

GEOLOGIC FACTORS AFFECTING THE QUALITY OF LIMESTONE
CONSTRUCTION AGGREGATE: AN EXAMPLE FROM THE
FARLEY LIMESTONE, NE KANSAS

by

J. McKirahan
R.H. Goldstein
E.K. Franseen

Kansas Geological Survey
Open-file Report 98-65

Disclaimer

The Kansas Geological Survey does not guarantee this document to be free from errors or inaccuracies and disclaims any responsibility or liability for interpretations based on data used in the production of this document or decisions based thereon. This report is intended to make results of research available at the earliest possible date, but is not intended to constitute final or formal publication.

**Geologic Factors Affecting the Quality of Limestone
Construction Aggregate: An Example from the
Farley Limestone, NE Kansas**

By

J. McKirahan¹, R.H. Goldstein¹ & E.K. Franseen²

¹University of Kansas, Department of Geology, Lawrence, KS 66045

²University of Kansas, Kansas Geological Survey, Lawrence, KS 66047

Kansas Geological Survey Open-File Report 98-65

Introduction

The goal of this study is to evaluate geologic and physical properties of limestone aggregates in an attempt to find criteria that can be used to quickly and efficiently identify highly durable aggregates and those subject to decay over time. Most past concrete aggregate-related research in Kansas has concentrated on a type of deterioration known as d-cracking. D-cracking is characterized by fine, closely spaced, parallel cracks that have blue, black, gray, or white deposits in the crack at the pavement surface. It typically develops parallel to joints or cracks in the pavement. (Crumpton *et al.*, 1994).

An early study related to d-cracking was conducted by the Kansas Department of Transportation (KDOT) in 1944 and suggested a significant relationship between coarse aggregates and d-cracking. As a result, the sizes of aggregate used in pavement concrete were reduced, resulting in improved pavement performance. In 1973 Bukovatz *et al.* presented the results of another study on d-cracking and again concluded that coarse aggregates and specifically coarse limestone aggregates were a main cause of d-cracking. They stated that pavements that contained more than 35 percent coarse limestone aggregates were more likely to be d-cracked than pavements with less than 35 percent coarse limestone aggregates. Most pavements without limestone coarse aggregate were rated as good.

Best (1974) reported the results of a seven-year study with the goal of finding a specific cause for d-cracking. Although this study concluded that the exact cause of d-cracking still remained a mystery, it was suggested that the freezing and thawing of water within the pavements was a main contributor. This study also supported the previous suggestion that coarse, limestone aggregates were a cause of the problem.

Based on the results of the early studies and those reported by Bukovatz and Crumpton (1981), KDOT adopted new requirements for selecting limestone

aggregates. The plan adopted was to evaluate each quarry, subdivided into beds, and to approve or reject each individual bed based upon the results of laboratory freeze-thaw testing of concrete beams containing the coarse limestone aggregate from each bed (Wallace & Hamilton, 1982). Those aggregates that meet a minimum set of requirements concerning durability, freeze-thaw resistance and expansion are considered class 1 aggregates and are approved for use as construction grade material. The testing system outlined by the 1982 report is used today, and the use of aggregates meeting the established criteria has reduced occurrences of d-cracking. The tests are costly and time consuming, however, taking a minimum of six months to perform.

This paper reports attempts to identify geologic parameters that can be used to identify quality aggregates more easily. During the preliminary stages of the project several quarries currently producing class 1 limestone aggregate in eastern Kansas were visited. The units examined included the Tarkio Limestone, the Merriam and Spring Hill Limestones, the Argentine Limestone, and the Farley Limestone. Based on preliminary observations of outcrops and hand samples at the start of this study, specific geologic variables to be discussed, seem to affect whether a unit passes or fails the class 1 aggregate physical tests. These variables allowed the development of several general working hypotheses testable in the Farley Limestone.

- (1) Micrite-rich, phylloid-algal lithologies consistently produce durable aggregates.
- (2) Fine-grained, matrix-rich limestones tend to pass, whereas coarser carbonate grainstones with coarse cements tend not to pass.
- (3) High amounts of acid-insoluble residue in the rock has a negative impact.
- (4) Distinct, sharp stylocumulates and shale beds have little or no impact on durability, whereas diffuse stylocumulates have a negative impact.

(5) Argillaceous limestones tend to fail testing; therefore the presence of clay minerals in the insoluble residues has a negative impact.

(6) Abundant, coarse, sparry calcite in the rock has a negative impact.

This study uses the Farley Limestone as a test case because it varies significantly both laterally and vertically in aggregate quality and allows initial testing of all of the hypotheses. If an understanding of how geologic factors interact to produce high-quality rock in the Farley is established an analog for other similar limestone units in different locations can be developed.

Methodology

To gather data on the various geologic variables, detailed measured stratigraphic sections were described in eight quarries. Included in these sections were both active and inactive quarries from which KDOT has produced both class 1 and nonclass 1 aggregates from the Farley Limestone. All stratigraphic sections were measured at or near the locations from which KDOT had recently tested aggregates. Also included in the stratigraphic study were descriptions of outcrops and drill cores. These sections helped fill gaps between quarry exposures so that a more accurate stratigraphic reconstruction of the field area was possible. Information obtained includes bedding nature, preliminary lithologic classification, fossil types, and the percentage of the rock volume composed of sparry calcite. Descriptions of outcrops also emphasized determining the percentage of each stratigraphic interval that contained clay-rich zones. Shale beds, concentrated stylocumulates, diffuse stylocumulates, and disseminated argillaceous material were documented. Percentages of the total section that contained each form of argillaceous material were recorded. The different types of clay-rich zones are discussed in greater detail below.

After stratigraphic sections were measured and described in the field, samples were collected. For each of the stratigraphic sections, hand samples were collected, and

polished slabs and thin sections were made. These slabs and thin sections allowed a more accurate, detailed description of each lithology using the Dunham classification for carbonate rocks (Dunham, 1962). The descriptions include dominant depositional fabric, identification of fossils and other carbonate grains, and a more accurate estimation of the percentage of sparry calcite.

In addition to hand samples, 10 bulk rock samples of 250 pounds each were collected and turned over to the Materials and Research Division of KDOT for physical testing according to their established guidelines and procedures. After initial crushing of these ten samples, 3 pounds of the crushed aggregate was obtained from KDOT for each sample. This split included both $\frac{3}{8}$ and $\frac{1}{2}$ inch crushed aggregate. Independent tests conducted on the crushed aggregates included determining acid insoluble residue percentage, grain-size distributions of insoluble residues, x-ray identification of residues, and thin-section petrography to examine lithologies and spar content.

KDOT Physical Tests

Ten 250 pound rock samples were obtained from the Farley Limestone in Johnson and Wyandotte counties and were identified as sample numbers KU-1 to KU-10. These samples were then tested by KDOT using the normal testing protocols prescribed by KDOT to determine aggregate durability. Physical test data for samples recently tested by KDOT from the Farley Limestone are also used in the study. These samples are referred to as KDOT-1 to KDOT-20. Stratigraphic sections were measured and described at or near the site of the KDOT sampling, so their test results could be compared directly to field observations.

The following sections summarize the parameters measured by the physical tests conducted by the Materials and Research Division of KDOT. The results of these tests constitute the data that are compared to data on geologic variables.

Absorption

Absorption is a measure of porosity and permeability of an aggregate sample and is determined as part of the physical tests conducted by KDOT. The reported value is given as a percentage of weight gain after soaking the aggregate in water for 24 hours.

Modified Freeze-Thaw Test (Soundness)

The modified freeze-thaw test (soundness) is used as the first cut to determine whether an aggregate will undergo additional testing. The test determines an aggregate's resistance to freezing and thawing and is performed on raw aggregate that has been size graded and weighed. The aggregate is size graded so that only $1/2$ and $3/8$ inch aggregates are tested. Following 25 cycles of freezing and thawing, the aggregate is size graded again and reweighed to determine how much mass the original sample has lost. The reported freeze-thaw value is the percentage of the aggregate's original mass that is retained after 25 cycles of freezing and thawing. If the modified freeze-thaw value is 0.85, the value reported in this study would be 85 percent. This indicates the sample lost 15 percent of its mass due to degradation from freezing and thawing. At present, KDOT requires a minimum modified freeze-thaw value of 0.85 to continue with testing. If samples do not have a 0.85 modified freeze-thaw value, they are classified as nonclass 1, and no further tests are conducted on that aggregate.

L.A. Wear Test

The L.A. wear test examines the resistance to degradation by abrasion and impact of the limestone aggregates using the ASTM Test C131-89. It is done by size grading the aggregates, weighing them, and tumbling them in a large rotating drum with several large steel balls. Following the test, the aggregate is resized and weighed again. The value reported indicates the percentage of the original mass lost due to size

reduction from degradation by abrasion and impact. This test is not typically useful in classifying aggregates relative to durability.

Expansion

Expansion percentages are determined as part of ASTM Test C666-92 Procedure B. It is accomplished by making three concrete beams out of the limestone aggregate to be tested and a standard cement mix. Two pins are placed in the beams, and after the beam is cured a precise measurement of the distance between the pins is measured. The beam is subjected to cycles of freezing and thawing; at periodic intervals the beam is examined and the distance between the pins is remeasured. The value reported is a percentage of expansion over the original measurement. KDOT currently uses an average of 0.02 percent expansion for the three beams as the maximum expansion limit allowed for class 1 aggregate.

Durability Factor

Durability factor is used to indicate an aggregate's durability and resistance to freezing and thawing. The durability factor is determined using ASTM Test C666-92 Procedure B. The value is related to the percent change in the fundamental transverse frequency of the beams, which is reported as the relative dynamic modulus of elasticity. The modulus of elasticity is a ratio of stress to strain in the elastic region and is an overall measurement of stiffness of a material. The durability factor measures the change in stiffness of the beams after a specified number of cycles of freezing and thawing. Currently, KDOT requires a durability factor of at least 95 to qualify an aggregate as class 1.

Lithologic Parameters

The following sections summarize the specifics of lithologic parameters that were compared to the results of the KDOT physical tests.

Lithology

Lithology was determined by examination of outcrops, hand samples and thin sections. Aspects of lithology considered include depositional fabric (Dunham textural classification), matrix type, fossils, and grain types. Comparing lithology to KDOT physical tests allows for identification of lithologies that might consistently produce durable aggregates. Lithologic examination also allows conclusions concerning the importance of micrite and microspar versus coarser cement (sparry calcite). Although these lithologic properties are qualitative in nature, there is potential for the identification of characteristics that are important in aggregate durability.

Spar Content

Accumulations of coarse spar (clear, crystalline calcite) constitute 10 to 60 percent of the limestones in the Farley. These spar accumulations resulted from either cementation of pore space or neomorphism of micrite matrix. In the Farley Limestone, sparry cement is found in fractures, in molds, and in original pore spaces between or within grains. Neomorphic spar fabrics are also common in the Farley Limestone and dominated by microspar and pseudospar fabrics with crystals defined by Folk (1965) to be in the range of 4 to 50 micrometers in size.

Bulk Spar Percentage

For the purpose of this paper, bulk spar percentage is defined as the percentage of the rock composed of visible, coarsely crystalline material including fracture fillings, spar-filled fossil molds, replaced fossils, and any spar-filled interparticle porosity (Figure 1). Estimates of spar content were made from examination of quarry outcrops and from cut and polished hand samples. Any visible accumulation of spar larger than approximately 0.5 mm was considered in the estimate. The value reported is an estimate of the total percentage of the rock volume that is composed of spar.

Average Spar Crystal Size and Crystal Form

By examining thin sections made from hand samples of each rock subjected to KDOT physical tests, average spar crystal size for each sample was determined. Because 80 to 90 percent of micrite matrix in the rocks of the Farley Limestone was recrystallized to microspar or pseudospar, those crystals finer than 50 micrometers are considered matrix and are not included in the estimates of average crystal size. Also noted during examination of thin sections were various types and shapes of spar present in the rocks. Table 3.1 is a summary of how the spar was classified and described.

Spar Percentage of Crushed Aggregates (Aggregate Spar)

As defined for this paper, spar percentage of crushed aggregates, referred to as aggregate spar, refers to the percentage of rock composed of spar following crushing and sorting of the original rock. This estimate includes only spar coarser than 50 micrometers. Any spar finer than 50 micrometers is considered matrix and therefore is

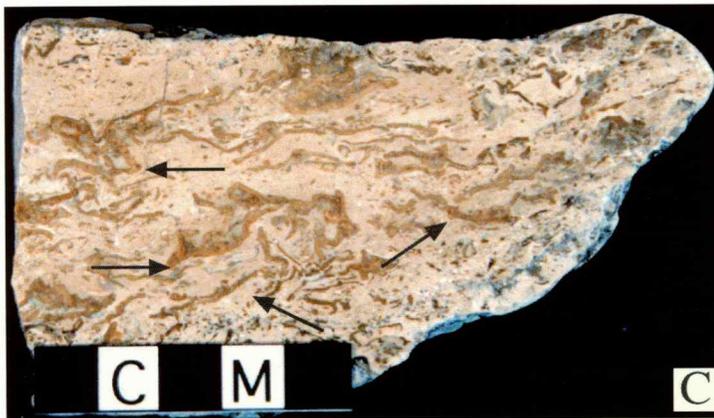


Figure 1. Hand samples showing different types of spar accumulations found in the rocks of the Farley Limestone.

(A) Phylloid algal wackestone with spar in shelter pores (1) and phylloid algal molds (2).

(B) Phylloid algal wackestone with spar dominantly in fractures (1) and phylloid algal molds (2).

(C) Phylloid algal packstone with spar found almost exclusively in phylloid algal molds (arrows).

not included in this percentage. Whereas the bulk spar percentage discussed above is determined from outcrops and hand samples, the aggregate spar percentage was estimated following petrographic examination of splits of aggregate samples subjected to KDOT physical tests in order to deal with differences before and after crushing. Because this property is obtained from crushed aggregates, data were only available for those 10 samples for which crushed aggregates were available (KU-1-KU-10).

Table 1. Table of spar characteristics observed in the rocks of the Farley Limestone.

Spar Type	Crystal Shape	Crystal Size	Boundary Shape
Sparry Cement	Equant: crystals have essentially equal length and width Bladed: length to width ratios are between 1.5:1 and 6:1 Fibrous: length to width ratio is greater than 6:1	Wide range of crystal sizes ranging from approximately 50 microns to several millimeters.	Intercrystalline boundaries of equant crystals are typically planar with even contacts. Irregular boundaries are present in small (under 70 microns) equant crystals and on some bladed crystals.
Neomorphic Spar	Exclusively equant crystals	Microspar: equant crystals of 5-10 microns. Pseudospar: equant crystals of 10-50 microns	Neomorphic spar is typically found in mosaics of microspar or pseudospar with crystal boundaries of an irregular nature.

Clay Percentage and Type

All data concerning clay percentages and forms for all rocks studied were compiled from field observations and laboratory testing.

Total Percentage of Clay-Rich Strata

The total percentage of clay-rich strata is an estimate of the total thickness of the stratigraphic interval that contains any type of clay-rich zone. To calculate this value, estimates of the thickness of individual beds that contained any clay-rich material were

made. From these estimates of clay content of individual beds, a total percentage of clay-rich strata was calculated for each stratigraphic interval.

Clay Distribution

Clay is typically distributed within a stratigraphic interval as shale beds, concentrated stylocumulates, diffuse stylocumulates, and disseminated material. Commonly it is found in concentrated clay-rich seams or stylocumulates defining bedding planes or within individual beds (Figures 2, 3). Shale beds and concentrated stylocumulates were identified by their size, shape, and relationship to the surrounding carbonate. The concentrated stylocumulates are typically ≥ 5 mm thick and are dominantly planar to slightly undulose with uniform thicknesses along their lengths. The seams generally have sharp to slightly gradational contacts with surrounding carbonate and commonly contain fossil material. Concentrated stylocumulates and shale strata are easily identified because they can be removed from the surrounding carbonate with a hammer or pick or by crushing the rock. This is possible because there is little carbonate within the clay-rich area and it is easily separated from the surrounding limestone. Therefore, this occurrence of clay generally does not become a part of the aggregate because it is crushed into fine particles.

Some clays are in diffuse stylocumulates spread out within limestone beds (Figures 2 & 4). These diffuse stylocumulates are composed of numerous subparallel microstylolites and have a wispy to patchy appearance commonly dying out into the surrounding limestone. Because the diffuse stylolites are composed of numerous microstylolites spread throughout the limestone, they cannot easily be separated from the surrounding limestone with a pick or by crushing the rock. Because

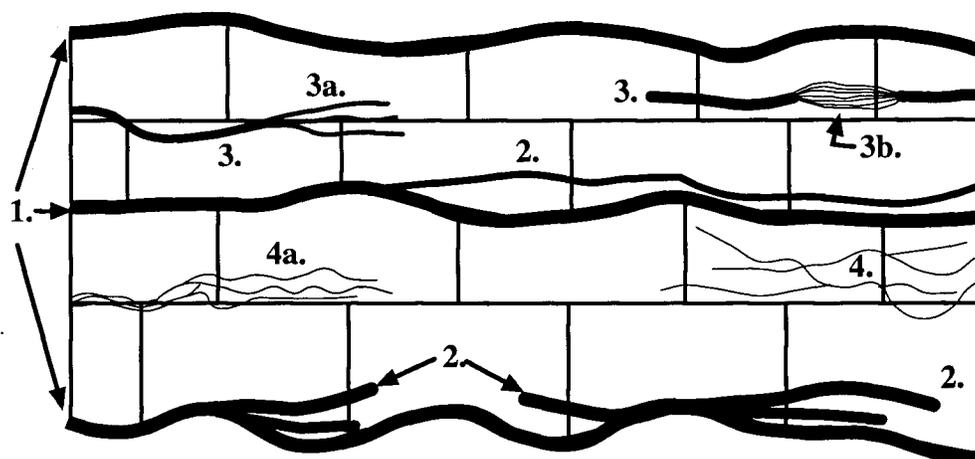


Figure 2. Hypothetical illustration of two limestone beds with various forms of clay distributed within them (1). Concentrated stylocumulates or thin shale beds are typically located along bedding planes and may branch into surrounding limestones (2). Concentrated stylocumulates also occur within limestone beds (3). These often branch into slightly more diffuse stylocumulates near their ends (3a) or have zones of diffuse stylocumulates within them (3b). Diffuse stylocumulates also occur as thin wisps or stringers of clay-rich material within limestones (4), and may have a horsetail appearance (4a).

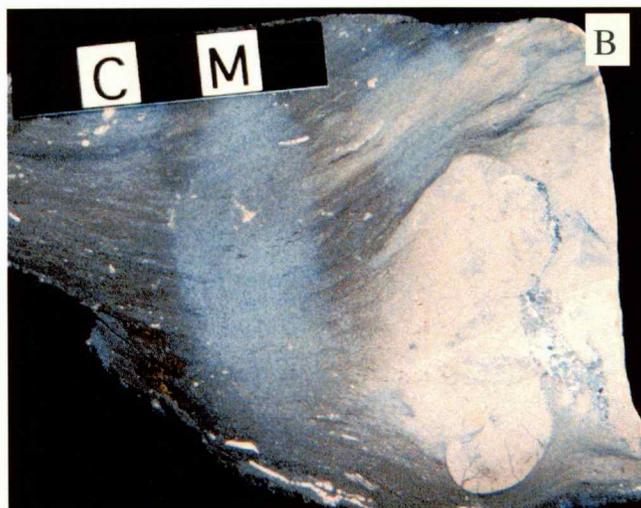


Figure 3. Photos of concentrated stylocumulates as they appear on outcrop. (A) Thin shale bed located between bedding planes. (B) Concentrated stylocumulate that branches into thinner and slightly more diffuse stylocumulates from left to right. (C) Concentrated stylocumulate that becomes more and more diffuse from left to right. The clay on the left would likely separate from the limestone in crushing whereas that on the right would likely remain in the aggregate after crushing.





Figure 4. (A) Photo of thin, diffuse stylocumulates on outcrop. The irregular pattern, thinness and distribution throughout the limestone would likely cause these clay-rich zones to become part of the aggregate following crushing of the rock.



(B) Hand sample of argillaceous skeletal wackestone (locality SRS) showing the stringy, and wispy nature of the diffuse stylocumulates. These wisps of clay-rich material will not be separated from the limestone when the rock is crushed.



Figure 5. Photo of a bed of phylloid algal wackestone with completely disseminated argillaceous material throughout its thickness. This form of clay is recognized by the bluish-gray color it imparts to the rock. Due to the disseminated nature of the clay, it will become part of the aggregate following crushing of the rock.

of its diffuse nature and distribution throughout limestone beds, this occurrence of clay generally will be retained in the crushed aggregates

Clay also occurs as completely disseminated argillaceous material in limestone. In these occurrences there are no visible discrete seams or stylolites. Instead, this clay distribution is typically recognized in outcrops by the bluish-gray color the disseminated clay imparts to the rocks (Figure 5). Like diffuse stylolites, argillaceous material that is completely disseminated throughout the limestone cannot be separated from the limestone and will become part of the crushed aggregate.

Insoluble Residues

Data on insoluble residue percentages of aggregate samples KU 1 to KU-10 were determined by the author, whereas percent insoluble residue for aggregate samples KDOT 1 to KDOT-20 were determined by the Materials and Research Division of KDOT as part of their testing protocol. Other data concerning insoluble residues, including grain size distributions and compositions, were determined by the author for samples KU-1 to KU-10 only.

Percent Insoluble Residue

Percent insoluble residue represents the weight percent of aggregate composed of acid insoluble residue determined by digesting crushed aggregate samples in dilute hydrochloric acid, weighing the filtered residues, and calculating the total percentage by weight.

Insoluble Residue Grain Sizes & Aggregate Clay Percentage

Grain size distributions of the insoluble residues were determined for each aggregate sample tested for this study (KU-1 to KU-10). This was accomplished by weighing the residues, dispersing them in water, and sieving them. Following sieving, the mass of each fraction retained on the sieves and the mass of the fine fraction that

passed through the finest sieve was determined and a percentage of the original sample was calculated for each grain size.

Using the percentage of each sieved residue composed of clay-sized material, a value was calculated that represents the weight percentage of the original aggregate mass composed of clay-sized material. This value is referred to as the aggregate clay percentage. Insoluble residue grain size data were not available for samples taken by KDOT.

Insoluble Residue Composition

Mineralogical compositions of insoluble residues of samples KU 1 to KU-10 were determined using x-ray diffractometry. These data were not available for samples taken by KDOT.

Results

In order to evaluate the hypotheses outlined at the beginning, data concerning the geologic variables must be evaluated relative to the results of the KDOT physical tests. Durability factor is the most important measurement in determining if an aggregate is a class 1 aggregate. For this reason, geologic variables are compared to the results of ASTM Test C666-92, Procedure B, which KDOT uses to determine durability factor. Other important test results used in KDOT's determination of whether an aggregate qualifies as class 1 include the expansion percentage and the modified freeze-thaw (soundness) ratio. Therefore, some geologic variables were also compared to these results and correlations are discussed where applicable. Because durability factor is so highly correlated to expansion percentage (Figure 6), however, it is apparent that in most cases only one of these variables need be compared to lithologic

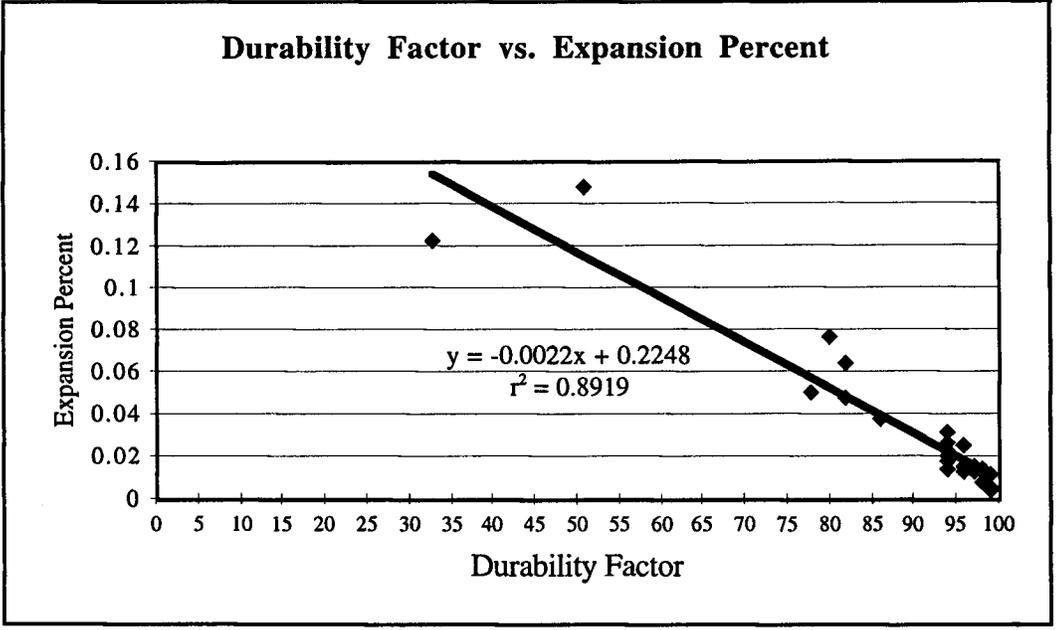


Figure 6. XY plot illustrating the relationship between durability factor and expansion percentage (n = 25).

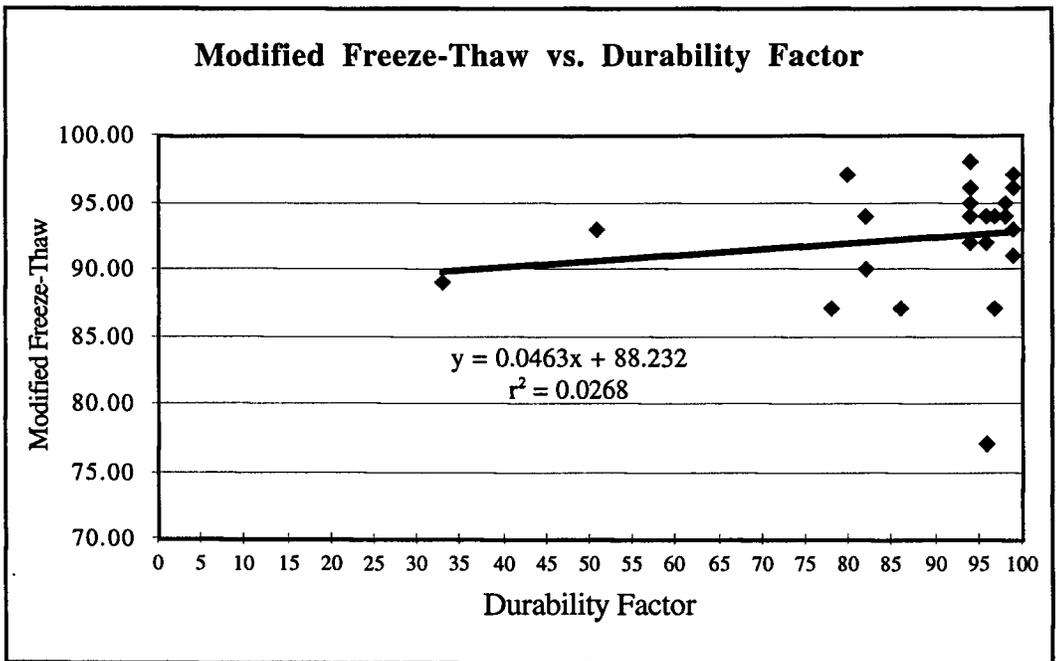


Figure 7. XY plot showing the relationship between durability factor and modified freeze-thaw (soundness) value (n = 30).

parameters. Alternatively, because the results of the modified freeze-thaw test essentially do not correlate to durability factor (Figure 7), the soundness test may either be reflecting an influence of different variables or may suggest that the soundness test is in need of further evaluation.

To compare most data to the durability factor, simple XY scatter plots were compiled. Then, using simple linear regression, any possible correlations or trends were examined. Although the regression data are not meant to represent rigorous statistical testing, they provide the means to simply evaluate trends useful for indicating those variables that may play a significant role in aggregate durability. In the future, as more comprehensive data are accumulated, these data may be conducive to multivariate statistical analysis. For other, more qualitative data such as lithology, spar types, and clay form, comparisons were made by categorizing the data into classes and compiling histograms.

Lithology

The rocks tested for this study (samples KU-1 to KU-10) and other recent KDOT tests (samples KDOT-1 to KDOT-20) are of six different lithologies (Table 3.2). Of the thirty aggregates examined in the study, 25 had durability-factor data. Nineteen of those 25 aggregates are phylloid-algal lithologies. Of those nineteen, eight have durability factors of at least 95, six have durability factors of 90 to 94, and only five fall within the 0 to 89 range (Figure 8).

Coarser grained, micrite-poor lithologies such as skeletal grainstone (KU-3) and skeletal, peloidal packstone (KU-7) have durability factors of at least 95. Finer grained, micrite or microspar matrix-rich lithologies such as skeletal wackestone (KU-8) and phylloid algal wackestone (KU-5) also have durability factors of at least 95. Therefore, it does not appear possible to predict durability based exclusively on the

Table 2. Information regarding lithology of each aggregate source. Information includes locality and stratigraphic unit from which each sample was taken, lithology, matrix or cement type and dominant grain type. Also given are durability factors for each aggregate (NC= not calculated).

Lab. #/Sample #	Sample Source	Lithology	Dominant Matrix or Cement	Dominant Grain Type(s)	Dblty Factor
97-3685/KU-1	SRS L. Frly	Argil. Sk. Wckstn	Pseudospar & Microspar	Skeletal Fragments (Bryozoan, Crinoid, Brachiopod)	NC
97-3686/KU-2	SRS U. Frly	Phyl. Algal Wckstn	Micrite & Microspar	Phylloid Algae	94
97-3687/KU-3	SRO L. Frly	Skel. Grnstrn	Equant Cement	Skeletal Frags., Quartz Grains, Peloids	97
97-3688/KU-4	SRBS L. Frly	Oolite	Isopach., Micrite, Eqnt Cement	Ooids, Peloids, Skeletal Fragments	98
97-3689/KU-5	SRBS U. Frly	Phyl. Algal Wckstn	Peloidal Micrite & Microspar	Phylloid Algae, Bryozoans	99
97-3690/KU-6	RQ U. Frly	Phyl. Algal Pckstn	Peloidal Micrite & Microspar	Phylloid Algae	96
97-3858/KU-7	SRS U. Frly	Pel. Sk. Pckstn	Equant Cement	Micritized Peloids, Skel. Frags (Crinoids, Brachs)	96
97-4058/KU-8	HM L. Frly	Skel. Wckstn	Micrite & Microspar	Fusulinids, Brach. & Bryozoan Frags.	97
97-4059/KU-9	HM U. Frly	Phyl. Algal Wckstn	Peloidal Micrite & Microspar	Phylloid Algae	99
97-4060/KU-10	HM U. Frly	Osagia, Brach Wckstn	Micrite & Microspar	Osagia, Brach Frags, Phylloid Algae, Ooids	82
95-0634/KDOT-1	SRS U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae	98
95-634-P/KDOT-2	SRS L. Frly	Phyl. Algal Wckstn	Microspar & Micrite	Phylloid Algae Frags, Bryozoans, Brachs, Crinoids	94
93-4579/KDOT-3	SRO U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae, Bryozoans	78
93-4579/KDOT-4	SRO U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae, Bryozoans	86
94-0607/KDOT-5	SRBS M. Frly	Mixed Lith.	Equant Cement & Micrite	Peloids, Ooids, Skel. Frags.	82
94-0607/KDOT-6	SRBS U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae, Bryozoans	80
94-2268/KDOT-7	HM U. Frly	Phyl Algal Wckstn	Peloidal Micrite	Phylloid Algae	99
94-2268/KDOT-8	HM U. Frly	Phyl Algal Wckstn	Peloidal Micrite	Phylloid Algae	99
94-2268/KDOT-9	HM U. Frly	Phyl Algal Wckstn	Peloidal Micrite	Phylloid Algae	98
94-2268/KDOT-10	HM L. Frly	Phyl Algal Wckstn	Microspar & Micrite	Phylloid Algae, Peloids, Skel. Frags.	94
94-2268/KDOT-11	HM L. Frly	Sk. Wckstn	Micrite & Microspar	Fusulinids, Bryozoan & Brach. Frags.	NC
93-4579/KDOT-12	SRO M. Frly	Sk. Grnstrn	Equant Cement	Skel. Frags., Quartz Grains, Peloids	NC
95-634-P/KDOT-13	SRS L. Frly	Mixed Lith.	Equant Cement	Peloids, Crinoid Frags, Skel Frags.	NC
81-0083/KDOT-14	LQ L. Frly	Arg. Phyl. Algal Wckstn	Micrite & Microspar	Phylloid Algae, Brachiopods	33
81-0083/KDOT-15	LQ L. Frly	Arg. Phyl. Algal Wckstn	Micrite & Microspar	Phylloid Algae, Brachiopods	51
81-0083/KDOT-16	LQ U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae	94
81-0083/KDOT-17	LQ U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae	94
97-2114/KDOT-18	OAQ U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae	96
97-2114/KDOT-19	OAQ U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae	94
97-2114/KDOT-20	OAQ U. Frly	Phyl. Algal Wckstn	Peloidal Micrite	Phylloid Algae	NC

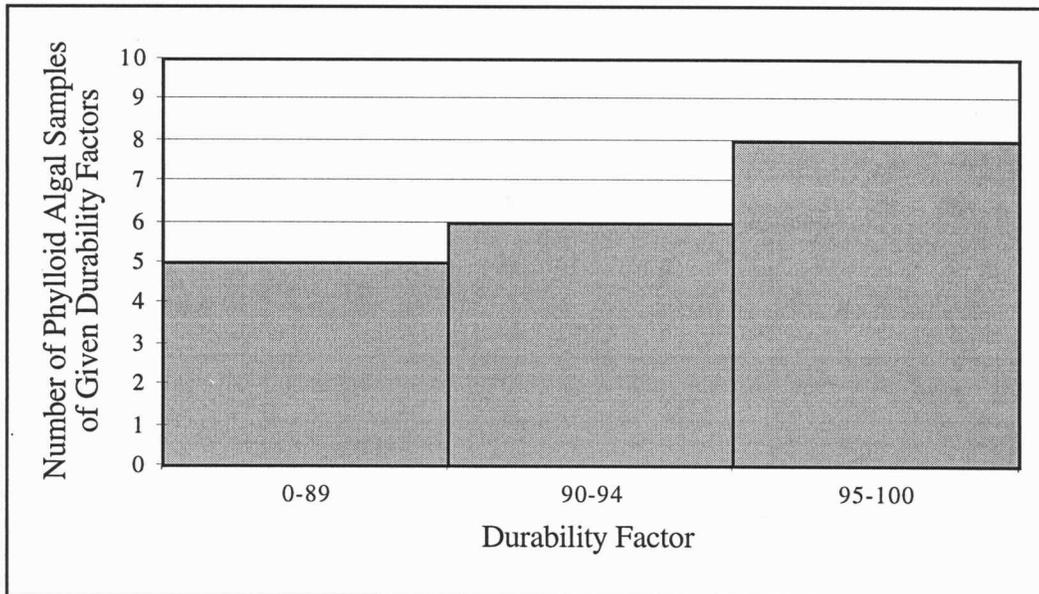


Figure 8. Histogram showing the number of samples of phylloid-algal limestone within durability-factor categories.

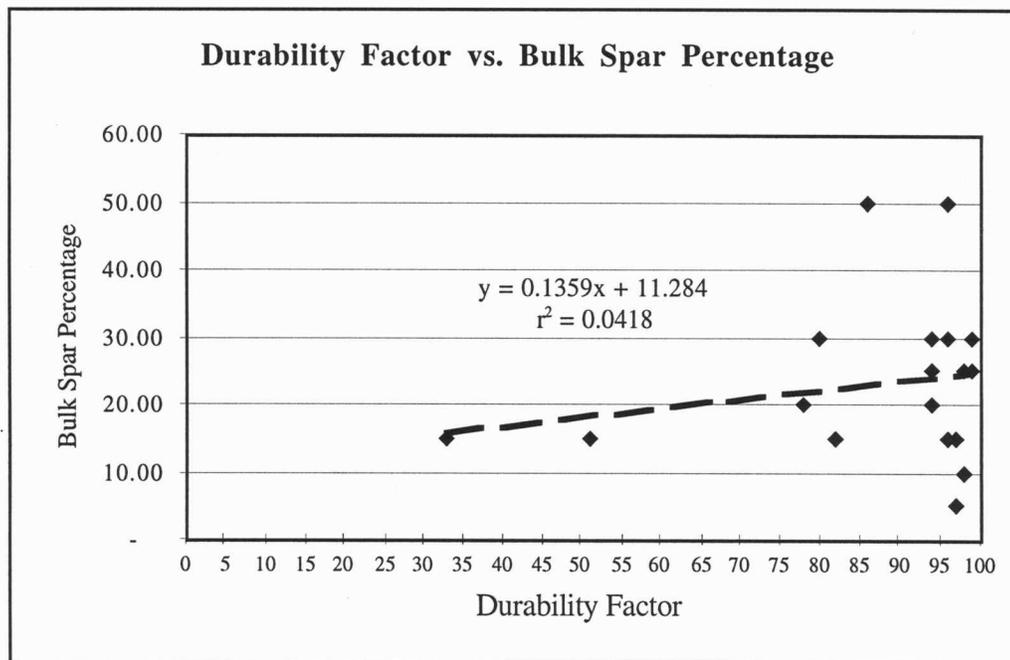


Figure 9. XY Plot showing relationship of durability factor to bulk spar percentage ($n = 25$). The weak relationship suggested is that as bulk spar percentage increases, durability increases.

variation in Dunham-classified lithologies in the Farley Limestone. Instead, the results of durability testing indicate that both matrix-rich lithologies such as phylloid-algal wackestone and skeletal wackestone-packstone and matrix-poor lithologies such as skeletal grainstone produce durable aggregates. This indicates that aggregate quality is largely controlled by factors other than lithologic composition. It does seem, however, that matrix-rich lithologies such as phylloid-algal wackestone and skeletal wackestone-packstone generally produce durable aggregates.

Bulk Spar Percentage

The relationship between bulk spar percentage and durability factor is shown in Figure 9. Although the statistical correlation is weak, using the data to evaluate the trend visually is useful. The possible relationship suggested by the regression line is the higher the bulk spar percentage the higher the durability factor, but the fit is so weak. We must conclude that, within this data set, there is no real relationship between bulk spar percentage and durability. It is possible, however, that within a larger data set with greater variance a stronger correlation may be established.

Average Crystal Size

The relationship between average crystal size and durability factor is illustrated in Figure 10. This variable was evaluated by determining the average crystal size for each aggregate and then dividing the data into two classes: (1) average crystal size in spar-rich aggregates (≥ 25 percent bulk spar) and (2) average crystal size in spar-poor aggregates (< 25 percent bulk spar). As with the durability factor-bulk spar percentage relationship, the correlations are weak. The regression lines for both classes vaguely suggest that as average crystal size decreases, durability increases. Although the correlations are weak, they are stronger than the correlation between bulk spar percentage and durability factor.

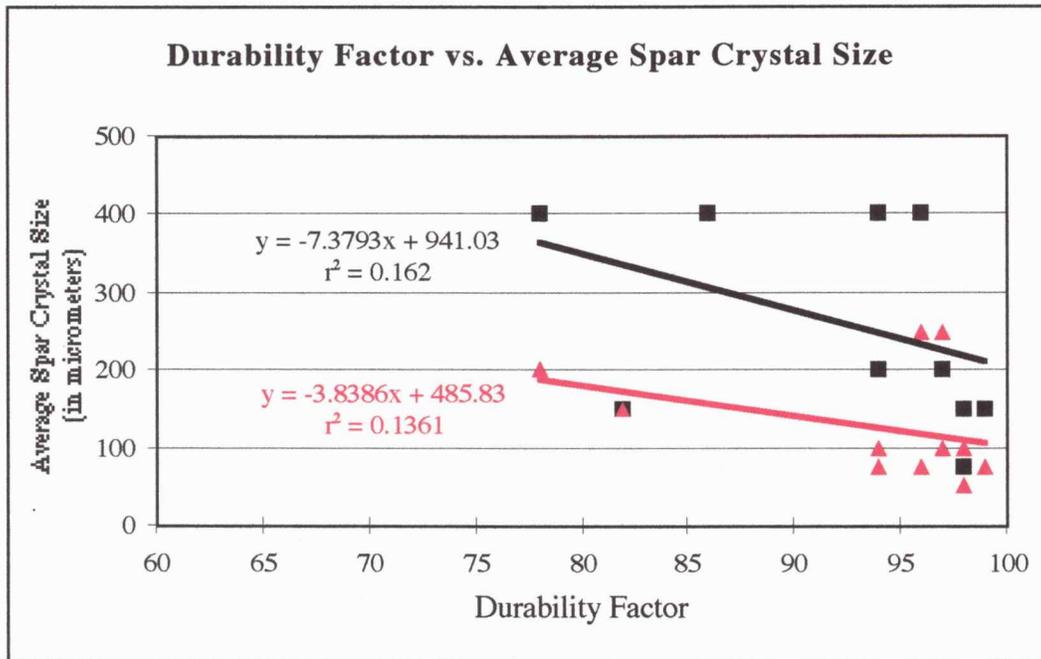


Figure 10. XY plot showing the relationship between average crystal size (in micrometers) and durability factor. Red data points represent spar-poor samples ($n = 12$) and black are spar-rich samples ($n = 12$).

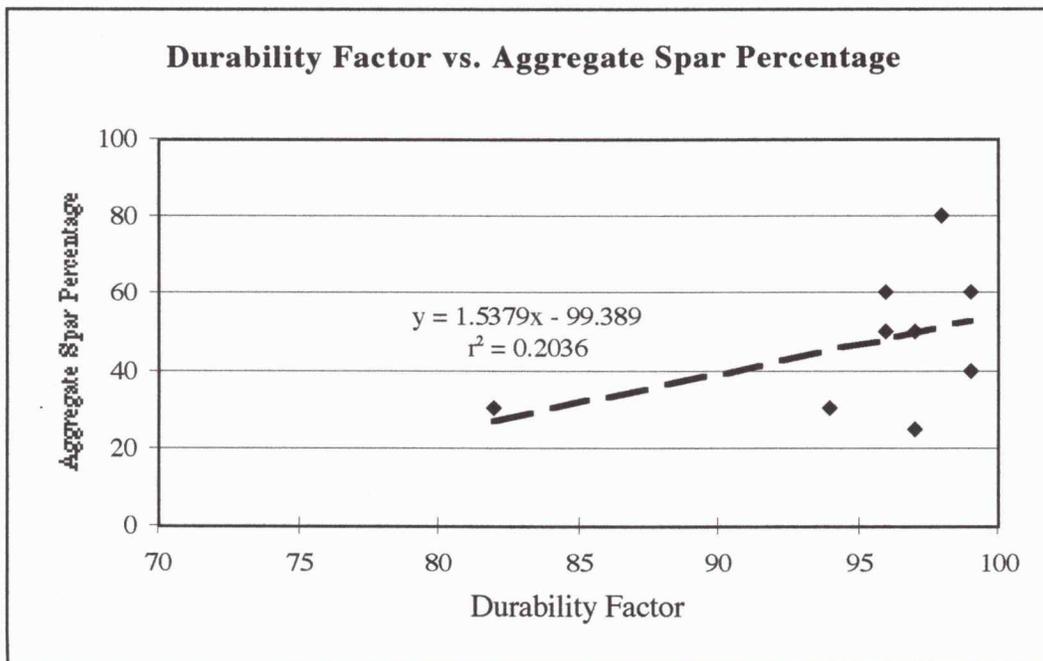


Figure 11. XY Plot comparing the total aggregate spar percentage to durability factor ($n = 9$). The regression line suggests a weak relationship; the higher the aggregate spar percentage the higher the durability.

Aggregate Spar Percentage

Comparison between durability factor and aggregate spar percentage (Figure 11) shows a slightly stronger correlation than in the other comparisons of bulk spar percentage and average crystal size. Although the plot shows that one data point dominates the correlation, the fit of the regression line suggests that the higher the percentage of aggregate spar, the higher the durability. We must, however, conclude that within this data set, there is no useful correlation. But again, examination of this variable within the context of a larger data set with greater variance may illustrate a more useful correlation.

Total Percentage of Clay-Rich Strata and Distribution of Clay

Comparing the total percentage of clay-rich strata to durability factor provides one of the stronger correlations. The fit of the regression line in Figure 12 suggests that the lower the total percentage of clay-rich strata the higher the durability factor. The correlation between outcrop clay percentage and expansion percentage also produces a relatively strong correlation and suggests that the higher the outcrop clay percentage the higher the expansion (Figure 13). These two plots compare the total clay percentage, including shale beds, concentrated stylocumulates, diffuse stylocumulates, and disseminated argillaceous material, to durability factor and expansion percentage. Because shale beds and concentrated stylocumulates are likely to be removed from the limestone during quarrying and crushing, however, correlations between the total percentage of clay-rich strata and durability factor and expansion percentage are not the best representations of the actual aggregate composition. Instead it would be more beneficial to evaluate the impact of only those occurrences of clay that become a part of the aggregate.

For this reason, a separate estimate was made of the percentage of the strata that contains only diffuse stylolites. Additionally, because the number of samples that contained enough disseminated clay to be detectable in outcrop is low, disseminated

material was also included in this estimate so that the value is a total percentage of diffuse and disseminated clay. These values offer the closest approximations of the actual composition of the aggregate and best illustrate the impact of clay and its distribution on aggregate durability. When the percentage of strata that contains both diffuse and disseminated clay is compared to durability factor, the suggested correlation is stronger than that between total percentage of clay-rich strata and durability factor (Figure 14). Additionally, if the percentage of rock that contains diffuse stylolites and disseminated argillaceous material is compared to expansion percentage, another relatively good correlation is suggested (Figure 15).

Percent Insoluble Residue

Evaluation of insoluble residue data suggests possible trends and relationships, but the correlation is relatively weak. The relationship observed between total percent insoluble residue and durability factor suggests that the lower the insoluble residue percentage the higher the durability factor (Figure 16). A similar, slightly stronger correlation exists between expansion percentage and insoluble residue percentage (Figure 17). These are the relationships we would expect to see based on the relationship of durability factor and expansion to percent clay. The fact that the correlations related to insoluble residue percentage are considerably weaker than those related to total clay percentage creates a possible contradiction if it is assumed that the bulk insoluble residue percentage should be a reflection of the total percentage of clay-rich strata.

The bulk insoluble residue percentage of the aggregates is not a direct measure of the amount of clay in the rocks. Instead the insoluble residue percentage is a measure of not only the amount of clay in the rocks but also includes things such as quartz, feldspar and organic residue. Therefore, rocks appear to contain no clay can in fact

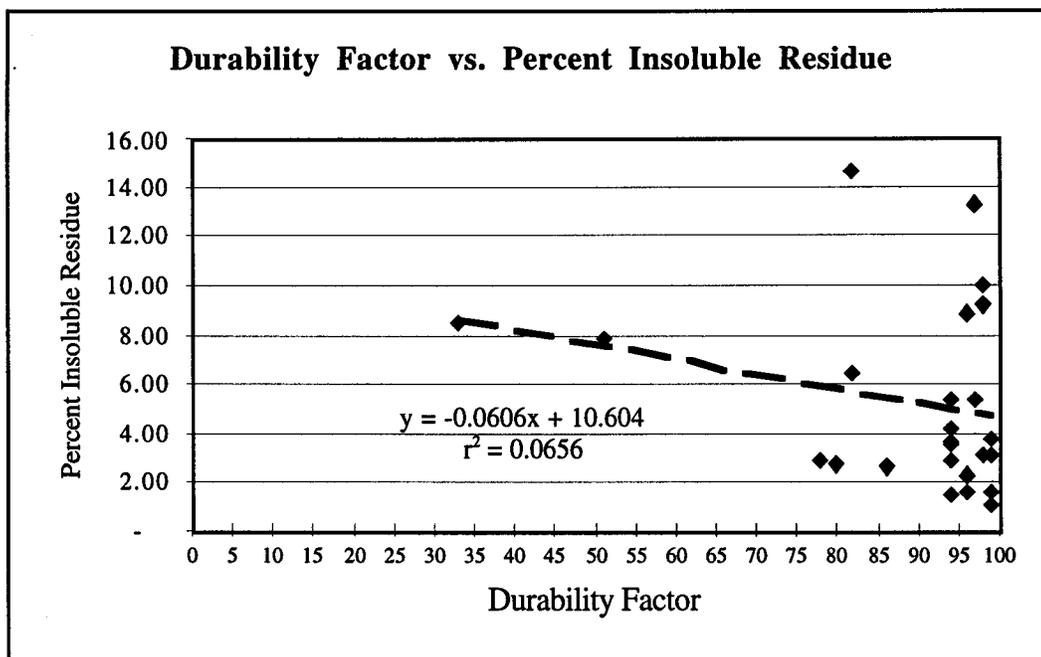
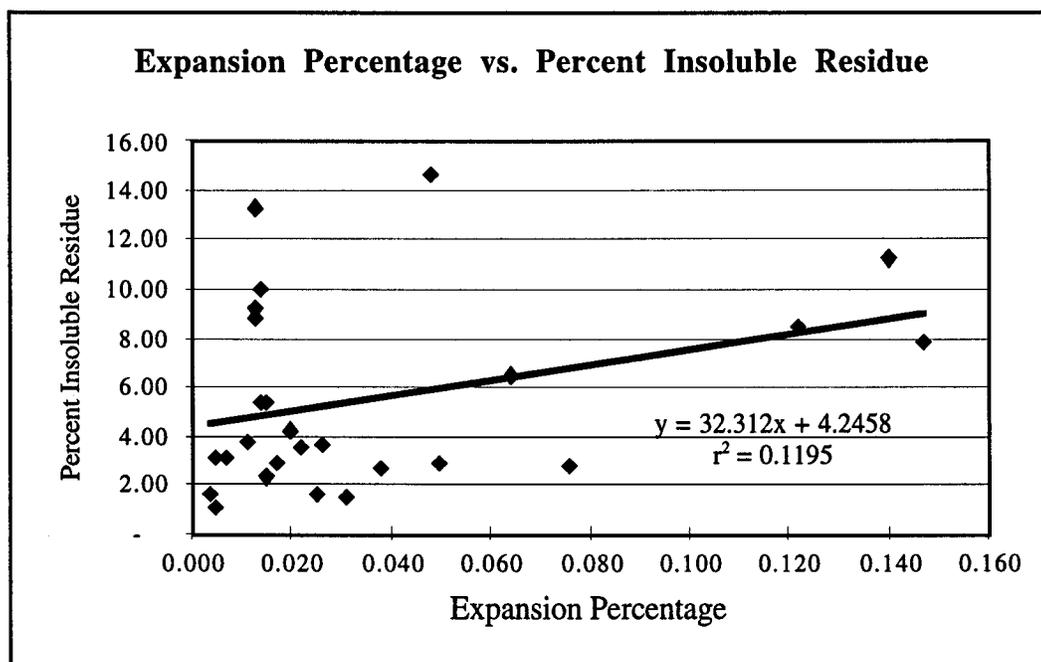


Figure 16. XY plot showing the relationship between durability factor and percent insoluble residue ($n = 25$).



have significant amounts of insoluble residue. For example, samples KU-3 and KU-4 have low total clay percentages (2 percent) but relatively high insoluble residue percentages (9.22 percent and 13.32 percent respectively). This indicates that some lithologies that have little to no clay visible on outcrop may contain insoluble materials other than clay, such as quartz, feldspar or organic residue. Furthermore, because insoluble residue percentages are calculated by weight percent, if there is abundant quartz or feldspar in the residue, the insoluble residue percentage is skewed towards the high side because these minerals are heavy relative to clay minerals.

The difference in correlations between insoluble residue percentage and total percentage of clay-rich strata indicates that the presence of minerals such as quartz and feldspar have a much less negative impact on durability factor than do clay minerals. This suggestion is further discussed and supported in the following section.

Insoluble Residue Composition & Aggregate Clay Percentage

All residues examined contain quartz and feldspar, and all but one residue contains illite/mica. Other clay minerals in residues include smectite and kaolinite (Table 3.3). Comparison of residue mineralogy with durability factor and expansion percentage, although not a quantitative comparison provides useful information.

Of those aggregates that have durability factors below 95 (KU-2, KU-10) or had testing terminated due to poor performance (KU-1), all contain three detectable clay minerals: illite, smectite, and kaolinite (Table 3.3). Additionally, these aggregates that contain three identified clays in their insoluble residues also have the highest expansion percentages (Table 3.3). There is also an apparent relationship between durability and the aggregate clay percentage in those aggregates that contain the three detectable clay minerals. The aggregate that contains the three clays and has the highest aggregate clay percentage (9.73 percent) is KU-1. This aggregate performed so poorly that testing was terminated due to degradation and no durability factor was calculated. There was

however, an expansion percentage calculated for this aggregate and it was much higher than those expansion percentages calculated for the other aggregates (Table 3.3).

Table 3.3. Composition of each insoluble residue for which x-ray diffractometry data were obtained. Also shown are the calculated durability factors (NC = not calculated) and expansion percentages for each of the ten aggregates, as well as the calculated aggregate clay percentages.

Lab. #/Sample #	Quartz	Feldspar	Illite/Mica	Smectite	Kaolinite	Durability Factor	Expansion %	Agg. Clay %
97-3685/KU-1	X	X	X	X	X	NC	0.14	9.73
97-3686/KU-2	X	X	X	X	X	94	0.02	3.64
97-3687/KU-3	X	X	X			97	0.013	6.44
97-3688/KU-4	X	X	X			98	0.013	7.4
97-3689/KU-5	X	X	X			99	0.011	3.18
97-3690/KU-6	X	X	X	X		96	0.015	1.97
97-3858/KU-7	X	X	X		X	96	0.013	8.04
97-4058/KU-8	X	X	X		X	97	0.015	3.87
97-4059/KU-9	X	X				99	0.005	3.02
97-4060/KU-10	X	X	X	X	X	82	0.064	5.8

The seven remaining aggregates have durability factors of at least 95. Of these seven, three (KU-6, KU-7, KU-8) contain a combination of only two detectable clay minerals in the residues, illite and smectite or illite and kaolinite. Although these aggregates have similar expansion percentages, a connection may exist between the presence of smectite and lower durability. Aggregate KU-6 contains smectite but has a relatively low percentage of aggregate clay (1.97 percent), whereas aggregates KU-7 and KU-8 contain higher aggregate clay percentages (8.04 percent and 3.07 percent respectively) and contain no smectite. Although, aggregate clay percentages do not indicate the percentage of smectite exclusively, it is reasonable to infer that smectite is present in higher proportions (as are the other clay minerals) in aggregates with higher aggregate clay percentages. This suggests that the presence of smectite, even in small quantities, may negatively impact durability more than does the presence of other clay minerals in higher quantities.

Three aggregates (KU-3, KU-4, KU-5) contain only one detectable clay mineral, and one aggregate (KU-9) contains no detectable clay minerals. These

aggregates all have the highest durability factors (97 or higher) and the lowest expansion percentages. Two of these four aggregates contain high aggregate clay percentages (6.44 percent and 7.4 percent). Apparently having only illite or lacking smectite or kaolinite indicates the potential for high durability as long as some clay percentage is not exceeded, but this critical percentage is unknown at this time.

Absorption

The absorption value is a measure of the porosity and permeability of an aggregate. The correlations between durability factor and absorption are weak or nonexistent (Figure 18), and the correlation between expansion percentage and absorption is only slightly stronger (Figure 19). The fit of the regression lines suggest that the lower the absorption percentage the higher the durability factor and the lower the expansion percentage, but the correlations are so weak that, within this data set, We must concluded that there is no relationship between absorption and durability or expansion.

Discussion

KDOT requires class 1 aggregates to meet three specifications: (1) a modified freeze-thaw ratio of 0.85 (85 percent) or greater; (2) a durability factor of 95 or higher; and (3) an expansion percentage of 0.02 percent or lower. Therefore, determining which geologic variables seem to have a direct affect on these three physical properties is important in recognizing what KDOT recognizes as durable aggregate. Because the correlations examined between modified freeze-thaw value and the geologic properties were all weak to nonexistent, however, the following discussion will concentrate on the comparisons that were made to durability factor and expansion percentage.

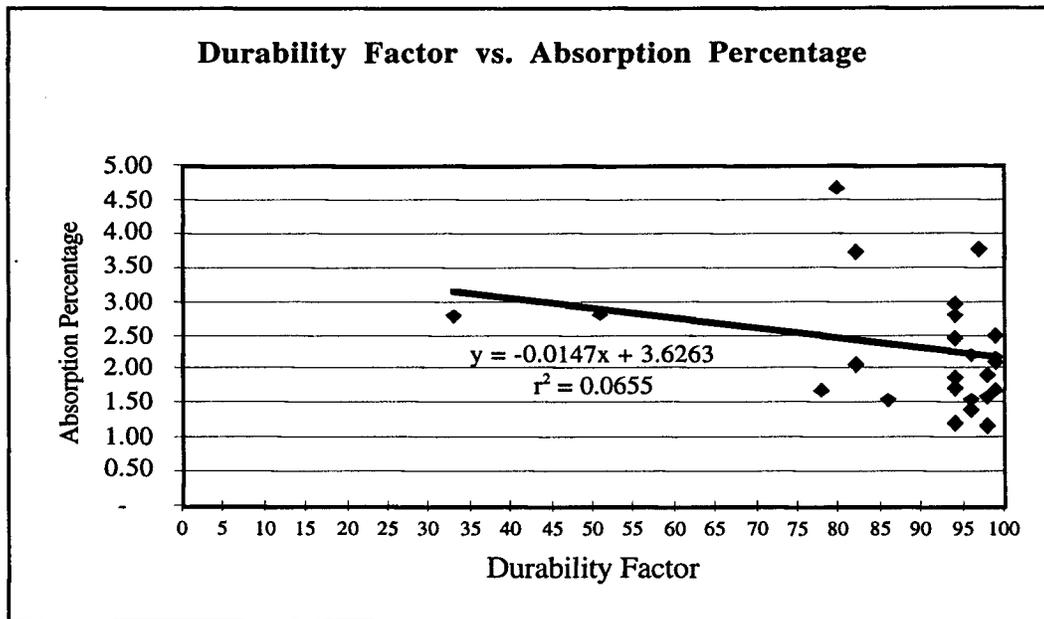


Figure 18. XY plot showing the relationship between durability factor and absorption percentage (n = 25).

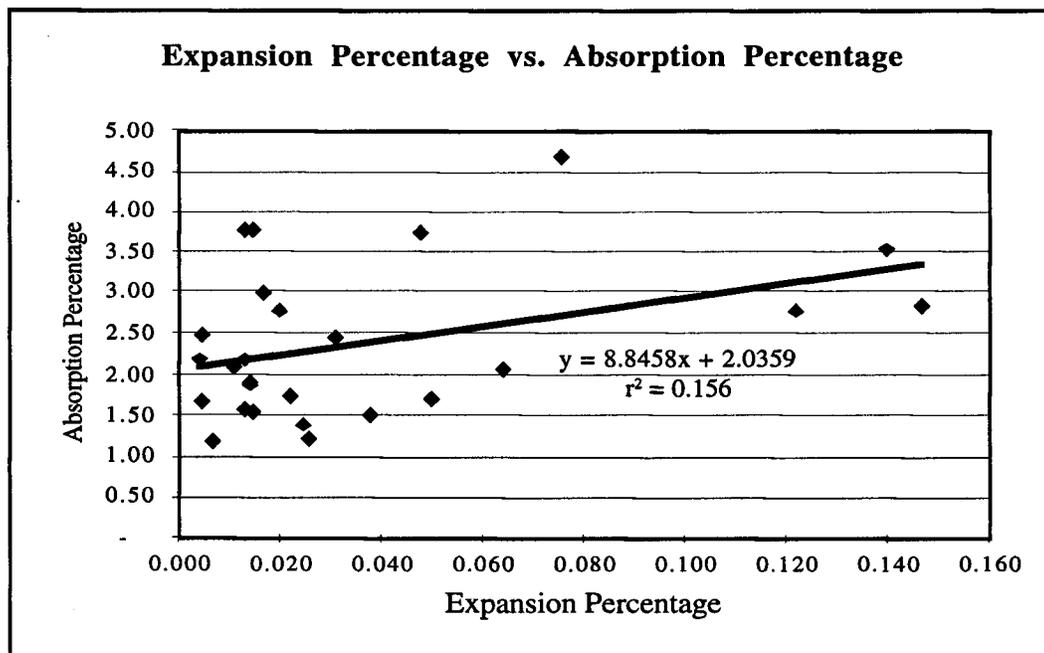


Figure 19. XY plot showing the relationship between expansion percentage and absorption percentage (n = 26).

Of the lithologies examined micrite or microspar matrix-rich lithologies as well as sparry cement-rich lithologies attain class 1 status. Therefore, it seems unlikely that

the presence of micrite or microspar matrix in the rocks preferentially produces higher durability aggregates than does the presence of abundant sparry cement. The hypothesis that micrite-rich phylloid-algal lithologies produce durable aggregates seems to be largely supported however. Additionally, other micrite or microspar matrix-rich lithologies such as skeletal wackestone-packstone also commonly produce durable aggregates. Because there are exceptions to these trends and because cement-rich lithologies such as oolite also produce durable aggregates, textural classification cannot be used to confidently predict aggregate durability.

The effect of coarse spar on durability is difficult to establish based on the data collected for this study. The correlation between bulk spar percentage and durability suggests that the more coarse spar present the higher the durability. Alternatively, the correlation between average crystal size and durability suggests that finer average crystal sizes yield higher durability aggregates. Because the correlations are weak for this data set, it is impossible to conclude with certainty that the amount or coarseness of spar present in the rocks has any impact, positive or negative.

In their report on aggregate durability, Wallace and Hamilton (1982) determined that the insoluble residue percentage was significant in predicting aggregate durability. For this reason they included percent insoluble residue value in the Pavement Vulnerability Factor (PVF) calculation that they used to initially identify durable aggregates until physical testing was completed. The correlations between durability factor and percent insoluble residue in my study show no strong correlation. The weak trend suggests that the lower the percent insoluble residue the higher the durability factor and the lower the expansion percentage. Therefore, the hypothesis that high amounts of insoluble residue in the rocks has a negative affect is not refuted. Because the correlations are weak and both class 1 and nonclass 1 aggregates contain variable

percentage of insoluble residue, however, support for the hypothesis is tenuous at best, and it is clear that variables other than insoluble residue percentage must be involved.

Of the hypotheses examined, those related to the abundance, distribution, and mineralogy of clay in the rocks and insoluble residues produce the strongest correlations. The most accurate indicator of durability seems to be the total percentage of strata that contain diffuse stylocumulates plus disseminated argillaceous material. These occurrences of clay are most likely to become part of the aggregate following crushing and sorting. The relationship observed suggests that those rocks with low percentages of diffuse stylocumulates and disseminated argillaceous material are likely to qualify as class 1 aggregate. Furthermore, those rocks dominated by concentrated stylocumulates and clay beds with little diffuse stylocumulates and disseminated argillaceous material are also likely to produce durable aggregates. Therefore, the hypotheses regarding the presence of concentrated and diffuse stylocumulates as well as disseminated argillaceous material are supported.

As mentioned previously, the main cause of d-cracking is thought to be the expansion and contraction of aggregates caused by freezing and thawing of water entrapped in the aggregate. Given this cause of d-cracking and the information presented regarding clay minerals, it is reasonable to believe that the presence of some clay minerals in the aggregates would negatively impact aggregate durability.

Of the three clay minerals detected in the aggregates examined, smectite is likely to have the most negative impact on aggregate durability. The outstanding characteristic of the smectite group of clays is their capacity to absorb water molecules, thus producing marked expansion of the structure (Klein & Hurlbut, 1993). This characteristic explains why those aggregates that contain larger amounts of smectite also exhibit the greatest expansion percentages (Table 3.3). Similarly, because expansion is so closely related to the durability factor (Figure 6), the presence of smectite is likely to

cause a reduction in durability. Clearly smectite must be present in the aggregates in enough abundance to impact negatively durability. Determining the exact threshold for the amount of smectite that negatively impacts durability will require further work.

Conclusions

All limestone textural classifications may produce class one aggregate and the presence of abundant micrite or microspar matrix or abundant sparry cement has no apparent impact on durability. Micrite or microspar matrix-rich lithologies such as phylloid algal wackestones and packstones and skeletal wackestones and packstones, however, are commonly good sources of durable aggregates.

Other geologic properties such as bulk spar percentage, spar size, insoluble residue percentage and grain size produce suggestive trends when related to durability and expansion. These factors do not, however, seem to be reliable indicators of durability.

Of the geologic parameters examined in this study, those related to the abundance, distribution, and mineralogy of clay seem to be the most significant. The strongest correlations between geologic properties and physical test results are related to the total clay percentage, clay distribution, and composition of insoluble residues. The more clay observed in outcrops (total percentage of clay-rich strata) the lower the durability and the higher the expansion percentage. Limestones that contain clay only in concentrated stylocumulates or shale beds are likely to produce class 1 aggregate because the clays and shales are crushed too finely to become part of the aggregate. Limestones with diffuse stylocumulates and disseminated clay are less likely to produce class 1 aggregates.

A further indicator of durability is the composition of the insoluble residues. If the residues contain three clay minerals (illite, kaolinite, and smectite) the durability is likely to decrease. Limestones without detectable clay minerals are likely to produce

durable aggregates. Furthermore, if even a small amount of smectite is present in the residues, there is a higher likelihood of failure due to the expansive properties of this group of clay minerals.

References

- Best, C.H., 1974, D-cracking in PCC pavements—cause and prevention: Manhattan, KS: Department of Applied Mechanics, Kansas State University: Report No. KSU-EES-2472.
- Bukovatz, J.E., Crumpton, C.F., Worley, H.E., 1973, Study of d-cracking in Portland cement concrete pavements: Report 1, Field Phase: Topeka, KS: State Highway Commission of Kansas, Planning and Development Department, Research Division.
- Bukovatz, J.E., and Crumpton, C.F., 1981, Study of d-cracking in Portland cement concrete pavements: V. 2- Laboratory Phase: Topeka, KS: Kansas Department of Transportation, Planning and Development Department, Research, Development and Implementation Section: Report No. FHWA-KS 81-2.
- Crumpton, C.F., Wojakowski, J., Wallace, H., and Hamilton, L.D., 1994, Study of d-cracking in Portland cement concrete pavement: V. 4—Petrographic phase and final report: Topeka, KS: Kansas Department of Transportation, Division of Operations, Bureau of Materials and Research: Report No. FHWA-KS-94/3.
- Dunham, R.J., 1962, Classification of carbonate rocks according to depositional texture *in* Classification of Carbonate Rocks- A Symposium: American Association of Petroleum Geologists, Memoir, no. 1, p. 108-121.
- Folk, R.L., 1965, Some aspects of recrystallization in ancient limestones *in* Pray, L.C., and Murray, R.C., eds., Dolomitization and Limestone Diagenesis: A Symposium: Society of Economic Paleontologists and Mineralogists, Special Publication, No. 13, p. 14-48.
- Klein, C., and Hurlbut, C.S., 1993, Manual of Mineralogy, 21st Edition, John Wiley & Sons: New York, 681 p.
- Wallace, H.E., and Hamilton, L.D., 1982, An Investigation of Kansas Limestones as they Pertain to the "D-Cracking" Phenomena: Unpublished paper presented to D-Cracking Workshop, Overland Park Kansas, February, 17 & 18: Kansas Department of Transportation, 19 p.