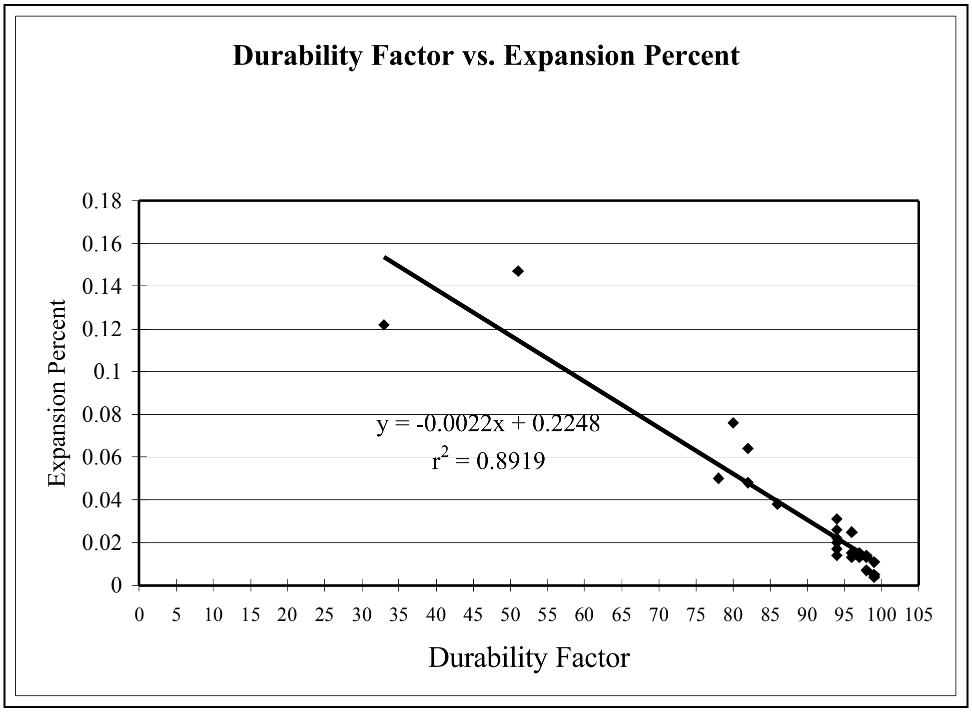

Figure 3.6. XY plot illustrating the relationship between durability factor and expansion percentage (n = 25).

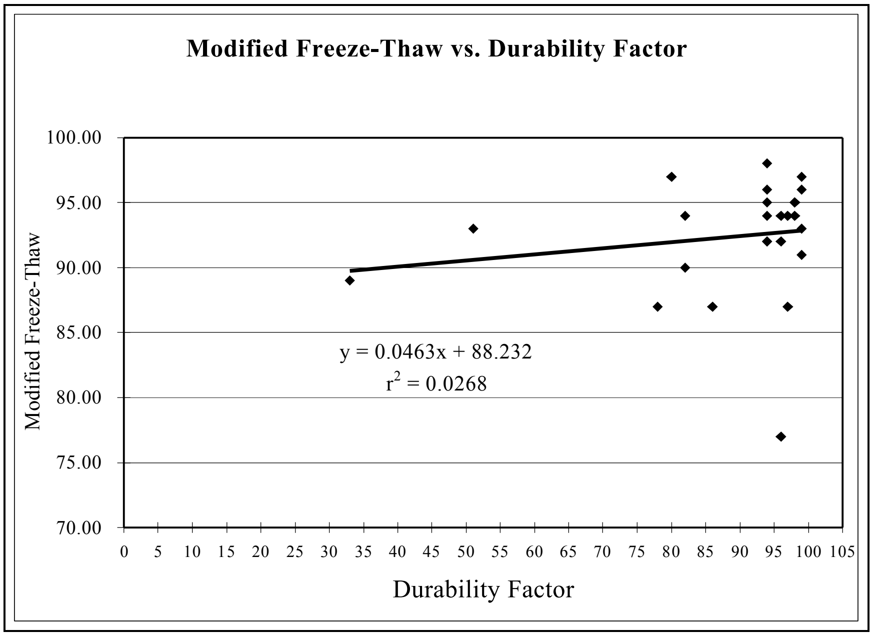

Figure 3.7. XY plot showing the relationship between durability factor and modified freeze-thaw (soundness) value (n = 30).

parameters. Alternatively, because the results of the modified freeze-thaw test essentially do not correlate to durability factor (Fig. 3.7), 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 30 aggregates examined in the study, 25 had durability-factor data. Nineteen of those 25 aggregates are phylloid-algal lithologies. Of those 19, 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 3.8).

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 3.2. 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	DominantMatrix 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. Grnstn	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. Grnstn	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

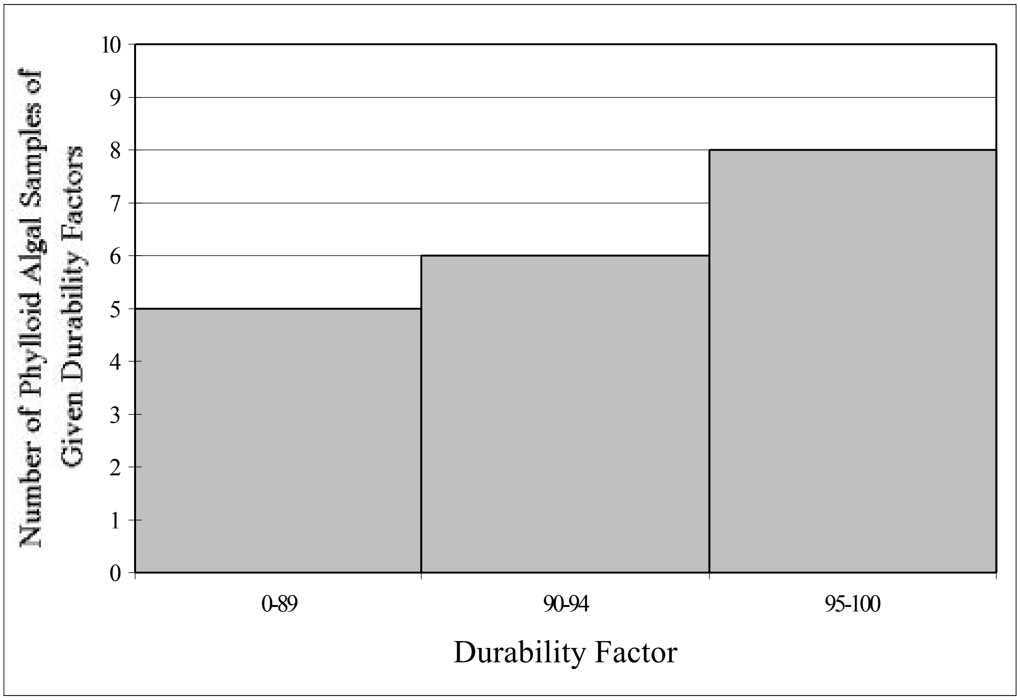

Figure 3.8. Histogram showing the number of samples of phylloid-algal limestone within durability-factor categories.

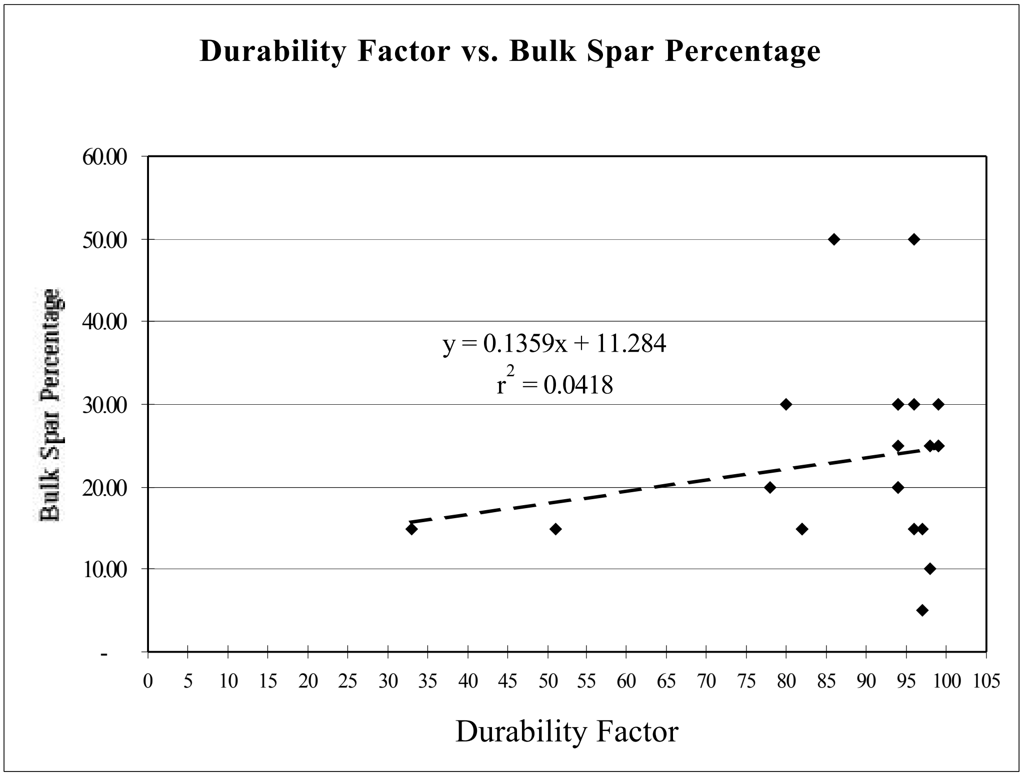

Figure 3.9. XY Plot showing relationship of durability factor to bulk spar percentage (n = 25). The weak relationship suggested is that as bulk spar percentage increases, durability increases.

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 3.9. 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 3.10. 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.

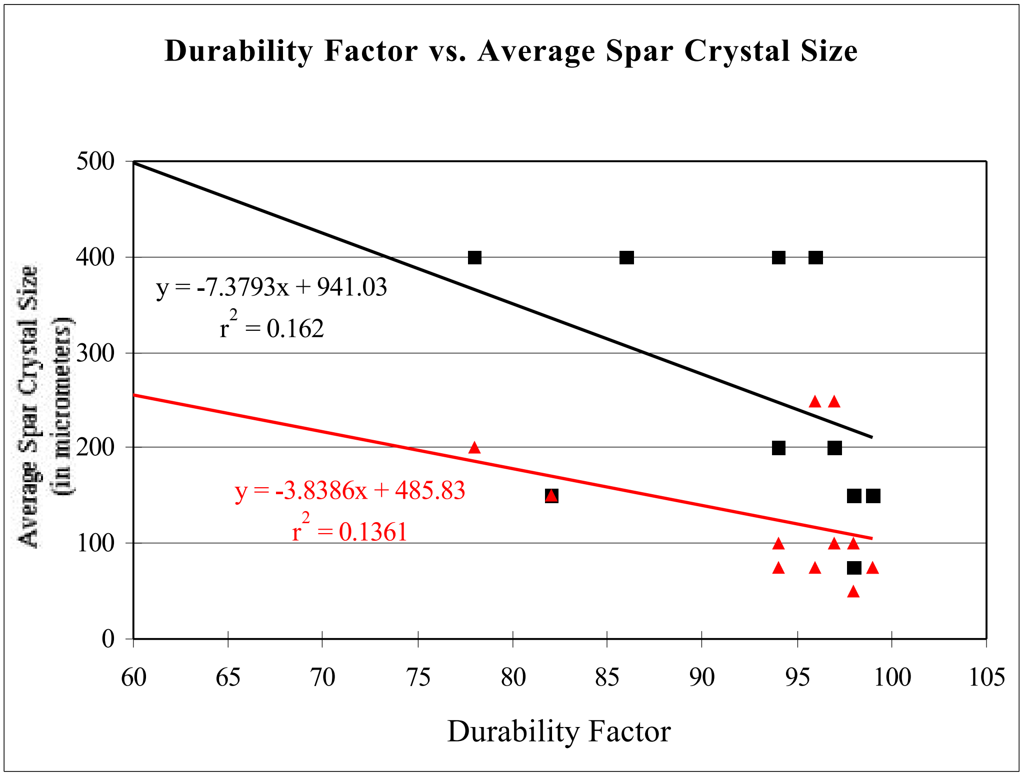

Figure 3.10. XY plot showing the relationship between average crystal size (in micrometers) and durability factor. Triangles represent spar-poor samples (n = 12) and squares are spar-rich samples (n = 12).

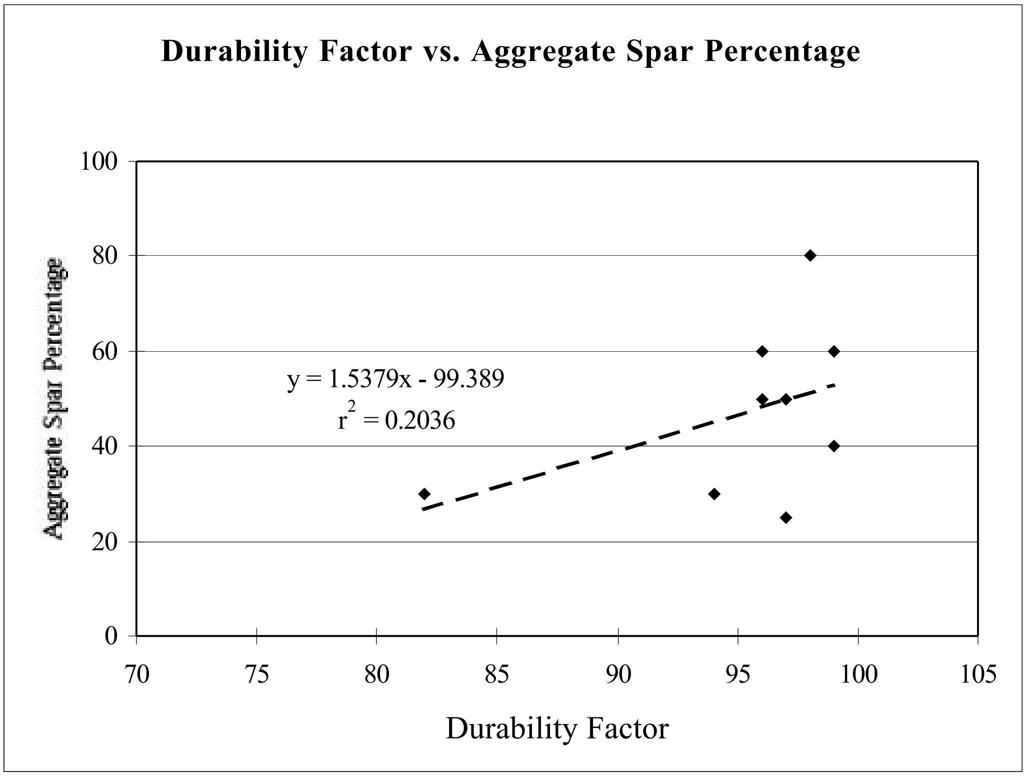

Figure 3.11. XY Plot comparing the total aggregate spar percentage to durability factor (n = 9). The regression line suggests a weak relationship; the higher the aggregate spar percentage the higher the durability.

Aggregate Spar Percentage

Comparison between durability factor and aggregate spar percentage (Fig. 3.11) 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 3.12 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 3.13). 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 3.14). 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 3.15).

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 3.16). A similar, slightly stronger correlation exists between expansion percentage and insoluble residue percentage (Fig. 3.17). 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 reside 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

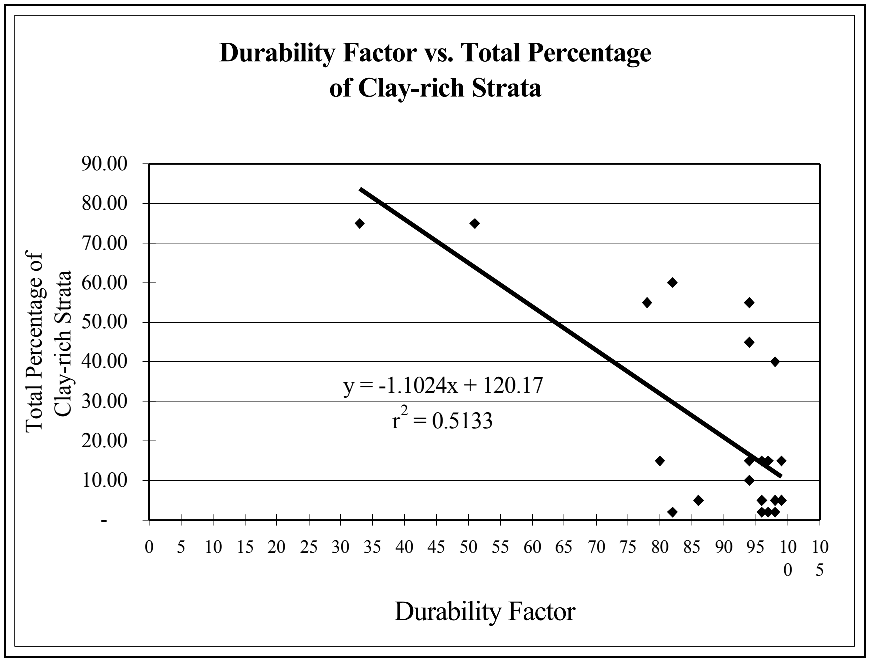

Figure 3.12. XY plot comparing durability factor to total outcrop clay percentage (n = 25). This percentage includes concentrated stylocumulates, diffuse stylolites, and disseminated argillaceous material.

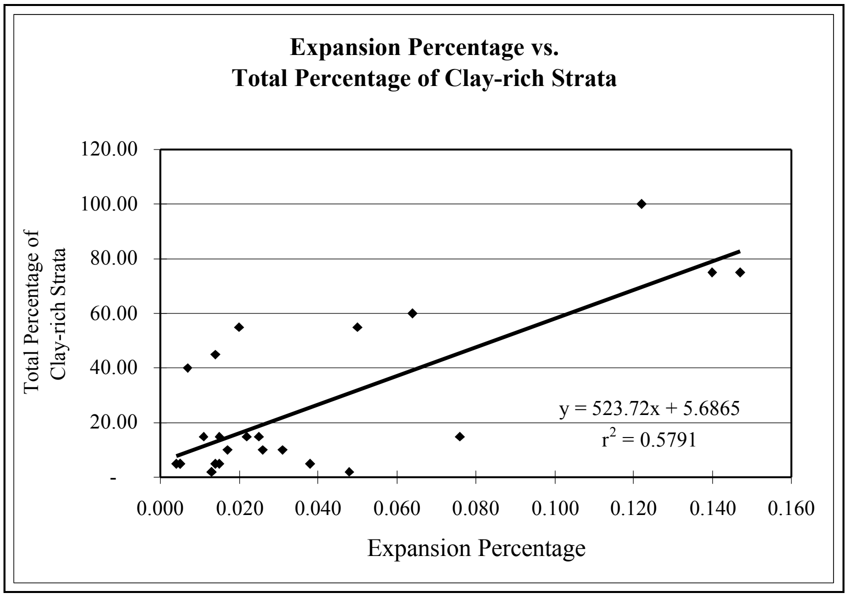

Figure 3.13. XY plot comparing expansion percentage to total outcrop clay percentage (n = 26). This percentage includes all three forms of clay.

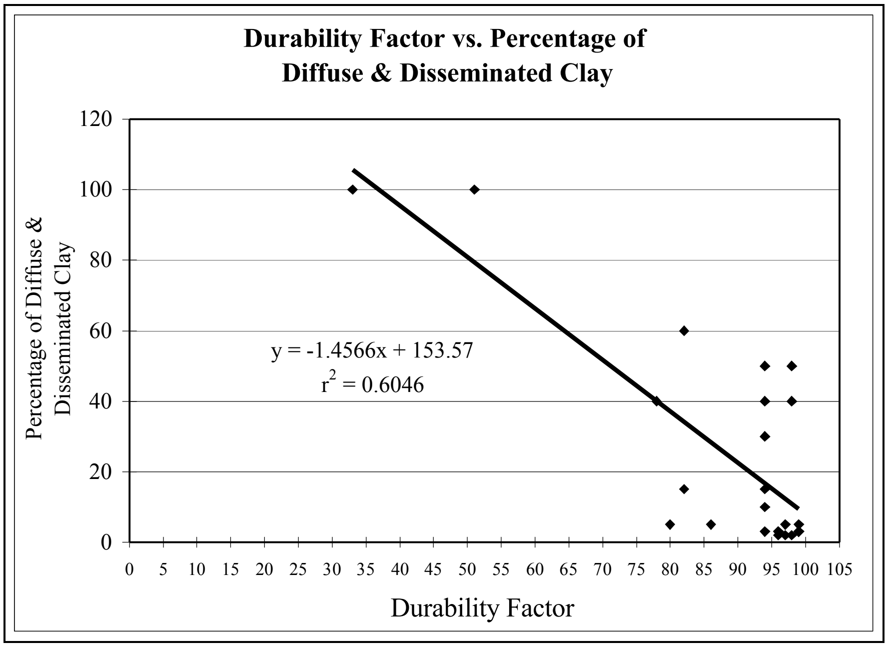

Figure 3.14. XY plot comparing durability factor to the percentage of rock that contains only diffuse stylolites and disseminated argillaceous material (n = 25).

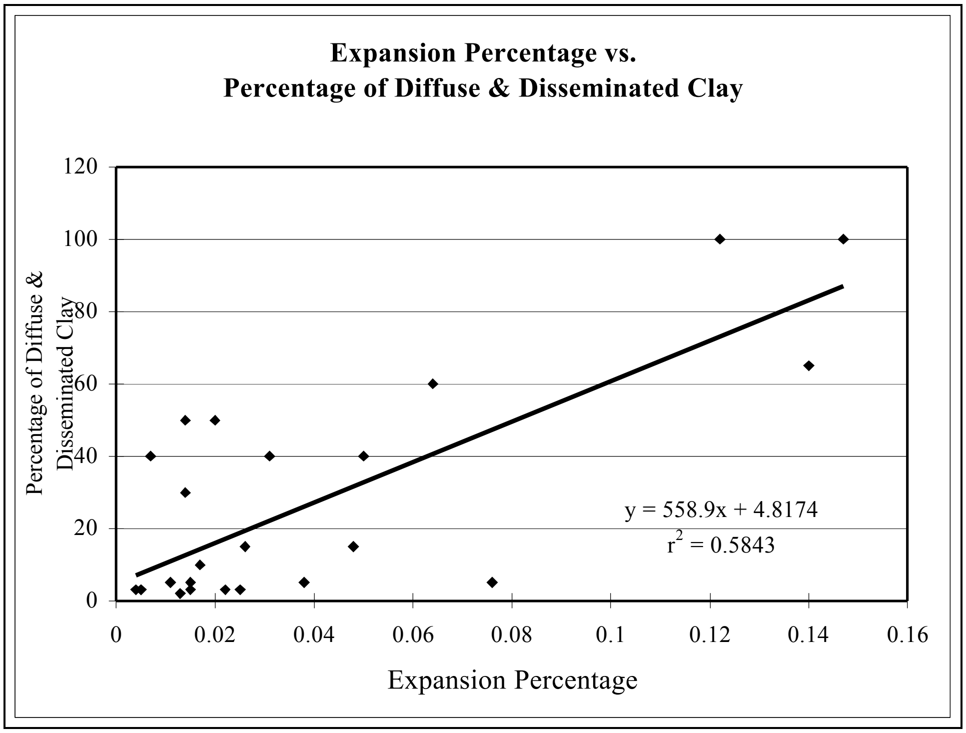

Figure 3.15. XY plot comparing expansion percentage to the percentage of rock that contains only diffuse stylolites or disseminated argillaceous material (n = 26).

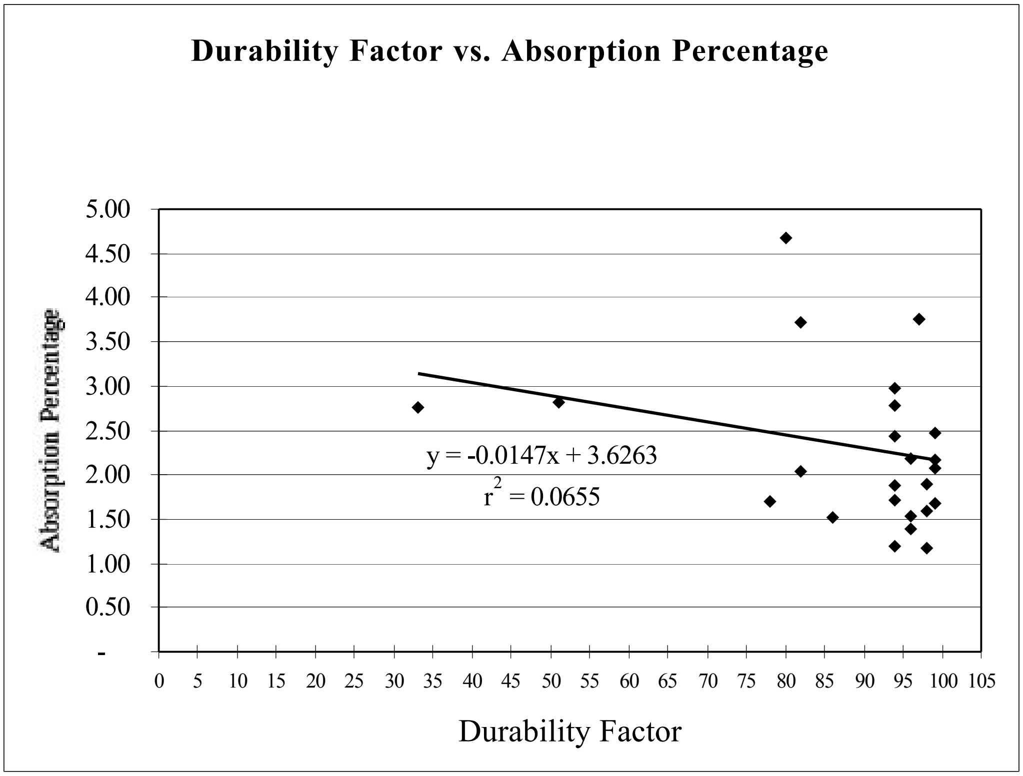

Figure 3.16. XY plot showing the relationship between durability factor and percent insoluble residue (n = 25).

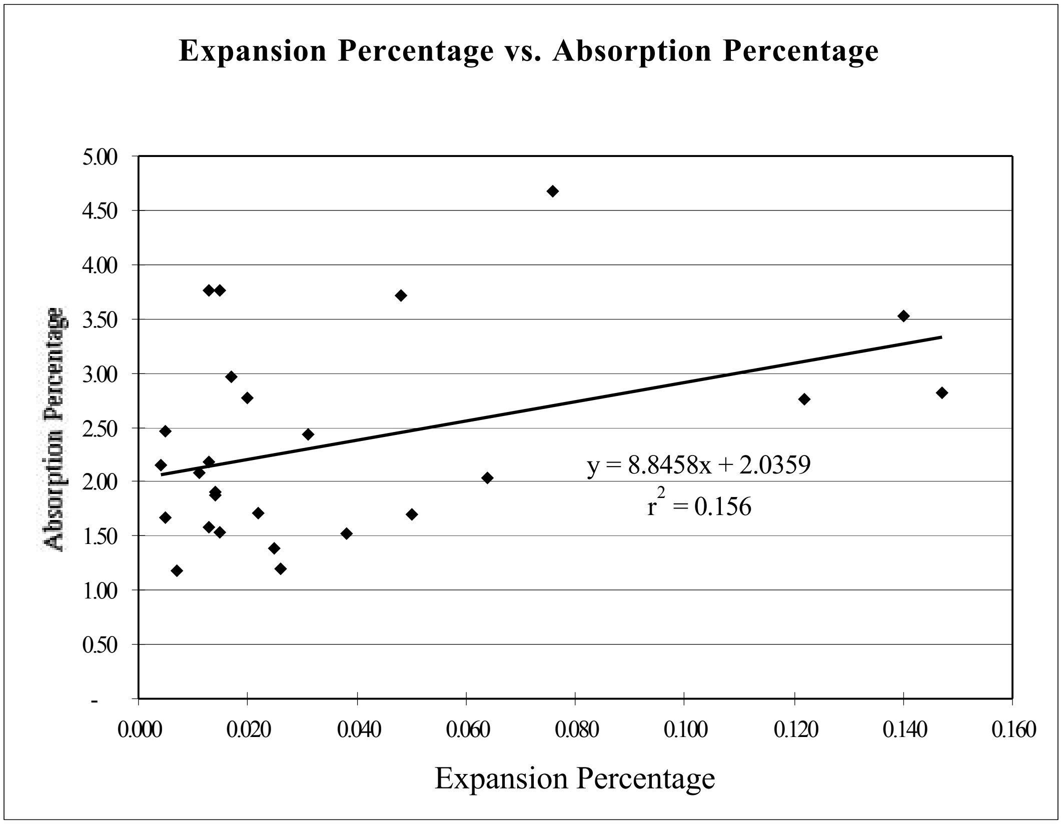

Figure 3.17. XY plot showing the relationship between expansion percentage and percent insoluble residue (n = 26).

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 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 (Fig. 3.18), and the correlation between expansion percentage and absorption is only slightly stronger (Figure 3.19). 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 conclude 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, the following discussion will concentrate on the comparisons that were made to durability factor and expansion percentage.

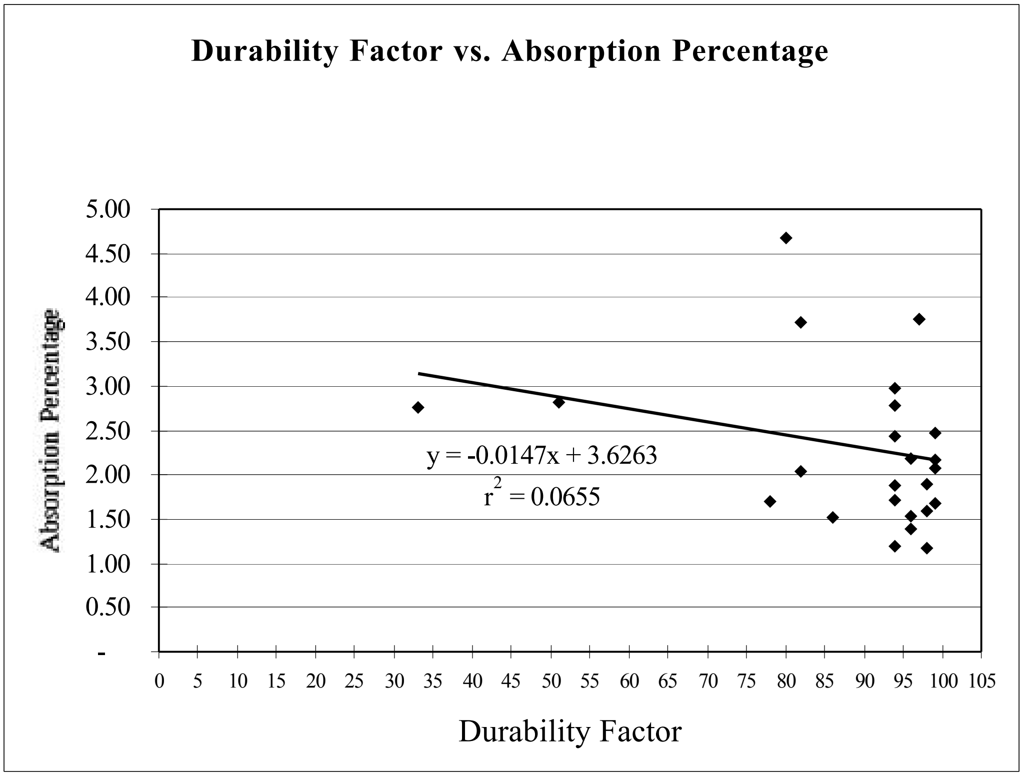

Figure 3.18. XY plot showing the relationship between durability factor and absorption percentage (n = 25).

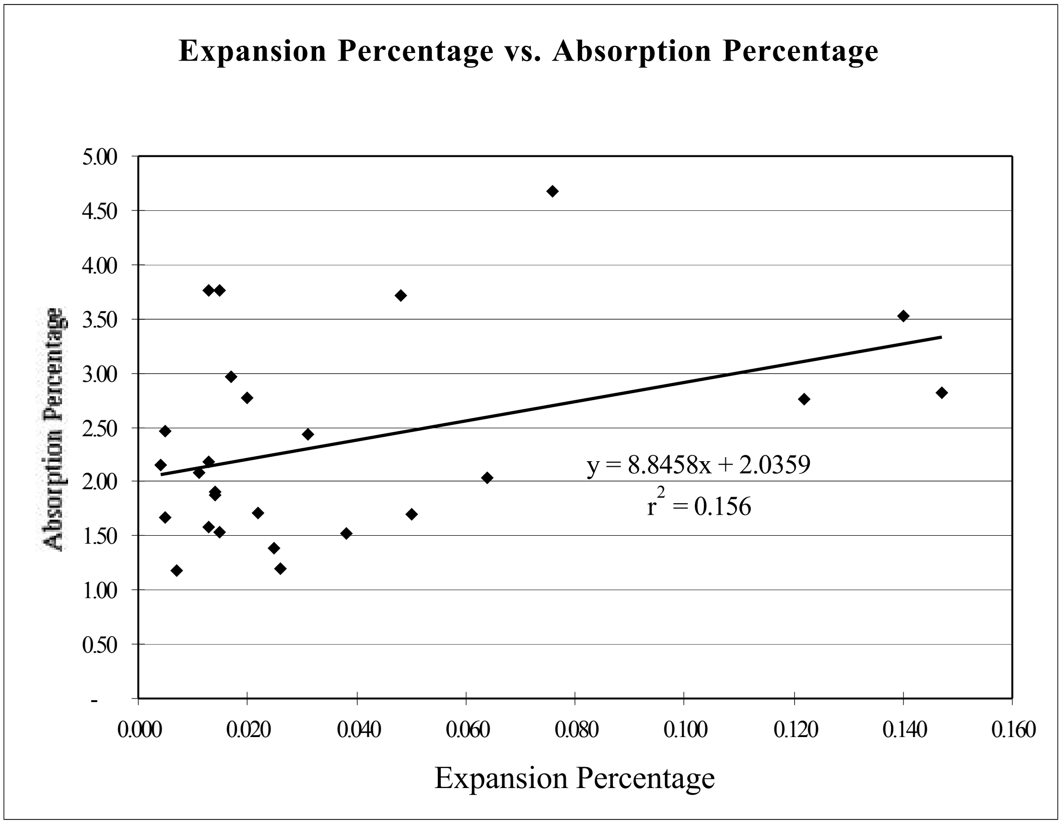

Figure 3.19. XY plot showing the relationship between expansion percentage and absorption percentage (n = 26).

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, 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 (Fig. 3.6), 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