	0.39	1.31	2.38	1.36
RN-4	25 - 35	Dry, reddish-brown, firm, massive sandy soil with plant roots	3.64	92.67	3.69	0.09	0.16	0.18	0.28	0.30	0.38	1.20	3.33	1.54
RN-4	35 - 50	Dry, reddish-brown, firm, massive sandy soil with plant roots	2.40	93.09	4.51	0.08	0.15	0.16	0.27	0.30	0.40	1.07	3.75	1.63
RS-1	0 - 25	Dry, light brown, loose, granular sandy soil with dead plant roots	3.34	94.33	2.33	0.16	0.24	0.26	0.32	0.36	0.60	1.17	2.25	1.58
RS-1	25 - 35	Dry, light brown, firm, massive sandy soil	3.77	94.18	2.05	0.15	0.18	0.26	0.32	0.39	0.70	1.16	2.60	1.97
RS-1	35 - 50	Dry to moderately moist, light brown, firm, massive sandy soil with plant roots	5.05	92.88	2.07	0.12	0.21	0.24	0.30	0.35	0.80	1.37	2.92	1.95
RS-2	0 - 25	Dry, light brown, loose, sandy soil with dead plant roots	4.53	93.19	2.28	0.12	0.21	0.25	0.34	0.40	0.70	1.30	3.33	1.83
RS-2	25 - 35	Dry, light brown, firm, massive sandy soil	4.50	93.31	2.19	0.10	0.20	0.23	0.32	0.39	0.65	1.36	3.90	1.80
RS-2	35 - 50	Dry to moderately moist, light brown, firm, massive sandy soil with plant roots	5.16	92.47	2.37	0.14	0.25	0.27	0.36	0.42	0.80	1.24	3.00	1.79
RS-3	0 - 25	Dry, light brown, loose, granular sandy soil with dead plant roots	3.70	94.80	1.50	0.16	0.25	0.27	0.32	0.38	0.60	1.20	2.38	1.55
RS-3	25 - 35	Dry, light brown, firm, massive sandy soil	2.78	95.43	1.79	0.13	0.22	0.24	0.31	0.37	0.58	1.20	2.85	1.62
RS-3	35 - 50	Dry, light brown, firm, massive sandy soil	3.19	94.77	2.04	0.10	0.20	0.23	0.31	0.38	0.60	1.39	3.80	1.73
RS-4	0 - 25	Dry, light brown, loose, granular sandy soil with dead plant roots	3.55	95.46	0.99	0.15	0.25	0.27	0.31	0.38	0.60	1.28	2.53	1.55
RS-4	25 - 35	Dry, light brown, firm, massive sandy soil	4.12	94.21	1.67	0.15	0.24	0.26	0.32	0.39	0.62	1.16	2.60	1.61
RS-4	35 - 50	Dry to moderately moist, light brown, firm, massive sandy soil with plant roots	4.97	92.78	2.25	0.13	0.23	0.25	0.34	0.40	0.70	1.20	3.08	1.74
ACN-1	0 - 25	Dry, brown-greyish, loose, granular sandy gravel soil with plant roots and rock fragments	18.16	76.82	5.02	0.09	0.22	0.25	0.35	0.60	1.60	1.16	6.67	2.70
ACN-1	25 - 35	Dry, brown-greyish, hard, granular gravel sandy soil with rock pebbles	15.98	79.09	4.93	0.10	0.22	0.25	0.35	0.44	1.40	1.42	4.40	2.52
ACN-1	35 - 50	Dry, brown-greyish, hard, granular gravel sandy soil with rock pebbles	22.40	72.55	5.05	0.08	0.14	0.15	0.30	0.70	1.80	0.40	8.75	3.59
ACN-2	0 - 25	Dry, brown-greyish, loose, granular sandy gravel soil with plant roots and rock fragments approximately >5 cm in diameter	21.38	73.29	5.33	0.08	0.09	0.11	0.30	0.60	1.60	0.25	7.50	4.22
ACN-2	25 - 35	Dry, brown-greyish, hard, granular gravel sandy soil with rock pebbles	20.84	73.86	5.30	0.08	0.13	0.15	0.28	0.42	1.60	0.67	5.25	3.51
ACN-2	35 - 50	Dry, brown-greyish, hard, granular gravel sandy soil with rock pebbles	17.38	77.70	4.92	0.08	0.14	0.16	0.29	0.36	1.30	0.89	4.50	3.05
ACS-3	0 - 25	Dry, brown-greyish, loose, granular sandy gravel soil with plant roots and rock fragments approximately 5 cm in diameter	19.06	75.60	5.34	0.08	0.13	0.15	0.25	0.32	1.20	0.88	4.00	3.04
ACS-3	25 - 35	Dry, brown-greyish, hard, granular gravel sandy soil with rock pebbles	16.44	79.56	4.00	0.09	0.19	0.21	0.30	0.35	0.90	1.40	3.89	2.18
ACS-3	35 - 50	Dry, brown-greyish, hard, granular gravel sandy soil with rock pebbles	16.69	79.16	4.15	0.15	0.23	0.25	0.32	0.37	0.90	1.13	2.47	1.98
ACS-4	0 - 25	Dry, brown-greyish, loose, granular sandy gravel soil with plant roots and rock fragments approximately ~5 cm in diameter	19.04	79.13	1.83	0.10	0.20	0.23	0.32	0.40	1.50	1.32	4.00	2.74
ACS-4	25 - 35	Dry, brown-greyish, hard, granular gravel sandy soil with rock pebbles	18.49	79.55	1.96	0.09	0.16	0.20	0.32	0.40	1.50	1.11	4.44	3.06
ACS-4	35 - 50	Dry, brown-greyish, hard, granular gravel sandy soil with rock pebbles	21.41	77.19	1.40	0.13	0.23	0.25	0.34	0.60	1.80	0.80	4.62	2.80

Table 4. Soil types at different depths; parameters of Grain Distribution Curves for Rehoboth North (RN), Rehoboth South (RS) and Acacia (ACN, ACS) shown in Figs 17, 18 and 19; D_{10} = Effective size (10% finer); D_{25} = 25% finer; D30 = 30% finer; D_{50} = Median grain size; D_{60} = 60% finer; D_{75} = 75% finer; $C_u = D_{60}/D_{10}$; $C_c = (D_{30})^2/(D_{60}D_{10})$; $S_0 = \sqrt{D_{75}/D_{25}}$

Sample Name	Weight of container M_c (g)	Weight of container + wet soil M_{CMS} (g)	Weight of container + dry soil M_{CDS} (g)	Mass of soil solids M_s (g)	Mass of pore water M_w (g)	Water Content w (%)
RS1 0-25	6.7	292.3	290.9	284.2	1.4	0.5
RS1 25-35	6.7	317.7	314.6	307.9	3.1	1.0
RS1 35-50	6.5	313.5	310.0	303.5	3.5	1.2
RS2 0-25	6.7	289.3	286.0	279.3	3.3	1.2
RS2 25-35	6.6	268.4	267.0	260.4	1.4	0.5
RS2 35-50	6.7	259.9	256.9	250.2	3.0	1.2
RS3 0-25	6.6	283.9	282.7	276.1	1.2	0.4
RS3 25-35	6.8	217.3	215.2	208.4	2.1	1.0
RS3 35-50	6.6	241.0	238.4	231.8	2.6	1.1
RS4 0-25	6.8	294.0	292.6	285.8	1.4	0.5
RS4 25-35	6.8	287.4	284.5	277.7	2.9	1.0
RS4 35-50	6.6	237.4	233.8	227.2	3.6	1.6
RN1 0-25	6.8	223.1	222.6	215.8	0.5	0.2
RN1 25-35	6.7	239.7	239.2	232.5	0.5	0.2
RN1 35-50	6.8	221.6	221.2	214.4	0.4	0.2
RN2 0-25	6.7	191.1	190.6	183.9	0.5	0.3
RN2 25-35	6.7	272.6	272.0	265.3	0.6	0.2
RN2 35-50	6.9	241.0	240.5	233.6	0.5	0.2
RN3 0-25	6.7	304.3	303.8	297.1	0.5	0.2
RN3 25-35	6.6	300.8	300.4	293.8	0.4	0.1
RN3 35-50	7.0	207.2	206.8	199.8	0.4	0.2
RN4 0-25	6.7	260.1	259.7	253.0	0.4	0.2
RN4 25-35	6.7	220.2	219.8	213.1	0.4	0.2
RN4 35-50	6.8	205.2	205.0	198.2	0.2	0.1
ACN1 0-25	6.7	277.7	276.4	269.7	1.3	0.5
ACN1 25-35	6.6	276.2	274.4	267.8	1.8	0.7
ACN1 35-50	6.8	219.1	218.0	211.2	1.1	0.5
ACN2 0-25	6.8	228.2	227.1	220.3	1.1	0.5
ACN2 25-35	6.8	227.4	190.3	183.5	37.1	20.2
ACN2 35-50	7.0	251.4	249.9	242.9	1.5	0.6
ACS3 0-25	7.0	227.9	227.4	220.4	0.5	0.2
ACS3 25-35	7.1	246.4	245.8	238.7	0.6	0.3
ACS3 35-50	7.1	237.1	236.4	229.3	0.7	0.3
ACS4 0-25	6.9	269.0	268.1	261.2	0.9	0.3
ACS4 25-35	6.8	259.1	258.5	251.7	0.6	0.2
ACS4 35-50	6.9	355.0	353.2	346.3	1.8	0.5

Table 5. Water content of samples from Rehoboth North (RN), Rehoboth South (RS) and Acacia (ACN, ACS)

Depth (cm)	RN-1 (N)	RN-2 (N)	RN-3 (N)	RN-4 (N)
5	300	400	300	390
10	380	380	340	440
25	420	475	375	490
35	420	500	520	550
45	580	460	505	500

Table 6. Manometer readings for borings at Rehoboth North

Depth (cm)	RS-1 (N)	RS-2 (N)	RS-3 (N)	RS-4 (N)
5	-	490	510	440
10	425	495	500	510
20	420	560	560	570
30	460	530	600	540
40	525	540	480	700

Table 7. Manometer readings for borings at Rehoboth South

Depth (cm)	ACN-1 (N)	ACN-2 (N)	ACS-3 (N)	ACS-4 (N)
5	440	400	410	230
10	470	460	430	390
20	420	520	430	450
30	470	500	480	470
40	530	540	470	500
50	-	680	-	-

Table 8. Manometer readings for borings at Acacia (Windhoek)

N (Newton) equals force exacted upon cone pushed into the soil

Depth (cm)	RN-1 (MPa)	RN-2 (MPa)	RN-3 (MPa)	RN-4 (MPa)
5	1.5	2	1.5	1.95
10	1.9	1.9	1.7	2.2
25	2.1	2.375	1.875	2.45
35	2.1	2.5	2.6	2.75
45	2.9	2.3	2.525	2.5

Table 9. Cone resistances at varying depths for borings at Rehoboth North

Depth (cm)	RS-1 (MPa)	RS-2 (MPa)	RS-3 (MPa)	RS-4 (MPa)
5	-	2.45	2.55	2.2
10	2.125	2.475	2.5	2.55
20	2.1	2.8	2.8	2.85
30	2.3	2.65	3	2.7
40	2.625	2.7	2.4	3.5

Table 10. Cone resistances at varying depths for borings at Rehoboth South

Depth (cm)	ACN-1 (MPa)	ACN-2 (MPa)	ACS-3 (MPa)	ACS-4 (MPa)
5	2.2	2	2.05	1.15
10	2.35	2.3	2.15	1.95
20	2.1	2.6	2.15	2.25
30	2.35	2.5	2.4	2.35
40	2.65	2.7	2.35	2.5
50	-	3.4	-	-

Table 11. Cone resistances at varying depths for borings at Acacia (Windhoek)

MPa (Megapascal) =
N/cm^2 (cone base area) * 0.01
equals soil resistance to penetration

Category	Cone Resistance (qc) Range (MPa)	Soil Description
I	qc > 8.0	Very stiff to hard clays, dense sands, and gravels
II	3.0 - 8.0	Stiff clays, medium-dense sands, and gravels
III	1.5 - 3.0	Firm clays, loose to medium-dense sands and gravels
IV	0.5 - 1.5	Soft clays, silty clays, loose sands
V	0.2 - 0.5	Very soft clays, organic soils
VI	< 0.2	Water or fluidized soils

Table 12: Six categories of classifying soil using the Begemann Penetration Resistance (BPR) system (Libric *et al*., 2017)

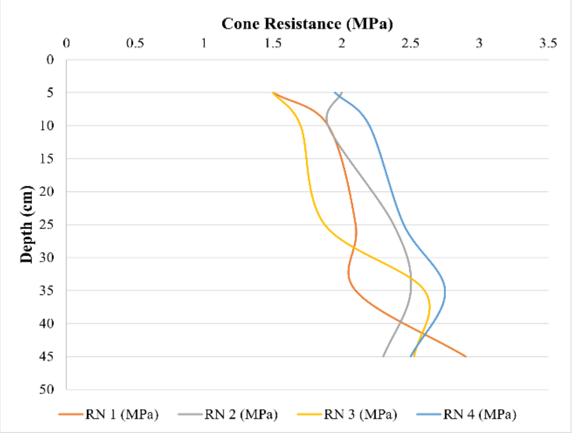


Figure 8. Strength analysis curves for borings at Rehoboth North up to a depth of 45 cm

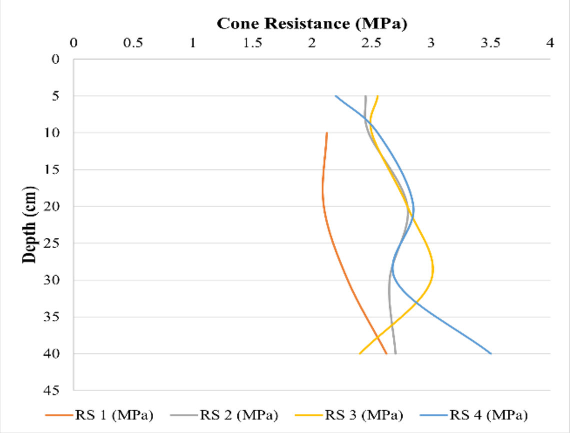


Figure 9. Strength analysis curves for borings at Rehoboth South up to a depth of 40 cm

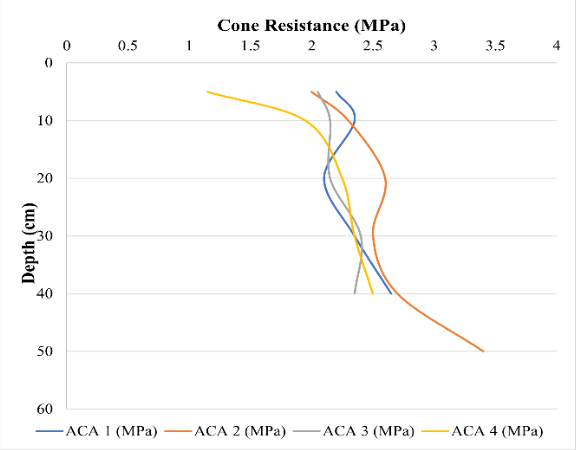


Figure 10. Strength analysis curves for borings at Acacia to depths of 40 cm and 50 cm, respectively

Remarks:

Compaction/cone resistance (qc) of the tested soils increases with depth (as is common), except in borings RN-2, RN-3, RN-4, RS-3, and ACS-3 where it decreases indicating less compacted soil at depth. According to the BPR system (Table 12), the overall cone resistance (qc) of soils at the three sites falls into category III (1.5 – 3 MPa) excluding ACN-2 (with qc > 3 MPa down depth falling into Category II). These resistances are typical for firm clays, and loose to medium-dense sands and gravels, which implies conditional suitability for (light) construction.

X-ray Fluorescence (XRF) and X-ray Diffraction (XRD) analysis of soil samples

Table 13 shows the major and trace element composition of the soil samples from the three investigated sites as determined by portable XRF. Apart from quartz and albite, which are present at all three investigated sites, X-ray diffraction peaks of composite soil samples from borings RN-1 (Fig. 11), RN-3 (Fig. 12), RS-1 (Fig. 13), ACN-2 (Fig. 14) and ACS-4 (Fig. 15) in addition show ferroan magnesiohornblende at Rehoboth North and microcline at Rehoboth South. Associated clay minerals are koninckite (Rehoboth South), polylithionite and dickite (Acacia; Table 14). These findings suggest that the clay fraction of the soil is dominated by non-expansive clays (koninckite and dickite), with polylithionite the only expansive clay mineral observed. As non-expansive clays tend to be more stable when wet, with less potential for shrinkage or cracking during dry periods, this increases overall soil strength as well as shear strength and reduces the soil's propensity for erosion.

SAMPLE NO	Si %	Al %	Fe %	K %	Mg %	Ca %	Ti %	P %	S %	Ba %	Mn ppm	Cr ppm	Zr ppm	Sr ppm	Rb ppm	Zn ppm	Cu ppm	Ni ppm
ACN- 1	22.04	29.16	4.88	4.76	3.74	0.86	0.59	0.15	0.02	0.04	687	153	238	86	110	81	31	53
ACN- 2	23.15	29.96	5.17	4.59	3.68	0.74	0.6	0.13	0.03	0.04	704	174	235	97	113	84	28	49
ACS- 3	26.1	24.75	3.36	3.53	2.78	0.49	0.54	0.11	0.02	0.02	678	172	196	60	69	39	26	40
ACS- 4	26.04	24.6	4.22	3.91	3.19	0.68	0.56	0.11	0.02	0.03	747	204	272	94	95	62	29	32
RN- 1	25.02	19.68	3.69	3.34	2.22	1.12	0.54	0.12	0.02	0.05	611	108	124	82	85	31	44	50
RN- 2	27.19	19.93	3.59	3.43	2.37	1.19	0.55	0.13	0.02	0.05	497	131	142	80	88	26	44	66
RN- 3	26.48	19.71	3.66	3.39	1.91	1.22	0.61	0.12	0.02	0.05	550	138	207	79	83	27	44	51
RN- 4	26.32	19.95	3.81	3.73	1.29	1.12	0.52	0.1	0.01	0.05	587	128	219	79	85	30	43	66
RS- 1	32.19	14	1.89	2.33	1.17	0.52	0.35	0.1	0.03	0.02	324	150	199	62	45	13	15	23
RS-2	30.88	15.85	2.14	2.58	1.69	0.57	0.45	0.13	0.03	0.02	332	144	156	64	53	20	17	32
RS-3	30.78	15.26	2.01	2.41	1.88	0.57	0.42	0.16	0.03	0.02	337	139	227	61	52	25	44	35
RS- 4	26.04	11.07	2.11	2.3	1.01	0.56	0.41	0.13	0.02	0.02	326	127	131	57	49	22	< LOD	< LOD

Remarks: 1% = 10 000, 1ppm = 0.0001%

Table 13. X-ray Fluorescence results showing geochemical composition of the soils at Rehoboth (North and South) and Acacia (Windhoek)

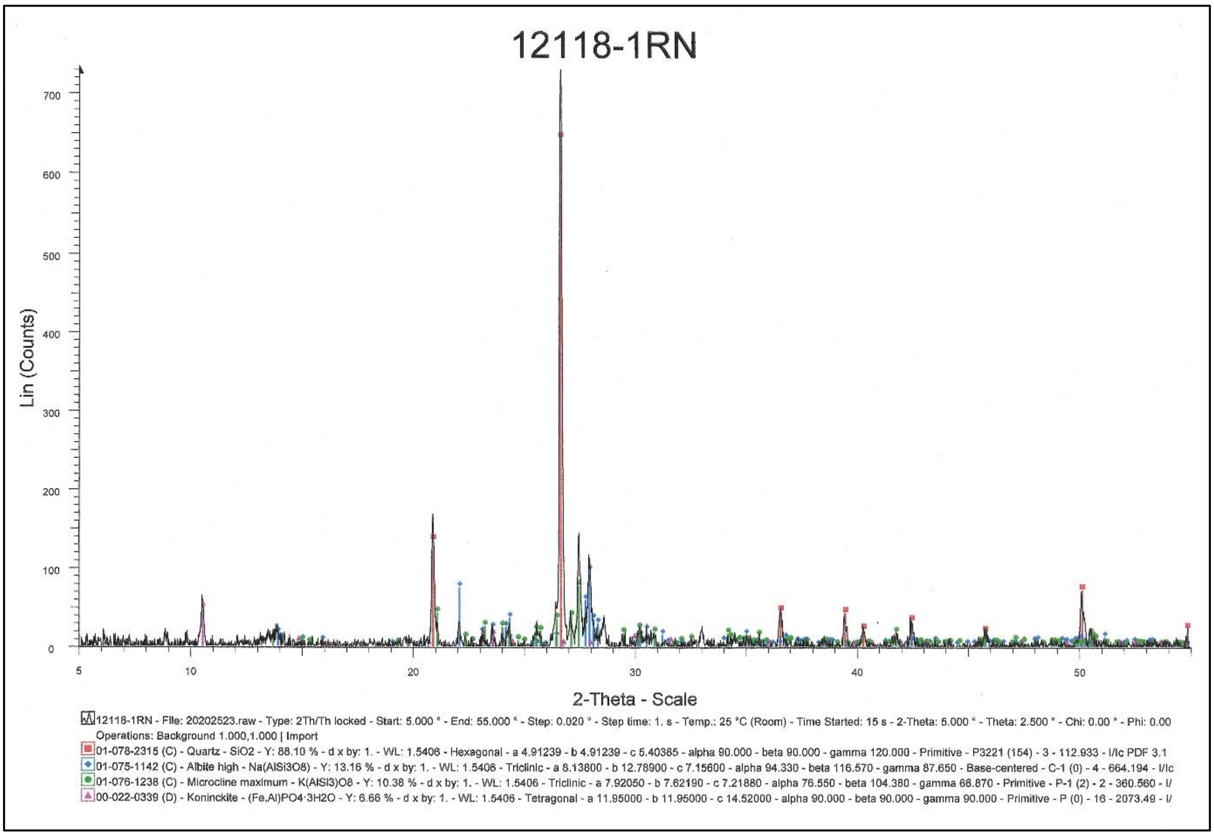


Figure 11: XRD graph for combined samples from boring RN-1 (Rehoboth North) indicating the presence of quartz, albite, microcline and koninckite

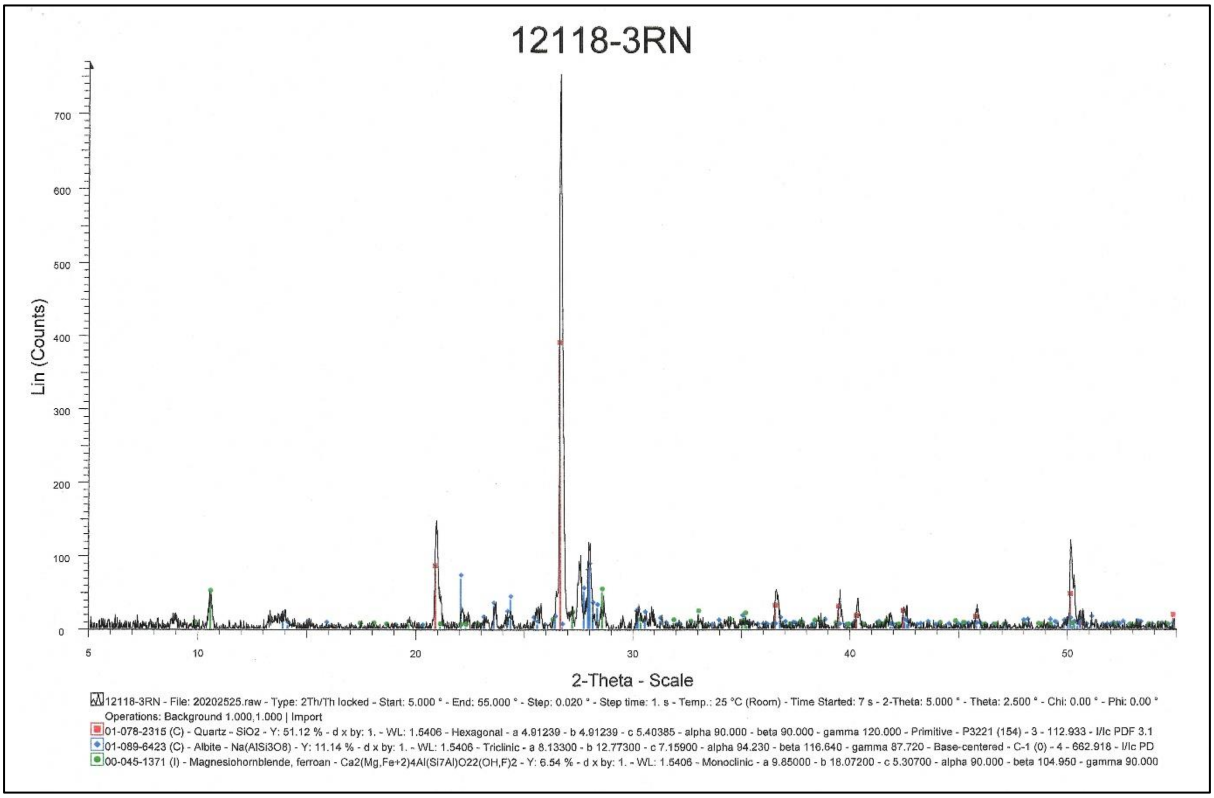


Figure 12: XRD graph for combined samples from boring RN-3 (Rehoboth North) indicating the presence of quartz, albite and magnesio-hornblende

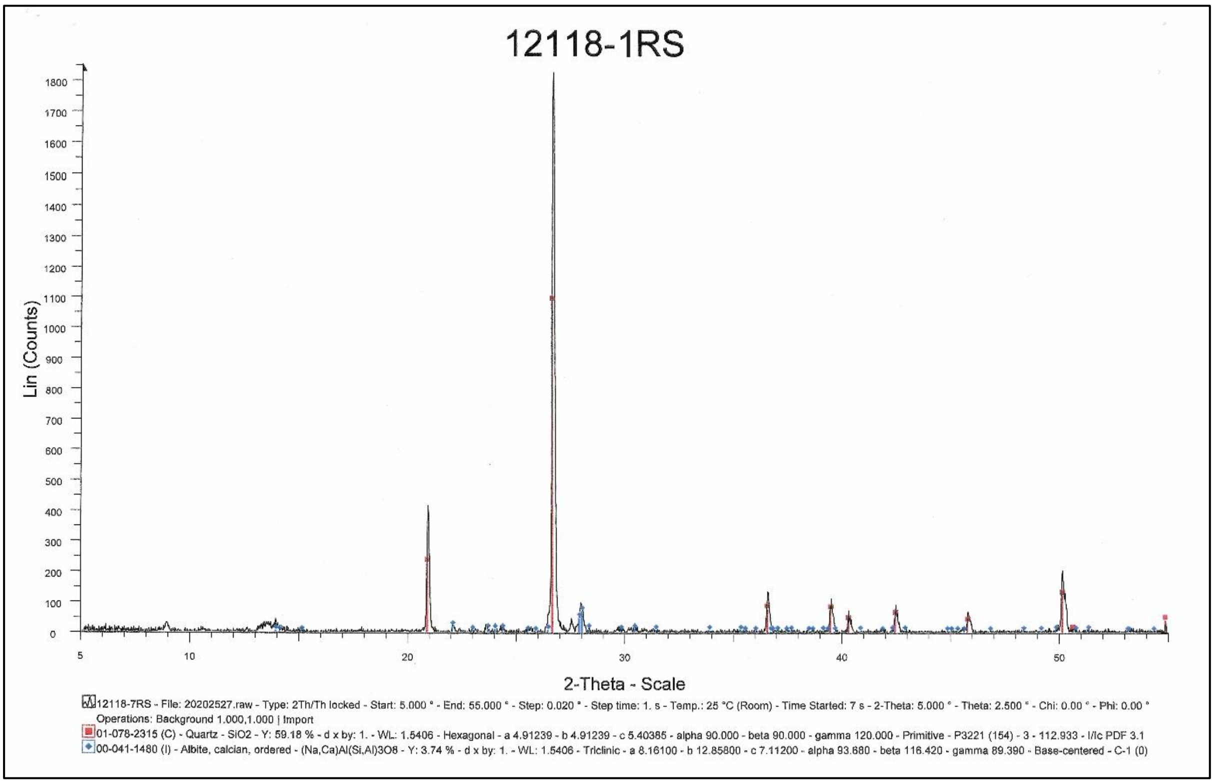


Figure 13: XRD graph for combined samples from boring RS-1 (Rehoboth South) indicating the presence of quartz and calcian albite

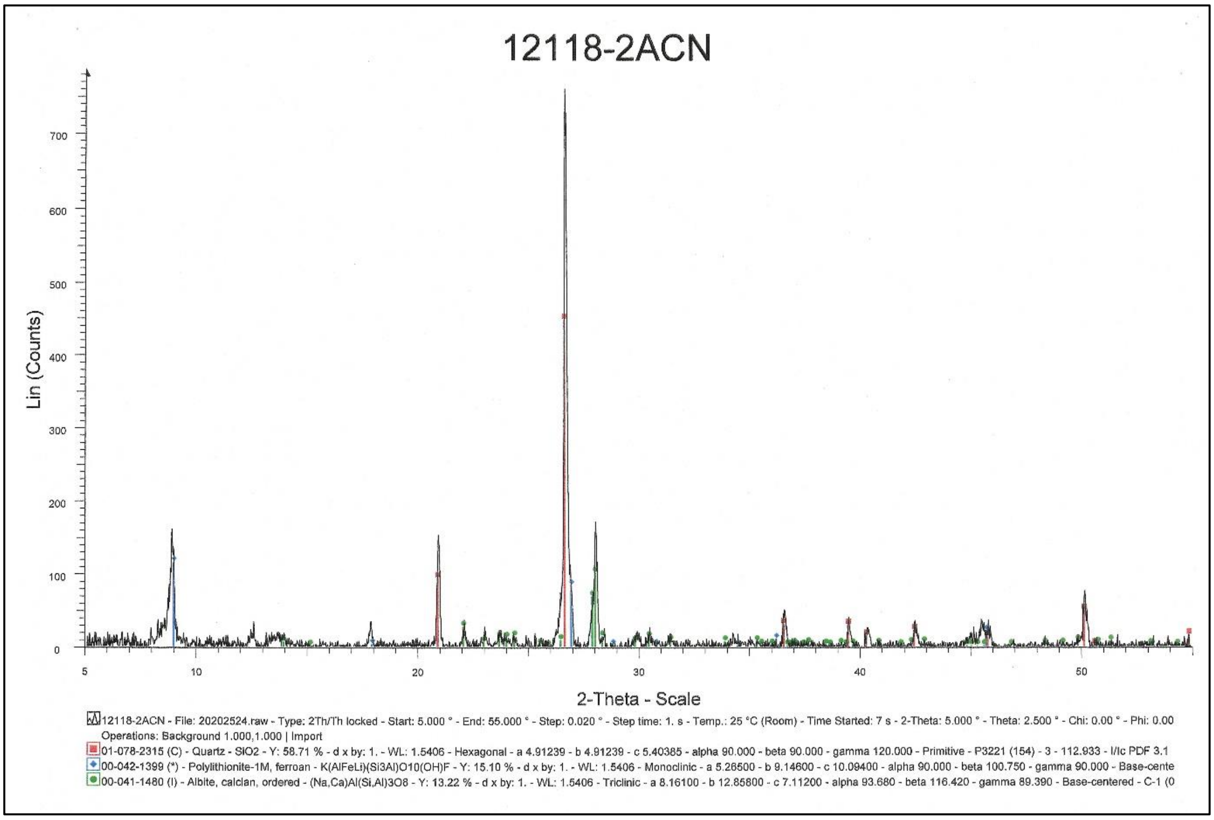


Figure 14. XRD graph for combined samples from boring ACN-2 (Acacia) indicating the presence of quartz, polylithionite and calcian albite

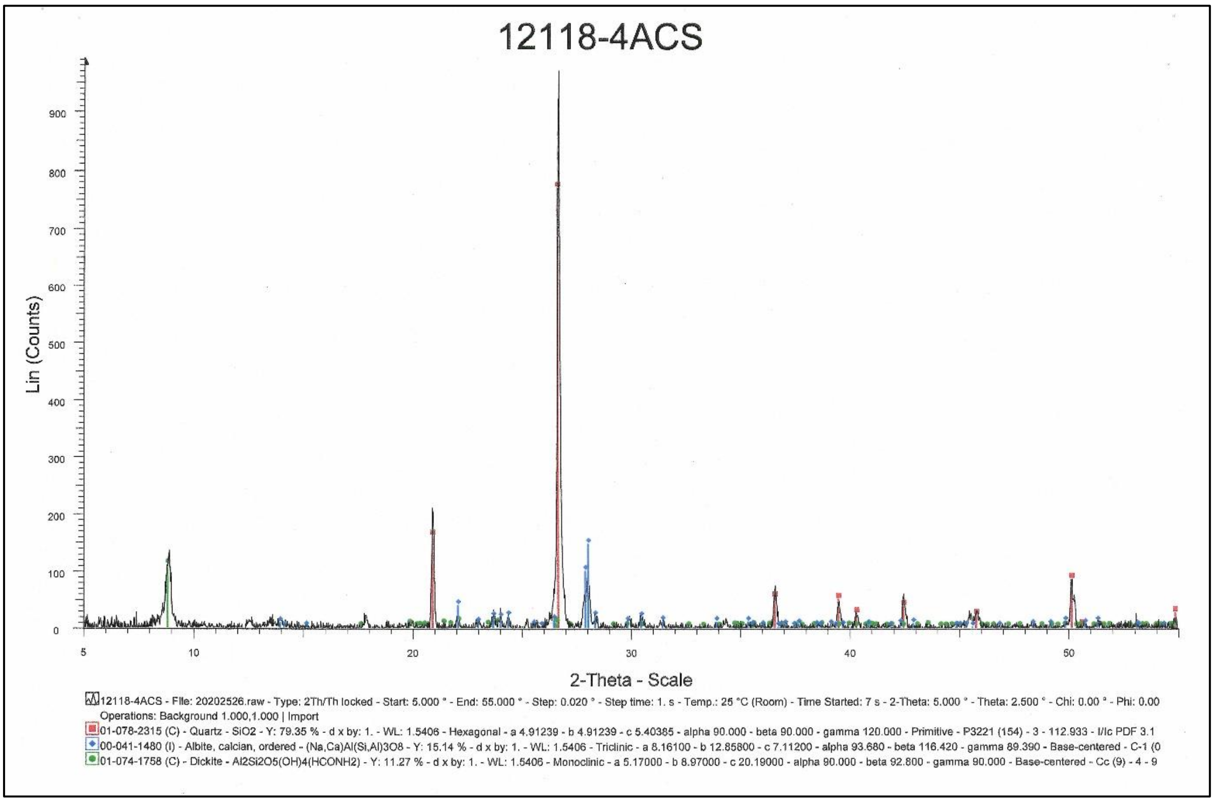


Figure 15: XRD graph for combined samples from boring ACS-4 (Acacia) indicating the presence of quartz, calcian albite and dickite

Sample No	Location	Minerals
12118-3RN	Rehoboth North	Quartz (SiO_2); albite ($Na[AlSi_3O_8]$); ferroan magnesio-hornblende ($Ca_2[Mg,Fe*2]_4Al[Si_7Al]O_{22}[OH,F]_2$
12118-1RN	Rehoboth North	Quartz (SiO_2); albite ($Na[AlSi_3O_8]$); microcline ($K[AlSi_3O_8]$); koninckite ($[Fe,Al]PO_4*3H_2O$)
12118-1RS	Rehoboth South	Quartz (SiO_2); calcian albite ($[Na,Ca]Al[Si,Al]_3O_8$)
12118-2ACN	Acacia	Quartz (SiO_2); polylithionite $K(Al,Fe,Li)(Si_3Al)O_{10}(OH),F$; calcian albite ($[Na,Ca]Al[Si,Al]_3O_8$)
12118-4ACS	Acacia	Quartz (SiO_2); albite ($Na[AlSi_3O_8]$); dickite ($Al_2Si_2O_5[OH]_4[HCONH_2]$

Table 14. Mineralogical composition of composite samples from the three investigates sites

Sieve analysis and soil gradation

Results of average sieve analyses for soils from the three investigated locations are presented in Table 15. It is of note that the soil at the Acacia site contains considerably less sandy material and more gravel than the soil at the two locations in Rehoboth, with Rehoboth North soil containing the smallest proportion of gravel; the percentage of fines is more or less even at all sites.

Acacia:	Sand 77%	Gravel 19%	Fines (clay and silt) 4%
Rehoboth North:	Sand 94.1%	Gravel 2.0%	Fines (clay and silt) 3.9%
Rehoboth South:	Sand 94%	Gravel 4.0%	Fines (clay and silt) 2%

Table 15. Sieve analysis for the three sites

In general, well-graded soils with a balanced mix of different particle sizes are more suitable for construction than poorly graded soils (composed, for instance, predominantly of fines), as they are more stable and capable of supporting greater loads (Das, 2022). They are also more permeable, which allows water to drain away from the foundations. In the classification of soils, logarithmic intervals (decades) and grain size curvature (S_0) are used to describe grain size distribution (Tables 4 and 16).

S_0 provides insight into the distribution of particle sizes between the quartiles D_{75} and D_{25}. While S_0 values close to 1 indicate a relatively uniform distribution of particle sizes between D_{75} and D_{25}, values significantly higher or lower than 1 suggest a more curved distribution, where particles are concentrated towards either the coarser (D_{75}) or finer (D_{25}) end of the range. Other important parameters to describe soil gradation are the Uniformity Coefficient (C_u) and the Coefficient of Curvature (C_c; Table 4). C_u measures the range of particle sizes present in the soil on the grain size distribution curve, while C_c compares the proportion of fine and coarse particles relative to medium-sized particles. Figure 16 visualises the main gradation types.

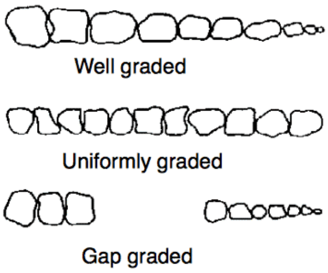


Figure 16. Soil gradation classification

Decade	Description	Particle Size (mm)	Logarithmic Size Interval	Example Particles
-1 - 0	Very fine silt and clay	0.01 – 0.1	10^{-2} - 10^{-1}	Fines (very fine silt and clay)
0 - 1	Very fine sand and silt	0.1 - 1	10^{-1} - 10^{0}	Clay, silt, very fine sand
1 - 2	Fine and medium sand	1 - 10	10^{0} - 10^{1}	Fine sand, medium sand
2 - 3	Coarse and very coarse sand	10 - 100	10^{1} - 10^{2}	Coarse sand, very coarse sand, small gravel

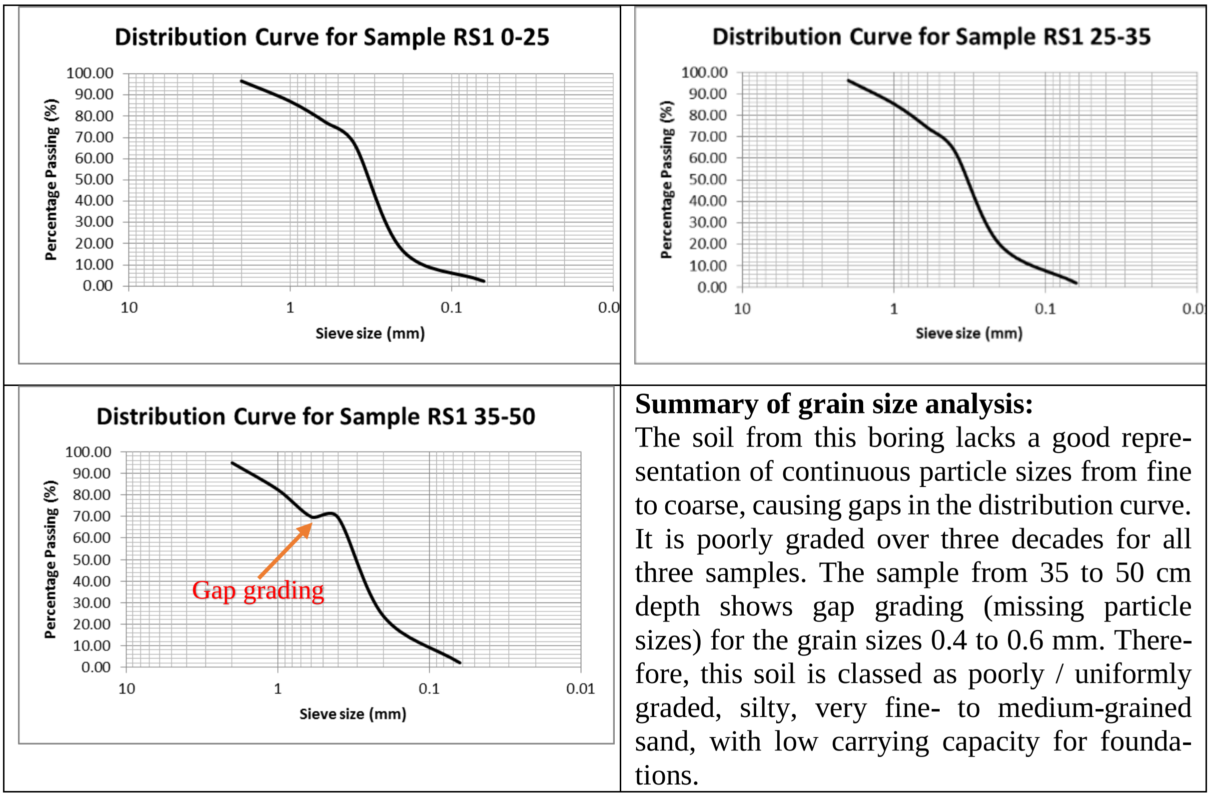
Table 16. Grain size classification according to Unified Soil Classification System (USCS)

A number of soil classification systems (Table 17) are used because they offer different levels of detail and specification. ASTM and USCS (Unified Soil Classification System) provide a broad classification based on C_u and C_c, while standards developed by the American Association of State Highway and Transportation Officials (AASHTO) or the American Concrete Institute (ACI) delve deeper into specific applications or materials (e. g. permeability for road construction or concrete mix design).

Representative grain size distribution curves for the three sites are shown in figures 17, 18 and 19; detailed sieve analysis results are given in Appendix A and Shuuya (2016). Comparison between figures 17, 18 and to 19 (based on decades) and Table 17 (based on C_c and C_u), with reference to suitability of the investigated sites for construction, shows the soil at Rehoboth North as poorly graded over three decades (Fig. 18), but well-graded according to USCS standards (C_c = 1.25 and C_u = 3.04; Table 17). The Rehoboth South site classifies as poorly graded both over three decades (Fig. 17) and by C_c (1.25) and C_u (2.93; after ASTM), while the soil at Acacia is poorly graded over three decades (Fig. 19), and gap-graded with C_c = 0.95 and C_u = 5.04 according to ACI standards (Table 17). Based on these classifications, the investigated sites are considered suitable for the planned light construction of single storey housing development, with Rehoboth North possessing the best gradation of the three.

Cu Range	Cc Range	Grading	Suitability	Reference
< 3	Any	Poorly graded	Light construction only	ASTM D2487-17
3 - 6	1 - 3	Well-graded	Most construction, good load-bearing capacity	USCS
3 -6	< 1 or > 3	Gap-graded	May be suitable for specific applications, requires further testing	ACI 318-19
> 6	Any	Poorly graded	Not recommended for most construction	AASHTO T88-22

Table 17. Suitability of soils for construction based on uniformity coefficient (*Cu*) and curvature coefficient (*Cc*)



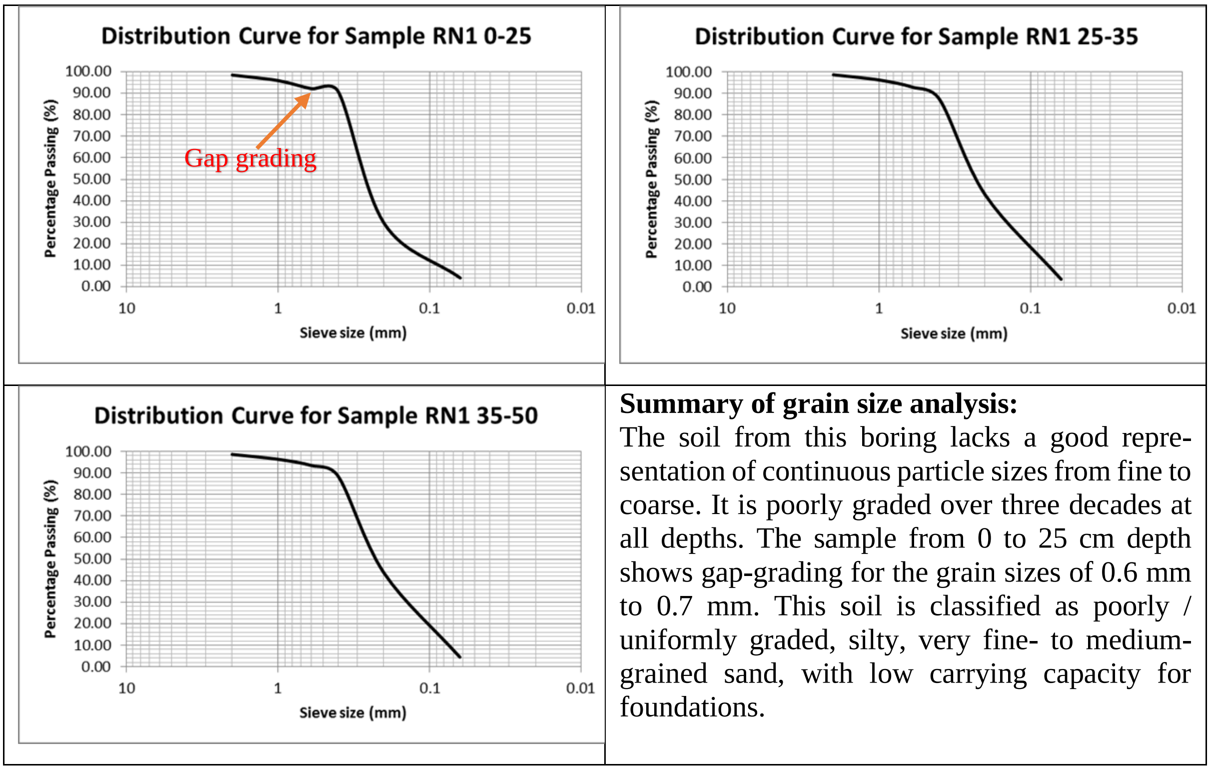
Distribution Curve for Sample RS1 0-25

Distribution Curve for Sample RS1 25-35

Distribution Curve for Sample RS1 35-50

Summary of grain size analysis:
The soil from this boring lacks a good representation of continuous particle sizes from fine to coarse, causing gaps in the distribution curve. It is poorly graded over three decades for all three samples. The sample from 35 to 50 cm depth shows gap grading (missing particle sizes) for the grain sizes 0.4 to 0.6 mm. Therefore, this soil is classed as poorly / uniformly graded, silty, very fine- to medium-grained sand, with low carrying capacity for foundations.

Figure 17. Representative grain size distribution curves for Rehoboth South taken from boring RS-1 at varying depths from surface to 50 cm



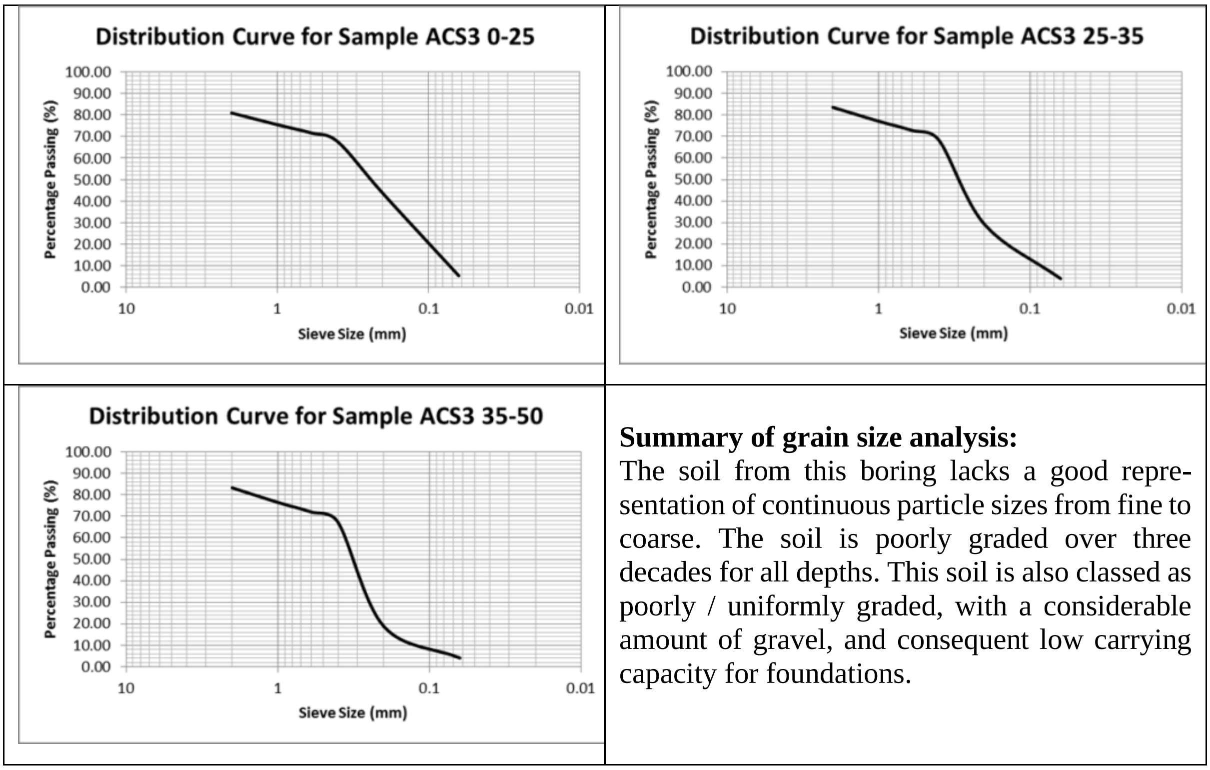
Distribution Curve for Sample RN1 0-25

Distribution Curve for Sample RN1 25-35

Distribution Curve for Sample RN1 35-50

Summary of grain size analysis:
The soil from this boring lacks a good representation of continuous particle sizes from fine to coarse. It is poorly graded over three decades at all depths. The sample from 0 to 25 cm depth shows gap-grading for the grain sizes of 0.6 mm to 0.7 mm. This soil is classified as poorly / uniformly graded, silty, very fine- to medium-grained sand, with low carrying capacity for foundations.

Figure 18. Representative grain size distribution curves for Rehoboth North taken from boring RN1 at varying depths from surface to 50 cm



Summary of grain size analysis:
The soil from this boring lacks a good representation of continuous particle sizes from fine to coarse. The soil is poorly graded over three decades for all depths. This soil is also classed as poorly / uniformly graded, with a considerable amount of gravel, and consequent low carrying capacity for foundations.

Figure 19. Representative grain size distribution curves for Acacia (Windhoek) taken from boring ACS-3 at varying depths from surface to 50 cm

Discussion

The study of soil properties, the most critical of which are summarised and discussed below, is essential in foundation design in order to avoid failure or damage to structures with resulting high costs and/or loss.

Water Content

Soil samples for this study were collected during the dry season at three sites vegetated by tree-and-shrub savannah, which is the typical vegetation of the central Namibian Khomas Highlands. Water content, expressed as a percentage of the dry weight of the soil, is an important factor to consider when choosing foundation types and depths. In general, soils with high water content are more likely to swell and shrink, which can cause damage to foundations; consequently, foundations in soils with high water content should be deep enough to reach stable ground. Other factors influencing foundation depth are soil type, water table fluctuations, expected loads, as well as local building codes and regulations. Foundations should be placed below the anticipated maximum water table level to minimise buoyancy and potential uplift. Table 5 shows the water content of soil samples taken at different depths in Acacia and Rehoboth. At Rehoboth South, the water content of the soil increases with depth, which is normal as water tends to drain downwards, leaving the topsoil drier than the bottom. The presence of vegetation can influence water content by siphoning off water from the soil or by shading the surface and thus reducing evaporation. At Rehoboth North, the water content in the soil is very constant at 0.2%, with a variation of 0.1%, indicating a uniformly dry soil due to a high proportion of sand; in such soils water can drain quickly through the pore space between grains, preventing significant moisture retention. In contrast, at Acacia a high variation in water content was observed, owing to the variable composition of the soil. At this site, it contains significant proportions of gravel, sand, silt and clay (Table 15), which have different water-retaining capacities; because of its greater particle size and porosity, sand has a lower capacity to hold water than clay and will consequently be drier. Generally, the water content at the three sites varies between 0.1% and 1.6%, except in boring ACN-2. Here, at a depth of 25-35 cm, the soil was found to contain

20.2% water due to an accumulation of clay minerals, with a high capacity to retain water, due to their low porosity and high surface area.

Penetration

Cone penetration tests (CPT) were conducted on twelve soil borings. The strength analysis curves for Rehoboth North, Rehoboth South and Acacia show the relationship of cone resistance to depth (Figs 8, 9 and 10). At Rehoboth North, the cone resistance of the soil increases to a depth of 45 cm, which is typical of a normally compacted soil. In Rehoboth South, the situation is similar, with the difference that in boring RS-3 a layer of weak soil with lower cone resistance was encountered at a depth of approximately 30 cm. Due to their larger grain size and higher porosity sand and gravel compact more easily than clay or silt, requiring less force to penetrate. CPT results show (in accordance with Table 17) the soil in Rehoboth South to be poorly graded, with most soil samples having $C_u < 3$ and $C_c > 1$, except for four samples from borings RS-2 (0-25, 25-35 and 35-50 cm) and RS-3 (35-50 cm); in these cases, $C_u > 3$ and C_c between 1 and 3 indicate a well-graded soil, suitable for most construction projects. At the Acacia sites layer(s) of weak soil, composed of mixed clays, sands and gravels, occur at depths > 40 cm in all four borings, including the waterlogged layer in ACN-2.

In general, soils with high cone resistance are capable of carrying considerable loads, while soils with low to medium cone resistance, as encountered at the three investigated sites, require treatment - such as compaction or stabilisation - before they can bear structures with safety. However, other parameters, such as moisture content, grain size, chemical and mineralogical composition, all of which are interlinked, need to be taken into consideration.

Geochemical composition

Elemental composition of the soil samples was determined with a portable X-ray Fluorescence Analyser. Results show that the soils at the three investigated sites are composed primarily of silica, aluminium, iron and potassium (Table 13), which are the most common constituents of all rocks and soils. Concomitant with the decrease in silica is an increase of most other major and trace elements (Table 18); titanium, phosphorus, sulphur and barium show very little variation in all the samples.

	Si %	Al %	Fe %	K %	Mg %	Ca %	Mn ppm
Rehoboth South	29.97	14.05	2.04	2.41	1.44	0.56	330
Rehoboth North	26.25	19.82	3.69	3.47	1.95	1.16	561
Acacia	24.33	27.12	4.41	4.20	3.35	0.69	704
	Cr ppm	**Zr ppm**	**Sr ppm**	**Rb ppm**	**Zn ppm**	**Cu ppm**	**Ni ppm**
Rehoboth South	140	178	61	50	20	21	25
Rehoboth North	126	173	80	85	28.5	44	58
Acacia	176	235	84	97	66.5	28.5	43.5

Table 18. Summary of XRF results showing average element concentrations from the three sites

Mineral composition

The mineral composition of the investigated soils was determined by X-Ray diffraction. It was found to be similar at all three sites, consisting mainly of quartz and albite, with subordinate hornblende, microcline and various clay minerals (Table 14), which suggests relatively slow to moderate decomposition and erosion of the parent rocks. Expansive clays, which can pose a serious threat to the stability of foundations by recurrent shrinking and swelling during the dry and wet seasons, were observed only at the Acacia site (polylithionite), while other minerals harmful to the stability of foundations, such as sulphates and pyrite, are absent. As the latter react with water to form corrosive acids, they can damage concrete and thus cause foundation failure.

Recommendations and Limitations

Table 19 summarises the test results of the three construction sites in Rehoboth and Windhoek. Based on particle size distribution, water content, compaction, geochemical and mineralogical composition, it is concluded that the soils at the three investigated sites are conditionally suitable for light construction, i. e. after appropriate treatment to improve bearing capacity and/or with the design of adequate foundations to mitigate inherent deficiencies. Two types of soil were observed, i. e. (reddish) sandy soil (Rehoboth) and gravelly sandy soil with pebbles (Acacia). All soils are poorly graded over three decades but well-graded over one decade, which makes them unsuitable as foundation material for double-storey structures. It is recommended that the foundation ground in Rehoboth (both North and South) be replaced with a compactable soil allowing easy water drainage; alternatively, foundations could be placed in solid rock (after the removal of the soil cover), in which case the integrity of the bedrock needs to be examined. Grain size variation in the gravelly soil at Acacia ensures adequate drainage even when closely packed.

Site	**Test results**			**Suitability for planned construction**
	Grain size composition/Grading (Sieve analysis)	**Water content**	**Compaction (Cone Penetration Test)**	
Acacia	Poorly graded/Gap-graded	Low	Moderate	Suitable for light construction
Rehoboth North	Poorly graded to well graded	Low	Moderate	Suitable for light construction
Rehoboth South	Poorly graded	Low	Moderate	Conditionally suitable for light construction

Table 19: Overall soil testing results from the three investigated sites

Foundations

The type of foundation to be laid depends on subsoil conditions and the structure to be erected. The parameters for the design of an appropriate foundation system encompass foundation type, depth, bearing capacity of the soil and the type of structure to be erected (Gopi, 2009). In accordance with the test results obtained, two types of foundations are recommended for the three sites, i. e. raft and strip foundations, both of which are shallow foundation types. French (1999) defined raft foundations as continuous concrete slabs covering the entire footprint of the building, thus distributing the weight evenly. This type of foundation is suitable for soft or loose soils with low bearing capacity (as encountered at Rehoboth South and North), for buildings with large or concentrated loads and for structures in areas with high seismic activity. Strip foundations are defined as continuous concrete strips laid under the walls of a building, transferring the load directly to the soil (Sivakugan, 2021). Strip foundations are thus preferred for soils with good to moderate grading (e. g. gravelly soil at Acacia), for smaller buildings with evenly distributed loads and in areas with low seismic activity.

According to the field investigations, laboratory tests and engineering analyses carried out for this study, the following recommendations are made:

Acacia:

- **Foundation type**: Strip foundations, potentially with pre-treatment such as physically altering the soil structure to improve its properties
- **Foundation depth**: Deeper than 40 cm to avoid weak layers
- **Limitations:** Variable water content, which can lead to differential settlement, necessitating drainage solutions and foundation monitoring

Rehoboth (North and South):

- **Foundation Type**:

a) without soil replacement: raft foundations

b) with soil replacement: after replacement with a compactable soil of higher bearing capacity, e. g. soil with dominant sand (~60%) and significant silt (~20%), strip foundations may be considered, subject to a thorough geotechnical investigation and engineering analysis to confirm their stability in the new soil conditions.

- **Depth**: Deeper than 30 cm to avoid the weak layer
- **Limitations**: Poorly graded soil can lead to settlement in the long term. Monitoring of foundation performance and soil improvement techniques (e. g. mechanical and chemical stabilisation, geosynthetics and soil replacement) are advisable.

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Appendix A: Sieve analysis results for grain size distribution curves shown in figures 17, 18 and 19

	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
Sample RS-1: 0-25 cm	2	368.70	378.30	9.60	3.34	96.66
	1	310.30	337.80	27.50	9.58	87.08
	0.6	289.50	318.00	28.50	9.92	77.16
	0.4	299.70	328.50	28.80	10.03	67.13
	0.2	254.30	399.30	145.00	50.49	16.64
	0.0063	238.60	279.70	41.10	14.31	2.33
Pan		893.80	900.50	6.70	2.33	0.00
		Total weight of sample (g):		287.20	100.00	

	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
Sample RN-1: 0-25 cm	2	368.70	371.80	3.10	1.46	98.54
	1	310.30	315.80	5.50	2.58	95.96
	0.6	289.50	297.60	8.10	3.80	92.16
	0.4	299.70	302.80	3.10	1.46	90.70
	0.2	254.30	384.50	130.20	61.16	29.54
	0.0063	238.60	292.70	54.10	25.41	4.13
Pan		893.80	902.60	8.80	4.13	0.00
		Total weight of sample (g):		212.90	100.00	

	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
Sample RS-1: 25-35 cm	2	368.70	380.50	11.80	3.77	96.23
	1	310.30	344.30	34.00	10.88	85.35
	0.6	289.50	324.30	34.80	11.13	74.22
	0.4	299.70	332.80	33.10	10.59	63.63
	0.2	254.30	391.30	137.00	43.83	19.80
	0.0063	238.60	294.10	55.50	17.75	2.05
Pan		893.80	900.20	6.40	2.05	0.00
		Total weight of sample (g):		312.60	100.00	

	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
Sample RN-1: 25-35 cm	2	368.70	371.90	3.20	1.34	98.66
	1	310.30	316.10	5.80	2.42	96.24
	0.6	289.50	297.60	8.10	3.38	92.86
	0.4	299.70	313.00	13.30	5.56	87.30
	0.2	254.30	360.60	106.30	44.40	42.90
	0.0063	238.60	332.90	94.30	39.39	3.51
Pan		893.80	902.20	8.40	3.51	0.00
		Total weight of sample (g):		239.40	100.00	

	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
Sample RS-1: 35-50cm	2	368.70	382.60	13.90	5.05	94.95
	1	310.30	344.60	34.30	12.45	82.50
	0.6	289.50	324.40	34.90	12.67	69.84
	0.4	299.70	300.60	0.90	0.33	69.50
	0.2	254.30	381.00	126.70	45.99	23.51
	0.0063	238.60	297.70	59.10	21.45	2.06
Pan		893.80	899.50	5.70	2.07	-0.01
		Total weight of sample (g):		275.50	100.01	

	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
Sample RN-1: 35-50cm	2	368.70	371.60	2.90	1.36	98.64
	1	310.30	315.10	4.80	2.25	96.39
	0.6	289.50	295.70	6.20	2.91	93.48
	0.4	299.70	310.30	10.60	4.97	88.51
	0.2	254.30	349.80	95.50	44.81	43.70
	0.0063	238.60	322.20	83.60	39.23	4.47
Pan		893.80	903.30	9.50	4.46	0.01
		Total weight of sample (g):		213.10	99.99	

Sample ACS-3: 0-25 cm	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
	2	368.70	400.80	32.10	19.06	80.94
	1	310.30	319.40	9.10	5.40	75.53
	0.6	289.50	295.90	6.40	3.80	71.74
	0.4	299.70	306.40	6.70	3.98	67.76
	0.2	254.30	295.00	40.70	24.17	43.59
	0.0063	238.60	303.00	64.40	38.24	5.35
Pan		893.80	902.80	9.00	5.34	0.01
		Total weight of sample (g):		168.40	99.99	

Sample ACS-3: 25-35 cm	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
	2	368.70	399.50	30.80	16.44	83.56
	1	310.30	322.30	12.00	6.41	77.15
	0.6	289.50	297.60	8.10	4.32	72.83
	0.4	299.70	308.10	8.40	4.48	68.35
	0.2	254.30	327.70	73.40	39.19	29.16
	0.0063	238.60	285.70	47.10	25.15	4.01
Pan		893.80	901.30	7.50	4.00	0.00
		Total weight of sample (g):		187.30	99.99	0.01

Sample ACS-3: 35-50 cm	Sieve - Aperture ∅ (mm)	Mass of empty sieve/pan (g)	Mass of sieve/pan + soil retained (g)	Soil retained (g)	Percentage retained (%)	Percentage passing (%)
	2	368.70	400.90	32.20	16.69	83.31
	1	310.30	323.40	13.10	6.79	76.52
	0.6	289.50	298.20	8.70	4.51	72.01
	0.4	299.70	309.00	9.30	4.82	67.19
	0.2	254.30	347.60	93.30	48.37	18.82
	0.0063	238.60	266.90	28.30	14.67	4.15
Pan		893.80	901.80	8.00	4.15	0.00
		Total weight of sample (g):		192.90	100.00	