Geotechnical Properties of Sedimentary Bedrock in Calgary, Alberta

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ABSTRACT
The bedrock in Calgary belongs to the Paskapoo Formation which consists of flat lying to gently dipping sandstone (SS), siltstone (SI) and mudstone locally known as claystone (CS). The Paskapoo Formation has over 50 % of SI and CS deposits (Hamblin 2004). The SS and SI are typically much stronger than CS which can have the consistency of stiff to hard clay. The bedrock units are inter-fingered, laterally discontinuous and their geotechnical properties are highly variable which pose challenges for tunneling and slope stabilization projects involving rock cuts. The variability in the geotechnical properties of the Calgary bedrock was investigated by performing extensive laboratory testing on bedrock samples collected from several investigations performed in all quadrants of the City of Calgary. For CS, the investigated geotechnical properties included Atterberg Limits, slake durability, swelling strains and swelling pressures, rock mineralogy, shear strength parameters (cohesion, friction angle), uniaxial compressive strengths, tensile strengths and durability under freezing and thawing conditions. For SS, the investigated properties included shear strength parameters, uniaxial compressive strengths, tensile strengths, abrasiveness and durability under freezing and thawing conditions. This paper presents the laboratory test results for the investigated geotechnical properties and their impacts which are critical for the selection of the Tunnel Boring Machines (TBMs), associated muck conveyance system and tunnel lining systems. The paper also discusses the impacts of investigated geotechnical properties on the slope stabilization of the rock-mass of the Paskapoo Formation.

RÉSUMÉ
Le substratum rocheux de Calgary appartient à la Formation de Paskapoo qui se compose de grès plat à légèrement incliné (SS), de siltstone (SI) et de mudstone connu localement sous le nom d'argile (CS). La Formation de Paskapoo compte plus de 50 % de gisements SI et CS (Hamblin 2004). Le SS et le SI sont généralement beaucoup plus résistants que le CS, qui peut avoir la consistance d'une argile rigide à dure. Les unités de substratum rocheux sont entrelacées, latéralement discontinues et leurs propriétés géotechniques sont très variables, ce qui pose des défis pour les projets de tunnel et de stabilisation des talus impliquant des déblais rocheux. La variabilité des propriétés géotechniques du substrat rocheux de Calgary a été étudiée en effectuant des tests approfondis en laboratoire sur des échantillons de substrat rocheux prélevés lors de plusieurs enquêtes effectuées dans tous les quadrants de la ville de Calgary. Pour le CS, les propriétés géotechniques étudiées comprenaient les limites d'Atterberg, la durabilité des boues, les déformations et les pressions de gonflement, la minéralogie des roches, les paramètres de résistance au cisaillement (cohésion, angle de frottement), les résistances à la compression uniaxiale, les résistances à la traction et la durabilité dans des conditions de gel et de dégel. Pour SS, les propriétés étudiées comprenaient les paramètres de résistance au cisaillement, les résistances à la compression uniaxiale, les résistances à la traction, l'abrasivité et la durabilité dans des conditions de gel et de dégel. Cet article présente les résultats des essais en laboratoire pour les propriétés géotechniques étudiées et leurs impacts qui sont essentiels pour la sélection des tunneliers, système de transport de boue associé et des systèmes de revêtement de tunnel. L'article discute également des impacts des propriétés géotechniques étudiées sur la stabilisation des pentes de la masse rocheuse de la Formation de Paskapoo.

1 INTRODUCTION

The bedrock in Calgary is sedimentary and non-marine belonging to the Paskapoo or Porcupine Hills Formations (Prior et al. 2013). The distinction between the Paskapoo and Porcupine Hills Formations is primarily regional. Calgary is located at the transition zone between the two formations as shown in Figure 1. Both formations are similar in depositional environment and geotechnical properties; therefore, the bedrock formation in the Calgary area is referred to as the Paskapoo Formation in this paper.

The Paskapoo Formation consists of flat lying to gently dipping SS, SI and CS. All three bedrock units are non-marine, calcareous, interbedded and laterally/vertically discontinuous. The Paskapoo Formation has over 50 % of CS and SI deposits (Hamblin 2004). There is a weathered zone near the bedrock surface generally 1 m to 2 m thick. In some cases, the weathered zone is thicker than 2 m and may extend 4 m to 6 m below the bedrock surface.

The depth to bedrock across Calgary is highly variable. Bedrock outcrops at surface at some locations and is at depths greater than 30 meters below ground surface (mBGS) at other locations.

Crockford (2012) reviewed several field investigations performed in Calgary to compile the Uniaxial Compressive Strength (UCS) data of the bedrock of the Paskapoo Formation and to estimate the percentages of each bedrock unit. The data analyzed in the study comprised 145, 109 and 96 UCS tests on SS, SI and CS, respectively. The median UCS of SS, SI and CS were 23.7 MPa, 22 MPa and 0.99 MPa, respectively and the observed percentages of SS, SI and CS were 18.4 %, 33.8 % and 47.8 %, respectively. Crockford (2012) concluded that the rockmass in Calgary is heterogeneous, inter-fingered and discontinuous laterally; therefore, it is not possible to draw a direct correlation between boreholes even within a specific project site.

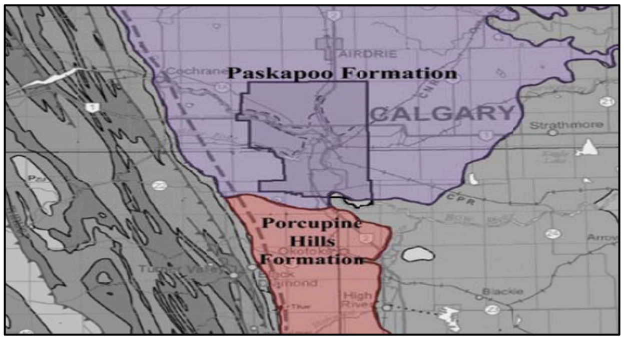

Figure 1: Calgary location with respect to the Paskapoo and Porcupine Hills Formations (Crockford 2012)

Due to the heterogeneous rockmass, it is not possible to predict if foundations, slopes and tunnels at a particular location will be installed within a single bedrock unit or several interbedded bedrock units. The uncertainty with respect to bedrock type and bedrock characteristics at a particular location makes it challenging to select suitable means and methods for construction of foundations, tunnels, slopes and bedrock excavation.

This paper presents geotechnical properties of CS, SI and SS measured in all four quadrants of the City of Calgary (the City). The geotechnical properties of CS, SI and SS presented in this paper may assist designers, planners and contractors in the selection of suitable means and methods for construction of tunnels, foundations and rock excavation.

2 CHALLENGES IN CALGARY BEDROCK

The sedimentary bedrock in Calgary is heterogeneous in nature and consists of CS, SI and SS. The geotechnical properties of CS are significantly different from harder layers of SI and SS and pose various challenges for the design and construction of infrastructure involving deep excavations, construction of foundations and installation of water and sewer pipes using Tunnel Boring Machines (TBMs) and Microtunnel Boring Machines (MTBMs) and other trenchless methods. Specific challenges for construction in CS and harder layers of SI and SS are presented in the following sections. For the purposes of this paper, SI and SS will be discussed together and referred to as SI&SS, unless otherwise noted.

2.1 Claystone (CS)

Bedrock strength classification was performed in accordance with the Journal of International Society of Rock Mechanics (ISRM 1981). The CS in Calgary is extremely weak (R0) to weak (R2). The CS is of low to medium plasticity, has swell potential and disintegrates quickly when exposed to weathering and cycles of freeze and thaw. Specific design and construction challenges in CS are summarized below.

Clogging Potential: CS is sticky and has clogging potential which is critical for the selection of the cutterhead of TBMs/MTBMs, muck conveying system and separation plant. The clogging potential is assessed using the universal classification diagram for critical consistency changes regarding clogging and dispersing shown in Figure 2 using soil index properties including natural moisture, Liquid Limit and Plastic Limit and any water added during tunneling (Hollmann and Thewes 2013).

Swelling Potential: The CS is comprised of non-clay and clay minerals and is known to have swelling potential. The assessment of the magnitude of swelling is required for selection of the overcut around the TBM/MTBM and selection of lubricants to be used in the annulus around the TBM/MTBM to reduce friction between the TBM/MTBM and ground. The swelling mechanism and magnitude of swelling is assessed by performing X-Ray Diffraction (XRD) and free swell tests.

Slake Durability: The CS in the Calgary area disintegrates when exposed to wetting, drying or abrasion. The ability of the CS to resist the effect of repeated cycles of wetting/drying and abrasion is assessed by performing slake durability tests. The disintegration of CS may result in overhang of the overlying SS layers resulting in toppling failures as shown on Figure 3; therefore, assessment of slake durability of CS is critical.

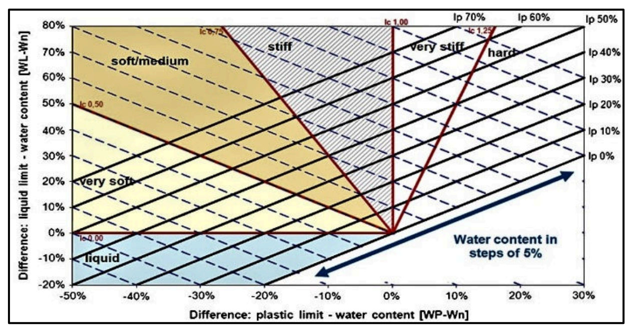

Figure 2. Universal classification diagram for critical consistency changes regarding clogging and dispersing (from Hollmann and Thewes 2013)


Figure 3. Slaking of CS and Resulting Overhang of SS

2.2 Sandstone and Siltstone (SS&SI)

The SI&SS are very weak (R1) to strong (R4) in accordance with ISRM (1981) and are abrasive. Excavation and tunneling in SI&SS requires blasting, hydraulic break hammers or dozers equipped with ripper teeth and TBMs/MTBMs equipped with appropriate cutting tools. The strength and abrasiveness of SI&SS is assessed by performing UCS tests and abrasiveness tests providing Cerchar Abrasiveness Index (CAI). These parameters are used for the selection of cutting tools for TBMs/MTBMs and the selection of means and methods for excavations in SI&SS.

3 MEASURED GEOTECHNICAL PARAMETERS

In addition to the challenges discussed above for CS and SI&SS, other parameters of interest for Calgary bedrock presented in this paper include:

- Tensile Strength – tensile strength influences the rock deformability and blasting results and was assessed using Brazilian Tensile Strength tests.
- Secant Young's Modulus at 50 % of the Ultimate UCS (E_{50}) is one of the basic geo-mechanical parameters used in rock engineering. The E_{50} is determined in conjunction with UCS testing.
- Shear Strength Parameters – Shear strength parameters including effective cohesion (c'), effective friction angle (ϕ'), residual cohesion (c_r) and residual friction angle (ϕ_r) are used for slope stability analyses and for estimating rock mass properties. The shear strength parameters of CS, SI&SS were estimated by performing direct shear tests on intact samples, saw cut samples and samples with a natural discontinuity.
- Freeze Thaw Tests – The bedrock in Calgary is subject to freeze thaw cycles resulting in weathering and erosion. The durability of bedrock under freezing and thawing conditions was assessed using freeze thaw tests on CS and SS samples.
- The estimation of bedrock type proportion (CS, SI and SS) is critical for assessing the rippability of bedrock and for the selection of means and methods for rock excavation. The percentage of each bedrock unit was estimated from rock cores retrieved from boreholes.
- Rock Quality Designation (RQD) is used to assess the quality of bedrock. The RQD was estimated from the rock cores retrieved from boreholes.

The data presented in this paper is based on 150 boreholes drilled in all four quadrants of the City. The borehole depths ranged from approximately 10 m to 100 m. The data is based on a total bedrock cored length of approximately 2112 m. The percentage of each bedrock unit and RQD were also measured and are presented in this paper. Laboratory testing was performed on bedrock core samples to characterize and measure bedrock properties. A summary of the laboratory testing performed on bedrock core samples is presented Table 1.

Table 1. Summary of Laboratory Testing on CS, SI and SS

Test Parameters	Number of Tests	Bedrock Type	ASTM Standard
Atterberg Limits	262	CS	ASTM D4318
Free Swell	42	CS	ASTM D4546
Swell Pressure	19	CS	ASTM D4546
Slake Durability Index	69	CS	ASTM D4644
Rock Mineralogy (XRD)	65	CS	NA
Bedrock Durability Under Freeze/Thaw	4	CS/SS	ASTM D5312 (Modified)
UCS	118	CS	ASTM D7012
UCS	229	SI/SS	ASTM D7012
UCS and E_{50}	26	CS	ASTM D7012
UCS and E_{50}	43	SI/SS	ASTM D7012
Tensile Strength	9	CS	ASTM D3967
Tensile Strength	19	SI/SS	ASTM D3967
CAI	67	SI/SS	ASTM D7625
Direct Shear	28	CS	ASTM D5607
Direct Shear	14	SI/SS	ASTM D5607

3.1 Percentage of CS, SI and SS

The occurrences of CS, SI and SS were measured in the boreholes and were expressed as percentages. The observed percentages of CS, SI and SS were 48.2 %, 14.9 % and 36.9 %, respectively. This information in conjunction with the RQD and UCS is used to select the means and methods for excavation and for classifying the bedrock that can be ripped with a specific dozer equipped with a ripper tooth and that cannot be ripped and requires blasting or a hydraulic hammer for excavation.

3.2 Rock Quality Designation (RQD)

The RQD is a general indicator of the rock mass quality and is a rough measure of the degree of jointing or fracture in the rock mass. The RQD values were obtained by measuring the total length of recovered bedrock core pieces longer than 100 mm expressed as a percentage of the total length of the core run. Based on the RQD values, the rock mass can be classified from very poor to excellent (Deere 1964). The frequency distribution of measured RQD values is presented in Figure 4.

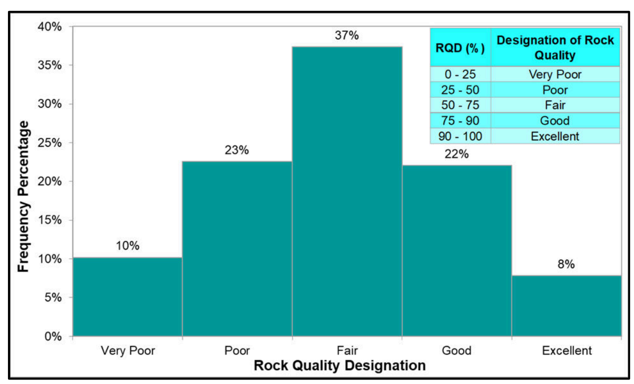

Figure 4. Frequency Distribution of RQD Values

3.3 Atterberg Limits – CS

Atterberg Limits are used to assess the clogging potential of CS in accordance with the method developed by Hollman and Thewes (2013). Atterberg Limits were measured by performing tests on 262 CS samples. The test results are plotted on the plasticity chart presented in Figure 5 which indicates that the CS is of low to medium plasticity and has the potential for clogging the TBM/MTBM cutter head, muck conveyance system and separation plant (for slurry based TBMs/MTBMs).

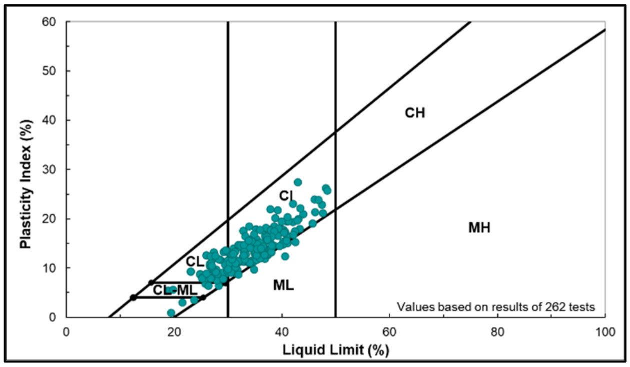

Figure 5. Plasticity Chart of CS samples

3.4 Rock Mineralogy – CS

XRD tests were performed on 65 CS samples to determine the rock mineralogy. Based on the test results, the CS is comprised of non-clay minerals (quartz, feldspar, plagioclase, calcite and dolomite), non-swelling clay minerals (illite, mica, kaolinite and chlorite) and swelling clay mineral (smectite). Swelling of CS is caused by smectite and varies with the percentage of smectite in the CS. Figure 6 provides the minimum, maximum, average and median percentages of non-clay minerals, non-swelling clay minerals and swelling clay minerals. The test results indicate that the percentage of smectite mineral is variable with an average of approximately 21 %. In correlation with the variable smectite content, the swell potential of CS is also variable as indicted by the summary of free swell test results in Section 3.5.

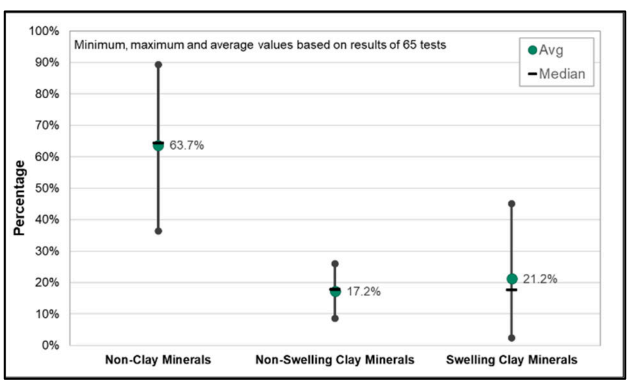

Figure 6. Summary of XRD Test Results – CS

3.5 Swell Strain and Swell Pressure – CS

Free swell tests were performed on 19 samples to determine the swelling strain of the CS when subjected to wetting. The swelling strain of the CS samples varied from 0.54 % to 3.9 % indicating that the CS has variable swelling potential which is explained by the variability of the smectite content and plasticity of CS. Figure 7 shows a maximum measured free swelling strain of 3.7 % for a CS sample. It is evident from Figure 7 that swelling occurred within 24 hours after CS was subjected to wetting.

Swell pressure tests at a constant strain were also performed on 24 samples to determine the pressure exerted by CS. The swell pressure varied from 24 kPa to 1330 kPa. The highest swell pressure was noted for a sample with a Liquid Limit of 48.1 % and a free swell strain of 3.7 % as shown in Figure 8.

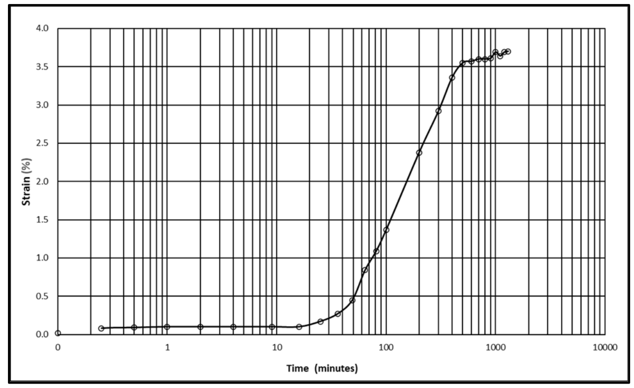

Figure 7. One Dimensional Free Swell Test Results on a CS Sample – Swell = 3.7 %, Liquid Limit = 48.1 %

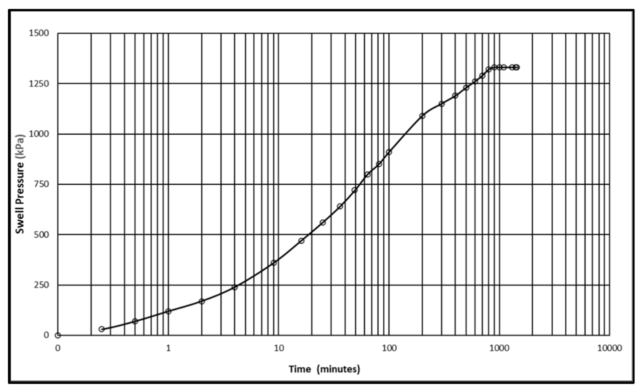

Figure 8: One Dimensional Swell Pressure Test at Constant Strain on a CS Sample – Maximum Swell Pressure = 1330 kPa, Free Swell = 3.7 %

3.6 Slake Durability

Slake durability tests were performed on 69 CS samples to assess their resistance to disintegration when subjected to two standard cycles of drying and wetting. The results of the slake durability tests are reported as an index (Id_2). This index is the weight of the dry sample remaining in the test drum after two cycles of wetting and drying ("slaking") which is then expressed as a percentage of the initial dry sample weight. The bedrock samples with Id_2 approaching zero (0 %) are highly susceptible to slaking and bedrock samples with Id_2 approaching 100 % are not susceptible to slaking.

The frequency distribution of slake durability index Id_2 is presented in Figure 9. The test results indicate that CS has very low slake durability and will disintegrate quickly when exposed to cycles of wetting and drying.

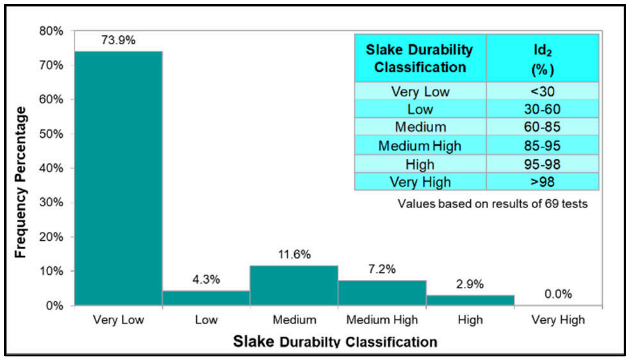

Figure 9: Frequency Distribution of Slake Durability Test Results on CS Samples

Figure 10 shows a CS sample with very low slake durability subjected to cycles of wetting and drying.

Figure 10. Slake durability test on CS

3.7 Freeze and Thaw Tests – CS and SS

Tests were performed on two CS samples and two SS samples to determine their durability under freezing and thawing conditions. The samples were first immersed in water for 24 hours then subjected to 3 cycles of 24 hour freezing and thawing.

The mass loss of the two SS samples after three 24 hour cycles of freezing and thawing was 0.11 % and 2.01 %. The test results indicate a small amount of mass loss which is an indication that SS is resistant to freeze thaw cycles. This is consistent with observations of SS outcrops in Calgary showing very little weathering.

Conversely, one of the CS samples completely disintegrated during immersion in water while the material loss in the second CS sample was approximately 64.92 % which indicates that the CS will disintegrate when subjected to freeze/thaw cycles consistent with observations of the bedrock outcrop in Calgary showing weathering of the CS. Figures 11A, 11B and 11C present photographs of a CS sample prior to testing, after 24 immersion and after 3 cycles of freezing and thawing.

Figure 11A. Freeze/Thaw Test – CS Sample Prior to Testing

Figure 11B. Freeze/Thaw Test – CS Sample After 24 Hour Immersion

Figure 11C. Freeze/Thaw Test – CS Sample After 3 Cycles of Freezing and Thawing

3.8 Tensile Strength – CS, SI and SS

Brazilian tensile strength tests were performed on 5 CS samples, 4 SI samples and 19 SS samples. The minimum, maximum, average and median tensile strengths of CS, SI and SS are shown in Figure 12. The test results indicate that CS and SI have low tensile strength and a low resistance to weathering and abrasion; whereas, SS has a highly variable tensile strength and is resistant to weathering and abrasion.

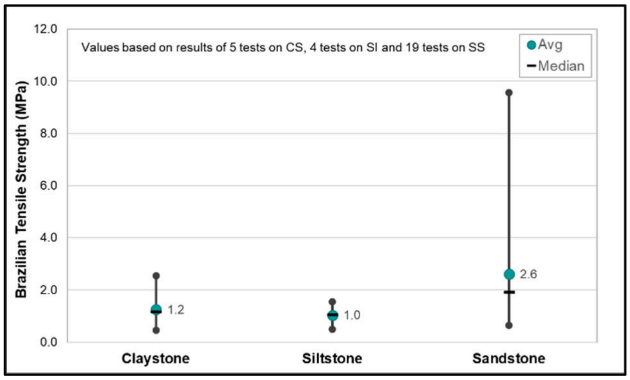

Figure 12: Summary of Tensile Strength Test Results

3.9 Cerchar Abrasiveness – SI&SS

Cerchar abrasiveness tests were performed on 67 SI&SS samples to determine the CAI. The test results are shown in Figure 13. The measured CAI of SI&SS varied from 0.48 to 1.92 indicating that abrasiveness of SI&SS varies from very low to medium (ASTM D7625).

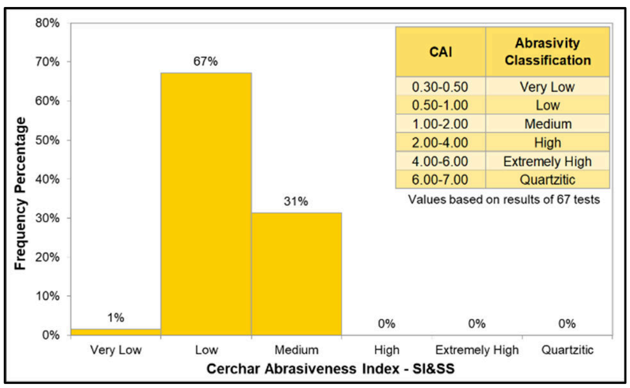

Figure 13: Frequency Distribution of Cerchar Abrasiveness Test Results for SI&SS

A sample Cerchar Abrasiveness test result on a SS sample is shown in Figure 14.

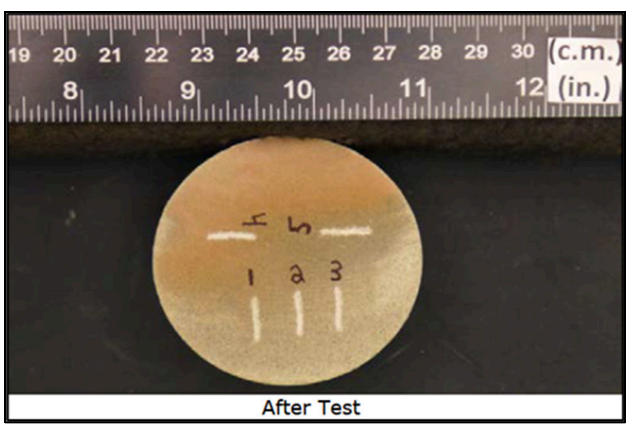

Figure 14. Cerchar abrasiveness test on SS

3.10 Uniaxial Compressive Strength (UCS) and Secant Young's Modulus (E_{50})

UCS tests were performed on 118 CS samples and 229 SI&SS samples. The UCS of CS varied from 0.05 MPa to 24.5 MPa indicating the CS is extremely weak (R0) to weak (R2). The frequency distribution of measured UCS values for CS is shown in Figure 15.

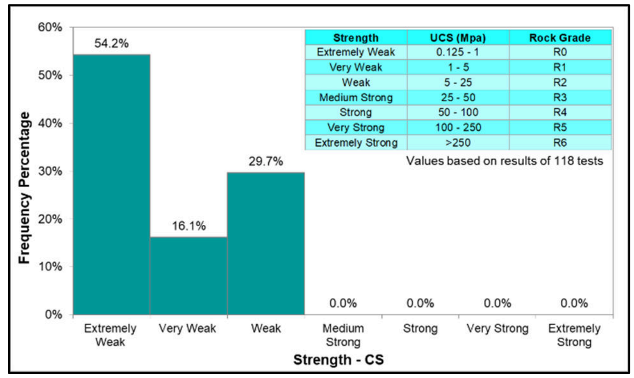

Figure 15: Frequency Distribution of Measured UCS Values for CS

The UCS of SI&SS varied from 1.4 MPa to 89.3 MPa indicating that the SI&SS are very weak (R1) to strong (R4). The frequency distribution of measured UCS for SI&SS is shown in Figure 16.

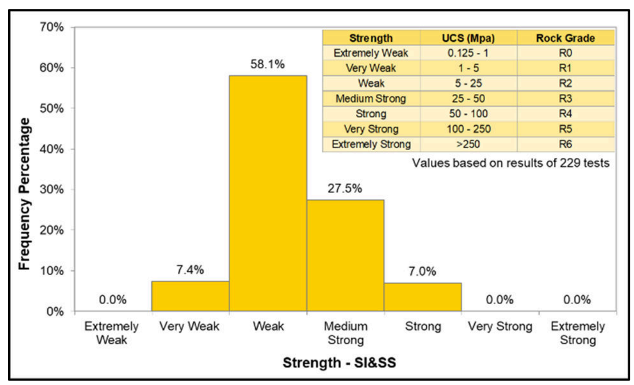

Figure 16: Frequency Distribution of Measured UCS Values for SI&SS

The E_{50} was measured in conjunction with the UCS for 26 CS samples and 43 SI&SS samples in accordance with ASTM D7012. The test results are presented in Figures 17 and 18 for CS and SI&SS, respectively.

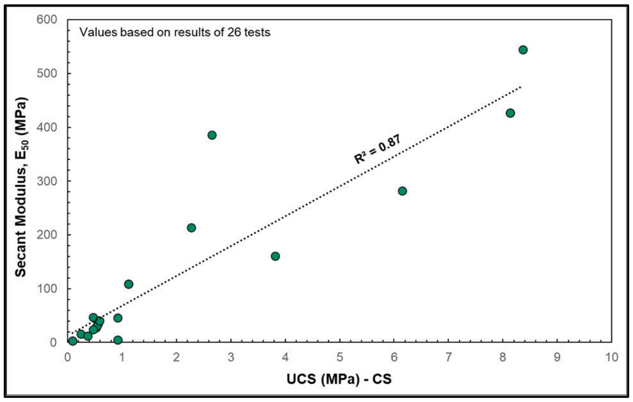

Figure 17: Correlation Between E_{50} and UCS for CS

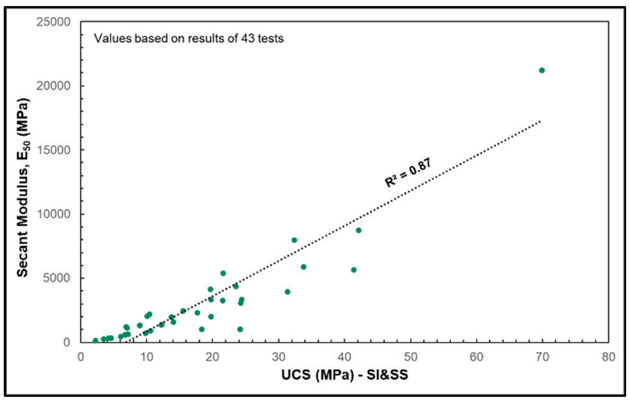

Figure 18: Correlation Between E_{50} and UCS for SI&SS

Regression analysis was performed to develop correlations between the E_{50} and UCS for CS and SI&SS. Simple correlations are presented in Table 2 between E_{50} and UCS. These correlations have high coefficients of determination (R^2) and may be used for estimating the E_{50} from the UCS for CS and SI&SS in the Calgary area.

Table 2. Regression Analysis Results for UCS-E_{50}

Bedrock Type	Equation	R^2
CS	E_{50} = 55.4 (UCS) + 12.9	0.87
SI&SS	E_{50} = 274.6 (UCS) + 1881.1	0.87

3.11 Shear Strength Parameters

Direct shear tests were conducted on intact bedrock core samples to determine the peak cohesion (c'), peak friction angle (ϕ'), residual cohesion (c_r) and residual friction angle (ϕ_r) for CS and SS. Test results are presented in Tables 3 and 4 for CS and SS, respectively.

Table 3. Measured Shear Strength Parameters – Intact CS Core Samples

Parameter	Minimum	Maximum	Average	No. of Tests
c' (kPa)	0	1180	260	27
ϕ' (degree)	4	62	28	27
c_r (kPa)	0	220	85	5
ϕ_r (degree)	23	30	27	5

Table 4. Measured Shear Strength Parameters – Intact SS Core Samples

Parameter	Minimum	Maximum	Average	No. of Tests
c' (kPa)	85	12960	7115	9
ϕ' (degree)	52	88	83	9
c_r (kPa)	49	2560	1580	9
ϕ_r (degree)	39	84	70	9

Direct shear tests were also conducted on two SS samples with natural discontinuities and three saw cut samples to determine shear strength parameters of SS under these conditions. Test results are presented in Tables 5 and 6.

Table 5. Measured Shear Strength Parameters – SS Samples with a Natural Discontinuity

Parameter	Minimum	Maximum	Average	No. of Tests
c' (kPa)	150	580	365	2
ϕ' (degree)	39	47	43	2
c_r (kPa)	51	146	99	2
ϕ_r (degree)	38	43	41	2

Table 6. Measured Shear Strength Parameters – SS Samples with a Saw Cut Surface

Parameter	Minimum	Maximum	Average	No. of Tests
c' (kPa)	5	785	270	3
ϕ' (degree)	19	40	32	3
c_r (kPa)	5	463	163	3
ϕ_r (degree)	30	40	36	3

4 CONCLUSIONS AND RECOMMENDATIONS

The sedimentary bedrock in Calgary is heterogeneous consisting of discontinuous layers of CS, SI and SS. The properties and behaviour of each bedrock unit are significantly different and pose challenges for the design and construction of tunnels, foundations and excavations in bedrock.

The results presented in this paper indicate that bedrock is comprised of approximately 50 % of CS and 50 % of hard layers of SI&SS. These percentages may be different at specific locations.

The test results presented in this paper indicate significant variability in CS properties including plasticity and percentages of non-clay mineral, non-swelling clay mineral and swelling clay minerals which influence the swell potential and swell pressure of CS. Swell pressures are high and may be detrimental to structures if CS is not protected from swelling.

The CS in its in-situ state is hard and does not have clogging potential. However, the addition of water during tunneling changes the consistency of CS and may result in CS becoming sticky with strong clogging potential. The use of additives and water is needed to disperse the sticky CS and reduce the clogging potential. The clogging potential of CS plays a vital role in the selection of the tunneling equipment including the cutter head of the TBMs/MTBMs, muck conveyance system and separation plant for slurry type MTBMs.

CS has very low slake durability when exposed to wetting and drying cycles, low tensile strength and has very low durability against freeze/thaw cycles impacting the slope stability of rock cuts. The CS in rock cuts requires protection from disintegration due to wetting/drying cycles freeze/thaw cycles. The CS will disintegrate if not protected resulting in overhang of the overlying hard layers of SI and SS and toppling failures.

The SI&SS layers are weak to strong and have low to medium CAI. These properties need to be considered in the selection of cutting tools for the TBMs/MTBMs and the means and methods for excavations including blasting and hydraulic hammers.

Simple correlations have been developed between E_{50} and UCS for CS and SI&SS. The correlations were confirmed by the regression analyses. The correlations have high co-efficient of determination (R^2 value) and may be used for estimating the E_{50} from UCS for CS and SI&SS in Calgary.

The shear strength parameters of CS and SI&SS are highly variable and depend on many factors including the UCS and plasticity for CS.

Considering the variability in the bedrock properties, site specific investigations and testing are recommended to assess bedrock properties which are critical for the design of structures in bedrock, selection of suitable means and methods for tunneling and bedrock excavations, slope stability assessments and for assessment of rock fall hazards in rock cuts.

5 REFERENCES

ASTM D3967. Splitting Tensile Strength of Intact Rock Specimens (Brazilian Disc Tensile Test).

ASTM D4318. Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils.

ASTM D4546. One Dimensional Swell or Collapse, Method B, Swell Strain and Swell Pressure.

ASTM D4644. Slake Durability of Shales and Similar Weak Rocks.

ASTM D5312. Durability of Rock for Erosion Control Under Freezing and Thawing Conditions – ASTM D5312 Modified.

ASTM D5607. Direct Shear Strength Tests of Rock Specimens Under Constant Normal Force.

ASTM D7012. Compressive Strength and Elastic Moduli of Intact Core Specimens Under Varying Stress and Temperatures, Method D.

ASTM D7625. Abrasiveness of Rock Using the Cerchar Method.

Crockford, A.M. 2012. Shallow Urban Tunneling Through Heterogeneous Rockmasses: Practical Experience from Small Scale Tunnels in Calgary, Alberta and the Influence of Rockmass Layering on Excavation Stability and Support Design. Department of Geological Sciences and Geological Engineering, Queen’s University, Kingston, ON, Canada.

Deer, D.U (1964). Technical Description of rock cores, Rock Mechanics Engineering Geology, 1 (16-22).

Hamblin, A.P. (2004). Paskapoo-Porcupine Hills Formation in Western Alberta; Synthesis of Regional Geology and Resource Potential. Geological Survey of Canada (Open File 5392).

Hollmann, F., Thewes, M. (2013). Assessment Method for Clay Clogging and Disintegration of Fines in Mechanised Tunneling. TUST 37, pp. 96-106.

Journal of International Society for Rock Mechanics (ISRM,1981).

Prior, G.J., et.al. (2013). Bedrock geology of Alberta; Alberta Energy Regulator, AER/AGS (Map 600).