Geoengineering Characterization of the Basaltic Lava Rock Masses in and around Taiz City, Yemen

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ABSTRACT
Engineering properties of the rocks play an important role for designing urban infrastructures in natural hazard prone areas. The entire Taiz city in Yemen is built on volcanic flows and their variants. This paper presents the first report on the description and the engineering characteristics of the Tertiary basaltic lava rock masses in and around Taiz city, Yemen. Geoengineering assessment was made by well established direct and indirect approaches. The direct approach involved the evaluation of physical and mechanical characteristics as well as discontinuity measurements of 23 representative outcrops and field tests. The indirect approach is comprised of characterization of rock masses using Rock Mass Rating (RMR) system and determination of Geological Strength Index (GSI), shear strength parameters (c, φ), compressive strength (σcm), tensile strength (σtm) and deformation modulus (Erm) of the jointed basaltic lava flow rock masses using the generalized Hoek–Brown criterion employing RocLab software program. The basaltic lava flow rocks unit is subdivided into two geotechnical subunits based on field observations viz., (1) jointed basaltic lava flow rocks (JBL-Tb1/Tb2) and (2) massive basaltic lava flow rocks (MBL-Tb1/Tb2). Each subunit was further subdivided into zones based on lithology and rock mass structural properties. The attitude of discontinuities was found varying from one location to another. Stereographically, at each investigated site three or four joint sets are identified in addition to other joints orientated randomly. Most of discontinuities strike in NE-SW and NW-SE directions following the trends of the regional faults. According to Jv j/m3, the jointed lava rock masses show moderate to very high degree of jointing while the massive lava rock masses posses low degree of jointing. The jointed basaltic lava flow rocks in the investigated sites also show wide variations in the range of geo-engineering characteristics. For example, values of the shear strength parameters (c and φ) and the other rock mass parameters (σtm, σc, σcm and Erm) increase with increase in the quality of rock mass and with increasing values of the intact rock properties.

Keywords
Volcanic rocks, Jointed basalt, Massive basalt, geotechnical characterization, Taiz city.

1. INTRODUCTION
Taiz city, located in the middle of the Central Highlands of Yemen is bound by the latitudes 13° 31' 49"N - 13° 44' 29"N and longitudes 43° 54'17" E - 44° 09' 04"E (Fig. 1). Taiz city and its surroundings are covered by Tertiary bimodal volcanic deposits (basic and felsic deposits) and associated intrusions (granitic plutons, dykes and sills) as well as sediments of Quaternary and Recent origin. The basaltic lava flows are very common geological formation in Taiz area and cover 153 sq.km of the total area of 390 sq km. Taiz city is rapidly expanding and more buildings and water tanks are being constructed on Tertiary rock masses in addition to the existing ones. Landslides and damages to the buildings due to the collapse of the foundation as well as badly cracked walls in the homes, roads, sidewalks etc., are vivid pictures of the city which have kept the citizens to constantly worry for their lives and properties. Knowledge of geological, geotechnical and engineering geological characteristics of these materials are essential in order to save the lives and properties of the innocent citizens. Apart from the varied distribution of different rock types, heterogeneity of the geological properties of rock masses is very significant in geoengineering issues [1]. At times, a single rock mass subjected to variable degree of weathering within a limited area presents uncertainty thus warranting in depth study of the field and mechanical properties of the rock.

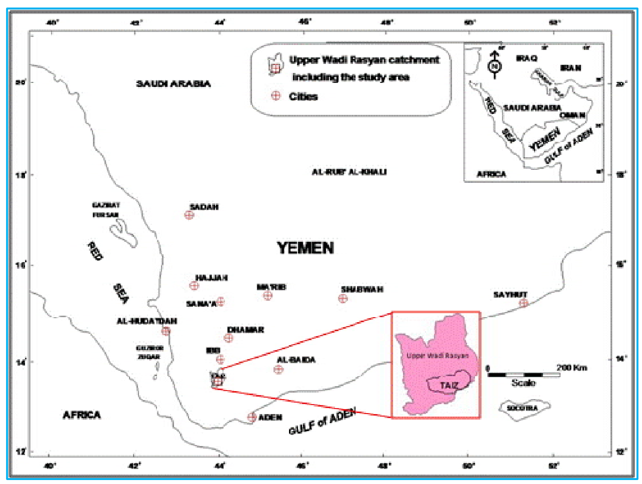

Fig. 1. Location map of the study area

This paper aims to derive geotechnical data regarding the Tertiary volcanic basaltic lava rock masses in and around Taiz city, Yemen by direct (field and laboratory investigations) and indirect approaches. Well established methods such as the Rock Mass Rating (RMR) system and Geological Strength Index (GSI) for characterization of basaltic rock masses were adopted, in addition to the estimation of the strength and deformability of these rocks using the generalized Hoek–Brown criterion.

2. GEOLOGY OF THE STUDY AREA

The study area is covered by Tertiary bimodal volcanic materials and associated intrusions (granite pluton of Sabir, mafic and felsic dykes and sills) and Quaternary and recent sediments.

Tertiary bimodal volcanic materials are represented by alternating sequences of volcanic lava flows and volcaniclastic deposits of variable composition ranging from the mafic to the silicic types. These sequences of volcanic lava flows and volcaniclastic deposits which were erupted in five phases (three mafic phases (Tb1, Tb2 and Tb3), and two silicic phases (Tr1 and Tr2)) in a repeated manner are, from bottom upwards composed of (1) Tertiary lower mafic sequence (Tb1), (2) Tertiary lower silicic sequence phase (Tr1), (3) Tertiary middle mafic sequence phase (Tb2), (4) Tertiary upper silicic sequence phase (Tr2) and (5) Tertiary upper mafic sequence phase (Tb3) (exposed outside the present study area)(Fig. 2). The volcanic sequences range in age from the Oligocene to the lower Miocene [2].

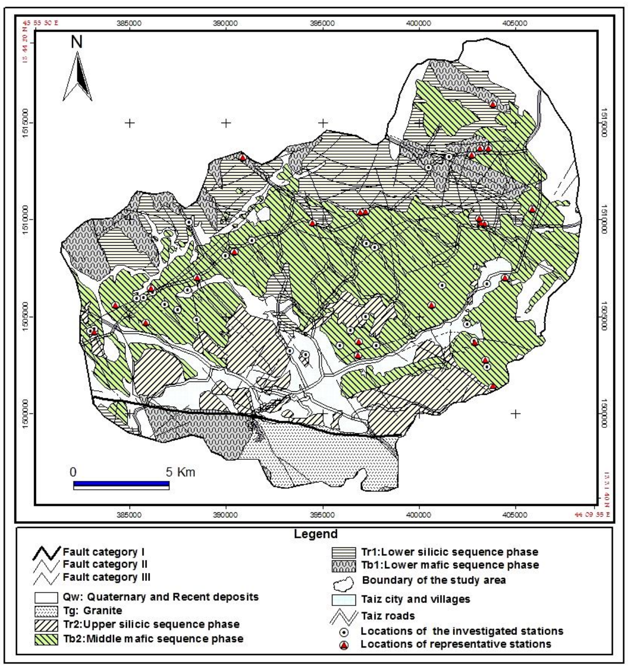

Fig. 2. Geological map of the study area, including locations of the investigated stations (modified after [3, 4, 5, 6]).

Tb1 sequence corresponds to the oldest volcanic phase and consists of basaltic lava flows and associated basaltic volcaniclastic materials. Basaltic lava flows occur interbeded /alternated with varicoloured basaltic volcaniclastic materials. These rocks display varying colours ranging from dark grey in fresh surface to chocolate brown or dark reddish brown on outer weathered/altered surface. In most location, various kinds of joints (irregular, columnar joints...etc) have developed in basaltic lava flows dividing the rocks into huge blocks which are strong as well as very angular, with sharp edges, due to the largely fine texture. These rocks at places display porphyritic,texture especially due to the presence of the plagioclase and/or olivine phenocrysts which are visible by naked-eye even on the hand specimens [6].

Tb2 similar to Tb1 are extruded primarily through the feeders like- dykes and are represented by basaltic lava flows and volcaniclastic deposits. They are separated from Tb1 by a volcanic silicic phase. In the study area, the rocks and deposits of Tb2 have a greatest areal extent of all other units in Taiz area with a thickness of about 100 m, and cover 39.61 % of total area (Fig.2). They form the undulating plains inside Taiz plain area and are dissected by major Wadis. The most important feature of Tb2 is its occurrence as alternating sequence of more than one lava flow (in most states) with widely varying characteristics viz., colour, heterogeneity, discontinuity, thickness, horizontal attitude, weathering/alteration, intercalation and repetition with depth. These heterogeneities are noticed even within the same site, in both vertical and horizontal directions, and are attributed to the eruption type, mode of transport, distance travelled from the vent, temperature of the deposits, particle size, water content and paleorelief of older silicic sequence [6].

Petrographically, Tb1 and Tb2 show (1) a variety of textures including porphyritic, glomeroporphyritic, trachytic texture or flow structure and the vesicles/ amygdales structures, 2) growth zoning in plagioclase with oscillatory variations in composition characterises, 3) microfractures intersecting olivine and/or plagioclase phenocrysts and the fine groundmass and (4) the alteration of olivine phenocrysts at their rims and along cracks into iddingsite.

3. METHODOLOGY

3.1 Field Procedures

Site investigations were carried out on exposures of Tb1 and Tb2 along road cuts and on the natural rock outcrops at 47 locations; 23 of them were selected to be representative field stations or sites. At each representative site, the rock mass was divided into a number of rock mass units or zones (27 zones) based on change in lithology and rock mass structural properties and according to the guidelines followed by Bieniawski [7]. Field Scanline (tape) surveys [8] were carried out to record discontinuity in three dimensions (as possible) and the following characteristics were recorded according to the procedures recommended by ISRM [9]: orientation or attitude of discontinuity (dip/dip direction (deg.)), persistence (m), aperture (mm), roughness, state and thickness of filling material, water flow and wall weathering. The rock mass description sheet and the discontinuity survey data sheet were used for this purpose as suggested by Anon [10]. The discontinuity orientations data was plotted stereographically (equal-area stereographic projection) using RockWorks/14 (Rock-Ware, [11]), and the joint sets were distinguished for all scaline data and then the pole concentrations were contoured. According to del Potro and Hürlimann [12], the maximum density points or average density on the contour diagram were selected as the best representation of the orientation of each discontinuity set. The mean discontinuity spacing was calculated for each recognized discontinuity set. Occurrence of more than one set of discontinuity and the existence of more complicated jointing patterns prompted the present investigators to give the lowest (minimum) rating for spacing [13]. Where the measurements are possible on the rock exposures in three dimensions, the volumetric joint count (Jv) is measured. It was measured from the joint set spacings within a volume of rock mass [14, 15, 16] and [17, 18]. Random joints are included because they represent a significant part of the number of measured discontinuities, neglecting them would lead to erroneous quantifications of the discontinuity nature of rock mass [19]. As suggested by Palmström [14], the spacing of 5m for each random joint was taken, thus, the volumetric joint count (Jv) can be generally expressed as

Jv = 1/S1+1/S2……….1/Sn + Nr (5√A) …………… (1)

where S1, S2 and S3 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 m2. In this study, the obtained values of Jv index were used to determine the Rock Quality Designation (RQD) [20] based on the following Equation:

RQD=110 - 2.5 Jv …………… (2)

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

Geomechanics classification system known as Rock Mass Rating (RMR) [21, 7] was employed in this study for geotechnical characterization of basaltic rock masses in the field. The input basic parameters of Rock Mass Rating (RMR) [7] are six. They are: Uniaxial compressive strength of intact rock (UCS) (A1), Rock quality designation (RQD) (A2), Spacing of discontinuities (A3), condition of discontinuities (A4), groundwater condition (A5) and orientation of discontinuities (A6). These parameters (Excluding the sixth parameter-A6) were obtained numerically/descriptively for the various investigated zones. Only the first five parameters ratings (with no adjustment for discontinuity orientation) are calculated for RMR76 and RMRBasic 89 based on the Tables given by Bieniawski [21] and Bieniawski [7] respectively. Here, the accurate ratings of A1 (uniaxial compressive strength) and A2 (RQD) were determined using the charts suggested by Bieniawski [7] (Figs. 3a and 3b).These charts are helpful for borderline cases and also remove an impression that abrupt changes in ratings occur between categories. The sum ratings of five parameters (A1+A2+A3+A4+A5) yield the RMR values (C: RMR).

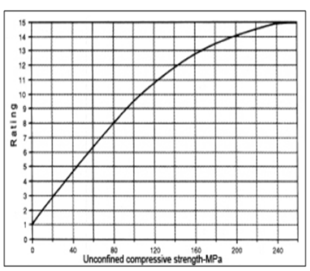

Fig.3a. Variation of rating for the uniaxial compressive strength (After [7]).

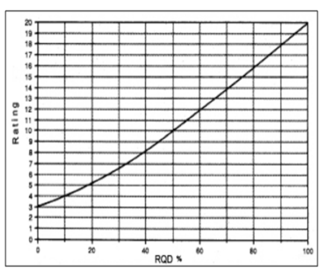

Fig.3b. Variation of rating for the RQD (After [7])

The Geological Strength Index (GSI) system was also applied in this study for characterization of Tertiary basaltic lava rock masses. A quantitative numerical basis to estimate more precise values was provided by Hamasur [22]. This quantitative rock mass classification was modified after Hoek et al., [23], Hoek [24], Marinos and Hoek [25] and Sonmez and Ulusay [26]. The main components 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 following Equation:

SR= 100-17.5322lnJv …………… (3), where Jv is volumetric joint count (J/m3).

Surface condition rating (SCR) is estimated from sum of the roughness, weathering and infilling materials ratings; which are an assessed visually in the field. Because the GSI is based on the RMR76 [23], then the roughness, weathering and infilling ratings (SCR) must be based on the RMR76, in which the sum of these three parameters ranges from 0 to 15 [22]. The intersection of these ratings (SCR and SR) on the modified quantitative GSI chart gives precise value of GSI. The derived values from the GSI chart for the various investigated sites are given in the Tables. Finally, at representative sites, rock block samples also were selected for the geotechnical laboratory tests.

3.2 Laboratory Procedures

The physical characteristics of the Tertiary basaltic lava flow rocks were determined in the laboratory on rock specimens prepared from rock block samples collected from the investigated representative sites. The water content (Wc), unit weight (γ), dry density (ρd), porosity, water absorption (W. Ab), bulk specific gravity (Gs) and apparent specific gravity (A.Gs) tests were carried out according to suggested methods by the ISRM [27]. The mechanical characteristics include uniaxial compressive strength (UCS), Point load test (PLT) and Schmidt Hammer rebound test, (SH) (in the field and lab.). These tests were performed as per the procedures prescribed by many researchers and organizations. [9, 28, 29, 30, 31]. All these geotechnical tests were performed in the materials laboratory of Sheba General Contracting Co. Ltd, main branch, Taiz, and in Technical institute, Al-Hassib, Taiz, Yemen.

The point load strength (PLS) test was used as cheaper and effective alternative to the UCS test when the rock specimen for UCS tests could not be obtained from rock exposures. This test was carried out on geometrical form rock samples (regular specimens) or /and irregular lumps in the laboratory and according to Brook [29] and ISRM [30].The following relationship between the PLS and UCS and suggested by Rusnak and Mark [32] was used:

UCS = 21*Is (50) …………… (4), where Is (50) = Point load strength index of a specimen of 50 mm diameter.

Schmidt hammer tests using an N-type hammer were undertaken on some of exposed rock faces (10 zones), as suggested by Barton and Choubey [31] as well as on rock samples (as geometrical forms- 5 rock samples) in the laboratory. To get Schmidt hammer rebound number, initially ten impact readings were undertaken in each case, and the average of the 5 highest readings taken to represent a mean rebound value (r) [9]. The N- type rebound data obtained were converted to L- type data using the following empirical correlation developed by Ayday and Grktan [33]:

Rn (N) =7.124 +1.249Rn (L), (r2 = 0.882) …………… (5)

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 Deere and Miller [34]. The UCS of intact rock in some sites was also estimated in the field based on the geological hammer and according to suggested procedures by ISRM [35], CGS [36], Marinos and Hoek [37].The study of the physo-mechanical properties of the Tertiary basaltic rock masses is based on block samples weighting between 30 to 50 kg and with a minimum thickness of 10 cm to allow cubing of samples. On pieces of these block samples; the physical characteristic tests were performed in the laboratory. Before tests, the rock samples prepared as geometrical forms were immersed in water for 48 hours for the purpose of testing their strengths in the worst situation. The results of the all mechanical properties of basalt samples are explained on section in Table 2.

Based on the pervious obtained data field measurements and laboratory tests, the generalized Hoek–Brown failure criterion [38] is applied for estimating the strength and deformability of the Tertiary jointed basaltic lava rock masses in and around Taiz city, employing RocLab software program [39]. In applying the Hoek and Brown criterion to achieve this task, three parameters are required (as input parameters). These are: uniaxial compressive strength (σci) of the intact rock pieces, value of the Hoek-Brown constant (mi) for these intact rock pieces, and value of the Geological Strength Index (GSI). The σci is obtained from laboratory and/or field tests. The quantified geological strength index (GSI) values were obtained as mentioned before. The intact rock constant (mi) was estimated according to rock type and then quoted from the Table proposed by Hoek and Brown [40] and Hoek [41]. Accordingly, the intact basalt constant (mi) is 25. The disturbance factor (D) which depends upon amount of stress relaxation, weathering, and blast damage associated with the method of excavation has been taken into account in the 2002 version of the Hoek-Brown criterion [38]. The value of D ranges from 0 to 1 and represents a progressive transition between the criteria for disturbed and undisturbed rock masses [38]. Here, based on the guidelines recommended by Hoek, et al. [38] and Hoek [41], the estimated D value used in generalized Hoek–Brown failure criterion is 0.7 (partially disturbed). Also the intact rock deformation modulus (Ei) is required as input value for the determination of the rock mass deformation modulus. In this study, no direct values of the intact modulus (Ei) are available so these values were also estimated using average values of modulus ratio MR of intact rock which are obtained from the Table modified by Hoek and Diederichs [42], based on Deere [43] and Palmstrom and Singh [44]. Accordingly the MR value for intact basalt is 350. This value also is entered into RocLab software program [39] for calculating the rock modulus or modulus of elasticity (Ei).

The parameters (input parameters; sigci, GSI, mi, D and MR) related to basaltic geotechnical subunits were entered into RocLab software (Fig.4a) to compute the values of the rock mass properties (c, phi, sigt, sigc, sigcm and Erm) (as output parameters) (Fig. 4b).

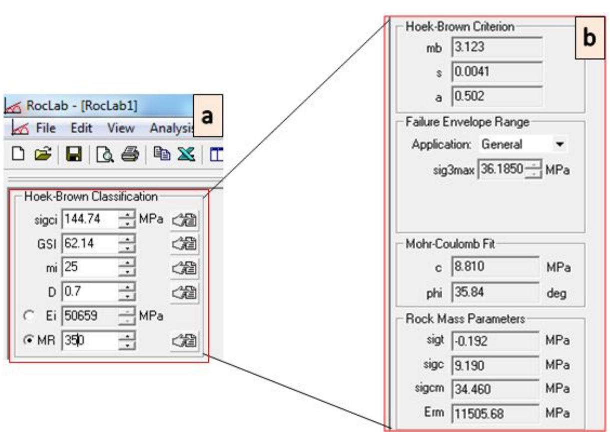

Fig. 4. Left bar of RocLab software; a) Input parameters (sigci, GSI, mi, D and MR), b) Output parameters ((the Generalized Hoek-Brown failure envelope parameters; mb, s and a),(Equivalent Mohr-Coulomb Parameters; C, phi) and (other Rock Mass Parameters; Sigt, Sigc, Sigcm and Erm)). Here, the values of sigci, GSI, mi, D and MR for the basalt at station no. 1-zone III were entered into RocLab software as example for estimation of rock mass properties as listed in the sidebar (b).

4. RESULTS

4.1 Geotechnical Characteristics of Basaltic Lava Rock Masses (BL-Tb1/Tb2)

For the geo-engineering purposes, the lavas belonging to Tertiary lower and middle mafic sequence phases (Tb1and Tb2) can be grouped into one main geotechnical unit [45, 12] on the basis of similar physical characteristics or distribution in the field. This can be termed as basaltic lava flow rock masses (BL-Tb1/Tb2). Here, the term “lavas” are used to describe the jointed /massive part of a volcanic sequence and also included are all small intrusions (dykes and sills) which show similarities in their characteristics to lavas. Basaltic lava flow rock masses (BL-Tb1/Tb2) are more frequent at the top of Tertiary volcanic sequences than at different levels in the sequences and often they are present as alternated/intercalated beds with varicoloured volcaniclastic deposits vertically and/or laterally. The basaltic lavas are represented by olivine basalt and trachybasalt. A detail account on the geological and petrographical features of these rocks is reported by Al-Qadhi et al. [6]. In the field, two types of basaltic lava flow rock masses were identified as geotechnical subunits. These are: jointed basaltic lava flow rocks (JBL-Tb1/Tb2) (irregular and columnar joints), and massive basaltic lava flow rocks (MBL-Tb1/Tb2) (contain widely spaced joints and fractures). The field descriptions of two subunits and their geotechnical characteristics are illustrated in the Table 1.

The mechanical behaviour of rock mass is governed by both intact rock characteristics and characteristics of discontinuities which are interrupting that rock mass.

4.1.1 Intact rock characteristics

4.1.1.1 Physical characteristics

The principal parameters to evaluate the physical characteristics of intact materials considered here are: Dry density (ρd g/cm3), porosity (n%), water absorption (W. Ab %), bulk specific gravity (Gs) and apparent specific gravity (A.Gs). These properties were determined for 83 rock specimens taken from jointed/columnar basaltic lavas and from massive basaltic/trachy-basaltic lavas. The obtained mean minimum and maximum values of the above mentioned parameters are 2.464-3.073 g/cm3; 1.450 -7.554 %; 0.499-3.360%; 2.539-3.051 and 2.654-3.131 for jointed/columnar basaltic lavas while the values of these properties for massive basaltic/trachy-basaltic lava rock masses are 2.530 g/cm3, 8.377 %, 3.319 %, 2.614 and 2.761 respectively. According to values of dry density and porosity the JBL -Tb1/Tb2 rocks are described as moderate to very high dense with medium to low porosity while MBL -Tb2 is described as moderate dense and medium porosity rock [46]. The ranges of unit weight (γ KN/m3) vary widely from 24.5 KN/m3 to 30.3 KN/m3 for jointed/columnar basaltic lavas while the massive basaltic/trachy-basaltic lava rock has 25.20 KN/m3 (Table 2).

Table 1. Summary of field descriptions for geotechnical subunits identified in the study area.

Basaltic lava flow rocks (BL- Tb1/Tb2)	Jointed/massive basaltic lava flow rocks (J/MBL -Tb1/Tb2)	Chocolate-brown or dark reddish brown (on weathered /altered surface) to dark greenish grey coloured (on fresh surface), fresh to slightly and moderately to highly weathered (W1-W2, W3-W4), porphyritic/ fine grained and vesicular, weak to very strong, fractured basaltic lava flows. The joints either irregular (a) or columnar (b). 3 and 4 close to wide spacing (as average), smooth to very rough joint sets, with very low to very high persistence forming cubic, prismatic, columnar, tabular or/and rhombohederal lava blocks. Joints either tightly closed with iron-oxides stain, or moderately wide with thick hard/soft infill (<5- >5 mm). Lava flows lie on surface with different orientations or attitudes Generally no seepage or evidence of water flow.	a  b 
	Massive basaltic lava flow rocks (MBL-Tb1/Tb2)	Chocolate-brown or dark reddish brown (on weathered /altered surface) to dark greenish grey coloured (on fresh surface), fresh weathered (W1), porphyritic / fine grained / trachytic, moderately strong, massive basaltic lava flows. 3 wide spacing (as average), very rough joint sets, with medium persistence. Joints either tightly closed with iron-oxides stain, or moderately and wide with thick hard infill (>5 mm). Lava flows lie on surface with different dips and directions. Generally no seepage.	

Table 2. Laboratory test results of some physical-mechanical characteristics of intact rock of basaltic lava flow rock masses (BL-Tb1/Tb2) in the study area.

Characteristic	Property		Basaltic lava flow rock masses(BL-Tb1/Tb2)			
			JBL-Tb1/Tb2		MBL- Tb2	
Physical characteristics	Range /(ave.) of Wc %		0.383-1.475 / (0.888)	n=12	1.712	n=1
	Range /(ave.) of (γ) (KN/m3)		24.5-30.3 / (27.85)	n=12	25.20	n=1
	Range of ave. ρd (gm/cm3)		2.464-3.073	n=74	2.530	n=9
	Range of ave. n (%)		1.450-7.554	n=74	8.377	n=9
	Range of ave. W.Ab. (%)		0.499-3.360	n=74	3.319	n=9
	Range of ave. Gs (Ssd)		2.539-3.051	n=74	2.614	n=9
	Range of ave. A. Gs		2.654-3.131	n=74	2.761	n=9
Mechanical characteristics	σci (UCS) (in lab.)(MPa), range /(ave.)		26.40-75.68/(43.89)	n=5	17.56	n=1
	σci (PLT)(MPa), range /(ave.) (1)		2.09-291.98/(107.08)	n=19	34.73	n=1
	σci (SH)(MPa)(2)	In field, range /(ave.)	13.5-79.58/(51.50)	n=8	16	n=1
		In lab, range /(ave.).	24-60/(37.36)	n=4	-	-
	σ_{ci} (UCS) (GH)(MPa)		15,175(95)	n=2	-	-
	Average of σ_{ci} (UCS)(MPa) (as range)*		13.05-216.72	n=38	22.76	n=3

JBL.: Jointed Basaltic Lava rock mass, MBL: Massive Basaltic Lava rock mass , 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, UCS: Uniaxial compressive test in the laboratory conditions, PLT: Point Load Test, (1): these values are obtained using Equation (4) SH: Schmidt Hammer, (2): the values were converted using Equation (5) and depending on a chart proposed by Deere and Miller[34], GH: Geological Hammer,* the ranges of averaged results from all strength tests (see Table 4), n: number of tested specimens.

4.1.1.2 Mechanical characteristics

The mechanical characteristics evaluated indicate that the uniaxial compressive strength, σci (UCS) (MPa) values of jointed/columnar basaltic lava rocks vary from 26.40 to 75.68 MPa (ave. 43.89MPa). These values indicate a moderately strong to strong rocks [47]. The massive basaltic/ trachy-basaltic lava rock has an average strength of 22.76 MPa (from all strength test types); this value corresponds to a moderately strong rock [47] (Table 2).

Schmidt hammer σci (UCS) (SH) (MPa) values (in the laboratory and field) obtained based on Equation (5) and chart proposed by Deere and Miller [34] indicate also a moderately strong to strong jointed/columnar basaltic lavas [47]. From Table 2, the lower strength values from Schmidt hammer (SH) test compared with strength values computed by point load test (PLT) for jointed/columnar basaltic lavas may probably reflect the sensitivity of the Schmidt hammer to surface alteration of the materials in the field and size of the rock sample in the laboratory.

The strength values obtained from the uniaxial compressive strength (UCS-lab), point load test (PLT), Schmidt hammer (SH) and geological hammer (GH) were averaged and used as one of parameters required in rock masses classification (Rock mass Rating system, RMR) and for calculations of the properties of rock masses.

4.1.2 The discontinuity characteristics

For the evaluation of the characteristics of the discontinuities in the jointed/massive basaltic lava rock masses (J/MBL-Tb1/Tb2), 23 representative outcrops were selected as field survey stations (27 zones). The scanline surveys were done in three directions[8] and the following parameters were recorded along each scanline and for each joint (totally 1433 joints; 1413 in JBL and 20 in MBL), according to ISRM [9]: Orientation of the discontinuities (dip and dip directions), average spacing, persistence, aperture, roughness, infilling, wall weathering, ground water condition (Table 3). The main joint sets were identified by plotting the orientation data stereographically using RockWorks/14 [11].

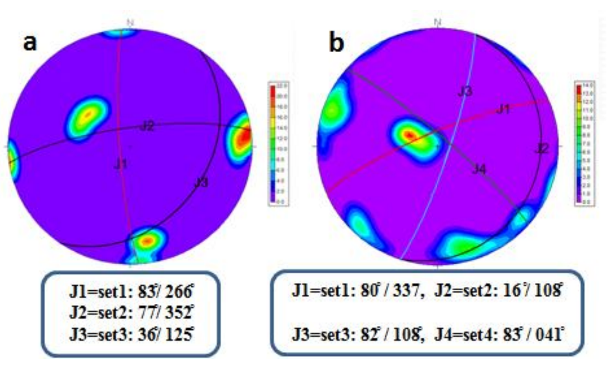

Fig. 5. Two examples for equal-area stereographic projection used for identify the main discontinuity sets in jointed basaltic lava rocks (JBL-Tb1/Tb2); a) Three joint sets –station no. 10-zone I, b) Four joint sets –station no. 14-zone I.

JBL-Tb1/Tb2: In each zone of jointed basaltic lava rocks, three principal joint sets were identified in addition to random joints which have produced different sized and shaped blocks; at places, four principal joint sets were also identified in some zones (Fig. 5 and Table 3). In general, the discontinuities in the jointed basaltic lava rocks take different dips and dip directions almost in all directions and the strike direction of most of these discontinuities are in conformity with the strike direction of the major primary and secondary structures of the investigated area (Fig.6) and (see Fig. 2).

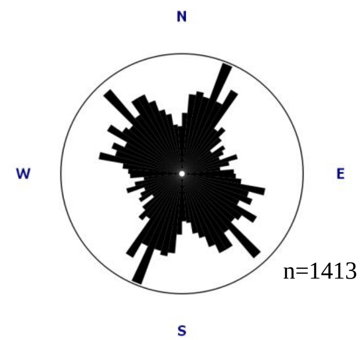

Fig.6. Rose Diagram shows the local variations in the strikes of all surveyed joints in the different zones of the jointed basaltic lava rocks (JBL-Tb1/Tb2).

The average discontinuity (joint) spacing are typically close to moderate (6 – 60 cm); however, widely spaced (60 - 200 cm) discontinuities are also noticed. Discontinuities appear either closed/very tight or opened with the width of the apertures ranging from 1 mm to more than 5mm (moderately wide) and in rare instances, may have exceeded 10 mm such as in the station no. 22-zone I. The persistence of discontinuities in this subunit varies from very low to very high (< 1->20 m). The very high persistence is seen at the contact surfaces between two heterogeneous units or zones. The morphology of the discontinuity surface is generally smooth to slightly rough and undulating to planar; although, the rough surfaces are also encountered. The walls of discontinuities are stained by iron oxides caused by hydrothermal solutions injected through them. The most common filling materials that were observed include predominantly mixture of iron oxides, carbonates minerals and fine soil found as sheets, carbonate minerals (able to be broken by fingers) and cryptocrystalline silicates/quartz (hard to very hard). The fractures filled with angular rock fragments cemented by carbonate material/calcite are commonly found especially near dykes [6]. The soft silty sand infilling material of > 5mm thickness was also observed such as in the station no. 21-zone I. Generally, discontinuities are dry in all investigated stations except station no. 21 in which the filling materials were damp, but no free water is present.

The volumetric joint count (Jv j/m3) is one of the parameters used to describe the degree of jointing. From average spacing of joint sets within a volume of rock mass on outcrop, the volumetric joint count (Jv j/m3) was calculated based on Equation (1). The obtained Jv values range between 6.08 j/m3 and 39.48 j/m3 indicating that degree of jointing of these rocks is moderate to very high respectively [20]. The high degree of jointing is commonly (Table 3) noticed in and around Taiz city.

Table 3. Characteristics of the discontinuities and calculation of GSI parameters for jointed/massive basaltic lava rock masses in and around Taiz city, Yemen.

Geotechnical subunit			Jointed basaltic lava flow rock masses (JBL-Tb1/Tb2)													
Station no.			1	2	9	9	14	17	26	27	34	34	45	50	51	59
Zone			III	I	I	II	I	I	I	I	I	IV	I	I-2	I	I
Orientation (dip/dip dir) and Average Spacing (m) of Discontinuities	Main Joint Sets	Set1	16/196 (0.18)	78/315 (0.19)	82/185 (0.19)	75/076 (0.34)	80/337 (0.73)	72/297 (0.19)	40/105 (0.12)	78/040 (0.09)	76/037 (0.54)	75/070 (0.22)	27/058 (0.31)	87/074 (0.25)	76/231 (0.46)	38/275 (0.39)
		Set2	83/109 (0.13)	63/118 (0.21)	66/290 (0.17)	74/045 (0.39)	16/108 (0.29)	85/040 (0.20)	64/022 (0.15)	47/118 (0.10)	74/073 (0.21)	75/180 (0.32)	63/118 (0.21)	34/185 (0.18)	53/054 (0.49)	80/022 (0.25)
		Set3	82/293 (0.27)	17/011 (0.15)	85/010 (0.27)	70/012 (0.82)	82/108 (0.56)	52/343 (0.12)	72/209 (0.07)	75/308 (0.18)	31/164* (1.53)	78/017 (0.38)	17/011 (0.15)	84/354 (0.35)	64/127 (0.44)	65/075 (0.34)
		Set4	-	-	-	11/302* (1.7)	83/041 (0.26)	78/106 (0.22)	-	-	-	-	-	-	-	76/348 (0.32)
	Set 4/5(random)		5/3= 1.67	5/3= 1.67	5/2= 2.5	5/1=5	5/2= 2.5	5/4= 1.25	5/4= 1.25	5/4= 1.25	5/3= 1.67	5/1=5	5/4= 1.25	5/1=5	5/3= 1.67	5/2= 2.5
	Min. Spacing		0.13	0.15	0.17	0.34	0.26	0.12	0.07	0.09	0.21	0.13	0.15	0.18	0.44	0.25
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	C.dry	C.dry
Discontinuities Condition	Persistence (m)		< 1 [6]	< 1[6]	1-3[4]	1- >20[3]	< 1 [6]	< 1 [6]	< 1 [6]	< 1 [6]	1-3[4]	< 1 [6]	< 1 [6]	< 1 [6]	< 1 [6]	< 1 [6]
	Aperture (mm)		1-3[1]	1-5[1]	1-3[1]	1-2[1]	>5[0]	>5[0]	1-5[1]	1-3[1]	None [6]	>5[0]	None[6]	1-5[1]	1-5[1]	1-5[1]
	Roughness		Rough surfaces [5]	Sr surfaces [3]	Smooth surfaces [1]	Sm -Sr surfaces [2]	Rough surfaces [5]	Sm -Sr surfaces [2]	Sr surfaces [3]	Smooth surfaces [1]	Sm -Sr surfaces [2]	Sr surfaces [3]	Sm -Sr surfaces [2]	Smooth surfaces [1]	Rough Surfaces [5]	Smooth surfaces [1]
	Infilling		No infilling [6]	Hd & Sf filling <5mm [3]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	No infilling [6]	No infilling [6]	Hd filling < 5mm [4]	No infilling [6]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]
	Weathering		Slightly [5]	Md [3]	Slightly [5]	Md-H [2]	Slightly [5]	S-Md [4]	Md [3]	Slightly [5]	Md-H [2]	Slightly [5]	Slightly [5]	Md [3]	Fresh [6]	Slightly [5]
GSI Parameters	Roughness Rating (Rr)		4	2	1	1.5	4	1.5	2	1	1.5	2	1.5	1	4	1
	Weathering Rating (Rw)		4	2	4	1.5	4	3	2	4	1.5	4	4	2	5	4
	Infilling Rating (Rf)		5	2	3	3	5	5	3	5	3	3	3	3	3	3
	Surface Condition Rating (SCR)		13	6	8	6	13	9.5	7	10	6	9	8.5	6	12	8
	Structure Rating (SR)		49.77	50.03	52.23	64.65	58.20	44.33	40.32	41.92	63.83	60.19	60.01	55.01	65.66	54.99
	Geological Strength Index (GSI)		62.14	40	47.50	46.25	67.92	48.10	39.38	49.14	45.42	55	53.08	41.79	67.69	48.33
Volumetric joint count (Jv)(J/m3)			17.55	17.29	15.25	7.51	10.85	23.94	30.09	27.47	7.87	9.69	9.78	13.01	7.09	13.03
Degree of Jointing			High	High	High	Md	High	High	V. High	High	Md	Md	Md	High	Md	High
Rock Quality Designation, RQD (%)			66.12	66.77	71.88	91.22	82.87	50.15	34.79	41.33	90.33	85.78	85.54	77.47	92.28	77.42

Table 3. Continued

Geotechnical subunit			Jointed/columnar basaltic lava flow rock masses (JBL-Tb1/Tb2)												MBL
Station no.			62	64	92	92	93	97	103	I	10	21	22	96	53
Zone			I	II	I	II	I	I	I	I	I	I	I	I	I
Orientation (dip/dip dir) and Average Spacing (m) of Discontinuities	Main Joint Sets	Set1	63/268 (0.33)	74/208 (0.20)	83/311 (0.25)	40/104 (0.10)	16/070 (0.12)	70/047 (0.13)	27/237 (0.32)	81/268 (0.27)	83/266 (0.59)	81/268 (0.28)	80/335 (0.32)	83/266 (0.31)	77/182 (1.23)
		Set2	71/226 (0.45)	73/144 (0.13)	12/214 (0.22)	81/296 (0.12)	81/295 (0.06)	71/296 (0.37)	76/156 (0.36)	54/020 (0.23)	77/352 (0.40)	54/020 (0.35)	41/157 (0.42)	77/352 (0.79)	12/325 (1.60)
		Set3	43/173* (0.12)	55/111 (0.12)	61/031 (0.19)	11/222 (0.14)	73/212 (0.07)	61/330 (0.20)	87/247 (0.24)	85/115 (0.20)	36/125 (1.13)	85/115 (0.28)	10/089 (0.73)	36/125 (0.29)	76/242 (1.31)
		Set4	75/084 (1.30)	82/146 (0.17)	-	-	-	-	-	-	-	-	-	-	-
	Set 4/5(random)		5/3= 1.67	5/4= 1.25	5/4= 1.25	5/3= 1.67	5/1=5	5/2= 2.5	5/2= 2.5	5/2= 2.5	5/4= 1.25	5/4= 1.25	5/3= 1.67	5/3= 1.67	-
	Min. Spacing		0.12	0.12	0.19	0.10	0.06	0.13	0.24	0.20	0.40	0.28	0.32	0.29	1.23
Ground water condition			C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	C.dry	Damp	C.dry	C.dry	C.dry
Discontinuities Condition	Persistence (m)		< 1- >20 [3]	< 1 [6]	1-3[4]	< 1[6]	1-3[4]	1-3[4]	<1 [6]	<1 [6]	1-3[4]	< 1 [6]	1-3[4]	1-3[4]	3-10 [2]
	Aperture (mm)		None [6]	1-5[1]	1-3[1]	None[6]	0.1-1[4]	>5[0]	>5[0]	None[6]	None[6]	None[6]	>5[0]	None[6]	No ->5[3]
	Roughness		V. rough surfaces [6]	Smooth surfaces [1]	V. rough surfaces [6]	Smooth surfaces [1]	Sm -Sr surfaces [2]	Smooth surfaces [1]	Sr surfaces [3]	Sr surfaces [3]	Sr surfaces [3]	Sr surfaces [3]	Rough Surfaces [5]	Sm -Sr surfaces [2]	V. rough surfaces [6]
	Infilling		Hd filling < 5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	No infilling [6]	Hd filling <5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Hd filling < 5mm [4]	Sf filling > 5mm [0]	Hd filling > 5mm [2]	Hd filling < 5mm [4]	Non-Hd filling > 5mm [4]
	Weathering		Md [3]	Md [3]	Md [3]	Slightly [5]	Md [3]	Slightly [5]	Slightly [5]	Fresh [6]	Fresh [6]	Fresh [6]	Md [3]	Fresh [6]	Fresh [6]
GSI Parameters	Roughness Rating (Rr)		5	1	5	1	1.5	1	2	2	2	2	4	1.5	5
	Weathering Rating (Rw)		2	2	2	4	2	4	4	5	5	5	2	5	5
	Infilling Rating (Rf)		3	3	3	3	5	3	3	3	3	0	1	3	3
	Surface Condition Rating (SCR)		10	6	10	8	8.5	8	9	10	10	7	7	9.5	13
	Structure Rating (SR)		52.57	41.76	52.99	42.83	35.55	51.62	58.83	54.43	68.35	55.60	58.61	61.99	86.18
	Geological Strength Index (GSI)		54.29	37	54.29	43.33	41.88	47.08	53.85	55	62.33	45	46.67	57.5	84.17
Volumetric joint count (Jv)(J/m^3)			14.96	27.71	14.61	26.08	39.48	15.8	10.47	13.45	6.08	12.59	10.6	8.74	2.20
Degree of Jointing			High	High	High	High	V. High	High	High	High	Md	High	High	Md	Low
Rock Quality Designation, RQD (%)			72.61	40.73	73.48	44.81	11.29	70.51	83.83	76.37	94.8	78.54	83.5	88.15	100(1)

Where: m: meter, (…): the values in parentheses are the mean discontinuity set spacings, Min: Minimum,* : contact between two zones, 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 [7] , SR= 100-17.5322lnJv [22], Jv = volumetric joint count= 1/S1+1/S2….1/Sn + (5vA) [14], Rr, Rw and Rf values are estimated from conditions of discontinuities, SCR= Rr+ Rw+Rf, GSI is estimated depending on GSI chart modified by Hamasur [22] after Hoek [24], Marinos and Hoek[25], Sonmez and Ulusay [26] (Fig.8). Degree of Jointing is estimated depending on Jv values and according to Palmstrom [20], RQD =Rock Quality Designation = 110-2.5Jv [20], (1) RQD = 100 because Jv < 4 Palmstrom [20], MRL: Massive basaltic lava flow rock masses masses.

Rock Quality Designation index (RQD)

In addition to spacing and volumetric joint count (Jv j/m3), the Rock Quality Designation index (RQD) is also another parameter used to describe the degree of jointing. Here, due to not available cores, RQD is estimated from the volumetric joint count (Jv j/m3) using Equation (2) suggested by Palmstrom [20]. The RQD values obtained for each zone in JBL-Tb1/Tb2 vary from 11.29% (very poor quality rock) to maximum 94. 8 % (excellent quality rock) [47] with an average of 70.48 % (Table 3). The value of Rock Quality Designation (RQD) indicates that the density of the discontinuities varies with location within the rock mass.

MBL-Tb2: In the massive basaltic lava rocks, three sets of joint have been recognized (Fig.7) in addition to random joints. They are characterized by wide spaced apertures (ave. 1.23 -1.60 m) with medium persistence (3 - 10m). Joint surfaces are very rough and freshly weathered. Very rough surface reflects the fabric or texture of the trachy-basalts showing vesicles/ amygdales structures. The openings of joint apertures do not show uniformity; some are closed or very tight to wide (< 0.1- > 5mm). Generally, the joint surfaces are dry with no evidence of water flow. The volumetric joint count (Jv j/m3) value is 2.2 j/m3indicating that the degree of jointing is low. The RQD value calculated from Jv is 100 % (excellent quality), because Jv < 4 [20] (Table 3).

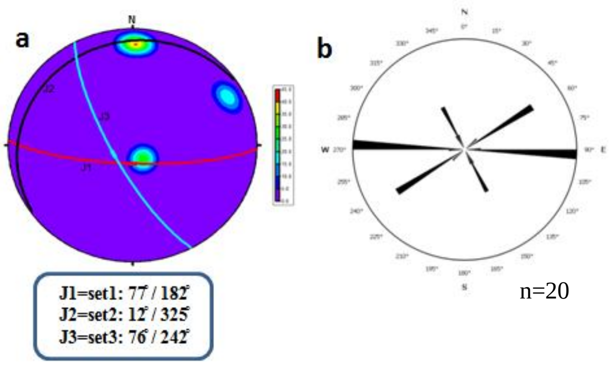

Fig.7. a) Shows the identified three main discontinuity sets using equal-area stereographic projection in massive basaltic lava rocks (MBL- Tb2) at station no. 53-zone-I; b) Rose diagram shows strikes of three main joint sets recognized in (a) at the same station.

4.2 Geotechnical Classification of Basaltic Lava Rock Masses (BL-Tb1/Tb2)

The jointed/massive basaltic lava rock masses (J/MBL-Tb1/Tb2) at 27 zones were classified according to the following geotechnical classification systems:

4.2.1 Rock Mass Rating (RMR)

In this study, both Rock Mass Rating (RMR76) [21] and the basic Rock Mass Rating (RMRBasic 89) [7] systems were employed. The input basic parameters of both RMR76 and RMRBasic89 used are five (A1, A2, A3, A4 and A5). These parameters were obtained numerically /descriptively for the jointed/massive basaltic lava subunits (J/MBL-Tb1/Tb2) and rated according to the weight of each one in the classification system. Ratings (based on the Table proposed by Bieniawski [7]) for five parameters were summed up to yield the basic RMR89 with no adjustment for discontinuity orientation. Also the five parameters of classification are rated (based on Table proposed by Bieniawski, [21]) and summed to yield the RMR76. The values and ratings of five parameters in addition to RMR76 and RMRB89 classes at 23 stations (27 zones) are presented in Table 4.

JBL-Tb1/Tb2 have RMR76 and RMRB89 ratings of (42.2–73.3) and (51.2-77.6) respectively, which categorized them as (fair – good) rocks, or classes III (41– 60) - II (61-80) of Beniawski [21, 7]. In some investigated zones, the values of RMRB89 of 58.9 and 58.5 (≈59) indicate that the rock mass is on the boundary between the 'Fair rock' and 'Good rock' categories. According to RMR76 values, about 62 % of them belong to fair rock masses. The lowest total rating values (fair rock) for RMR76 and RMR89 are assigned to the moderately and highly weathered jointed basaltic rocks (JBL-Tb1/Tb2)

MBL-Tb2 is classified as good quality rock or II (61-80) [21, 7] (Table 4).

4.2.2 Geological Strength Index (GSI)

Hamasur [22] provided a quantitative numerical basis to estimate more precise values of GSI. This quantitative rock mass classification was modified after Hoek et al., [23], Hoek [24], Marinos and Hoek [25] and Sonmez and Ulusay [26]. The main components 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 (3). Surface condition rating (SCR) is estimated from sum of the roughness, weathering and infilling material ratings; which are assessed visually in the field. These parameters and their ratings as well as results of the calculations are provided in Table 3. Because the GSI is based on the RMR76 (Hoek et al., [23]), then the roughness, weathering and infilling ratings (SCR) are also must be based on the RMR76, in which the sum of these three parameters ranges from 0 to 15 [22] (Table 3).The intersection of these ratings (SCR and SR) on the modified quantitative GSI chart of Hamasur [22], gives precise value of GSI (Fig.8). The derived values from the GSI chart for the various zones are given in the Table 3.

JBL-Tb1/Tb2: the GSI values obtained for this subunit range from 37 to 67.92 with an average of 50.38. About 65 % of the GSI values obtained within this range represent very blocky (VB) structure while about 27% and 8 % of GSI values are for the rocks showing blocky (B) and blocky/disturbed (B/D) structures. The ***MBL- Tb2:*** GSI value for this subunit is 84.17. This value indicates intact or massive structure (Fig.8).

4.3 Indirect Estimation of the Rock Masses Properties

Reliable estimates of the rock mass properties are required for almost any form of analysis used especially in the preliminary stages of design of slopes, foundations and underground excavations in rock. The estimation of rock mass properties can be achieved by laboratory testing, in situ testing, back analysis or the use of rock mass classifications (GSI, RMR, etc.).

Table 4. Calculation of the RMR parameters for the basaltic lava rock masses in the investigated area (after Bieniawski [21, 7])

St. no.	Geotech-nical sub-unit	Zone	A1		A2		A3		A4		A5		C: RMR= A1+A2+A3+A4+A5		
			Values	Rating 76=89	Values	Rating 76=89	Values (m) (min.)	Rating 76/89	Values	Rating 76/89	Values (desc.)	Rating 76/89	Rating 76/89	RMC	RMD
1		III	144.74	13	66.12	13.1	0.13	10/8	From Table 3	18/23	Dry	10/15	64.1/ 72.1	II / II	Good/ Good
2		I	51.7	4.8	67.77	13.4	0.15	10/8		11/16	Dry	10/15	48.2/57.2	III/III	Fair/Fair
9		I	77.07	7.8	71.88	14.3	0.17	10/8		10/5	Dry	10/15	52.1/60.1	III/II	Fair/Good
9		II	15(1)	2.5	91.22	17.9	0.34	20/10		6/11	Dry	10/15	56.4/56.4	III/III	Fair/Fair
14		I	196.26	14	82.87	16.4	0.26	10/10		17/22	Dry	10/15	67.5/77.5	II / II	Good/ Good
17		I	55.23	6	50.15	10	0.12	10/8		13/18	Dry	10/15	49/57	III/III	Fair/Fair
26		I	43.89	4.9	34.79	7.2	0.07	10/8		12/17	Dry	10/15	44.1/52.1	III/III	Fair/Fair
27		I	44.31	5	41.33	8.4	0.09	10/8		14/19	Dry	10/15	47.4/55.4	III/III	Fair/Fair
34		I	13.05	2.3	90.33	17.9	0.21	10/10		12/17	Dry	10/15	52.2/62.2	III/II	Fair/Good
34		IV	34.02	4.2	85.78	16.9	0.22	10/10		13/18	Dry	10/15	54.1/64.1	III/II	Fair/Good
45		I	62.79	6.6	85.54	16.9	0.31	20/10		18/23	Dry	10/15	71.5/71.5	II / II	Good/ Good
50		I-2	42.63	4.9	77.47	15.3	0.18	10/8		10/15	Dry	10/15	50.2/58.2	III/III	Good/ Good
51	JBL-	I	79.58	7.9	92.28	18.4	0.44	20/10		17/22	Dry	10/15	73.30/73.3	II / II	Good/ Good
59	Tb1/Tb2	I	44.56	5	77.42	15.3	0.25	10/10		12/17	Dry	10/15	52.30/62.3	III/II	Fair/Good
62		I	25.61	3.3	72.61	14.3	0.12	10/8		17/22	Dry	10/15	54.6/62.6	III/II	Fair/Good
64		II	31.92	3.9	40.73	8.3	0.12	10/8		10/15	Dry	10/15	42.2/51.2	III/III	Fair/Fair
92		I	27.93	3.5	73.48	14.4	0.19	10/8		13/18	Dry	10/15	50.9/58.9	III/III	Fair/Fair
92		II	81.90	8.1	44.81	9	0.10	10/8		17/22	Dry	10/15	54.1/62.1	III/II	Fair/Good
93		I	122.77	10.9	11.29	4.1	0.06	10/8		15.5/20	Dry	10/15	50.5/58.5	III/III	Fair/Good
97		I	28.9	4	70.51	14	0.13	10/8		9/14	Dry	10/15	47/55	III/III	Fair/Good
103		I	175(1)	12	83.83	16.7	0.24	10/10		13/18	Dry	10/15	61.7/71.7	II / II	Good/ Good
1		I	216.72	14.5	76.37	15.1	0.20	10/8		20/25	Dry	10/15	69.6/77.6	II / II	Good/ Good
10		I	58.59	6.2	94.80	18.8	0.40	20/10		17/22	Dry	10/15	72/72	II / II	Good/ Good
21		I	211.26	14.4	78.54	15.5	0.28	10/8		16/21	Damp	7/10	62.9/68.9	II / II	Good/ Good
22		I	75.6	7.7	83.50	16.5	0.32	20/10		9/14	Dray	10/15	63.2/63.2	II / II	Good/ Good
96		I	118.94	10.7	88.15	17.4	0.29	10/10		17/22	Dray	10/15	65.1/75.1	II / II	Good/ Good
53	MBL-Tb2	I	22.76	3.2	100*	20	1.23	25/15	Table 3	16/21	Dry	10/15	74.2/74.2	II/ II	Good/ Good

St. no.: Station number, RMR (76 or 89) : Rock Mass Rating related to the year of that version, RMRB89 : Basic RMR89 with no adjusting factor for joint orientation., 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 (minimum spacing is taken from Table 3, according to Edelbro,[13] , A4:ratings for the condition of discontinuities obtained from Table 3, A5: ratings for the groundwater condition, (desc.): descriptive term, C: Rock mass classes demined from total ratings, RMC: Rock mass class, RMD: Rock mass description, (*): RQD = 110 - 2.5 Jv = 100 because Jv < 4 [20], (1) this value was estimated using the geological hammer.

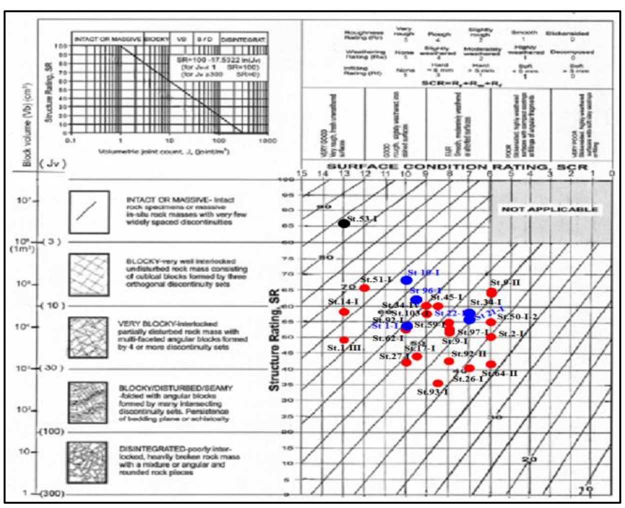

Fig. 8. Values of GSI plotted based on SR and SCR ratings calculated in Table 3 for Tertiary jointed basaltic lava flow rock masses (J/MBL-Tb1/Tb2) in and around Taiz city, Yemen (red points= jointed (irregular) basalts, blue points= jointed (columnar) basalts and black point = Massive basalt).

In this study, the most recent version of the generalized Hoek–Brown failure criterion [38] included geological strength index (GSI) is applied for estimating the strength and deformability of the Tertiary jointed basaltic rock masses in Taiz city and its surrounding, employing RocLab software program [39]. The input variables required in this program for calculation of rock mass properties for this volcanic geotechnical subunit are given in Table 5. Following this calculation, the output parameters included are Hoek-brown classification parameters (mb, s and a), Mohr-Coulomb Fit (shear strength parameters; c, Φ) and rock mass parameters given in terms of compressive strength (σc), tensile strength (σtm), deformation modulus (Erm) and global strength (σcm). The obtained values of the parameters for jointed basaltic rock masses (JBL-Tb1/Tb2) are presented in Table 6. These values ranges from 0.57 to 13.41MPa, 24.34° to 38.53°, -0.004 to - 0.438 MPa, 0.24 to 19.06 MPa, 1.89 to 55.63 MPa and 368.3 to 21092.3 MPa for cohesion, friction angle, tensile strength, compressive strength, global strength and deformation modulus respectively. Also, application of generalized Hoek–Brown failure criterion for estimating these parameters for massive basaltic lava rocks (MBL-Tb2) is possible as they contain many joint sets (3 joint sets-see Table 3). The input and output parameters for these rocks are given in Table 5 and Table 6 respectively. Generally, values of the shear strength parameters (cohesion- c and friction angle - Φ) and the other rock mass parameters (σtm, σc, σcm and Erm) for basaltic lava rock masses depend on rock mass quality and properties of intact rock and in the present study it was observed that the rock mass parameters increase with increase in the quality of rock mass and with increasing values of the intact rock properties.

Table 5. Input data used for estimation of rock mass properties for basaltic lava rock masses (J/M BL- Tb1/Tb2) in and around Taiz city, Yemen.

Geotechnical sub-unit and abbreviation	No. investigated zones	σci (MPa)	GSI	mi	D	MR
Jointed basaltic lava rocks (JBL Tb1/Tb2)	26	Table 4 (A1)	Table 3	*25*	0.7	350
Massive basaltic lava rocks (MBL-Tb2)	1	Table 4 (A1)	Table 3	*25*	0.7	350

GSI: Geological strength Index, mi= Intact rock constant estimated according to rock type (here, mi=25 used for basalts), D: disturbance factor; here, D= 0.7 for partially disturbed in situ rock mass, MR: Modulus Ratio estimated according to rock type from the Table modified by Hoek and Diederichs [42], based on Deere [47] and Palmstrom and Singh [44].

Table 6. Results of estimated basaltic lava flow rock mass properties in Taiz city and its surrounding following the GH-B failure criterion for input parameters referred to them in Table 5.

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
1	JBL-Tb1/Tb2	III	3.123	0.0041	0.502	8.810	35.84	-0.192	9.19	34.46	11505.68
2		I	0.925	0.0002	0.511	1.985	25.67	-0.009	0.606	6.313	1053.68
9		I	1.397	0.0005	0.507	3.493	29.05	-0.027	1.631	11.873	2468.84
9		II	1.304	0.0004	0.507	0.662	28.483	-0.005	0.288	2.224	444.01
14		I	4.29	0.0096	0.502	13.406	38.53	-0.438	19.057	55.629	21092.27
17		I	1.444	0.0005	0.507	2.534	29.33	-0.021	1.223	8.661	1837.06
26		I	0.894	0.0002	0.512	1.661	25.4	-0.008	0.489	5.254	864.11
27		I	1.541	0.0006	0.506	2.084	29.87	-0.018	1.075	7.202	1589.91
34		I	1.266	0.0004	0.508	0.568	28.107	-0.004	0.236	1.894	368.25
34		IV	2.109	0.0015	0.504	1.796	32.510	-0.024	1.270	6.550	1756.98
45		I	1.898	0.0011	0.505	3.192	31.62	-0.037	2.031	11.427	2871.95
50		I_2	1.021	0.0002	0.510	1.705	26.47	-0.009	0.577	5.508	962.72
51		I	4.236	0.0093	0.502	5.511	38.43	-0.174	7.598	22.398	8459.32
59		I	1.462	0.0006	0.506	2.055	29.43	-0.017	1.004	7.036	1503.98
62		I	1.237	0.0004	0.508	1.107	28.048	-0.007	0.456	3.688	714.14
64		II	0.785	0.0001	0.514	1.141	24.34	-0.004	0.293	3.537	553.23
92		I	2.029	0.0013	0.504	1.455	32.18	-0.018	0.989	5.269	1379.85
92		II	1.111	0.0003	0.509	3.391	27.16	-0.020	1.252	11.102	2026.4
93		I	1.026	0.0002	0.510	4.921	26.51	-0.026	1.673	15.907	2787.17
97		I	1.367	0.0005	0.507	1.300	28.87	-0.010	0.593	4.403	903.59
103		I	1.98	0.0012	0.504	9.036	31.97	-0.110	5.997	32.583	8407.2
1		I	2.109	0.0015	0.504	11.451	32.51	-0.151	8.096	41.75	11199.2
10		I	3.155	0.0043	0.502	3.580	35.92	-0.079	3.773	14.029	4707.58
21		I	1.218	0.0003	0.508	9.073	27.92	-0.060	3.681	30.15	5786.5
22		I	1.335	0.0004	0.507	3.366	28.67	-0.025	1.5	11.353	2297.46
96		I	2.42	0.0021	0.503	4.198	33.67	-0.007	3.404	15.683	4566.24
53	MBL-Tb2	I	10.476	0.1008	0.500	2.253	45.87	-0.219	7.221	11.116	4177.57

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.

5. CONCLUSIONS AND RECOMMENDA-TIONS

In the present study, the basaltic rock masses characterization is carried out based on laboratory and field investigations. The laboratory tests of physical-mechanical characteristics were performed on cubic rock specimens prepared from rock block samples collected from representative sites (23 field stations; 27 zones). The results obtained from experimental study show that jointed basaltic rock masses have range of variations in its dry densities, porosities, water absorption tendencies, bulk and apparent specific gravities and uniaxial compressive strengths, due to variable degrees of weathering, alteration and the presence of microfractures. The lower strength ranges obtained from. The lower strength ranges obtained from Schmidt hammer (SH) compared with strength ranges taken by (PLT) for jointed/columnar basaltic lavas probably reflect the sensitivity of the Schmidt hammer to surface alteration of the materials in the field and size of the rock sample in the laboratory. The characterization of basaltic rock masses using RMR showed that most investigated sites have rock masses with fair classes due to influence of the rock discontinues; where high degree of jointing of these rocks are common. The modified quantitative GSI system applied here provided useful information about rock mass characteristics and thus can be used at all stages of any engineering project constructs on/in theses rocks, especially at the preliminary design stage where only limited information is available. The mechanical properties of rock masses are varied, depending on rock mass quality and properties of intact rock. It was observed that the rock mass parameters increase with increase in the quality of rock mass as well as the values of the intact rock properties.

The results of this study recommend that for design and construction of any engineering project (especially, underground openings) in/on the Jointed basaltic rock masses (JBL-Tb1/Tb2), the continuous subsurface investigations and laboratory tests are required, due to the unexpected variations in rock conditions and behaviors especially where these rocks are highly fractured or/and intercalated with weak volcanic accumulation materials. The paper also aims at providing a data base on the geomechanical properties of rocks of Taiz city for design.

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