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Investigating statistical relationships among clay mineralogy, index engineering properties, and shear strength parameters of mudrocks

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ABSTRACT

Clay mineralogy and standard index engineering properties measured for a large and diverse set of mudrocks show high variability and clearly relate to shear strength parameters. From the best-correlated variable downward, cohesion is related to slake durability index, specific gravity, percentage of expandable clay minerals, and liquid limit, whereas friction angle is related to percentage of expandable clay minerals, absorption, percent of clay $<2\ \mu m$, and liquid limit. Using all parameters (with transformations to maximize normality) explains 50% of the total variation in cohesion and 36% of friction angle. The variability and unpredictability of shear strength parameters result from the heterogeneity of mudrocks, and the low R^2 values indicate that additional factors must be sought in order to explain and predict strength parameters at levels useful for engineering purposes.

1. Introduction

Mudrocks (fine-grained siliciclastic sedimentary rocks) are especially problematic for engineering geologists, for a multitude of reasons. They are generally weak, with low durability, low compressive and shear strengths, and high swelling potential. The shear strength parameters of cohesion ("c") and friction angle ("ϕ") are crucial properties for appropriate design of engineering structures built on or within mudrocks, but they are hard to measure, because (1) obtaining undisturbed samples of the required dimensions is quite difficult given that mudrocks are typically weak, deeply weathered, and fall apart easily, (2) mudrock samples typically deteriorate severely with transportation from the field to the lab and time elapsed between sampling and laboratory testing, (3) the tests require expensive equipment, and (4) the test procedures are time-consuming.

Worse, mudrocks are the most abundant of all sedimentary rocks, constituting about 45% to 55% of stratigraphic sequences (Blatt, 1982), so they are encountered in all types of geotechnical engineering projects. The inferior properties of mudrocks have been documented as causing problems in underground excavations such as mines and tunnels (Lee and Klym, 1978; Olivier, 1979; Chugh et al., 1981; Hasan, 1982; Madsen and Muller-Vonmoos, 1985; Hirt and Shakoor, 1992; Atkinson et al., 2003; Atkinson et al., 2004; Molinda and Oyler, 2006; Hajdarwish, 2007; Molinda and Mark, 2010), building foundations (Ola, 1982; Bérubé et al., 1986; Goodman, 1992; Bell, 1994; Greene, 2001; Hobbs et al., 2002; Morris, 2004), dams and spillways (Ramachandran et al., 1981; Zeng, 1981; U.S. Army Corps of Engineers, 1988; Greene, 2001; Qi et al., 2009), slopes(Regues et al., 1995; Shakoor, 1995; Dick and Shakoor, 1995; Sadisun, et al., 2005; Mourice, et al., 2006; Lund et al., 2011; Admassu et al., 2012), and quarry faces and highway embankments (Strohm et al., 1978; U.S. Department of Transportation, FHWA, 1980; Oakland and Lovell, 1985; Pye and Miller, 1990; Dick and Shakoor, 1992; Dounias et al., 2002).

Standard practice has been to design very conservatively when mudrocks are involved, but, if possible, an alternative solution would be to use clay mineralogy and more easily determined index engineering properties of mudrocks, measured on smaller irregular samples or broken pieces, in an attempt to make reliable predictions of their shear strength parameters. However, mudrocks are notoriously variable, so this has been problematic. Previous research on other properties of mudrocks, such as durability (Dick et al., 1994), swelling potential (Sarman, 1991; Sarman et al., 1994), and compressive strength (Greene, 2001) indicates moderate to strong relationships among some of those properties, lithologic characteristics, and index engineering properties, but results have not always been consistent between studies, and similar relationships have not yet been investigated in detail for the shear strength parameters. Olgaard et al. (1997) studied the influence of swelling clay minerals on the deformation behavior of mudrocks, and concluded that swelling clay content was inversely proportional to friction angle of the mudrocks and (surprisingly) correlated positively with cohesion. They therefore suggested that clay mineralogy may be a useful means of predicting the mechanical properties of mudrocks such as friction angle and Young's

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modulus. However, they reported on only nine samples, which is very few, particularly given the heterogeneity of mudrocks.

Therefore, the immediate objectives of our research were (1) to characterize shear strength parameters (cohesion and friction angles), clay mineralogy (clay content, clay-mineral composition), and standard index engineering properties (natural water content, Atterberg limits, specific gravity, dry density, void ratio, absorption, adsorption, and slake durability index) for a large variety of mudrocks, and (2) to explore relationships between these parameters to investigate how much of the variation in shear strength they can reasonably explain in a large and diverse data set. This paper provides analytical results for a large variety of mudrocks, shows that we can now potentially explain up to 50% of the variability in shear strength measurements from standard engineering and mineralogical parameters, and lays a foundation for the next round of work toward the ultimate goal of successfully predicting shear strength from more easily measured parameters (although that goal remains elusive, for now).

2. Research methods

2.1. Sampling

In order to characterize a large and diverse set of mudrocks, we collected 49 mudrock samples, representing 11 different states in the U.S. from Pennsylvania to Utah, 8 different geological periods from Cambrian to Eocene, and some of the major shale units in the U.S. (Table 1 and Figure 1).

Mudrock samples were collected from highway cuts, dam sites, and natural outcrops, selected on the basis of published lithologic descriptions and observations of durability behavior made during exploratory sampling trips. Maximum care was taken to ensure that the collected samples were as fresh as possible. At a few locations, fresh mudrock samples were collected from active highway and dam excavations. However, at most locations, fresh samples were manually excavated using a shovel, rock pick, crow bar, and chisels. The weathered zone that had to be removed

Table 1
Ages and locations of sampled mudrocks from across the U.S.A.

#	Unit	Age	U.S. state	Road	Location
1	Monongahela	Penn	WV	I-77S	3 miles S of Rockport exit
2	Conemaugh	Penn	OH	I-77 N	2 miles N of Dexter City exit
3	Dunkard	Perm	OH	Oh-7S	1 mile N of Loganport exit, Mile 14
4	Conemaugh	Penn	OH	Oh-7S	15 miles S of #3
5	Allegheny	Penn	PA	I-79S	1 mile N of Carnegie exit
6	Glenshaw	Penn	PA	I-79S	S of Mt Morris exit
7	Washington	Perm	PA	I-79 N	Bridgeville exit ramp
8	Pottsville	Perm	PA	I-76E	Cranberry exit @ PA-19
9	Conemaugh	Penn	WV	I-77S	Ripley/Fairplain
10	Conemaugh	Penn	WV	I-77S	Ripley/Fairplain
11	Conemaugh	Penn	WV	I-77S	Eden Fork exit ramp
12	Monongahela	Penn	OH	Oh-22E	13 miles W of Oh-7
13	Dunkard	Perm	OH	Oh-7S	3 miles S of New Matamoras exit
14	Mowry	Cret	SD	I-90 W	1 mile N of Oacoma
15	Monongahela	Penn	OH	Oh-7S	1 mile N of Belpre exit, Marietta
16	Lewis	Cret	WY	Wy-16 W	4 miles E of Newcastle
17	Lewis	Cret	WY	Wy-85 N	Mile 239
18	Green River	Eoc	WY	I-80 W	Mile 282
19	Green River	Eoc	WY	I-80 W	Mile 216
20	Red Pine	Prot	UT	UT-191S	1 mile E of Flaming Gorge Dam
21	Green River	Eoc	UT	UT-191S	1 mile S of Duchesne
22	Straight Cliffs	Cret	UT	Ut-10S	8 miles S of Price
23	Chinle	Trias	UT	I-70 W	1 mile E of exit 147 (Lake Powell)
24	Fruitland	Cret	CO	Co-139 N	27 miles N of Loma
25	South Park	Pal	CO	Co-139S	15 N of Loma
26	Mancos	Cret	CO	I-70E	Mile 50
27	Wasatch	Eoc	CO	I-70E	Mile 156
28	Dakota	Cret	KS	Ks-159S	700 m S of I-70, gray mudstone
29	Dakota	Cret	KS	Ks-159S	700 m S of I-70, red & gray claystone
30	Chase	Perm	KS	I-70E	2 miles W of exit 307, Manhattan
31	Chanute	Penn	KS	I-435S	Holiday Drive exit, Kansas City
32	Tradewater	Penn	KY		Natcher Parkway Mile 52
33	Conemaugh	Penn	PA		Point Marion Dam, 90 river miles above Pittsburgh
34	Glenshaw	Penn	PA		Point Marion Dam, 90 river miles above Pittsburgh
35	Conemaugh	Penn	PA		Point Marion Dam, 90 river miles above Pittsburgh
36	Glenshaw	Penn	PA		Point Marion Dam, 90 river miles above Pittsburgh
37	Pierre	Cret	CO	I-70	Rooney Road, Golden
38	Lewis	Cret	UT	Ut-295	1 mile N of Joe's Valley Reservoir Dam
39	Mancos	Cret	CO	Co-325S	1 mile east of reservoir dam
40	Pierre	Cret	SD		Rapid City, SD School of Mines
41	Rome	Camb	TN	Tn-381 N	Bristol Motor Speedway
42	Milboro	Dev	VA	Va-11 N	2 miles N of Radford
43	Brallier	Dev	VA	Va-100 W	1 mile from Va-822
44	Allegheny	Penn	WV	I-77 N	1 mile N of Camp Creek exit
45	Catskill	Dev	PA	Pa-872	Austin Dam, Potter County
TS1	Kope	Ord	OH	I-74	0.5 miles E of I-75, Cincinnati
TS2	Kope	Ord	OH	I-74E	0.25 miles E of I-75, Cincinnati
TS3	Conemaugh	Penn	PA		Strip mine off Curry Hollow Road, Pittsburgh
TS4	Olentangy	Dev	OH	I-270S	3 miles W of I-71, Columbus

Abbreviations for states: CO = Colorado, KS = Kansas, KY = Kentucky, OH = Ohio, PA = Pennsylvania, SD = South Dakota, TN = Tennessee, UT = Utah, VA = Virginia, WV = West Virginia, WY = Wyoming. Note: 1 mile = 1.6 km.