partment of the Interior. The views and conclusions presented are ours and should not be interpreted as necessarily representing the official policies or recommendations of the Bureau of Mines or the U.S Department of the Interior. Finally, we appreciate the support of D'Appolonia Consulting Engineers, Inc., in the preparation of this paper.

## REFERENCES

1. American Geological Institute. Dictionary of Geological Terms. Anchor Press, Doubleday and Co. Inc., Garden City, NY, 1962, 545 pp.
2. A.F.S. Nettleton. An Investigation into a Physico-Chemical Aspect of the Slake Durability Weathering Test. Univ. of New South Wales, Kensington, New South Wales, Australia, UNICIV Rept. R-128, 1974, 3 pp.
3. N.R. Morgenstern and K.D. Eigenbrod. Classification of Argillaceous Soils and Rock. Journal of Geotechnical Engineering Division, ASCE, Vol. 100, No. GT10, 1974, pp. 1137-1156.
4. D.E. Andrews, J.L. Withiam, E.F. Perry, and H.L. Crouse. Environmental Effects of Slaking of Surface Mine Spoils: Eastern and Central United States. Bureau of Mines, U.S. Department of Interior, Denver, CO, Final Rept., 1980, 247 pp.
5. J.H. Shamberger, D.M. Patrick, and R.J. Lutton. Design and Construction of Compacted Shale Embankments: Volume 1--Survey of Problem Areas and Current Practices. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Rept. FHWA-RD-75-61, Interim Rept., 1975, 288 pp.

*Publication of this paper sponsored by Committee on Engineering Geology.*

---

# Statistical Analysis of Shale Durability Factors

**PETER P. HUDEC**

**The results of a study performed to develop durability tests for shales for use in embankments and swamp fills are presented. Forty-three shale samples, representing all exposed shale units in Ontario, were collected. The samples were subjected to a variety of tests, some standard soundness tests, some recently developed shale durability tests, and some special tests devised by the author. The tests included freeze-thaw durability, Franklin slake test, wet-dry deterioration, modified "rate of slaking", water adsorption at controlled humidities, water absorption, abrasion, and dry bulk density. The results of the tests were statistically analyzed. The principal analytic method was multivariate stepwise regression analysis, but other statistics were also obtained. The stepwise regression analysis picks the testing procedures that have the greatest influence on the desired property and produces a multitest equation that can be used to determine that property. A series of seemingly unrelated tests can thus be used to determine the durability of shales. For instance, wet-dry deterioration is related to and can be calculated from water absorption, freeze-thaw, and abrasion results. The results obtained apply to the variety of shales found in southwestern Ontario. A larger data base may be necessary to extend the conclusions to all shales as a group.**

Shale as a construction material has always been shunned. Its tendency to "slake", or turn to mud, is too well known in the construction industry. However, not all shale slakes equally, and some shale is rocklike--i.e., very little affected by weathering. Shale exists in many different forms, ranging from soft mudstone to indurated hard slate. The behavior of shale cannot be predicted from its composition, since the main constituent of any shale is clay. The amount of clay, the degree of natural compaction, cementation, and organic content all have a bearing on the physical properties of shale.

The purpose of the research described in this paper, supported by the Ontario Ministry of Transportation and Communications, was to develop durability tests for shale material and to classify Ontario shales as to their durability. Ontario shales are no less varied than shales found elsewhere. Some are highly susceptible to weathering, whereas others are rocklike in all aspects. All varieties of exposed shale across the province were collected--some from brick quarries, some from fresh road cuts, some from weathered road cuts. Although shales from weathered road cuts are not as desirable, they were included because no other examples of shales in that locality were available. The 43 different samples obtained represented all formational shale units found in the province. The formational units sampled and the number of samples representing the unit are given below. The total number of samples permits statistical treatment of data, which is the main purpose of this paper.

| Shale Unit | No. of Samples |
|---|---|
| Upper Devonian, Kettle Point (black shale) | 1 |
| Middle Devonian, Hamilton Group (grey shale) | 4 |
| Mid-Low Silurian | |
| Clinton-Cataract Group | 7 |
| Decew dolomite | |
| Cabbot Head shale | |
| Rochester shale | |
| Billings shale | |
| Upper Ordovician | |
| Queenston formation (red shale) | 10 |
| Georgian Bay formation | 11 |
| Dundas shale | |
| Blue Mountain shale | |
| Meaford shale | |
| Whitby formation | 3 |
| Precambrian (shale and slate) | 7 |
| Rowe formation | |
| Gunflint formation | |
| Sibley shale | |

## CAUSES OF SHALE DETERIORATION

Shale and water interaction, with or without attendant freezing, can be considered as the main cause of shale deterioration. The actual processes involved in the breakdown are still not fully understood; however, it is known that shale-water interaction causes expansion of the shale. This expansion may be due to a number of factors: (a) "structuring" of water on clay surfaces, (b) osmotic pressure, and (c) frost action.

The structuring of water in clay-water mixtures causes the well-known thixotropic effect, in which the viscosity of the water increases as the water becomes oriented and more structured as the clay surface is approached. Shales have a high internal surface area, which is measured in terms of square meters per gram. Water molecules adsorbed by these surfaces tend to completely fill the internal pores. Some believe that the adsorbed water may become strongly structured under the influence of the surface and may increase in specific volume. Volume expansion of water in turn causes volume expansion of the rock.

Expansion may be due to osmotic pressures generated within the rock. The pore size of shale is extremely small, less than 1 µm in diameter. Water in such pores has a lower vapor pressure over it than does bulk water. Water, therefore, is impelled to enter the rock, which creates pressure within the pore and causes the pore and the rock to expand. This mechanism differs from the one above only in the method of expansion; both rely on surface-held water to initiate the force.

Saturating the clay with water causes the clay to expand. Conversely, drying the clay causes it to contract as the capillaries filled with water get progressively smaller and exert increasingly higher tensional stress on the pore walls. Alternate wetting and drying of some shales (and some argillaceous rocks) causes their disintegration.

Freezing and thawing can be considered principally a wetting and drying process, since very little contained water in the small shale pores actually freezes. However, cooling the pore water to below freezing temperatures does significantly lower its vapor pressure, possibly below the vapor pressure of ice at equivalent temperature, and causes water vapor transfer from water in larger pores, ice, or bulk water to the smaller pores, setting up expansion. Expansion of cement gel under slow cooling conditions (without any or only minor freezing) has been observed. Cement gel as a system is analogous to a clay-shale system.

Based on the above, it is evident that cyclic wetting and drying of shale or freezing and thawing will result in cyclic application of tensional and compressional stress between pore walls and between clay particles. As the shale forms, the clay particles are often simply pressed together and dewatered by the weight of the overlying sedimentary column. The removal of the confining pressure and immersion in water result in the complete disintegration of the shale particles to the original mud.

The presence of cement containing $CaCO_3$, $SiO_2$, and various hydrous iron compounds tends to prevent the particle dispersal on unloading. However, in some shales, the tensional stress of water-clay interaction is great enough to overcome the tensional strength of such cement, and the shale disintegrates.

Shales subject to metamorphism are often indurated and recemented and tend to be quite resistant to water-induced stresses. However, such shale, because of extreme alignment of clay particles or their metamorphic equivalents, exhibits pronounced parallel and subparallel cleaving. Such material is no longer shale but slate.

## SELECTION AND DESCRIPTION OF TESTS

Based on the above considerations, any test that accurately measures the disintegration of shale due to cyclic wetting and drying (and freezing and thawing) or a test that measures the amount of the tightly held surface, pore, and capillary water will, therefore, be a direct indicator of the durability of the shale. Statistical evaluation will show the relation between tests and the contribution of each test to the overall durability of the rock.

The following tests were carried out in this research:

1. Franklin slake,
2. Rate of slaking,
3. Wet-dry deterioration,
4. Water adsorption (at 45 and 95 percent relative humidity),
5. Abrasion,
6. Density, and
7. Freezing and thawing resistance.

A very brief description of each of these tests is given below. In all tests, the sample was crushed to -19-mm, +9.5-mm fragments. In the Franklin slake test and the wet-dry deterioration test, a five-cycle sequence was performed and losses were determined at the end of each cycle. One-, three-, or five-cycle results were used in later statistical analyses.

### Franklin Slake Test

The Franklin slake test was first described by Chandra (1) and Franklin and Chandra (2) and was adopted by the Commission of Standardization of Laboratory and Field Tests of the International Society of Rock Mechanics.

The test uses a steel mesh drum with 2-mm-diameter openings. The sample is placed in the drum, and the drum is rotated while submerged in water for 10 min and 200 revolutions. The slaking products fall through the mesh and the remainder is removed, dried, and weighed to determine the lost mass.

### Wet-Dry Deterioration Test

The process of wetting and drying is the most commonly observed cause of deterioration of shales. The simplest way to determine the resistance of shale to wetting and drying is to do just that--alternately wet and dry the shale for a given number of cycles. In this case, 500 g of crushed and sized sample was placed in mason jars, saturated for 8 h, decanted, and dried for 16 h at 65°C. Drying at 110°C was avoided to prevent possible alteration of the clay structure. Loss was determined on the 9.5-mm sieve.

### Rate of Slaking

The rate of slaking test, first developed by Morgenstern and Eigenbrod (3), consists of saturating the sample contained in a funnel with a filter paper. The water absorbed by the shale (after free water has filtered through the paper) is determined. The second part of the test consists of determining the Atterberg limits on the slaked portion and the crushed and sieved unslaked portion of the sample. Only the first part of the test--i.e., the absorption--was done. The test, whether in its original or modified form, is misnamed, since no time measurement is involved. It is simply an absorption test.

### Adsorption at 45 and 95 Percent Relative Humidity

Shales rapidly adsorb water on their internal surfaces when exposed to moisture in the air. The adsorbed water fills the very small pores and partially fills the larger capillaries. Expansion of the shale due to adsorbed water alone has been noted. Thus, a test designed to measure the amount of adsorbed water will indicate the proportion of fine pores in the shale. The two humidities used give some indication of pore-size distribution. The adsorption test does not directly indicate the size

Table 1. Test results.

| Sample No. | FRZTHW12 (%) | FRZTHW25 (%) | SLAKE1 (%) | SLAKE3 (%) | WETDRY1 (%) | WETDRY3 (%) | SLAKEADS (%) | ADSGLYC (%) | ADSSULF (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 31.58 | 64.36 | 0.62 | 1.70 | 0.00 | 1.31 | 3.12 | 0.34 | 0.45 |
| 2 | 36.16 | 69.77 | 0.55 | 1.28 | 0.00 | 0.18 | 2.97 | 0.26 | 0.31 |
| 3 | 36.18 | 73.63 | 0.68 | 1.35 | 0.04 | 0.42 | 1.88 | 0.23 | 0.34 |
| 4 | 89.89 | 98.47 | 8.04 | 40.53 | 16.89 | 67.80 | 8.04 | 0.50 | 0.63 |
| 5 | 49.04 | 74.95 | 0.91 | 4.47 | 1.18 | 4.62 | 2.63 | 0.25 | 0.38 |
| 6 | 97.54 | 99.32 | 16.31 | 57.73 | 22.83 | 84.41 | 9.21 | 0.48 | 0.70 |
| 7 | 99.33 | 100.00 | 43.04 | 84.99 | 31.24 | 81.95 | 10.82 | 0.78 | |
| 8 | 38.67 | 75.04 | 0.80 | 1.89 | 0.00 | 0.62 | 3.09 | 0.31 | 0.41 |
| 9 | 56.23 | 79.76 | 0.96 | 2.52 | 0.00 | 0.79 | 3.13 | 0.38 | 0.43 |
| 10 | 98.09 | 100.00 | 35.95 | 78.18 | 43.47 | 81.37 | 9.63 | 0.62 | 0.95 |
| 11 | 96.44 | 99.90 | 28.78 | 82.63 | 38.48 | 80.54 | 10.72 | 0.69 | 0.91 |
| 12 | 34.05 | 62.72 | 1.43 | 3.45 | 0.00 | 1.15 | 4.48 | 0.24 | 0.37 |
| 13 | 31.95 | 66.67 | 0.86 | 1.84 | 0.01 | 3.26 | 3.24 | 0.32 | 0.45 |
| 14 | 46.00 | 90.67 | 1.05 | 2.40 | 0.07 | 4.21 | 3.30 | 0.32 | 0.46 |
| 15 | 29.19 | 64.57 | 0.89 | 2.19 | 0.00 | 0.80 | 2.88 | 0.32 | 0.42 |
| 16 | 3.82 | 9.14 | 0.22 | 0.60 | 0.00 | 0.96 | 1.63 | 0.14 | 0.09 |
| 17 | 99.45 | 100.00 | 62.82 | 93.72 | 82.50 | 93.38 | 25.55 | 0.33 | |
| 18 | 96.72 | 100.00 | 47.03 | 94.91 | 89.92 | 100.00 | 23.18 | 0.36 | 0.74 |
| 19 | 100.00 | 100.00 | 71.74 | 99.06 | 98.04 | 100.00 | 23.31 | | |
| 20 | 1.78 | 2.31 | 0.24 | 0.57 | 0.00 | 0.00 | 1.66 | 0.09 | 0.14 |
| 21 | 96.16 | 100.00 | 54.08 | 89.13 | 82.41 | 95.32 | 20.66 | 0.68 | 0.58 |
| 22 | 92.06 | 96.16 | 57.65 | 63.11 | 63.39 | 68.77 | 17.20 | 0.13 | 0.21 |
| 23 | 97.76 | 99.30 | 68.30 | 85.21 | 71.80 | 83.33 | 25.97 | 0.37 | 0.52 |
| 24 | 91.43 | 97.06 | 39.91 | 59.73 | 35.53 | 50.11 | 20.27 | 0.32 | 0.67 |
| 25 | 68.91 | 81.77 | 8.23 | 17.50 | 2.65 | 6.61 | 5.44 | 0.19 | 0.28 |
| 26 | 34.29 | 54.64 | 0.83 | 1.97 | 0.03 | 0.23 | 2.09 | 0.13 | 0.21 |
| 27 | 100.00 | 100.00 | 81.76 | 97.36 | 98.98 | 100.00 | 37.72 | | |
| 28 | 100.00 | 100.00 | 81.30 | 99.76 | 100.00 | 100.00 | 36.02 | | |
| 29 | 48.73 | 87.12 | 1.08 | 2.70 | 0.03 | 0.32 | 3.33 | 0.32 | 0.47 |
| 30 | 100.00 | 100.00 | 89.04 | 100.00 | 100.00 | 100.00 | 32.28 | | |
| 31 | 18.17 | 37.29 | 0.56 | 1.59 | 0.00 | 0.30 | 3.74 | 0.59 | 0.85 |
| 32 | 85.64 | 96.38 | 4.15 | 21.39 | 11.20 | 54.49 | 6.60 | 0.77 | 1.27 |
| 33 | 97.51 | 100.00 | 3.14 | 9.32 | 1.15 | 9.91 | 3.09 | 0.77 | 0.96 |
| 34 | 96.85 | 100.00 | 5.86 | 17.34 | 7.28 | 18.73 | 4.06 | 0.83 | 0.92 |
| 35 | 86.18 | 98.82 | 2.43 | 18.18 | 3.60 | 32.14 | 5.09 | 0.63 | 1.03 |
| 36 | 62.89 | 94.07 | 1.28 | 4.16 | 1.70 | 5.58 | 4.37 | 0.81 | 1.11 |
| 37 | 22.66 | 40.92 | 0.31 | 0.56 | 0.00 | 0.11 | 5.01 | 0.67 | 0.92 |
| 38 | 24.66 | 59.08 | 0.18 | 0.65 | 0.00 | 0.18 | 2.77 | 0.93 | 1.04 |
| 39 | 19.26 | 65.32 | 0.16 | 0.34 | 0.00 | 0.25 | 3.54 | 1.30 | 1.50 |
| 40 | 40.06 | 85.97 | 0.31 | 0.69 | 0.00 | 0.11 | 1.39 | 0.36 | 0.45 |
| 41 | 47.06 | 88.69 | 0.55 | 2.32 | 0.00 | 1.46 | 2.43 | 0.47 | 0.55 |
| 42 | 11.37 | 21.21 | 0.01 | 0.17 | 0.00 | 0.00 | 2.27 | 0.82 | 1.00 |
| 43 | 22.86 | 52.28 | 0.63 | 1.34 | 0.00 | 0.00 | 2.39 | 0.51 | 0.60 |

of pores as does mercury intrusion porosimetry; it does, however, differentiate between pores of less and greater diameter than approximately 5 µm.

The test consists of placing a dry shale (dried for 24 h at 65°C and cooled over a dessicant) into a chamber where humidity is maintained at desired level. The humidity is controlled by saturated salt solutions. After 72 h, near equilibrium is established; that is, the sample has adsorbed almost all the moisture it can hold at that humidity. The weight gain is the measure of adsorbed water.

### Abrasion

The strength of the natural cement holding the clay particles determines, in part, how well the shale is able to withstand the expansive forces of wetting. Any test designed to physically "pry" the particles apart will measure the relative strength and amount of the cement. Abrasion can be considered as prying apart surface particles from the body of the rock. To simulate abrasion, the Franklin slaking machine was used. The dry shale sample, along with five steel balls of 19-mm diameter, was rotated at 20 rpm for 400 revolutions. Loss of weight was a measure of abrasion. Although the test is similar to the Los Angeles abrasion test, the intensity of abrasion is approximately one magnitude lower than in the Los Angeles abrasion test.

### Density

Since shales consist of clay particles as principal constituents and clays have similar specific gravity, the density of the sample determines the degree of compaction and/or induration with cementing materials. Because of the slaking nature of the shale, water cannot be used as a displacement medium for volume determination. A mercury displacement technique with a specially designed mercury volumeter was used.

### Freeze-Thaw Resistance

Shale is exposed to freezing and thawing in the northern latitudes and at higher altitudes. However, before freezing can do any damage the shale must be wet. Thus, a component of wetting and drying deterioration is incorporated into the freeze-thaw loss. However, freezing does contribute to the deterioration of the shale.

A freeze-thaw test designed by the author consisted of placing the sample in a mason jar, saturating it in 5 percent sodium chloride solution (to accelerate frost action) for 2 min (to minimize slaking), and draining. The jar was capped to prevent moisture loss, frozen at -20°C for 15-17 h, and thawed for 5-7 h. Loss of mass on the 9.5-mm sieve was determined after 12 and 25 cycles, respectively.

## TEST RESULTS

The following designations for tests are used throughout the paper:

FRZTHW12 = 12-cycle freeze-thaw test, loss of mass (%),

| ADSSLAKE (%) | ADS45 (%) | ADS95 (%) | ABRASION (%) | DENSITY (g/cm$^3$) |
|---|---|---|---|---|
| 0.31 | 0.37 | 1.01 | 0.36 | 2.61 |
| 0.24 | 0.31 | 0.79 | 0.32 | 2.57 |
| 0.26 | 0.29 | 0.70 | 0.39 | 2.65 |
| 0.66 | 0.84 | 1.93 | 0.53 | 2.58 |
| 0.30 | 0.43 | 1.00 | 0.36 | 2.65 |
| 0.80 | 0.92 | 2.07 | 0.53 | 2.59 |
| 1.03 | 1.07 | 2.41 | 0.83 | 2.48 |
| 0.35 | 0.36 | 0.86 | 0.37 | 2.57 |
| 0.36 | 0.38 | 0.93 | 0.39 | 2.59 |
| 0.76 | 0.94 | 2.41 | 0.55 | 2.51 |
| 0.75 | 0.94 | 2.54 | 0.67 | 2.53 |
| 0.22 | 0.25 | 0.68 | 0.71 | 2.49 |
| 0.32 | 0.31 | 0.77 | 0.44 | 2.65 |
| 0.33 | 0.35 | 0.87 | 0.45 | 2.63 |
| 0.41 | 0.35 | 0.67 | 0.36 | 2.63 |
| 0.15 | 0.22 | 0.64 | 0.42 | 2.36 |
| 0.43 | 0.93 | 2.71 | 0.62 | 2.42 |
| 0.35 | 0.94 | 2.74 | 1.23 | 2.43 |
|  | 1.00 | 3.03 | 0.72 | 2.45 |
| 0.09 | 0.14 | 0.37 | 0.34 | 2.43 |
| 0.49 | 0.97 | 3.17 | 0.77 | 2.40 |
| 0.21 | 0.61 | 1.86 | 0.91 | 2.78 |
| 0.32 | 1.33 | 3.47 | 2.73 | 2.45 |
| 0.44 | 0.07 | 1.99 | 2.04 | 2.65 |
| 0.23 | 0.44 | 1.12 | 0.83 | 2.65 |
| 0.13 | 0.14 | 0.36 | 0.43 | 2.46 |
|  | 0.71 | 1.95 | 0.63 | 2.49 |
|  | 0.74 | 2.00 | 0.75 | 2.56 |
| 0.30 | 0.33 | 0.80 | 0.77 | 2.48 |
|  | 0.81 | 1.93 | 0.71 | 2.29 |
| 0.56 | 0.00 | 1.52 | 0.36 | 2.63 |
| 1.07 | 1.16 | 1.89 | 1.31 | 2.67 |
| 0.82 | 0.84 | 1.32 | 0.95 | 2.68 |
| 0.94 | 0.92 | 1.49 | 0.65 | 2.57 |
| 0.91 | 0.87 | 1.63 | 1.00 | 2.41 |
| 0.91 | 0.92 | 1.80 | 0.48 | 2.32 |
| 0.76 | 0.84 | 1.57 | 0.59 | 2.32 |
| 1.08 | 1.05 | 1.55 | 0.41 | 3.19 |
| 1.45 | 1.07 | 2.54 | 0.62 | 2.60 |
| 0.39 | 0.37 | 0.62 | 0.24 | 2.71 |
| 0.48 | 0.49 | 0.85 | 0.36 | 2.65 |
| 1.05 | 0.89 | 1.74 | 0.26 | 2.72 |
| 0.56 | 0.50 | 0.88 | 0.40 | 2.66 |

FRZTHW25 = 25-cycle freeze-thaw test, loss of mass (%),
SLAKE1 = 1-cycle Franklin test, loss of mass (%),
SLAKE3 = 3-cycle Franklin test, loss of mass (%),
WETDRY1 = 1-cycle wet-dry test, loss of mass (%),
WETDRY3 = 3-cycle wet-dry test, loss of mass (%),
SLAKEADS = rate of slaking absorption test, gain (%),
ADSGLYC = glycerine solution slaked, adsorption at 45 percent relative humidity (%),
ADSULF = sulphate solution slaked, adsorption at 45 percent relative humidity (%),
ADSSLAKE = water slaked, adsorption at 45 percent relative humidity, gain (%),
ADS45 = adsorption on original sample at 45 percent relative humidity, gain (%),
ADS95 = adsorption on original sample at 95 percent relative humidity, gain (%),
ABRASION = dry abrasion in Franklin slaking machine (%), and
DENSITY = mercury immersion density (g/cm³).

The test results are given in Table 1.

## STATISTICAL ANALYSIS

The results obtained were analyzed by using both simple and multivariate statistical techniques. The purpose of the statistical analysis was to establish relations between tests and, through multivariate statistics, to determine the factors that affect the durability of shales. The summary statistics for the tests are given in the table below. The mean obtained is not particularly instructive, and the standard deviation simply implies the range or dispersal of the results about the mean.

| Variable | N | Mean | Standard Deviation |
|---|---|---|---|
| FRZTHW12 | 43 | 61.3 | 33.7 |
| FRZTHW25 | 43 | 78.8 | 26.1 |
| SLAKE1 | 43 | 19.2 | 28.3 |
| SLAKE3 | 43 | 31.4 | 39.1 |
| WETDRY1 | 43 | 23.4 | 35.7 |
| WETDRY3 | 43 | 33.4 | 40.9 |
| SLAKEADS | 43 | 9.4 | 10.2 |
| ADSGLYC | 39 | 0.5 | 0.3 |
| ADSSULF | 37 | 0.6 | 0.3 |
| ADSSLAKE | 39 | 0.5 | 0.3 |
| ADS45 | 43 | 0.6 | 0.3 |
| ADS95 | 43 | 1.6 | 0.8 |
| ABRASION | 43 | 0.7 | 0.5 |
| DENSITY | 43 | 2.6 | 0.2 |

### Correlation Matrix

The "best-seven" correlation matrix for the tests is given in Table 2. Each test is taken in turn as a dependent variable, and the seven other tests with the best correlation are ranked against it. The confidence level number is given as a ratio and should be multiplied by 100 to give percentage confidence limits. Thus, 0.0001 indicates that 0.01 percent or less of the variation is unexplained.

In Figures 1-9, some of the tests that showed high correlation are graphed to show the nature of the relation between tests. The equation of the line of best fit through the points was calculated and used to derive classification limits for each test. The equations are given in Table 3. The classification is somewhat arbitrary, in that more or less arbitrary limits were established for the five-cycle Franklin slake test, and these limits then were substituted into the equations to obtain equivalent limits for the other tests. The Franklin test limits are given in Table 4 and the derived limits in Table 5. The tests given in Table 5 are arranged in order of reliability or applicability. The Franklin and wet-dry tests, however, are roughly equivalent in results and reliability and can readily substitute for each other.

### Multivariate Statistics

The bivariate relation between tests described in the previous section can compare the relations between the two tests involved. However, the shale, like any material, has an inherent set of properties that respond somewhat differently to each test. Or to put it in another way, each test emphasizes a different property, or a mix of different properties, of the shale. To determine the interrelation of the tests, a multivariate statistical approach was used. The best stepwise regression technique was chosen (since this method involves choosing a dependent variable property of a test), against which other tests are compared. The test with the greatest correlation is chosen first. Other tests are chosen that, in turn, improve the correlation or the "model". In this stepwise fashion, an equation is developed that relates the tests to each other and to the dependent variable.

Two methods of stepwise regression were used. In one, all the tests were compared with the selected dependent variable. In the second, the closely related tests were excluded to better evaluate the contribution of nonrelated tests to the model. The

Table 2. Correlation matrix.

| Test | Item | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|---|
| FRZTHW12 | Test | FRZTHW25 | WETDRY3 | SLAKE3 | SLAKE1 | WETDRY1 | ADS95 | SLAKEADS |
| | Correlation coefficient | 0.889 | 0.851 | 0.826 | 0.722 | 0.720 | 0.698 | 0.697 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| FRZTHW25 | Test | FRZTHW12 | WETDRY3 | SLAKE3 | ADS95 | SLAKE1 | WETDRY1 | SLAKEADS |
| | Correlation coefficient | 0.889 | 0.645 | 0.619 | 0.541 | 0.531 | 0.531 | 0.520 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0002 | 0.0002 | 0.0002 | 0.0004 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| SLAKE1 | Test | WETDRY1 | SLAKEADS | SLAKE3 | WETDRY3 | FRZTHW12 | ADS95 | FRZTHW25 |
| | Correlation coefficient | 0.976 | 0.969 | 0.942 | 0.894 | 0.722 | 0.701 | 0.531 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0002 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| SLAKE3 | Test | WETDRY3 | WETDRY1 | SLAKE1 | SLAKEADS | FRZTHW12 | ADS95 | FRZTHW25 |
| | Correlation coefficient | 0.979 | 0.946 | 0.942 | 0.903 | 0.826 | 0.802 | 0.619 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| WETDRY1 | Test | SLAKE1 | SLAKEADS | SLAKE3 | WETDRY3 | ADS95 | FRZTHW12 | FRZTHW25 |
| | Correlation coefficient | 0.976 | 0.963 | 0.946 | 0.915 | 0.729 | 0.720 | 0.531 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0002 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| WETDRY3 | Test | SLAKE3 | WETDRY1 | SLAKE1 | SLAKEADS | FRZTHW12 | ADS95 | FRZTHW25 |
| | Correlation coefficient | 0.979 | 0.915 | 0.894 | 0.866 | 0.851 | 0.810 | 0.645 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| SLAKEADS | Test | SLAKE1 | WETDRY1 | SLAKE3 | WETDRY3 | FRZTHW12 | ADS95 | FRZTHW25 |
| | Correlation coefficient | 0.969 | 0.963 | 0.903 | 0.866 | 0.697 | 0.670 | 0.520 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0004 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| ADSGLYC | Test | ADSSLAKE | ADSSULF | ADS45 | ADS95 | SAMPNO | FRZTHW25 | DENSITY |
| | Correlation coefficient | 0.958 | 0.940 | 0.687 | 0.493 | 0.481 | 0.176 | 0.153 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0014 | 0.0019 | 0.2829 | 0.3509 |
| | No. of samples | 39 | 37 | 39 | 39 | 39 | 39 | 39 |
| ADSSULF | Test | ADSSLAKE | ADSGLYC | ADS45 | ADS95 | SAMPNO | FRZTHW25 | FRZTHW12 |
| | Correlation coefficient | 0.953 | 0.940 | 0.696 | 0.555 | 0.504 | 0.259 | 0.250 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0004 | 0.0015 | 0.1222 | 0.1352 |
| | No. of samples | 37 | 37 | 37 | 37 | 37 | 37 | 37 |
| ADSSLAKE | Test | ADSGLYC | ADSSULF | ADS45 | ADS95 | SAMPNO | FRZTHW12 | FRZTHW25 |
| | Correlation coefficient | 0.958 | 0.953 | 0.706 | 0.469 | 0.440 | 0.205 | 0.199 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0026 | 0.0050 | 0.2106 | 0.2240 |
| | No. of samples | 39 | 37 | 39 | 39 | 39 | 39 | 39 |
| ADS45 | Test | ADS95 | ADSSLAKE | ADSSULF | ADSGLYC | WETDRY3 | FRZTHW12 | SLAKE3 |
| | Correlation coefficient | 0.797 | 0.706 | 0.696 | 0.687 | 0.588 | 0.583 | 0.530 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0003 |
| | No. of samples | 43 | 39 | 37 | 39 | 43 | 43 | 43 |
| ADS95 | Test | WETDRY3 | SLAKE3 | ADS45 | WETDRY1 | SLAKE1 | FRZTHW12 | SLAKEADS |
| | Correlation coefficient | 0.810 | 0.802 | 0.797 | 0.729 | 0.701 | 0.698 | 0.670 |
| | Confidence limit | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0001 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| ABRASION | Test | ADS95 | FRZTHW12 | SLAKEADS | SLAKE3 | SLAKE1 | WETDRY3 | FRZTHW25 |
| | Correlation coefficient | 0.557 | 0.528 | 0.477 | 0.462 | 0.456 | 0.449 | 0.423 |
| | Confidence limit | 0.0001 | 0.0003 | 0.0012 | 0.0018 | 0.0021 | 0.0025 | 0.0047 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |
| DENSITY | Test | WETDRY1 | SLAKE3 | SLAKEADS | WETDRY3 | SLAKE1 | ADS95 | FRZTHW12 |
| | Correlation coefficient | -0.338 | -0.337 | 0.322 | -0.322 | -0.319 | -0.227 | -0.227 |
| | Confidence limit | 0.0266 | 0.0269 | 0.0352 | 0.0355 | 0.0373 | 0.1427 | 0.1439 |
| | No. of samples | 43 | 43 | 43 | 43 | 43 | 43 | 43 |

Note: The seven test variables ranged across the table are from greatest to least correlation.

Figure 1. Slake loss versus wet-dry loss.

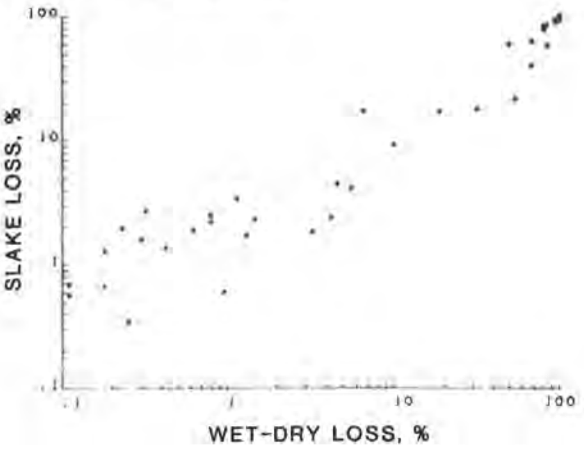
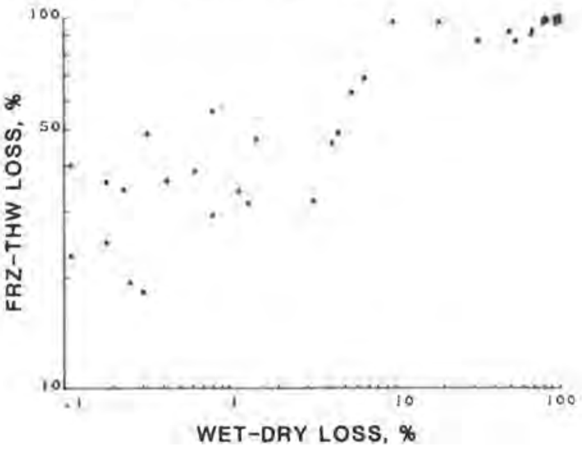


Figure 2. Freeze-thaw loss versus wet-dry loss.



results of the first are given in Table 6, the second in Table 7.

## DISCUSSION OF RESULTS

The results of statistical analysis show that the Franklin slake test and the wet-dry test give very similar results. Correlation between them is very high. Multivariate stepwise regression indicates that, for instance, results of the three-cycle Franklin slake test can be determined from one- and three-cycle wet-dry test results by the following relation:

$$\text{Franklin SLAKE1} = 1.553 + 0.486(\text{WETDRY1}) + 0.556(\text{WETDRY3}) \quad (1)$$

Figure 3. Slake loss versus absorption.

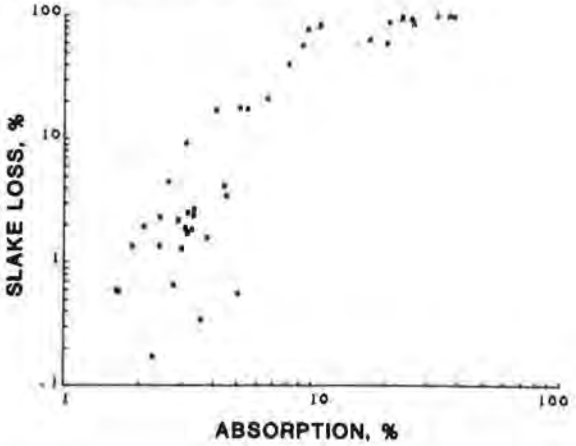


Figure 4. Freeze-thaw loss versus slake loss.

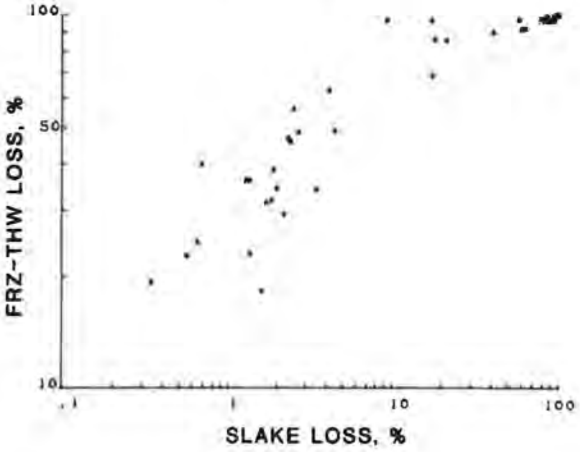


Figure 5. Adsorption at 95 percent relative humidity versus absorption.

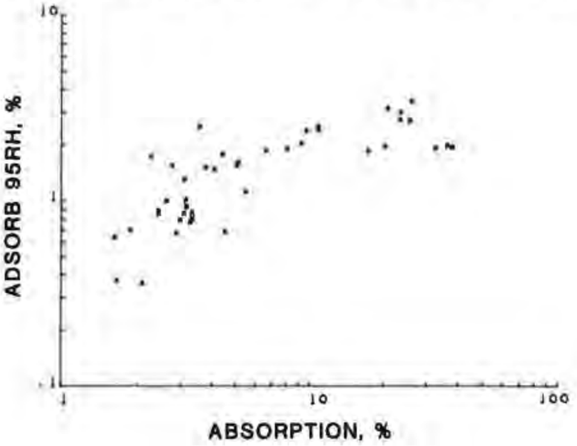


Figure 6. Adsorption at 95 percent relative humidity versus slake loss.

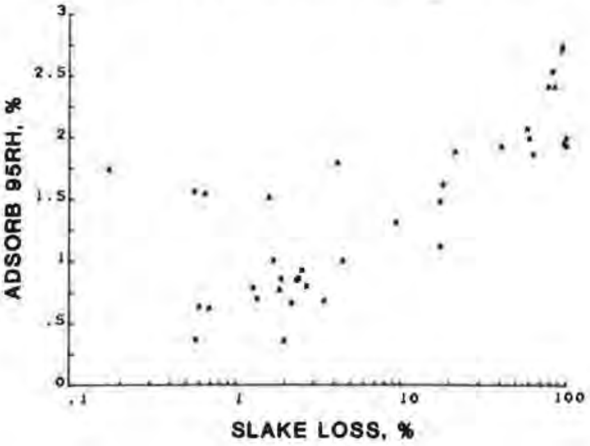


Figure 7. Freeze-thaw loss versus absorption.

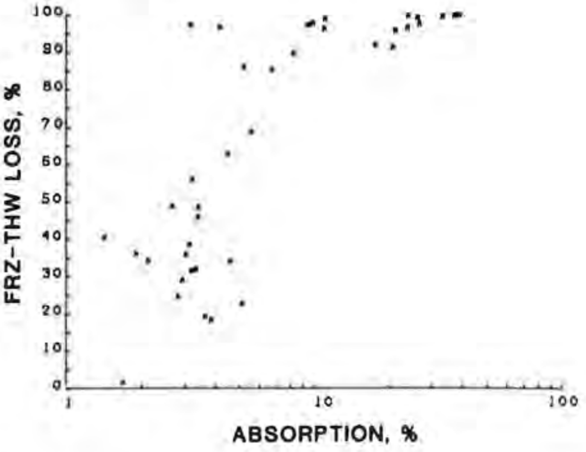
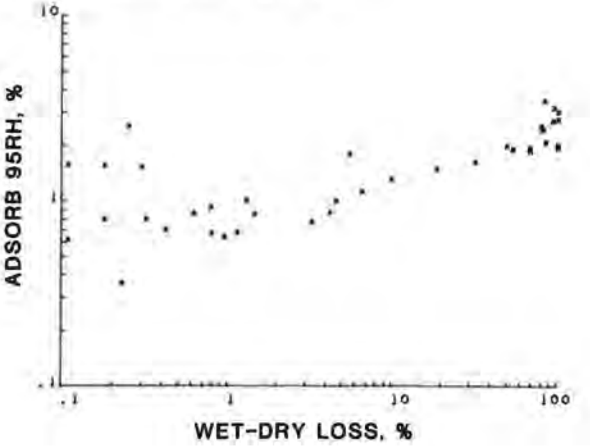


Figure 8. Adsorption versus wet-dry loss.



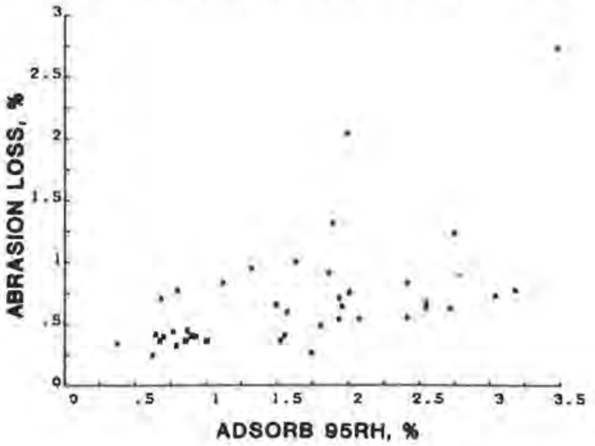
Likewise, three-cycle wet-dry results can be obtained from the Franklin slate test by

$$\text{WETDRY3} = 0.239 - 0.544(\text{SLAKE1}) + 1.375(\text{SLAKE3}) \quad (2)$$

Adsorption at 45 percent relative humidity enters both relations as a third significant variable, improving them slightly. The improvement is not significant but simply points to the importance of adsorbed water as a factor in the deterioration of shales.

Resistance to freezing and thawing is related to the results of many tests (as in the case of the 12-cycle freeze-thaw test in Table 6). The partial F's indicate that results of the WETDRY3 test have the strongest influence on freezing and thawing results. Abrasion and water absorption are also important but less significant. SLAKE3 results show a marginal effect on the relation.

Figure 9. Abrasion loss versus adsorption at 95 percent relative humidity.



When the strongly related tests are excluded from the analysis (Table 7), it is possible to determine the relations of other tests to Franklin slake and wet-dry tests. As can be expected, the above two tests are influenced by much the same tests and in much the same order of importance. What is different, however, is the degree of influence exhibited by the independent variables. The Franklin SLAKE3 test, for instance, is strongly related to water absorption of shale and less so to FRZTHW12 and ABRASION results. The WETDRY3 test shows proportionately less dependence on water absorption and more on FRZTHW12 and ABRASION properties.

## CONCLUSIONS

The results of statistical analysis have indicated that some of the tests used to measure shale durability are strongly interrelated. The following can be concluded:

1. Wetting and drying degradation can be equally well tested by simple alternate wetting or drying or by the more sophisticated Franklin slake test.
2. Wetting and drying deterioration is influenced by the ability of the shale to absorb water and, to a lesser degree, by its freeze-thaw and abrasion resistance.
3. Freezing and thawing resistance is strongly related to wetting and drying resistance and, to a lesser degree, to abrasion resistance and absorption.
4. The relations are valid for the shale group studied. A wider sampling and a larger sample base are required to derive similar relations for shales as a group.

Table 3. Linear regression equations for Figures 1-9.

| Figure | Dependent Variable (Y) | | Slope (M) | | Independent Variable (X) | | Intercept (on Y) | R |
|---|---|---|---|---|---|---|---|---|
| 1 | Slake loss | = | 0.91 | x | Wet-dry loss | - | 0.40 | 0.967 |
| 2 | Freeze-thaw loss | = | 13.16 | x | ln (wet-dry loss) | + | 34.20 | 0.915 |
| 3 | Slake loss | = | 34.7 | x | Absorption | + | 34.2 | 0.914 |
| 4 | Freeze-thaw loss | = | 17.6 | x | ln (slake loss) | + | 20.7 | 0.850 |
| 5 | Adsorb 95RH[a] | = | 0.7 | x | Absorption | + | 0.33 | 0.850 |
| 6 | Adsorb 95RH[a] | = | 0.016 | x | Wet-dry loss | + | 0.97 | 0.809 |
| 7 | Freeze-thaw loss | = | 28.2 | x | Absorption | + | 11.58 | 0.803 |
| 8 | Adsorb 95RH[a] | = | 0.31 | x | Slake loss | + | 0.84 | 0.706 |
| 9 | Abrasion | = | 0.32 | x | Adsorb 95RH[a] | + | 0.17 | 0.560 |

[a] Adsorption at 95 percent relative humidity.

Table 4. Durability classification: five-cycle slaking loss, +13-mm sample size.

| Classification | No. of Samples | Loss Limit (%) | Nature of Loss |
|---|---|---|---|
| Rocklike | 20 | 0-5 | No discernible effect |
| Low loss | 6 | 5-25 | Minor spalling along bedding planes |
| Intermediate loss | 3 | 25-60 | Spalling and disintegration |
| High loss | 14 | 60-100 | Disintegration into mudlike consistency |

Table 5. Durability limits of shales.

| Test | Rocklike | Low Loss | Intermediate Loss | High Loss |
|---|---|---|---|---|
| Slaking loss (%) | 0-5 | 5-25 | 25-60 | 60-100 |
| Wet-dry deterioration (%) | 0-6 | 6-28 | 28-66 | 66-100 |
| Rate of slaking, $H_2O$ absorbed (%) | 0-2.6 | 2.6-4.7 | 4.7-12.9 | 12.9-40[a] |
| Freeze-thaw loss, 12 cycles (%) | 0-49 | 49-70 | 70-88 | 88-100 |
| $H_2O$ adsorption at 95 percent relative humidity, 30°C (5) | 0-1.0 | 1.0-1.4 | 1.4-2.1 | 2.1 |
| Abrasion loss | 0-0.47 | 0.47-0.72 | 0.72-1.0 | 1.0 |

[a] Extrapolated upper limit.

Table 6. Stepwise regression of all test data.

| Variable | B-Value | Significance Level | F | $R^2$ |
|---|---|---|---|---|
| Three-Cycle Slaking Conditions | | | | |
| One-variable model | | | 507.5 | 0.935 |
| Intercept | 0.594 | | | |
| WETDRY3 | 0.876 | 0.01 | 507.5 | |
| Two-variable model | | | 490.5 | 0.967 |
| Intercept | 1.553 | | | |
| WETDRY1 | 0.486 | 0.01 | 31.5 | |
| WETDRY3 | 0.556 | 0.01 | 76.1 | |
| Three-variable model | | | 334.3 | 0.968 |
| Intercept | 3.558 | | | |
| WETDRY1 | 0.469 | 0.01 | 29.2 | |
| WETDRY3 | 0.593 | 0.01 | 73.6 | |
| ADS45 | −4.395 | 20.15 | 1.7 | |
| Three-Cycle Wet-Dry Conditions[a] | | | | |
| One-variable model | | | 507.5 | 0.935 |
| Intercept | 0.865 | | | |
| SLAKE3 | 1.068 | 0.01 | 507.5 | |
| Two-variable model | | | 317.0 | 0.949 |
| Intercept | 0.239 | | | |
| SLAKE1 | -0.544 | 0.48 | 9.1 | |
| SLAKE3 | 1.375 | 0.01 | 155.5 | |
| Three-variable model | | | 240.5 | 0.956 |
| Intercept | -4.328 | | | |
| SLAKE1 | −0.477 | 0.91 | 7.6 | |
| SLAKE3 | 1.283 | 0.01 | 133.6 | |
| ADS45 | 9.635 | 2.63 | 5.4 | |
| Four-variable model | | | 194.3 | 0.960 |
| Intercept | −2.434 | | | |
| SLAKE1 | −0.549 | 0.30 | 10.3 | |
| SLAKE3 | 1.278 | 0.01 | 141.7 | |
| ADS45 | 18.741 | 0.60 | 8.7 | |
| ADSGLYC | −13.670 | 7.54 | 3.4 | |
| Twelve-Cycle Freeze-Thaw Conditions[a] | | | | |
| One-variable model | | | 68.3 | 0.661 |
| Intercept | 37.397 | | | |
| WETDRY3 | 0.760 | 0.01 | 68.3 | |
| Two-variable model | | | 37.1 | 0.685 |
| Intercept | 31.586 | | | |
| WETDRY3 | 0.633 | 0.01 | 37.9 | |
| ABRASION | 12.166 | 11.21 | 2.7 | |
| Three-variable model | | | 28.8 | 0.724 |
| Intercept | 31.118 | | | |
| WETDRY3 | 0.961 | 0.01 | 30.8 | |
| ABRASION | 27.637 | 1.02 | 7.4 | |
| SLAKEADS | −2.616 | 4.03 | 4.6 | |
| Four-variable model | | | 21.9 | 0.732 |
| Intercept | 31.990 | | | |
| WETDRY3 | 0.658 | 0.01 | 23.5 | |
| ABRASION | 30.795 | 0.67 | 8.4 | |
| SLAKEADS | −3.629 | 2.94 | 5.2 | |
| SLAKE3 | 0.504 | 32.60 | 1.0 | |

Note: Addition of more variables does not improve the model significantly.
[a] All variables allowed.

Table 7. Stepwise regression of selected data.

| Variable | B-Value | Significance Level | F | $R^2$ |
|---|---|---|---|---|
| Three-Cycle Wet-Dry Conditions[a] | | | | |
| One-variable model | | | 91.2 | 0.723 |
| Intercept | −5.428 | | | |
| SLAKEADS | 4.487 | 0.01 | 91.2 | |
| Two-variable model | | | 80.9 | 0.826 |
| Intercept | −21.200 | | | |
| SLAKEADS | 2.919 | 0.01 | 32.3 | |
| FRZTHW12 | 0.468 | 0.01 | 20.3 | |
| Three-variable model | | | 76.2 | 0.874 |
| Intercept | −15.467 | | | |
| SLAKEADS | 4.262 | 0.01 | 53.1 | |
| FRZTHW12 | 0.502 | 0.01 | 30.8 | |
| ABRASION | −24.403 | 0.13 | 12.5 | |
| Four-variable model | | | 67.3 | 0.894 |
| Intercept | -1.698 | | | |
| SLAKEADS | 3.959 | 0.01 | 50.1 | |
| FRZTHW12 | 0.834 | 0.01 | 27.2 | |
| ABRASION | −24.400 | 0.06 | 14.3 | |
| FRZTHW25 | −0.400 | 2.04 | 5.9 | |
| Five-variable model | | | 62.4 | 0.910 |
| Intercept | −6.240 | | | |
| SLAKEADS | 3.943 | 0.01 | 56.7 | |
| FRZTHW12 | 0.743 | 0.01 | 23.1 | |
| ABRASION | −25.085 | 0.02 | 17.2 | |
| FRZTHW25 | −0.382 | 1.83 | 6.2 | |
| ADS45 | 14.715 | 2.59 | 5.5 | |
| Three-Cycle Slaking Conditions[b] | | | | |
| One-variable model | | | 163.3 | 0.823 |
| Intercept | −6.763 | | | |
| SLAKEADS | 4.338 | 0.01 | 163.2 | |
| Two-variable model | | | 120.8 | 0.877 |
| Intercept | −17.000 | | | |
| SLAKEADS | 3.320 | 0.01 | 71.8 | |
| FRZTHW12 | 0.303 | 0.05 | 14.7 | |
| Three-variable model | | | 127.4 | 0.921 |
| Intercept | −12.017 | | | |
| SLAKEADS | 4.488 | 0.01 | 113.9 | |
| FRZTHW12 | 0.333 | 0.01 | 26.2 | |
| ABRASION | −21.209 | 0.02 | 18.2 | |
| Four-variable model | | | 112.6 | 0.934 |
| Intercept | −1.860 | | | |
| SLAKEADS | 4.264 | 0.01 | 113.6 | |
| FRZTHW12 | 0.578 | 0.01 | 25.5 | |
| ABRASION | −21.199 | 0.01 | 21.1 | |
| FRZTHW25 | −0.295 | 1.71 | 6.3 | |

Note: Addition of more variables does improve the model significantly.
[a] WETDRY1, SLAKE1, SLAKE3 excluded.
[b] SLAKE1, WETDRY1, WETDRY3 excluded.

## REFERENCES

1. R. Chandra. Slake Durability Test for Rocks. Imperial College of Science and Technology, Univ. of London, Master's thesis, Rock Mechanics Res. Rept., 1970.
2. J.A. Franklin and R. Chandra. The Slake Durability Test. International Journal of Rock Mechanics and Mining Sciences, Vol. 9, 1972.
3. N.R. Morgenstern and K.D. Eigenbrod. Classification of Argillaceous Soils and Rocks. Journal of Geotechnical Engineering Division, ASCE, Vol. 100, No. GT10, Oct. 1974.

*Publication of this paper sponsored by Committee on Engineering Geology.*