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Geotechnical Characterization of Sevier and Rome Shale, East Tennessee

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ABSTRACT: A complex mosaic of Sevier (Ordovician) and Rome (Cambrian) Shale are widely distributed throughout the sedimentary sequences in the southern Appalachians. These shales exhibit variable geotechnical characteristics including the strength and durability. We have investigated the factors controlling the Unconfined Compressive Strength (UCS) and Slake Durability Index (SDI) of Sevier and Rome Shale in order to better understand site-specific engineering problems associated with these shales and to predict their geotechnical behavior. The results have shown the variation in mineral content including expanding clay, calcite, gypsum, and presence of microfractures filled with calcite have significantly affected the durability and strength of shale rock mass. In order to obtain realistic estimate of time-dependent weathering patterns in the Sevier and Rome Shale, we have performed multi-cycle SDI; results have indicates that a 5-cycle SDI better estimates the disintegration pattern of shale and can be used to classify shale in terms of the degree of weathering.

1. INTRODUCTION AND OBJECTIVE

Shales are very fine-grained argillaceous sedimentary rocks in which more than 50% of the clastic grains are smaller than 0.06mm in diameter [3]. These rocks are often intensely fractured and weathered and have highly variable geotechnical characteristics, which cause significant construction problems and damage to civil structures each year. In order to evaluate geotechnical properties, geologists estimate shale strength in terms of Unconfined Compressive Strength (UCS) and durability in terms of the Slake Durability Index (SDI). UCS measures the strength of a rock and its ability to bear the load of civil structures, and SDI determines a rock's resistance to weathering. UCS and SDI are widely used in construction design and in rock engineering. Because of their variable clay content, degree of induration, shrink-swell behavior, and intensity and infilling of fractures and micro fractures, shales exhibit geotechnical properties that range from low strength, low durability, fissile rocks to hard and compact types [6, 16, 15, 17]. As a result, quantification of shale strength, weathering characteristics, and capacity of foundation support become challenging. Consequently, common practice among geologists and engineers is to treat shales as if they were soils and not coherent lithified materials. Thus, lithified shales are not often analyzed quantitatively. This practice yields over-conservative design parameters, which, in turn, cause unnecessarily high construction expenditures.

A complex mosaic of weathered Sevier (Ordovician) and Rome (Cambrian) Shale are widely distributed throughout the landscape and form a majority of the sedimentary sequences in the southern Appalachians. As ongoing population pressure leads to an increased need for new construction sites (e.g., office buildings, highways, landfills etc.) in eastern Tennessee, many of these sites are being built on Sevier and Rome Shale and/or use shale as construction materials. These shales exhibit varying degrees of disintegration due to weathering (SDI values) and show inconsistent compressive strength (UCS). Therefore, our first objective is to investigate the factors controlling UCS and SDI of Sevier and Rome Shale in order to better understand the site-specific engineering problems associated with shale and to predict its strength and durability behavior in construction sites.

While understanding the various effects on the UCS and SDI values of shale is extremely important, estimating the degree of weathering in terms of SDI is also critical. Weathering is a time-dependent process and it is often difficult to assess how shale will respond to prolonged exposure to seasonal wetting and drying cycles. According to ASTM standard procedure [1], SDI in terms of 2-cycle slake durability index (Id2) estimates the durability of rocks. However, Bell [2] indicated that 2-cycle slake durability tests often do not accurately indicate the durability of weak rocks such as shale. Instead, a 4-cycle slake durability test provides more accurate results [10, 8]. Therefore, our second objective is to investigate the disintegration pattern of shale samples through multi-cycle slake durability in order to obtain a more accurate estimate of time-dependent weathering patterns in the Sevier and Rome Shale.

Lastly, our third objective aims to realistically measure the UCS of shale. There are standard procedures for measuring UCS using rock cores. However, rock cores are difficult to obtain for highly laminated and/or weathered shales. Instead, the Point Load and Schmidt Hammer tests can be used to estimate UCS. Both of these methods have limitations, however, and here we evaluate the applicability of these methods for estimating the UCS of weak, laminated, and anisotropic rocks such as shale.

2. GENERAL GEOLOGY

The Cambrian Rome Formation and the Ordovician Sevier Shale are two of the dominant shale bearing formations in northeastern Tennessee. Both occur repeatedly across northeastern Tennessee as folded and faulted sequences within the fold and thrust belt. Structurally, both formations are important as decollement surfaces and serve as the dominant glide plane surfaces for thrust faults in the region.

The Rome Formation occurs above the Shady Dolomite and below the Conausaga Group. It is described as a heterogeneous and variegated mixture of sandstone, siltstone, shale, dolomite and limestone [11]. Maroon colored shales and carbonates dominate the northeastern exposures while coarse clastic units become more common toward the northwest [14]. The Rome Formation commonly preserves ripple marks, dessication structures, fossils, animal track-ways and feeding traces, all indicative of a shallow marine depositional environment. The Rome Formation often occurs above major thrust sheets and is commonly intricately folded and imbricated. Consequently, it often shows no base. Reported formation thickness is in the order of 370 m (1,200 feet) [14]. Exposed sequences of the Rome Formation often occur as friable weathered slopes. Continued weathering produces bright red to maroon clays.

The Sevier Shale is a blue-gray silty to sandy, generally calcareous, shale. In many sections it is also strongly carbonaceous. In northeastern Tennessee the Sevier Shale overlays the Knox Group carbonates and underlies the Bays Formation. It is commonly heavily folded and its close association with thrust faults and obvious truncations makes estimation of a true stratigraphic thickness problematic. However, Rodgers [14] reports a minimum stratigraphic thickness of 800 m (2,500 feet) in the Bays Mountain synclinorium and likely thicknesses in the order of 2,300 m (7,000 feet). Road cut exposures commonly exhibit multiple cleavage directions and calcite veining. Some sections expose pencil cleavage sequences which are indicative of high levels of dissolution. The Sevier Shale produces graptolites, sometimes pyritized, trilobites and brachiopods. It is interpreted as a sequence dominated by deep water marine sediments deposited in a forearc basin environment [14]. The presence of carbonates, minor sands and conglomerates clearly indicates a more complex depositional history which suggests a shallow water influence.

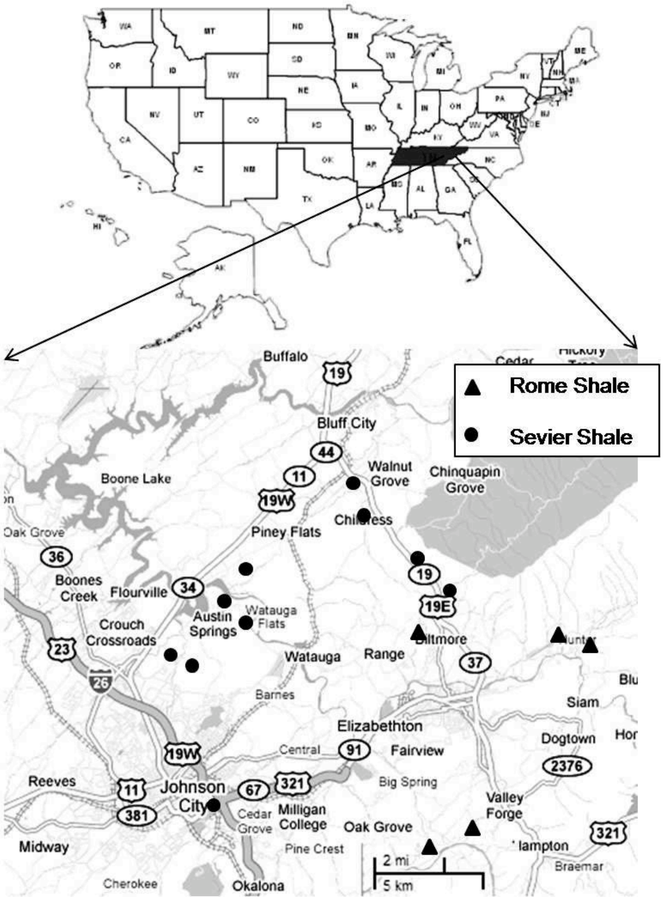

Fig. 1. Location map.

Both the Rome Formation and Sevier Shale sequences commonly exhibit complexly folded sections, especially when in close proximity to fault planes. These sections contain rocks that are often both strongly fractured and cleaved. Secondary pyrite growth, gypsum growth and calcite veining is ubiquitous and exposed sequences weather to friable and unstable slopes, and ultimately, to soft clays. These sequences are exposed over a large area of east Tennessee, an area currently undergoing rapid development. Therefore, understanding the engineering characteristics of these formations is of paramount importance.

3. DATA COLLECTION AND METHODS

3.1. Sample Collection

A total of twenty-six shale samples (from five locations of Rome Formation and eight locations of Sevier Shale) were collected from various rock exposures and road cuts. The shale samples range in age from Cambrian to Ordovician, and have dissimilar depositional environments. Relatively fresh block samples were collected in the field by first removing the weathered, surficial soil. Block samples were then extracted from the outcrop using a hammer and chisel, and care was taken to avoid creating additional fractures in the shale during collection. Figure 1 shows the sampling locations in the Tri-Cities region of eastern Tennessee.

3.2. Analysis Methodology

In order to address our objectives, several field and laboratory tests were performed to determine the physical and chemical properties of the shale samples. Whole rock observations, such as orientation, state of weathering, and presence of microfractures, were recorded in the field. Additionally, Schmidt Hammer and Point Load tests were used to estimate UCS and anisotropy of the two formations and the durability in terms of SDI was evaluated using multi-cycle Slake Durability test.

Thin section preparation from weak rocks such as shale is especially difficult, since about 50% of the clastic material is mud (<0.06mm). The samples disintegrated easily along fissile planes, fracture planes, and micro fractures filled with softer minerals. Thin sections were not used for analysis.

X-ray diffraction (XRD) analysis was performed on powdered shale samples in order to assess the whole rock mineralogy. Samples were analyzed at Appalachian State University on a Shimadzu XRD 6000 diffractometer run at 40.0 kV and 30.0 mA. The data were collected from 05° to 45° 2-theta with a continuous scan of 2.0°/min and 0.02° sampling pitch. XRD peaks (reported as degrees 2-theta) were converted to d-spacings (in Å) using Bragg's Law. Scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) microanalysis, completed on an FEI Quanta ESEM housed at Appalachian State University, complemented the XRD studies.

Furthermore, scanning electron microprobe analysis was used in order to (1) determine the mineral and cement composition, (2) confirm the presence of micro fractures, and (3) identify the fracture infill of the shale samples, The chemical properties were correlated with UCS and SDI to determine the factors responsible for variable strength and durability of the shales.

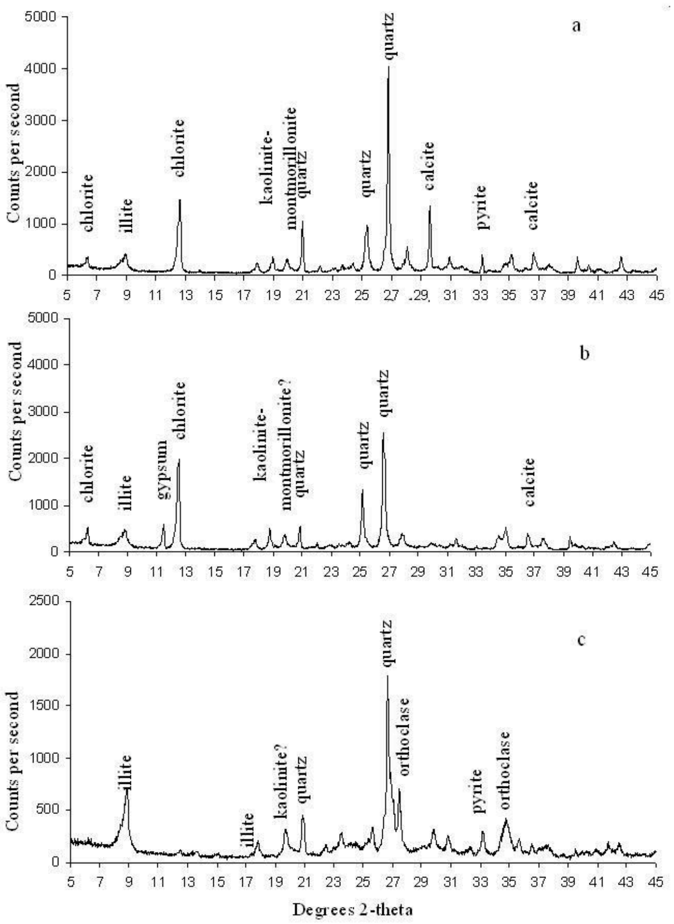

Fig. 2. X-Ray diffractogram of shale samples from the Sevier Shale (a, b), and Rome Shale formation (c)

3.3. Petrographic Data

XRD analysis revealed that Sevier Shale is composed of quartz, calcite, chlorite, gypsum, pyrite, illite, and mixed layer kaolinite – montmorillonite, and Rome Shale is composed of quartz, orthoclase feldspar, pyrite, and illite (Figure 2). EDX results indicate that elements such as O, Si, Al, Ca, Fe, Mg, Na, K, and S (in decreasing order of abundance) are prolific in Sevier Shale samples (Figure 3). The phase mineral composition of these elements is quartz, calcite, chlorite, illite, kaolinite, montmorillonite, pyrite and gypsum. Observations from SEM analysis of spot 2 in Figure 3 indicate that Ca is the dominant element along the fracture planes of the shale samples with reduced concentrations of Si and Al.

3.4. Unconfined Compressive Strength

The unconfined compressive strength of the rock units was evaluated by Schmidt Hammer test and Point Load test. The Point Load test is a simple estimation of the UCS of rocks. The equipment is comprised of a loading

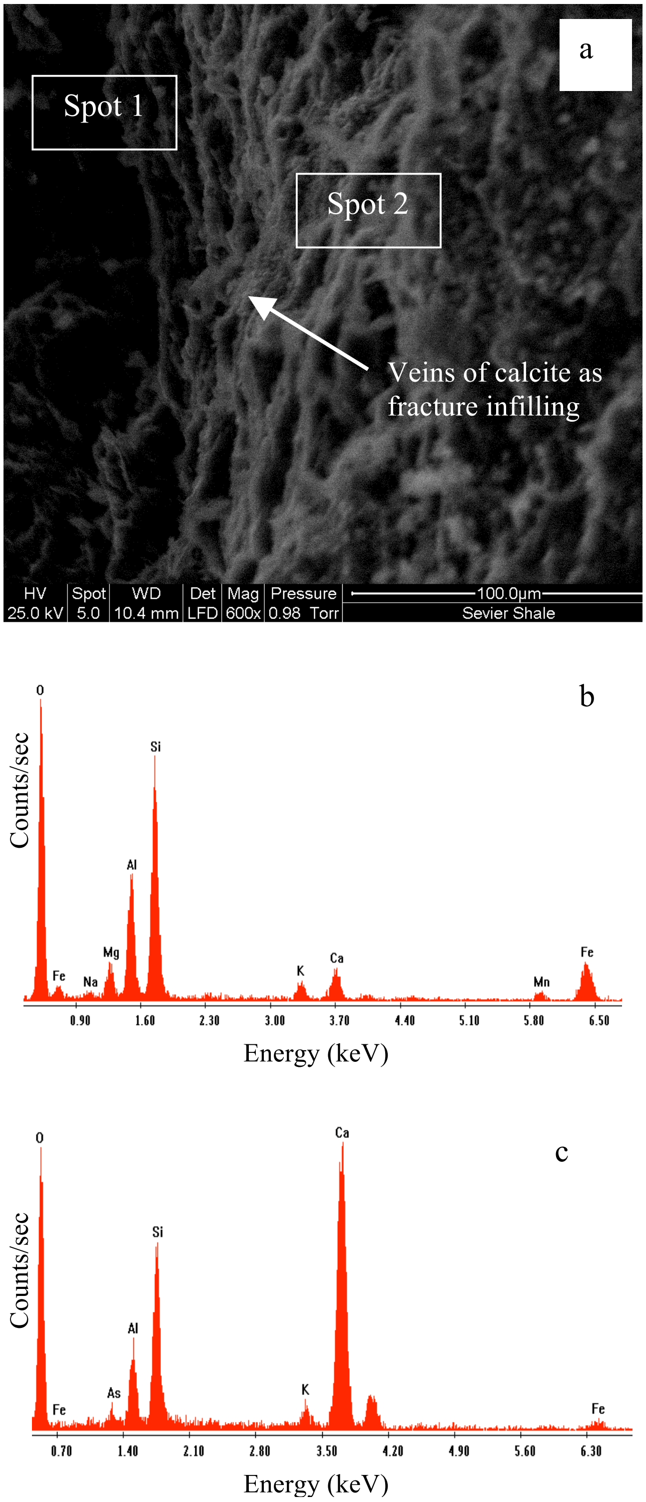

Fig. 3. SEM image of a fracture in Sevier Shale filled with calcite veins (a), EDX microanalysis of spot 1(b), and spot 2(c).

frame that measures the force necessary to split the sample and a scale that measures the distance between the two contact loading points. The Point Load test can be performed on samples with different shapes, both cylindrical (core) and irregular [4]. Cylindrical core samples were not obtained, as fissile shale samples often shatter during the coring process. Instead, irregular block samples were used to determine the Point Load index (reported as Is50) and the average value of three trials is reported here. Blocks was size corrected to obtain the Is50 using the equation:

$$Is50 = \frac{P}{D^2} \times F \qquad (1)$$

where P is the peak load, D is the distance between the two contact loading points, and F is a size correction factor [12]. The UCS of the rock samples can be reasonably estimated by multiplying the Is50 value by 24 [5]. However, the empirical conversion factor can range from as low as 8 to as high as 35 for weak rocks, including shale. Table 1 shows the range of Is50 values and UCS values for Sevier and Rome Shale.

A type N Schmidt Hammer was used to evaluate rock hardness in field. The instrument measures the distance of rebound of a controlled impact on a rock surface. The recovery distance depends on the hardness of the rock, which is a direct measure of the UCS. Care was taken to avoid surfaces that had cracks to a depth of at least 6cm, and loose surface material was removed before the field test. Ten impacts of the Schmidt Hammer were conducted for each shale sample, and the average value was calculated. A number of studies have indicated the usefulness of the Schmidt Hammer test on different rocks and have established its strong correlation with UCS through numerous empirical equations [9, 17,]. Schmidt Hammer Rebound (R) values were directly used in the analysis and were not converted to UCS, since there is no standard conversion designated for shale. Table 1 shows the range of R values for Sevier and Rome Shale.

Table 1. Estimated Unconfined Compressive Strength of shale samples.

	Strength Parameter	Avg	Min.	Max.	Strength Class
Sevier Shale	Schmidt Hammer Rebound	30	19	38	Weak to Medium Strong to Strong [13]
	Point Load Index (Id50) in N/mm2	2.20	0.90	4.67	
	UCS in N/mm2	53	22	112	
Rome Shale	Schmidt Hammer Rebound	38	23	44	Medium Strong to Strong [13]
	Point Load Index (Id50) in N/mm2	4.04	1.60	5.69	
	UCS in N/mm2	97	38	143	

3.5. Slake Durability

The Slake Durability test was developed by Franklin and Chandra [7] and was standardized by the American Society for Testing and Materials [1]. This test evaluates the durability of rock in terms of the Slake Durability Index (SDI). The durability of rock is described as the resistance to weathering over time and slaking is defined as the swelling of a rock containing clay minerals when it comes in contact with water [7].

For each slake durability test, 10 representative rock pieces were used, each weighing between 40g and 60g, with a total sample weight ranging from 450g to 600g. The sample is placed in a screen drum, immersed in distilled water, and rotated at 20 rpm for 10 min. The sample is then oven-dried to a constant weight and then subjected to five consecutive cycles of wetting and drying. A multiple cycle slake durability test was then performed to evaluate the response of the shale samples with prolonged weathering. The multiple cycle slake durability (ID_n) was estimated by the following equation

$$ID_n = \frac{W_n - W_D}{W_{n-1} - W_D} \times 100 \qquad (2)$$

where W_{n-1} is the mass of the drum plus the oven-dried sample before the nth cycle, W_n is the mass of the drum plus the oven-dried sample retained after the nth cycle, and W_D is the mass of drum. Figures 4a and 4b show the slake durability pattern for Sevier and Rome Shale in response to prolonged weathering.

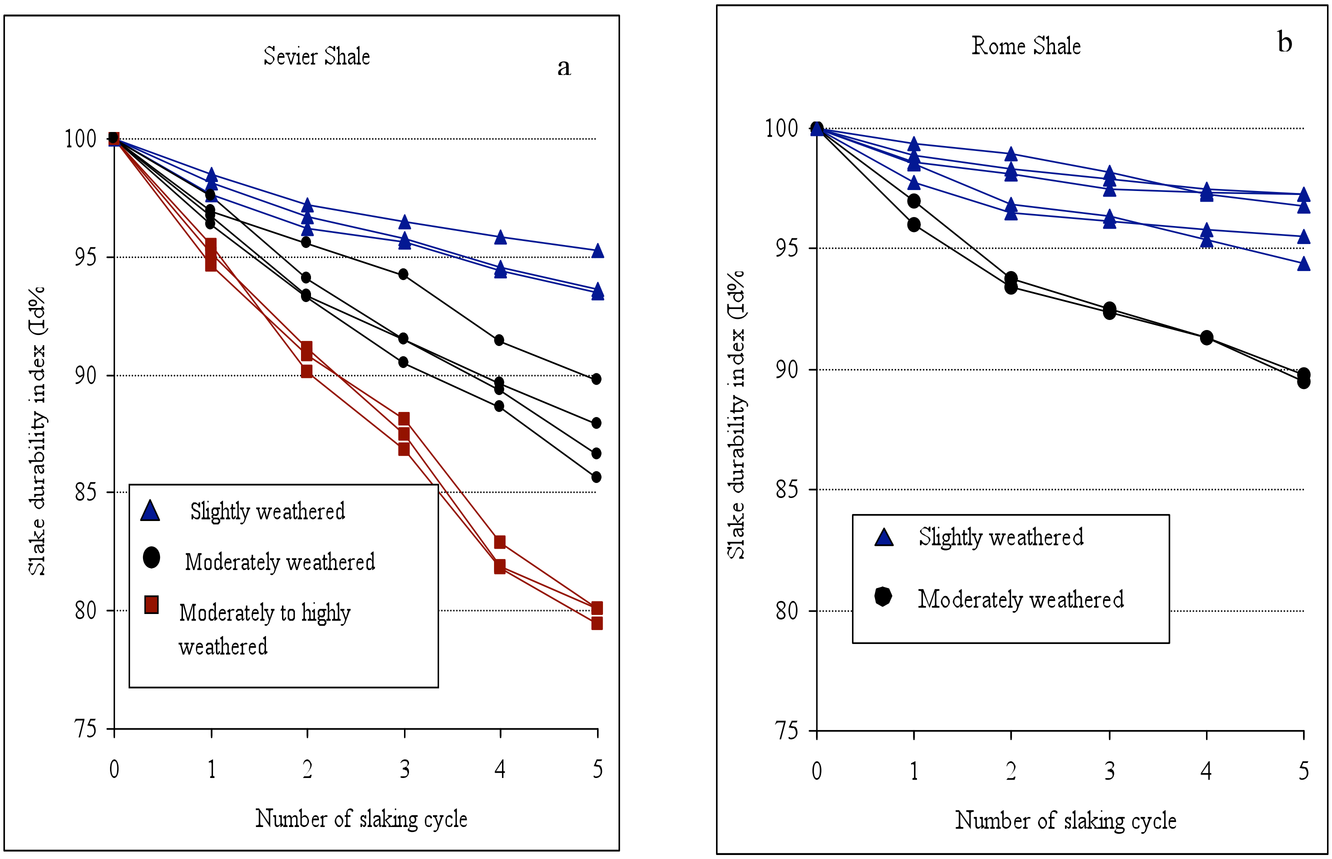

Fig. 4 Relationship between the number of slaking cycles and slake durability index for Sevier shale (a) and Rome shale (b).

4. DISCUSSION

XRD results indicate that the Sevier Shale is composed of quartz, calcite, chlorite, gypsum, pyrite, illite, and mixed layer kaolinite – montmorillonite (Figure 2). Quartz is a major non-clay component of this shale and calcite occurs as the dominant cement as well as the infilling material in the microfractures. Of the four types of clay minerals, illite, chlorite and kaolinite are non-expanding types whereas montmorillonite is a smectitic (expanding) clay. The presence of expandable clay minerals has a pronounced effect on the durability of shale since these clays are prone to slaking or disintegration when in contact with water. X-ray analysis reveals that highly weathered Sevier Shale samples contained less calcite and more gypsum, which is an alteration product of pyrite. Weathered shales possibly contain smectite, however their peaks overlap with chlorite and illite and therefore the presence of smectite has not yet been confirmed. Higher percentages of quartz, calcite, and non-expanding clays would be expected in less weathered Sevier Shale samples. XRD results indicate that quartz, orthoclase feldspar, pyrite, and illite are the dominant minerals in the Rome Shale with some questionable peaks of kaolinite (Figure 2). Orthoclase feldspar weathers into the clay mineral kaolinite and finally into illite by diagenetic reaction. The presence of more stable minerals like quartz and orthoclase, along with the paucity of expanding clay, explains the durability and strength of the Rome Shale.

Apart from bulk mineralogy, microfractures play an important role in the strength and durability of shale, since disintegration is initiated along the fracture planes during wetting and drying cycles due to capillary suction of water. SEM results indicate that microscopic calcite crystals are present in Sevier Shale microfractures, and likely form by secondary mineralization (as groundwater flows through the fractured shale). Calcite is a relatively soft mineral and is susceptible to weathering when mildly acidic water converts calcite into soluble calcium and bicarbonate ions, which are volumetrically larger and promote slaking in the shale. Furthermore, in addition to the weak fissile planes in the Sevier Shale, the calcite-filled microfractures act as potential planes of weakness and have a profound effect on the physical strength of the rock mass.

The UCS of the Sevier and Rome Shale was estimated using Point Load Strength Index (Is50) and Schmidt Hammer Rebound (R) values. The Is50 value for Sevier Shale ranged from 0.9 N/mm^2 for weathered, more fissile shales to 4.67 N/mm^2 for more durable samples, with an overall average value of 2.20 N/mm^2. According to the classification scheme of Marinos, and Hoek [13], UCS values of Sevier Shale are classified in the Weak, Medium Strong, and Strong categories. The Is50 values of Rome Shale ranged from 1.60 N/mm^2 to 5.96 N/mm^2 with an average of 4.04 N/mm^2. Rome Shale is therefore classified as Medium Strong to Strong. In many instances the weak, fissile, and anisotropic shale samples failed along predefined fissile planes even when the direction of loading was perpendicular to the weakness. This may have significantly affected the Point Load test results. A simpler alternative to the Point Load test is the Schmidt Hammer test. In this study, R values, which ranged from 19 to 38 (average = 30) for Sevier Shale and 23 to 44 (average = 38) for Rome Shale, were used to estimate UCS. Although the Schmidt Hammer test is generally reported to be less dependable than the Point Load test, the Schmidt Hammer test may be a more reliable option when dealing with anisotropic weak rocks. The range in the UCS value can be explained by the presence of variable amount of clay minerals, calcite, and gypsum in the shale, which have swelling potential and a pronounced effect on the reduction of UCS. In general, the UCS of Rome Shale is higher than Sevier Shale and can be explained by the presence of more stable minerals, such as quartz and orthoclase, and the paucity of swelling minerals.

The effects of short-term and prolonged weathering on Sevier and Rome Shale were investigated using 2-cycle (Id2) to 5-cycle (Id5) Slake Durability Index results. Id2 values ranged from 90.1% to 97.8% for Sevier Shale, and from 93.4% to 98.98% for Rome Shale. Results indicate that both Sevier and Rome Shale are durable against short-term wetting and drying cycles. The 5th cycle represents longer term wetting and drying cycles, and the Sevier and Rome Shales showed dissimilar behavior. Some of the Sevier shale samples yielded to long term weathering and were classified as Moderately to Highly Weathered (Id5 = 93.45% to 95.24%). Samples with Id5 values ranging from 93.4% to 95.2% are Slightly Weathered, and Id5 values ranging from 85.7% to 89.7% are classified as Moderately Weathered. In the case of the Rome Shale, the samples were more durable than Sevier Shale with very few exceptions, and are classified in the Slightly to Moderately Weathered category. The durability variation in both Sevier and Rome Shale indicate that the presence of swelling minerals influences the degree of weathering, likely because those minerals expand on contact with water, contract in a dry environment, and therefore significantly affect the rock's durability.

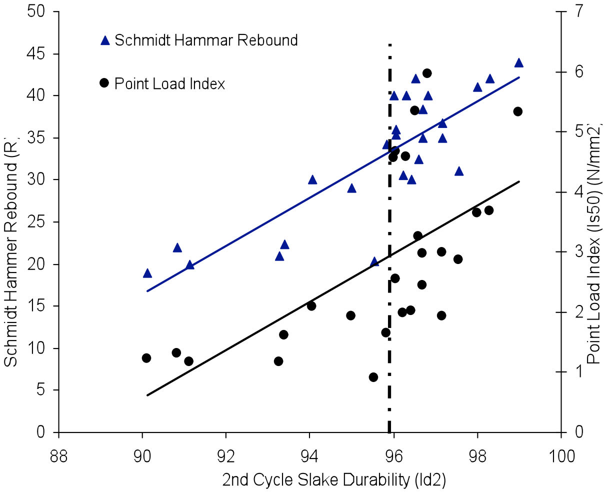

Fig. 5 Relationship between 2-cycle slake durability index with Schmidt Hammer Rebound and Point Load Index.

In order to assess the relationship between the SDI and UCS of Sevier and Rome Shale, we performed a regression analysis. The 2-cycle (Id2) and 5-cycle (Id5) slake durability tests were separately evaluated against the Is50 and R values (Figures 5 and 6). Regression

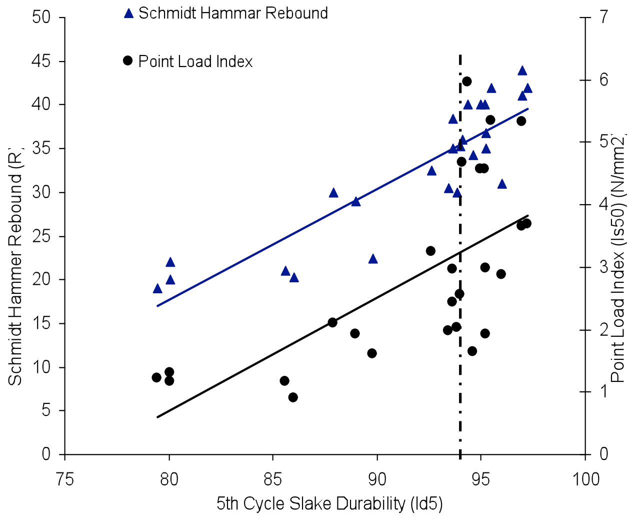

Fig. 6 Relationship between 5-cycle slake durability index with Schmidt Hammer Rebound and Point Load Index.

results indicate that both Id2 and Id5 values have a positive correlation with the UCS in terms of R value (Table 2). Is50 values show a positive correlation with the increase in SDI, but correlation is poor. SDI values above 96% for Id2 and above 94% for Id5 (those values to the right of the dotted line in Figures 5 and 6) show a wide range of UCS values correlated with a narrow range of durability. The samples to the left of this line show lesser variability, indicating that the regression equations are probably better suited for Slake Durability values less than the indicated limit.

Table 2.Regression equation and r^2 for the relationship between the Schmidt Hammer Rebound, Point Load Index and 2nd and 5th cycle slake durability index.

		Schmidt Hammer Rebound (R)	Point Load Index (Is50)
2nd cycle slake durability (Id2)	Linear Relation	R=2.86 Id2 – 241.27	Is50 = 0.40 Id2 – 35.52
	r^2	0.69	0.38
5th cycle slake durability (Id5)	Linear Relation	R = 1.27 Id5 – 83.9	Is50 = 0.18 Id5 – 13.86
	r^2	0.78	0.44

5. CONCLUSION

Weathered Ordovician-age Sevier Shale and Cambrian-age Rome Shale are widely distributed throughout eastern Tennessee and form a majority of the sedimentary sequences in the southern Appalachians. Sevier and Rome Shale samples were analyzed in the field and in laboratory in order to investigate the relationship between their mineralogy, fracture infilling, and geotechnical properties to better classify them for engineering purposes. For Sevier Shale, XRD results indicate a bulk mineralogy that consists of quartz, calcite, chlorite, illite, and mixed layer kaolinite – montmorillonite, with the possible presence of smectite in relatively weak and weathered samples. According to the SDI, Sevier Shale samples are classified as Moderately to Highly Weathered, Moderately Weathered, and Slightly Weathered. This range is due to variation in mineral content including expanding clay, calcite, and gypsum, which are prone to swelling and degradation. Based on the R and Is50 values, the UCS of Sevier Shale ranges from Weak to Medium Strong to Strong Rock. While the presence of quartz, kaolinite, and calcite cement increased the compressive strength of Sevier Shale, the presence of montmorillonite, gypsum, and calcite decreased the durability. The Rome Shale contains quartz, orthoclase feldspar, muscovite, hematite, and illite. The Rome Shale is classified as Moderately to Slightly Weathered, Medium Strong to Strong rock. The presence of more stable minerals such as quartz and orthoclase, as well as the lack of expanding clay, explains the durability and strength of the Rome Shale. In addition to mineralogy, it is also important to consider the presence and abundance of microfractures as well as the material infilling those fractures when evaluating the shale for engineering design purposes. The presence of microfractures filled with calcite in the Sevier Shale significantly affected the durability and strength of the rock mass.

This study indicates that a 5-cycle Slake Durability test better estimates the prolonged disintegration pattern of shale and can be used to classify shale in terms of the degree of weathering. Therefore, this study effectively establishes a correlation between the SDI and UCS of shale. In addition, R values correlate well with the 5-cycle Slake Durability test. The weak correlation between SDI and Id50 is due to the fact that the shale failed along predefined planes of weakness (due to fissility) and along calcite filled microfractures. Therefore, for weak rocks, the Schmidt Hammer Rebound Test seems to be a more appropriate and reliable testing method.

Finally, this study asserts that while a correlation exists between the mineralogy and the strength and durability of shale, a quantitative assessment of the overall bulk composition of the rock, cement mineralogy, and composition of microfracture infill would further strengthen this relationship. Future work will involve development of such a quantitative analysis of bulk mineralogy using EDX and microprobe analyses.

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