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GEOTECHNICAL CHARACTERIZATION OF THE VOLCANICLASTIC ROCKS IN AND AROUND TAIZ CITY, YEMEN

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Abstract

An attempt has been made to evaluate the geotechnical characteristics of volcaniclastic rocks in Taiz city of Republic of Yemen for slope stabilisation of the existing civil structures and new construction purposes. The aim of this paper is to define the quality of volcaniclastic rock mass into several "classes" based on which the concerned civil engineer can take suitable measures for the stabilisation of the rock mass itself.Classifications are made based on field analysis and laboratory measurements. Finally, the indirect method of assessing the quality of the rock mass is also adopted. Rock quality assessment based on two attributes (1) properties of intact rock and (2) joints has been made by determining the Uniaxial Compressive Strength (UCS), Rock Quality Designation (RQD) index and Rock Mass Rating (RMR) system. The volcaniclastic rocks in the study area are represented by tuffs, ignimbrites, breccias and volcanic agglomerates rocks. All these volcanic materials are mainly of mafic and felsic (basalt and rhyolite) composition and belong to different phases of Tertiary volcanism. Volcanics show wide variation in their colours, thicknesses, degree of consolidation, degree of compactness and homogeneity. The different volcaniclastic rocks are grouped into two geotechnical subunits based on their strengths; strongly welded basaltic/rhyolitic volcaniclastic rocks (SBVc- Tb1/Tb2 /SRVc - Tr1/ Tr2) with strengths more than 25 MPa and weakly welded basaltic/ rhyolitic volcaniclastic rocks (WBVc-Tb1/Tb2 /VRVc -Tr1/ Tr2) which have strengths less than 25 MPa. These rocks are heterogeneous material having low to high porosity and low to moderate density, with high levels of water absorption depending on the size, the shape and petrological composition of the grains/fragments in addition to the type of matrix, the degree of packing between all components and the degree of consolidation and compaction state of these deposits. In some sites, the volcanic pyroclastic rocks (especially, tuffs and ignimbrite flows) are affected by discontinuities aligned principally in NE-SW and NW-SE directions following the trends of the regional structures. Stereographically, at most investigated sites, typically three joint sets are identified in addition to other joints orientated randomly. The study based on several geotechnical parameters brings to light that weakly welded volcaniclastic materials are causing instability to the civil structures in the region.

Keywords:Volcaniclastics, Taiz city in Yemen, geotechnical characterization, RMR, GSI.

Introduction

Taiz city in Yemen and its surrounding areas are underlain by variably weathered volcaniclastic rock masses. The city and its peripheral areas are witness to intense urban development in recent years. In response to the urbanization, rapid development of buildings and other infrastructure facilities have caused unfavourable changes in the configuration of Tertiary rock slopes causing instability to the buildings in the form of the development of cracks in the walls of the buildings, foundation problems leading to collapse of the buildingsand also landslides (Fig. 1), thus bringing undesirable socio-economic changes in the lives of the citizens. The situation demands a clear understanding of geologic conditions and the geotechnical properties of the rock masses in the area. From the geotechnical point of view, the knowledge about the volcaniclastic rocks or engineering geology is very scarce. The only research work to be mentioned is the work of Al-Qadhi [1] who has carried out geo-engineering assessment of some of the rocky outcrops. The present situation warrants the assessment of rock-mass strength and deformability of the volcaniclastic materials of Taiz area.

Rock mass classification systems are mainly used in order to understand the geotechnical properties of rock mass [2]. Many classification systems have been proposed by various researchers such as, RMR system introduced by Bieniawski [3], Q system of Barton et al [4], GSI published by Hoek [5] and RMi proposed by Palmstrom [6]. The evaluation of the geotechnical properties is done by studying the intact rock and discontinuity characteristics of the rock-mass and also by using the generalized rock-mass failure criterion [7].

Fig.1. Photographs showing dilapidatedconditions of buildings underlain by Tertiary volcaniclastics in the study area.

Land development and management planning in Taiz area warrant that stability of the volcaniclastic materials receives strong consideration. The present work was aimed at assessing and evaluating the engineering geological and geotechnical conditions of the Tertiary volcaniclastic materials in and around Taiz city, Yemen, based on field and laboratory investigations. In addition, the present work also focuses on the description and characterization of Tertiary volcaniclastic rocks (Vc) using the well established geotechnical classification systems. These data throw light on the geotechnical problems associated with volcaniclastic materials as well as may help to plan, design and maintain engineering projects.

Study Area

Taiz is one of the biggest cities in Yemen, located on the middle of the Central Highlands of Yemen. The city forms a part in the watershed area of upper Wadi Rasyan, and lies at the foot hill and slope regions of Sabir mountain. It is bound by the latitudes 13° 32' N - 13° 44' N and longitudes 43° 54' E - 44° 10' E (Fig. 2). In the investigated area, volcaniclastic rocks are of basaltic/rhyolitic in composition and are represented mainly by tuffs, ignimbrites, breccias and volcanic agglomerates. These volcaniclastics show a large variation in their colors, thickness, grain sizes, welding degrees, degree of compactness and homogeneity. They appear as discontinuous layers/sheets /lenses alternated and/or intercalated both vertically and/or laterally with basalts or rhyolite/dacite lava flows almost in all Tertiary volcanic sequences (Tb1, Tr1, Tb2 and Tr2). The geological and petrographical characteristics of these rocks were reported by Qadhi et al [8]. The brief field descriptions of basaltic /rhyolitic volcaniclastic rocks and their geotechnical characteristics are illustrated in the Table 1.

Materials And Methods

From a geotechnical perspective, Tertiary bimodal volcanic materials in the study area are classified as elsewhere in the world [9-12] into: (1) lava and domal rocks (L) (2) volcaniclastic rocks (Vc) and (3) volcanic soils (Vs). In the present study, the term volcaniclastic is used to include all volcanic particles regardless of their origin while the term pyroclastic is used to refer only to volcanic materials ejected from a volcanic vent. Representative samples in the form of block samples were collected mainly for the evaluation of intact characteristics whereas the discontinuity characteristics were studied mainly on the exposed parts of volcaniclastic rocks in the field.

The method consisted of detailed field studies, collection of representative samples of basaltic/rhyolitic volcaniclastic rock masses followed by their physico-mechanical analysis. This was followed by the geomechanical classification of the rock masses based on RQD Index, RMR classification and Geological Strength Index (GSI).

The investigated parameters under each one of these analyses and the methodology followed in the analysis of each one of the parameters are enumerated below:

The physico-mechanical behaviour of rock mass is governed by both intact rock characteristics and characteristics of discontinuities of the rock masses.

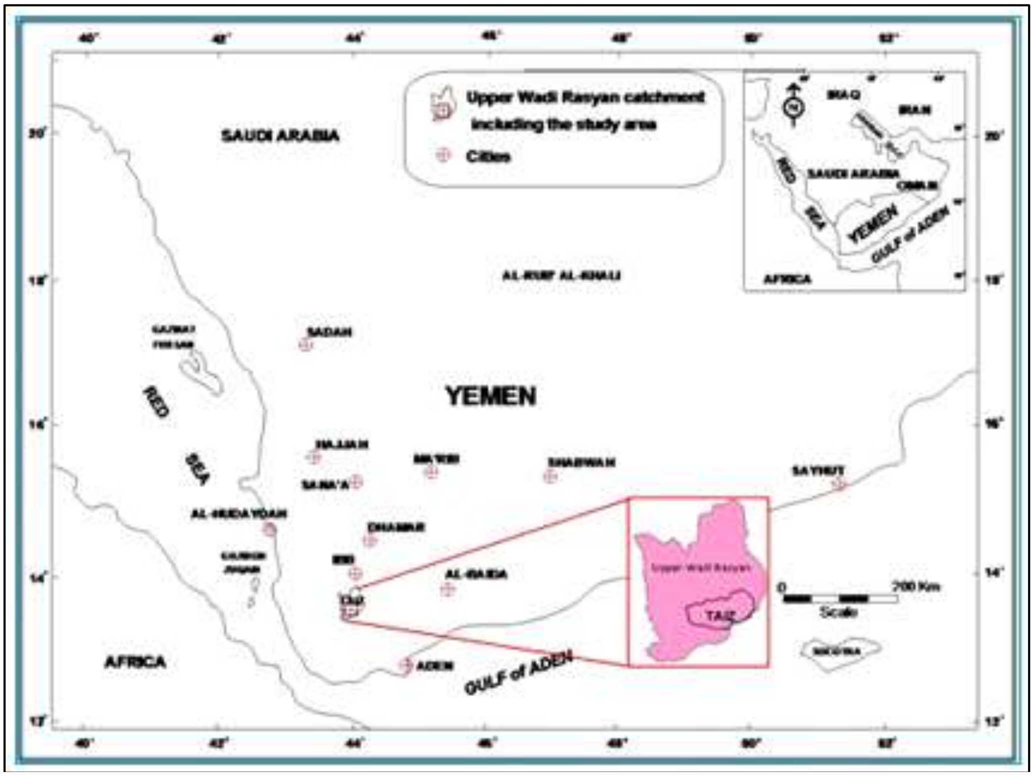


Fig.2. Location map of the study area.

I. Intact rock characteristics

Evaluation of the physical properties and the mechanical characteristics of the intact materials of the rock types were carried out on rock specimens prepared from block samples collected from the various representative sites, using common techniques available in the materials laboratory of Sheba General Contracting Co. Ltd, main branch, Taiz and in laboratory of the Technical institute, Al-Hassib, Taiz, Yemen.

Physical characteristics

The measured physical properties on rock specimens of welded basaltic/rhyolitic volcaniclastic rock masses are water content (Wc), unit weight (γ), dry density (ρd), porosity (n), water absorption (W. Ab), bulk specific gravity (Gs) and apparent specific gravity (A.Gs). These tests were carried out according to the procedures given by the ISRM [13].

Mechanical characteristics

Evaluation of the mechanical strength of the volcaniclastic rock masses was carried out by uniaxial compressive strength test (UCS) [14]; Point Load Test (PLT) [15, 16] and Schmidt Hammer rebound test (SH) (in the field and lab.) [17, 18]. The PLT test was carried out on welded basaltic and rhyolitic volcaniclastic rocks samples of regular geometrical form and also on irregular lumps in the laboratory and following the procedures prescribed by Brook [15] and ISRM [16]. For converting the Point Load Index (Is50) into the equivalent UCS, the following Equation [19], is used:

UCS = 21*Is (50) ……………………… (1)

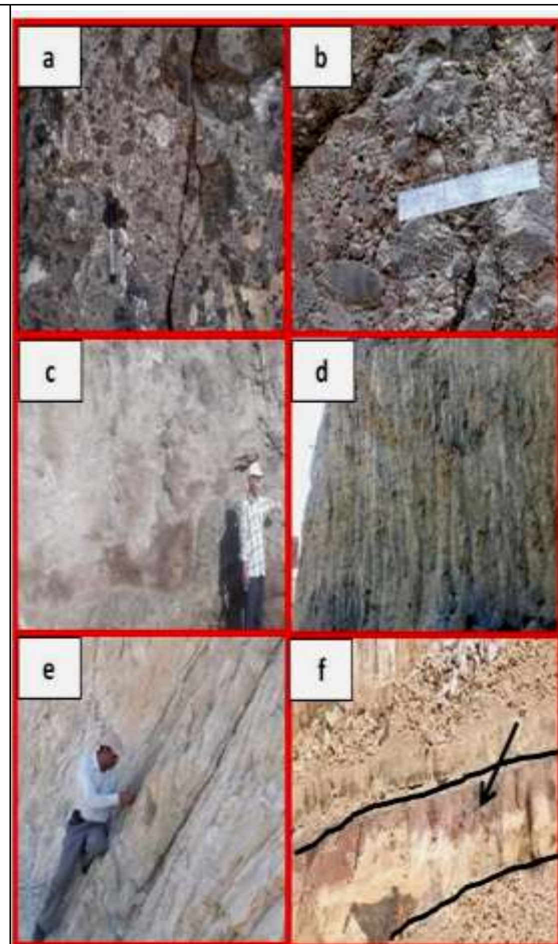
where Is (50) = Point load strength index of a specimen of 50mm diameter.

The Schmidt hammer test [17, 18] was carried out on some of the exposed rock faces (in 7 zones) and also on 8 rock samples of regular geometric form in the laboratory using N-type hammer. The N- type rebound data obtained were converted to L- type data using the following empirical correlation developed by Ayday and Grktan [20]:

Rn (N) =7.124 +1.249 Rn (L), ($r2 = 0.882$) ……………………… (2)

where Rn (L) and Rn (N) are respectively the L-type and N-type Schmidt hammer rebound numbers; and r2 is the determination coefficient. Conversion to equivalent uniaxial compressive strength values was undertaken using the Equation and chart of Miller presented by Dear and Miller [21].

Table 1. Summary of the field descriptions of the basaltic /rhyolitic volcaniclastic rocks of the Taiz area and their geotechnical characteristics.

Volcaniclastic rocks (Vc)	(a) Brown to light/dark grey in colour, weak to medium strong, moderately weathered **agglomerates**. The clasts are poorly sorted, angular to subangular, rounded to sub-rounded, vesicular/amygdaloidal to non-vesicular, irregular interlocked cemented by volcanic ash and iron oxides. They are either massive or include closed spaced, very low persistence, closed to opened apertures, rough joints. (b) Dark grey to light reddish brown coloured, weak to medium strong, slightly to moderately weathered **tuff-breccia.** The clasts are poorly sorted, angular, irregular interlocked, cemented by volcanic ash and iron oxides (c) White, greenish grey, grey to reddish brown coloured, welded, compacted/ massive weak to medium strong, slightly to highly weathered **lapilli-tuffs**. They are either compacted/ massive rocks or contain close to very wide spacing, very low to medium persistence, rough to slightly rough joints. (d) Grey/ light reddish brown in colour, welded and compacted, weak to medium strong, slightly to moderately **lapillistones**. They contain voids and thunder eggs (lithophysae) features. (e) Creamy-white, whitish grey, yellowish grey and reddish brown coloured, very weak to medium strong, fresh to highly weathered **coarse/fine tuffs**. They display either massive /compact or as jointed rocks. (f) Reddish brown, white to reddish grey coloured, weak to very strong, fresh to moderately weathered, massive /**columnar/ jointed ignimbrites**. They have widely to closely spaced, very low to very high persistence, closed to moderately opens, smooth to slightly rough joints.	

II. Characteristics of discontinuity

Scan line survey [22] was conducted to investigate the discontinuity features of the welded volcaniclastic rocks along road cuts and on the natural rock. Outcrops at 568 spots comprising 17 zones of intense discontinuity rocks and another 16 zones characterized by scarce discontinuity by following the procedure recommended by ISRM [18]. The discontinuity parameters evaluated are shown in Table 2. The discontinuity orientations data were plotted stereographically (equal-area stereographic projection) using computer software, called RockWorks/14 [23] and the joint sets were distinguished for all scan line data and then the pole concentrations were contoured.

Volumetric joint count (Jv)

Volumetric joint count (Jv) was computed from the joint set spacing in a fixed volume of rock mass (m^3) as recommended by Palmström [24-26] and Sen and Eissa [27, 28] using the Equation[24]:

$Jv = 1/S_1+1/S_2 \ldots\ldots 1/S_n + Nr\,(5\sqrt{A})$ ……………………… (3)

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where S_1, S_2 and S_3 are the average spacings for the joint sets, Nr is the number of random joints in the actual location and A is the area in m^2.

III. Geomechanical classification

During the survey, the attitude of the discontinuities was measured and other discontinuity features such as aperture width, persistence and infilling materials were studied. The following classification methods were adopted:

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Table .2 Characteristics of the discontinuities and calculation of GSI parameters for basaltic/rhyolitic volcaniclastic rock masses in and around Taiz city, Yemen.

Geotechnical subunit			**Strongly welded basaltic/rhyolitic volcaniclastic rock masses (SBVc- Tb1/Tb2, SRVc - Tr1/ Tr2)**											
Station no.			5	10	11	12	23	46	61	61	64	65	75	83
Zone			I	II	I	I	I	I	I	II	I	II	II	I
Orientation (dip/dip dir) and Average Spacing (m) of Discontinuities	Main Joint Sets	Set1	80/036 (0.44)	82/200 (0.37)	78/327 (0.53)	84/071 (0.54)	78/014 (0.77)	77/089 (0.20)	66/041 (0.49)	69/022 (0.64)	71/310 (0.20)	76/211 (0.16)	58/037 (0.15)	73/327 (0.80)
		Set2	82/144 (0.51)	60/292 (0.43)	76/068 (0.83)	81/132 (0.39)	75/344 (0.40)	61/160 (0.21)	77/353 (0.67)	80/151 (0.45)	59/286 (0.46)	77/182 (0.12)	73/302 (0.21)	76/277 (0.44)
		Set3	15/257* (1.80)	25/129* (1.91)	86/097 (1.05)	10/271 (0.49)	36/176 (0.79)	37/269* (6.10)	24/258* (1.43)	45/355 (1.70)	76/146 (1.11)	82/330 (0.11)	33/131 (0.44)	60/151 (0.82)
		Set4	-	-	-	-	-	-	-	-	-	-	-	-
	Set 4/5(random)		5/2= 2.5	-	-	-	5/3= 1.67	-	5/2= 2.5	-	5/3= 1.67	5/1=5	5/3= 1.67	-
	Min. Spacing		0.44	0.37	0.53	0.32	0.40	0.20	0.49	0.45	0.20	0.11	0.15	0.44
Ground water condition			C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry
Discontinuities Condition (A4)	Persistence (m)		<1-10 [4]	<1- >20 [3]	<1- >20 [3]	<1- >20 [3]	<1- >20 [3]	<1-10 [4]	<1-3 [5]	<1-3 [5]	<1 [6]	< 1 [6]	<1-3 [5]	< 1-3 [5]
	Aperture (mm)		1-5[1]	1-3[1]	None [6]	None [6]	None [6]	None [6]	None[6]	None[6]	None[6]	None[6]	>5[0]	None[6]
	Roughness		Sm -Sr surfaces [2]	S. rough surfaces [3]	Sm -Sr surfaces [2]	Sm -Sr surfaces [2]	Sm -Sr surfaces [2]	Sm -Sr surfaces [2]	Sm -Sr surfaces [2]	Rough surfaces [5]	V. rough surfaces [6]	Rough surfaces [5]	Sm -Sr surfaces [2]	S. rough surfaces [3]
	Infilling		No infilling [6]	Sf filling < 5mm [2]	No infilling [6]	No infilling [6]	No infilling [6]	No infilling [6]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Sf filling < 5mm [2]	Sf filling > 5mm [0]	Sf filling < 5mm [2]
	Weathering		Slightly [5]	Slightly [5]	Fresh [6]	Fresh [6]	Fresh [6]	Slightly [5]	Fresh [6]	Slightly [5]	Slightly [5]	Md [3]	Md [3]	Fresh [6]
GSI Parameters	Roughness Rating (Rr)		1.5	2	1.5	1.5	1.5	1.5	1.5	4	5	4	1.5	2
	Weathering Rating (Rw)		4	4	5	5	5	4	5	4	4	2	2	5
	Infilling Rating (Rf)		5	1	5	5	5	5	3	3	3	1	0	1
	Surface Condition Rating (SCR)		10.5	7	11.5	11.5	11.5	10.5	9.5	11	12	7	3.5	8
	Structure Rating (SR)		71.14	69.95	75.50	67.30	69.60	59.76	73.12	74.14	62.12	44.37	53.36	72.70
	Geological Strength Index (GSI)		66.25	52.92	72	67.33	68.33	59.17	63.64	69.17	66.25	41	33.57	57.5
Volumetric joint count (Jv)(J/m^3)			5.19	5.55	4.04	6.46	5.67	9.93	4.63	4.37	8.68	23.87	14.3	4.74
Degree of Jointing			Md	Md	Md	Md	Md	Md	Md	Md	Md	High	High	Md
Rock Quality Designation, RQD (%)			97.03	96.12	99.89	93.86	95.84	85.19	98.42	99.07	88.31	50.31	74.25	98.14

Where: m: mater, * : contact between two zones, (…): the values in parentheses are the mean discontinuity set spacings, Min: Minimum, C.dry: Completely dry, S: Slightly, Sr: Slightly rough, Sf.: Soft, Hd.: hard, Sm.: Smooth, Md: Moderately/Medium, V.: Very, [ ]: rating of a parameter according to Beniawski [32], Rr, Rw and Rf values are estimated from conditions of discontinuities, SCR= Rr+ Rw+Rf, SR= 100-17.5322lnJv [33], GSI is estimated depending on GSI chart modified by Hamasur [33] after [34-37], Jv = volumetric joint count= 1/S1+1/S2….1/Sn + (5√A) [24], Degree of Jointing is estimated depending on Jv values and according to Palmstrom,[31], RQD =Rock Quality Designation = 110-2.5Jv [31].

Table .2 Continued

Geotechnical subunit			**WBVc- Tb1/Tb2, WRVc - Tr1/ Tr2**				
Station no.			30	35	54	73	99
Zone			I	I	III	I	II
Orientation (dip/dip dir.) and Average Spacing (m) of Discontinuities	Main Joint Sets	Set1	82/281 (0.69)	66/343 (1.67)	19/313 (0.13)	70/234 (0.18)	23/322 (0.39)
		Set2	46/109 (0.89)	71/115 (1.09)	81/055 (0.21)	80/040 (0.37)	79/093 (0.85)
		Set3	81/023 (0.76)	25/143* (2.48)	83/114 (0.33)	33/170 (0.67)	82/238 (1.22)
		Set4	23/170* (2.13)	-	-	-	-
	Set 4/5(random)		5/1=5	-	-	5/3= 1.67	5/2= 2.5
	Min. Spacing		0.69	1.09	0.13	0.18	0.39
Ground water condition			C.dry	C.dry	C.dry	C.dry	C.dry
Discontinuities Condition (A4)	Persistence (m)		< 1-3 [5]	3-10 [2]	<1- >20 [3]	<1- 10 [4]	<1-10 [4]
	Aperture (mm)		>5[0]	>5[0]	None[6]	>5[0]	None[6]
	Roughness		Smooth Surfaces [1]	S. rough surfaces [3]	Rough surfaces [5]	Rough Surfaces [5]	Rough Surfaces [5]
	Infilling		Sf filling >5mm [0]	No infilling [6]	Hd filling < 5mm [4]	Sf filling < 5mm [2]	Hd filling < 5mm [4]
	Weathering		Md [3]	Slightly[5]	Slightly[5]	Hw[1]	Slightly[5]
GSI Parameters	Roughness Rating (Rr)		1	2	4	4	4
	Weathering Rating (Rw)		2	4	4	1	4
	Infilling Rating (Rf)		0	5	3	1	1
	Surface Condition Rating (SCR)		3	11	11	6	9
	Structure Rating (SR)		73.40	75.7	51.97	59.02	71.92
	Geological Strength Index (GSI)		40	70	56.54	43.21	61.67
Volumetric joint count (Jv)(J/m^3)			4.56	1.92	15.49	10.35	4.96
Degree of Jointing			Md	Low	High	High	Md
Rock Quality Designation, RQD (%)			98.60	100$^{(1)}$	71.29	84.12	97.60

Where: m: mater, * : contact between two zones, (…): the values in parentheses are the mean discontinuity set spacings, Min: Minimum, C.dry: Completely dry, S: Slightly, Sr: Slightly rough, Sf.: Soft, Hd.: hard, Sm.: Smooth, Md: Moderately/Medium, V.: Very, Hw: highly weathered, [ ]: rating of a parameter according to Beniawski [32], Rr, Rw and Rf values are estimated from conditions of discontinuities, SCR= Rr+ Rw+Rf, SR= 100-17.5322lnJv [33], GSI is estimated depending on GSI chart modified by Hamasur [33] after [34-37], Jv = volumetric joint count= 1/S1+1/S2….1/Sn + (5√A) [24], Degree of Jointing is estimated depending on Jv values and according to Palmstrom [31], RQD =Rock Quality Designation = 110-2.5Jv [31], $^{(1)}$: RQD=100 becouas Jv < 4 [31].

a) Rock Quality Designation (RQD) Index

This index was introduced by Deere [29] and developed by Deere et al [30] to provide a quantitative estimate of rock mass quality by recovering drilling core logs. It is defined as the ratio of the total length of intact core greater than 100mm in length to the total length of the core run. When no core is available as in this study but discontinuity traces are visible in surface exposures, the RQD may be estimated from the number of discontinuities per unit volume (Jv j/m3) as suggested by Palmström [24] using the Equation [31]:

RQD=110 - 2.5 Jv ……………………… (4)

where RQD = 0 for Jv > 44 and RQD = 100 for Jv < 4.

b) Rock Mass Rating (RMR)

The Rock Mass Rating (RMR) System [32] known as geomechanic classification system was employed in this study for geotechnical characterization of rock masses. This system is based on classification of rock masses in situ using the following six parameters: Uniaxial Compressive Strength (UCS) of intact rock (A1), Rock Quality Designation (RQD) (A2), spacing of discontinuities (A3), condition of discontinuities (A4), groundwater condition (A5) and orientation of discontinuities (A6). Here, only basic Rock Mass Rating (Basic RMR89) was summed up based on the first five parameters ratings (A1+A2+A3+A4+A5) with no adjustment for discontinuity orientation (A6). The accurate ratings of A1 (uniaxial compressive strength) and A2 (RQD) were determined using the charts constructed by Bieniawski [32]. Before applying this system, the rock mass was divided into a number of rock mass units or zones based on variation of the rock mass structural properties and according to the guidelines prescribed by Bieniawski [32].

c) Geological Strength Index (GSI)

The Geological Strength Index (GSI) system provides quantitative numerical basis to estimate more precise values for rock mass classification [33] that was modified after Hoek et al [34], Hoek [35], Marinos and Hoek [36] and Sonmez and Ulusay [37]. The principalcomponents of this modified quantitative rock mass classification are the structure rating (SR) and surface condition rating (SCR). The structure rating (SR) is determined from volumetric joint count (Jv) and according to the Equation [33]:

SR= 100-17.5322lnJv ……………………… (5)

where Jv is volumetric joint count (J/m3).

Surface condition rating (SCR) is estimated from sum of the roughness,degree of weathering and infilling materials ratings; which are assessed visually in the field (Table 2). Because the GSI is based on the RMR76 [34], roughness, weathering and infilling ratings (SCR) are also based on the RMR76 [3], in which the sum of these three parameter values range from 0 to 15 [33].The intersection of these ratings (SCR and SR) on the modified quantitative GSI chart of Hamasur [33] gives precise value of GSI.

Geotechnical characterization of massive and compact pyroclastic masses with few discontinuities was made by using the GSI chart constructed by Hoek et al [38]; Marinos and Hoek [36, 39]. The range in GSI values was plotted on the standard chart based on the field study of structure of rock mass and surface condition of the discontinuities expressed by roughness and weathering.

IV. Indirect estimates of the rock masses properties

Based on the laboratory tests and Geological Strength Index (GSI), the strength and deformability parameters of basaltic/rhyolitic volcaniclastic rock masses affected by discontinuities were estimated applying the generalized Hoek–Brown failure criterion [7] and employing RocLab software program [40]. The strength and deformability parameters include C (Cohesion, MPa), Φ = Cohesion (MPa) and Friction Angle in degree), σtm (Tensile Strength, MPa), σc (Uniaxial Compressive Strength, MPa), σcm (Global Strength, MPa) and Erm (Deformation Modulus (MPa).

Results

The volcaniclastic rocks (tuffs, ignimbrites, breccias and volcanic agglomerates) are classified into two geotechnical units based on their intact rock strengths (International Society for Rock Mechanics [ISRM][41]; Canadian Geotechnical Society [CGS][42]; Marinos and Hoek [39] and British Standards Institution (BS EN ISO 14689-1:[43]) viz., 1) strongly welded basaltic/rhyolitic volcaniclastic rocks (SBVc- Tb1/Tb2/ SRVc - Tr1/Tr2); these rocks have UCS values more than 25MPa (≈ >3,600 Psi), and 2) weakly welded basaltic/rhyolitic volcaniclastic rocks (WBVc- Tb1/Tb2/ WRVc - Tr1/Tr2) having less than 25MPa (≈< 3,600 Psi).

(1) Strongly welded basaltic/rhyolitic volcaniclastic rock masses (SBVc- Tb1/Tb2/ SRVc - Tr1/Tr2)

I. Intact rock characteristics

a) Physical characteristics

Water content in the strongly welded basaltic/rhyolitic volcaniclastic rock masses range from 0.298- 2.459% and unit weight (γ) from 18.843 to 25.328 KN/m3 with mean values of 1.208% and 22.778 KN/m3 respectively. The average values of dry density (ρd), porosity (n), water absorption (W.Ab), bulk specific gravity (Gs) and apparent specific gravity (A.Gs) vary from 1.917-2.481 gm/cm3, 2.698-23.257%, 1.127-12.673 %, 2.150-2.520 and 2.428-2.672 respectively (Table 3). According to the values of dry density and porosity, the rock samples belong to the class “Low” to “Moderate” density and “Low” to “High” porosity [44] respectively. The “Low” dry density values of the rocks of the study area may be attributed to the high density of voids or the brecciated mass containing vesicular fragments. On the other hand, volcaniclastic rocks containing massive fragments free from voids showed relatively higher density values.

b) Mechanical characteristics

The values of UCS test carried out in the laboratory on cubic samples range from 6.73 MPa to 77.60 MPa with an average of 42.34 MPa. The obtained results of PLT test vary from 20.51 MPa to 226.4 MPa with an average of 90.02 MPa (Table 3). The values of UCS obtained from Schmidt hammer tests in the field and laboratory show a range in values from 39.95MPa to 73 MPa and from 5.79 MPa to 67 MPa respectively. The field estimates of UCS of intact rock were also undertaken in three zones using the geological hammer and according to the procedures suggested by Marinos and Hoek [39]. The average of UCS values obtained from all testes vary from 25.71MPa to 119.38 MPa indicating that strongly welded basaltic/rhyolitic volcaniclastic rock masses are "Medium Strong" (R3) to "Very Strong" (R5) [39, 41- 43].

Table 3. Laboratory test results of the physico-mechanical characteristics of intact rock of basaltic/rhyolitic volcaniclastic rock masses (B/RVc-Tb1/Tb2, Tr1/Tr2) in the study area.

Characteristic	Property		Basaltic/rhyolitic volcaniclastic rock masses (B/RVc-Tb1/Tb2, Tr1/Tr2)			
			SBVc- Tb1/Tb2, SRVc - Tr1/ Tr2		WBVc- Tb1/Tb2, WRVc - Tr1/ Tr2	
Physical characteristics	Range /(ave.) of Wc %		0.298-2.459 / (1.208)	n=14	0.40-6.012/(3.208)	n=13
	Range /(ave.) of (γ) (KN/m3)		18.843-25.328 / (22.778)	n=13	17.394-24.704/(21.058)	n=13
	Range of ave. ρd (gm/cm3)		1.917-2.481	n=80	1.714-2.529	n=78
	Range of ave. n (%)		2.698-23.257	n=80	1.272-26.545	n=78
	Range of ave. W.Ab. (%)		1.127-12.673	n=80	0.580-15.503	n=78
	Range of ave. Gs (Ssd)		2.150-2.520	n=80	1.977-2.641	n=78
	Range of ave. A. Gs		2.428-2.672	n=80	2.184-2.850	n=78
Mechanical characteristics	σci (UCS) (in lab.)(MPa), range /(ave.)		6.73-77.60 /(42.34)	n=8	2.85-22.57/(10.59)	n=18
	σci (PLT)(MPa), range /(ave.)		20.51-226.4/(90.02)	n=14	18.50-63.19/(39.95)	n=3
	σci (SH)(MPa)	In field, range /(ave.)	39.95-73/(47.53)	F=7	7-27/(19.42)	F=7
		In lab, range /(ave.)	5.79-67/(30.06)	n=8	0.9-27.12/(15.96)	n=4
	σ_{ci} (UCS) (GH)(MPa)[(1)]		31	n=1	15, 15/(15)	n=2
	Average of σ_{ci} (UCS)(MPa) (as range)*		25.71-119.38	n=38	4.02-22.88	n=34

Wc: Water content, ave.: average, γ: Unit weight, ρd: Dry density, n : Porosity, W. Ab.: Water Absorption, Gs(Ssd): Bulk Specific gravity (Saturated-surface-dry mass) , A.Gs=Apparent specific gravity, σci: Uniaxial compressive strength of intact rock, UCS: Uniaxial compressive test in the laboratory conditions, PLT: Point Load Test, SH: Schmidt Hammer, GH: Geological Hammer,[(1):] the UCS values are estimated on intact samples of massive basaltic/rhyolitic volcaniclastic rock masses (B/RVc-Tb1/Tb2, Tr1/Tr2) in the field, * the ranges of averaged values from all strength tests (see Table 4), n: number of tested specimens/samples, F: number of the tested rock faces.

Discontinuity characteristics

Joints developed in strongly welded basaltic/rhyolitic volcaniclastic rock masses display local variation in their strikes (Fig.2); however, the present investigators could identify three principal joint sets stereographically in each zone; vertical (80° -90°), diagonal (35° -80°) and almost horizontal (<35°) (Fig. 3 and Table 2), in addition to less significant randomly oriented joints. The average spacing of discontinuities range between 0.20 m and 2 m, indicating "Moderate" to "Wide" spacing; however, the discontinuities with "Close" spacing with 0.06 - 0.20 m do occur (Table 2). Discontinuity spacing with more than 6 m is also found but is uncommon. The persistence of discontinuity show wide variation from "Very Low" (<1 m) to "Very High" (> 20 m). The "Very High" persistence is observed at the lithological contacts between the different units. The surface morphology of discontinuities is "Smooth to Slightly Rough" in ignimbrites and "Rough to Very Rough" in tuffs and tuff-breccias and also in volcanic agglomerates. These surfaces reflect the fabric or texture of these rocks. The surfaces of discontinuities are "Fresh" to "Moderately" weathered. At places, the surface is intensely weathered. Permeation of iron-rich solution along the surface of discontinuities is common as evidenced from the red stains caused by the precipitation of iron oxides. The apertures of discontinuities in most of the outcrops are tight and closed. However, some of the apertures are open and are found to have been filled by soil or secondary minerals. The infilling materials are either hard or soft. The hard infilling materials are represented by iron oxides, sands and silts and carbonates of <5mm thickness or soft in the form of friable silts, sands and carbonates with > 5mm thickness. The obtained values of volumetric joint count (Jv) ranging from 4.04 - 9.93 j/m3 indicate that the degree of jointing in strongly welded basaltic/rhyolitic volcaniclastic rock masses is "Moderate" to "high" [31]. About 83 % of Jv values of the study area signify "Moderate" degree of jointing (Table 2).

Geomechanical classification

The calculated RQD values of the strongly welded basaltic/rhyolitic volcaniclastic rock masses vary from 50.31% "Poor/Fair quality rocks" to 99.89 % "Excellent quality rocks" with an average of 89.70% "Good/Excellent quality rocks"(Table 2). Almost 67 % of the RQD values obtained belong to the class "Excellent" quality rocks (90-100%) of Deere [45]. These are mainly represented by ignimbrites and rhyolitic tuffs in the study area.

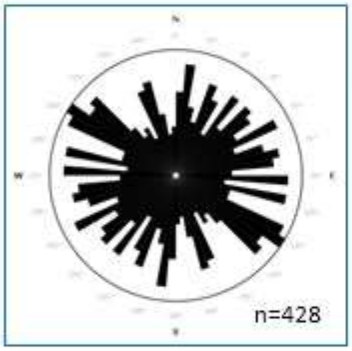

Fig.2. Rose Diagram showing the local variations in the strikes of all the surveyed joints in different zones of the strongly welded basaltic/ rhyolitic volcaniclastic rocks (SBVc-Tb1/Tb2/ SRVc - Tr1/Tr2).

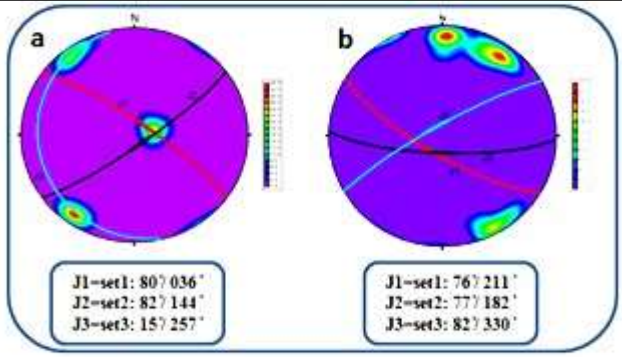

Fig.3. Two examples of equal- area stereographic projection of the main joint sets of SBVc- Tb1/Tb2/SRVc - Tr1/Tr2 rocks ; a) Three joint sets –station 5- zone I, b) Three joint sets –station 65- zone II.

The Rock Mass Rating (RMR) values vary from 52.1 to 80.3 "Fair to Good/Very Good". Almost 83% of RMRBasic89 values fall in the range of 61- 80 indicating the class "Good" rock (class-II) [3, 32] (Table 4).

The derived values from the GSI chart for the all zones of strongly welded basaltic/rhyolitic volcaniclastic rock masses affected by discontinuities are given in the Table 2.These values range from 33.57 to 72 with a mean value of 59.76. Almost 92% of GSI values for blocky strongly welded basaltic/ rhyolitic volcaniclastic rock masses vary from 41 to 72 with an average of 62.14.

The GSI chart prepared by Hoek et al [38]; Marinos and Hoek [36, 39] (Fig. 4) depict various classes based on the range of GSI values. The obtained GSI values for most part of the strongly welded volcaniclastic rock masses with "Blocky /Very Blocky" structures vary from 40 to 60 and for "Massive/Blocky" structures, the value is from 65 to 85. Based on quantified GSI values and middle values of the ranges of GSI, the strongly welded volcaniclastic rock masses are classified within the GSI range 33.57 to75.

(2) Weakly welded basaltic/rhyolitic volcaniclastic rock masses (WBVc- Tb1/Tb2/ WRVc - Tr1/Tr2)

I. Intact rock characteristics

a) Physical characteristics

In weakly welded basaltic/rhyolitic volcaniclastic rock masses, water content ranges from 0.40-6.012% with a mean value of 3.208%. The obtained values of other physical characteristics evaluation parameters are as follows: unit weight (γ) vary from 17.394 -24.704 KN/m3 with an average of 21.058 KN/m3, dry density (ρd) from 1.714 to 2.529 gm/cm3; porosity (n %) from 1.272 to 26.545%; water absorption (W. Ab %) from 0.580 to 15.503%; bulk specific gravity (Gs) from 1.977 to 2.641 and apparent specific gravity (A.Gs) from 2.184 to 2.850. According to the values of dry density and porosity, these rocks belong to "Very Low– Moderate" dry density and "Medium–High" porosity classes respectively [44] (Table 3).

b) Mechanical characteristics

The range in the values of UCS and PLT tests conducted in lab are 2.85 - 22.57 MPa and 18.50 - 63.19MPa respectively. The values of SH test carried out in the field range from 7 to 27 MPa and in the lab, the values vary from 0.9 to 27.12 MPa (Table 3). These rocks have average UCS values ranging between 4.02 MPa to 22.88 MPa which correspond to "Weak" (R2) to "Very Weak" (R1) rocks [39, 41- 43].

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Table 4. Calculation of the RMR parameters for the basaltic/rhyolitic volcaniclastic rock masses in Taiz area (after Bieniawski [32]).

St. no.	Geotech-nical sub-unit	Zone	A1		A2		A3		A4		A5		C: RMR= A1+A2+A3+A4+A5		
			Values	Rating	Values	Rating	Values (m) (min.)	Rating	Values	Rating	Values (desc.)	Rating	Rating	RMC	RMD
5	SBVc-Tb1/Tb2, SRVc - Tr1/ Tr2	I	77.60	7.8	97.03	19.4	0.44	10	From Table 2	18	C. dry	15	70.2	II	Good
10		II	40.74	4.8	96.12	19	0.37	10		14	C. dry	15	62.8	II	Good
11		I	78.36	7.9	99.89	19.9	0.53	10		23	C. dry	15	75.8	II	Good
12		I	119.19	10.8	93.86	18.7	0.39	10		23	C. dry	15	80.3	II/I	Good/V.gd
23		I	119.38	10.8	95.84	19.1	0.40	10		23	C. dry	15	77.9	II	Good
46		I	44	5	85.19	16.9	0.20	8		23	C. dry	15	68.3	II	Good
61		I	67.85	7.1	98.42	19.6	0.49	10		23	C. dry	15	74.7	II	Good
61		II	42	4.8	99.07	19.8	0.45	10		25	C. dry	15	74.6	II	Good
64		I	48.72	5.3	88.31	17.7	0.20	8		27	C. dry	15	73	II	Good
65		II	30.95	3.8	50.31	10	0.11	8		22	C. dry	15	58.8	III	Fair
75		II	38.54	4.5	74.25	14.6	0.15	8		10	C. dry	15	52.1	III	Fair
83		I	32.56	3.9	98.14	19.5	0.44	10		22	C. dry	15	70.4	II	Good
30	WBVc-Tb1/Tb2, WRVc - Tr1/ Tr2	I	4.02	1.4	98.60	19.6	0.81	15	From Table 2	9	C. dry	15	60	III	Fair
35		I	10.43	2.2	100*	20	1.01	15		16	C. dry	15	68.2	II	Good
54		III	18.36	2.7	71.29	14.2	0.13	8		23	C. dry	15	62.9	II	Good
73		I	16.23	2.6	84.12	16.5	0.18	8		12	C. dry	15	54.1	III	Fair
99		II	18.56	2.7	97.60	19.4	0.39	10		22	C. dry	15	69.1	II	Good

RMR = Basic RMR89 with no adjusting factor for joint orientation., St. no.: Station number, A1:ratings for the uniaxial compressive strength of the intact material(MPa), A2: ratings for the Rock Quality Designation (RQD %), A3: ratings for the spacing of discontinuities (average minimum spacing is taken from Table 2, according to Edelbro [46] , A4:ratings for the condition of discontinuities obtained from Table 2, A5: ratings for the groundwater condition, C.dry:Completely dry, (desc.): descriptive term, C: Rock mass rating demined from total ratings, RMC: Rock mass class, RMD: Rock mass description, (*): RQD = 110 -2.5 Jv = 100 because Jv < 4 [31], V.gd: Very good.

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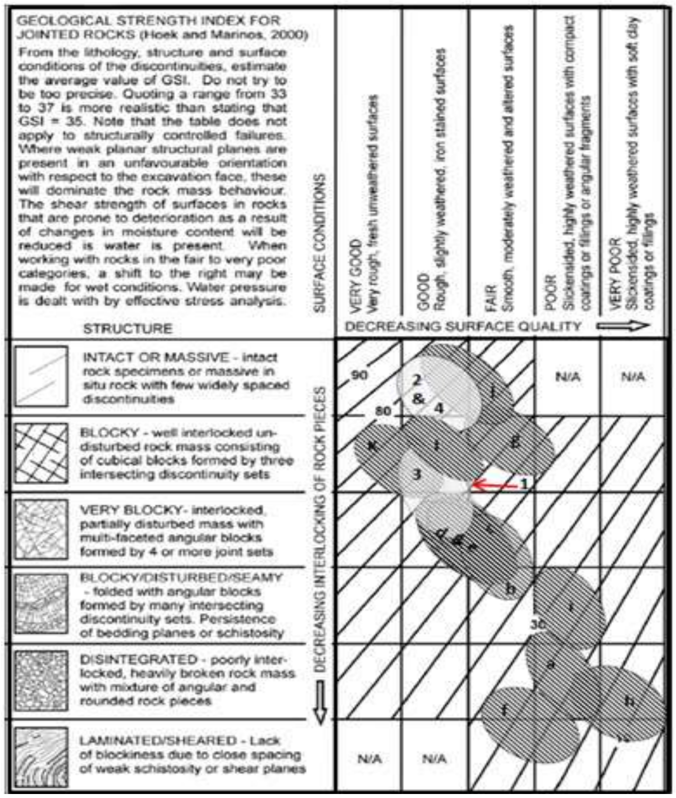

Strongly volcaniclastics (white areas)

1= station 7, zone II (GSI=55-75)	**3= station 17, zone II (GSI=50-70)**
2= station 7, zone III (GSI=65-85)	**4= station 40, zone II-2 (GSI=65-85)**

Weakly volcaniclastics (shaded areas)

a = station 1, zone II (GSI=15-30)	**g = station 46, zone II-2 (GSI=45-65)**
b= station 2, zone II (GSI=35-50)	**h= station 48, zone II (GSI=5-20)**
c = station 5, zone II (GSI=40-60)	**i = station 50, zone I-1 (GSI=20-35)**
d= station 26, zone II (GSI=40-60)	**j = station 59, zone II (GSI=65-85)**
e = station 27, zone II (GSI=40-60)	**k = station 96, zone II (GSI=60-80**
f = station 36, zone II (GSI=15-30)	**l =Station.98, zone II (GSI=55-75)**

Fig. 4 Chart showing Geological Strength Index (GSI) of the basaltic/rhyolitic volcaniclastic rock mass types recognized in some zones. (Classification Table from Hoek et al., [38]; Marinos and Hoek [36, 39]).

II. Discontinuity characteristics

Weakly welded basaltic/rhyolitic volcaniclastic rock masses occur as disjointed blocks by the development of discontinuities/joints and also as massive and compact rock masses where discontinuities are scarce. In the first case, totally 140 discontinuities were investigated at 5 representative sites using the field scanline surveys suggested by Brady and Brown [22]. Orientation (dip/dip direction) of discontinuities/joints and their characteristics and groundwater condition are measured/described following the procedures recommended by ISRM [18] (Table 2). The strikes of these discontinuities are represented in Fig.5.

Similar to strongly welded volcaniclastic rocks, these rocks are also predominately have three main sets of joints at each surveyed zone; however, the fourth joint set is also noticed uncommonly (Fig.6), in addition to minor sets of random joints. The average spacing varies from “Close” spacing to “Very Wide” spacing (from 0.13 to 2.48m). The persistence is observed from “Very Low” (<1 m) to “Very High” (> 20 m). The “Very High” persistence is noticed at the surface contacts between the varying lithological units in sequence. The morphology of discontinuity surfaces is variable with “Rough, Undulating”, “Slightly to Moderately and Highly” weathered, stained by iron oxides, dry with no evidence of water flow. The width or aperture of discontinuities range from “Very Tight or Closed” (<0.1mm) to “Moderately and Wide”(> 5mm).

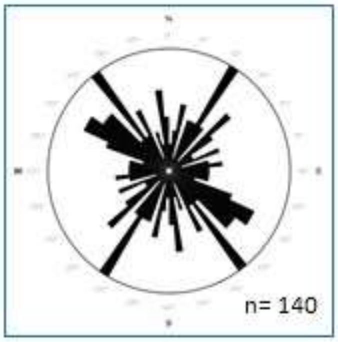

Fig.5 Rose Diagram showing the local variations in the strike of surveyed joints in the different zones of the welded weakly welded basaltic/ rhyolitic volcaniclastic rocks (WBVc-Tb1 /Tb2 / WRVc - Tr1/Tr2).

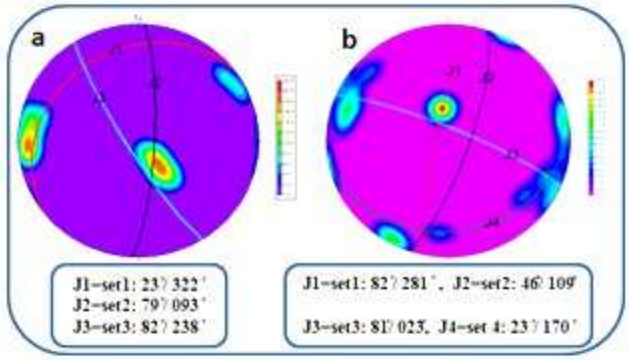

Fig.6. Two examples for equal-area stereographic projection of the main discontinuity sets in weakly welded basaltic/rhyolitic volcaniclastic rocks (WBVc-Tb1/Tb2 /WRVc-Tr1/Tr2) ; a) Three joint sets–station 99- zone II; two sets are almost vertical and on horizontal b) Four joint sets –station 30-zone I; two sets are almost vertical, one set diagonal and one set is almost horizontal.

Volumetric joint count (Jv) calculated by Equation (3) varies from 1.92 j/m3 to 15.49 j/m3 indicating "Low" to "High" degree of jointing for these rocks [31] (Table 2).

III. Geomechanical classification

The RQD values of weakly welded basaltic/rhyolitic volcaniclastic rock masses range in values between 71.29% and 100 % corresponding to the classes "Fair" and "Excellent" quality rocks respectively (Table 2).

The basic RMR89 rating values for rock masses vary from 54.1 to 69.1 (Table 4) suggesting "Fair" to "Good" quality rocks (class-III-II) respectively [3. 32].

The obtained GSI values (Table 2) for the rock types range from 40 to 70 with an average value of 54.28. About 60 % of the rocks showing this range of the GSI values exhibit blocky structure.

In the second case, where these rocks appear as massive and compact rock masses with scarce or few discontinuities, the characterization of these rocks at 12 zones were undertaken based on GSI chart as suggested by Hoek et al [38]; Marinos and Hoek [36, 39]. The weakly welded basaltic/rhyolitic volcaniclastic rock masses have wide GSI values ranging from 5 to 85 (Fig.4). GSI values of the weak volcaniclastic rock masses with laminated /sheared/ disintegrated structure classes range from 5 to 30. Rocks with blocky/disturbed structure showed GSI values from 20 to 35. Rocks showing very blocky/ blocky disturbed structure have GSI values from 35 to 60. For the weakly welded basaltic/rhyolitic volcaniclastic rock masses showing blocky structure, GSI values range from 45 to 80 and for massive/blocky structure from 65 to 85 (Fig. 4).

IV. Indirect estimates of the rock masses properties

Reliable estimates of the strength and deformation characteristics of rock masses on large-scale are required for the design of slopes, foundations and underground excavations. At present, almost all direct field tests of the deformation modulus (Erm) and shear tests are still expensive, time consuming, pose operational difficulties and the reliability of the results of these tests is sometimes questionable. Also, the laboratory tests of rock mass are difficult because the samples need be undisturbed and sufficiently of large volume to be representative of the discontinuity conditions. For these reasons, many empirical Equations have been suggested by several authors[47-63] for indirect estimates of strength and deformation modulus of rock mass. These empirical equations are based on geotechnical classification systems (GSI, RMR, Q, etc.). In this study, the strength and deformability parameters of basaltic/rhyolitic volcaniclastic rock masses affected by discontinuities were estimated applying the generalized Hoek–Brown failure criterion [7] and employing RocLab software program [40]. The input data required in this software program for calculation of rock mass parameters are: the uniaxial compressive strength of the intact rock (σci), value of the Hoek-Brown constant (mi) for the intact rock, the value of the Geological Strength Index (GSI) and the factor of disturbance (D) due to excavations or stress release. All these input parameters are shown in Table 5. By using the software, the obtained output parameters are (1) Hoek-brown classification parameters (mb, s and a), (2) Mohr-Coulomb Fit (shear strength parameters; c, φ) and (3) Rock mass parameters given in terms of compressive strength (σc), tensile strength (σtm), deformation modulus (Erm) and global strength (σcm). The obtained values of these parameters for basaltic/rhyolitic volcaniclastic rock masses investigated at 17 zones are presented in Table 6. As shown in the Table 6, the values of the cohesion- c and friction angle - φ (shear strength parameters) for the SBVc- Tb1/Tb2/ SRVc - Tr1/Tr2 vary from 0.984 MPa to 8.197 MPa and from 18.144° to 35.844° respectively while for WBVc- Tb1/Tb2/ WRVc - Tr1/Tr2 the values vary from 0.122 MPa to 1.2 MPa and from 20.706° to 36.231° respectively. The ranges of σtm, σc, σcm and Erm parameters of the SBVc- Tb1/Tb2/ SRVc - Tr1/Tr2 are (-0.008 to -1.096 MPa, 0.260-20.439 MPa, 2.717 to 32.067 MPa and 484.19 to 25097.1 MPa) respectively. These variations have a bearing on rock mass quality and properties of intact rock, and demonstrate that the values of the rock mass parameters increase with increase in the quality of rock mass and with increase in the values of the intact rock properties (Fig. 7).

Table 5. Input data used for the determination of rock mass parameters for basaltic/rhyolitic volcaniclastic rock masses in the study area.

Geotechnical sub-unit/unit and abbreviation	No. investigated* zones	σci (MPa)	GSI	mi	D
Strongly basaltic/rhyolitic volcaniclastic rocks (SBVc- Tb1/Tb2/ SRVc - Tr1/Tr2)	4	Table 4	Table 2	10(1)/13/19	0/0.7
Weakly welded basaltic/rhyolitic volcaniclastic rocks (WBVc- Tb1/Tb2/ WRVc - Tr1/Tr2)	12	Table 4	Table 2	13/19	0/0.7

*: The investigated zones in strongly/weakly basaltic/rhyolitic volcaniclastic rocks affected by discontinuities, σci (MPa): Uniaxial compressive strength of intact rock obtained from Table 4, GSI: Geological Sstrength Index obtained as precise values (Table 3), mi = Intact rock constant estimated according to rock type and based on Table proposed by Hoek and Brown (1997) and Hoek (2007). (accordingly, 19 for volcanic breccias and volcanic agglomerates and 13 for volcanic tuffs), (1): This value of im was used for ignimbrite as reported in some litterateurs such as del Potro and Hürlimann [10], D: disturbance factor; here, D= 0 for undisturbed in situ rock mass, 0.7 for partially disturbed in situ rock mass and based on the guidelines recommended by Hoek, et al [7] and Hoek [64].

Table 6. Results of estimated basaltic/rhyolitic volcaniclastic rock mass properties in Taiz city and its surrounding following the GH-B failure criterion.

St. No.	Geotech-nical sub-unit	Zone	Hoek-Brown classification			Mohr-Coulomb fit		Rock mass parameters(MPa)			
			mb	s	a	C (MPa)	Φ (deg)	σtm	σc	σcm	Erm
5	SBVc-Tb1/Tb2, SRVc - Tr1/ Tr2	I	1.565	0.0075	0.502	3.97	29.859	-0.372	6.667	13.714	6587.9
10		II	0.978	0.0011	0.505	1.665	26.145	-0.045	1.302	5.345	1580.96
11		I	3.679	0.0446	0.501	5.823	36.871	-0.949	16.48	23.292	18067.1
12		I	3.114	0.0265	0.502	8.02	35.561	-1.015	19.292	31.182	24339.4
23		I	3.227	0.0296	0.502	8.197	35.844	-1.096	20.439	32.067	25097.1
46		I	2.327	0.0107	0.503	2.547	33.205	-0.203	4.491	9.423	6615.12
61		I	1.356	0.0051	0.502	3.257	28.709	-0.257	4.812	10.996	5024.03
61		II	2.389	0.0115	0.501	2.473	33.415	-0.202	4.469	9.188	4099.74
64		I	2.974	0.0075	0.502	2.978	35.369	-0.123	4.186	11.53	6893.53
65		II	0.743	0.0002	0.511	1.103	23.955	-0.008	0.393	3.394	953.81
75		II	0.338	0.0001	0.518	0.984	18.144	-0.008	0.264	2.717	484.19
83		I	1.258	0.0021	0.503	1.472	28.16	-0.055	1.466	4.914	1685.68
30	WBVc-Tb1/Tb2, WRVc - Tr1/ Tr2	I	0.481	0.0002	0.511	0.122	20.706	-0.001	0.047	0.352	70.23
35		I	4.453	0.0357	0.501	0.78	38.656	-0.084	1.961	3.247	2292.98
54		III	1.194	0.0018	0.504	0.813	27.735	-0.028	0.77	2.691	895.7
73		I	0.574	0.0003	0.509	0.531	22.02	-0.008	0.246	1.576	341.73
99		II	3.307	0.0141	0.503	1.2	36.231	-0.079	2.183	4.731	3106.29

GH-B: Generalized Hoek-brown failure criterion, mi, mb, s and a =Material Constants, C and Φ = Cohesion (MPa) and Friction Angle (deg.) respectively, σtm = Tensile Strength (MPa), σc = Uniaxial Compressive Strength (MPa), σcm= Global Strength (MPa), Erm=Deformation Modulus.

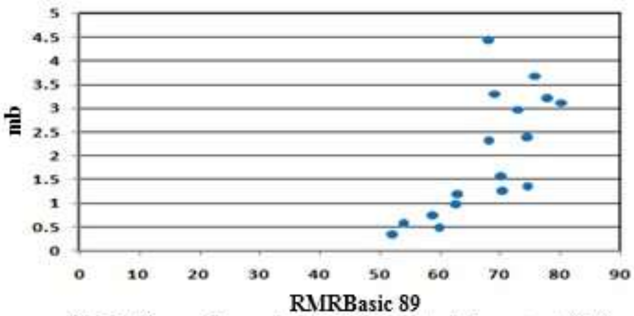

Fig.7a. Shows the variation of the material constant (mb) with increase of the RMRBasic 89 for B/R Vc Tb1-Tb2/Tr1-Tr2) in the study area.

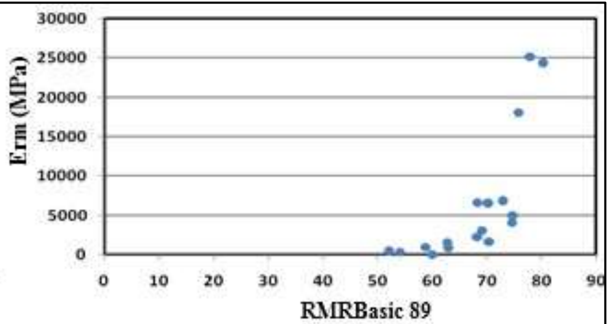

Fig.7b. Shows the increasing of the Deformation Modulus (Erm) with increase of the RMRBasic 89 for B/R Vc Tb1-Tb2/Tr1-Tr2) in the study area.

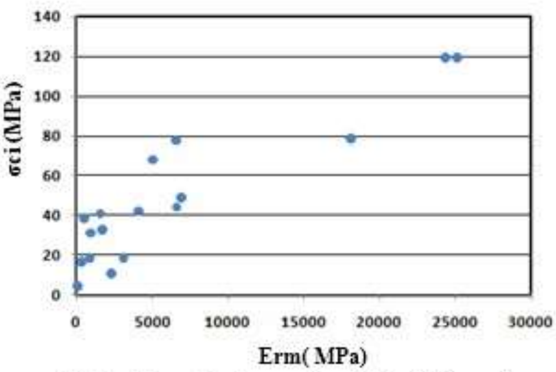

Fig.7c. Shows the increasing of the Deformation Modulus (Erm) with increase of the uniaxial compressive strength (MPa) of intact material (σci) (MPa) for B/R Vc Tb1-Tb2/Tr1-Tr2) in the study area.

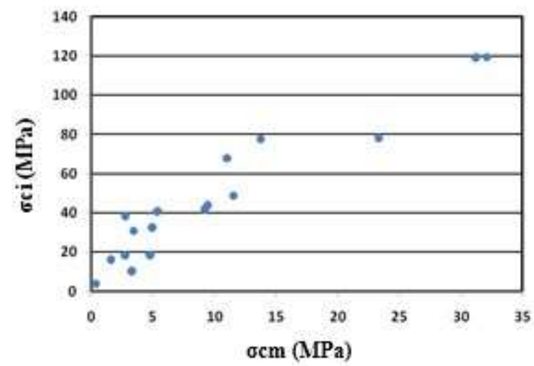

Fig.7d. Shows the increasing of the Global strength (σcm) (MPa) with increase of the uniaxial compressive strength (MPa) of intact material (σci) (MPa) for for B/R Vc Tb1-Tb2/Tr1-Tr2).

Summary And Conclusions

The present study deals with the rock mass characterization and evaluation of geo-engineering properties of Tertiary volcaniclastic rock masses of Taiz area in Yemen for the first time based on the field and laboratory investigations. The study area consists of strongly and weakly welded basaltic/rhyolitic volcaniclastic rock masses. Physico-mechanical behavior of these rock masses was evaluated by studying intact rock characteristics and characteristics of discontinuity in addition to employing Rock Mass Rating (RMR) and Geological Strength Index (GSI).

The basaltic/rhyolitic volcaniclastic rocks are heterogeneous material with low to high porosities and low to moderate densities. The rocks have high levels of water absorption depending on the size, the shape and petrological composition of the grains/fragments in addition to the type of matrix, the degree of packing between all components and the degree of consolidation and compaction state of these deposits.

Welded ignimbrite show higher UCS values while volcanic agglomerates, volcanic breccias, tuffs and weathered ignimbrites are characterized by lower values. The uniaxial compressive strengths of these geological units are expected to be more because the tests were carried out on submerged rock samples in water for 24 hours wherein they may lose their strengths by an average of 30%. RMR showed that the geotechnical subunits have wide range in their qualities and belong to well established classes from “Fair” to “Good” or “Very Good”.

The modified quantitative GSI system applied here provided useful information about rock mass characteristics that can be used at all stages of any engineering project in the study area, especially at the preliminary design stage where only limited information is available. GSI values of the strongly welded basaltic/rhyolitic volcaniclastic rock masses and the weakly basaltic/ rhyolitic volcaniclastic rock masses show wide ranges from 33.57 to 85 and from 5 to 85 respectively.

GSI index was also used in the generalized Hoek–Brown failure criterion to calculate the rock mass parameters. The values of these parameters for the strongly/weakly welded basaltic/rhyolitic volcaniclastic rock masses are varied, depending on rock mass quality and properties of intact rock. It is observed that the values of the rock mass parmeters increase with increase in the quality of rock mass and with increasing values of the intact rock properties.

The occurrence of the weakly welded volcanic rocks within Tertiary volcanic sequences plays an important role in causing instability of rock masses in the study area due to their geological features and geotechnical characteristics. The results of this study recommend that for designing and construction of any engineering structures, especially underground openings within the domain of the Tertiary volcanic rock masses, subsurface investigations and laboratory tests are essential due to the unexpected variations in the geotechnical conditions of the rocks as established from the wide range in the values of the various geotechnical parameters and their behaviors especially where these rocks are stratified or highly fractured or/and intercalated with weak volcanic accumulation materials.

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