The effect of degree of saturation on the unconfined compressive strength of selected sandstones

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Abstract: Unconfined compressive strength is one of the primary parameters by which sandstone rocks are evaluated for their usefulness as engineering materials. The unconfined compressive strength of sandstones is known to be controlled by such factors as loading rate, bedding orientation, presence of microfractures, and petrographic characteristics (grain size, grain shape, matrix-cement mineralogy, etc.). Research has also shown that unconfined compressive strength is significantly reduced upon saturation with water. The aim of this research was to characterize the relationship between unconfined compressive strength and varying degrees of saturation for sandstone rocks, and to explain this relationship using index properties and petrographic characteristics.

Eighteen NX-size cores were prepared from each of nine different sandstone formations that were sampled from Central Ohio through Central Pennsylvania, USA. Laboratory tests were conducted to determine absorption, dry density, specific gravity, and porosity values for each core. Cores were then tested for unconfined compressive strength at 0%, 20%, 40%, 60%, 80%, and 100% saturation. The sandstones were also classified according to Okada's classification in order to further characterize them and provide a means of explaining the measured trends of compressive strength decrease with increasing degree of saturation for each sandstone formation.

Laboratory test results show that the sandstones tested have absorptions values ranging from 1.32% to 6.93%, dry density values of 126.7 pcf (2.03 Mg/3m) to 58.5 pcf (2.54 Mg/3m), porosities of 3.35% to 14.11%, and dry compressive strength values ranging from 2426 psi (16.73 MPa) to 21700 psi (149.66 MPa). Data analysis indicates significant trends of unconfined compressive strength reduction with increasing degree of saturation. The trends are more consistent for high-strength sandstones than those of medium to low strength which display less predictable behavior. Some sandstones show a majority of strength reduction having occurred by 20% saturation, with minimal to indiscernible strength reductions at higher saturation levels. Strength reductions of up to 71.6% between dry and saturated states are observed. Based on these results, prediction equations are developed for sandstones that are grouped according to their absorption levels.

Résumé: Dix-huit noyaux de taille NX ont été préparés à partir de chacun des neuf grès obtenus à Ohio et à Pennsylvania, Etats-Unis. Pour chaque noyau, des essais au laboratoire ont été effectués pour déterminer l'absorption, la densité sèche, la densité, et les valeurs de porosité. Puis, les noyaux ont été testés pour la résistance à la pression non-confinée aux saturations de 0%, 20%, 40%, 60%, 80%, et 100%. L'analyse statistique indique que la résistance à la pression non-confinée diminue de manière significative (autant que 71.6%) avec l'augmentation du degré de saturation. Les relations entre la résistance à la pression non-confinée et le degré de saturation sont plus consistantes pour les grès à haute résistance que celles à moyenne or basse résistance. Ces grès montrent moins de comportement prévisible. Quelques grès montrent une majorité de réduction de résistance avec une saturation jusqu'à 20%, avec réductions minimales à imperceptibles aux saturations plus élevés. D'après ces résultats, des équations de prévision sont développées pour les grès qui sont groupés selon leurs niveaux d'absorption.

Keywords: Sandstone, compressive strength, saturation, uniaxial tests, density.

INTRODUCTION

Because of their widespread occurrence, sandstones are often encountered in engineering practice as tunnelling and foundation material. They are also frequently used as building stone, aggregate material, and riprap. Unconfined compressive strength is one of the most important properties taken into consideration when sandstones are evaluated for engineering purposes. Therefore, much research has been devoted to the problem of correlating unconfined compressive strength of sandstones with their engineering index properties such as specific gravity, density, degree of saturation, absorption, porosity, and pore size distribution (Colback and Wiid, 1965; Broch, 1974; Michalopoulos and Triandafilidis, 1976; Venkatappa Rao et al., 1985; Shakoor and Bonelli, 1991; Hawkins and McConnell, 1992; Haney and Shakoor, 1994; Ulusay et al., 1994). The effect of petrographic characteristics (grain size and shape, type and amount of cement, nature of grain to grain contacts, and degree of sorting) on unconfined compressive strength of sandstones has also been studied by various researchers (Fahy and Guccione, 1979; Winkler, 1986; Shakoor and Bonelli, 1991; Haney and Shakoor, 1994; Ulusay et al., 1994; Hale and Shakoor, 2003). The primary reason for attempting to correlate unconfined compressive strength with other properties of sandstones is that proper preparation of cores for unconfined compression testing can be more time consuming and costly than other properties.

Reduction of unconfined compressive strength due to saturation has been observed in a number of studies (Colback and Wiid, 1965; Wiid, 1970; Ramamurthy and Goel, 1973; Ballivy et al., 1976; Michalopoulos and Triandafilidis, 1976; Venkatappa Rao et al., 1985; Dyke and Dobereiner, 1991; Hawkins and McConnell, 1992). Colback and Wiid (1965) showed unconfined compressive strength reductions of up to 50% between the dry and saturated states for quartzitic sandstones. Broch (1974) reported unconfined compressive strength reductions of 33 to 53% for phaneritic igneous and metamorphic rocks of low porosity (0.3 to 1.2%) upon saturation. He demonstrated that most of the strength was either lost between 0 and 25% saturation or that the strength reduction with increasing saturation was linear. He also observed that rocks of lower porosity experienced a greater loss in strength than rocks of higher porosity. Michalopoulos and Triandafilidis (1976) showed that the unconfined compressive strength of different rock types, including sandstones, decreased with an increase in the degree of saturation. The compressive strength of sandstone used in their study decreased 23.6% from the air-dried to the saturated state. They also observed that more competent sandstones showed larger decreases in strength upon saturation. This observation was also made by Hawkins and McConnell (1992) for a large group of sandstones which is in contrast to the conclusions of Dyke and Dobereiner (1991) who state that weaker sandstones are more susceptible to unconfined compressive strength reduction upon saturation. Hawkins and McConnell (1992) observed large variations in sandstone strength between saturated and dry conditions, with strength decreases ranging from 8.2% to 78.1% depending on compositional variations between various types of sandstone tested. They also noted that most of the compressive strength decrease occurred at moisture contents between 0% and 33% of the fully saturated condition. Venkatappa Rao et al. (1985) found consistent reduction in compressive strength of a sandstone rock with increasing moisture content, the majority of the strength loss occurring at low moisture contents.

RESEARCH OBJECTIVES

The main objective of this study is to investigate the relationship between varying degrees of saturation and unconfined compressive strength of different sandstones and explain the observed trends in terms of index properties and petrographic characteristics. The study is aimed at improving the existing knowledge about the strength behaviour of sandstones at varying degrees of saturation at which they commonly occur in the field.

RESEARCH METHODS

Sample collection and preparation

Large, slab-like blocks of eight sandstone formations from Ohio and Pennsylvania were sampled for the study. These included the Berea Sandstone, Black Hand Sandstone, Cow Run Sandstone, Homewood Sandstone, Juniata Sandstone, Lower Freeport Sandstone, Lower Mahoning Sandstone, and Sharon Sandstone. Two separate locations of the Berea Sandstone Formation were sampled and designated Berea Sandstone A and Berea Sandstone B, resulting in a total of nine separate sampling locations. For each of the nine sandstones, eighteen 54-mm diameter (NX size) cores were prepared for unconfined compressive strength testing in general accordance with the American Society of Testing and Materials (ASTM) method D 2938 (ASTM, 1996).

Laboratory Testing

Determination of engineering properties

Laboratory tests were performed to determine dry density, absorption, bulk specific gravity, saturated surface-dried bulk specific gravity, effective porosity, and unconfined compressive strength. Dry density of each core sample was determined by dividing the oven-dried weight by its volume. Absorption, bulk specific gravity, and saturated surface-dried bulk specific gravity values were obtained according to the guidelines set by ASTM method C 127 (ASTM, 1996). Phase relations were used to calculate effective porosity of each core by taking the ratio of the maximum volume of water absorbed by each core during 24-hour saturation to its total volume. ASTM method D 2938 (ASTM, 1996) was used to perform the unconfined compressive strength tests. Cores for compression testing were prepared at 0%, 20%, 40%, 60%, 80%, and 100% saturation, and three cores each of the nine sandstones were tested at each degree of saturation. Cores tested at 0% saturation were oven dried at 105° C for 24 hours and cooled to room temperature. Cores to be tested at 20%, 40%, 60%, 80%, and 100% saturation were immersed in water for 24 hours to achieve complete saturation. Cores tested at 100% degree of saturation were tested at this time while cores tested at 20%, 40%, 60%, and 80% degrees of saturation were placed on paper towels and air-dried at either room temperature or with the aid of fans and/or warm air blowers with occasional turning to prevent concentration of water in any particular section of the core. During the drying process, cores were periodically weighed until they had reached a previously calculated weight corresponding to the prescribed degree of saturation at which time they were immediately tested for unconfined compressive strength.

Petrographic analysis

One thin section of each of the nine sandstones, prepared perpendicular to the bedding, was studied for determination of petrographic characteristics. A petrographic microscope was then employed to perform a random 300 point-count modal analysis on each thin section. Estimates of grain size, grain shape, and degree of sorting were made for all nine sandstones. All sandstones were found to be well sorted. Based on the results of petrographic analysis (Table 1), sandstones were classified according to the classification system proposed by Okada (1971).

Data analysis

Unconfined compressive strength, degree of saturation, dry density, absorption, bulk specific gravity, saturated surface-dried bulk specific gravity, effective porosity, and petrographic data obtained during laboratory testing were compiled, organized, and analyzed using Microsoft Excel and SPSS 12.0 data analysis software. For each property, the range, mean, standard deviation, and variance were determined. Regression analysis was performed on these data to investigate significant correlations between unconfined compressive strength and degree of saturation, effective porosity, dry density, absorption, bulk specific gravity, and saturated surface-dried bulk specific gravity. Equations were developed for statistically significant correlations.

Table 1. Results of petrographic analysis.

	Modal Composition (N = 300)												
						Cement			QRF* Percentages				
Sandstone	Quartz	Feldspar	Rock Fragments	Matrix	Musc. Mica	Hematite	Calcite	Pore	Quartz	Feldspar	Rock Fragments	Matrix %	Okada Name
Berea A	196	20	61	9	2	1	3	8	70.8	7.2	22.0	3.0	Lithic Arenite (subclass A)
Berea B	200	23	45	4	0	10	0	18	74.6	8.6	16.8	1.3	Lithic Arenite (subclass A)
Black Hand	199	34	21	22	0	0	0	24	78.3	13.4	8.3	7.3	Quartzose Arenite (subclass B)
Cow Run	162	35	63	1	0	7	0	32	62.3	13.5	24.2	0.3	Lithic Arenite (subclass A)
Homewood	172	1	99	9	18	0	0	1	63.2	0.4	36.4	3.0	Lithic Arenite (subclass A)
Juniata	103	6	118	5	0	48	0	20	45.4	2.6	52.0	1.7	Lithic Arenite (subclass A)
Lower Freeport	180	24	47	2	1	18	0	28	71.7	9.6	18.7	0.7	Lithic Arenite (subclass A)
Lower Mahoning	176	58	25	1	0	0	0	40	68.0	22.4	9.6	0.3	Feldspathic Arenite (subclass A)
Sharon	219	34	23	3	0	1	0	20	79.3	12.3	8.4	1.0	Quartzose Arenite (subclass A)

*QRF: Quartz, Rock Fragment, Feldspar

ENGINEERING PROPERTIES OF SANDSTONES STUDIED

Table 2 shows the mean values of the dry unconfined compressive strength and index properties of the studied sandstones. The Juniata Sandstone is the strongest sandstone with a mean dry unconfined compressive strength value of 21464 psi (148 MPa). The Juniata Sandstone also has the lowest absorption and highest dry density values. This is in agreement with the published research (D'Andrea et al., 1965; Shakoor and Bonelli, 1991; Hawkins and McConnell, 1992; Haney and Shakoor, 1994; Hale and Shakoor, 2003) showing dry density and absorption to be strong indicators of unconfined compressive strength. The Cow Run Sandstone is the weakest of the tested sandstones with a mean dry unconfined compressive strength value of 2824 psi (19.5 MPa). The low strength of the Cow Run Sandstone can be attributed to its having the lowest mean dry density and second highest mean absorption. The Lower Freeport Sandstone shows an unusually low mean dry unconfined compressive strength of 5870 psi (40.5 MPa) in spite of its lower absorption value. According to the strength classification proposed by Deere and Miller (1966), all of the studied sandstones fall in the low or medium strength category with the exception of Cow Run Sandstone which classifies as a very low strength rock and Juniata Sandstone which classifies as a high strength rock.

The mean dry density of the sandstones ranges from 157.5 pcf (2.52 Mg/m^3) for the Juniata Sandstone to 129.1 pcf (2.07 Mg/m^3) for the Cow Run Sandstone (Table 2). Mean absorption values range from 6.06% for the Berea Sandstone B to 1.63% for the Juniata sandstone. It is notable that the while the Cow Run Sandstone has the lowest density, this low density does not translate into the highest absorption demonstrated by the Berea Sandstone B. Mean bulk specific gravity values range from 2.09 for the Cow Run Sandstone to 2.53 for the Juniata Sandstone. The Juniata Sandstone and Cow Run Sandstone each also have the highest and lowest mean saturated surface-dried bulk specific gravity values of 2.57 and 2.22, respectively. Lastly, the effective porosity values for the studied sandstones range from 4.12% to 12.72% for the Juniata Sandstone and Berea Sandstone B, respectively.

Table 2. Mean values of engineering properties for each sandstone.

Sandstone	Dry Density (pcf)*	Absorption (%)	Bulk Specific Gravity	Bulk Specific Gravity (Saturated Surface Dried)	Effective Porosity (%)	Mean Dry Unconfined Compressive Strength (psi)**
Lower Freeport	134.3	4.33	2.17	2.27	9.31	5870
Berea A	135.0	5.42	2.17	2.29	11.72	10846
Homewood	152.7	2.95	2.44	2.52	7.23	14385
Juniata	157.5	1.63	2.53	2.57	4.12	21464
Berea B	131.0	6.06	2.11	2.24	12.72	6718
Sharon	132.9	5.53	2.14	2.26	11.77	7116
Lower Mahoning	137.9	3.62	2.22	2.30	8.00	11459
Cow Run	129.1	6.05	2.09	2.22	12.51	2824
Black Hand	133.2	5.41	2.15	2.26	11.54	7585

*pcf = pounds per cubic foot; **psi = pounds per square inch; 1 pcf = 0.016 Mg/m^3; 1 psi = 0.006895 MPa

RELATIONSHIP BETWEEN UNCONFINED COMPRESSIVE STRENGTH AND DEGREE OF SATURATION

Bivariate regression analysis

Bivariate regression analysis was performed to evaluate the relationship between unconfined compressive strength and degree of saturation. Several statistical parameters such as correlation coefficient (R), coefficient of determination (R^2), adjusted R^2, F statistic, standard error of the estimate, and significance level were used to evaluate the strength of correlations. Results of bivariate regression analysis are shown in Table 3. While nearly all sandstones showed a clear reduction in unconfined compressive strength between the dry and fully saturated states, consistency in strength reduction at intermediate levels of saturation was not evident in the Lower Freeport Sandstone, Berea Sandstone A, Berea Sandstone B, Lower Mahoning Sandstone, Cow Run Sandstone, and Black Hand Sandstone. The majority of the strength reduction in these sandstones occurred between the dry state and 20% degree of saturation. Strength decreases above 20% saturation were less evident and seemed to be negligible enough to be masked by the inherent variability in strength values between cores tested at the different degrees of saturation. The relatively low linear correlation coefficient values for these sandstones reflect this trend (Table 3). It should be noted that this trend of most strength being lost at low saturation levels has been observed by several other researchers as explained previously.

The Homewood and Juniata sandstones showed large reductions (62.6% and 71.6%, respectively) in unconfined compressive strength between the dry and saturated states. These large reductions were matched by very consistent unconfined compressive strength reductions at intermediate levels of saturation as indicated by the very high correlation coefficient values (Table 3). It should be noted that the Homewood and Juniata sandstones had the highest mean dry strengths and lowest absorption values among the tested sandstones. Therefore, there seems to be a relationship between very strong, low absorption sandstones and large, consistent reductions in unconfined compressive strength upon saturation. The trend observed in this study of strong sandstones displaying the largest saturation-caused reductions in unconfined compressive strength has also been pointed out by other researchers such as Michalopoulos and Triandafilidis (1976) and Hawkins and McConnell (1992), and is in contrast to the conclusions of Dyke and Dobereiner (1991). The statement by Broch (1974) that rocks of low porosity experience the largest saturation-caused strength reductions holds in this research in that the Homewood and Juniata sandstones have the lowest porosities of the sandstones tested.

Table 3. Results of bivariate regression analysis.

Sandstone	R	R^2	Adjusted R^2	F	Standard Error of the Estimate	Significance	Relationship
Lower Freeport	-0.74	0.55	0.52	19.26	438.54	0.00	Unconfined Compressive Strength vs Square Root % Saturation
Berea A	-0.73	0.53	0.50	17.89	681.34	0.00	Unconfined Compressive Strength vs Square Root % Saturation
Homewood	-0.97	0.93	0.93	218.40	0.0366	0.00	Log Unconfined Compressive Strength vs Square Root % Saturation
Juniata	-0.95	0.91	0.90	160.85	1612.45	0.00	Unconfined Compressive Strength vs Square Root % Saturation
Berea B	-0.56	0.31	0.27	7.25	698.40	0.02	Unconfined Compressive Strength vs Square Root % Saturation
Sharon	-0.51	0.26	0.21	5.51	596.52	0.03	Unconfined Compressive Strength vs % Saturation
Lower Mahoning	-0.63	0.40	0.36	10.43	1055.61	0.01	Unconfined Compressive Strength vs Square Root % Saturation
Cow Run	-0.88	0.78	0.77	57.26	0.0456	0.00	Log Unconfined Compressive Strength vs Square Root % Saturation
Black Hand	-0.50	0.25	0.21	5.38	780.60	0.03	Unconfined Compressive Strength vs Square Root % Saturation

Multivariate regression analysis

SPSS 12.0 software was used to perform a multivariate linear regression analysis on the unconfined compressive strength, engineering index properties, and degree of saturation data collected for all core samples. A separate analysis was performed for each of the nine sandstones. The log and square root values of each parameter, except for the degree of saturation, were included in the analysis as a means of providing for the best possible correlations. Only the square root value of the degree of saturation for each core was used in the analysis. The purpose of this analysis was to find the best empirical equations for predicting the unconfined compressive strength for each tested sandstone using degree of saturation and engineering index property data. The engineering index property data was included to help account for the scatter in unconfined compressive strength values found at varying degrees of saturation. The reliability of empirical equations generated by multivariate analysis was judged through use of statistical parameters that included correlation coefficients (R, R^2, and adjusted R^2), F statistic, standard error of the estimate, and significance values. Table 4 shows an example of the results of multivariate regression analysis for the Lower Freeport Sandstone.

Table 4: Results of multivariate regression analysis for Lower Freeport Sandstone.

R	R^2	Adjusted R^2	F	Standard Error of the Estimate	Significance	Empirical Predictive Equation
0.84	0.71	0.67	18.12	363.83	0.00	UCS (psi) = 5850.882 + 24.420(%S) - 377.689(SR%S)

UCS: unconfined compressive strength; psi: pounds per square inch; %S: degree of saturation
SR%S: square root of degree of saturation

Similar multivariate analyses were conducted for the remaining eight sandstones and predictive equations were developed. The results of multivariate analyses for all sandstones are summarized in Table 5. In general, there is a significant increase in the predictive capability of the empirical equations generated by multivariate analysis (Table 5) compared to bivariate analysis (Table 3), as indicated by a comparison of statistical parameters (adjusted R^2, F statistic, and standard error of the estimate). Clearly, the inclusion of engineering index properties in multivariate regression analysis (Table 5) allowed for a much better prediction of the saturation-induced unconfined compressive strength reduction in nearly all of the studied sandstones.

Table 5. Results of multivariate regression analysis ranked according to adjusted R^2 values of predictive equations.

Sandstone	Adjusted R^2	Standard Error of the Estimate	Significance	Empirical Predictive Equation
Homewood	0.97	2.4778	0.00	SRUCS = 119.430 + 0.391(%S) - 8.121(SR%S)
Juniata	0.94	1320.11	0.00	UCS (psi) = -232210 + 1611.055(DD) - 1383.319(SR%S)
Cow Run	0.91	140.57	0.00	UCS (psi) = -7991.562 + 5194.215(BSG) + 16.611(%S) - 288.260(SR%S)
Berea B	0.84	322.47	0.00	UCS (psi) = -99196.6 + 807.241(DD) - 562.331(SR%S) + 43.965(%S)
Lower Freeport	0.67	363.83	0.00	UCS (psi) = 5850.882 + 24.420(%S) - 377.689(SR%S)
Berea A	0.62	590.61	0.00	UCS (psi) = 10816.422 + 34.628(%S) - 546.446(SR%S)
Lower Mahoning	0.48	950.70	0.00	UCS (psi) = -107102 + 854.424(DD) - 168.970(SR%S)
Sharon	0.38	528.09	0.01	UCS (psi) = -78120.7 + 640.423(DD) - 8.875(%S)
Black Hand	0.36	698.46	0.01	UCS (psi) = 7493.679 + 36.445(%S) - 488.109(SR%S)

Absorption as a predictor of unconfined compressive strength

A multivariate linear regression analysis, similar to the one performed on the data for individual sandstones, was also performed using the data from all nine sandstones in an attempt to develop a predictive empirical equation that would be applicable to all sandstones similar to the ones tested in this study. However, the results of this analysis showed that a reasonably reliable predictive equation for unconfined compressive strength could not be achieved without the input of an unreasonably large number of independent variables. Therefore, instead of treating all sandstones in the same manner, they were grouped into different absorption classes. The absorption classes are A (1%-3% absorption), B (3%-5% absorption), C (5%-6% absorption), and D (6%-7% absorption). These classes are chosen on the basis that sandstones in each class demonstrated similar unconfined compressive strength sensitivity to saturation.

Absorption Class A (Absorption = 1% - 3%)

Absorption Class A is based on data from the Homewood and Juniata sandstones with each having mean absorption values of 2.95 and 1.63, respectively. Both of these sandstones had the lowest absorptions and highest unconfined compressive strengths amongst the sandstones tested in this study. These sandstones demonstrated similar behavior with respect to their saturation-induced unconfined compressive strength decrease with each showing a steady, consistent decrease in unconfined compressive strength throughout the range of saturation degrees at which the cores samples were tested. The multivariate regression equation for Absorption Class A is given in Table 6. This equation might also be used for sandstones with absorption values less than 1% but further research is needed to confirm this.

Table 6. Results of multivariate regression analysis for Absorption Class A.

R	R^2	Adjusted R^2	F	Standard Error of the Estimate	Significance	Empirical Predictive Equation
0.97	0.94	0.94	253.87	0.0471*	0.00	LogUCS = 4.590 - 0.155(%ABS) - 0.041(SR%S)

* Approximately +/- 1200 psi on average; LogUCS: log of unconfined compressive strength in psi; %ABS: percent absorption; SR%S: square root of degree of saturation

Figure 1 provides a plot of predicted (using equation in Table 6) versus actual unconfined compressive strength values for sandstones belonging to Absorption Class A. The strength of the equation at predicting the unconfined compressive strength at varying degrees of saturation and absorption values is indicated by how closely the data points fall to a 1:1 line. The R^2 value for a linear regression line (not shown) through the data points in Figure 1 is 0.93.

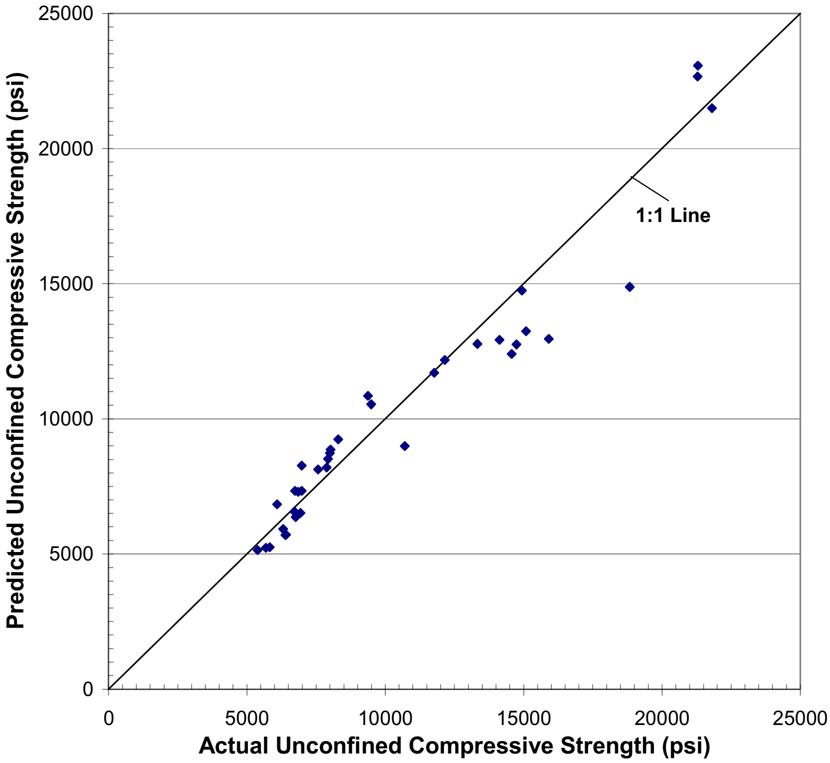

Figure1. Predicted versus actual unconfined compressive strength values for Absorption Class A.

Absorption Class B (Absorption = 3% - 5%)

Absorption Class B is based on data obtained from the Lower Mahoning and Lower Freeport sandstones with mean % absorption values of 3.62% and 4.33%, respectively. Both of these sandstones show the same pattern of loss in the majority of their unconfined compressive strength between 0% and 20% degrees of saturation with little reduction at higher saturation levels. Table 7 provides the predictive equation for Absorption Class B with an adjusted R^2 value of 0.87, a significant improvement over R^2 values for individual sandstones (Table 5).

Table 7. Results of multivariate regression analysis for Absorption Class B.

R	R^2	Adjusted R^2	F	Standard Error of the Estimate	Significance	Empirical Predictive Equation
0.94	0.88	0.87	119.37	0.0601	0.00	LogUCS = -6.752 - 0.004(SR%S) + 0.078(DD)

* Approximately +/- 950 psi on average; LogUCS: log of unconfined compressive strength in psi; SR%S: square root of degree of saturation; DD: dry density in pounds per cubic foot

Figure 2 provides a plot of predicted versus measured values of unconfined compressive strength for Absorption Class B. The cluster of data in the lower left corner of Figure 2 pertains to the Lower Freeport Sandstone while the data points in the upper right corner are from the Lower Mahoning Sandstone. The R^2 value for a linear regression line (not shown) through the data points in Figure 2 is 0.88.

Absorption Class C (Absorption = 5% - 6%)

Absorption Class C is based on data from the Berea A, Sharon, and Black Hand sandstones. These sandstones have mean % absorption values of 5.42%, 5.53%, and 5.41%, respectively. None of the three sandstones individually showed very predictable saturation-induced unconfined compressive strength decreases with the highest adjusted R^2 values being 0.62 for Berea Sandstone A, 0.38 for the Sharon Sandstone, and 0.36 for the Black Hand Sandstone (Table 5). However, the Absorption Class C equation (Table 8) can be thought of as being the strongest with regard to its reliability in predicting the behavior of other sandstones since it is based on data from three different sandstone formations from within an absorption range of only 1% (5% - 6%). Figure 3 provides a plot of the actual unconfined compressive strengths versus those predicted by the Absorption Class C equation (Table 8). The R^2 value for a linear regression line (not shown) through the data points in Figure 3 is 0.76.

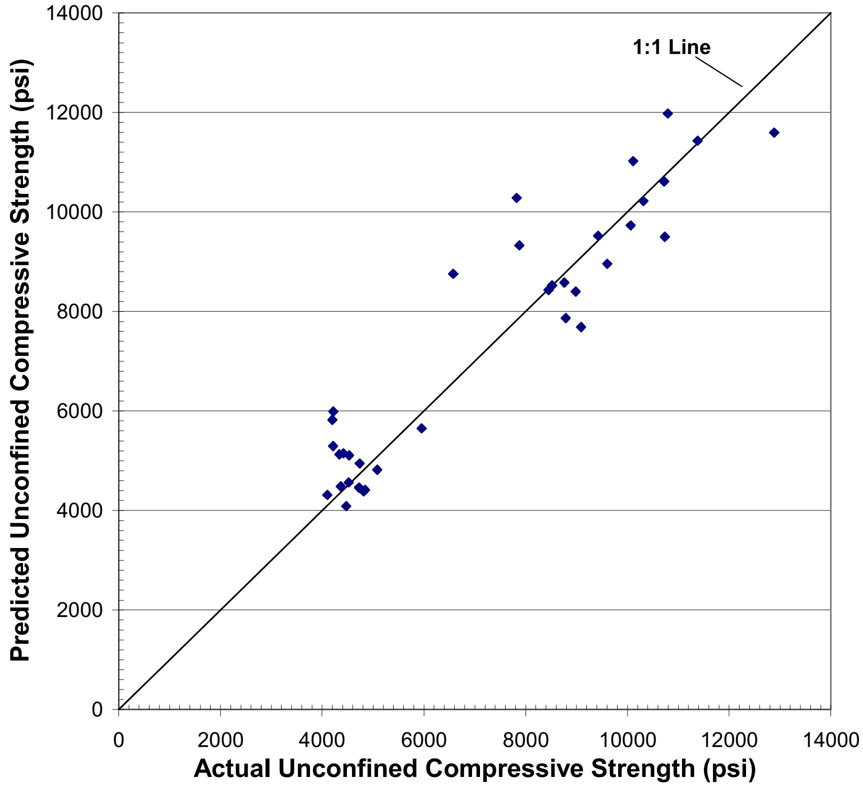

Figure 2. Predicted versus actual unconfined compressive strength values for Absorption Class B.

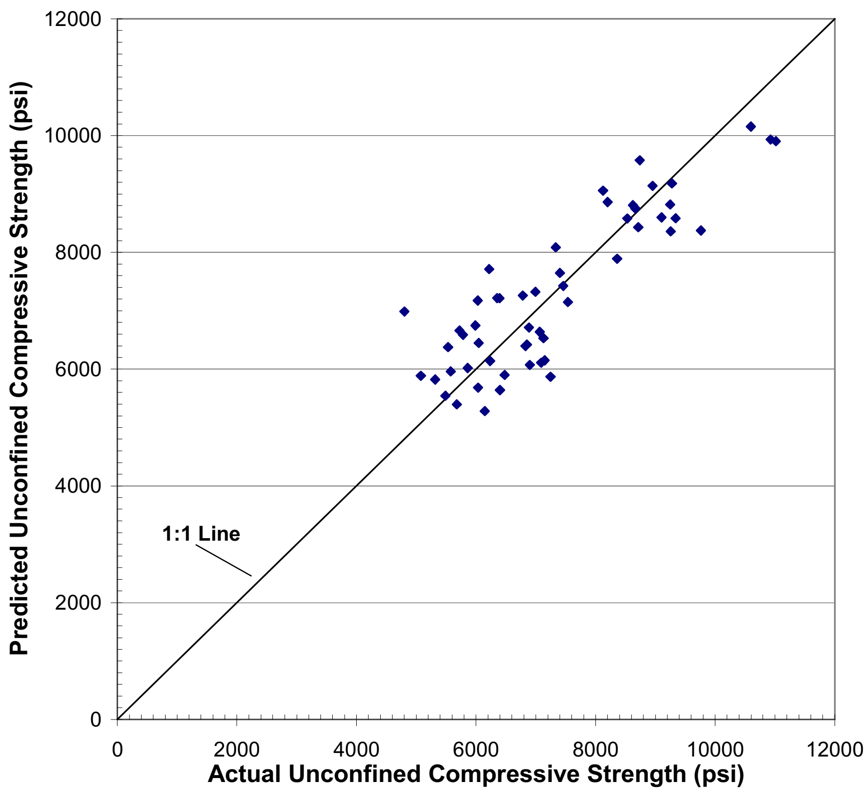

Figure 3. Predicted versus actual unconfined compressive strength values for Absorption Class C.

Table 8. Results of multivariate regression analysis for Absorption Class C.

R	R^2	Adjusted R^2	F	Standard Error of the Estimate	Significance	Empirical Predictive Equation
0.87	0.76	0.75	78.77	777.52	0.00	UCS (psi) = -186110 + 85657.691(SSDBSG) - 158.271(SR%S)

UCS: unconfined compressive strength; psi: pounds per square inch; SSDBSG: saturated surface-dried bulk specific gravity; SR%S: square root of degree of saturation

Absorption Class D (Absorption = 6% - 7%)

Absorption Class D is based upon data collected from the Berea Sandstone B and Cow Run sandstones whose respective mean absorption values are 6.06% and 6.05%, respectively. Sandstones having absorption values covering a wider array of the 6% - 7% range would have been preferable but the grouping of the sandstones tested in this study allowed for the Berea B and Cow Run sandstones to represent an absorption class despite their very similar absorption values. Nevertheless, these two sandstones should provide a useful indication of the saturation-induced unconfined compressive strength behaviour of sandstones falling within Absorption Class D. As a conservative measure, the predictive empirical equation presented in Table 9 should be considered more applicable to sandstones between 6% and 6.5% absorption than for sandstones between 6.5% and 7% due to both sandstones, upon which the empirical equation is based, having mean absorption values very close to 6%. Figure 4 provides a plot of predicted versus actual unconfined compressive strength values for the equation in Table 9. The R^2 value for a linear regression line (not shown) through the data points in Figure 4 is 0.82.

It is hoped that the absorption class equations presented above can provide a useful tool in predicting the unconfined compressive strength of any sandstone whose absorption falls within the 1% to 7% range. All of the absorption class equations presented above have statistically significant adjusted R^2 values and provide for a reasonably accurate prediction of the unconfined compressive strength through input of one or a few engineering index properties along with the degree of saturation.

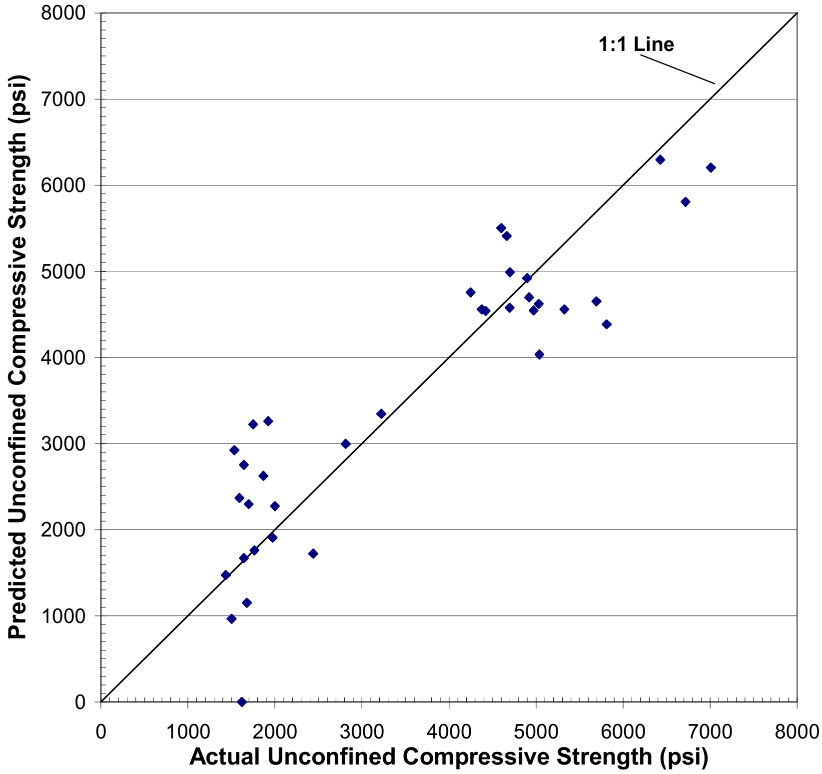

Figure 4. Predicted versus actual unconfined compressive strength values for Absorption Class D.

Table 9. Results of multivariate regression analysis for Absorption Class D.

R	R^2	Adjusted R^2	F	Standard Error of the Estimate	Significance	Predictive Empirical Equation
0.90	0.81	0.79	33.48	829.16	0.00	UCS (psi) = - 398654 + 1115.835(DD) + 687985.4(Log%ABS) - 46168.4(%ABS) - 164.424(SR%S)

UCS: unconfined compressive strength; psi: pounds per square inch; DD: dry density in pounds per cubic foot;
Log%ABS: log of % absorption; %ABS: % absorption; SR%S: square root of degree of saturation

CONCLUSIONS

The following conclusions can be drawn from this study:

- The sandstones used in this study show a significant reduction (up to 71.6%) in unconfined compressive strength between the dry and saturated states. Stronger, lower absorption sandstones show consistent, linear reduction in unconfined compressive strength with increasing degrees of saturation. For weaker sandstones the majority of unconfined compressive strength is lost between 0% and 20% saturation with minimal or irregular strength losses at higher degrees of saturation.
- Multivariate linear regression analysis allows for development of statistically significant predictive equations for the unconfined compressive strength of sandstones based on input of the degree of saturation along with one or more engineering index properties.

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