Indexed in
Scopus Compendex and Geobase Elsevier,
Geo-Ref Information Services-USA, List B of Scientific
Journals, Poland, Directory of Research Journals

International Journal of Earth Sciences and Engineering

www.cafetinnova.org

ISSN 0974-5904, Volume 09, No. 03

June 2016, P.P.420-425

Geotechnical Characteristics of Volcanic Soils in and around Taiz City, Yemen

JANARDHANA M R AND ABDUL-ALEAM AHMED A D AL-QADHI
Department of Geology, Yuvaraja's College, University of Mysore, Mysuru, INDIA
Email: *drmrjanardhana@rediffmail.com, abdul.aleam.q@gmail.com*

Abstract: This paper presents the geotechnical assessment of volcanic soils in the Taiz area of Yemen based on the field and laboratory investigations. The field study involved the evaluation of the physical properties and the collection of soil samples. Water content, specific gravity, particles size distribution and consistency limits such as Liquid Limit (LL), Plastic Limit (PL) and Plastic Index (PI) of both cohesive and non-cohesive soil samples were evaluated in the laboratory and the results are presented. The studies bring to light that the volcanic soil of the study area is found underlain or overlain and/or intercalated with the Tertiary volcanic rocks and has medium to very high degree of expansiveness. Wetting of soil during the rain fall season causes expansion due to the presence of montmorillonite and kaolinite types of clays thus causing the soil instability which in turn endangering the lives of the local people and damage to their properties. The geographical distribution of the volcanic soil in the study area can be demarcated as the hazardous zone and prevent the authorities in permitting the citizens to construct the buildings.

Keywords: *volcanic soils, Taiz city, Yemen, geomechanical properties, soil stability*

1. Introduction

Soil stability and urban design study have received the attention of the researchers [1, 2] in view of the vulnerability of the population to disasters. Cracking of foundations, walls, driveways, swimming pools, and roads due to soil instabilities cost millions of dollars each year in repairs and severe or recurring damage can lower the value of a house or property [3]. Volcanic soils are widely encountered around the world and cover more than 124 million hectares of the Earth's surface [4]. They underlay several cities, making an understanding of their geotechnical properties of great importance since geological materials of volcanic origin show geomechanical properties and geotechnical behaviour completely different of materials with non-volcanic origin [5]. Volcanic soils are highly sensitive to moisture conditions, which markedly affect their strength properties. Under intense rainfall, there is a rapid increase in pore pressures and a marked drop in strength, which may give rise to slope instability problems [5]. Swan [6] made an attempt to identify the problem and its nature, and then to discuss possible solutions when working with foundations on: I. Weak/Compressible Soils; II. Collapsible Soils; and III. Expansive Soils.

Structures that have been built up in Taiz city and its surrounding areas are being damaged and collapsed due to the foundation failures and these concrete structures have come up on Tertiary volcanic flows and volcanic soils. This paper deals with the evaluation of physical characteristics of volcanic soils of Taiz area and tries to find a solution to the existing problems through its evaluation. The present study involves both field and laboratory investigations and relies on the weathering characteristics of the products of volcanism in Taiz area.

2. Study Area

Yemen (Arabia Felix) lies at the South West of the Arabian Peninsula. The study area encompasses an urbanized area named Taiz city and its surroundings, located on the southwest of Yemen highlands, in the watershed area of upper Wadi Rasyan. It is bound by the latitudes 13° 32' N - 13° 44' N and longitudes 43° 54'E - 44° 10'E (Fig. 1). Topographically, the study area is well represented by mountains, isolated hills, steep slopes, undulating eroded lands with major wadis, and plains and loess covered plateau (Al-Janad Plateau). The elevation of these physical features varies from 800 m to 3000 m above mean sea level (Fig.2). Climatically, the area is characterized by an arid to semi-arid climatic condition. The average annual rainfall in the study area is about 520 mm [7].

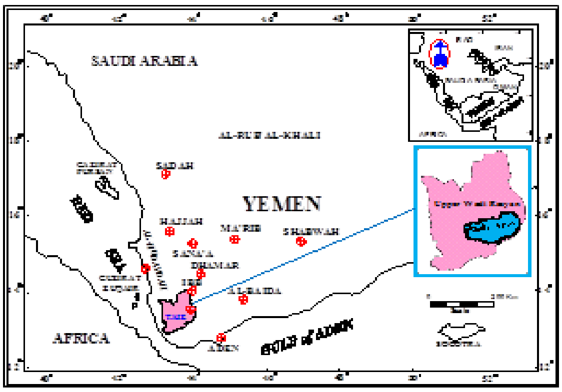

Figure1. *Location map of the study area*

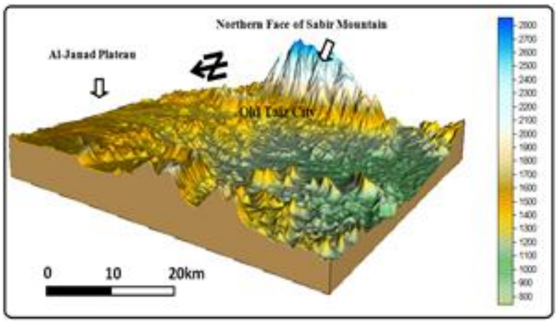

Figure2. *3D Model (DEM) illustrates the topographic features in the study area*

Geologically, the study area is covered with product of magmatism comprising typical Tertiary bimodal volcanic flows, intrusive bodies (such as Sabir granitic pluton, basic/acidic dykes and sills), and Quaternary and Recent sediments. Tertiary bimodal volcanic materials (basic and felsic deposits) can be considered to have erupted in five phases and in a repeated manner [8-10]. These form from bottom to top the following: (1) Tertiary lower mafic sequence phase (Tb1), (2) Tertiary lower silicic sequence phase (Tr1), (3) Tertiary middle mafic sequence phase (Tb2), (4) Tertiary upper silicic sequence phase (Tr2) and Tertiary upper mafic sequence phase (Tb3) (is exposed outside of the studied area) (Fig.3). The age of these volcanic flows range from the Oligocene to the lower Miocene [11]. The identifiable between these phases is mainly based on composition and stratigraphy criteria. The Jabal Sabir granite pluton (Tg) is one of igneous bodies emplaced as laccolithic inside the Tertiary bimodal volcanic materials, forming the dominant morphological feature (Sabir Mountain) overlooking the city of Taiz in the southern part of the study area. Almost, all the previous formations are cut by numerous dykes and sills of basaltic/rhyolitic composition. The Quaternary and Recent deposits in the study area consist mainly of (1) silts, clays, sands and gravels of loess type of deposits, (2) gravels, sands, silts, clays, cobbles, and boulders derived from the rock masses of plutonic and volcanic origin with a matrix of silt and clay soils of colluvial-alluvial origin and (3) volcanic soil of residual origin that are stratified, fractured and/or intercalated with weak volcanic accumulated materials [7]. A general account on the different phases of volcanism and their associated intrusive bodies has been dealt by [12, 9]. Detailed geological and petrological studies of the different phases and their associated intrusive bodies (Sabir granitic pluton, dykes and sills) were carried out by [10, 13].

3. Volcanic Soils in Investigated Area

The volcanic soils in Taiz area are represented by varicoloured volcanic ash-fall deposits (volcanic ejecta), as a product of in situ weathering and also as hydrothermal alteration product of volcaniclastic materials. These deposits are well exposed along the faces of road cuts and on the sides of the natural slopes. The soil horizon thickness ranges from 0.3m to more than 6 m.

Texturally, volcanic soils are predominately clayey sands, silty sands, sandy silts and sandy clays soils. At places, the soil may also contain angular to sub-angular and sub-rounded gravel and cobble sized fragments of basaltic/rhyolitic composition. These soils form the weakest volcanic accumulated materials overlaid by /intercalated/interbedded and also subjacent to basalt/rhyolite lava flows and/or with welded to semi-welded volcaniclastics. In most cases, they are represented by unconsolidated or semi-consolidated deposits sandwiched between the Tertiary volcanic sequences.

Wide variation is noticed in the properties of volcanic soils from one place to another place as regard to their colour, particle size, structure, fabric, weathering degree with depth, compaction, discontinuity, consolidation with depth and thickness. The wide variations in the properties of the soil may be attributed to the phenomena of complex volcanic eruption, transportation processes, depositional environment and depositional history of the materials. The brief field descriptions of volcanic soils and their geological characteristics are illustrated in the Table 1.

4. Materials and Methods

During the field work, 14 stations were demarcated so as to represent the whole area under investigation. Soil samples for each of the test were chosen considering the anisotropy of the soil for each one of the parameters.

Table 1: *Summary of the field descriptions of the volcanic soils of the Taiz area and their geological characteristics*

Volcanic soils	Reddish brown /grey/ creamy-white, whitish grey, greenish white, loose to semi-consolidated residual soils. Most of these soils are developed from weathered/altered volcanic tuffs. These soils (ashes) are overlain or /and intercalated with both mafic / acidic pyroclastic rocks. They varied in their sizes from gravel (colluvial) to sandy silts and clayey grain size. The volcanic soils in some sites are contained on discontinuities and commonly lie under and/or intercalated with Tertiary basaltic/ rhyolitic lavas. These soils are either non-cohesive or cohesive. No seepage.
	

The chosen samples were subjected for geotechnical tests in the main branch of materials laboratory of Sheba General Contracting Co. Ltd, Taiz, Yemen. The testing was done to assess the geotechnical characteristics of the volcanic soils in the studied area. The laboratory testing involved the measurement of physical parameters such as water content and specific gravity. In addition classification tests (particles size distribution and consistency limits) were also carried out. Among the cohesive type of soils, Water Content (Wc) and Bulk Density (γb) of 10 samples were determined, whereas the specific gravity (Gs) of 6 samples, Liquid Limit (LL), Plastic Limit (PL) and Plastic Index (PI) of 5 samples and Particle Size Distribution (PSD) of 6 samples were evaluated. Wc of 12 samples, γb of 11, Gs of 7, LL, PL and PI of 8 and PSD of 8 noncohesive volcanic soil samples were determined.

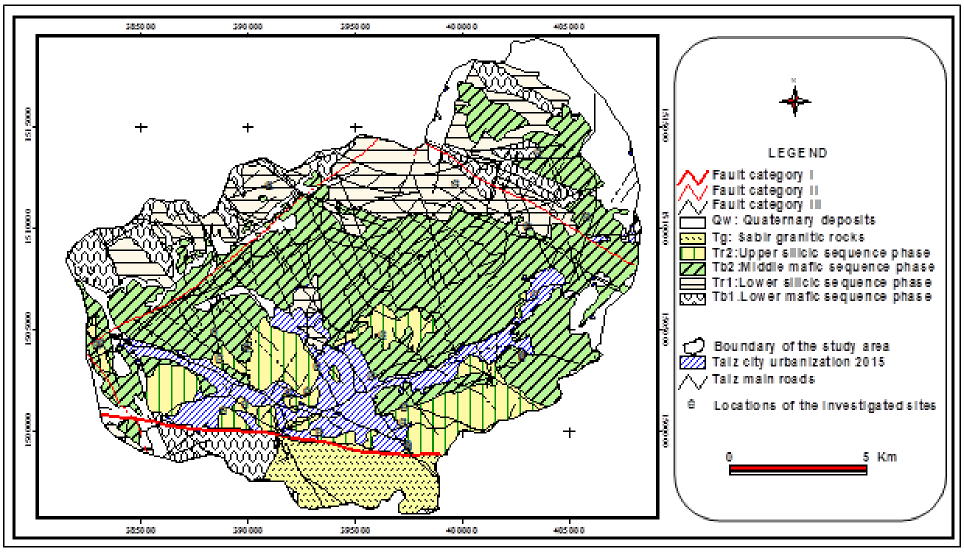

Figure 3 *Geological map of the study area with the locations of the investigated stations (modified after Kruck and Schaffer [8]; DEY [9]; Malek [10]; Al-Qadhi, et al.[13])*

According to the [14] D-4959-89 and standard, the water content (Wc) in the volcanic soil samples of the study area was determined for 22 volcanic soil samples. The determination of the specific gravity (Gs) of the 13 volcanic soil samples of the study area was carried out according to the procedure prescribed in [14] D-854-91. The bulk density of the soil samples were measured in the field using steel cylindrical sampling tube with cutting edge (7.91cm height and 8.1 cm inner diameter). For the measurement of the particle size distribution (PSD) in the soil samples, the sieve analysis was performed for 14 representative volcanic soil samples using the wash sieving method and according to the procedure given in [14] D-422-90(Fig 4). Determination of the consistency limits or Atterberg limits of the fine grained soil mass is another requirement to classify the soil for engineering purpose. In the present study, the plasticity test was carried out after ensuring 5 % of the fine grained material passes through sieve No. 200. In this study, the Liquid Limit (LL) and Plastic Limit (PL) were evaluated as per [14] D-4318-84 and classified as of low plasticity (lean soil) if the LL <50 %, and as high plasticity (fat soil) if the LL is ≥ 50 % ([14], D2487-90) (Fig. 5). For identifying the expansive soils or degree of expansiveness, the standard chart suggested by [15] was used. In this study, the mechanical tests could not be carried out on these soils due to a number of difficulties including the compact nature of the soil, stiff or dry condition, presence of cracks or fractures, wide range in grain sizes and nonavailability of suitable soil sampling equipments at the laboratories of Taiz city which hampered the task of obtaining undisturbed soil samples.

5. Results and Discussion

The water content ratios of cohesionless and cohesive soil respectively vary from 2.21 to 17.10 % and 3.18-19.30%. The bulk density of cohesive soil range from 1.29 to 1.91gm/cm³ while cohesionless varies from 1.54 to 1.94 gm/cm³. The specific gravity values vary from 2.20 and 2.77 with an average value of 2.53 for cohesive soil and between 2.28 and 2.61 with an average of 2.42 for cohesionless soil.

The results of PSD analysis were plotted on semi-log sheets paper and by reading the obtained curves (Fig.4). According to the Unified Soil Classification System (USCS) [14], four soil types two each in cohesive and cohesionless soils were identified during the present study.

These are: I. Clayey sand (SC) and Silty sand (SM) in cohesionless soil, II. Sandy low to high plasticity silt (ML, MH) and Sandy low to high plasticity clay (CL, CH) in cohesive soil.

The ranges in the values of LL, PL and PI for cohesive soil of the studied area are 38.59-92.4 %, 17.85-36.38 % and 19. 35-66.96 % respectively while for cohesionless soil, the values range from 43 to73.82 %, 14.59 to 46.88 % and 18 to 33.50 % respectively (Fig. 5). Here, the LL % values were used to identify expansive soils.

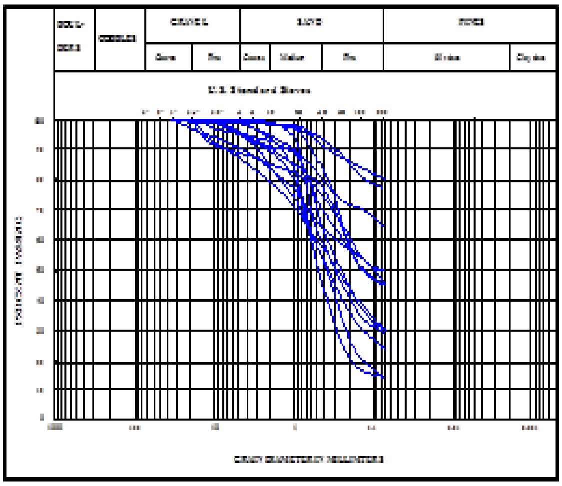

Figure 4 *Soil particle distribution of 14 volcanic soil samples from Taiz city and its surrounding, Yemen*

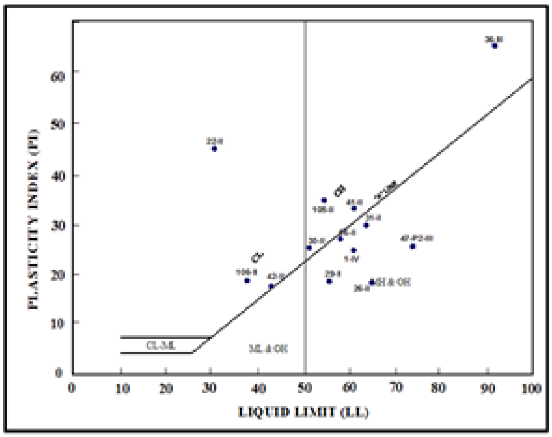

Figure5. *Representation of fine-grained volcanic soils of Taiz city and surrounding on Casagrade plasticity*

The larger the PI values, the greater will be the engineering problems associated with using the soil as an engineering material, such as foundation support for residential building and road sub grades [16].

Expansive Soils

A number of methods have been proposed by various workers [16-18, 14] to identify the soil type as regard to the determination of the degree of expansion when it comes in contact with water. The parameters determined are clay content, PI, LL, Shrinkage Limits (SL) (both volumetric and linear) and Shrinkage Index (SI). Based on the values obtained, soils are classified into Low, Medium, High and Very High degrees of potential expansiveness.

The purpose of identification of the mineralogical composition of these soils, the X-ray diffraction (XRD) tests on soils samples collected from different sites indicated that the clay minerals namely montmorillonite and kaolinite represent the major mineral phase in most of the samples while mica group of minerals such as muscovite, vermiculite and chlorite form minor faction [13]. In addition, talc, feldspar, calcite and halloysite are also found in relatively minor amounts. Quartz is commonly present in almost all the soil samples. As a simplest identification of such volcanic soils in the field, wide spread shrinkage cracks on the ground surface can be observed as shown in Figure 6.

In the present study, for classification of expansive soils or degree of expansiveness, values of LL were plotted against the PI values on the standard chart (Fig. 7) as suggested by [15].

In most investigated zones, the volcanic soil samples show Medium, High and Very High degrees of potential expansiveness (Fig. 7 and Table 2), as they contain montmorillonite which can expand several times to its original volume when it comes in contact with water.

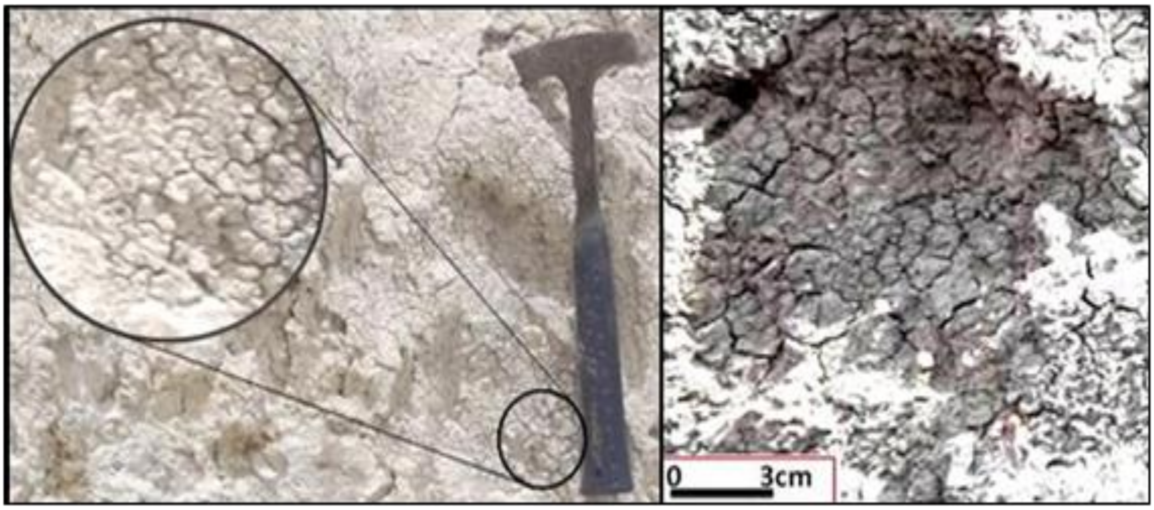

Figure 6 *Field photograph showing volcanic expansive soil with ground* shrinkage *cracks under dry conditions. Length of hammer 32.5cm*

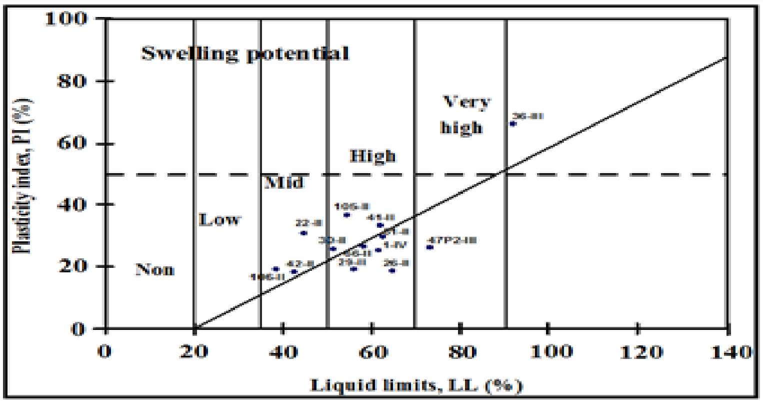

Figure7. *Plot of volcanic soils of Taiz city and surrounding on potential expansiveness Chart*

Table 2: *Classification of degree of expansion or swelling potential of the volcanic soil samples from Taiz city and its surrounding [15].*

Liquid limit value (LL %)	**Degree of expansion**	**Sample no. = (St. no. & zone)**
LL> 70	Very high	(36-III) and 47P2-III
50 < LL ≤ 70	High	1-IV, 26-II, (29-II), 30-II, (31-II), 41-II, 66-II and (105-II)
35 < LL ≤ 50	Medium	22-II, 42-II and (106-II)
20 ≤ LL ≤ 35	Low	-

The values in parentheses indicate cohesive soils

Generally, some mechanical characteristics such as the internal friction angles (Ø˚) of SM and SC soils are expected to be high because they contain a large proportion of sand-sized fractions while for clayey soils (CH, CL), they are expected to be low due to rise in the cohesion angles (C) which can be attributed to cementation processes between particles. In silty soils (MH, ML), the internal friction angles are expected to be generally low. The presence of highly absorbent minerals and an open microfabric with weak particle junctions determines a highly unstable behaviour both in static and dynamic conditions [20].

6. Conclusions

The present study deals with the evaluation of geotechnical properties of Tertiary volcanic soil of Taiz area in Yemen for the first time based on the field and laboratory investigations.

The weak volcanic soils are at places are overlain by hard and compact well jointed lava flows. The rocks of volcanic lava flows have high densities and open discontinuities especially vertical joints which can induce instability and infiltration of water into the lower layer. Alternating layers of different lithologies (very hard jointed lavas such as basalts/rhyolites with weakly volcaniclastic deposits) may cause the differential settlements in foundations constructed on them. Landslides and collapse of the buildings built over volcanic soils in Taiz area can be attributed to their low strength as determined from their capacity to water absorption especially during rainfall periods, their low densities and high porosity values in addition to the development of discontinuities in the soils. Buildings in Taiz city and its surroundings, that have come up on the well jointed lava flows have also become vulnerable for all kinds of damages. This may be attributed to the collapse of high-density upper hard jointed lava flows due to erosion and removal of the underlain weak volcaniclastics and the presence of expansive volcanic soils. This can be noticed along the slope regions in the study area which cause overhang of upper jointed lava.

The response strategies that could be resorted to before construction once the target site exhibits soils with swell tendency [21] include: Removal of problem soils before construction, (2) Elimination of source of water, (3) Maintainance of moisture equilibrium, (4) Chemical treatment with quicklime and (5) Use of Piling. However, in the study area volcanic ash and weak volcaniclastic materials are found sandwiched between and also in juxtaposition with the well jointed lava flows, hence it is recommended that the severely weaken soil zone areas should be discarded and if the geologic condition permits, deep foundation till the encounter of the hard rock is recommended.

7. Acknowledgment

The authors are deeply grateful to the manager of Sheba General Contracting Co. Ltd, main branch, Taiz, Yemen and its technical staff at the materials laboratory who gave us the opportunity to carry out the physical tests of volcanic soils.

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