Analysis of Textural and Physical Factors Contributing to the Abrasion Resistance of Some Indiana Carbonate Aggregates

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Introduction

This study was accomplished as a by-product of research under the National Cooperative Highway Research Program (NCHRP) Project 4-2, Degradation of Aggregates, which is being carried out at Purdue University. This paper is restricted to a study of selected crushed stone aggregates in Indiana, these all being carbonate aggregates (limestone, dolomites, and combinations thereof). The overall NCHRP project encompasses various aggregate types from widespread areas.

In the aggregate degradation study the surface wearing effects or abrasion resistance of aggregates has been carefully studied in its relation to the degradation or reduction in size of aggregate masses during and after highway construction. In this regard the investigators were confronted with the problem of ascertaining what factors contributed to the abrasion of rock particles. It was through this search for contributing factors that the data for this paper were obtained.

Review of Textural Analysis of Aggregates

The analysis of aggregate textures in addition to mineral identification and weathering characteristics is accomplished through petrographic examination. This commonly consists of megascopic plus microscopic examination, the latter by use of the petrographic microscope.

Petrography in the geological sense pertains to the description and classification of rocks; this description being primarily microscopic in character. In the field of aggregates, however, there is a trend to include under this title other laboratory determinations involving techniques of mineral identification such as X-ray diffraction, differential thermal analysis electron microscope, infra-red and other analyses. A further discussion of the scope of petrography has been pesented previously by Lounsbury and Schuster (6) and Lounsbury and West (7).

Aggregate textural analysis includes the study of the grain properties such as shape and roundness and the mutual relationships of the grains characterized by orientation and interlock of the various component grains. The bibliography pertaining to rock textures in the geological field is a lengthy one but in the area of aggregates much less has been done in regard to grain texture and aggregate properties or behavior.

A relationship between grain texture and aggregate properties has been noted previously by Rhoades and Mielenz (10), again by Mielenz (9) and more recently by K. Mather (8), and by Gillott (4). West and Aughenbaugh (14) recognized the importance of texture in relation to the aggregate properties in their review of the aggregate degradation problem and Aughenbaugh *et al.* (3) reported on the effect of texture on in-service degradation.

In the past few years petrographic analyses including textural studies have been used in conjunction with other research techniques in a number of aggregate studies made at Purdue University. In unpublished studies by Schuster (12), Aughenbaugh *et al.* (3) and by West *et al.* (15), petrographic techniques were employed in addition to other research activities. Shupe and Lounsbury (11) related skid resistance of carbonate rocks to their petrographic properties, whereas Schuster and Lounsbury (13) made a study of chert and shale constituents in gravels in which petrographic studies were included.

More recently textural analysis has been used in conjunction with engineering test data and has been compared to performance. Lounsbury and West (7) reported on the effect of texture on engineering test values of selected Indiana carbonate aggregates. In addition several other investigators, for example Lemish, Hadley, and others, are working actively on the effect of texture on aggregate behavior.

The petrographic techniques used in this study were essentially those developed in the unpublished report by West *et al.* (15) in conjunction with research on aggregate degradation of base and sub-base material. At present, further refinements in technique are being made as a portion of the current research on NCHRP Project 4-2. This paper, however, does not include the results of the continuing research done for the project on this subject.

Textural Parameters

The petrographic analysis of the aggregate samples was accomplished in three steps, (1) hand specimen examination, (2) polished-section examination, and (3) thin-section analysis.

Hand specimen analysis was used to recognize surface weathering, depth of weathering and gross characteristics of the aggregate such as veins, cracks and large fossils. Polished-sections were viewed megascopically and also microscopically using a stereographic, binocular microscope. Carbonate rocks of a bedded appearance and those of an argillaceous nature were well delineated by this procedure.

In rock thin sections the following characteristics were observed:

1. Average grain size
2. Grain-size distribution
3. Grain roundness
4. Grain interlock
5. Void content
6. Weathering characteristics

The procedure used for making these measurements of thin sections has been described previously by Lounsbury and West (7).

In the laboratory additional tests of a chemical nature were made. These included insoluble residue percentage, the chemical composition of the total aggregate mass, and the insoluble residue material by X-ray diffraction techniques.

Engineering Laboratory Tests

In this study the abrasion resistance of the aggregates was used as a basis of comparison with the textural parameters and in some cases

with other engineering tests. The Los Angeles abrasion machine, ASTM C 535-64T (1), was used to find the abrasion resistance of the aggregates.

The Los Angeles abrasion equipment is widely used by highway departments in the U. S. and is perhaps one of the most popular tests for aggregate quality determination. For this reason it is a useful means for comparing aggregate abrasion resistance.

The Los Angeles abrasion machine consists of a hollow steel cylinder closed at both ends in which a combination of aggregate sample and steel balls is rotated according to the test specifications (1).

Following the test, the sample is sieved. The difference between the original weight and the final weight retained by a #12 sieve is expressed as a percentage of the original weight and reported as the percentage of wear. Therefore, the higher the percentage of wear by the Los Angeles abrasion test the less the abrasive resistance of the rock.

The laboratory test results from other engineering tests were obtained for some of the aggregates. The tests included were bulk specific gravity, saturated surface dried; percent of absorption; and percent loss in sodium sulfate. Further information can be obtained from ASTM standards on these test procedures (1).

Statistical Analysis

After obtaining the textural and engineering test data a multiple regression and correlation analysis was made on the data. This method permits a simultaneous comparison of a number of independent variables to see how they affect the single dependent variable. In this analysis the percentage of wear by Los Angeles abrasion was made the dependent variable and all the other factors were designated independent variables.

This method is particularly valuable in geology because of the numerous variables that act on a single geological problem. There is no simple means of assessing the importance and interaction of these variables without some similar statistical approach.

A simple graph consisting of a straight line relationship between two variables is an example of a regression analysis. The independent variable is conventionally the abscissa and the dependent variable the ordinate. By selecting a value for the independent variable and intersecting the straight line a value for the dependent variable is obtained.

In the multiple regression portion of this analysis each independent variable is paired in turn with the dependent variable. As a result a listing of the independent variables in order of their ability to predict the dependent variable is obtained. These data are given in the form of coefficients for the independent variables used and from these a predicting equation for the dependent variable can be obtained using the independent variables.

Correlation coefficients are also obtained from this analysis. These coefficients are related to the variables through correlation theory rather than regression theory.

The correlation between two parameters or variables is indicated by a number ranging from plus to minus one. The number plus one

indicates perfect correlation between two variables and zero indicates no correlation at all. The sign of these numbers can be plus or minus, plus indicates a direct correlation, for example, as A increases B increases whereas minus indicates a reverse relationship or as A increases, B decreases. Correlation does not imply any dependent variable relationship with respect to arbitrary changes in an independent variable.

Results and Interpretation

In this study four statistical analyses have been made. Twenty-five quarry aggregates were examined prior to this research which compose

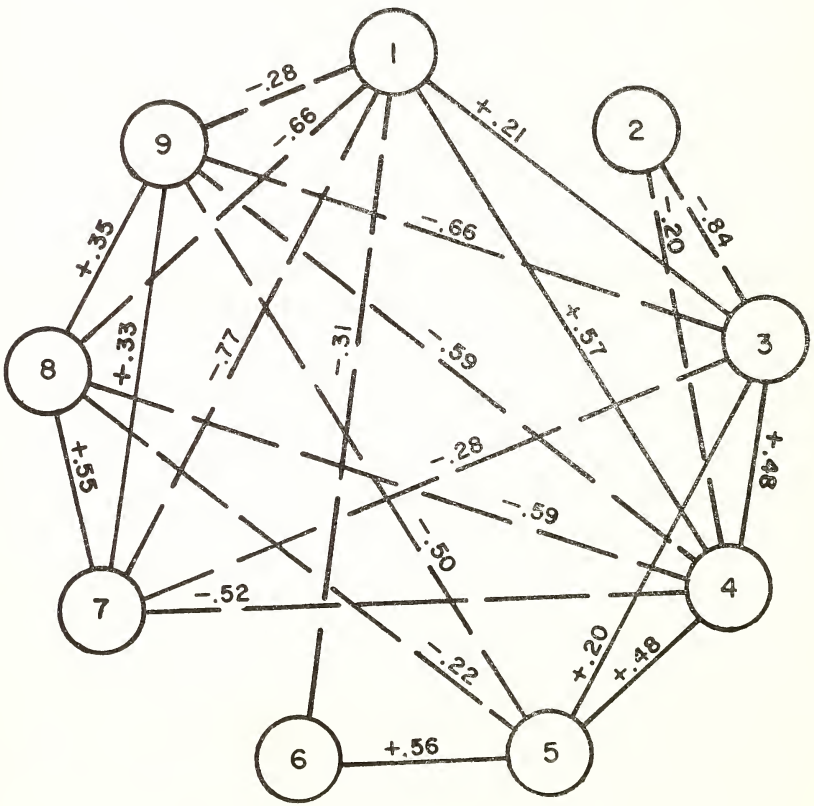

Figure 1

INDIANA I

Cluster Diagram of Simple Correlation Coefficients for Some North-Central Indiana Carbonate Aggregates

LEGEND:

1. Los Angeles Abrasion
2. $CaCO_3$ Content
3. $MgCO_3$ Content
4. Percent Voids
5. Average Grain Size (mm)
6. Grain Size Variation (mm)
7. Grain Shape—Highest number indicates most angular particles
8. Grain Interlock—Highest number indicates best interlock
9. Percent Insoluble Residue

the first analysis. The petrographic characteristics were measured in a somewhat qualitative sense using verbal descriptions and a numerical base was added for programming purposes.

Figure 1 is a simple correlation cluster diagram for this analysis. A simple correlation coefficient shows the relationship between two variables but the problem of inter-relation between the various parameters is not corrected for in this procedure. The cluster diagram shows the simple correlations between parameters measured in pairs. The coefficients which are less than $\pm$ 0.2 have been omitted as these are assumed to be of insignificant importance (5).

Some interesting observations can be made concerning Figure 1 which are summarized as follows:

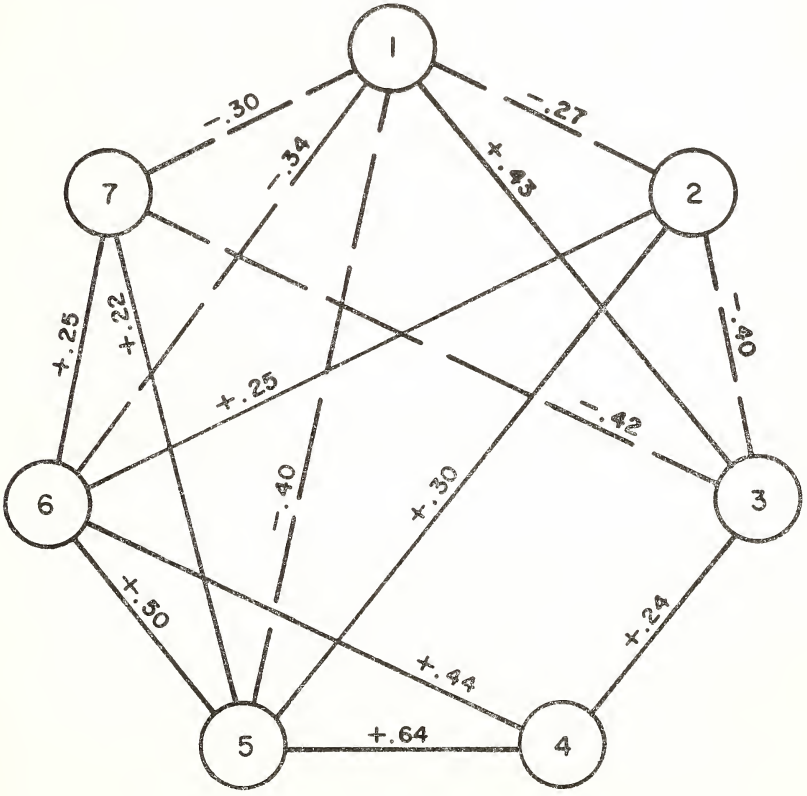

Figure 2

INDIANA I-A

Cluster Diagram of Simple Correlation Coefficients for Some North-Central Indiana Carbonate Aggregates

LEGEND:

1. Los Angeles Abrasion
2. Percent Insoluble Residue
3. Percent Voids
4. Average Grain Size (mm)
5. Grain Size Variation (mm)
6. Grain Shape—Highest number indicates most rounded particles
7. Grain Interlock—Highest number indicates best interlock

1. A positive relationship exists between percent voids and percent loss by Los Angeles abrasion, that is as the voids increase the abrasion loss increases.
2. A strong relationship between $CaCO_3$, $MgCO_3$ and insoluble residue exists. This is to be expected because together they form a closed system of 100%.
3. A positive relationship occurs between $MgCO_3$ and void content. This is due to the fact that many reef dolomites in Indiana have increased voids in comparison with their calcium-rich counterparts.
4. A negative relationship exists between percent loss by Los Angeles abrasion and interlock, that is, as the interlock becomes poorer the abrasion loss gets greater. Also the angularity of the grains decreases as the abrasion loss increases.

Figure 2 is a simple correlation diagram for the same 25 quarry aggregates as used in Figure 1, but numerically based measures were used directly when analyzing the aggregates in this case.

It can be observed in this diagram that:

1. The positive relationship between percent loss by Los Angeles abrasion and percent voids is still indicated.
2. A negative relationship between grain size variation and abrasion loss is indicated. As the aggregate becomes more dense owing to a greater range in grain size the abrasion loss is reduced.
3. The interlock and shape have a lesser effect on abrasion resistance than in Figure 1. This is probably due in part to the fact that these properties are being measured more precisely and side effects have been lessened to some degree.

Figure 3 is a third simple correlation chart. These data were obtained from about 15 quarries through the state of Indiana. In this example, engineering test data other than that for the Los Angeles abrasion test have been obtained. In addition, in-service performance data regarding aggregate degradation have been obtained as well. In this analysis the interplay between various tests, textural properties, and performance is shown. The following conditions are observed:

1. There is a negative relationship between percent loss by Los Angeles abrasion and degradation performance. As the abrasion becomes greater the aggregate is more susceptible to degradation.
2. The positive relationship between void content and abrasion loss persists.
3. A positive relationship between absorption values and bulk specific gravity is indicated.

Figure 4 is a partial correlation coefficient cluster diagram for the same 15 aggregates analyzed for Figure 3. Partial correlation coefficients are used to examine an independent variable paired with the dependent variable while the other independent variables are kept constant or the effect of their presence is kept constant. In other words, the independent

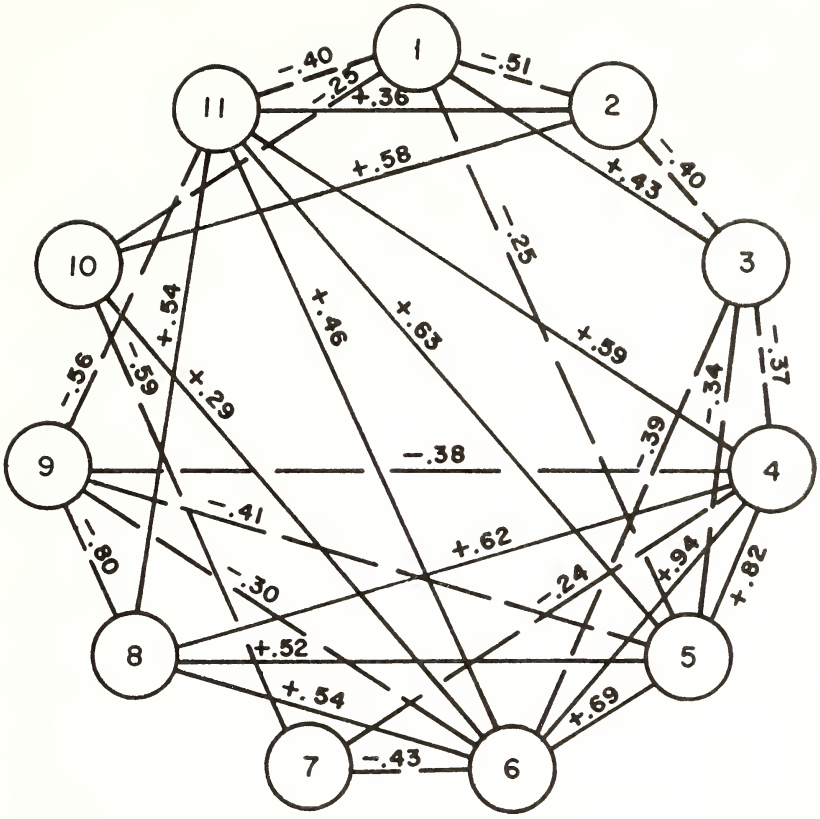

Figure 3

INDIANA II

Cluster Diagram of Simple Correlation Coefficients for Selected Indiana Carbonate Aggregates

LEGEND:

1. Los Angeles Abrasion
2. Percent Insoluble Residue
3. Percent Voids
4. Average Grain Size (mm)
5. Grain Size Variation (mm)
6. Grain Shape—Highest number indicates most rounded particles
7. Grain Interlock—Highest number indicates best interlock
8. Specific Gravity
9. Percent Absorption
10. Percent Loss—Sodium Sulfate Test
11. Degradation Value—Highest number indicates best performance

variable is truly being used independently without the side effects of other variables being noted.

In Figure 4 only five of the ten independent variables actually contribute markedly to changes in the dependent variable. It can be observed that:

1. The insoluble residue component has changed sign from minus to plus between Figures 3 and 4. This means that when the side effects are removed, a direct relation is shown to exist between these two measures.

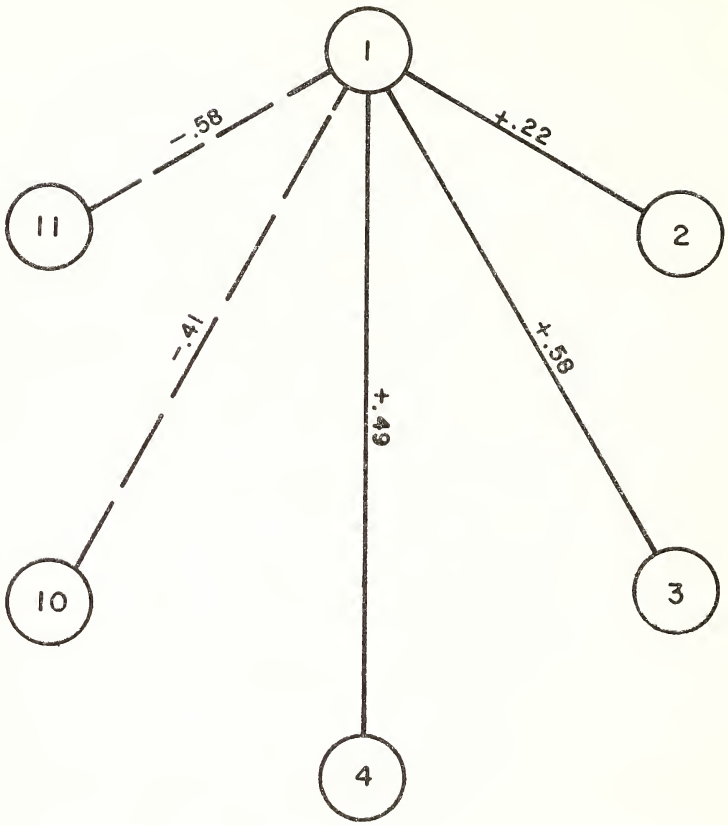

Figure 4

INDIANA II-A

Cluster Diagram of Simple Correlation Coefficients for Selected Indiana Carbonate Aggregates

LEGEND:

1. Los Angeles Abrasion
2. Percent Insoluble Residue
3. Percent Voids
4. Average Grain Size (mm)
5. Grain Size Variation (mm)
6. Grain Shape—Highest number indicates most rounded particles
7. Grain Interlock—Highest number indicates best interlock
8. Specific Gravity
9. Percent Absorption
10. Percent Loss—Sodium Sulfate Test
11. Degradation Value—Highest number indicates best performance

2. The average grain size has emerged as the strong tie with abrasion resistance rather than size distribution which was indicated by simple correlation (Figure 3).
3. The relationship between abrasion resistance and performance in degradation has been strengthened.

As a final point of discussion we can turn once more to the area of multiple regression analysis which has been discussed in the statistical

analysis portion of this paper. The parameters that are significant in regression analysis are the same as those which appear as important partial correlation coefficients. In order of importance for the 15 quarry study (Figures 3 and 4) these parameters are:

1. Insoluble residue
2. Void content
3. Degradation value
4. Average grain diameter
5. Sodium sulfate loss

Together these 5 account for 55% of the variability noted in the percent loss in the Los Angeles abrasion test, that is, they predict 55% of the variability in the abrasion values noted. This means that other factors should be found to account for the remaining variation. This 55% value is somewhat better than the 38% which was obtained for the analysis in Figure 1, however.

The regression analysis yields regression coefficients as well as indicating the order of importance of independent variables. These coefficients can be used to obtain an equation for the curve which best predicts the percent of wear by Los Angeles abrasion. The equation is as follows:

$$X_1 = 32.12863 + 0.14603\ X_2 + 0.68276\ X_3 - 1.5452\ X_{11} + 0.01155\ X_4 - 0.18746\ X_{10}$$

where

X_1 = percent loss, Los Angeles abrasion
X_2 = percent insoluble residue
X_3 = percent voids
X_4 = Average grain diameter (mm)
X_5 = Grain size variation (mm)
X_6 = Grain shape
X_7 = Grain interlock
X_8 = Specific gravity
X_9 = Percent absorption
X_{10} = Percent loss, Sodium Sulfate
X_{11} = Degradation Evaluation

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