Strength and deformation properties of volcanic rocks in Iceland

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ABSTRACT
Tunnelling work and preinvestigations for road traces require knowledge of the strength and deformation properties of the rock material involved. This paper presents results related to tunnelling for Icelandic water power plants and road tunnels from a number of regions in Iceland.

The volcanic rock from Iceland has been the topic for rock mechanical studies carried out by Icelandic guest students at the Department of Civil Engineering at the Technical University of Denmark over a number of years in cooperation with University of Iceland, Vegagerðin (The Icelandic Road Directorate) and Landsvirkjun (The National Power Company of Iceland). These projects involve engineering geological properties of volcanic rock in Iceland, rock mechanical testing and parameter evaluation. Upscaling to rock mass properties and modelling using Q- or GSI-methods in combination with the finite element code Phase 2 from Rocscience have been studied by the students and are available in their MSc-theses, but will not be covered here.

The present contribution gives a short engineering geological overview of the volcanic rock formations in Iceland. Furthermore, the results of a number of unconfined, Brazilian, and a limited number of triaxial compression tests are presented and evaluated. The results are grouped according to engineering geological classification and classification properties as bulk density. We find correlations between the bulk density and the logarithm to the elasticity modulus and strength parameters.

Keywords: Volcanic rocks, Iceland, UCS test, Brazilian test, elasticity modulus.

1 INTRODUCTION

This paper presents extracts from a number of MSc-theses in Rock Mechanics carried out by Icelandic students at the Technical University of Denmark (DTU) in cooperation with University of Iceland, Icelandic Engineering Companies and Vegagerðin and Landsvirkjun representing the Icelandic Road Directorate and Power Administration.
Most of these studies have been related to ongoing tunneling projects and include engineering geology, description of selected cores from representative boreholes, laboratory classification, and strength and deformation tests. Based on this the students have evaluated element properties of the actual volcanic rock types and established an upscaling of these to rock mass parameters which then have been used for numerical analysis using international methods like GSI, RMR and Q-methods for stability, stand-up time and necessary support, i.e. shotcrete thickness and rock bolt spacing. These evaluations is not covered in any details in this contribution but can be retrieved from DTU.
During the projects valuable support and data from the engineering investigations have been provided from our cooperation partners, and the student reports are in full handed over to these authorities when the MSc-theses have been defended. In this paper we present selected results of the rock mechanical testing and give an overview on basic classification properties covering different Icelandic rock types. The studied projects cover sites from several regions of Iceland.

2 SHORT GEOLOGICAL OVERVIEW

Iceland is situated on the Mid-Atlantic ridge on the rifting plate boundary between the Eurasian and North American plates. When the plates drift apart, the gap between them fills constantly with extrusive and intrusive igneous rock. The active zone of rifting and volcanism is found across the country from the southwest Reykjanes peninsula to the northeast where it connects with the Iceland-Jan Mayen ridge. Iceland is geologically very young and all bedrock was formed within the past 25 million years. The stratigraphical succession of Iceland covers two geological periods, the Tertiary and the Quaternary. The oldest rock observed at the surface are about 15 million years old, and is late Tertiary time. It is found in the Northwest and Eastern coast of Iceland. The rock closer to the rifting plate boundary is younger.
The surface of Iceland has changed radically with time. The rocks are weathered by the frequent change of the frost and thaw, and the wind, seas and glaciers deteriorate down the land.

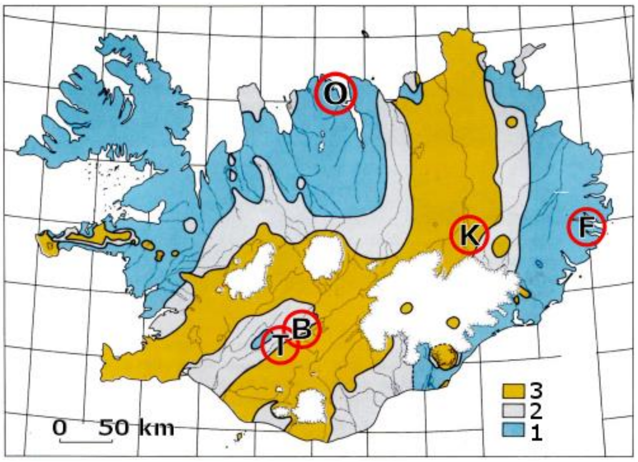

Figure 1 Extent of the Islandic geological formations. Bedrock: 1) Tertiary Basalt Formation; 2) Grey Basalt Formation, Late Pliocene and Early Pleistocene; 3) Móberg (eng. Hyaloclastite) Formation, Late Pleistocene. Site locations: Olafsfjörður (O), Núpur and Þórsá (T), Kárahnjúkar (K), Fáskrúðsfjörður (F) and Búðarhálsvirkjun (B). Based on Map from Einarsson (1994).

The studied sites are placed in regions being representative for the Tertiary Basalt Formation and volcanic features from the Quaternary period (The Grey Basalt Formation and the Móberg formation).
Figure 1 is extracted from the monograph by Thorleifur Einarsson: "Geology of Iceland. Rocks and Landscape" (Figure 24-2; Page 233) and edited to include the localization of the different tunnel sites discussed. The Icelandic bedrock consist of primary numerous, extensive but relatively thin basaltic lava flows, lying on top of each other, interbedded with subordinate acidic rock and relatively thin sedimentary beds. The bedrock's overall composition is as follows:

- 80–85% basalt lava flows,
- 10% acidic and intermediate rocks,
- 5–10% sedimentary interbeds originating from both erosion and transport of volcanic rocks. Mainly consolidated tuff and eolian soil and to some extent sandstones and conglomerates.

Each lava flow may be divided into three parts as follows:

- The top scoria, often 10–25 % of the lava flow thickness,
- The dense crystalline middle part, often 60–85 % of the lava flow thickness,
- The bottom scoria, often 5–10 % of the lava flow thickness.

The top scoria is to the uppermost portion of a lava flow, characterized by rapid cooling and expansion of gas. The matrix of scoria is highly vesicular and glassy. The structure is chaotic, with large voids of any size, some up to several meters. When the subsequent deposition of sediment occurred, these voids were infiltrated and filled with sand and silt. Palagonitisation later cemented the sediment into a sandstone or siltstone and gives the rock mass a relatively compact aspect. In cores the top scoria often has character of a matrix supported breccia with scoria fragments. The vesicles in the scoriaceous fragments are also often filled with secondary zeolites or calcite. The scoria can be recognized from its specific structure and because of its red, orange and green colour, which contrast the grey colour of the basalts.
The crystalline middle lava consists of hard, dense basalt of light to dark grey colour. The rock is usually affected by subvertical columnar jointing, resulting from the cooling of the lava. The frequency of the joints is low

for these large columnar jointed basalts with spacing between 1–2 m. Correspondingly the frequency is high for small columnar jointed basalts and between 0.1– 0.3 m, showing a sugarcube structure. The joint surfaces are usually smooth to slightly rough, undulating with gauge absent or only with thin clayey coatings or calcites.

The bottom scoria is commonly observed to be thin, well consolidated, sometimes containing sandstone fillings, originating from underlying sediments.

The basalt is classified according to Walker's classification system based on petrology and texture of the rock and is divided into the following three different petrographic types (Walker, 1959):

- Tholeiite basalt,
- Olivine basalt,
- Porphyritic basalt.

Table 1 gives a number of rock engineering properties of which UCS for fresh basalts show relatively high strengths (Jónsson, 1996).

3 ROCK MECHANICAL PROPERTIES EXTRACTED FROM MSC-THESES

3.1 Gudmundur Nikulasson (1987): "Tunneler i vulkanske bjergarter i Island"

This MSc-thesis was carried out based on project investigations in cooperation with Vegagerðin Rikisins – the Islandic Road

Table 1 Icelandic basalt classified according to rock engineering properties, Jónsson (1996).

Field mapping of Icelandic basalts[1]	**Proposed geo-technical field mapping of basalt**	**Structural and mechanical properties**		
		Scoria content	Common thichness of lava unit (m)	Common UCS strength[2] (MPa)
Tholeiite basalt	Tholeiite, thin layered (from central volcanoes)	25–35	3–8	>200 (150–300)
	Tholeiite, thick, regional	15–20	10–20	>200 (150–300)
Porphyritic basalt	Porphyritic basalt esp. massive. Phenocrysts>10% by volume	1–5	10–20	200 (100–300)
	Porphyritic basalt. Phenocrysts < 10% by volume	5–15	10–20	200 (150–300)
Olivine tholeiite	Olivine basalt			
	Compound lavas, from lava shield volcanoes	0–5	20–80	100 (80–140)

[1]According to Walker (1959)
[2]Fresh basalt

Directorate – for a road tunnel at Olafsfjörður Muli in Northern Iceland established 1988–1990.

Rock samples from the Tertiary Basalt Formation were selected from boreholes OM1-4 under guidance of Hrein Haraldsson and Gunner Bjarnason from Vegagerðin Rikisins. Five different basalt types were selected (Porphyritic B1, Olivin B2, Olivinporphyritic B3, Tholeiite B4 and Tholeiiteporphyritic

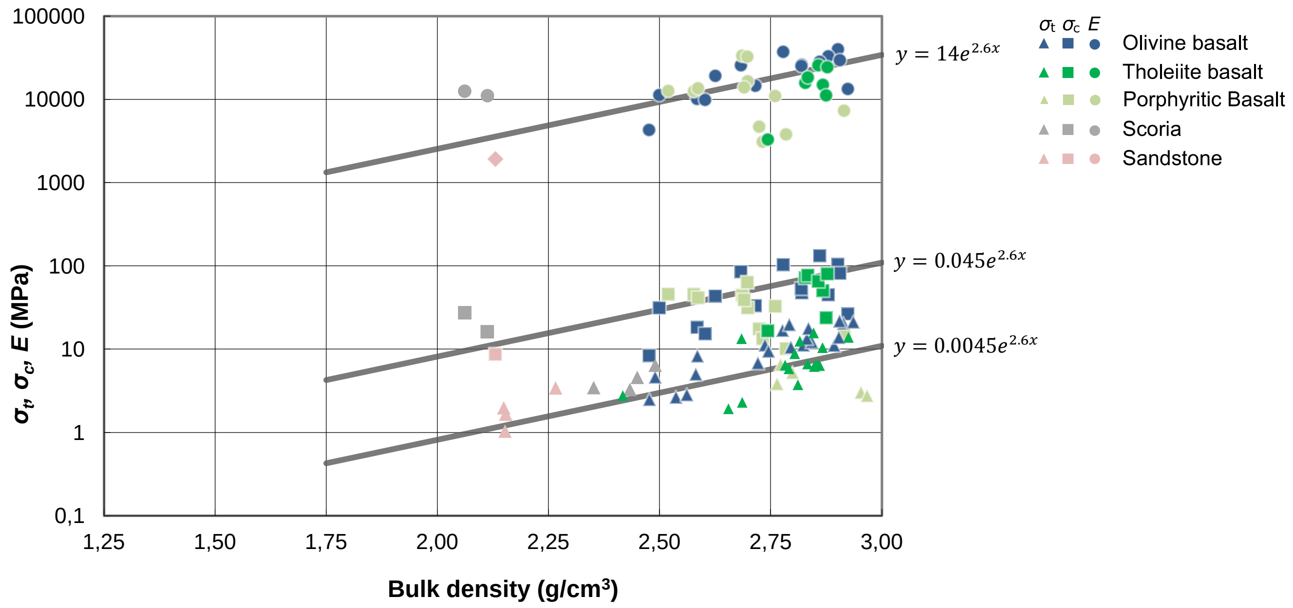

Figure 2 Rock mechanical test results from Olafsfjörður Muli (Nikulasson, 1987).

B5) together with Scoria and sedimentary samples, all from the Tertiary Basalt Formation.

The rock mechanical testing by the student at the Rock Mechanical Laboratory at the Danish Geotechnical Institute involved classification tests, 86 point load tests, 51 Brazilian tests and 41 unconfined compression tests in which 10 were performed used strain gauge techniques for Young's *E*-modulus and Poisson's ratio and the rest using external LDVT's for determination of only *E** (where the index * include bedding effect at end platens in the compression machine and we found the ratio $E/E^* = 1.80 \pm 0.57$).

Figure 2 shows the main results of the strength and deformation properties correlated with the bulk density determined on water saturated surface dry test specimens.

3.2 Karen Kristjana Ernstdottir (2003): "Rock mechanical studies for a hydroelectric power station–Near Núpur and Þórsá, Iceland"

This MSc-study was carried out in cooperation with Landsvirkjun and Almenna Consulting Ltd. with Björn Stefánsson and Jón Skulason as contacts. The project investigations related to preliminary plans for a hydroelectric powerstation at Núpur and included 12 km headrace tunnels. The main subject of this project was to obtain rock parameters for the different rock in the region based on laboratory tests on rock samples from drilling cores made available. The geology in the area around the mountain Núpur and the river Þórsá is various and complicated including the 8700 years old Þórsá lava being the most significant rock layer in the area. It overlies sedimentary layers, e.g. silt-and sandstone, volcanic sand and conglomerate being 1.64 million years old.

For the present project 12 different volcanic and sedimentary rock types were selected from 12 boreholes in the area which contributed to 48 test specimens used for 82 Brazilian tests, 46 unconfined compression tests and 5 triaxial tests.

The results in form of σ_t, σ_c and *E* with different signatures for the studied rock types are plotted as function of the bulk density in water saturated surface dry condition being saturated as part of the preparation of the test specimens. Figure 3 shows the main results grouped in selected rock types together with a regression analysis of the trendlines for the 3 set of results with great variation depending on bulk density and lowest values for the Móberg formations. The triaxial tests confirm the level of friction angle and cohesion for Tillite, Porphyritic Basalt, and Hyaloclastic.

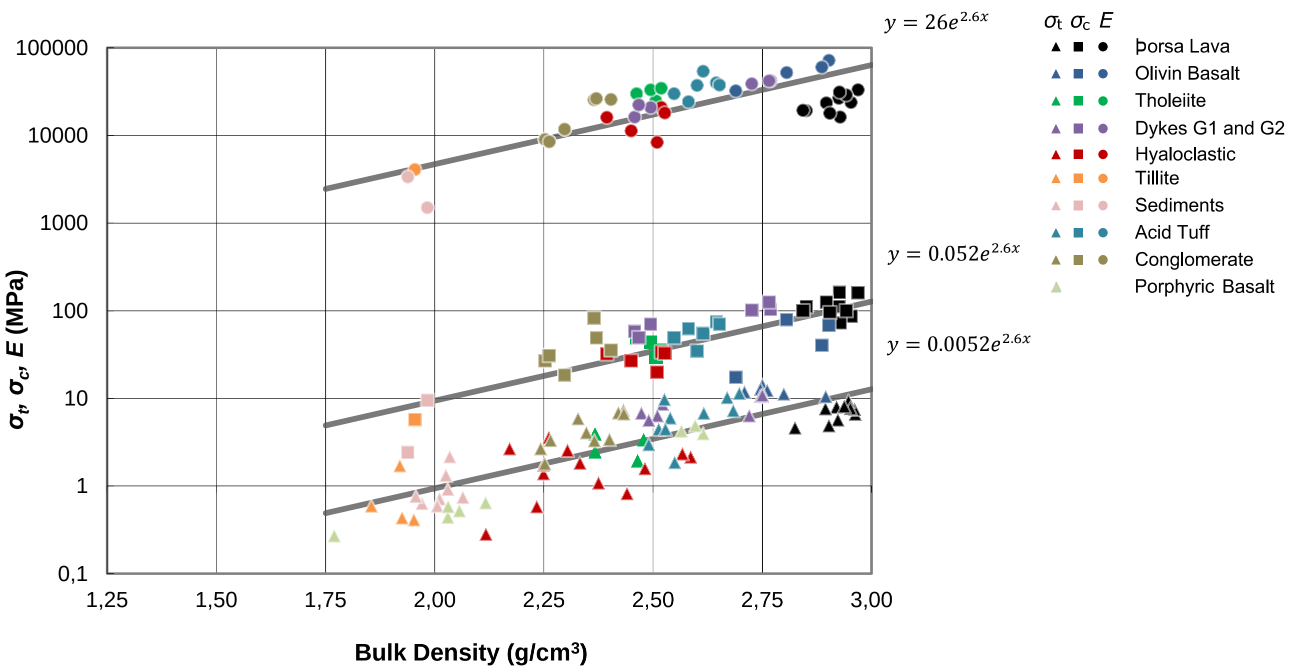

Figure 3 Rock mechanical properties from volcanic rock types in the Núpur – Þórsá region (Ernstdottir, 2003).

3.3 *Hlif Isaksdottir (2004): "Rock mechanical studies of volcanic tephra for a hydroelectric power station–Near Núpur and Þórsá, Iceland"*

This MSc project was carried out on one of the largest tephra layers found below the Þórsá Lava with varying thickness from a few to about 30 m and properties ranging from slightly cemented sand to sandstone. The layer is a result of a sub-glacial volcanic activity 10300 years ago followed by an outburst flood. From this tephra layer three different types of samples were available: Two buckets of variable cemented sand and a sandstone core from borehole NK-28. Generally, RQD and Q-index are very low (0–3% and 0 respectively with exemption of the core from NK-28 having RQD = 88 and Q = 3–46). The tephra particles have a vesicular nature with air trapped inside the grains, weathering may change density due to when volcanic glass alters to palagonite. Four and two subsamples from the two buckets of tephra showed low saturated bulk density of 1.74 g/cm^3 to 1.79 g/cm^3 and w_{sat} from 43% to 39% compared to natural water contents w_{nat} from 13% to 12.5%. Deformation properties in consolidation test on the tephra showed very low E_{oed}-moduli and consequently the material may be vulnerable to creep and to additional settlements under dynamic loads. The tephra sands in Bucket 1 and 2 were very friable and could not be orderly used for Brazilian tests in saturated condition. However, at natural water content the partially saturated test specimens showed $\sigma_t \approx$ 0.28 MPa and 0.025 MPa, respectively. Properly conducted tensile strength tests on six cemented subsamples from the cores from NK-28 with saturated bulk density of ρ_{bulk} = 2.01 g/cm^3 showed a mean value of σ_t = 0.69 MPa. Four triaxial tests and one unconfined compression test on test specimens from NK-28 carried out in the MTS 815 rock mechanical equipment at DTU showed in combination with the Brazil tests for ρ_{bulk} = 2.02 g/cm^3 a friction angle of φ = 55.4^o and c = 1.35 MPa for sandstone.

3.4 *Gunnar Arnar Gunnarsson (2008): "Rock Mass Characterisation and Reinforcement Strategies for Tunnels in Iceland, Fáskrúðsfjörður Tunnel."*

This MSc-thesis was worked out in cooperation with the University of Iceland, Faculty of Civil and Environmental Engineering (Sigurður Erlingsson) and GeoTek Ltd. (Oddur Sigurðsson) and Vegagerðin – the Islandic Road Administration. Hallgrimur Örn Arngrimsson (a fellow student) participated at GEO (The Danish Geotechnical Institute) and DTU in the rock cores classification and preparation of test specimens and the actual laboratory testing.
The project investigation for this site being established 2003–2005 was used and twelve rock cores were collected for supplementary testing mainly of scoria and sediments. A large laboratory test dataset from the headrace tunnel in the Kárahnjúkar hydroelectric project was analysed for comparison of strength properties for the Fáskrúðsfjörður tunnel having a geological age of about 6.5 and 10 mill years, respectively. Consequently, focus has been on scoria or porous basalts and sediments in the present case. Gunnar used a comparison method applied on limestone from the construction of the Citytunnel in Malmö (Foged et al., 2004) based on the semilogarithmic plot of tensile strength, unconfined compression strength and Young's modulus versus bulk density for the different rock types. The comparison is available in Figure 5 and Figure 4 and the reduced rock mechanical properties at Fáskrúðsfjörður compared to Kárahnjúkar is discussed to be due to different age, weathering and high stress conditions.

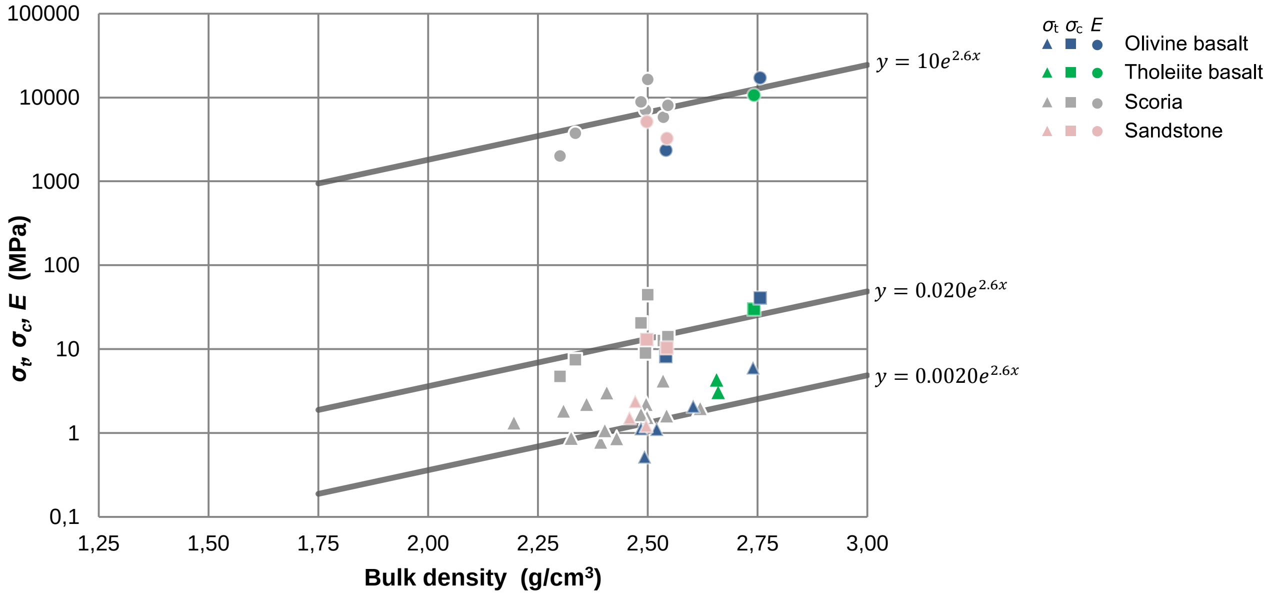

Figure 5 Rock mechanical properties for the Fáskrúðsfjörður region (Gunnarsson, 2008).

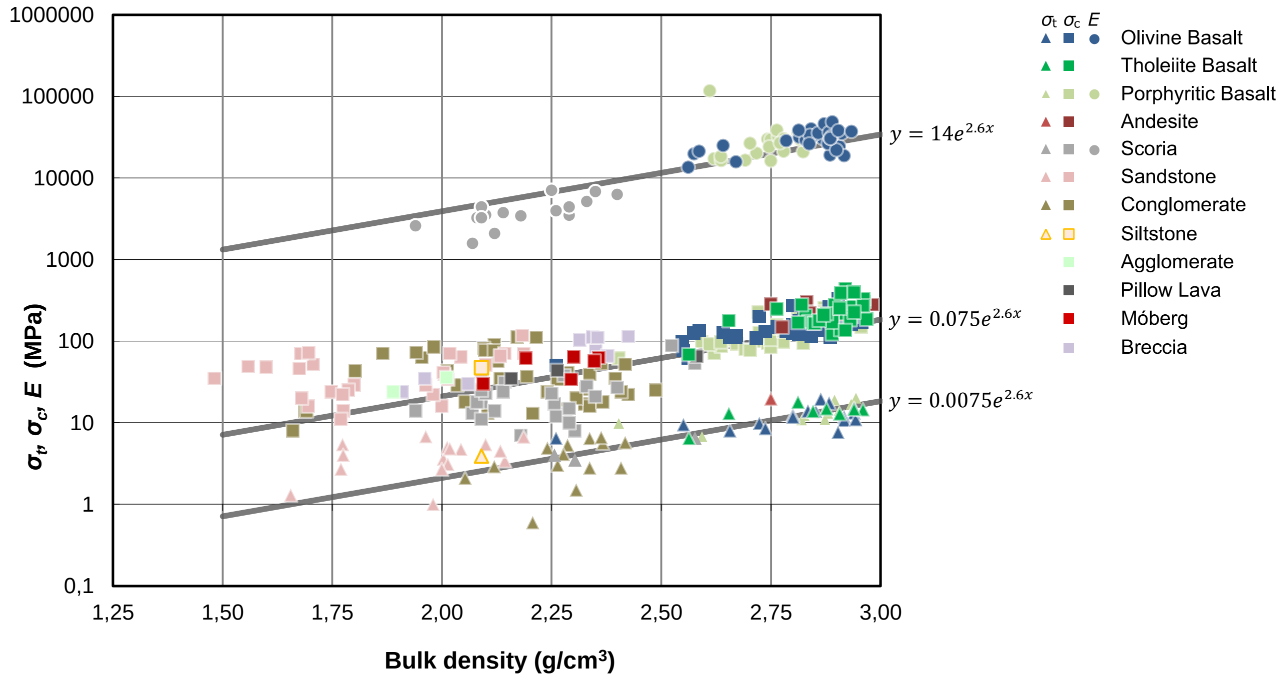

Figure 4 Rock mechanical properties for the Kárahnjúkar region (Gunnarsson, 2008). Data received from the Kárahnjúkar hydroelectric project.

3.5 Hallgrimur Ôrn Arngrímsson & Þorri Björn Gunnarsson (2009): "Tunneling in acidic, altered and sedimentary rock in Iceland, Búdarhálsvirkjun"

This MSc project was performed in cooperation with the University of Iceland, Faculty of Civil and Environmental Engineering (Sigurður Erlingsson) and Landsvirkjun (Matthias Loftsson and Jón H. Steingrimsson) and was in part funded by the Icelandic Road Administration (Vegagerðin). The focus of this thesis is tunnelling in soft rock formations like acidic, altered and sedimentary rock. The top part of Búðarháls formation is pillow lava generated by subglacial eruption during the last glacial period (hyaloclastic rock approx. 0.7 million years old). It is underlain by multiple basaltic lava flows

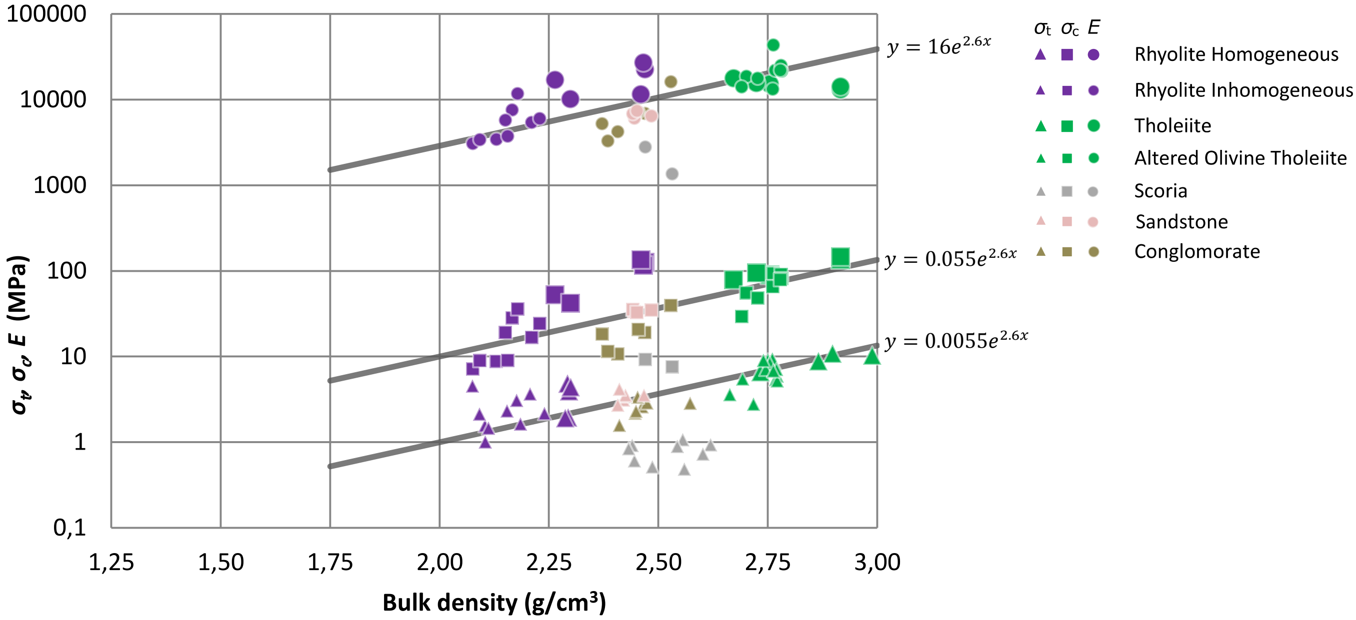

Figure 6 Rock mechanical properties for the Búðarháls region (Arngrímsson & Gunnarsson, 2009).

and sediment layers. The oldest rock is altered basalt over 2.0 million years old. At the power house location the relatively rare rhyolite was found calling for supplementary mechanical testing. Core samples were collected on eight different rock types which were used for Brazilian, unconfined compression and triaxial compression tests performed at Geo and DTU. The Geological Strength Index GSI was used to estimate rock mass properties analysed in three different tunnel cross-sections using the finite element program Phase^2 and the designed rock support classes recommended in the contract documents (Arngrímsson et al., 2010).

4 ROCK MECHANICAL TESTS AND EVALUATION

All test specimens were cut from the available cores (or recored) to the wanted dimensions *H* and *D* measured by a caliper. The cutting was done using a water-cooled diamond saw. Afterwards the test specimens were water saturated under vacuum in order to determine the water-saturated bulk density in surface dry condition. This property was used as abscissa in the preceding figures showing the obtained strength parameters σ_t and σ_c and elasticity moduli *E* as ordinates on logarithmic scale. When performing rock mechanical surveys the traditional tests are unconfined uniaxial compression tests (UCS) and Brazilian tests. The Brazilian tests are performed according to the ISRM standard for determining indirect tensile strength of rock materials (Bieniawski & Hawkes, 1978), and the setup is as seen in Figure 7 (C). The purpose of the uniaxial compressive tests is to measure the uniaxial compressive strength and to determine stress-strain curves for Young's modulus *E* and Poisson's ratio υ. Figure 7 (A) and (B) illustrate the different deformation measuring methods: Strain clips and strain belts, LVDT's and strain gauges glued upon the test specimen cylindrical surface. Most of the *E*-moduli have been determined as *E** using LDVT's which include bedding effects at end platens in the compression machine and we have found the ratio E/E* = 1.80±0.57 in comparison to strain gauges measurements.

The uniaxial compressive tests are performed according to the ISRM standard for determining the uniaxial compressive strength (Bieniawski et al., 1979). More advanced test schemes have comprised triaxial tests in the DTU MTS-815 rock testing facility according to the ISRM standard for determining the strength of rock materials in triaxial compression (ISRM 1983). The triaxial tests are

performed for obtaining the strength at higher confining pressures to determine the friction angle, φ (°), and the cohesion, *c*.
In the cases where triaxial tests are not performed it is possible to use the procedure described by Madland et al. (2002) to combine UCS and Brazilian test results and determine the friction angle by:

$$\sin\varphi = \frac{\sigma_c - 4\sigma_t}{\sigma_c - 2\sigma_t} = \frac{\sigma_c/\sigma_t - 4}{\sigma_c/\sigma_t - 2}, \quad (1)$$

where σ_c (MPa) is the UCS strength and σ_t (MPa) is the Brazilian strength. This procedure requires that the material is isotropic and that both the extensional and compressional failure can be described by the Mohr-Coulomb failure criteria, which is not always the case (Ramsay & Chester, 2004; Labuz & Zang, 2015).

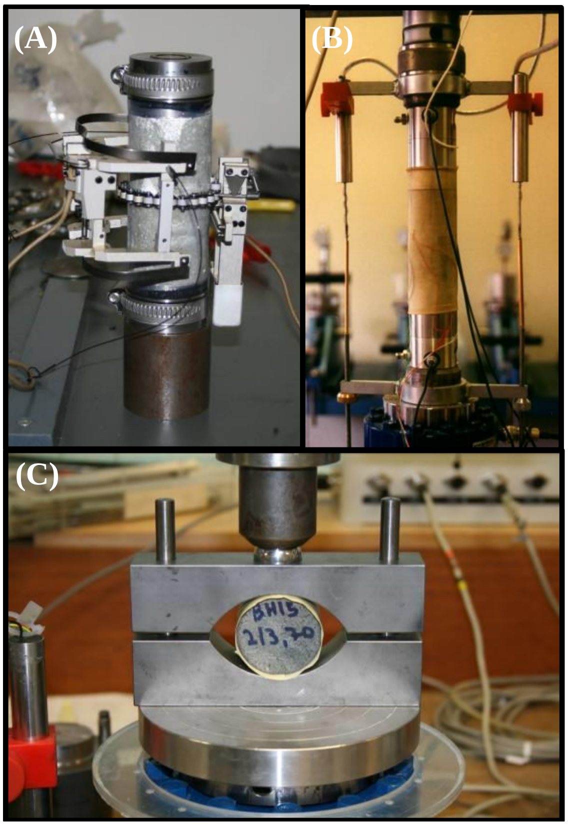

Figure 7 Test setup overview with specimens equipped for strain measurements. (A) Triaxial test. (B) UCS test. (C) Brazilian test.

5 EVALUATION AND CONCLUSION

The trends established for compression strength, tensional strength and elasticity modulus must be taken with some caution. The different rock types included and the local variability should be included in an overall evaluation.

Table 2 Parameter evaluation for the five sites presented in Section 3 taking into account that the exponential factor in the regression equations is equal as listed here: $\sigma_c = A \exp(2.6\, \rho_b)$, $\sigma_t = B \exp(2.6\, \rho_b)$ and $E = C \exp(2.6\, \rho_b)$.

		Coefficients for:				
		σ_c	σ_t	E		
Locality	Type	A	B	C	A/B	C/A
Olafsfjörður	Tertiary Basalt	0.045	0.0045	14	10	311
Nupur Þórsá	Early Pleistocene/ Þórsá Lava	0.052	0.0052	26	10	500
Kárahnjúkar *	Early Pleistocene Moberg	0.075	0.0075	14	10	187
Fáskrúðsfjörður	Tertiary Basalt	0.020	0.0020	10	10	500
Búðarháls virkjun	Early Pleistocene/ Móberg and Rhyolite	0.055	0.0055	16	10	290

* C/A influenced by low density or porous rock types.

However, the main finding that an exponential factor of 2.6 in the regression equations fit all the different plots from sites in different geological type formations seem to be well defined. Consequently, using the Madland method discussed in Section 4 the ratio for σ_c/σ_t = A/B = 10 gives a first order estimate for the friction angle

$$\varphi = \sin^{-1}\left(\frac{\sigma_c/\sigma_t - 4}{\sigma_c/\sigma_t - 2}\right) = \sin^{-1}(0.75) = 49°, \quad (2)$$

for most volcanic rock types. A lower bound value may be A/B ≈ 8, i.e. $\varphi = 41°$. As φ is difficult and costly to determine using triaxial tests on such rock formations this makes evaluations of strength parameters simpler taking into account that the internal cohesion *c* may be estimated from (Madland et al., 2002)

$$c = \sqrt{3}\sigma_t\,. \quad (3)$$

The design value of σ_t should be carefully estimated as a lower bound value related to the actual rock types and their classification properties in form of saturated surface dry bulk density.

Using the constants A, B and C summarized in Table 2 the differences between sites are evident related to the different volcanic rock types like scoria and sand- and siltstone derived from tephra. Beside the influence of porosity and variable mineralogy there seems to be an effect of weathering and age of the volcanic formations. The Tertiary Basalt sites show lower strength parameters than the Þórsá Lava and especially all formations prone to weathering like scoria sedimentary interbeds of acidic tuffs show very variable strength and deformation properties depending on their position in the basaltic successions.

Most of the determination of elasticity moduli has been done with LVDT's measuring the total deformation between end platens in the compression machine. As this include bedding effects the *E*-modulus may be underestimated which may explain the relative low E/σ_c=187 to 500 where values of 500 to 1000 were expected.

In conclusion the present analysis of test results from MSc theses on well-defined formations (Einarsson, 1994; Jónsson, 1996) including provided data from Kárahnjúkar gives a frame for comparison with future rock mechanics test results. The evaluation principles may guide the use of established parameters towards an upscale to field parameters.

6 ACKNOWLEDGEMENTS

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