STRESS RELAXATION OF ROCKS AND ITS RELATIONSHIP TO ROCK DURABILITY PROPERTIES

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ABSTRACT: Carbonate and other rocks subjected to an initial fixed uniaxial stress at constant strain adjusted and partially relaxed, and the stress gradually decreased. The rate of relaxation was log-normal, and varied with the rock sample. The rocks were tested at three stress levels: 3.45, 6.9, and 10.3 MPa. When expressed as percent of original stress, the relaxation was maximum at 6.9 MPa. Saturated samples of the rock generally relaxed at more than twice the rate of the dry samples. In about half of the 44 samples studied, the relationship between dry and wet relaxation was linear at the 3.45 MPa level stress, and in the other half, a curvilinear 2nd order relationship was noted. However, at the two higher stress levels, the relationship between dry and wet relaxation was linear in all samples. When the durability characteristics of the rock were compared, statistically significant differences were found between the curvilinear and the linear relationship rock groups. The freeze-thaw breakdown, water adsorption and absorption, and thermal expansion coefficient were all significantly lower in the former, whereas Young's moduli, overall relaxation rates, and the differences in rates between dry and wet samples were all significantly higher in the latter group. The rock strength and the Young's moduli were related to rock density. The rate of relaxation at all stress levels and in both dry and wet state correlated with the water adsorption characteristics of the rock. The relaxation comparison between dry and wet rocks at all stress levels was related to the grain size of the rock. The pore size, and the interaction of water in the rock pore have been shown to have a significant influence on the strength and durability properties of the rocks.

RESUME: Les roches carbonifères étaient initialement chargées d'une tention uniaxiale au déformation constante. La pression dans les roches s'accommodait, la relaxation dans les roches s'est présentée, et la pression s'abaissait graduellement. L'ampleur de la relaxation a été logarithmique et différente dans certaines roches. On a testé les roches à trois degrés de charges: 3.45, 6.9 et 10.3 MPa. En exprimant la part du pourcentage de relaxation à la pression originelle, la relaxation a été supérieure à 6.9 Mpa. La relaxation des échantillons saturés a été généralement majeure à deux fois de plus que celle des roches déhydratées. En étudiant environ la moitié des 44 échantillons, la relation entre la relaxation en état sec et en état hydraté, à la pression 3,45 Mpa a été linéaire, dans la seconde moitié on a noté la relation de courbe (quadrilatère). Cependant le rapport entre la relaxation en état sec et en état hydraté à tous les deux pressions majeure a été linéaire pour tous les échantillons.

A la comparaison statistique des qualités qui quaractérisent la solidité, on a constaté des différences entre les roches au rapport linéaire et au rapport de courbe. La désintégration au moment de congélation et décongélation, absorption et adsorption de l'eau, coéfficient de l'expantion thermique ont été supérieurs d'une manière importante dans le groupe linéaire, tandis que les modules Young (de déformation), la relaxation générale et les différences en grandeur de la relaxation en état sec et hydraté ont été supérieure d'une sorte importante pour le groupe de courbe. La solidité et les modules Young des roches sont en relation avec la densité des roches. L'étendue de la relaxation des roches à toutes les pressions dans tous les deux états – secs et hydratés ont eu une importante corrélation avec des qualités des roches l'eau d'adsorption. Il s'est montré que la largeur des vides et l'interaction de l'eau de la surface des roches dans les vides ont une influence importante aux qualités solides des roches.

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INTRODUCTION

The purpose of this research was to determine the relationships between the pore properties and the contained nature of fluids in rocks and their elastic behaviour under stress. The proportion of adsorbed and absorbed water in the rock, and the elastic moduli in dry and wet state were determined and compared.

The behaviour of rocks depends upon their physical and mechanical properties. The voids or pore spaces affect the mechanical properties the most (Farmer, 1983). Effective pore space permits the penetration/retention of water or other liquids into/by the rock (Popovics, 1992). Moisture and dissolved salts promote rock decay. The complexity of the capillarity of a rock determines the hygric properties that are induced by moisture (Winkler, 1994). Water absorption and degree of saturation are related to rock durability. The rate at which water and salt solutions enter the rock, i.e., saturate will determine how the rock will behave during weathering (Hudec, 1989). The damage to weak rocks and concrete containing them by repeated wetting and drying cycles is well known. The freezing and thawing damage of rocks is also governed by pore size and pore size distribution.

Porosity

The number, size, shape and the degree to which rock the pores are interconnected strongly influence rocks' physical properties. The mean pore size affects the internal surface area, which plays an important role in the adsorption behaviour of rock. Porosity will only contribute to the ingress of fluid if the pores are interconnected (open pores) and accessible to molecules or ions in the surrounding environment. Closed pores are those without communication with the surroundings and are not associated with the adsorption and the permeability of molecules, but they influence the mechanical properties of rocks. Hudec (1993) presented both theoretical arguments and experimental evidence linking the characteristics of the pore surface and pore size to the expansion and failure of aggregates and concrete. Surface forces on the pore surfaces are determined by the type of mineral, its crystal matrix stability and the type of crystal surface. He recognized four types of internal pore surfaces: surface on an amorphous solid, crystal face surface, cleavage surface and fracture surface (Figure 1). Under dry conditions, most of the rocks are resistant to weathering - they disintegrate or abrade slowly by mechanical forces (wind erosion, thermal dilation, unloading, etc.). On the other hand, water can cause severe deterioration either as a medium that transports chemical weathering agents (chemical weathering), or as an agent of weathering of the rock itself by its chemical, physical or thermodynamic properties (Ondrasik, 1996).

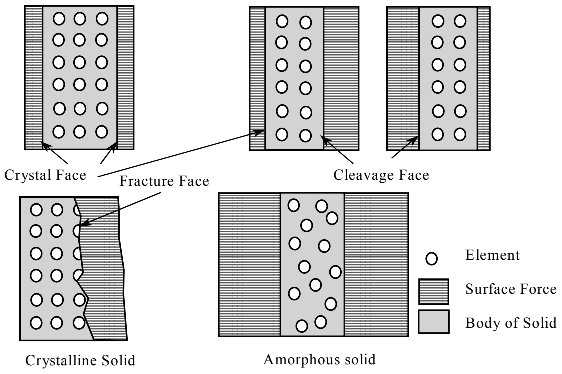

Figure 1. Surface forces on solids. (after Hudec, 1993)

Water in rocks

Rocks invariably contain some water, even in desert environments. The sources of moisture in rocks are from rain, snow, relative humidity (RH) in the atmosphere, condensation, rising ground moisture, rivers, lakes, seas, leaking pipes etc. Three types of water may be distinguished in rocks: chemically bound water, physically bound water, and free (bulk) water (Rhzevsky and Novik, 1971). The proportion of the latter two is dependent on rocks' mineral composition, particle-size and shape distribution, and environmental conditions. The magnitude of the surface forces determines the amount of water that can be adsorbed to the surface. Water is a dipolar fluid whose polarity is due to the uneven distribution of hydrogen ions in the molecule. The positively charged H^+ of the water are attracted to the negatively charged pore surfaces. The water molecule adheres tightly to the capillary walls with two or three layers on each side of the wall (Fig 2). The charge decreases exponentially with the distance from the wall. Physical adsorption is an exothermic process, requires no activation energy, therefore it occurs nearly as fast as a water molecule reaches a surface. The process is reversible and equilibrium is established rapidly, unless the process is limited by diffusion through a fine porous structure. The physically bound water is attached to the solid walls of the capillary and envelops them as a thin film. The thickness of this film is 2 to 3 nm. The moisture fills capillaries 0.1 μm or smaller (Winkler, 1994). If ions are present in the solution, they are preferentially adsorbed to the walls, and they in turn adsorb water, which leads to the increase in the surface held water. Dissolved salts in pores increase considerably the adsorption of moisture from the air. The physically bound water does not move within the rocks. However, its presence considerably alters the physical properties of rocks.

The adsorbed water has lower vapour pressure. If the pore is small enough to be completely filled with adsorbed water, the low-vapour pressure water acts as an osmotic fluid, setting up osmotic pressures and expansion. While the total porosity amount can be correlated with other physical parameters, e.g., compressive strength and ultrasound velocities, the porosity distribution permits a full evaluation of the progressive effect of weathering of rocks (Winkler, 1994).

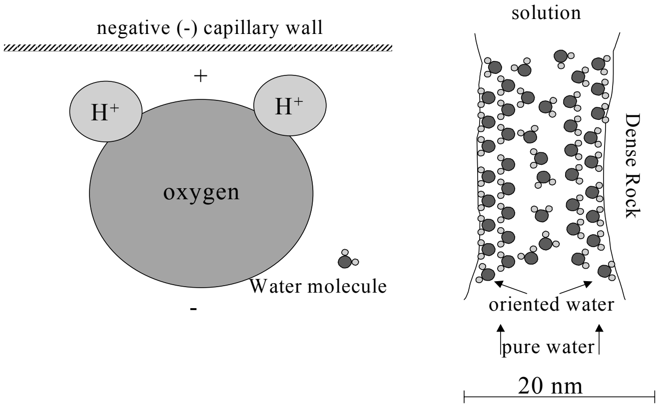

Figure 2. Water molecule and “ordered” water in stone capillary (after Winkler, 1994)

Free or capillary water in larger capillaries is held by forces of capillary action. The liquid phase always occupies the narrowest pores of the porous media and forms a concave surface (meniscus) between liquid and gas. Capillaries up to 1 mm in diameter show a significant capillary tension or capillary rise. Capillary water is capable of flow, and rocks containing large capillaries are readily saturated by immersion, and equally readily drained.

SAMPLE DESCRIPTION AND PREPARATION AND EXPERIMENTAL APPARATUS

Forty-four samples of different rock types, consisting mostly of carbonate rocks (limestones and dolomites) and three sandstones, two marbles, shale, granite, and a syenite were used in the experiments. Three cores from each rock were tested. The diameter of the rock cores was 19 mm and the length from 40 to 55 mm, depending on the character and dimensions of original rock. For the Brazilian test, one of the three rock cores was cut into five 10 mm pieces (depending on the length of the sample).

EXPERIMENTAL PROCEDURES

Grain size estimation, density, water absorption, and water adsorption tests were performed on the rock cores prior to uniaxial testing. For capillary rise experiments, the gain in weight was measured once per minutes for 30 minutes; for immersion absorption rate experiments, the gain in weight was also measured once a minute for 30 minutes, then in log-time intervals for the next 24 hours. The results were graphed as the amount of water absorbed versus the log time; the slope of the 2nd order equation of the trend line was used for statistical analysis. The capillary rise rate and immersion absorption rates were plotted against each other. The slope of line was close to 1, but varied from less than to greater than 1. The slope variations were used for statistical comparison. The higher than 1 immersion vs. capillary rise slope suggests that the sample contains larger, more open porosity. The work by Ondrasik (1996) on the same rock group determined the presence or absence of freezing occurring in the saturated samples of these rocks. This information was also used in the statistical analysis and classification of the rock samples.

Uniaxial test frame equipment recently constructed at the department of Earth Sciences at the University of Windsor (Fig. 3.) was used for stress/strain and strength the tests. The equipment was used to attain a level of stress and resultant strain, and the change in stress under constant strain was monitored on the sample over time. The same equipment was used to determine the Brazilian tensile strength of the samples.

Rate of relaxation of stress at a constant strain in dry and wet state

A dried specimen (at 105°C) was placed in the uniaxial stress frame, and the initial stress of 3.45 MPa (500 psi) was applied and locked. Instantly the rock began to relax, and the stress gradually decreased. The stress decay was measured every 60 seconds for 10 minutes. The strain remained constant. The procedure on the dry sample of three cores of each sample was applied for the stress levels of 6.9 MPa (1000 psi) and 10.3 MPa (1500 psi). The experiment was then repeated on the 24-hour water saturated samples.

Figure 3. The uniaxial test frame, showing load cell, strain gauge and sample holder

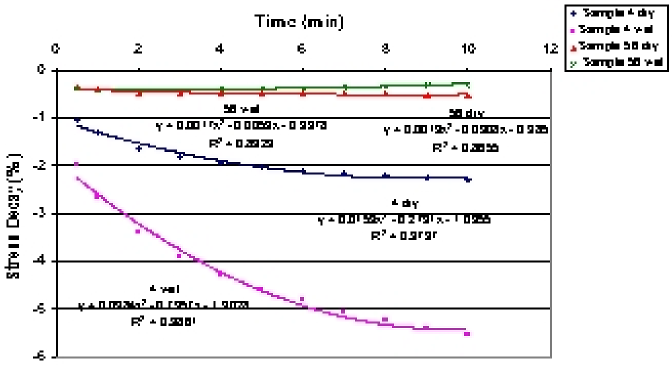

Figure 4. Example of Stress Decay with Time for dry and wet samples no. 4 and 56

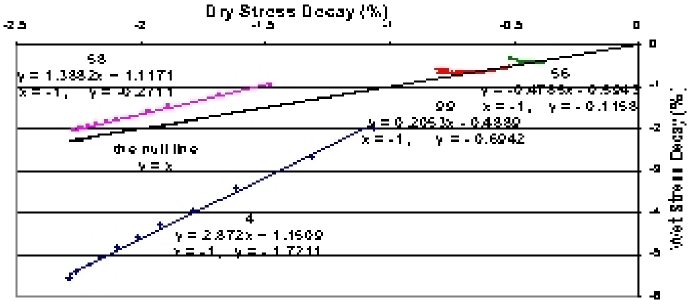

Figure 5. Linear Dry vs. Saturated Stress Decay for samples no. 4, 56, 58, and 99 (limestones)

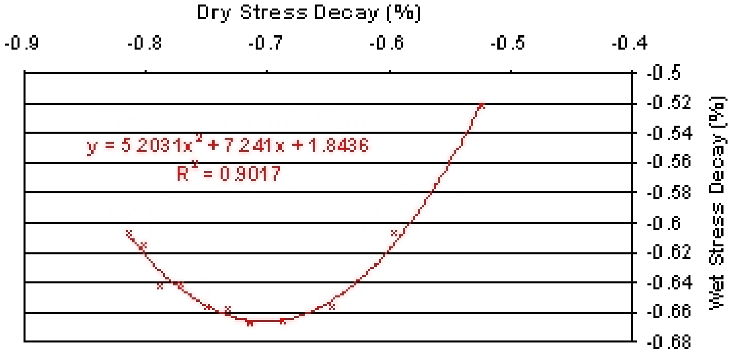

Figure 6. Curvilinear Dry vs. Saturated Stress Decay for sample no. 56 (dolomite)

For all the three stress levels, the stress decrease was expressed as a percentage of the original stress. When plotted with time as x-axis, the line of best fit resulted in a 2nd order polynomial equation (Fig. 4). Substituting the value of x equal 1, a stress value was obtained which represented relaxation after 1 minute. The y-intercept (constant) was omitted, since the initial relaxation was attributed to instrument-sample adjustment. The one-minute stress relaxation value was used in all statistical comparisons.

The graphs of the dry relaxation versus the wet relaxation examples are shown in Figures 5 and 6. Figure 5 show linear responses typical of fine-grained limestones. Figure 6 shows a curvilinear response typical of coarse-grained dolomites.

Young's modulus Determination

Dried specimens (at 105°C) were placed in the uniaxial machine and the load was gradually increased to 20.7 MPa (3000 psi). The Young's modulus was then calculated from the linear portion of the stress-strain curve and used for statistical evaluation. According to Hook's Law, strain within elastic range is proportional to stress:

$$E = \frac{stress}{strain} = \frac{\sigma}{\varepsilon} \text{ (Pa)} \tag{1}$$

Where *E* is Young' modulus or the modulus of elasticity. Its value is determined experimentally from the slope of the straight-line part of stress/strain curve.

Brazilian (indirect, diametrical tensile) strength test.

Four properly dimensioned cylinders were cut from one of the three cores for each sample. An oven-dried specimen was placed horizontally between the blocks of the press. The load was then applied until the specimen broke along the diametrical plane. The ultimate tensile strength σ_T was then determined from

$$\sigma_T = 2F/\pi dl, \tag{2}$$

where F is the load applied to the specimen (kg), d is the diameter of the specimen (mm), and l is the length of the specimen (mm). The result is an average of at least four values.

RESULTS AND STATISTICAL ANALYSIS

Various statistical methods were applied to study the relationship among the test results (variables) to determine the governing factors behind the relationships, to classify or group the samples based on these relationships, and to explain the behaviour of rocks under the test conditions.

Bi-Variate Relationships and Correlations:

A high correlation between tests, which are related or similar to each other (such as the tests of relaxation – the absolute values and rates, stresses moduli and strength, absorption and immersion), can be expected as they represent and describe the same characteristics. A positive correlation, in some cases greater than 0.900, was observed within the group of relaxation variables. Immersion slope versus absorption showed very high (0.9240) and capillary slope versus absorption high positive correlation (0.7638), which means, that the rate of water absorption and the total absorption are related to each other, i.e., the samples with higher total absorption also have greater rate of water intake. Correlation coefficients between tests for different properties also showed high and moderate correlation. Density versus rate of water intake (capillary slope) showed high negative correlation (-0.7054), expressing the relationship of pore space to density. The higher the density, the less porosity and fewer voids are available for filling with water. This is also the case of density versus immersion slope (-0.6757) and density versus absorption (-0.7519). High correlation of adsorption and the wet and dry relaxation characteristics shows the influence of internal structure and water, especially adsorbed water on the behaviour of rocks. Adsorbed water seems to be the controlling factor on the rate of the saturated relaxation. The relationship of adsorption to the wet relaxation is shown in Figure 7. The outliers from the normal distribution were excluded.

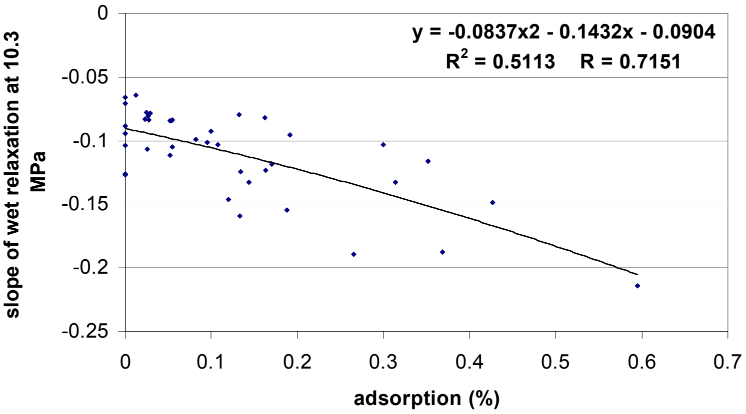

Figure 7. Graph of adsorption versus wet relaxation slope at 10.3 Mpa

Multivariate Relationships and Groupings:

Linear vs. Curvilinear Comparisons:

Rock samples were grouped by the nature of relationship between the dry and wet relaxation (c - curvilinear and l – linear) for the two-group student t-test. Only the variables between which significant differences existed were considered.

Linear Relationship:

The statistics showed that adsorption and degree of saturation values, all total relaxation values, microwave heat absorption values, powder suspension, expansion and freeze-thaw values were significantly higher for the group of rocks which showed linear relationship.

Curvilinear Relationship:

The values of the rates of relaxation, deformation modulus and bulk water fraction are significantly higher for the curvilinear group. This suggests that the types of relationship between dry and saturated relaxation divides rocks into two different groups of different characteristics and behaviour. The rocks with the curvilinear relationship have lover adsorption, freeze-thaw loss and total relaxation, and higher saturated modulus of elasticity and bulk water fraction. This implies greater durability of rocks in this group.

Grouping of samples by similar physical properties - Cluster Analysis:

Cluster analysis is a multivariate technique that groups or clusters samples of similar properties into mutually exclusive groups. Cluster analysis yielded 4 clusters:

Cluster 1

Cluster 1 contains 19 samples with low density, coarse grain size, high absorption, adsorption and relaxation, and low strength and Young's modulus. The rocks can be characterized as not very durable and weak rocks and the cluster is labeled as 'weak, non-durable quality' rock group. Cluster 1 contains a mixture of different rocks: 7 limestones, 8 dolomites, 3 sandstones and 1granite. Ten of these rocks give linear dry/wet relaxation relationship and 7 curvilinear; 16 did not show freezing, 3 did. The cluster contains 7 samples with an immersion/capillary absorption rate slope (I/C) higher and 12 lower than 1.

Cluster 2

Cluster 2 contains only one rock (marble) that shows the best parameters for almost all variables. The sample can be described as 'excellent quality'. The marble gives curvilinear relationship, does not show freezing and the I/C slope >1.

Cluster 3

Cluster 3 contains 9 cases that are characterized by median values for the majority of the variables, but have higher density and strength, and lower grain size and capillary rise rate than those in cluster 4. These rocks can be characterized as 'strong, good quality'. Seven dolomites, 1 limestone and 1 sandstone are found cluster 3. Five rocks showed curvilinear relationship (4 linear), four freezing (5 no freezing) and 7 samples have I/C slope >1.

Cluster 4

Cluster 4 contains 15 members with low absorption, adsorption, rates of absorption and Young's modulus and lower tensile strength and density. This group can be labeled as 'average, good quality' rocks. Cluster 4 contains 10 dolomites, 3 limestones and 2 crystalline rocks. Eight samples showed curvilinear relationship (7 linear), nine showed freezing and nine had I/C slope >1.

In summary, Clusters 2, 3, 4, contain rocks with better durability properties, and are mostly composed of dolomites and crystalline rocks. They also have higher ratio between immersion and capillary slopes. Differences between freezing and relationship of dry and wet relaxation are not obvious.

Grouping of Rock Properties based on Stress Relaxation - Factor analysis:

Factor analysis groups variables (tests) that correlate or produce similar responses. The factors can be named according to the high correlation variables they contain. The procedure was run on samples grouped by their behaviour between dry and saturated relaxation at 3.45 mPa, i.e., curvilinear vs. linear. Variance indicates the strength or dominance of the factor.

Curvilinear Relationship Groupings:

For the curvilinear relationship, variables were automatically divided into six groups (Factors). The terms D and W imply dry and saturated relaxation respectively; 5, 10, and 15 the 3.45, 6.9, and 103 mPa stress levels respectively, and DW the dry/wet relaxation ratios at the respective stress levels.

Factor 1,"Capillarity" factor: The first factor accounts for almost 37 % of the total variance. This factor groups immersion/capillary slopes with grain size, Young's modulus, density, absorption, DW5 and W15 relaxation variables.

Factor 2, "Strength" factor: The second factor accounts for almost 20 % of the total variance and correlates together relaxation variables with the tensile strength, size and Young's modulus.

Factor 3, "Absorption" factor: Capillary slope, absorption and density are members of the third factor that accounts for almost 11 % the variance.

Factor 4, "Relaxation" factor: The forth factor correlates W5, D15, DW5, accounts for almost 7 % of the variance.

Factor 5, "Adsorption" factor: The fifth factor contains adsorption with capillary versus immersion slope and accounts for 5 % of total variance.

Factor 6, "Wet 6.9 MPa" factor: The last factor groups W10 and DW10 and accounts for almost 5 % of total variance.

The first three factors, accounting for most of the variance, are the most important.

Linear Relationship Groupings:

The procedure groups variables into 5 factors.

Factor 1, "Relaxation" factor: The first factor accounts for almost 36 % of the total variance. This factor groups D10, W10, D5, D15, W15, D5, Adsorption and deformation modulus variables

Factor 2, "Capillarity" factor: The second factor accounts for almost 28 % of the total variance and correlates together immersion/capillary slopes with absorption and immersion slope.

Factor 3, "Strength" factor: The third factor correlates capillary slope, density, absorption, immersion slope, tensile strength and Young's modulus, and accounts for almost 11 % of the variance.

Factor 4, "dry/wet ratio" factor: This factor groups dry versus wet relaxation ratios and accounts for 7 % of the total variance.

Factor 5, "size" factor: The last factor contains size and tensile strength, accounts for 6 % of the total variance.

The analysis of the major factors in each of the two groupings above suggests that adsorbed water plays a major role in the linear relationships, whereas absorbed water is the dominant player in the curvilinear group.

Effect of rock type - The Discriminant Analysis

Discriminant Analysis determines if a given categorical variable or class has a significant influence on the measured properties of the samples. In the instance, the discriminant analysis calculation was done on samples grouped by the main rock types: 1-limestones, 2-dolomites and 3-sandstones and crystalline rocks. Seventy seven percent of cases were correctly classified.

A canonical plot shows the distribution of the test results, expressed as canonical factors. Canonical factors represent the degree of similarity or a difference between samples grouped according major rock types. The enclosing ellipses mark the 75% significance limit (samples within the ellipse have 75 % commonality). The smaller the area of the envelope, the closer are the members of the group. Figure 8 shows the difference of properties between groups of rocks. The groups do not overlap each other, and the envelopes are quite small, which means, that there are significant differences between the rock types.

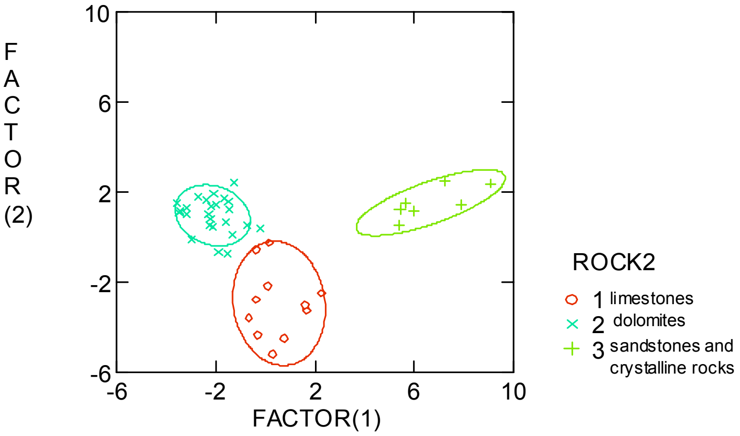

Figure 8. Canonical plot of rocks grouped by rock types

DISCUSSION

The experiments were designed to investigate the influence of pore size, and the interaction of water in rock pores on the rocks' behaviour under fixed stress. The test results and their statistical evaluation revealed resulted in some significant insights into the behaviour of pore water under stress.

The equation, and more specifically, the slope of the trend line of the immersion versus the capillary rate of absorption divided the rocks into two groups: those with slopes greater or less than 1. The first group with slope >1 has 24 members; the second group with slopes <1 contains 20 rocks. The first group had significantly higher density, deformation moduli, and lower absorption properties, porosity, strain and magnesium sulphate loss. This suggests that the rocks with higher value of immersion versus capillary rise slope are stronger, denser, less porous, and more durable.

Factor analysis of samples with curvilinear relationship created a factor named 'Capillarity' that placed the capillary variables with grain size, Young's modulus and wet relaxation at 3.45 MPa. This suggests that the rate of capillary rise and absorption rates and the ratio of immersion and capillary slopes are functions of the grain size and density; these variables characterize porosity and pore size. This also means that these properties, which characterize the internal structure and the behaviour of rocks and their interaction with water are responsible for the observed type of response to the stress when the samples were saturated.

At all the three stress levels (3.45, 6.9, 10.3 MPa) under both the dry and wet conditions, after the initial fixed stress was applied to the rock core, the stress started to drop (Figure 4). The maximum stress drop was observed in the beginning, and then the relaxation rate decreased gradually (roughly exponentially) with time. The behaviour of the saturated samples at the 6.9 and 10.3 MPa stress levels was similar to those in the dry condition. At the 3.45 MPa wet condition, the behaviour was the same for 21 samples as well, but for other 23 samples, the stress initially decreased, and after 3-6 minutes, (depending on the sample) the stress started to increase. The samples that showed an increase in stress in the wet state also showed a lower total dry relaxation at all stress levels; they also had the wet relaxation lower than the dry ones. However, for these samples, no increase of stress was observed at higher stress levels. Comparing the 10-minute relaxation under dry and wet condition, the higher wet relaxation was observed at the 6.9 and 10.3 MPa stress levels for almost all samples. The different behaviour between dry and wet relaxation is clearly shown when dry and wet relaxation, expressed as a percentage of the original stress, are plotted against each other (Figure 5 and 6). The relationship at the 6.9 and 10.3 MPa levels was linear for all samples. However, at 3.45 MPa the samples that showed an increase in stress (about ½ of the samples), this relationship was curvilinear.

Rocks with lower overall relaxation under dry conditions have a significantly higher strength, moduli, density, lower freeze-thaw loss, and absorption. At 3.45 MPa, they have lower porosity and adsorption. The dry relaxation, as could be expected, is dependent on the density, porosity and strength properties of rocks. The rocks from the curvilinear group have significantly greater strength (Table 1), which explains their lower dry overall relaxation. Density and strength properties play important roles at all three stress levels. The rocks with higher density and strength and with lower porosity relax less and tend to maintain the stress for longer time.

Table 1. Two sample t –test grouped by the nature of relationship between dry and wet relaxation C – curvilinear relationship, l – linear relationship, equal variances assumed

Variable	**c/l**	**N**	**Mean**	**Std. Dev.**	**t**	**df**	**Sig. 2-tailed**
ADS	c	23	0.061	0.074	**-3.909**	42	0.000
Adsorption	l	21	0.216	0.173			
REL5D	c	23	13.499	6.580	**-3.113**	42	0.003
difference in stress (final-initial) 3.45 MPa, dry	l	21	21.075	9.430			
REL5W	c	23	5.187	6.215	**-5.293**	42	0.000
difference in stress (final-initial) 3.45 MPa, wet	l	21	36.160	27.331			
REL10D	c	23	37.063	4.348	**-2.693**	42	0.010
difference in stress (final-initial) 6.9 MPa, dry	l	21	45.104	13.591			
REL10W	c	23	35.087	4.787	**-4.624**	42	0.000
difference in stress (final-initial) 6.9 MPa, wet	l	21	67.371	33.140			
REL15D	c	23	44.590	4.936	**-3.376**	42	0.002
difference in stress (final-initial) 10.3 MPa, dry	l	21	56.836	16.627			
REL15W	c	23	45.133	6.409	**-5.344**	42	0.000
difference in stress (final-initial) 10.3 MPa, wet	l	21	81.953	32.388			
D5	c	23	-0.062	0.036	**4.275**	42	0.000
slope of the dry relaxation at 3.45 MPa	l	21	-0.118	0.049			
W5	c	23	-0.054	0.038	**5.086**	42	0.000
slope of the saturated relaxation at 3.45 MPa	l	21	-0.198	0.130			
DW5	c	23	-0.835	0.681	**3.666**	42	0.001
slope of the dry vs. wet relaxation at 3.45MPa	l	21	-1.595	0.693			
D10	c	23	-0.110	0.018	**2.114**	42	0.041
slope of the dry relaxation at 6.9 MPa	l	21	-0.130	0.042			
W10	c	23	-0.108	0.017	**4.583**	42	0.000
slope of the saturated relaxation at 6.9 MPa	l	21	-0.196	0.090			
DW10	c	23	-0.985	0.191	**4.296**	42	0.000
slope of the dry vs. wet relaxation at 6.9 MPa	l	21	-1.426	0.450			
D15	c	23	-0.087	0.010	**3.123**	42	0.003
slope of the dry relaxation at 10.3 MPa	l	21	-0.109	0.033			
W15	c	23	-0.087	0.012	**5.135**	42	0.000
slope of the saturated relaxation at 10.3 MPa	l	21	-0.156	0.064			
DW15	c	23	-1.031	0.193	**4.337**	42	0.000
slope of the dry vs. wet relaxation at 6.9 MPa	l	21	-1.424	0.385			
MQADS (Ondrasik)*	c	22	0.096	0.091	**-3.169**	41	0.003
heat absorbed by adsorbed water	l	21	0.243	0.196			
SUSPENSION (Rigbey)*	c	23	1.809	0.826	**-3.168**	42	0.003
suspension test	l	21	3.114	1.779			
FT2 (Rigbey)*	c	20	8.188	12.130	**-3.070**	36	0.004
freeze-thaw loss	l	18	22.858	17.135			

* data from Rigbey (1980), and Ondrasik (1996)

At 3.45 MPa, the adsorption properties of rocks seem to be a significant factor in their behaviour. The rate and amount of relaxation is strongly related to adsorption. This is confirmed by almost all the statistical methods applied. Correlation of adsorption with dry and saturated relaxation rates at all three tested stress levels (3.45, 6.9, 10.3 MPa) is high or moderate. Factor analysis also groups adsorption together with the relaxation data in a factor named 'compression'. This is also the case in the factor analysis of rocks showing the linear relationship between the dry and wet relaxation.

In the factor analysis of the group of rocks with the curvilinear relationship, the adsorption test in the fifth factor. As the first two factors are the main factors which best characterize the studied data set, adsorbed water does not influence the behaviour of these rocks. The first factor named "capillarity" is more important, containing mostly immersion/capillary variables plus grain size, Young's modulus, density and absorption. These variables describe the internal pore structure, which controls the water movement inside the rock, and thus are responsible for the relaxation behaviour of rocks in the curvilinear group.

For rocks with linear relationship, the saturated relaxation is higher than the dry relaxation for all stress levels. For the curvilinear group the saturated relaxation was lower at the 3.45 MPa, and for some rocks also lower at the 6.9 and 10.3 MPa levels. The fact that the saturated relaxation of the rocks showing curvilinear relationship is lower than the dry relaxation can be explained by the behaviour of water, and especially adsorbed water. Rocks with lower total wet relaxation have significantly lower adsorption, freeze-thaw loss, expansion under different temperatures and humidity, lower amount of microwave heat absorbed by adsorbed water, and have higher saturated deformation modulus. The samples with lower total wet relaxation at 3.45, which showed curvilinear relationship, have also significantly higher porosity. The difference in porosity suggests that the communication between these pores and the amount of adsorbed water on the walls of the rock pores seems to be the key explanation of different behaviour of rock under pressure when saturated, especially at the 3.45 MPa level.

The curvilinear behaviour is restricted to coarse pored, sound, and durable rocks. These rocks contain mostly normal or 'bulk' water in large pores, and only relatively small amounts of adsorbed water in small pores. The non-durable rocks are fine pored, and contain mostly adsorbed water. Adsorbed water has been shown to be low vapour pressure, surface influenced, somewhat structured water, thermodynamically somewhere between normal water and ice. Ice is compressible, and by analogy, so may be the adsorbed water. Bulk, normal water is not compressible. Under all levels of stress, the adsorbed water, since it may be compressible, acts as an elastic solid, and the stress-strain behaviour such as the elastic modulus and stress relaxation would be similar in both the dry and saturated states, and their relationship would be linear.

If smaller capillaries separate large pores (the throat effect), the surface forces between of the pore walls acting on adsorbed water prevent free water movement between the bigger pores. This may explain the observation that the increase in stress occurred only at the 3.45 MPa level under wet conditions. Lower pressure cannot force the water from smaller pores, but higher pressure (6.9 and 10.3 MPa) is able to "push" the water through the smaller pores and to the outside of the sample, and therefore no increase in stress was observed at higher stress levels.

Another possible explanation for rocks containing mostly normal incompressible water in large pores is offered: As the stress is applied and then maintained at constant level, the volume of the large, roughly spherical pores shrinks, and the water is forced into smaller, tabular pores. Transfer of water from a spherical to a tabular pore results in a net volume increase. Because the small tabular pore does not transmit water easily, the increase in the volume of many small pores will cause expansion of the total rock volume; if the rock is confined, as in these experiments, the net result will be a small reversal in stress relaxation. Larger confining stresses would either force the water through the small pores, or fully counteract the small pore expansion.

All of the limestones showed a linear relationship, and together with the shale and few dolomites, the limestone belongs to the 'linear' group. The majority of the dolomitic rocks, the crystalline rocks (granite, syenite and both marbles) and sandstones belong to the 'curvilinear' group. Differences between the rock types are well displayed on the canonical plot of the discriminant analysis (Figure 8).

Considering pore water freezability of these rocks (Ondrasik, 1996), the majority of 'curvilinear' rocks showed freezing. All dolomitic rocks and all three sandstones showed freezing. The few rocks from this group that did not show freezing were the crystalline rocks. One dolomitic rock, which did not show freezing, had a very slight curvilinear, almost linear relationship. Most of linear group of rocks showed no freezing of their pore water.

CONCLUSIONS

Tests performed and the statistical evaluation of the results from these tests confirmed that there is a relationship between the internal structure and the thermodynamic properties of rocks. The pore size and the interaction of water in the rock have a significant influence on the strength and durability properties.

The stress relaxation behaviour of rocks in dry and wet states (especially at 3.45 MPa) differentiates rocks based on their pore and durability properties. 'Linear' relationship rocks are non-durable, fine-pored, and contain mostly adsorbed water in the pores. Their pore water does not freeze. Rocks are all limestones and few dolomites. Adsorbed water may acts as an elastic quasi-solid, which means it may be compressible, and therefore the stress-strain behaviour is similar in both the dry and saturated states.

'Curvilinear' relationship rocks are coarse-pored, sound, and durable rocks. They contained mostly bulk water in large pores, and showed freezing of the contained water. They contain only small amounts of adsorbed water in small pores. Rocks are dolomites, crystalline rocks and sandstones. The pore size and the pore size distribution, not the total porosity are responsible for the stress relaxation behaviour. The rates of the capillary rise and the total immersion absorption of water give indirect but valuable information on the pore size distribution. The less durable rocks have significantly greater wet relaxation than durable rocks, and greater difference in dry and wet relaxation.

The most significant finding of the research suggests that adsorbed pore water may be compressible.

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