

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM  
REPORT

98

**TESTS FOR  
EVALUATING DEGRADATION OF  
BASE COURSE AGGREGATES**

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM  
REPORT **98**

# TESTS FOR EVALUATING DEGRADATION OF BASE COURSE AGGREGATES

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION  
OF STATE HIGHWAY OFFICIALS IN COOPERATION  
WITH THE BUREAU OF PUBLIC ROADS

SUBJECT CLASSIFICATIONS  
MINERAL AGGREGATES  
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## **NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM**

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Transportation.

The Highway Research Board of the National Academy of Sciences-National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity, it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway departments and by committees of AASHO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Highway Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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This report was prepared by the contracting research agency. It has been reviewed by the appropriate Advisory Panel for clarity, documentation, and fulfillment of the contract. It has been accepted by the Highway Research Board and published in the interest of effective dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

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## FOREWORD

*By Staff*

*Highway Research Board*

This report contains a proposed procedure for determining the suitability of natural aggregates for use as base and subbase courses of pavement structures. Although the full procedure has not been used by a highway department, its development has depended heavily on existing tests and petrographic analysis data of aggregates from sources with reported performance histories. Individual highway agencies will need to determine limits of acceptability for use with the procedure, taking into consideration such factors as climatic conditions, traffic loads, economics, and desired pavement performance levels. Highway materials and testing engineers, specification writers, and pavement designers will find the report of particular value. Construction engineers, aggregate suppliers, and others, such as geologists, soil engineers and petrographers, should also find the information of interest.

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Determining the acceptability of aggregates for use in construction continues to be a problem for highway agencies in many parts of the country. The fact that more than 90 percent of the materials used in roadway construction are aggregates (currently about 750 million tons annually) serves to demonstrate the importance of adequate attention to proper utilization of this important natural resource. Although aggregates are subjected to different conditions when used in base courses, bituminous mixtures, portland cement concrete pavements, and structural components of highways, testing to ascertain suitability has historically been rather uniform for all uses, with the general criterion being to use the highest quality material available. Only recently has attention been directed to the need for a separate set of acceptance procedures and criteria for aggregates according to the function they will serve in the pavement and the level of service desired. In the case of aggregates to be used in a pavement base or subbase course, the degradation (increase in the percentage of fine material) of the aggregate is considered to have a significant influence on pavement performance and test procedures for determining a relative degradation value for a potential aggregate source are needed.

The over-all objective of the study undertaken by the Purdue University researchers was to develop procedures for predicting the amount and effects of degradation for different aggregates when used in a roadway base or subbase course. The use of additives or other methods of modifying the aggregates to reduce the detrimental effects of degradation were not a part of the study. To accomplish the objective, many aggregate samples were obtained from highway agencies, along with test data and information on performance experience. Standard laboratory tests, such as determination of specific gravity, freeze-thaw resistance, and Los Angeles abrasion loss, were conducted by the research agency. Many additional data, primarily of a petrographic nature, were also collected. Finally, an analysis was made of the standard laboratory data, the petrographic information, and reported field

performance to determine the group of tests most likely to predict the degradation of an aggregate source.

It should be recognized that the proposed procedure for predicting the relative degradation of an aggregate used in a base or subbase course and the suggested acceptance values are based solely on the data and performance histories of the aggregates tested during this research and the best engineering judgment of the researchers.

Several concepts, including (1) the grouping of aggregates by types, (2) the analysis of the data from a battery of tests rather than a single test, and (3) increased use of petrographic techniques, appear to provide the means for predicting the degradation potential of an aggregate source to be used in a base course, as well as a useful approach for acceptance testing of aggregates in general, regardless of the intended use.

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Special thanks are extended to the engineers and geologists of the state highway departments and governmental agencies who through their contribution of time, effort, samples, and data helped to make this study possible. The list of these departments and agencies is too lengthy to allow specific mention of all those involved, as only a few of the 50 state highway departments have not contributed in some way. Only through this enormous cooperation were the numerous samples and accompanying data, used in this study, amassed for further testing and analysis.

The authors are indebted to R. W. Lounsbury, Professor of Geology, formerly of Purdue University, and to Professor E. J. Yoder, of the School of Civil Engineering, Purdue University, who served as consultants to the project. Recognition is also made of the efforts of R. C. Parks, who prepared the illustrations



# TESTS FOR EVALUATING DEGRADATION OF BASE COURSE AGGREGATES

## SUMMARY

Base course degradation has been recognized recently as a serious highway engineering problem. Since the early 1900's interest has grown in aggregate degradation and today considerable research is being conducted in this area.

In 1963, the National Cooperative Highway Research Program contracted with Purdue University for research on degradation of base and subbase materials. The suggested aims and accomplishments of the proposal included analysis of aggregate textures and their influence on degradation and engineering tests; compilation and correlation of these data, which would hopefully yield a new test for base course degradation; and analysis of a selected quarry to determine the effects of aggregate milling and processing.

Following an initial information gathering phase, aggregate samples were collected from 140 separate quarry sources in twelve states. These were supplied by state highway departments or collected with their aid. The aggregates were divided into four groups before examination—carbonates and clastic sedimentaries, coarse-grained igneous and metamorphics, basalts and basalt-like rocks, and heterogeneous gravels.

During the study determinations were obtained on most of the samples for (1) percent loss, Los Angeles abrasion; (2) freeze-thaw loss; (3) specific gravity; (4) percent absorption; (5) insoluble residue; (6) differential thermal analysis; (7) X-ray diffraction analysis; (8) petrographic analysis, including (a) polished section, and (b) thin section grain size, matrix size, grain roundness and grain interlock, grain, matrix and void content, maximum-minimum length of grain ratio, and matrix length-grain length ratio.

In the petrographic analysis, 200 grains were measured per thin section. All of the foregoing data were statistically compared using multiple correlation and regression analysis, as well as analysis of variance.

Based on the results of the investigation, the following conclusions were reached:

### *Los Angeles Abrasion*

1. Los Angeles abrasion loss is inversely related to the degradation resistance of carbonates and is a reliable estimator of carbonate degradation.

2. Aggregates with higher abrasion losses generally produce more fines. Argillaceous carbonates and graywacke sandstones may produce more fines than their relative abrasion value suggests.

3. For acceptable carbonate aggregates, abrasion by the Los Angeles machine occurs primarily by the removal of surface material. In aggregates with greater abrasion loss, fracture of aggregate particles also occurs.

### *Thin Section Analysis*

4. In general, average grain diameter is directly related to abrasion loss. For coarse-grained carbonates (>0.1 mm) in particular, an increased abrasion occurs with increased grain size.

5. High void percentage in carbonates increases Los Angeles abrasion. Many carbonates show no voids petrographically; but, as other factors influence abrasion, absence of voids does not insure low abrasion loss.

6. Carbonate freeze-thaw values are directly related to Los Angeles abrasion and inversely to degradation resistance. The measure is not as correlative with degradation as is Los Angeles abrasion.

7. Grain roundness and interlock were not found to be correlative with abrasion resistance for carbonates.

8. For relatively homogeneous rocks the variation in grain size between adjacent carbonate thin sections is less than between aggregate samples selected from the quarry. These samples, in turn, show less variation than that obtained between quarries.

9. In heterogeneous carbonate quarries, textural data are needed for each lithology or the variation among the limited measurements will approach that between separate quarries.

10. The remaining parameters measured in thin section (see previous list) were not particularly correlative with abrasion loss or degradation value.

11. Surface-volume values of textures were found to be extremely dependent on grain size rather than on grain shape or angularity.

### *Other Aggregate Relationships*

12. For coarse-grained igneous and metamorphic rocks, average size, freeze-thaw and abrasion loss are directly correlative among themselves but inversely correlative with degradation resistance.

13. For basalts, Los Angeles abrasion loss is not correlative with degradation value. Petrographic analysis in which the contents of such deleterious materials as volcanic glass and the minerals palagonite and chlorophaeite are determined, is the most promising technique available for indicating a degradation-prone basalt.

### *Indiana Quarry Study*

14. In the Indiana quarry study no significant variation within horizontal beds and a quite significant variation vertically among these beds was indicated through the analysis of Los Angeles abrasion data.

15. The three formational units were not transported to the processing plant in the same proportions in which they were present in the quarry.

16. The quarry unit with the highest average Los Angeles abrasion loss reduced most in percentage during processing, thus emphasizing its lower abrasion resistance.

17. The average loss on abrasion during and after processing was less than that measured in the quarry face.

### *Aggregate Abrasion Test*

18. A test for aggregate degradation for base and subbase material is proposed. Aggregates are divided into three groups, each of which has its own test procedure. These groups are (1) carbonates, clastic sedimentaries, and coarse-

grained igneous and metamorphic rocks; (2) basalt and basalt-like aggregates; and (3) heterogeneous gravels. Suggested tests for group 1 are Los Angeles abrasion, freeze-thaw, and limited petrographic tests; for group 2, Los Angeles abrasion, wet Los Angeles abrasion, freeze-thaw, and a complete microscopic petrographic analysis; for group 3, Los Angeles abrasion, freeze-thaw, and a megascopic examination of the gravel particles. General limitations for acceptable aggregates are made with the understanding that such values are a function of the local factors of climate, soil type, traffic, construction practice, and expected service.

## CHAPTER ONE

# INTRODUCTION AND RESEARCH APPROACH

The term "degradation," when used in a general way, pertains to a reduction in rank or in condition. Applied specifically in the area of geology and geomorphology, it means mechanical erosion or the wearing away of a land-mass. In the field of aggregates, degradation takes on another specific meaning which, nevertheless, may differ somewhat among various investigators. Defined in its broadest sense, aggregate degradation is the breakdown of aggregate pieces into smaller particles through chemical and/or physical processes. This definition embraces all aspects of aggregate breakdown, allowing for greater coverage of the subject, and as such serves as the basis for this discussion.

Two distinct mechanisms of degradation seem to be operating. The first is primarily mechanical in nature and occurs through the attrition of the aggregate pieces. The second occurs through the change of seemingly sound mineral constituents to a weak rock-water mixture in the presence of water and under applied loads. This latter mechanism is termed chemical degradation, as it appears that some mineralogical change of the affected aggregate occurs during this process. It may be argued that both mechanisms involve the reduction of large pieces into smaller ones, hence are both mechanical in nature. Yet a distinction between the two processes does exist, so that the problem becomes one of semantics alone. These terms seem most suitable to the authors.

Degradation may occur at several different intervals in the sequence of events from aggregate sizing until placement in service and even sometimes thereafter. Degradation during stockpiling, handling, and transporting is always a possibility. Construction degradation, most of which occurs during compaction, is considered to be an important factor. Lastly, in-service degradation, which occurs during the life of the pavement, is another contributor to the over-all problem

## CAUSES OF DEGRADATION

In recent years a widespread interest in the aggregate degradation problem has become apparent in this country and elsewhere in the world. Although aggregate degradation was recognized to some degree as early as the turn of this century, the present increased interest is of a fairly recent origin. This is due primarily to the concentrated efforts to improve pavement performance through materials research and proper quality control.

Aggregate degradation has been reported in several areas of highway construction. This is to be expected, because of the many ways in which aggregates are used as an engineering material. In seeking to unravel the various problems, some degradation studies were concerned only with base and subbase materials, some with bituminous mixes and surface courses, and still others with concrete aggregate uses. Because the various research programs were originated to solve different aggregate problems, the method of approach, the scope, and the objectives of each study have differed. Through the comparison of results, however, much useful information on the general subject of degradation can be compiled.

Several factors account for the current increased interest in aggregate degradation. Modern highway and airfield designs require greater densities in the aggregate masses than were previously specified. To achieve this end, "super-compactors" have been introduced that impose greater stresses on the aggregate during the construction phase. In-service demands on modern pavements are also more stringent as high-speed travel and increased traffic volume require better pavement performance. To insure such behavior, the design aggregate gradation and state of compaction must be achieved and maintained throughout the pavement life.

As previously indicated, aggregate degradation can occur (1) in bituminous mixes and surface coats, (2) in concrete aggregates, and (3) in base and subbase materials. This

research, however, was restricted to the degradation of base and subbase material and as such was concerned only with the aggregate material lying below the surface course or the concrete pavement and above the subgrade soil.

The physical and chemical processes that cause degradation can act singly or in combination. Aggregate degradation commonly results from the combined action of both processes, with one playing a vastly dominant role. Some investigators, who have worked with problems where one process has been dominant, have unrealistically considered all degradation to be the end product of that process. This explains why several different definitions have been proposed for aggregate degradation.

Aggregate degradation is not always detrimental and the general definition of the term does not make this a necessary supposition. Several states actually rely on limited breakdown during placement of the base course to yield the desired density. At present, detrimental considerations far outweigh any beneficial ones, but future investigations may show some important contributions in special cases.

Degradation is detrimental if it adversely alters the design or function of a road or structure. Some of the harmful effects that degradation can create are:

1. Raveling and instability in bituminous mixes.
2. Loss of base course support.
3. Excessive and differential settlement.
4. Reduction of drainage.
5. Creation of frost-susceptible material.
6. Distress in portland cement concrete.

Items 1 and 6 pertain to degradation outside of the realm of base and subbase material. They do, however, aid in understanding the problem as it pertains to base courses and are helpful from an over-all point of view. In the following paragraphs, the harmful effect of aggregate degradation is discussed. Only limited reference is made to specific publications pertaining to the discussion, as these are generally reserved for the literature review section which follows.

The harmful effects of aggregate degradation were first noticed in bituminous surface courses. The change in the design gradation through degradation caused an increase in aggregate surface area, which resulted in raveling and instability in the affected pavement. As a result, much of the early degradation research was done by investigators in the field of bituminous pavement design. The problem has not been eliminated, but engineers in the bituminous pavement field are aware that aggregates do undergo some crushing during rolling, which causes an increase in aggregate surface area and must be considered in the original design.

The loss of base course support has been reported by the investigators in the northwestern states of Washington, Oregon, and Idaho. Degradation of certain basalt aggregates creates excessive amounts of plastic fines in the base courses and overlays. The degraded plastic material yields a loss of pavement support, resulting in surface cracking and breakup of the bituminous surface course.

Degradation allows further densification to occur in the aggregate mass after construction compaction has been completed. Continued aggregate breakdown causes densification as cohesionless particles are reduced in size and

differential settlement can ensue. This detrimental effect has not been identified positively as a principal cause of highway settlement because other phenomena can cause similar results and extensive studies are seldom made in the failure area to see why the failure occurred. However, loss of grade owing to degradation and subsequent densification has been documented for railroad ballast (Goldbeck, 1948).\*

The permeability of a base course can be appreciably altered by aggregate degradation. Some coarse, granular, free-drained base courses develop pumping after a few years of service. In many cases this pumping is due to subgrade intrusion, but in other instances the failure is caused at least in part by degradation of the base course. This breakdown of aggregates yields fines that reduce the drainage of the course itself. A reduction of drainage can also cause a reduction in strength of the base course.

In regions where frost action is a problem, degradation can produce frost-susceptible materials in the base. Only a small amount of silt-size fines are needed to render a base course frost-susceptible. The U.S. Army Corps of Engineers has encountered this problem in some jet runways (Aughenbaugh et al, 1963).

Degradation of certain portland cement concrete aggregates in the mixer has been reported (Vaugh, 1943). This reduction in size is similar to that produced by the tumbling and ball mill action of the Los Angeles abrasion machine. This mechanism is discussed in the testing portion of this discussion. The increase in surface area of the aggregate can cause a reduction in strength, a decrease in workability, and a change in the concrete pore size and interconnection. An interesting point suggested recently (Corlett and DeGast, 1963) is that certain aggregates in concrete may continue to degrade long after the concrete has hardened. Aggregates from rock bodies that have been directionally stressed by earth pressures may undergo degradation resulting from stress relaxation within the rock pieces. This mechanism would expose more surface area of the aggregate and perhaps hasten attack by alkali reaction.

Aggregates may degrade to cause problems other than those mentioned. With the current interest in aggregate quality control, if other harmful effects are present they should be recognized in the near future.

## SEGREGATION AND CONTROL

Intimately associated with aggregate degradation is the problem of segregation. Segregation may be defined as the separation of a non-representative portion of a mixture from the total mass. The possible confusion between segregation and degradation was suggested at an early stage of this research through a communication with Harold Allen (1963), recently retired as Head of Research, U. S. Bureau of Public Roads.

When segregation of an aggregate mass occurs during processing or transportation it may be mistaken for a change in the gradation of the entire mixture; i.e., degrada-

\* References throughout this report are to entries in the bibliography (Appendix I)

tion. A comparison of results taken at progressive locations during aggregate processing may indeed suggest an increase in material of finer size. However, segregation of the finer material may have occurred, rather than degradation.

The effect of segregation during stockpiling has been studied in detail (*NCHRP Reports 5 and 65*). It has been shown that the method of forming stockpiles and removing material from them greatly affects the degree of segregation that occurs. If improper stockpiling procedures are used, sampling at progressive locations in the aggregate process may suggest degradation, although in reality segregation has occurred.

Aggregate quality control is another feature closely related to aggregate degradation. A natural variation in gradation exists between samples of an aggregate mass, so that sufficient samples must be taken to determine this variation. This may become a statistical sampling problem in some cases, if sizeable variation occurs in the gradation. Degradation is indicated by successive tests only if a greater reduction in grain size is observed than is to be expected for the sample variation at any one point during processing.

Pit-run gravels pose the greatest problem for gradation control. Owing to the mode of formation of gravel deposits, particle size gradation can vary both vertically and horizontally in the gravel pit. Although preliminary tests indicate an acceptable gradation, the natural variation may be great enough to yield a considerable change in gradation from place to place in the gravel deposit, with the net effect that in some locations the gradation is outside the specified limits. The problem becomes apparent when a gradation test is made on a sample from a subsequent location in the gravel bank following its transportation or compaction. If a greater percentage of fine material is found than in the preliminary test, the change cannot necessarily be attributed to degradation. Only in a testing program where the same aggregate batch is sampled repeatedly at various points in the process (with a statistically substantial number of samples each time) can it be determined if degradation is occurring enroute.

In summary, both segregation of material during stockpiling and transportation and the natural variation of gradation of the aggregate must be considered when degradation is being determined. This places certain restrictions on the sampling of aggregate masses suspect of degradation.

#### STATEMENT OF THE RESEARCH PROBLEM

The objective of this study was to develop procedures for predicting the amount and effects of degradation to be expected from different aggregates and to develop techniques for upgrading these aggregates for economic use in highway pavement structures.

The problem was specifically limited to aggregate materials used in the base or subbase of the highway pavement. This eliminates the consideration of degradation in bituminous mixes, surface courses, and portland cement concrete. It also excludes the use of additives and admixtures in the base course, such as bituminous binders. The problem includes only the use of rock particles as a loose aggregate mass when used in base and subbase courses.

A research plan was drawn up at the beginning of the project which had as its final goal the better understanding of predicting properties of degrading aggregates. This initial plan was altered only in response to the continuing research developments. The study included aggregates from throughout the United States which were described petrographically (using rock descriptions) and by engineering tests and performance evaluations. A comparison of results from these data was used to depict aggregates most susceptible to degradation. In view of the number of samples examined, the rock properties measured, and the engineering tests performed, statistical analysis of the data became a necessary tool for the investigation of the problem. In this report the relationship among aggregate textures, engineering tests, and the resistance to aggregate degradation is explored.

#### REVIEW OF THE LITERATURE

##### Degradation

The effects of aggregate degradation were first recognized in the United States near the turn of the century. Degradation became apparent when certain road surfaces were observed to undergo significant breakdown from horses' hoofs and buggy wheels, whereas other road surfaces were less affected. It was also during this period that the first detailed studies of the properties and performance of aggregates were made by Lord (1916) and Jackson (1916), whose findings apply in a general way today.

The mid-1930's marked the next important period of activity in aggregate studies. Investigators at this time attempted to reproduce field conditions in the laboratory by the use of model rollers and roadways. The designs differed considerably; for example, Goldbeck et al. (1934) used a circular track apparatus, whereas Tremper (1935) designed a movable rectangular box with a stationary roller to simulate actual conditions. This work advanced the knowledge of aggregate and pavement relationships; but because of the bulky nature of the equipment and the time-consuming aspects of the procedure, the tests could not be adapted to routine aggregate evaluation. During this same period the Los Angeles abrasion test was developed and in due course determined to be a practical laboratory test for aggregate quality (Rothgery, 1936).

Macnaughton (1937) investigated the effects of aggregate degradation in bituminous mixtures through laboratory compaction tests and observation of in-service pavement performance. Many factors were considered; for example, the method and degree of compaction, gradation, aggregate shape, amount and type of bituminous binder, and the location in the pavement (that is, in the center or near the edge). Aggregate rock type, however, was not considered in the study.

One of the first field studies on aggregate degradation was made in the late 1930's by Shelburne (1939), who investigated the crushing effects of steel-wheel rollers on aggregate particles for surface treatment and compared the field performance of the aggregate with the Los Angeles abrasion test results.

In the early 1940's two studies were made on the proper-

ties of road-making aggregates at the University of Witwatersrand, South Africa, in which degradation was one of the prime considerations (Croesser, 1944; Laburn, 1942). The professor who supervised these studies later conducted a three-year field and laboratory study on the factors that affect aggregate breakdown in asphalt mixes (Knight, 1953). He emphasized the importance of aggregate degradation to the highway engineer in a book which is a descriptive summary of aggregate properties and testing procedures to that date (Knight and Knight, 1948).

As an active agency in aggregate research, the British Road Research Laboratory has considered degradation in its studies. Shergold (1948) of this research organization made a literature search to evaluate the ability of physical tests to predict the in-service behavior of road-building aggregates. Degradation was one of the factors considered. He used statistical methods to rate physical tests according to their ability to indicate the performance and quality of the aggregate. Rock type was taken into account in the comparison. The Laboratory later conducted a three-year field study of degradation in surface-dressing. Some of the variables considered were (a) weight of roller, (b) number of roller passes, (c) rock type, (d) grading, (e) particle shape, and (f) binder effect (Shergold, 1954).

The late 1940's and early 1950's marked a period of increasing numbers of aggregate-quality investigations, but only a few of the studies considered the aspect of aggregate breakdown. Among the more notable ones that did include degradation were the studies by Melville (1948), Metcalf and Goetz (1949), and Philippi (1952). Melville attempted to devise a special laboratory test that would indicate aggregate susceptibility to in-service degradation. This study was begun shortly after the failure of several surface-treated, waterbound macadam pavements in Virginia a few years following construction. Metcalf and Goetz made a special study of sandstone in bituminous mixes to see if sandstone could be used in areas where more durable aggregates were lacking. One of the primary considerations in the study was the degradation of the sandstone. Philippi investigated nine different types of laboratory compaction equipment to ascertain how well they reproduced the amount of degradation and the degree of density obtained in the field.

The northwestern states in a large degree are responsible for the present impetus in aggregate degradation research. The State of Washington experienced considerable trouble in the mid-1950's when new pavements showed undue amounts of distress because of aggregate breakdown. An investigation was made by Turner and Wilson (1956) to determine the cause of aggregate failure and to develop a satisfactory routine test capable of identifying unsatisfactory material. This investigation was the first of many studies conducted in Washington, Idaho, and Oregon on the problem. Some of the results and information are summarized by Sibley (1958), Erickson (1958), Eske and Morris (1959), Minor (1959), Collet et al. (1962), Day (1962), and Harra (1962). In general the problem is described as a degraded mud layer that forms in the base course below the bituminous surface and causes loss of support by the base. The results of these investigations

have established that chemical breakdown is the prime cause of degradation in that part of the country.

Degradation research in other parts of the country has indicated that physical breakdown is equally important. Two studies completed at Purdue University have demonstrated that physical degradation can occur in significant amounts and is able to cause serious detrimental changes in design gradations. Moavenzadeh and Goetz (1963) studied the effects of gradation in bituminous mixes, utilizing a gyratory compactor. Aughenbaugh et al. (1962) made a field and laboratory study on construction compaction breakdown of aggregates and the effects of the fines on the frost susceptibility of the resulting base course material.

Other investigations have been made recently on the subject of degradation. T.W. Smith (1963) has reported on the durability of aggregates for highway construction. This report forms the basis for specifications concerning degradation in California. A study in New York State on a particular rock type (graywacke sandstone) that was considered for aggregate use also included degradation considerations (Bird, 1957).

Other investigations on the subject of degradation are known to be in progress. The Bureau of Public Roads has indicated that as many as 14 states have conducted research on the subject. Several contracts sponsored by the Bureau of Public Roads and the National Cooperative Highway Research Program deal, at least in a related fashion, with aggregate degradation. Questionnaires distributed in the past (Aughenbaugh et al., 1960, Erickson, 1960, Woolf, 1951) have disclosed considerable activity on the subject by many agencies.

Investigators outside of the United States are presently involved in degradation studies. Shergold, of the British Road Research Laboratory, is still actively involved in this research, having recently reported (1963) on the breakdown of argillaceous rocks under traffic. His results, interestingly enough, indicated that the sodium sulfate test showed evidence of correlation but was too time consuming for routine testing and that absorption and specific gravity data were not correlative.

During the present study, inquiries have been made concerning degradation by several investigators outside of the adjacent United States. The Alaska State Highway Department has inquired about information for their proposed specifications on degradation and New Zealand has inquired about information on the degradation of graywacke-like aggregates, which are so common in that country.

An attempt to give the historical development of aggregate degradation has been presented in this review. A detailed discussion of this subject from a slightly different point of view has been made by West and Aughenbaugh (1964).

#### Petrography

Petrographic techniques have been used extensively in this research project to investigate the relationship between rock textures and aggregate behavior both in laboratory tests and in field performance. In view of this situation, it

is fitting that a brief resume of the development of petrography applied to aggregate studies be presented in this historical review.

Petrography in the geological sense pertains to the description and classification of rocks, usually microscopic in nature. In the field of aggregates, the term petrography may suggest several types of investigations, depending entirely on the agency doing the analysis. In some cases only megascopic examination is included under petrographic analysis and is used to ascertain rock type, gross mineralogy, and weathering aspects. The Petrographic Number designation of the Ontario Highway Department is of this nature (Ontario Department of Mines, 1963). In other instances microscopic examination using the polarizing microscope is made in addition to visual observation.

There is presently a trend also to include several laboratory techniques in the general category of petrographic methods (Lounsbury and West, 1965). These include such tests as differential thermal analysis, X-ray diffraction, insoluble residue determination, and, possibly, electron microscopy and infrared studies

The megascopic and microscopic examination of rock textures has a long and important history in the area of geology. Textural analysis includes the study of the grain properties such as shape and roundness and the mutual relationship of the grains, characterized by orientation and interlock of the various component grains. The bibliography concerning rock textures in the geological field is a lengthy one and cannot be presented here in detail. In the area of aggregates, however, the literature is much less voluminous, because less research has been done concerning grain textures and their effect on aggregate properties or behavior.

In the geological area of texture evaluation, only the statistical analysis of grain parameters is considered here because of their importance in the development of techniques used in this study. The remaining geological aspects are of lesser importance to this development.

Statistical measurements are made microscopically by viewing rock sections through a polarizing microscope. Thin sections are thinly-ground (about 0.03 mm thick) rock slices that are mounted on glass slides by a cement. Light transmitted through non-opaque minerals of this thickness yield diagnostic properties for mineral identification, as well as indicating the shape and orientation of grains and the over-all two-dimensional texture of the rock.

In the mid-1930's one of the first important contributions was made in the area of statistical measurement of grain parameters by Krumbein (1935). He was interested in finding out the gradation of a deposit from thin-section analysis, suggesting that 500 grains be measured and correction coefficients used to adjust thin-section measurement (mean, standard deviation) to those of the deposit.

A great deal of statistical analysis has been done on thin-section compositions by Chayes (1951). He has shown that mineral compositions can be determined by the point counting method. The number of points required is a function of the number of minerals measured and the accuracy desired. Of the limited work done by him on grain-size determinations, Chayes suggests that for igneous

and metamorphic rocks grain-size determination may be difficult because of the irregularly shaped grains involved. In sedimentary rocks with nearly equant grains this problem should be minimized.

More recently, the adjustment of gradations from thin-section measurements to actual gradations have been refined further. Greenman (1951) qualified Krumbein's (1935) early work, and Packham (1955) later augmented this procedure using a slightly different approach. Most recently, Fleming (1965) has suggested 13 truly independent measures to describe the form of particles to replace the usual measures of sphericity and roundness. Numerous other articles are available in the literature on this subject.

In actuality, the most useful information obtained from the literature concerning aggregate textural analysis was (1) the method by which grains can be measured and (2) the suggestion that the number of measurements required is a function of the accuracy desired and the sample itself.

The petrographic approach to aggregate evaluation is a relatively recent development. A relationship between grain texture and aggregate properties was noted by Rhodes and Mielenz (1948) in their discussion on mineral aggregates. In general, they discussed the gross aspects of grain boundaries of various rock types and the directional properties of metamorphic textures, attempting to relate them to aggregate behavior. Mielenz (1955) later discussed the petrographic examination for heterogeneous gravels and occasional thin-section analysis for quarried stone.

K. Mather (1958) made a petrographic study of aggregates previously examined for their pore structure. The aggregates were described in detail, including grain diameters, mineralogy of grains, and composition of the clay fraction. Little attempt was made to relate the petrographic data to the pore characteristics, however.

Gillott (1963) analyzed in detail the petrographic aspects of the Kingston, Ontario, dolomitic limestone aggregate. Some of this material has proved to be reactive and expansive when used in portland cement concrete. He used thin-section examination, X-ray, differential thermal analyses, and insoluble residue determinations to describe the various beds of the problem aggregate. Chemical analyses were made and compared as well, but Gillott was unable to indicate by these methods specifically which beds were reactive and which were not.

Petrography is a tool used today by many investigators who work in the field of highway aggregates. It is applied in differing degrees of preciseness, depending on the problem under study and the researchers involved. The list is too great to mention all those who have contributed to this extent. The following discussion concerning work at Purdue University is presented as an example of the variety of ways in which it has been applied.

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 at Purdue University. In unpublished studies by Schuster (1961), Aughenbaugh et al. (1963), and West et al. (1964), petrographic techniques were employed in addition to other research activities. Moavenzadeh and Goetz

(1963) also used petrography to describe the aggregates used in their research.

In published studies, Shupe and Lounsbury (1958) related skid resistance of carbonate rocks to their petrographic properties and Schuster and Lounsbury (1960) made a study of chert and shale constituents in gravels in which petrographic analysis was included.

The petrographic techniques used in the present study were based on those developed in the research discussed in the unpublished report by West et al. (1964). These procedures and the refinements made on them through continued research formed the basis for the textural studies in this report. A discussion of their development and application is given in the description of laboratory testing.

### RESEARCH APPROACH

The approach used for this three-year research program is given in abbreviated form in the paragraphs that follow. It was developed through periodic appraisal of the accomplishments, followed by adjustments in the research techniques which were thought would best yield the desired objective. A complete discussion of the approach used in this work is given in Appendix A.

Two phases of work, each of about 1½ years duration, were needed to accomplish this research on aggregate degradation. The first phase was used primarily to gather information, although some auxiliary testing was done. In the second phase, laboratory testing and petrographic examination of the aggregates were the primary concern, followed by statistical evaluation of the data and drawing of final conclusions.

In Phase I, information on degrading aggregates was requested from state highway departments and governmental agencies. Some information of this type was already on file at the research agency prior to the initiation of the contract. This was augmented where needed. Data on both good and poor aggregates (with regard to degradation) were requested. In most cases small samples were supplied, along with the engineering test and performance data. Rock thin sections were made from these samples and their textures were studied in some detail. Certain mineralogical and chemical tests also were run on the samples. Much of the information received during the Phase I data collecting stage is presented in Appendix D and Appendix E.

A scale for evaluating the degradation of aggregates was devised during Phase I. A numerical base was used to transform the visual descriptions supplied by the various materials engineers. This number, termed the "degradation value" (DV), is used to designate this evaluation throughout the report. A scale from 1 to 10 was used, with the following designations:

1. Complete degradation.
2. Very poor.
3. Poor.
4. Marginal.
5. Intermediate.
6. Intermediate to good.
7. Good.

8. Very good.

9. Excellent (best in the state, etc.)

10. Perfect with regard to degradation.

This scale is such that numbers 1 and 10 are not easily used to describe any samples, because of their extreme nature. Hence, a value ranging from 2 to 9 was assigned to each description of the samples supplied.

At the start of Phase II it was decided that some standard engineering laboratory tests should be run on the samples. These tests, run on the same pieces of equipment, were necessary to establish a common basis for comparing the aggregate properties. Usually, additional samples of 50 lb each had to be requested from the various highway departments, as the previous sample amounts were too small to allow for this extensive testing program.

It was also decided to concentrate primarily on crushed quarried stone, thus relegating gravels to a less important role. This came about as a consequence of the thin-section petrography studies. The consensus of the investigators was that the greatest contribution to the problem of aggregate degradation could be made in the area of aggregate textures and their influence on the rock properties. The texture of a rock includes the size, shape, and interlocking characteristics of its constituent grains or crystals. Much of this textural work required the use of a petrographic microscope and tedious grain measurements. Heterogeneous gravels, because of their diverse rock types, are not conducive to thin-section analysis of this sort. Hence, less time was spent on the study of gravels, with the additional time spent in concentrated efforts on crushed stone.

The samples supplied by the state highway departments gave good geologic and geographic coverage. Midwest carbonate rocks were augmented by basalts from the northwestern states, gravels from several geographic locations, coarse crystalline rocks from Virginia and Georgia, and diabase from the eastern United States.

Samples were subdivided on the basis of rock type as they arrived. As previously mentioned, gravels were not studied in thin section because of their heterogeneous origins, but detailed megascopic studies were made on some samples. Basalts were put in a class by themselves because of their tendency toward chemical rather than mechanical degradation. Coarse-grained igneous rocks, carbonates, and graywackes were studied as a group.

Aggregates that were inherently weak and obviously degradation-prone were not studied. These included schists, slates, shales, and quartz sandstone. Because these rocks are known to degrade, it was not necessary to devise tests to show that they do. Engineers who have no choice but to use these materials know that they degrade and can take the necessary precautions. The purpose of this study was to delineate the degrading material. The problem of using weak aggregates was assumed to be beyond the scope of this study and can be taken up when studying the type and size of harmful fines.

The laboratory mineralogical tests performed included X-ray diffraction, differential thermal analysis, and limited electron microscope work. Details concerning these techniques are given in Appendix A.



The engineering laboratory tests were begun in earnest at the initiation of Phase II. The following tests were performed on some or all of the aggregate samples:

1. Percentage of wear, Los Angeles abrasion.
2. Breakdown of material by Los Angeles abrasion.
3. Amount of fine material produced in laboratory crushing
4. Mechanism of abrasion in Los Angeles equipment.
5. Freeze-thaw testing of aggregates.
6. Percentage of loss, sodium sulfate testing.
7. Repetitive loading testing.

The specific procedures and problems of testing are presented in Appendix A. Suffice it to say here that the Los Angeles abrasion test and an unconfined aggregate freeze-thaw test (patterned after that of Iowa) were ultimately selected as the two basic tests to run on all the aggregate samples. The decision to use these tests was based on ease of testing and reliability of results.

Three steps were used in the analysis of aggregate textures. Aggregates were examined in hand specimens, in polished sections, and in rock thin sections.

Hand-speciman analysis was used to recognize surface weathering features, depth of weathering, and gross rock characteristics such as veins, cracks, and large fossils. Each rock was named and described on the basis of the conventional tools—knife blade, acid bottle, and hand lens.

Polished sections were made for each sample at the time of thin sectioning. Cut by a diamond saw, the rock slabs were then polished to yield a flat smooth surface for viewing in reflected light. Gross aggregate textures can be noted from polished sections.

Thin sections were made of all the quarried rock samples. Prior to analyzing thin sections of all samples, a study was made to determine the variance in textures of aggregates from place to place in a quarry. The results indicated that the variation of textures within a single rock unit is only significant if it is obvious to a trained petrographer that the rock appearance has changed megascopically.

The technique for analyzing thin sections evolved as the study progressed. In the course of the work, techniques

were worked out for measuring grain size, grain size distribution, grain roundness, grain interlock, void content, and weathering characteristics. These details are presented in Appendix A. Several other techniques were also explored; these, too, are presented in Appendix A. In the final working approach, 200 grains were measured for each thin section to obtain the textural information. In Phase II more than 200 thin sections were analyzed using this time-consuming technique.

Statistical analysis was applied at several points in this research. Statistics were used to show the variation in rock texture with over-all megascopic variation of rock appearance. Analysis also was used to determine the minimum number of grains to measure per thin section and still be statistically meaningful. It was also used to obtain the grain parameters from the thin-section measurements. Finally, a statistical analysis was made of all the engineering laboratory data, the performance data (DV), and thin section data to see what factors were important in determining aggregate degradation.

In this study, the kind and size of fines formed during degradation was not investigated to the degree it might have been. Instead, emphasis was placed on determining which engineering tests and what petrographic parameters are closely related to degrading aggregates as delineated by the degradation value (DV). Degradation manifests itself in so many different forms, and may result in such various types of pavement distress, that a regional study of this type is unable to focus on the specifics of harmful fines for each situation. Such work must be left for later study. It was felt that the delineation of which rocks degrade and what tests indicate that they do is more of a basic consideration.

Neither was considerable effort expended on the development of aggregate beneficiation. By agreement with the contracting agency, this time was spent instead on a textural study of an Indiana quarry to determine the relationship between rock lithologies and engineering tests before and after processing. This is a beneficiation study of sorts and demonstrates the influence of lithologies on rock properties. A complete discussion on the Indiana quarry study is presented in Appendix C.

## CHAPTER TWO

### STUDY FINDINGS

In this study a considerable diversity of problems has been investigated. This was due to the basic nature of the research problem, which involved five distinct areas, as follows:

1. Mineralogical and engineering testing.
2. Petrographic analysis.
3. Statistical analysis of the combined data.

All three of these areas were considered in regard to aggregate degradation directly.

4. Comparison with data from field computation degradation.

5. The Indiana quarry study.

Problems were encountered and solved within each of the basic areas as the study continued and was ultimately brought to an end. The conclusions can best be listed under the five-fold framework of the problem.

A detailed development of the results from each of these five categories is presented in Appendix B. For background information or clarification of the findings presented in this chapter it is suggested that the reader consult the appropriate sections of that appendix.

#### MINERALOGICAL AND ENGINEERING TESTS

1. A combined analysis of insoluble residue determinations, X-ray diffraction of the total aggregate and of the insoluble fraction, and DTA can be used to identify the mineral content in carbonate aggregates to the degree required in this study. Electron microscopy is useful to confirm clay mineral composition, but is required only on a very limited basis.

2. Increased Los Angeles abrasion loss is accompanied by an increase in fine production during crushing, and also by an increase in fines generated during the abrasion test itself, for carbonate rocks similar to those used in this study. This suggests that excessive fine production may be indicative of material susceptible to degradation.

3. The wear phenomenon of the Los Angeles abrasion machine involves the removal of surface grains by attrition, rather than by fracture of individual particles, in the case of commonly acceptable carbonate aggregates. Aggregates with greater abrasion losses (in the upper 40 percent range of the foregoing) are reduced in size by particle fracturing as well as by surface abrasion.

4. After several hundred drum revolutions during Los Angeles abrasion testing, a cushioning effect of the generated fines appears to develop. This reduces the abrasion of the larger particles.

5. The freeze-thaw test used in this research, which was patterned after the Iowa "C" freeze test, yields useful, reproducible results when considered from the testing point of view.

6. The sodium sulfate test did not prove to be a useful or reliable test because of the great variability of the method. Because reproducibility between laboratories is nearly impossible for the sodium sulfate test, it was decided not to use it as a basic comparison of aggregates.

#### PETROGRAPHIC ANALYSIS

1. A combination of hand-specimen, polished-section, and thin-section analyses should be made on quarried aggregates to yield a complete petrographic description.

2. Two hundred is an acceptable number of grain measurements to read per thin section if a 95 percent confidence level is desired for the mean grain size.

3. The variation in grain diameter due to different orientations of the thin-section slice is negligible in comparison to the variation derived from quarry to quarry.

4. The variation between the mean grain size of companion thin sections taken a few inches apart is less than the variation of mean size from aggregate piece to aggregate piece in a quarry and considerably less than the variation from quarry to quarry. This indicates that a thin section will yield a true picture of a uniform texture from a quarry sample. Therefore, each different texture that is discernible by eye requires an individual analysis.

5. In carbonate quarries with heterogeneous textural differences between beds, the variation within the quarry can be as great as that between different quarries. Therefore, a thin section is representative of one bed only and not of the quarry as a whole.

6. The grain roundness and grain interlock classifications as devised in this study are useful in a descriptive sense, but are insensitive to changes in grain size. They are also not a reliable predictor of degradation as observed in the statistical analysis.

7. The surface-volume ratios as determined by the line projecting method are too grain-size dependent, being entirely responsive to grain-size differences. As a truly numerical value, however, they show promise in textural analysis.

8. Void content as measured in thin section is a useful predictor of degradation in the case when voids are abundant, as abrasion loss increases and degradation resistance decreases with increasing void content. Unfortunately there is a lower limit of about 5 microns below which voids cannot be viewed petrographically. This being the case, many aggregates are described as having no voids, so that their degrading characteristics are determined by other variables than void content.

9. Average or mean grain size and, to a lesser degree, the standard deviation of grain size are valuable predictors of degradation and Los Angeles abrasion loss in the coarser grain sizes of carbonate aggregates; but the correlation becomes somewhat obscured in the finer sizes, where the interplay of other factors determines the abrasion and degradation resistance. This is indicated by the moderate correlation of average grain size in the over-all carbonate study, but good positive correlation for three of the individual states compared (increase in abrasion loss with increased size), and the reverse for the fourth state, in which the aggregates are predominantly fine grained. A dividing line at about 0.1 mm may distinguish the small size from the larger group, in which grain size differences influence the abrasion and degradation characteristics to a marked degree.

10. The other parameters measured in thin section—percent matrix, matrix size and standard deviation, maximum-minimum diameter ratio of grains, and matrix size-grain size ratio—are not particularly useful in predicting variation in Los Angeles abrasion loss, degradation value, or freeze-thaw loss.

## STATISTICAL ANALYSIS

1. In the correlation and regression analysis, Los Angeles abrasion loss was found to be the best measure of degradation value for carbonate aggregates. Therefore, carbonate aggregates for use as base and subbase material should be tested for quality using the Los Angeles abrasion apparatus.

2. Carbonate freeze-thaw values correlate directly with Los Angeles abrasion and inversely with degradation resistance, but the measure has poorer correlation with degradation than does Los Angeles abrasion.

3. In regard to the petrographic measures of carbonate aggregates, average grain size, then void content, are the most responsive to Los Angeles abrasion (directly) and to degradation value (inversely).

4. For phaneritic or coarse-grained igneous and metamorphic rocks an increase in Los Angeles abrasion loss is registered with an increase in average size or in freeze-thaw loss (Table B-18). Los Angeles abrasion loss and freeze-thaw loss are also inversely related to degradation value. Hence, a combination of average grain size, Los Angeles abrasion, and freeze-thaw values is most responsive to changes in degradation values.

5. Multiple correlation and regression analysis of the igneous and metamorphic aggregates did not prove too successful because of limited sample size.

6. In the basalt aggregates study, Los Angeles abrasion and degradation values were found to be non-correlative. At the present time petrographic analysis of basalts in which the deleterious materials, volcanic glass, palagonite, and chlorophaeite are determined is the most reliable test for this chemical degradation.

## COMPARISON WITH FIELD COMPOSITION DEGRADATION DATA

1. A comparison of the Los Angeles abrasion loss values for all the carbonate aggregate tested (35) was made with the Los Angeles abrasion losses of three carbonate aggregates used in the field composition degradation study by Aughenbaugh et al. (1963). In the Aughenbaugh study the carbonate aggregate with the highest abrasion loss (Ind. 4) degraded the most, the aggregate with intermediate value (Ind. 12) degraded an intermediate amount, and the aggregate with the lowest abrasion loss (Ind. 11) degraded the least. The results of the field compaction degradation study are consistent with the finding of this report—that degradation loss increases with increasing Los Angeles abrasion loss for carbonate rocks.

2. In the Aughenbaugh study, Ind. 4 produced 1.5 percent fines using a steel roller and had an abrasion loss of 32.6 percent. This suggests that carbonate aggregates with abrasion losses substantially higher than this, perhaps around 40 percent, produce excessive amounts of fines.

3. It can be noted in Table B-19 that aggregates with losses in the high 30 percent ranges and above have degradation values that are generally 5 or less, indicating that

they are judged by the supplying agency to be poorly resistant to degradation. This in turn suggests that carbonate aggregates with degradation values of 5 or less can be expected to degrade substantially.

4. Freeze-thaw values for the Aughenbaugh aggregates were not arranged in the same increasing order as the Los Angeles abrasion loss values. Instead, the samples with high and intermediate degradation loss were interchanged in freeze-thaw loss. This suggests that freeze-thaw values are less useful in predicting degradation loss than are Los Angeles abrasion values. Nevertheless, freeze-thaw values are a useful measure for delineating degrading carbonate aggregates when used in conjunction with other tests as suggested by the statistical analysis portion of this report.

## INDIANA QUARRY STUDY

1. The Los Angeles abrasion values varied only slightly across the horizontal beds of the quarry, but varied significantly among various sedimentary layers in the vertical direction. This shows that in a rock sequence with obviously different lithologies a corresponding change in Los Angeles abrasion value will also occur.

2. It was statistically shown that of the three formational units (top to bottom: St. Louis, Salem, Harrodsburg) the Harrodsburg formed a greater portion of the samples after initial crushing than its portion of quarry face would suggest. This indicates that the rock units were not completely mixed during the blasting and loading operation.

3. A statistically significant decrease in the percentage of the Harrodsburg material occurred during aggregate processing, which showed it was less durable than the other two constituents.

4. A strong, negative correlation between the percentage of Harrodsburg and the Los Angeles abrasion value for both the initial and final process samples suggests that the abrasion value decreases with increasing Harrodsburg percentage, despite the fact that the Harrodsburg abrasion loss is the greatest for the three units in the quarry. This suggests that the Harrodsburg Los Angeles abrasion loss may have been reduced substantially during processing by the removal of weak, undesirable material.

5. An over-all reduction in Los Angeles abrasion values occurred between the in-progress samples and the quarry samples, thus indicating a beneficial effect through mixing and processing.

6. Predicting equations for Los Angeles abrasion values based on the percentages of the three rock formations present were obtained for both in-progress samples and the final sized samples. The equation for the final samples accounted for most of the variability in abrasion loss, but the equation for the in-progress samples accounted for only a minor amount of the variability. This suggests that grading has an effect on these predicting equations and that the rock percentages should be ascertained on the actual size that is tested.

## CHAPTER THREE

## APPLICATIONS

A number of recommendations of a practical nature can be made on the basis of the work accomplished during this research program. The results of this project, which combine several facets of aggregate testing and petrographic evaluation, suggest comments in a number of different areas. These areas may best be approached using two categories for discussion—identifying aggregate degradation, and a predictive test for aggregate degradation.

## IDENTIFYING AGGREGATE DEGRADATION

The problem of degradation was discussed in an earlier section. In the course of developing the subject the terms segregation and control were discussed in detail. A recommendation of importance in this regard is that extreme care should be taken to ascertain if degradation is really the problem in a particular instance rather than the more elusive problems of segregation and poor control.

The U. S. Bureau of Public Roads (Allen, 1963) has investigated a number of so-called degradation problems and found that the culprit, at least in part, has been segregation of stockpiles and/or poor field control. It is frustrating, indeed, to attempt to solve a problem assuming that one mechanism (degradation) is occurring when something entirely different is causing the problem.

## Predictive Test for Aggregate Degradation

One of the primary purposes of this study was to develop an improved test for aggregate degradation. This was attempted through analysis of existing tests and of the various aggregate types and their textures.

To a degree, this goal has been attained: a test procedure is outlined subsequently. However, the proposed test is presented with the understanding that regional factors will dictate the placement of the dividing line between harmful and non-harmful types and/or amounts of degradation in the various aggregates.

It is necessary to reiterate that this study was concerned only with degradation of base and subbase material. Therefore, the results and conclusions apply only to these materials and not to concrete aggregates or aggregates for bituminous mixes. In this same area of interest, it seems that truly separate specifications should be adopted for evaluating base course aggregates in one instance and concrete and bituminous aggregates in another. This would replace the prevalent practice of rating aggregates for both uses according to the same test procedures but assigning a lower minimum requirement for base course material. The two uses are sufficiently different that different approaches could be used to evaluate the aggregate in each case and base course aggregates should not necessarily be poorer material.

As it pertains to this discussion, however, it is hoped that the proposed test for degradation of base courses, which includes Los Angeles abrasion analysis, will not be condemned by those who believe that the Los Angeles test is unsuitable for evaluating concrete aggregates. It is important that the test be evaluated on its own merits and not on the basis of other issues.

The degradation test procedure is closely tied to the aggregate rock type. It was established early in this research that two distinct mechanisms of degradation are important. The first is primarily mechanical in nature and occurs through the breaking and attrition of the aggregate pieces. The second occurs through the change of seemingly sound mineral constituents to a weak rock-water mixture in the presence of water under applied loads. This latter mechanism, by which basalts seem to degrade, was termed chemical degradation in previous discussions.

As basalts and basalt-like materials appear to be prone to chemical degradation and most of the other common aggregates do not, some division of rock types is suggested. In addition, heterogeneous gravel aggregates cannot be analyzed petrographically on the microscale (thin sections), as the numerous rock types present make such examination unrealistic. Hence, the separate departmentation of heterogeneous gravels is made. Carbonate aggregates, which make up a major portion of those used in the United States, form another group, and coarse igneous and coarse metamorphic rocks form a fourth. Together these four groups comprise most of the aggregate rock types used.

The testing results indicate that a recombination of carbonate and coarse-grained igneous and metamorphic rocks into a larger group is in order. The data suggest, however, that the same test values may not necessarily be used to divide the acceptable and unacceptable aggregates for all rock types in this group. This is suggested because the abrasion loss for igneous and metamorphic aggregates appears to be less crucial than for carbonates, as the size of the degraded material is generally smaller for the carbonate material.

The remaining rock types, exclusive of basalts (and related rocks), carbonates, coarse igneous and metamorphic, and gravels, either are obviously too weak to be used or can be included in the other categories. Graywacke and other sandstones, for example, would be included under the carbonates and others group; but a different limiting value of acceptability may be necessary because some graywackes are prone to the production of fines.

The proposed procedure is outlined in Figure 1. In Group I it is suggested that Los Angeles abrasion, freeze-thaw testing, and petrographic analysis to determine

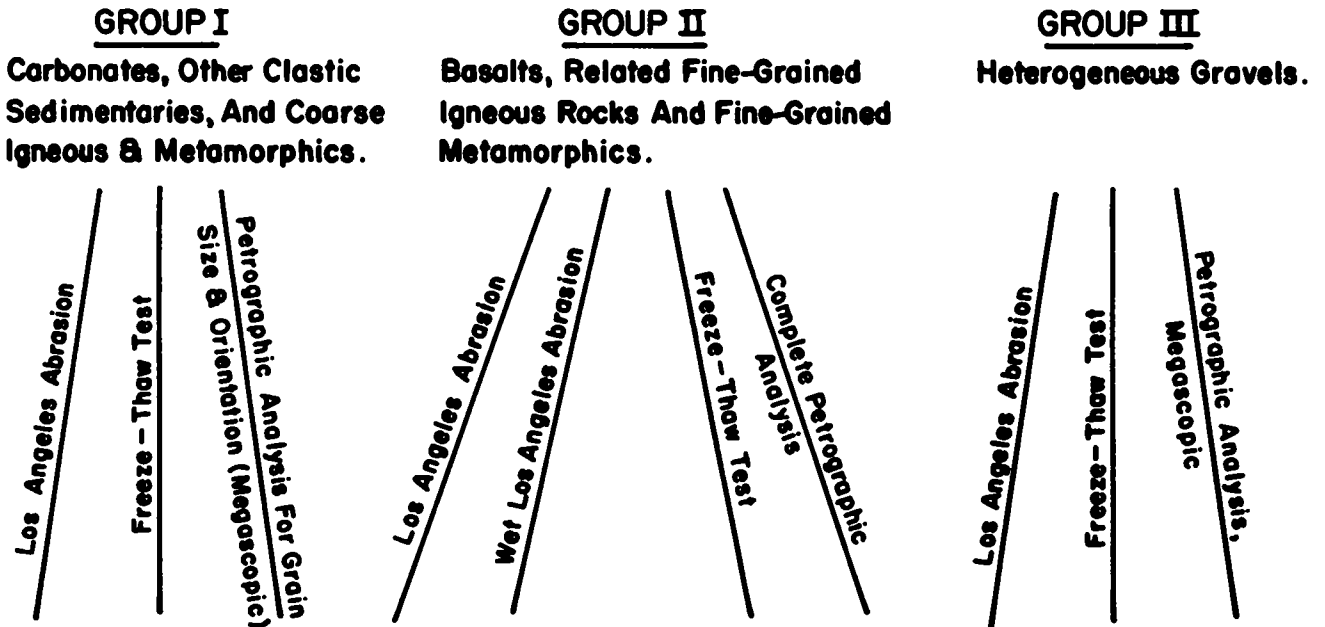


Figure 1 Schematic of proposed aggregate degradation test

particle grain size and orientation, be conducted. Much can be determined about grain size by use of a hand lens. If the grains are visible under the lens, the grain size can be estimated and the degree of orientation determined. If no grains are visible the texture is fine grained and grain size becomes less important. A combination of the Los Angeles test and the freeze-thaw test will determine the abrasion resistance and soundness of the aggregate. Undesirable is a combination of high abrasion loss, high freeze-thaw loss, and large grain size.

In Group II it is suggested that both wet and standard Los Angeles abrasion tests and the freeze-thaw test be run in addition to a complete petrographic analysis. The wet abrasion test and the freeze-thaw test could be run to determine the presence of unsound material with and without the addition of water. The petrographic analysis is used to determine the mineral content of the rock and a thin-section study is required. Undesirable are combinations of high abrasion, wet or dry; high freeze-thaw loss; and the presence of considerable devitrified glass and mineral reaction products as determined in thin section.

In Group III, Los Angeles abrasion, freeze-thaw, and megascopic petrographic analyses are suggested. For many heterogeneous gravels the values for abrasion and freeze-thaw loss will be quite low; but there is the possibility of high loss for occasional samples and such testing will indicate this. The megascopic rock analysis will indicate the relative amounts of poor material. It is possible in the gravels to have acceptable resistance and freeze-thaw values but substantial amounts of poor material because of the averaging effect. The undesirable features are combinations of high abrasion and freeze-thaw losses and the presence of undesirable materials such as shale, weak sandstone and schist, limonite, and porous chert.

The most difficult job in proposing this procedure is the setting of limits of acceptability in regard to degradation. As previously stated, this is a function of many local factors, including climate, traffic, soil type, and the performance expected from the pavement.

With the previous limitations in mind, several general suggestions can be made. The limit for abrasion loss may be in the 40-50 range for carbonate aggregates. This is suggested by studies made by Aughenbaugh et al. (1963) and augmented in the previous discussion. For coarse-grained igneous and metamorphic rocks the limit may best be set somewhat above this range; for certain graywackes, below it. The freeze-thaw loss limit may well be placed in the 15 percent range.

For most basalts, dry abrasion and freeze-thaw should be no problem, as these values are usually low. Wet abrasion values in the 40 range should be viewed with concern, as should extensive amounts of devitrified glass and altered or reaction products.

For the gravel samples, the accumulation of about 10 percent of weak and unsound material might be considered a dangerous proportion in regard to degradation.

It should be reemphasized that these limiting values are suggestions only and are not based on actual test results. They are, instead, an extension of the authors' personal feelings in this regard and are subject to modification by future findings. The precise limiting values must be set for each region, through testing programs and evaluation of subbase performance data. The problem of subbase and base course degradation is of national scope, but the limiting values for acceptability must be set on a local or statewide basis.

With these conditions in mind, Table 1 sets forth the concepts of the proposed test.

TABLE 1  
PREDICTIVE TEST FOR AGGREGATE DEGRADATION

| STEP | GROUP | DESCRIPTION AND TESTS RUN   |
|------|-------|---|
| 1    |       | <p>Megascopic examination, classify samples by rock type into three major groupings. Groups I and II are composed of crushed quarry stone or gravel that is predominantly of one rock type. Group III is made up of heterogeneous gravels containing several rock types</p> <p><i>Group I</i>—Consists of carbonate rocks (limestones, dolomites), graywacke sandstones and other clastic sedimentary rocks, coarse-grained igneous rocks (granites, diorites, gabbros), and coarse-grained metamorphic rocks (gneiss, marble, strong schists).</p> <p><i>Group II</i>—Consists of basalts and related fine-grained igneous rocks (andesite, diabase), and fine-grained metamorphic rocks (hornblende, schists, greenstones).</p> <p><i>Group III</i>—Restricted to gravel samples containing several rock types.</p>   |
| 2    | I     | <p>Carbonate rocks, sedimentaries, and coarse-grained igneous and metamorphics.</p> <p>(1) Petrographic analysis for grain size and orientation. Examination of the aggregate pieces using a hand lens will indicate the general size and distribution of grain diameters. If grains are quite large (&gt;2 mm or so) the aggregate may be degradation-prone. Orientation and interlocking of grains may be noted as well. Good interlock improves strength.</p> <p>(2) Los Angeles abrasion test, standard ASTM C 131-66. Abrasion loss in excess of 40% (for carbonates) should be considered excessive if used for base course for primary highways.</p> <p>(3) Freeze-thaw test. Unconfined aggregate test patterned after Iowa C freeze test. Limits difficult to place at this time. Maximum may be near 15% loss.</p> <p>(4) In special circumstances, as in the case of argillaceous carbonates, if freeze-thaw loss is reasonably high a wet Los Angeles abrasion test may be useful. Procedure and limits similar to those for Group II</p>   |
|      | II    | <p>Basalts and related fine-grained igneous and metamorphics</p> <p>(1) Complete petrographic analysis, including hand-specimen examination and thin-section analysis. In hand specimen, a weathered appearance with veins of clayey or altered material may signal poor chemical degradation resistance. In thin section, a high percentage of the minerals palagonite, smectite, and chlorophaeite, plus devitrified glass, are suspect materials. These materials in excess of 25% may prove to be a problem</p> <p>(2) Los Angeles abrasion test, standard ASTM C 131-66. Abrasion loss is often low for these materials, but the test is run to insure dry strength and to compare with the wet Los Angeles abrasion test.</p> <p>(3) Wet Los Angeles abrasion test, standard ASTM C 131-66, modified by adding 50% of the sample weight of water. Rocks susceptible to chemical degradation show greater losses using wet LA tests. Aggregates should be considered suspect if the wet LA loss is 50% or more than the dry abrasion loss.</p> <p>(4) Freeze-thaw test. Unconfined aggregate test patterned after the Iowa C freeze test. Limits difficult to place at this time but maximum may be near 15% loss.</p> |
|      | III   | <p>Heterogeneous gravels</p> <p>(1) Megascopic petrographic analysis. A complete analysis of the rock types and degree of weathering of a representative portion of the sample. Follow procedures suggested by ASTM C-295-65 on petrographic examination. Special attention should be paid to those rock types that are inherently weak, hence degrade easily. These include shale, clay lumps, ocher, weakly cemented sandstone, schist, and deeply weathered rocks. A petrographic number analysis similar to that given in Table B-8 may be developed for gravel materials, but this must be done on the basis of experience and specifically for local areas. Present limits suggest that no more than 10% of weak materials should be allowed in the aggregate.</p> <p>(2) Los Angeles abrasion test, standard ASTM C 131-66. Abrasion loss in excess of 40% should be considered excessive. This test is used to insure that over-all quality of the gravel is sufficiently high.</p> <p>(3) Freeze-thaw test. Unconfined aggregate test patterned after Iowa C freeze test. Limits difficult to place, but maximum may be near 15%. Used to insure over-all quality of gravel sample.</p>                            |

## CHAPTER FOUR

**SUGGESTED FUTURE RESEARCH**

Several areas of further research have been indicated in the progression of this study. Some of these areas will be investigated further by the authors through subsequent research endeavors.

The analysis of textures of highway aggregates materials presented here is probably the most detailed work of its kind to date. A stronger relationship between such textural properties as interlock, grain shape and grain roundness versus aggregate strength was suspected than was shown by the results of this study. This is taken to indicate that further refinements of textural measurements are required to prove the relationship. Additional work in the area of aggregate textures is planned for the future.

A great deal more specific information is needed to show the limits of acceptable degradation. This is really a study of performance data. Ever present, of course, is the nemesis of aggregate segregation, which must be ruled out first. Nonetheless, limits on how much fine production is allowable under various conditions of climate and traffic load are necessary before absolute limits can be established. In this research the authors had to assume that the supply-

ing agency could evaluate, through experience and limited performance records, which rocks were degraders and which were not. This is only qualitative at best and more specific information is required for further refinement.

The harmful types of fines constitute another area of needed research. The fines produced are certainly a function of the source rock. A fruitful area of research would be to determine what fines each rock type forms. Suggestions from the current work are that basalts and graywackes form plastic fines, as do certain carbonates, whereas coarse-grained igneous rocks only do so to a lesser extent. This problem alone could take a great deal of study.

The effects of sizes of fines also constitute an unanswered problem; some sizes of fines are more problematic than others, as a result of climate and other factors. Just which ones are important for base courses and which ones are not is a problem that goes unanswered. Both the nature and size of fines are tied up with the problem of plasticity index of rock powder. This alone has not been explained to the satisfaction of many highway engineers.

**APPENDIX A****DETAILED RESEARCH APPROACH****GENERAL**

The research on degradation of aggregates was accomplished in two phases, each of about 1½-year duration. The first phase consisted of information gathering, during which laboratory testing at Purdue University was augmented by information obtained from the various state highway departments. In the second and final phase, testing at Purdue University was of primary importance to assure a common basis for comparison between test results and performance records. Statistical analysis of all the data gathered completed the tasks for the final phase.

Prior to initiation of this research, agencies of 27 states had submitted to the research agency aggregates suitable for petrographic study. Most of the aggregates supplied were for use in portland cement concrete, with quality ratings from fair to excellent. A general rock name and locality formed the only information consistently supplied for the samples by the agencies.

At the outset of the investigation the states that had previously supplied samples were requested to send engineering and degradation performance data for the samples. Some were able to comply, but others could not because the agencies had selected random samples for shipment without associating the samples with a specific set of test results. In addition, many states had supplied only their good aggregates prior to the research program; therefore, additional samples of poor and marginal aggregates, with appropriate data, were requested. The usable materials already on hand were analyzed first to establish the properties that depict a good aggregate.

The highway departments of the states that had not supplied aggregates were contacted. In addition, the 46 Divisions and Districts of the Corps of Engineers, as well as the Bureau of Public Roads, the Bureau of Reclamation, and several private concerns, were also consulted.

Information concerning the following items was requested:

1. Specific name of the aggregate source, geologic description, and geographic location (located on a state map if possible).
2. Percentage of wear by Los Angeles abrasion, including the grading used.
3. Absorption and specific gravity data.
4. Freeze-thaw data, (including method of testing, cycles, etc.)
5. Petrographic data.
6. Insoluble residue data.
7. Sulfate soundness data.
8. Performance data.
9. Any additional data felt to be pertinent.

Some of the state highway departments were visited following the initial requests for samples and data. Those highway departments that had difficulty in obtaining samples or that wished to discuss the degradation problem before attempting to supply the samples and data were visited first. The highway departments visited during the first phase were Illinois, Indiana, Iowa, Missouri, Michigan, New Jersey, Ohio, Pennsylvania, and Wisconsin. It was felt that a better understanding of the aggregate degradation problem in each state, and in general, was obtained than could be accomplished through correspondence and examination of the literature alone. An appreciation also was acquired for the over-all aggregate problems of the various states.

Not all states that submitted aggregates and engineering data supplied the entire list of test information requested. Because each state operates its own testing program and uses its own specific procedures, it was no surprise that incomplete data often were submitted. For example, states south of the frost line normally do not perform freezing-and-thawing tests and specific soundness tests have only limited application. Most states provided percentage of wear values for Los Angeles abrasion, together with absorption and specific gravity data, only a few included sulfate soundness, freeze-thaw, petrographic, insoluble residue, or performance data. Only the Iowa Highway Commission supplied chemical analyses for their aggregates. Commonly, the geologic and geographic descriptions of the quarries were not included.

Each aggregate sample was rated according to its degradational properties by one or more members of the highway department that supplied the sample. It was realized that the standards by which the aggregates were judged would differ from state to state. In nearly all cases the decision was based on personal experience and over-all performance of the aggregate sources as a road-building material. There is little doubt that the specifications of the states were reflected in this judgment, with most suppliers feeling that their marginal aggregates were those that barely passed the specification limits. In a few states the evaluation was reinforced by considerably more than an over-all impression of the aggregates' suitability by being based on actual failure situations.

In many cases the states did not distinguish between

limited degradation that was not harmful and degradation that was harmful. This distinction is, of course, difficult without careful field examination of the damage. This evaluation is also a function of what a state highway department might consider to be adequate service or adequate pavement performance. Hence, the evaluations were accepted at face value in an effort to exclude further bias on the measures through a personal interpretation of the data supplied. A numerical base was used to transform the verbal descriptions into values that could be compared. A scale from 1 to 10 was used, with the following designations:

1. Complete degradation.
2. Very poor.
3. Poor.
4. Marginal.
5. Intermediate.
6. Intermediate to good.
7. Good.
8. Very good.
9. Excellent (best in the state, etc.)
10. Perfect with regard to degradation.

The scale was such that categories 1 and 10 were not used to describe any samples because of their extreme nature. A value ranging from 2 to 9 was assigned to each description of the samples supplied by the highway departments.

In Phase II, many of the highway officials were asked to rate their rocks directly to this scale. Agreement was quite good with the numbers assigned to the descriptions by the authors.

The samples supplied by the state highway departments gave good geographic coverage of the important geologic units used as aggregates in the United States. Midwest carbonate rocks were augmented by basalts from the northwestern states, gravels from most geographic regions, coarse crystalline rocks from Virginia, and diabase from the eastern United States. In all, 34 states and the Corps of Engineers supplied 260 samples with engineering data during Phase I.

By the time Phase II was under way it had become apparent that considerable testing of aggregates by the research agency would be required because (1) the same data were not available on all the supplied aggregates, so extensive comparison among them was not possible, and (2) the problem of multiple sources of data raised some doubt as to the reliability of such comparisons. With numerous machines being used for the same test, significant discrepancies could creep into the results. In addition an "average" result was often supplied for an aggregate source, rather than for the individual sample supplied.

To provide sufficient aggregates for the testing program, the state highway departments were again requested to submit 50-lb samples. In many cases this request was met. Other states suggested that the quarries be visited by a project investigator to obtain the proper perspective of the problem and to aid in sampling. The state highway departments of Wisconsin, Virginia, and Florida were visited for this purpose and in each case two or three days were



spent examining quarries and aggregate processing plants and collecting samples.

In addition, each highway department supplying aggregates was asked to rate them according to resistance to degradation by the scale previously given. This subject is discussed at length under laboratory testing.

In the second portion of the work the research was concentrated on quarried rock aggregates, with only a minor amount of work done on gravel samples. Concentration on quarried aggregates was necessary because of the emphasis placed on using a polarizing petrographic microscope for textural analysis. It is not practical to use such techniques on heterogeneous gravels. Therefore, the problem of gravels was treated briefly using a megascopic petrographic examination of rock type and quality.

#### LABORATORY MINERALOGICAL DETERMINATIONS

In the first phase of the study, several tests, primarily mineralogical in nature, were performed on the samples received. Insoluble residues were obtained from all carbonate rocks and from some clastic sedimentary rocks. Hydrochloric acid was used to dissolve the carbonate material and free the insoluble material. This method was employed in preference to dissolving the carbonate portion by acetic acid, which is sometimes used (Gillott, 1963) because it is less destructive to expanding-lattice clays. It was known in advance that expanding clays were seldom present in the samples under study; thus, the stronger, fast-acting hydrochloric acid could be used and would cause no difficulty in identifying clays. The absence of expanding-lattice clays was ascertained by analyzing, early in the work, several total samples using the X-ray diffraction method with full-scale intensity, which permitted the clay peaks to show up despite the predominance of carbonate. The time saved by using fast-acting hydrochloric acid made it possible to analyze all the samples in a minimum length of time.

Differential thermal analyses (DTA) were made on the carbonate rocks to determine the relative amounts of calcite ( $\text{CaCO}_3$ ) or dolomite ( $\text{CaMg}(\text{CO}_3)_2$ ) in the sample and to recognize other minerals present. The differential thermal analysis equipment employed was a two-furnace apparatus built by technicians of the Illinois State Geological Survey. The chemical reactions that occur with increasing temperature are recorded in the form of a thermogram by a photopen recorder activated by a separate light-reflecting galvanometer. A typical DTA thermogram is shown as Figure A-1.

Exothermic (heat loss) and endothermic (heat gain) reactions occur at specific temperatures for individual mineral species. These reactions, therefore, are the bases for mineral identification. Deflections to the right in Figure A-1 are endothermic reactions. Endothermic reactions are those that require heat for their occurrence and include reactions in which water or carbon dioxide is given off.

Differential thermal analysis is particularly suitable for carbonate identification and has been used both qualitatively and quantitatively in this regard (Lambe, 1951; Bowen, 1954). Pure mineral carbonate samples are

easiest to analyze quantitatively, whereas the accuracy for mixed mineral percentages is much less reliable. In this regard, calcite and dolomite were differentiated by this method. Throughout this section on laboratory tests the term dolomite is used in its mineralogical sense.

There is a tendency for one mineral to mask or substantially affect the thermal reactions of companion minerals in the sample and this method is normally used as a qualitative or semi-quantitative method when more than one mineral is present. More expensive DTA apparatus that is truly quantitative in nature is currently available, but in this research the DTA data were used in a semi-quantitative way to recognize the relative amounts of calcite and dolomite.

X-ray diffraction analyses were made of both the total rock constituents and the insoluble residue material to determine the amount and type of mineral constituents present. A recording diffractometer was used to analyze the samples. Copper radiation was used on all samples and a  $2\theta$  range of  $2^\circ$  to  $40^\circ$  was employed in most cases. The samples were scanned at a rate of  $2^\circ$  per minute. A typical X-ray diffraction pattern is shown as Figure A-2.

The total rock samples were prepared on porous ceramic tiles from a rock-powder slurry. A vacuum aspirator was used to draw the dispersal liquid through the tile, leaving

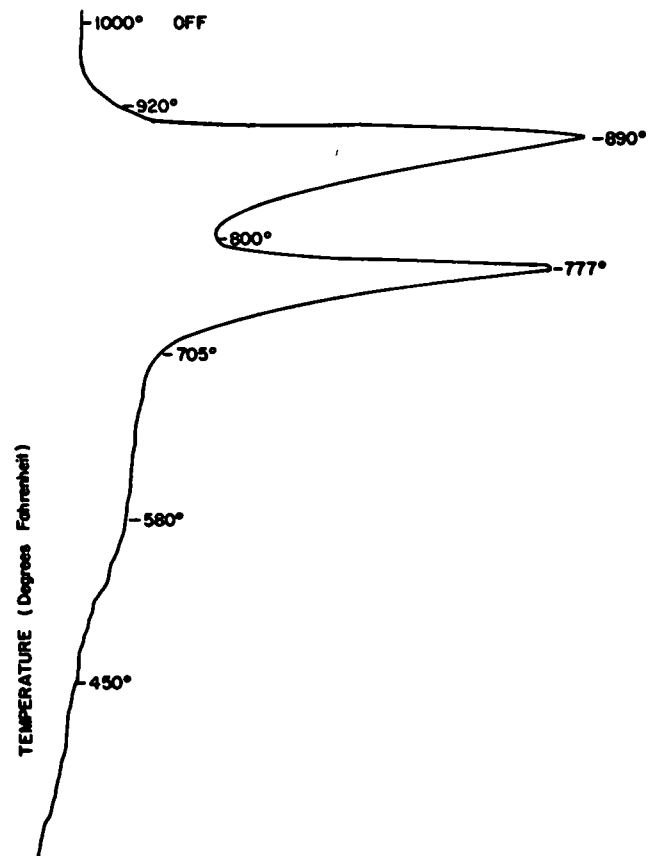


Figure A-1. Typical DTA thermogram for a carbonate rock (dolomite).

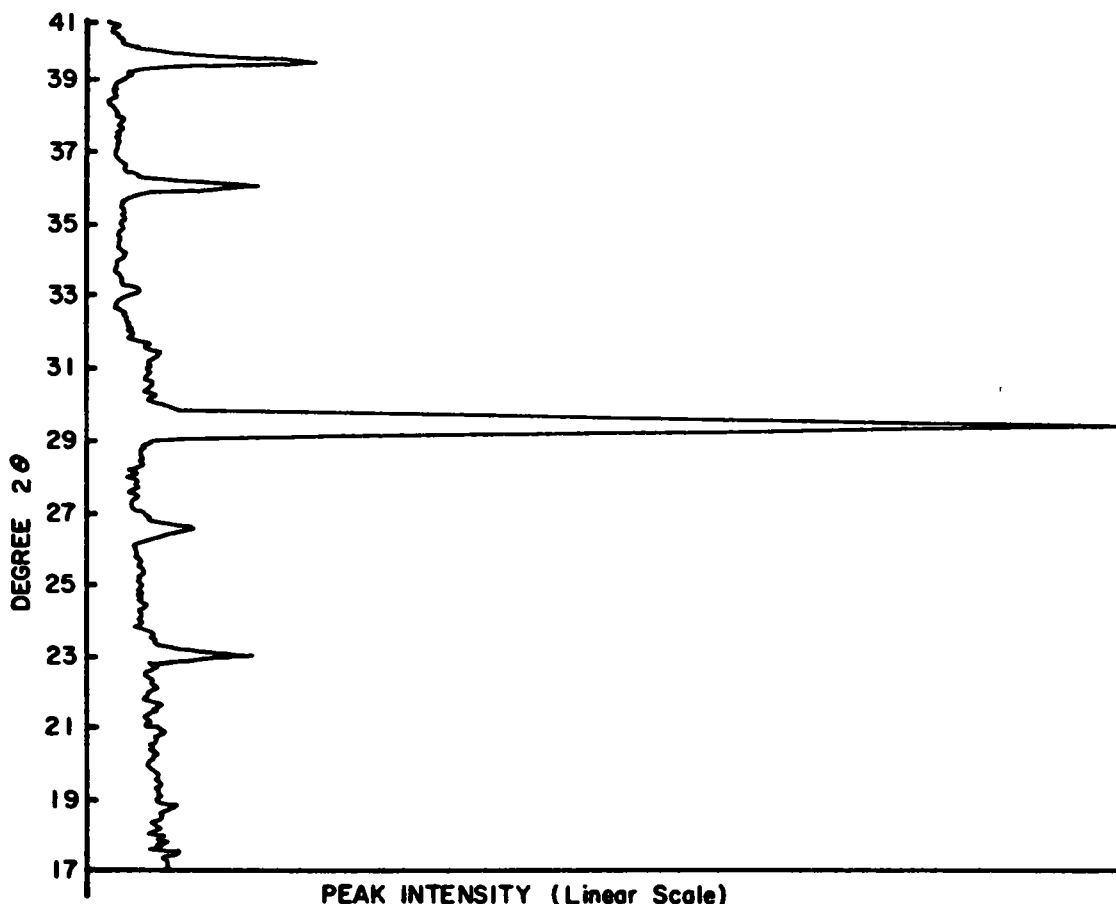


Figure A-2. Typical X-ray diffractometer tracing for a carbonate rock (limestone).

the solid constituents on the tile surface. X-ray samples of the insoluble residues were prepared in similar fashion except that the acid-insoluble fractions of the rocks were used to prepare the slide material rather than the total rock constituents.

X-ray analysis was used in a semi-quantitative manner for the analysis of carbonates in this project. More accurate quantitative methods are available for identifying carbonates by X-ray analysis (Snow et al., 1960), but they require much more time and more precise instrumentation. The quantitative methods are not without problems, for their greater precision does not necessarily produce greater accuracy. The difficulty arises because ionic substitution of magnesium for calcium, and *vice versa*, takes place to a limited degree in the carbonate minerals (Diebold et al., 1963) despite the considerable difference in ionic radii between calcium and magnesium.

X-ray analysis of the insoluble residue from carbonate material indicated that quartz and the clay minerals were the common noncarbonate constituents present. Quantitative analysis of clays by X-ray diffraction is made possible through the measurement of peak intensities, but the relationship is not a simple one—the peak intensities are not directly proportional to the relative amounts of each mineral present (Johns et al., 1954). However, a number of

mineral properties are important in determining the reflection of X-rays by a mineral. The elements present, the crystallinity, the degree of orientation of atoms in the lattice, and the particle size of the crystals are important variables. Absorption of X-rays by some substances, such as the iron-rich minerals, is an additional problem. Even the use of internal standards has proved faulty. Ideally, the standard mineral and the mineral to be assessed should be crystallographically identical; hence, they should reflect X-rays at exactly the same angles and with the same intensities. This is rarely the case.

The electron microscope was used to examine several clay mineral specimens obtained from the insoluble residue portion of several selected aggregates. By this technique an image is obtained through the scattering of electrons as the electron beam passes through the sample. Direct magnification from 3,000 to 15,000 times is possible by this method. Photographic enlargement allows for greater magnification if desired.

Electron micrographs, the photographs obtained by this procedure, are additional aids to identification. The important contribution of the method is that the mineral shapes are obtained, as well as their particle size. Particle shape determination is not possible in the X-ray diffraction technique.

The insoluble residue material was dispersed in a liquid of such a concentration that resolution was possible for the particle sizes involved. Figure A-3 is an electron micrograph of an insoluble residue showing illite particles in the range of 0.5 to 1 micron. Further information can be obtained on the subject of electron microscopy through the discussion and selected references given in Grim's text on clay mineralogy (1953).

#### ENGINEERING TESTS

Engineering testing in the laboratory began with initiation of Phase II of the study. The following tests were performed on some or all of the aggregates submitted or collected for analysis:

1. Percentage of wear, Los Angeles abrasion.
2. Breakdown of material by Los Angeles abrasion.
3. Amount of fine material produced in crushing.
4. Mechanism of abrasion in Los Angeles equipment.
5. Freeze-thaw testing.
6. Percentage of loss, sodium sulfate testing.
7. Repetitive load testing.

Each of the aggregate samples received was tested in the Los Angeles abrasion machine. ASTM standard procedure C 131-64T was used in the analysis. The B grading was used in all cases, because the aggregate particle size of the samples best fit this grading. The B grading requires 2,500 gm of aggregate passing the  $\frac{3}{4}$ -in. sieve and retained on the  $\frac{1}{2}$ -in. sieve, plus 2,500 gm passing the  $\frac{1}{2}$ -in. sieve and retained on the  $\frac{3}{8}$ -in. sieve. About 10 lb of sample are required for this test alone.

In addition to the standard Los Angeles abrasion test, a complete analysis of grain size was made of many samples following the actual abrasion test. The following size fractions were obtained:  $\frac{3}{4}$  in.- $\frac{1}{2}$  in.,  $\frac{1}{2}$  in.- $\frac{3}{8}$  in.,  $\frac{3}{8}$  in.-No. 4, No. 4-No. 10, No. 10-No. 30, No. 30-No. 50, No. 50-No. 60, No. 60-No. 80, and minus No. 80. The purpose of this test was to ascertain an accurate relationship between abrasion values and the range of particle sizes obtained during abrasion.

Wet Los Angeles abrasion tests were run on a limited number of samples. This test conformed to ASTM C 131-64T with the addition that 50% of the sample weight of water was added prior to testing. This variation of the basic abrasion test was used to ascertain the effect, if any, that water has on abrasion.

For a number of the aggregates supplied, the 50-lb samples were composed of rock pieces essentially of hand specimen size (equant pieces 2 to 3 in. on edge). As these had to be crushed before abrasion testing, the opportunity existed for comparing crushing characteristics with abrasion resistance. A specific setting on the jaw crusher was adhered to throughout the crushing of all samples involved. Following crushing, the entire sample was sieved over the range of screens previously mentioned, with the addition of measuring the plus  $\frac{3}{4}$ -in. material as well. Each fraction was weighed and recorded prior to the actual abrasion test.

Two samples were selected to obtain a more critical analysis of the mechanism of abrasion in the standard Los Angeles abrasion test. Both samples used were limestone aggregates from Indiana, but possessing different textural properties. Aggregate A was a fine-grained limestone,

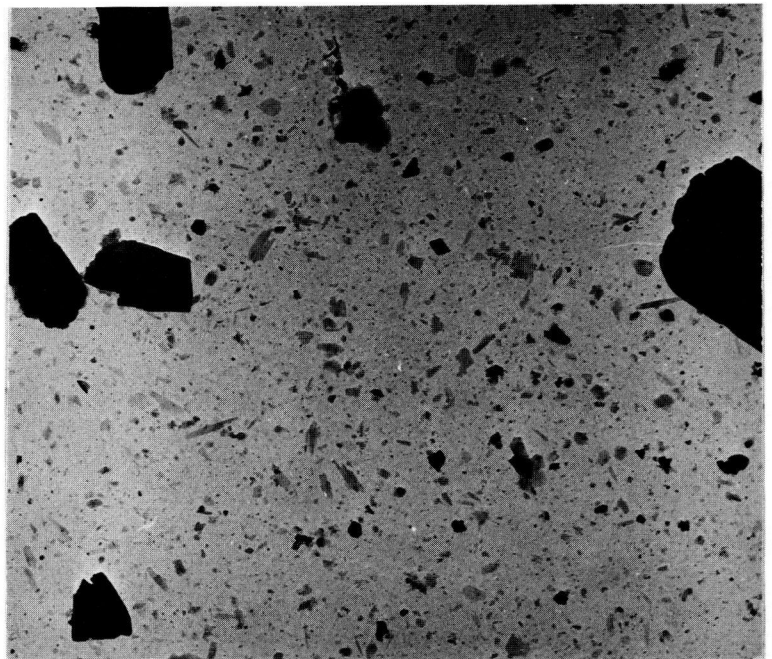


Figure A-3. Electron micrograph of a typical insoluble residue sample; 8,000 $\times$  magnification.

whereas aggregate B had a more coarse-grained texture. A Los Angeles abrasion "A" grading was used for these aggregates to allow for more size fractions. The A grading stipulates 1,250 gm each for the following sizes: 1½-in. to 1-in., 1-in. to ¾-in., ¾-in. to ½-in., ½-in. to ⅜-in. For these two samples the abrasion machine was stopped periodically for determination of the particle gradations. These divisions included the initial four gradations in the A abrasion test plus the other sizes found following the normal abrasion testing, that is, ⅜ in -No. 4, . . . , minus No. 80 Grain size determinations were made after each 50 revolutions up to 500 revolutions. The findings of this work are discussed in Appendix B.

Freeze-thaw tests were performed on all of the aggregates supplied. The test procedure used was modified slightly from the water freeze-thaw test described in the specifications of the Iowa State Highway Commission (1960) This test, known as the C freeze test by the Iowa Highway Commission, is performed on unconfined aggregates (not on concrete cylinders). As used in this study the aggregates were vacuum saturated at a pressure equal to 1 in. of mercury and stored under water until tested. The actual test consisted of 25 cycles of freezing for 30 min in air at 0F with water in the pan to a depth of 0.25-in. and thawing in air for 2 hr at 38F. The initial sample is composed of 2,000 gm sized between ¾-in. and the No. 4 sieve. Following the test the percent loss is reported as the initial weight of the sample less the amount retained on the No. 8 screen as a percentage of the initial weight.

The Iowa Highway Laboratory performs this standard test manually, with a technician placing the samples alternately in the freezer and in the thawing water according to the prescribed timetable. In the current project, however, the Purdue University automatic freeze-thaw machine, which conforms to ASTM C 290-63T standards, was used instead of the manual procedure to reduce the man-hours involved in testing.

The Iowa specifications list another freeze-thaw test, referred to as their method A test, in which a 0.5% (by weight) alcohol-water solution is used in place of regular water for the thawing and freezing of the aggregates. This greatly accelerates the breakdown of aggregates in freeze-thaw, and in the 16 cycles specified in this test, a greater loss is commonly recorded than in the 25 "C" freeze cycles. The Iowa Highway Commission places a great deal of reliance on the test in regard to chemical reactivity of aggregates. The alcohol freeze-thaw test was not performed during the current research because of the time limitations involved and the difficulty of setting up the test in the automatic freeze-thaw machine.

Sodium sulfate testing was performed on selected aggregate samples. The sodium sulfate test is currently under considerable discussion and many consider it to be a poor measure of the soundness of an aggregate. In the test, rocks saturated with sodium sulfate solution are dried at a prescribed temperature to allow sodium sulfate crystals to grow and exert internal stresses on the rock. This supposedly is analogous to the formation of ice crystals in a rock, hence a measure of its freezing and thawing qualities. An objection that has been raised is that

the test should be of a freeze-thaw type if freeze-thaw properties are really to be ascertained. The test is also criticized for its poor reproducibility, but the Illinois Highway Department engineers (Kiel, 1963) testify to its reliability in their laboratory testing. They submit that the soaking and drying temperatures are critical, but if ASTM specifications are adhered to, reproducible results can be obtained within a single laboratory. Finally, others claim that the test is a poor measure of performance as far as concrete aggregates are concerned. Dolch (1963) suggests that absorption and degree of saturation determinations are more reliable in predicting concrete performance. Despite the criticism, the sodium sulfate test is widely used by highway departments; therefore, because the current study is of national scope, the sodium sulfate test was tried as a basic comparison test. In addition, the criticism that the test takes too long is levied as a further argument by critics that dislike the test. It does take a long time, but so do the freeze-thaw test and many others.

The sodium sulfate test consists of 5 cycles of soaking of aggregate samples in saturated sodium sulfate solution for 16 to 18 hr at 70 F  $\pm$  2% followed by drying at 221 to 230 F until constant weight is obtained (ASTM C 88-63). Several size gradations are used to be tested simultaneously and the sample loss reported as a weighted average. In this research the test was limited to several of the coarse aggregate sizes because of limitations imposed by the samples supplied. The test portions consisted of 667 gm of material from ¾ in. to ½ in., 333 gm from ½ in. to ⅜ in., and 300 gm from ⅜ in. to No. 4. After sieving and weighing, the larger fractions are combined to make 1,000 gm and are tested in the sodium sulfate solution. The smallest (300-gm) sample is tested separately as another fraction. Following the test, the samples are sieved over the ⅜-in. and No. 5 sieves, depending on the appropriate size, and the loss is calculated as a percentage of the initial weight. A weighted average is used to obtain the value for the sample as a whole.

Absorption and degree of saturation determinations were not performed at the Purdue University laboratories during the testing phase. However, in most cases this information was obtained from the aggregate supplier. The preliminary statistical analysis on submitted samples at the end of Phase I indicated that these measures were not of importance in depicting aggregate breakdown. Therefore, other areas of the research were emphasized instead.

A limited number of repetitive loading tests were made on selected aggregate samples. A Lucite cylinder 9 in. high by 5-in. inside diameter was used to contain the aggregate during testing. A graded sample one-half the size of the Los Angeles B grading was used. This consisted of 1,250 gm between ¾ in. and ½ in. and 1,250 gm between ½ in. to ⅜ in. in size as measured by ASTM standard sieves.

The repetitive load testing was accomplished on a hydraulic loading system consisting of a loading frame, 5,000-lb capacity ram, and strip chart recorder. A repetitive load of 3 cycles per second was used for a total of 10,000 load applications. A sinusoidal load application of 25 psi was used to prevent a dynamic loading effect. Following the

test the samples were sieved using the nest of sieves employed in the Los Angeles abrasion tests ( $\frac{3}{4}$  in.  $\frac{1}{2}$  in.  $\frac{3}{8}$  in., No. 4, No. 10, No. 30, No. 50, No. 60, No. 80, and pan).

#### ANALYSIS OF AGGREGATE TEXTURES

Aggregate textures were analyzed in three steps—(1) hand-specimen examination, (2) polished-section examination, and (3) thin-section analysis. These procedures were followed on all the quarried rocks and therefore included samples of igneous, sedimentary, and metamorphic rocks.

Hand-specimen analysis was used to recognize surface weathering features, depth of weathering, and gross rock characteristics such as veins, cracks, and large fossils. This step was included because all aggregate investigators have an opportunity to view aggregates in this fashion without the need for laboratory equipment; as much information as possible should be gained from this type of observation. The fact that several aggregate evaluations are based on this examination (Ontario Department of Mines, 1963) made such examinations imperative. Each rock was named and described on this basis by use of the usual conventional tools—a knife blade, acid bottle, and hand lens.

Polished sections were made for each sample at the time of thin sectioning. The rocks were cut with a diamond saw to obtain a smooth surface; one half was used to make the thin section and the other half for a polished section. The cut face was polished on a polishing wheel apparatus with consecutively finer grinding powders. Krylon spray coating was applied to accentuate the surface features for good observation.

The polished sections were examined megascopically and microscopically. A Bausch and Lomb stereoscopic binocular microscope with a rated magnification of from  $66\times$  to  $45\times$  was used for the microscopic examination. The aggregate textures were noted and compared to the rock thin-section descriptions. No numerical measurements of the grain parameters were attempted.

Aggregates with coarse textures or with structures of a megascopic nature are particularly amenable to polished-section analysis. Bedded sedimentary rocks and those of an argillaceous nature were delineated by this method. Quite commonly, thick bedding is more easily examined on polished sections than by thin-section analysis with its increased magnification. The textures of coarse, crystal-line rocks were observed as well and the aggregate textural properties were described.

Thin sections were made of all the quarried rock samples supplied. Analysis of rock thin sections makes mineral identification possible, in addition to outlining the shape and orientation of individual minerals or grains and the fabric of the rock as a whole.

A rock thin-section-making machine was used to make several hundred thin sections after its acquisition during the research. Early sections were obtained from commercial laboratories on consignment.

Several thin sections were made of the same rock piece using different orientations. The availability of the thin-

section-making apparatus made this possible, as companion sections could be made on short notice if initial examination indicated a need for additional information. Oriented sections have proven particularly useful in bedded sedimentary rocks.

During Phase I, thin sections were analyzed using a polarizing microscope with a rated magnification from  $100\times$  to  $645\times$ . Grain size was ascertained using the field diameter criteria; that is, by estimating the number of grains of a particular size that would fill the field and dividing the diameter by the proper number. Although it was quite rapid and reasonably accurate, this method was improved upon during Phase II work.

Sedimentary and igneous rocks composed of crystals too small to see with the naked eye required thin-section analysis to discern grain properties. For these rocks, megascopic examination alone would have yielded a limited description of the texture.

In rock thin sections, the following characteristics were observed:

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

The technique for describing these parameters in thin section was arrived at after some preliminary work. In a study by Aughenbaugh et al. (1963) a group of Indiana rocks had been described petrographically. In an attempt to compare these rock properties, it was decided to assign numerical values to the written petrographic descriptions from that report. These descriptions originally had been based on visual inspection; the current numbering was only an attempt to rate the description types. Numerical values were assigned to these visual and empirical descriptions according to the relationships given in Table A-1.

It was necessary to translate or code the verbal descriptions into numbers in order to analyze the data statistically. This was a particularly cumbersome situation because this assignment of numbers to the verbal descriptions (a) was removed several years in time and (b) was done by a different investigator. The findings of this analysis are presented in Appendix B.

Following this preliminary work, an analysis was conducted of carbonate aggregates obtained during Phase I from the mid-continent states. Grain roundness, grain interlock, grain-size variation, average grain size, and percent voids were measured in thin sections of these aggregates. A numerical scale devised in advance for grain roundness and interlock yielded directly a numerical value of the textural properties rather than a description of properties that would have to be converted to numbers later. Assignment of numerical values to rock properties and aggregate quality has been done in the past (Ontario Department of Mines, 1963), but on the megascopic scale and not as a measure of textural properties alone.

Grain roundness was classified on a scale of 1 to 10, with 10 being perfectly rounded and 1 extremely angular or

TABLE A-1  
VALUES ASSIGNED TO EMPIRICAL PETROGRAPHIC DESCRIPTIONS

| NUMERICAL VALUE | DESCRIPTION     |                 |                      |
|-----------------|-----------------|-----------------|----------------------|
|                 | GRAIN ROUNDNESS | GRAIN INTERLOCK | GRAIN SIZE VARIATION |
| 10              | Very angular    | —               | —                    |
| 9               | Angular         | —               | —                    |
| 7               | Rhombic         | —               | —                    |
| 6               | Subangular      | —               | —                    |
| 5               | Subrounded      | Excellent       | Very high            |
| 4               | —               | Very good       | High                 |
| 3               | —               | Good            | Medium               |
| 2               | Rounded         | Fair            | Low                  |
| 1               | —               | Poor            | Very low             |

euهدral. It should be noted that these roundness numbers are in reverse order of the number assignment in the earlier numerical application. The adopted system, based on a pebble roundness chart (Fig. A-4) was used for comparison in an attempt to give consistent descriptions for similar grain shapes. This chart was devised for cobble-size pieces (16-32 mm) and adopted from Krumbein's work (1941), in which decimal values from 0.1 to 0.9 correspond to from 1 to 9, respectively, on the adopted scale. Despite the fact that the microscopic grains are

considerably smaller than the cobbles for which the scale was devised, the comparison was found to be quite workable. Euhedral grains such as dolomite and calcite rhombs were assigned values in the low range (1, 2, or 3) although this straight-edged, polygonal shape has no true counterpart on the pebble roundness chart.

The average grain size was also ascertained. The value was taken as the most commonly occurring grain size observed (modal grain size). No attempt was made to find the actual arithmetic mean in this phase of the research.

The grain size distribution for each thin section was also obtained. This was accomplished by noting the largest grain diameter and smallest grain diameter present in significant numbers. These maximum and minimum values, augmented by the average diameter, serve as a rough measure of grain size distribution. In reality it was little better than a measure of the range of grain size of the sample. However, it does have the advantage of being a rapid test procedure.

Grain interlock determinations also were made on the thin sections. A scale for the interlocking of grains was devised, again employing a range from 1 to 10. In the following scale the degree of interlock, or irregularity of mutual grain boundaries, increases with increasing number:

1. Seldom touching.
2. Commonly touching.
3. Point contacts only.

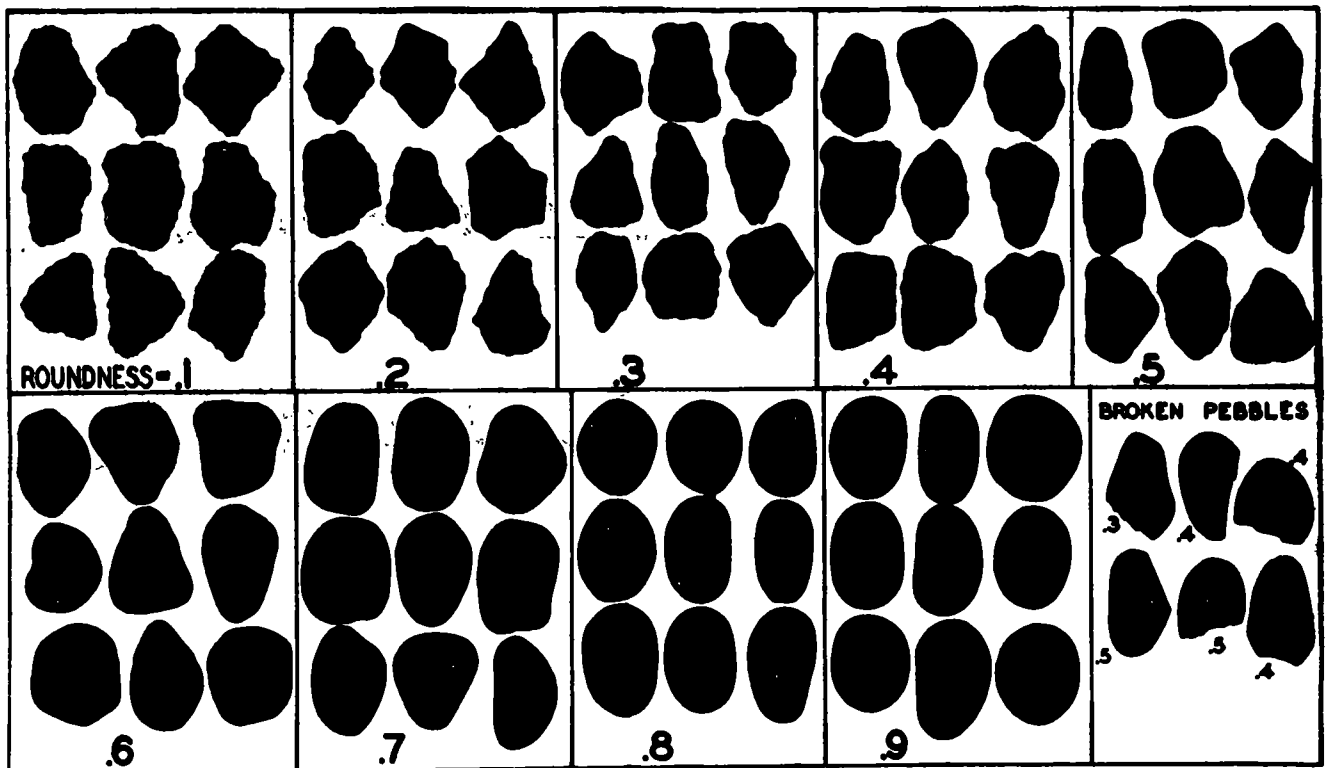


Figure A-4 Pebble images for visible roundness

4. Straight contacts to point contacts.
5. Straight contacts only.
6. Concavo-convex to straight.
7. Concavo-convex.
8. Concavo-convex, occasionally sutured.
9. Commonly sutured.
10. Sutured entirely.

Sutured contacts refer to grooved, interlocking surfaces which when observed in cross section yield a serpentine or S-shaped appearance. This type of texture, sometimes termed decussate texture, is normally restricted to metamorphic rocks such as quartzite.

Two types of grain interlock are shown as Figures A-5 and A-6. Figure A-5 is a photomicrograph showing straight interlock. The euhedral crystals shown are well-formed dolomite rhombs. In Figure A-6, concavo-convex to straight interlock is shown. This aggregate is also dolomitic and fairly typical. A hole in the slide can be observed in the lower left corner.

Void content was estimated visually, with the amounts recorded to the nearest 5 percent. This method was improved upon in later research.

The Indiana aggregates described by Aughenbaugh et al. (1963) were re-examined in the final stages of the Phase I work. The thin sections were analyzed using the newly devised numerical schemes for grain roundness and grain interlock. Average grain size and grain size distribution were determined in the manner described in the preceding paragraphs. Comparison of the two analyses of the same suite of thin sections was made in order to relate the two methods. The outcome of these tests is presented in Appendix B.

The Phase II portion of the research was initiated with the knowledge that more reliable quantification of thin-section characteristics was in order. The grain diameters and range of grain sizes needed further refinement if a reliable comparison with aggregate properties was to be made. In addition, the effect of particle orientation and the role of cement materials merited investigation.

The thin-section measurements in this phase were accomplished through the use of a newly acquired Bausch and Lomb research polarizing microscope. This microscope, through available optical attachments, allows for a rated magnification of from  $50\times$  to  $450\times$  with four intermediate magnifications. It is equipped with a mechanical stage and a micrometer eyepiece, thereby greatly facilitating the measurement of grains.

Grain size determinations were accomplished by use of the  $7.5\times$  micrometer ocular and mechanical stage with click stops. A Rosiwal traverse (Lord and Willis, 1951) was used to measure the grains for each thin section. In a Rosiwal traverse the grains are read continuously across the slide, one adjoining grain after another. Another method that is sometimes employed is the point count method. In this procedure the slide is moved a predetermined distance and the grain directly below the cross hairs is measured. The point count method has the advantage that a greater slide distance is traversed for the same number of readings than in the case of the Rosiwal

traverse. However, this should be no problem in a reasonably homogeneous material.

In the present study, parallel traverses were made across the slide, measuring each grain in turn along the line. The parallel traverses were made a minimum of several grain diameters apart. In practice, the number of traverses possible for the slide was determined first. Then a random number chart was used to decide what traverse would be made next until the prescribed number of grains was measured.

In the thin section, a number of grain determinations were made. For each measurement a decision had to be made initially as to whether the particle was grain or matrix-cement material. The grains were considered as the major fragments of the rock with the matrix as finer material and cement as finer or coarser material that seemed to fill in around the grains. After this was ascertained, the maximum, minimum, and intercepted diameters of the grain were determined. This information was then recorded on IBM coding sheets to expedite the placement on data cards.

Oriented thin sections were examined for many of the samples. Sections were cut parallel to the bedding, perpendicular to the bedding, and at some random angle. Measurement of these grain diameters was useful in determining orientation.

The orientation of grains in several slides was examined through a more tedious method. The long direction of the grain was located and recorded as an azimuth reading from the N-S polarizing direction. Analysis of the orientation of the long directions yielded the direction of average elongation.

The number of grains to be measured constituted a problem before a final number was decided upon. Two hundred grains is a number commonly suggested for measurement. K. Mather (U. S. Army Engineer Waterways Experiment Station, 1958) used 200 grain determinations per thin section and co-author N. M. Smith (1962) has indicated that he used this number for his Salem limestone studies. On the other hand, F. Chayes (1956, Chap. 8) suggests the order of 500 grain measurements for certain mineral composition determinations in thin section. The number to measure is, of course, a statistical problem and is taken up in a subsequent section. Suffice it to say at this point that 500 grains were measured at first but subsequently the number was reduced to 200 grain measurements per thin section.

During the Phase II analysis of aggregate textures, it was decided to attempt to quantify the interlock values if possible. The scale for boundary shapes discussed previously is really of a descriptive nature, so that a method with a true numerical base was desirable.

Wallace (1962), working under Dr. John Lemish at Iowa State University, developed a method for obtaining a volume-surface ratio. In the method, lines of known length are projected onto the texture mosaic and the number of hits and cuts are recorded. Figure A-7 shows the method for determining hits and cuts.

A hit occurs at the end of each projected line provided that each grain is counted only once; a and d have only one

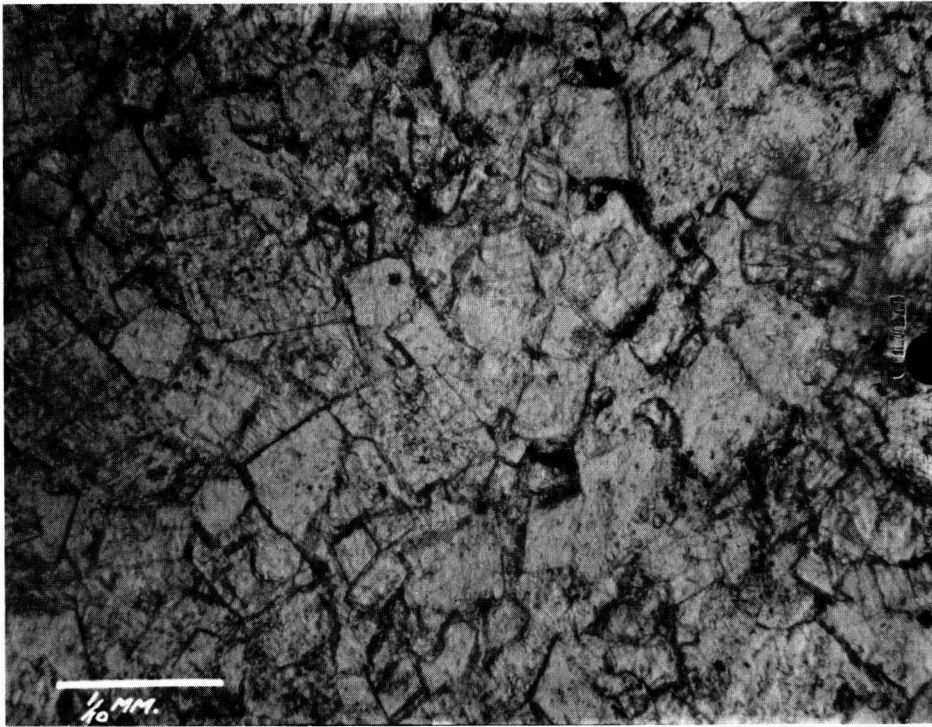


Figure A-5. Photomicrograph showing straight interlock.

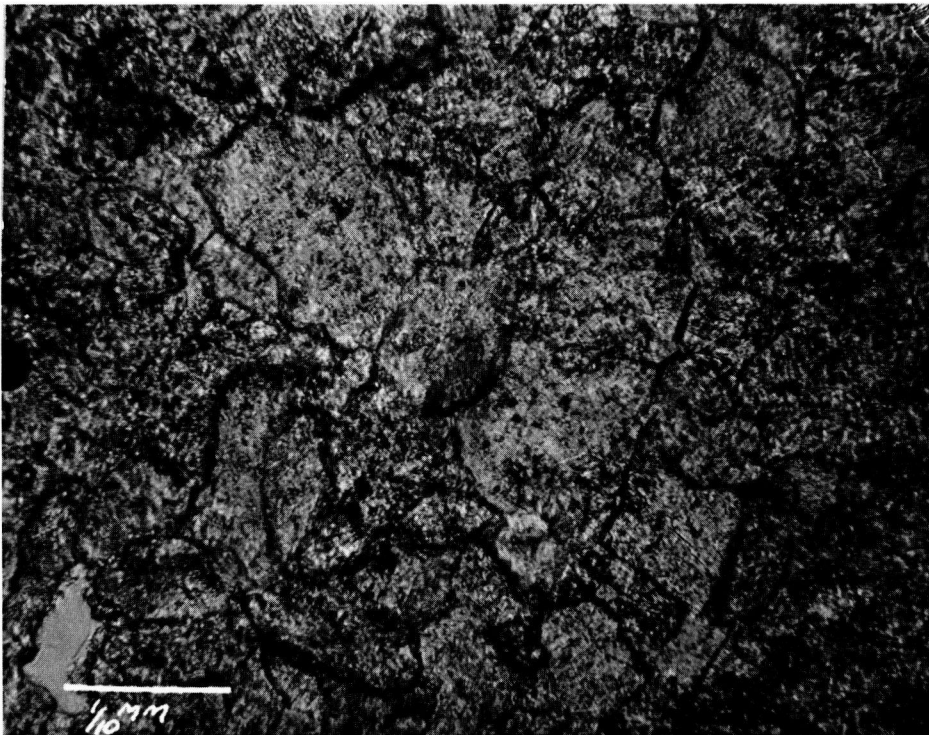


Figure A-6. Photomicrograph showing concave-convex to straight interlock.



hit, because the lines begin and terminate in the same grain. A cut is registered when a grain boundary is crossed; d has no cuts because the line is contained within a single grain.

The volume-surface ratio was obtained through an analysis by Crofton (1868). His results indicated that if a long line is projected repeatedly and at random over a closed figure in a plane, the average length of chord intersected by the figure will be proportional to the area-perimeter ratio.

Chalkey et al. (1949) revised Crofton's method in order to study the volume-surface ratio of cancer cells. They suggest

$$\frac{r h}{4c} = \frac{\text{volume}}{\text{surface}} \quad (\text{A-1})$$

in which

$r$  = length of projected line;  
 $h$  = number of hits; and  
 $c$  = number of cuts.

A mathematical proof of this relationship is presented by Cornfield and Chalkey (1951).

In the Iowa study Wallace (1962) projected 400 random equal-length lines onto each texture mosaic. The lines were randomized by use of a random number table using numbers as coordinates and angles of rotation. The method presented by Wallace was used in this study, except that care was taken that the lines were long enough so that at least one cut was recorded in each reading (a zero value in the denominator was an undesirable reading).

In the present study 400 lines were attempted at first. The results of this comparison are presented in Appendix B.

Two of the microphotographs used in the line projecting analysis are shown as Figures A-8 and A-9. Figure A-8 is a dolomite from Illinois with a concavo-convex interlock; Figure A-9 is a fossiliferous limestone aggregate that also has a concavo-convex interlock. Because the magnification is the same for both sections, the grain size in Figure A-9 is considerably larger than that in Figure A-8. Magnification for both figures is approximately  $80\times$ .

#### Statistical Application

The nature of the degradation problem made it apparent at the outset that a statistical comparison of data would be necessary. In this study of degradation, several related but separate areas of knowledge were developed through laboratory testing and other research. Briefly, these areas are: (1) a general knowledge of the performance of the aggregates relative to degradation as indicated by the agency supplying them; (2) engineering test data, including Los Angeles abrasion, freeze-thaw data, sodium sulfate soundness, absorption, and specific gravity data; (3) rock textural information, including grain size, roundness, orientation; and (4) mineralogical data from DTA, X-ray, and insoluble residue studies.

Collectively, the information available on the aggregate samples comprised a lengthy and fairly comprehensive list. By considering as well that more than 140 aggregate



- a. 1 hit and 2 cuts  
 b. 2 hits and 2 cuts  
 c. 2 hits and 1 cut  
 d. 1 hit and no cuts

After Wallace, 1962

Figure A-7. Method for determining hits and cuts in rock textures.

sources are represented in the over-all study, with multiple thin-section analyses for many individual sources, the wide scope of the problem becomes more apparent. Because of the number of samples involved and the diversity of the parameters measured, the necessity for statistical analysis was noted and the data were analyzed accordingly. The Purdue University IBM 7094 electronic computer was used for most of the required calculations.

In this research, statistics has been used in a limited fashion as an extension of the scientific reasoning of the authors. In no case was total reliance placed on the statistical approach; it was only used in conjunction with other information to reach conclusions. This report is not meant to be a text on statistics or statistical analysis of data.

The analysis of data following the Phase I research was accomplished by the application of two statistical procedures: (1) the determination of the "least squares" fit for a plot of percent wear by Los Angeles abrasion as the dependent variable and all of the other measured parameters as independent variables, and (2) multiple regression analysis.

The "least squares" curve fitting method is the commonly applied technique for choosing the curve that best fits the available data, such that the squares of the differences between the curve and the data are minimized. The mathematical development of the method is given in a number of engineering mathematics textbooks (see, for example, Gaskell, 1958, p. 229).

In the plot of percent wear, Los Angeles abrasion, versus degradation value, a linear best fit was obtained first. This yields an equation of the form

$$y = a_0 + a_1x \quad (\text{A-2})$$

The significance of the fit was checked by comparing the

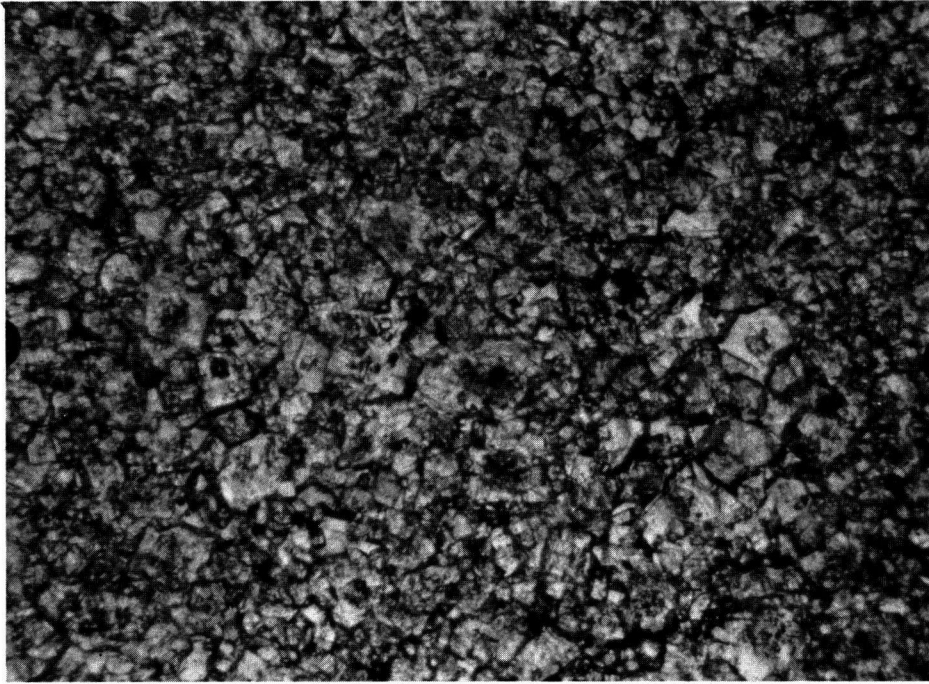


Figure A-8. Photomicrograph of dolomite aggregate (Ill. 4-B) used in line projecting study.

$F$ -value due to regression with that of a tabulated  $F$ -value, the latter being a function of the degrees of freedom and

confidence level desired for the fit. When  $F$  as calculated is greater than the tabulated  $F$ , the fit is significant at the

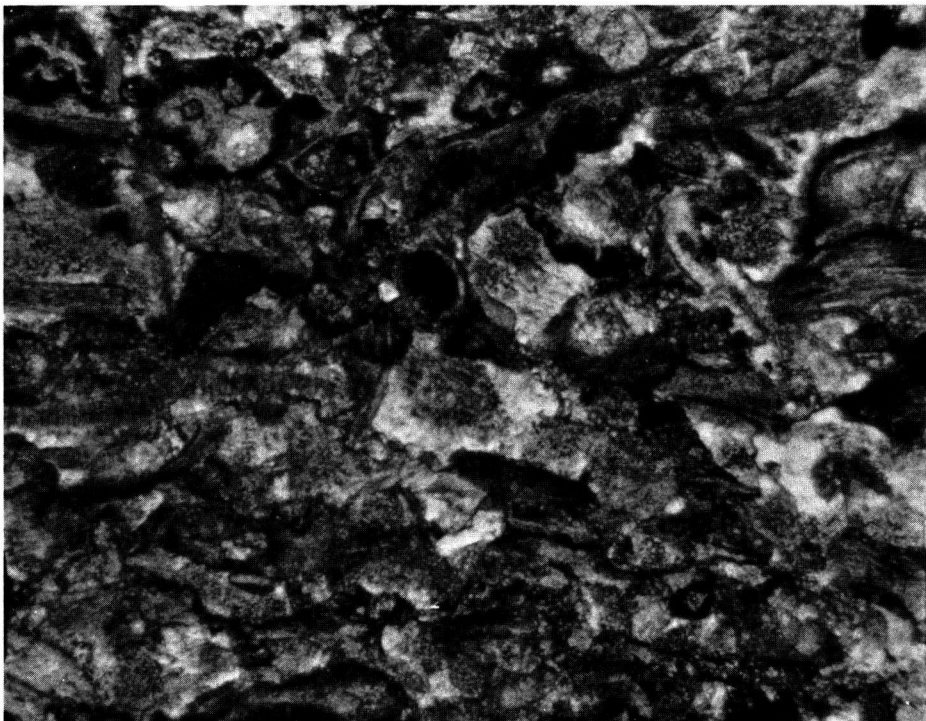


Figure A-9. Photomicrograph of fossiliferous limestone (Ill. 7  $\perp$ ).

level selected, usually 95 percent. Tables of  $F$  are found in the appendices of many texts on statistics (for example, Krumbein and Graybill, 1965; Dixon and Massey, 1957).

It is also possible in the foregoing case to ascertain how much of the variation in the dependent variable is being accounted for by the independent variables. The  $R^2$  measure indicates this relationship; it is a function of how much of the total variation is taken up by the regression line or least squares line. Hence, the less the scatter about the regression line, the greater the  $R^2$ -value and the better the fit.

Subsequently, polynomial regression fits were made of the Los Angeles degradation plot. This equation is of the form

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 \dots + a_n x^n \quad (\text{A-3})$$

The power terms were added progressively through the fourth power, yielding quadratic, cubic, and quartic regression fits of the data. Again the  $F$  test was applied to show the significance of each fit. For example, if the  $F$  criterion indicates significance at the 95 percent level, the curve should prove significant 95 percent of the time if a similar number of samples are taken from the over-all population. (See Krumbein and Graybill, 1965, for  $F$  test and  $R^2$  definitions.)

Multiple correlation and regression analyses also were made of the data. This useful form of analysis has been applied recently in several geological studies (Krumbein, 1959; Holmes and Goodell, 1964) and is a powerful means of comparing properties of materials and their interactions. Krumbein (1959) presents an explanation of this technique, including its geological significance and its area of application.

The polynomial curve fitting discussed previously is a type of multiple regression analysis in which powers of the same variable are used. In the general case, however, multiple, independent variables are related to the single dependent variable using regression theory. In this analysis each dependent variable is paired in turn with the dependent variable, and its ability to predict the variation in the dependent variable is obtained. The results are shown as a listing of the independent variables arranged in order of their ability to predict the dependent variable as indicated by decreasing computed  $F$ -values. The contribution of each independent variable is expressed in the form of a coefficient. From these coefficients, a predicting equation for the dependent variable can be obtained. As before, the  $R^2$ -value can be consulted to see how much of the variation in the dependent variable is being accounted for.

Correlation coefficients are obtained in addition to the regression data. Krumbein (1959) notes that the restrictions for correlation analysis are less stringent than for regression analysis. In regression analysis there is a cause-and-effect relationship that is not necessarily present in correlation analysis; therefore, Krumbein prefers to use regression analysis in addition to correlation analysis for geological problems.

The correlation between two variables is indicated by a number that can range from +1 to -1. The value 1 indi-

cates perfect correlation between two parameters or variables; 0 indicates no correlation at all. The signs for correlation coefficients can be either plus or minus, plus indicating a direct relationship (as A increases, B increases) whereas a minus value indicates an inverse relationship (as A increases, B decreases). Correlation does not imply, however, that a responsive change in one variable will occur with arbitrary changes in the other variable.

Two types of correlation coefficients were obtained in the analysis: (1) simple correlation coefficients, and (2) partial correlation coefficients. Simple correlation coefficients show the relationship between two variables or, indeed, how one varies in response to the other. Interaction of the other parameters under study influence the relationship, however. For example, if A and B are being compared, but both B and A vary with a third variable, C, A will be affected by variations in C as well as those in B as B is allowed to fluctuate through its range of values. This sometimes masks the true relationship between the variables being studied. Cluster diagrams as devised by Krumbein and Imbrie (1963) can be used to show the relation between various simple correlation coefficients. Diagrams of this type are used for this purpose in Appendix B.

Partial correlation coefficients have the advantage of indicating the relationship between two variables without being influenced by the interaction of the other parameters. In this analysis the dependent variable is paired with a single independent variable while the other independent variables are held constant, or the effect of their presence is held constant. In this manner, the independent variable is unaffected by side effects as it is compared with the dependent variable. In the analysis, coefficients are gotten only from pairings of independent variables with the single dependent variable and not between the independent variables themselves.

For both multiple regression analysis and partial correlation analysis, the coefficients obtained relate only the dependent variable with the various independent variables. The other variables can be treated as dependent variables, however, through a replacement and deletion process that substitutes another variable for the previously dependent variable. This substitution can be made in most instances because the actual independence or dependence of a variable is a rather moot point.

In Phase II of the research, both polynomial curve fitting and multiple regression and correlation analysis were used in the same manner as in Phase I. In regard to curve fitting, several pairs of variables were compared, rather than the sole application accomplished in Phase I (Los Angeles abrasion vs degradation value). In addition, data for these new comparisons were obtained from tests run in the research agency laboratories rather than from test data provided by the aggregate suppliers as used in the previous phase. The following plots were made: (1) Los Angeles loss versus degradation value, (2) Los Angeles loss versus mean grain size, (3) Los Angeles loss versus standard deviation of grain size, (4) Los Angeles loss versus freeze-thaw loss, and (5) freeze-thaw loss versus degradation value. Polynomial fits were made in addition

to the linear fits when the results suggested that further work was necessary. In the case of Los Angeles loss versus mean grain size and Los Angeles loss versus standard deviation of grain size, additional comparisons were made. Least squares curves were fitted to log transforms of the mean grain size and the standard deviation of the grain size. The results of these various fits are presented in Appendix B.

Multiple regression and correlation analyses were made of all the data available on the samples that could be compared. Aggregates were analyzed according to rock type, with carbonates, phaneritic metamorphic and igneous rocks, and the aphanitic igneous rocks (primarily basalts) making three distinct groups. They were analyzed as a group and then state by state in order to isolate any discrepancies from the over-all trend.

Several analyses of variance (commonly abbreviated as AOV) calculations also were made. This analysis was used to compare variations within an aggregate source with those between sources. It was also used to relate variations in subsequent thin sections for the same rock with the over-all variations from source to source. This analysis required a one-way or single-factor AOV in most cases. An example is given in Appendix B.

Analysis of variance is a measure of the variability between related samples in one unit or location versus the total variation of all the samples taken. The following is a possible example of one-way AOV. If the 10-sec reading for a hydrometer test is made three times for each of four

samples, the AOV calculation would show if significant difference exists in the grain size value of the samples associated with the 10-sec reading or if operator error masks the problem. In the method, the sums of squares of the deviation of each group of readings is compared with that of all the readings to see where the bulk of the variation lies.

Prior to the analysis of grains in the Phase II research, the required number of grain measurements had to be ascertained. As previously mentioned, an upper limit of about 500 grains had been suggested by F. Chayes (1956) for mineral compositions but not for grain measurements and several investigators suggested 200 grains as a working number for grain counting. To check the acceptability of the number of samples taken, the following equation was used and 95 percent confidence level was considered:

$$\text{Confidence level for mean} = \bar{x} \pm t_{0.975} (s/\sqrt{n-1}) \quad (\text{A-4})$$

in which

- $\bar{x}$  = mean diameter;
- $t$  = students  $t$  value for percent confidence;
- $s$  = standard deviation of mean; and
- $n$  = number of samples.

The same slide was analyzed twice for comparison, first using 500 grains and then 200 grains. The results, given in complete form in Appendix B, indicate that 200 grains were sufficient for the accuracy desired.

## APPENDIX B

### TEST RESULTS

#### GENERAL

Test results were compiled at the end of Phase I and a number of tentative conclusions based on the Phase I data were made. Several graphical plots and cluster diagrams were used to express these relationships. The complete lists of findings and implications are presented in Appendices D and E, but can be summarized as follows insofar as they pertain to this portion of the over-all degradation study:

1. Concerning the percent of wear, Los Angeles abrasion appears to be a good indicator of the degradation properties of carbonate rocks; that is, as the wear increases the susceptibility to degradation increases.
2. This relationship does not appear to hold for basalt rocks in general.
3. Two types of degradation may be operating—me-

chanical degradation, which dominates in carbonate rock breakdown and is indicated by Los Angeles abrasion loss, and chemical degradation, which may not be indicated by this test.

4. Petrographic studies seem to be useful means for identifying degrading rocks and it appears that textural parameters (grain size, roundness and distribution) are related to the Los Angeles abrasion wear value.

5. For phaneritic igneous and metamorphic rocks, a direct relationship appears to exist between grain diameter and loss in abrasion; that is, as grain size increases abrasion loss increases.

6. Carbonate mineral and clay mineral type (illite commonly present) are not of prime importance regarding carbonate degradation.

Following the summarization at the end of Phase I, additional information was obtained by analyzing and testing

the newly received 50-lb aggregate samples. The petrographic techniques were re-evaluated at this time and modified accordingly. In the final stages of the research, the over-all data were compared by statistical methods, including data from Phase II and some from Phase I when these were still applicable in light of the recent developments. The results can be divided into three basic categories—petrographic results, engineering test results, and the over-all results from statistical analysis.

## PETROGRAPHIC RESULTS

In the petrographic analysis portion of the research, most of the thin sections studied in an abbreviated manner in Phase I were re-examined during Phase II. Whereas only an estimated average grain size was obtained in the previous analysis, tedious, time-consuming measurements were made in Phase II. At least 200 grains were measured in each thin section, including the determination of maximum, minimum, and intercepted diameters of the grains. Table B-1 compares the estimated grain size (mode) and range of sizes determined in Phase I with the mean maximum grain diameter and its standard deviation from Phase II.

For the most part the estimated modal diameter is fairly close to the calculated mean grain size. This is particularly true for fine-grained textures of fairly uniform grain size. Some of the Illinois aggregates are notable exceptions to this close comparison; but many of these have a wide range of grain sizes, which makes it difficult to obtain meaningful estimates.

The two measures of spread of the grain size distribution are not nearly as closely related. The Phase I measurement, range of grain size, indicates only the upper and lower extremes of size and not really the manner in which the grains are distributed within those limits. The standard deviation of the mean, which in total incorporates 68 percent of the grain diameters, is a more meaningful portrayal of the grain size distribution. It does not, however, show anything about the extremes in grain size, which may be important—the upper grain size in particular. In general, the standard deviation is the preferred measure of the two, but it unfortunately precludes the measurement of numerous grains because the mean grain size must be determined first.

Several checks were made on a single thin section to determine how many grains had to be measured to determine acceptable mean and standard deviation values. By use of Eq. A-4, explained under "Statistical Application" in Appendix A, the data given in Table B-2 were obtained from a single thin section.

This table represents data from four separate analyses of a thin section of Illinois 6 aggregate. The section was oriented perpendicular to the direction of bedding. In analyses 1 and 2 the same methods of measurement were used with only the number of points counted being different. It can be seen that the means are comparable and also both fall within the 95 percent confidence interval of the opposing mean. In these analyses, the grain traverses were made perpendicular to the direction of bedding, thereby maximizing the number of grains from different strata. In

addition, the point counting method was used in this analysis. This method, as described previously, consists of measuring grains a prescribed distance apart rather than along a continuous path.

Measurements 3 and 4 were made parallel to the bedding and a continuous (Rosiwal) traverse was used. In this method, each consecutive grain is measured in turn across the slide. As previously mentioned, this method was finally adopted as the routine analysis because of the problem of deciding which grain to measure in the point count method when the cross hair falls on the boundary between two grains. There is a tendency to choose the better defined, or more easily measured grain in that procedure. This bias is highly undesirable when determining matrix and grain percentages.

For maximum and minimum diameter comparisons in measurements 3 and 4 the agreement is quite acceptable, as both mean values fall within the range of the opposing mean. For intercepted diameter this does not hold, because 3 and 4 were run by two different investigators with a span of several months between analyses, and the method of measuring intercepted diameters was changed during this time to facilitate the determination of matrix-grain ratios. In addition, the intercepted diameter for 1 and 3 are in agreement, both falling within the other range of mean at the 95 percent confident level. Readings 1, 2, and 3 were made by the first investigator and reading 4 by the second.

A considerable difference is noted between 1 and 2 as a group as compared to 3 and 4. This is suggestive of the effect of orientation of the traverse on the grain diameters obtained. Measurements 1 and 2 were made transverse to the bedding and 3 and 4 were made parallel to the bedding. In this respect it should be pointed out that the true value of the grain diameters in thin section is of secondary importance. As long as a consistent method of traversing is employed, the values obtained for different sections will retain their same relative position and correlation and regression analyses are not adversely affected. Krumbein (1935) has shown in his study of sandstones and their disaggregated particles that the grain size as measured in thin section must be adjusted by a correction factor to compare favorably with sieve analysis results. Sieve analysis, of course, is subject to its own difficulties (Lees, 1964), inasmuch as shape as well as size influence the values obtained. In the first analysis, however, a precise, reproducible result of grain size measurement in thin sections is the meaningful contribution of this comparison.

The implications of Table B-2 are: (1) 200 grains are a sufficient number of measurements to determine mean diameter and standard deviation, and (2) reproducible results for subsequent measurements by the same investigator or between experienced investigators can be obtained using the same thin section.

The time factor was also an important consideration in the grain measuring analysis. An experienced petrographer can measure about 100 grains per hour after becoming familiar with the technique involved. The measurement of 500 grains per thin section is prohibitive in view of the staggering number of thin sections measured in Phase II (148 thin sections from 135 quarries). In addition, the

TABLE B-1

COMPARISON OF GRAIN MEASUREMENTS,  
PHASES I AND II

| SAMPLE<br>DESIGNATION | MEASUREMENT (MM) |             |          |              | SAMPLE<br>DESIGNATION | MEASUREMENT (MM) |             |          |              |
|-----------------------|------------------|-------------|----------|--------------|-----------------------|------------------|-------------|----------|--------------|
|                       | PHASE I          |             | PHASE II |              |                       | PHASE I          |             | PHASE II |              |
|                       | MODE             | RANGE       | MEAN     | STD.<br>DEV. |                       | MODE             | RANGE       | MEAN     | STD.<br>DEV. |
| <b>Illinois</b>       |                  |             |          |              | <b>Wisconsin</b>      |                  |             |          |              |
| 1                     | 0.470            | 1 700-0 100 | 1 333    | 1 173        | 1                     | 0.065            | 0 750-0 030 | 0.091    | 0 048        |
| 2                     | 0 270            | 4 000-0.100 | —        | —            | 2                     | 0 075            | 0 150-0 030 | 0.179    | 0.097        |
| 3                     | 0 250            | 2.000-0.050 | 0 029    | 0 024        | 3                     | 0.150            | 0.250-0 077 | —        | —            |
| 4                     | 0.630            | 2.500-0.050 | 0 980    | 1 564        | 4                     | 0.070            | 0.120-0.030 | 0.100    | 0.052        |
| 5                     | 0 008            | 0 025-0 004 | 0.010    | 0 008        | 5                     | 0.100            | 0 250-0.020 | 0.144    | 0 078        |
| 6                     | 2 250            | 4.500-0.100 | 1.614    | 1 149        | 6                     | 0.060            | 0 175-0.020 | 0 097    | 0.051        |
| 7                     | 1 500            | 3 000-0 200 | 0 385    | 0 300        | <b>New York</b>       |                  |             |          |              |
| 8                     | 1.000            | 5 000-0 100 | —        | —            | 1                     | 0.090            | 0 175-0.040 | 0.113    | 0 054        |
| 9                     | 0.100            | 0.500-0 015 | 0.061    | 0.050        | 2                     | 0 025            | 0 045-0.015 | 0 032    | 0.036        |
| 10                    | 0 150            | 0 250-0.001 | —        | —            | 3                     | 0.038            | 2.000-0 010 | 0 650    | 0.699        |
| 11                    | 0.200            | 1.000-0 020 | 0.032    | 0 019        | 4                     | 0.000            | —           | —        | —            |
| 12                    | —                | —           | 0.005    | 0 002        | 5                     | 0.060            | 0.200-0.040 | —        | —            |
| <b>Missouri.</b>      |                  |             |          |              | 6                     | 0.500            | 1.000-0.100 | 0.408    | 0.482        |
| 1                     | 0 120            | 3 000-0 015 | 0.207    | 0 260        | 7                     | 0.020            | 0 050-0 007 | 0.028    | 0.022        |
| 2                     | 1.130            | 0.750-0 005 | 0.202    | 0 138        | 8                     | 0.035            | 0.085-0.010 | 0.047    | 0.025        |
| 3                     | 0 750            | 2 000-0 020 | 0 702    | 0 473        | 9                     | 0.085            | 0.250-0.010 | 0.100    | 0 046        |
| 4                     | 0.020            | 0 750-0 040 | 0 033    | 0.014        | <b>Virginia.</b>      |                  |             |          |              |
| 5                     | 0.070            | 2.000-0 020 | 0.134    | 0 095        | 1                     | 0 200            | 0.700-0.125 | 0 184    | 0.131        |
| 6                     | 0.035            | 0 060-0 010 | 0 033    | 0.013        | 5                     | 0.750            | 1.750-0.150 | 0.459    | 0 305        |
| 7                     | 0.260            | 0.450-0.050 | 0 196    | 0.189        | 6                     | 0.300            | 1.000-0.080 | 0.438    | 0 318        |
| 8                     | —                | —           | 0.148    | 0 130        | 7                     | 0.010            | 0 250-0 050 | 0.015    | 0 021        |
| 9                     | —                | —           | 0 021    | 0 011        | 9                     | 0.500            | 2.250-0 300 | 0.205    | 0.181        |
| 10                    | —                | —           | 1.015    | 0.726        | 11                    | 0.100            | 2.250-0.300 | 0.118    | 0 139        |
| 11                    | —                | —           | 0.018    | 0.010        | 17                    | 0 100            | 0.250-0 035 | 0.070    | 0.045        |
| 12                    | 0.150            | 0 700-0.050 | 0.176    | 0 158        | 18                    | 0.060            | 0 250-0.025 | 0.058    | 0.037        |
| 13                    | 0.200            | 1.500-0.050 | 0 157    | 0 123        | 20                    | 0 015            | 0.040-0.005 | 0 008    | 0.006        |
| 14                    | 0.014            | 0 020-0 005 | 0.009    | 0.004        | 21                    | 0.080            | 0.100-0.020 | 0.126    | 0.054        |
| 15                    | 0.035            | 0 060-0 010 | 0.047    | 0.018        | 22                    | 0.500            | 1.000-0.020 | 0.418    | 0 266        |
| 16                    | 0.008            | 0.020-0.005 | 0.007    | 0 003        | 23                    | 0 017            | 0 030-0.005 | 0 007    | 0 003        |
| 16A                   | —                | —           | 0 042    | 0 015        | 27                    | 0.400            | 1.000-0.015 | 0.436    | 0.353        |
| 17                    | —                | —           | 0 206    | 0.208        | 28                    | 0 020            | 0.035-0.006 | 0.009    | 0 005        |
| 18                    | —                | —           | 0.094    | 0.072        | 31                    | 0 050            | 0.100-0.020 | 0 119    | 0 119        |
| 19                    | 0 010            | 0 020-0.006 | 0.014    | 0 009        | 32                    | 0 300            | 0 750-0 100 | 0.240    | 0 224        |
| 20                    | 0 250            | 3.000-0.008 | 0.021    | 0 010        | 34                    | 0.025            | 0.220-0.005 | 0.017    | 0 015        |
| 21                    | 0 230            | 0 750-0.004 | —        | —            | <b>Iowa</b>           |                  |             |          |              |
| 22                    | 0 250            | 0 700-0 015 | 0 273    | 0.175        | 1-2                   | 0.030            | 0 058-0.015 | 0.036    | 0.016        |
| 23                    | —                | —           | 0.012    | 0 008        | 1-10                  | 0.030            | 0.058-0 000 | 0.032    | 0 014        |
| 24                    | —                | —           | 0 026    | 0 017        | 2-8                   | 0.035            | 0.070-0 017 | 0.043    | 0 024        |
| <b>Pennsylvania</b>   |                  |             |          |              | 3-1                   | 0.020            | 0.070-0 005 | 0.022    | 0.015        |
| 1 (1-1)               | 1.000            | 4 000-0.400 | —        | —            | 3-2                   | 0.030            | 0 060-0 015 | 0.021    | 0 012        |
| 2 (1-2)               | 0 015            | 0 300-0.005 | 0 068    | 0 052        | 4-3                   | 0.150            | 0 600-0.100 | 0.206    | 0.117        |
| 3 (2-1)               | 0.200            | 4.000-0.100 | —        | —            | 5-1                   | 0.400            | 1 500-0.100 | 0 010    | 0.011        |
| 4 (2-2)               | —                | —           | 0 461    | 0.532        | 5-4                   | 0.200            | 0.750-0 030 | 0.161    | 0 189        |
| 5 (3-1)               | 0.025            | 3.000-0 010 | 0 095    | 0.194        | <b>Oregon:</b>        |                  |             |          |              |
| 6                     | 0 050            | 0.170-0.020 | 0.043    | 0.024        | 1                     | 0.090            | 0.400-0 050 | 0.118    | 0 084        |
| 7                     | 0.130            | 0 250-0.030 | 0.125    | 0 062        | 2                     | 0.050            | 1.500-0.010 | 0 111    | 0 115        |
| 8                     | 0 040            | 0.125-0.010 | 0.034    | 0.019        | 3                     | 0 075            | 0.100-0.035 | 0.005    | 0.000        |
| 9                     | —                | —           | —        | —            | 4                     | 0.175            | 1.500-0 010 | 0 073    | 0.079        |
| 10                    | 0 065            | 0.250-0.015 | 0 092    | 0.051        | 5                     | 0 200            | 0.750-0.020 | 0.115    | 0 126        |
| 11                    | 0 500            | 1.500-0.100 | 0.519    | 0.399        | 6                     | 0 080            | 0.750-0.010 | 0.032    | 0.031        |
| 12                    | 0.060            | 0.750-0 010 | 0.054    | 0 039        | 7                     | 0 200            | 0.750-0.040 | 0 128    | 0.111        |
| 13                    | 1.000            | 2.000-0.100 | 0 618    | 0 398        | 8                     | 0.150            | 0 250-0 080 | 0.281    | 0.193        |
| 14                    | 0 080            | 0 500-0.040 | 0 047    | 0 043        | 9                     | 0.030            | 0.175-0.010 | 0.014    | 0 013        |
| 15                    | 0.010            | 0 060-0.005 | 0.002    | 0.000        | 10                    | 0 150            | 0.300-0.060 | 0.061    | 0.037        |
| 16                    | 0 060            | 0.700-0.010 | 0 138    | 0 134        |                       |                  |             |          |              |
| 17                    | 0.025            | 3.000-0 020 | 0.117    | 0.074        |                       |                  |             |          |              |
| 18                    | 0 015            | 1.750-0 007 | 0.013    | 0.012        |                       |                  |             |          |              |
| 19                    | 0.065            | 0.750-0.005 | 0.118    | 0.065        |                       |                  |             |          |              |
| 20                    | 0.220            | 0.750-0.030 | 0 192    | 0.185        |                       |                  |             |          |              |

TABLE B-2

DATA COMPARISON FOR A SINGLE THIN SECTION, SAMPLE ILLINOIS 6

| ANALYSIS NUMBER | MEAS TECHNIQUE AND ORIENTATION                        | NUMBER OF GRAINS MEAS. | MAXIMUM VALUE |       |                      |           |       |                      |           |       |                      |
|-----------------|---|------------------------|---------------|-------|----------------------|-----------|-------|----------------------|-----------|-------|----------------------|
|                 |   |                        | $\bar{x}$     | $s$   | CONFIDENCE INTERVAL  | $\bar{x}$ | $s$   | CONFIDENCE INTERVAL  | $\bar{x}$ | $s$   | CONFIDENCE INTERVAL  |
| 1               | Traverse perpendicular to bedding, point count method | 200                    | 0.859         | 0.353 | 0.049<br>0.908-0.810 | 0.501     | 0.251 | 0.035<br>0.536-0.466 | 0.627     | 0.272 | 0.038<br>0.665-0.591 |
| 2               | Traverse perpendicular to bedding, point count method | 500                    | 0.898         | 0.408 | 0.040<br>0.938-0.858 | —         | —     | —                    | —         | —     | —                    |
| 3               | Traverse parallel to bedding, continuous (Rosival)    | 500                    | 0.748         | 0.378 | 0.052<br>0.800-0.696 | 0.449     | 0.226 | 0.031<br>0.480-0.418 | 0.614     | 0.328 | 0.045<br>0.659-0.569 |
| 4               | Traverse parallel to bedding, continuous reading      | 500                    | 0.762         | 0.479 | 0.042<br>0.804-0.720 | 0.428     | 0.270 | 0.024<br>0.452-0.404 | 0.437     | 0.274 | 0.023<br>0.460-0.414 |

rate of 100 grains measured per hour is predicated on a short span of time; that is, 2 or 3 hours at best. This rate could not be maintained for an 8-hr day, because eye strain becomes a serious problem after several hours of analysis.

In essence, the limit of 200 grains is set as a minimum value for purposes of accuracy and reproducibility and as a maximum value in view of the length of time involved. It is by no means suggested, however, that a 200-grain measurement be proposed as a routine test for evaluating aggregate quality. This is purely a research technique and as such must be refined before being used as an aggregate acceptance test.

Several other petrographic problems also were analyzed. The variation of grain size from quarry to quarry, considering orientation as a major factor, was explored. The question to be answered was: Is the variation in grain size among quarries truly significant or do orientation differences in companion thin sections from the same quarry contribute enough variation to outweigh differences be-

tween quarries? An AOV calculation (Table B-3) was employed to check this supposition. This is a one-way, or single-factor, analysis.

The results show that the variation is much greater between quarries than within a single quarry, hence the grain diameter differences are significant from quarry to quarry. Whether the measurement is meaningful in regard to degradation is another matter that is discussed in a later section on statistical results.

A perplexing problem concerning thin-section analysis also was explored. Thin-section analysis is performed on the microscale, involving grain measurements of the order of 10 to 1,000  $\mu$  (1 mm) in diameter. Actually, thin sections are only about 2 sq in. in area and represent a relatively small rock mass. In a preceding discussion, the results showed that 200 grain diameter measurements were required to describe a thin section realistically. The subsequent extension from an accurate picture of a thin section

TABLE B-3

ANALYSIS OF VARIANCE FOR THIN-SECTION ORIENTATION ( $\text{mm} \times 10^3$ )

| ILL 3                | $i$<br>→ | ILL 4B         | ILL 5         | ILL 6                                      | ILL 7         | ILL 9                   | ILL 12         |
|----------------------|----------|----------------|---------------|--|---------------|-------------------------|----------------|
| III. 3PE 02.9        |          | III. 4B-1 09.3 | III. 5 01.0   | III. 6PA 76.2                              | III. 7PE 27.2 | III. 9 6.1              | III. 11 03.2   |
| ↓j III. 3PA 01.7     |          | III. 4B-2 05.1 | III. 5PE 01.2 | III. 6PE 72.8                              | III. 7PA 40.9 | III. 9PA 5.4            | III. 11PE 04.0 |
| $x_i$                | 4.6      | 14.4           | 2.2           | 149.0                                      | 68.1          | 11.5                    | 7.2            |
| $\bar{x}_i$          | 2.3      | 7.2            | 1.1           | 74.5                                       | 34.0          | 5.7                     | 3.6            |
| $x = 257.0$          |          |                |               |  |               |                         |                |
| $\bar{x} = 18.36$    |          |                |               |  |               |                         |                |
|                      |          |                |               | H: $\mu_1 = \mu_2 = \mu_3 = \dots = \mu_7$ |               |                         |                |
| Source of variations | ss       | df             | MS            | $F_{\text{calc}}$                          |               | $F_{\text{tab } 99.99}$ |                |
| Between categories   | 4454.7   | 7-1=6          | 742.4         | $\frac{742.4}{15.9} = 46.7$                |               | $F_{0.7} = 31.57$       |                |
| Between samples      | 109.76   | 7(1)=7         | 15.9          | $F_{\text{tab}} > F_{\text{calc}}$         |               |                         |                |
|                      |          |                |               | H: is rejected                             |               |                         |                |

to that of a rock particle and finally from the rock particle to the quarry are more difficult, however.

In the foregoing comparison of Illinois quarries, the variation from quarry to quarry was substantiated. In one of the quarries (Illinois 4) two distinct lithologies were indicated by contrasting textures. Grain size determinations substantiated this fact, but within an individual textural unit (Ill. 4B) the variation was not as great as among the quarries compared (Table B-3). In essence, if a textural difference cannot be discerned between subsequent lithologies with the aid of the naked eye, the variation as measured by thin section should not be too extreme.

Indiana aggregates were used to check the relationship between thin sections and quarry sources. Four quarries studied in the over-all degradation research were chosen from the group of Indiana quarries on the basis of comparatively uniform rock texture and availability of information on the quarries. Two aggregate pieces were selected from each of the 50-lb samples from the four quarries. Two thin sections were made from each of the eight rock samples. The companion sections were cut from parallel and opposite sides of the 5-in. aggregate pieces.

For the 16 thin sections, grain size, matrix size, and the percentage of voids, grains and matrix, were determined. These data are given in Table B-4 in addition to the maximum-minimum grain diameter ratio and matrix-grain diameter ratio. The findings are so arranged that companion thin sections made from a single aggregate piece are located directly below each other. Companion aggregate particles from the same quarry also are located in close proximity. As an example, Indiana 5 sample 1 has two companion thin sections, A and B, which are found in direct sequence.

The data in Table B-4 indicate that the void, matrix, and

grain content seem to vary somewhat sporadically. The amount of cement filling the voids may account for this variation. The ratio values on the right are also interesting in that the fairly consistent results obtained suggest that these ratios probably do not vary greatly in magnitude. This was borne out by the numerous thin-section measurements made in the over-all study.

The relationship among the maximum grain diameters listed in Table B-3 is given in Table B-5. This is presented in the form of a two-way analysis of variance calculation. Table B-5 consists of four columns, each representing an Indiana quarry; two rows for each of two aggregate pieces sampled in each quarry; and eight boxes with two entries per box, each entry representing the reading from an individual thin section of the same aggregate piece. The purpose of the calculation is to indicate here the significant variation that exists.

To the right of the original data are shown the row sums and the row means; immediately below are the column sums and the grand total. The calculations below the data are given in step-by-step fashion for the purpose of clarity. A further explanation of the analysis can be found in Krumbein and Graybill (1965, p. 205).

In this analysis,  $F_{calc}$  is compared with the  $F_{tab}$  value to check significance; if  $F_{calc}$  is the greater, significance is indicated. The results (Table B-5) show that the difference between successive thin sections of the same rock is insignificant in comparison with the other factors. The difference between aggregate pieces is greater than within thin sections. Also, the difference between quarries is extremely significant, much more so than between aggregate pieces from the same quarry. The calculation also shows that the interaction or "noise" between columns and rows is somewhat greater than differences between com-

TABLE B-4  
DATA COMPARISON FOR INDIANA COMPANION THIN SECTIONS

| QUARRY  | SAM-<br>PLE | SLIDE | MAX GRAIN           |                    | INTERCEPTED<br>MATRIX |                    | VOIDS<br>(%) | MATRIX<br>(%) | GRAINS<br>(%) | RATIO      |                 |
|---------|-------------|-------|---------------------|--------------------|-----------------------|--------------------|--------------|---------------|---------------|------------|-----------------|
|         |             |       | AVG<br>SIZE<br>(MM) | STD<br>DEV<br>(MM) | AVG<br>SIZE<br>(MM)   | STD<br>DEV<br>(MM) |              |               |               | MAX<br>MIN | MATRIX<br>GRAIN |
|         |             |       |                     |                    |                       |                    |              |               |               |            |                 |
| Ind 4   | 1           | A     | 0.1372              | 0.0741             | 0.0612                | 0.0207             | 9.7          | 3.8           | 86.5          | 1.582      | 0.604           |
|         | 1           | B     | 0.1454              | 0.0854             | 0.0606                | 0.0224             | 10.7         | 7.3           | 82.0          | 1.635      | 0.595           |
|         | 2           | A     | 0.1397              | 0.0842             | 0.0545                | 0.0230             | 3.0          | 11.5          | 85.5          | 1.376      | 0.537           |
| Ind. 5  | 2           | B     | 0.1292              | 0.0910             | 0.0545                | 0.0199             | 13.1         | 7.5           | 79.4          | 1.447      | 0.642           |
|         | 1           | A     | 0.0361              | 0.0191             | 0.0177                | 0.0091             | 10.6         | 9.7           | 79.7          | 1.218      | 0.597           |
|         | 1           | B     | 0.0382              | 0.0232             | 0.0166                | 0.0077             | 12.2         | 5.2           | 82.5          | 1.350      | 0.543           |
| Ind. 11 | 2           | A     | 0.0450              | 0.0271             | 0.0128                | 0.0055             | 6.5          | 5.8           | 87.6          | 1.449      | 0.377           |
|         | 2           | B     | 0.0477              | 0.0296             | 0.0190                | 0.0076             | 7.2          | 7.8           | 85.0          | 1.486      | 0.531           |
|         | 1           | A     | 0.0931              | 0.0608             | 0.0375                | 0.0126             | 7.2          | 1.5           | 91.4          | 1.440      | 0.549           |
| Ind. 11 | 1           | B     | 0.0916              | 0.0533             | 0.0350                | 0.0099             | 1.6          | 5.4           | 92.8          | 1.406      | 0.483           |
|         | 2           | A     | 0.0644              | 0.0394             | 0.0450                | 0.0167             | 4.7          | 9.1           | 86.2          | 1.436      | 0.885           |
|         | 2           | B     | 0.0458              | 0.0259             | 0.0421                | 0.0127             | 4.0          | 13.5          | 82.5          | 1.402      | 1.069           |
| Ind 12  | 1           | A     | 0.0172              | 0.0131             | 0.0105                | 0.0049             | 16.9         | 12.1          | 71.0          | 1.422      | 0.713           |
|         | 1           | B     | 0.0195              | 0.0134             | 0.0099                | 0.0029             | 15.8         | 11.4          | 73.8          | 1.348      | 0.605           |
|         | 2           | A     | 0.0190              | 0.0144             | 0.0097                | 0.0035             | 20.6         | 10.4          | 69.0          | 1.362      | 0.639           |
|         | 2           | B     | 0.0184              | 0.0118             | 0.0110                | 0.0042             | 15.7         | 11.4          | 72.9          | 1.363      | 0.740           |



TABLE B-5  
ANALYSIS OF VARIANCE FOR INDIANA THIN-SECTION DATA (mm × 10<sup>2</sup>)

|                   | <i>i</i> | <i>x<sub>j</sub></i> | $\bar{x}_j$       |       |   |  |               |  |  |
|-------------------|----------|----------------------|-------------------|-------|---|--|---------------|--|--|
|                   | 13.72    | 13.97                | 55.15             | 13.79 |   |  |               |  |  |
|                   | 14.54    | 12.92                |                   |       |   |  |               |  |  |
|                   | 28.26    | 26.89                |                   |       |   |  |               |  |  |
|                   | 3.61     | 4.51                 |                   |       |   |  |               |  |  |
|                   | 3.82     | 4.77                 | 16.71             | 4.18  |   |  |               |  |  |
|                   | 7.43     | 9.28                 |                   |       | $\mu_{c1} = \mu_{c2}$                       | $\frac{\textcircled{1}}{\textcircled{4}}$ Sign | $\neq$ reject |  |  |
| <i>i</i>          | 9.31     | 6.44                 |                   |       |   |  |               |  |  |
|                   | 9.16     | 4.58                 | 29.49             | 7.37  |   |  |               |  |  |
|                   | 18.47    | 11.02                |                   |       | $\mu_{r1} = \mu_{r2} = \mu_{r3} = \mu_{r4}$ | $\frac{\textcircled{2}}{\textcircled{4}}$ Sign | $\neq$ reject |  |  |
|                   | 1.72     | 1.90                 |                   |       |   |  |               |  |  |
|                   | 1.95     | 1.84                 | 7.41              | 1.85  |   |  |               |  |  |
|                   | 3.67     | 3.74                 |                   |       |   |  |               |  |  |
| $x_{i..} = 57.83$ | 50.93    |                      | $x_{.j} = 108.76$ |       |   |  |               |  |  |

|                  | SS  | DF           | MS                                       | $F_{calc}$                                | $F_{tab}$ | COMMENT               |
|------------------|---|--------------|--|---|-----------|-----------------------|
| Col. means (Sc)  | $\frac{\sum x_{.j}^2}{cn} - \frac{x_{.j}^2}{rcn}$                       | $c-1$        | $\frac{\textcircled{1} Sc}{c-1}$         | $\frac{\textcircled{1}}{\textcircled{4}}$ | $F_{1,8}$ |                       |
|                  | $= \frac{(57.83)^2 + (50.93)^2}{(4)(2)} - \frac{(108.76)^2}{(4)(2)(2)}$ | 1            | 2.98                                     | 8.75                                      | 5.31      | Significant           |
| Row means (Sr)   | $\frac{\sum x_{ij}^2}{cn} - \frac{x_{.j}^2}{rcn}$                       | $r-1$        | $\frac{\textcircled{2} Sr}{r-1}$         | $\frac{\textcircled{2}}{\textcircled{4}}$ | $F_{3,8}$ |                       |
|                  | $= \frac{(55.15)^2 + \dots + (7.41)^2}{(2)(2)} - 739.29$                | 3            | 107.35                                   | 316                                       | 4.06      | Extremely significant |
| Subtotal (Ss)    | $\frac{\sum \sum x_{ij}^2}{n} - \frac{x_{.j}^2}{rcn}$                   |              |  |   |           |                       |
|                  | $= \frac{(28.26)^2 + \dots + (3.74)^2}{2} - 739.29$                     |              |  |   |           |                       |
|                  | $= 337.24$  |              |  |   |           |                       |
| Interaction (Si) | $S_s - S_c - S_r$   | $(c-1)(r-1)$ | $\frac{\textcircled{3} S_i}{(c-1)(r-1)}$ | $\frac{\textcircled{3}}{\textcircled{4}}$ | $F_{3,8}$ |                       |
|                  | $= 337.24 - 298 - 322.04$   | 3            | 4.07                                     | 11.9                                      | 4.06      | Significant           |
|                  | $= 12.22$   |              |  |   |           |                       |
| Total (St)       | $\sum \sum \sum x_{ijk}^2 - \frac{x_{.j}^2}{rcn}$                       |              |  |   |           |                       |
|                  | $= (13.72)^2 + \dots + (3.74)^2 - 739.29$                               |              |  |   |           |                       |
|                  | $= 339.96$  |              |  |   |           |                       |
| Within           | $S_t - S_s$   | $rc(n-1)$    |  |   |           |                       |
|                  | $= 2.72$  | 8            | ④0.34                                    |   |           |                       |

panion thin sections. In summary, this calculation shows that the variation between the companion thin sections is negligible compared to the different aggregate pieces, different quarries, and even interacting "noise." This removes the doubt that a thin-section measurement may induce more variation in a study than that which the researcher is trying to determine. It must be remembered, however, that only homogeneous appearing textures were included.

Three Iowa quarries of a marginal nature regarding degradation were analyzed separately because of their heterogeneous nature. The individual beds were sampled and described on an aggregate collecting trip to Iowa during the first phase of research. It was observed, both in Iowa and in Illinois, that in many quarries where the rocks vary considerably in the vertical direction (or perpendicular to the bedding), substandard materials relative to degradation commonly are found. This is indicative of a changing sedimentary environment in which at least a few argillaceous and therefore marginal units are deposited.

An analysis was made to determine to what extent the extreme variations in the individual quarries overshadow variation from quarry to quarry. Table B-6 gives the AOV calculation for the Iowa quarries. The results suggest that the variation in the quarries is too great to use a single thin-section analysis as being in any way representative of the quarry, but all units must be analyzed in the study. In the testing phase of this project, test samples were taken from single designated and known ledges of each of the quarries. The engineering data were obtained from this single ledge sample, so that the problem indicated in Table B-5 was carefully avoided.

In Phase II an attempt was made to make the interlock evaluation more quantitative than the descriptive scale used in Phase I. It should be realized that the geological basis for the interlock scale devised during Phase I is well founded, as sedimentary petrographers have noted this textural relationship for some time (Brice, 1961). The

TABLE B-6  
ANALYSIS OF VARIANCE FOR HETEROGENEOUS IOWA QUARRIES (mm × 10<sup>2</sup>)

| IOWA 1  |                  | IOWA 3           |                 | IOWA 5                       |   |
|---|------------------|------------------|-----------------|------------------------------|---|
| BED   | MEAN<br>MAX. DIA | BED              | MEAN<br>MAX DIA | BED                          | MEAN<br>MAX DIA                                       |
| 1   | 2.24             | 1                | 2.23            | 1                            | 0.96  |
| 2   | 3.63             | 2                | 2.11            | 2                            | 8.76  |
| 4   | 71.24            | 3                | 2.71            | 4                            | 16.12   |
| 6   | 1.47             | 4                | 2.71            | 7                            | 0.82  |
| 8   | 3.52             |                  |                 |                              |   |
| 10  | 3.22             |                  |                 |                              |   |
|   | <u>85.32</u>     |                  | <u>9.76</u>     |                              | <u>26.66</u>  |
| $x = 101.75$  |                  | $\bar{x} = 7.27$ |                 |                              |   |
| Source of variation   | ss               | df               | MS              | $F_{calc}$                   | $H: \mu_{c1} = \mu_{c2} = \mu_{c3}$<br>$F_{tab 15\%}$ |
| Between categories  | 71.98            | 3-1=2            | 35.99           | 35.99                        |   |
| Between samples   | 819.90           | 3(3)=9           | 91.10           | $\frac{35.99}{91.10} = 0.40$ | $F_{2,9} = 4.26$                                      |
| $F_{calc} < F_{tab}$ No significant difference in grain diameter between quarries as compared to within quarries, in other words, the hypothesis holds that the means of the quarries are not different relative to the variation within the quarry itself. |                  |                  |                 |                              |   |

attempt was made to apply a purely numerical basis to this phenomenon.

The line projection method, explained in Chapter One, was used in an attempt to refine the interlock descriptions. Table B-7 gives a comparison of the two interlock methods. Mean grain size and its standard deviation are given in addition to the grain interlock and roundness numbers, and the surface/volume value (specific surface), which was obtained by the line projecting method. The results indicate that the specific surface determination is more sensitive to size than to interlock boundaries. The interlock evaluation, however, is fairly insensitive to size because it is primarily a measure of boundary shape. At first, this appears to have a serious drawback. For example, the interlock scale number assigned to an aggregate with an average grain size of 15  $\mu$  and straight interlock would be the same as for an aggregate with 75- $\mu$  average size and similar straight inter-

lock. The strength of the interlock would appear to be different because of the considerable difference in the length of the grain boundaries. Although the line projecting method showed promise in this regard, it was not used more extensively because of its strong dependence on grain size. As grain size values were being determined accurately by the grain counting method, it was decided not to use the line projecting method (another time-consuming effort) on all the samples because of the overlap of the two determinations. In addition, it was learned that the effect of grain diameter changes in the lower range of values was not significant in regard to changes in degradation resistance. Therefore an exhaustive study of surface-volume relationships was not warranted.

The number of line projections (400) suggested by Wallace (1962) was not changed in this study. It was found that enough variation occurs in the readings that 400

TABLE B-7  
COMPARISON OF DATA FOR INTERLOCK MEASUREMENTS

| THIN SECTION   | MEAN<br>MAX DIA<br>(MM) | STD DEV<br>(MM) | INTERLOCK<br>NO. | ROUND-<br>NESS<br>NO. | SURFACE<br>VOLUME<br>(MM) <sup>-1</sup> |
|----------------|-------------------------|-----------------|------------------|-----------------------|---|
| Ill. 4A        | 0.084                   | 0.043           | 4                | 4                     | 26.70                                   |
| Ill. 4B        | 0.051                   | 0.027           | 4                | 4                     | 30.14                                   |
| Ill. 7 $\perp$ | 0.273                   | 0.186           | 5                | 5                     | 18.54                                   |
| Ill. 8         | 0.039                   | 0.028           | 4                | 7                     | 42.94                                   |
| Ind. 4         | 0.137                   | 0.074           | 6                | 3                     | 36.06                                   |
| Ind. 5         | 0.036                   | 0.019           | 5                | 4                     | 50.51                                   |
| Iowa 4-3       | 0.206                   | 0.117           | 2                | 7                     | 21.10                                   |
| Mo. 2A         | 0.202                   | 0.128           | 6                | 4                     | 24.83                                   |
| Mo. 12         | 0.176                   | 0.158           | 7                | 5                     | 39.76                                   |

grains should be read for purposes of accuracy. In this regard, the method is quite good using 400 counts as indicated by the results of Illinois 4A and Illinois 4B. These thin sections represent two slightly different textures in the aggregate source and both the grain size determination and the surface/volume value bear out this difference.

As stated in Chapter One, only a limited petrographic study of heterogeneous gravel aggregates was possible in this research. Heterogeneous gravels are not amenable to analyses by use of the polarizing microscope because of the many rock types present. Therefore, only megascopic petrographic analysis was made of the gravel samples.

In general, the heterogeneous gravels supplied by the state highway departments that were listed as degrading aggregates had sufficient amounts of obviously weak constituents to suggest degradation as a possible problem. Shale, schist, soft limonite pieces, hard iron concretions, and soft chert particles were the commonest weak constituents. Gravels of predominantly one rock type, of course, did not fall into this category and were studied instead with the quarry rocks under the proper rock designation.

It was felt, however, that the analysis of the heterogeneous gravels should be made more quantitative. An attempt to quantify analysis of such gravels has been made in Canada by Bayne and Brownridge (1955) and the analysis has since been modified through experience and reported

through publications by the Ontario Department of Mines (1960, 1963). This examination is called the petrographic number (PN) analysis.

The PN is obtained by examining a weighed gravel sample in order to subdivide it into as many as 40 subdivisions based on rock name and particle soundness. An evaluation factor ranging from 1.0 for the most durable rock pieces to 6.0 for the most unsound is assigned to each category. The weight of the material for each category is determined, expressed as a weight percentage of the whole, and multiplied by its evaluation factor. A summation of these values for the various categories gives the PN, which can range from a low of 100 to a maximum of 600.

A PN analysis was made of an Indiana gravel in order to test the procedure. In keeping with the suggestions of Mielenz (1955) the sample size was such that more than 300 particles were present for analysis. The results of the analysis are given in Table B-8.

The data that lend themselves to condensation are summarized in Appendices D, E, F, and G. In Appendices D and E much of the engineering and petrographic data are listed on the state-by-state basis. X-ray insoluble residue findings are presented in Appendix F in a semi-quantitative fashion. Appendix H contains a minimal number of photomicrographs of the thin sections studied. Although each

TABLE B-8  
PETROGRAPHIC NUMBER ANALYSIS, INDIANA GRAVEL SAMPLE

| ROCK TYPE                 | SOUNDNESS                 | WEIGHT<br>(GM) | FRACTION<br>(%) | FAC-<br>TOR | PETROG<br>NUMBER |
|---------------------------|---------------------------|----------------|-----------------|-------------|------------------|
| Dolomite                  | Hard                      | 619.4          | 28.7            | 1.0         | 28.7             |
|                           | Sandy hard                | 21.1           | 1.0             | 1.3         | 1.3              |
|                           | Slightly weathered        | 41.4           | 1.9             | 1.5         | 2.8              |
|                           | Deeply weathered          | 8.2            | 0.4             | 2.0         | 0.8              |
|                           | Soft shaly and soft sandy | 1.5            | 0.1             | 2.0         | 0.2              |
| Limestone                 | Hard                      | 272.8          | 12.7            | 1.0         | 12.7             |
|                           | Sandy hard                | 13.0           | 0.6             | 1.3         | 0.8              |
|                           | Slightly weathered        | 43.8           | 2.0             | 1.5         | 3.0              |
|                           | Deeply weathered          | 8.2            | 0.4             | 2.0         | 0.8              |
|                           | Soft sandy                | 0.3            | 0               |             |                  |
| Quartzite                 | Ocherous                  |                |                 |             |                  |
|                           | Coarse                    | 137.4          | 6.4             | 1.2         | 7.7              |
|                           | Fine                      | 9.4            | 0.4             | 1.6         | 0.6              |
| Graywacke, arkose         |                           | 32.7           | 1.5             | 1.0         | 1.5              |
| Diorite, basalt, andesite | Hard                      | 293.6          | 13.6            | 1.0         | 13.6             |
|                           | Slightly weathered        | 67.1           | 3.1             | 1.5         | 4.6              |
| Granite                   | Hard                      | 198.7          | 9.2             | 1.0         | 9.2              |
|                           | Slightly weathered        | 35.4           | 1.6             | 1.5         | 2.4              |
|                           | Deeply weathered          | 9.7            | 0.5             | 4.0         | 2.0              |
| Gneiss                    | Hard                      | 25.2           | 1.2             | 1.2         | 1.4              |
|                           | Soft                      | 9.5            | 0.4             | 4.0         | 1.6              |
| Chert                     |                           | 229.7          | 10.6            | 5.0         | 53.0             |
| Sandstone                 | Hard                      | 24.1           | 1.1             | 1.2         | 1.3              |
|                           | Medium hard               | 12.9           | 0.6             | 3.0         | 1.8              |
|                           | Soft, friable             | 10.2           | 0.5             | 6.0         | 3.0              |
| Ocher, iron concretions   |                           | 22.9           | 1.1             | 6.0         | 6.6              |
| Shale                     |                           | 9.1            | 0.4             | 6.0         | 2.4              |
| All                       |                           | 2157.9         | 100.0           |             | 163.2            |

section studied was photographed, the listing presented is greatly abbreviated because of space restrictions. Appendix C contains supplementary data on the Indiana quarry study.

### ENGINEERING TEST RESULTS

The results of the engineering laboratory tests play an important role in the over-all comparison of results. As such they are presented and evaluated in the later section on "Results of Statistical Analysis." Engineering test results alone, neglecting their effect on other aggregate factors, can be discussed briefly here, as only several analyses qualify in this singular way. These are (1) production of fines during crushing prior to Los Angeles abrasion testing, (2) the results of abrasion loss versus the number of revolutions in the Los Angeles apparatus, (3) the comparison of grain size distribution resulting from Los Angeles abrasion testing, (4) the results of wet Los Angeles abrasion tests, and (5) repetitive loading test results.

It has been suggested that rocks with similar resistance to degradation will, to a degree, yield similar amounts of fines on crushing (Welp, 1963). A series of samples in this study were composed entirely of large hand samples (+ 2-in. size), thus making it possible to crush the aggregate using a constant setting on the jaw crusher prior to testing. These aggregates were sieved after crushing and prior to testing in the Los Angeles abrasion machine. The results of the size distribution analysis are given in Table B-9.

These samples were taken from a single Indiana quarry and collectively form the basis for a quality control study made in conjunction with the aggregate degradation study. This quarry research is separate and distinct from the textural analysis of degrading aggregates, but the laboratory data proved useful in describing abrasion behavior.

In the quarry study there were eight distinct horizontal lithologies, each of which was designated by a letter of the alphabet (A at the bottom of the quarry and H at the top).

Six samples were taken in each major zone, accomplished by sampling three locations on different days. Hence 1 and 4, 2 and 5, and 3 and 6 for any one level (letter) are taken from essentially the same point in the quarry.

Table B-9 indicates considerable variation in the Los Angeles abrasion results; this problem is considered in Appendix C. An interesting point, however, is the relationship between certain size fractions and the Los Angeles abrasion value. In the larger size fractions the fluctuation is considerable from sample to sample. This is to be expected because only a few additional rock fractures can cause considerable difference in gradation for the large fractions. In the smaller sizes this is less apparent, hence it forms a better basis for comparing particle losses. This is in keeping with Wolfe's findings for the Los Angeles test (1937); that is, the minus No. 12 size is a good size to use for Los Angeles abrasion loss because the results are more reproducible at this lower size fraction than for the larger sizes.

Figure B-1 shows a plot of Los Angeles abrasion versus (1) the percent less than No. 80 after crushing and (2) the percent less than No. 8 after crushing. This figure shows that for the minus No. 8 plot the results are more obvious, with the F unit definitely having a lower percentage passing the No. 8, as well as a lower Los Angeles abrasion loss. The B sample is highest in both abrasion loss and fines produced during crushing, with sample C in the intermediate position. The distribution of points also seems to indicate that the abrasion value for C1 may be in error.

In essence, the plot suggests that the percentage of fines formed during crushing, as indicated by the amount of minus No. 8 material produced, is greater for aggregates with higher Los Angeles abrasion losses. This is interesting in that several aggregate suppliers suggested that degrading aggregates are depicted by their high production of fines on crushing; hence, the association between Los Angeles abrasion and degradation value.

TABLE B-9  
SIEVE ANALYSIS FOLLOWING CRUSHING FOR AN INDIANA QUARRY STUDY

| SIEVE SIZE | ANALYSIS RESULTS (%) |      |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
|------------|----------------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
|            | RB1                  | RB2  | RB3  | RB4  | RC1  | RC2  | RC3  | RC4  | RC5  | RC6  | RF1  | RF2  | RF3  | RF4  | RF5  | RF6  |
| 1½-1       | 2.3                  | 1.6  | 2.6  | 0.9  | 2.6  | 3.8  | 1.3  | 1.8  | 5.2  | 2.4  | 2.3  | 3.1  | 2.0  | 1.1  | 1.7  | 1.3  |
| 1-¾        | 9.9                  | 9.5  | 9.7  | 14.3 | 12.6 | 12.0 | 14.6 | 13.3 | 16.6 | 15.7 | 16.7 | 13.1 | 14.5 | 10.9 | 10.9 | 12.5 |
| ¾-½        | 27.7                 | 35.5 | 31.6 | 39.8 | 25.2 | 36.7 | 39.6 | 37.7 | 37.3 | 35.1 | 37.8 | 37.0 | 42.5 | 37.6 | 42.4 | 39.1 |
| ½-⅜        | 20.8                 | 14.0 | 13.0 | 14.4 | 23.2 | 13.4 | 10.8 | 13.3 | 9.9  | 10.0 | 12.1 | 11.4 | 13.7 | 14.2 | 13.1 | 13.6 |
| ⅜-#4       | 15.3                 | 16.2 | 15.7 | 11.9 | 15.5 | 14.7 | 14.9 | 14.5 | 13.6 | 16.0 | 14.5 | 17.2 | 12.6 | 17.2 | 15.8 | 16.7 |
| #4-#8      | 8.8                  | 7.2  |      | 5.1  | 9.3  | 6.1  | 6.1  | 6.0  | 5.3  | 6.1  | 5.6  | 6.8  | 7.5  | 7.7  | 5.9  | 6.4  |
| #8-#30     | 8.5                  | 8.6  |      | 5.5  | 7.4  | 7.4  | 7.3  | 6.6  | 6.1  | 8.3  | 6.2  | 8.1  | 6.4  | 7.2  | 6.0  | 6.8  |
| #30-#50    | 1.9                  | 1.9  |      | 3.1  | 1.5  | 1.5  | 1.4  | 2.2  | 1.7  | 1.7  | 0.8  | 0.7  | 1.2  | 1.0  | 1.3  | 1.3  |
| #50-#60    | 0.4                  | 1.0  |      | 1.1  | 0.4  | 0.5  | 0.4  | 0.7  | 0.9  | 0.8  | 0.8  | 0.6  | 0.4  | 1.0  | 0.5  | 0.5  |
| #60-#80    | 1.1                  | 1.1  |      | 0.7  | 1.0  | 1.0  | 0.8  | 0.8  | 0.7  | 0.8  | 0.5  | 0.5  | 0.5  | 0.6  | 0.4  | 0.4  |
| Minus #80  | 2.8                  | 3.0  |      | 2.7  | 2.9  | 2.9  | 2.4  | 2.7  | 2.6  | 2.9  | 1.3  | 1.6  | 1.6  | 1.6  | 1.7  | 1.2  |
| +Loss      | 15.2                 | 16.0 |      | 14.0 | 13.2 | 13.3 | 12.7 | 13.4 | 12.3 | 14.7 | 9.9  | 11.5 | 10.1 | 11.4 | 10.2 | 10.4 |
| LA         | 31.2                 | 29.8 |      | 36.9 | 20.3 | 30.7 | 34.0 | 24.6 | 28.2 | 26.7 | 31.4 | 30.9 | 29.1 | 28.6 | 30.4 | 28.1 |

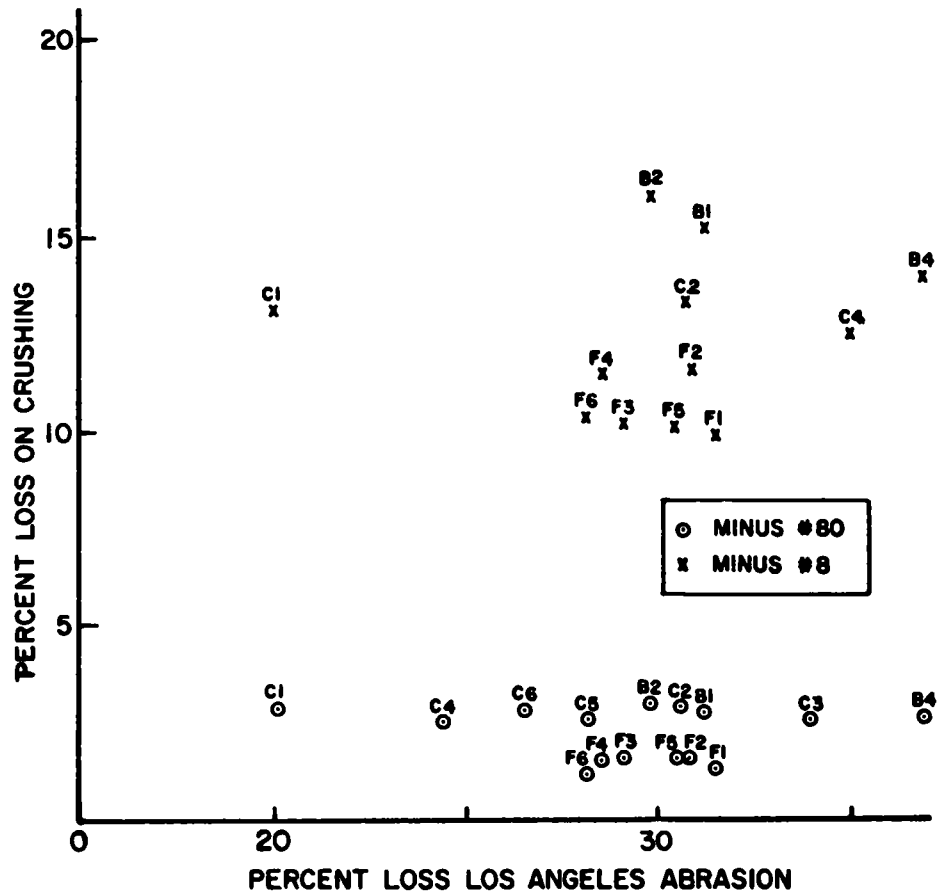


Figure B-1. Comparison of crushing loss and abrasion loss for an Indiana quarry study

Two Indiana carbonate samples of contrasting textural type were used for a critical examination of the mechanism of abrasion by the Los Angeles machine. As stated in Chapter One, the A grading was used in the analysis and the tests were interrupted after each 50 revolutions until the stipulated 500 revolutions were reached. The aggregate pieces of the upper two fractions (1½ in. to 1 in. and 1 in. to ¾ in.) were marked with a felt marking pen. A single line was used to mark the pieces in the 1½ to 1 in. fraction and an X was used for the 1 to ¾ in. fraction. When the abrasion test was interrupted after every 50 revolutions the markings were checked. By and large the aggregate pieces could be traced down to the ½-in.-to-¾-in. fraction, but not below. In some cases it was difficult to tell a portion of an X from a truncated straight line, but these situations were not overly common. After each 50-revolution increment, the sample was sieved over the entire range of sieves (1½ to 1, 1 to ¾, ¾ to ½, ½ to ⅜, ⅜ to No. 10, No. 10 to No. 30, No. 30 to No. 50, No. 50 to No. 60, No. 60 to No. 80, and minus No. 80) and the marked pieces were counted in each of the four largest fractions. Table B-10 gives the results of the sieve analysis after each 50 revolutions. CA1 is the coarse-grained limestone with an abrasion loss of 48.9 percent; RD7 is the fine-grained limestone with an abrasion loss of 32.0 percent.

Table B-11 gives the number and type of aggregate pieces present after each additional 50 revolutions. The number of particles in the larger fraction is given, as well as the size fraction from which it originated.

Abrasion loss versus the number of revolutions is shown in Figure B-2. The upper two curves are for loss of material as measured by the No. 10 sieve. The final point (500 revolutions) is essentially the Los Angeles abrasion value, A grading. It can be observed that CA1 has a consistently greater loss than RD7. Also, it is apparent that neither curve has leveled off markedly at the 500-revolution position. It has been suggested (Wolfe, 1937) that a leveling effect does occur, but this is most noticeable between 500 and 1,000 revolutions.

The bottom two curves are for loss of material below the No. 80 sieve. It can be observed that, except for the first 50 revolutions or so, CA1 experiences a greater loss in abrasion than does RD7. This difference shows a production of fine material for CA1 as well as a greater over-all abrasion (minus No. 10) and suggests a production of increasing amounts of fines with increasing abrasion loss, at least for carbonate rocks of this type. Lastly, the plots suggest that the supposition presented by some workers that increased abrasion is not accompanied by increased fine production does not hold for the rocks tested.

Figure B-3 shows the number of aggregate particles in a

TABLE B-10

## RESULTS OF SIEVE ANALYSIS DURING ABRASION TESTING

| NO.<br>OF<br>REV.                        | COARSE SIZE FRACTION (GM) |                 |                 |                 |                 |                |       | FINE SIZE FRACTION (GM) |                   |                 |                 |                 |       |      | L A<br>VALUE<br>(%) | LOSS IN MINUS NO 80 |  |
|--|---------------------------|-----------------|-----------------|-----------------|-----------------|----------------|-------|-------------------------|-------------------|-----------------|-----------------|-----------------|-------|------|---------------------|---------------------|--|
|  | 1½ IN.-<br>1 IN.          | 1 IN.-<br>¾ IN. | ¾ IN.-<br>½ IN. | ½ IN.-<br>⅜ IN. | ⅜ IN.-<br>NO 10 | MINUS<br>NO 10 | TOTAL | NO. 10-<br>NO 30        | NO. 30-<br>NO. 50 | NO 50-<br>NO 60 | NO 60-<br>NO 80 | MINUS<br>NO. 80 | TOTAL | (GM) |                     | (%)                 |  |
| (a) SAMPLE CA1, COARSE-GRAINED LIMESTONE |                           |                 |                 |                 |                 |                |       |                         |                   |                 |                 |                 |       |      |                     |                     |  |
| 50                                       | 905                       | 1044            | 1328            | 885             | 629             | 225            | 4976  | 97                      | 35                | 2               | 55              | 35              | 224   | 5 0  | 59                  | 1.2                 |  |
| 100                                      | 708                       | 1044            | 1125            | 755             | 725             | 525            | 4882  | 145                     | 14                | 87              | 73              | 205             | 524   | 12 5 | 323                 | 6.5                 |  |
| 150                                      | 627                       | 850             | 1055            | 665             | 934             | 661            | 4792  | 180                     | 79                | 62              | 65              | 270             | 656   | 17.3 | 478                 | 9.6                 |  |
| 200                                      | 625                       | 660             | 949             | 595             | 992             | 855            | 4676  | 215                     | 84                | 85              | 100             | 370             | 854   | 23 6 | 694                 | 13.9                |  |
| 250                                      | 467                       | 620             | 865             | 570             | 1060            | 1080           | 4662  | 282                     | 180               | 57              | 135             | 425             | 1079  | 28.4 | 763                 | 15 3                |  |
| 300                                      | 430                       | 557             | 750             | 510             | 1090            | 1245           | 4582  | 300                     | 234               | 57              | 160             | 490             | 1241  | 33.3 | 908                 | 18 2                |  |
| 350                                      | 350                       | 460             | 734             | 525             | 1037            | 1335           | 4451  | 295                     | 239               | 77              | 200             | 520             | 1331  | 37.7 | 1069                | 21 4                |  |
| 400                                      | 335                       | 429             | 590             | 400             | 1082            | 1405           | 4241  | 315                     | 310               | 77              | 220             | 480             | 1402  | 43.3 | 1239                | 24 8                |  |
| 450                                      | 226                       | 452             | 416             | 486             | 1130            | 1544           | 4254  | 351                     | 273               | 64              | 300             | 555             | 1543  | 45.8 | 1296                | 25 9                |  |
| 500                                      | 221                       | 383             | 362             | 418             | 1172            | 1688           | 4244  | 376                     | 125               | 206             | 174             | 805             | 1686  | 48 9 | 1561                | 31.0                |  |
| (b) SAMPLE RD7; FINE-GRAINED LIMESTONE   |                           |                 |                 |                 |                 |                |       |                         |                   |                 |                 |                 |       |      |                     |                     |  |
| 50                                       | 799                       | 1244            | 1230            | 865             | 869             | 0              | 5007  | 62                      | 9                 | 12              | 10              | 108             | 210   | 4 0  | 108                 | 2.2                 |  |
| 100                                      | 804                       | 1077            | 1200            | 747             | 825             | 309            | 4962  | 95                      | 29                | 7               | 15              | 160             | 306   | 6.9  | 198                 | 4 0                 |  |
| 150                                      | 435                       | 1220            | 1198            | 667             | 960             | 414            | 4894  | 130                     | 39                | 10              | 25              | 201             | 405   | 10.4 | 307                 | 6 1                 |  |
| 200                                      | 407                       | 1131            | 1093            | 656             | 1041            | 531            | 4859  | 156                     | 52                | 12              | 38              | 265             | 523   | 12.5 | 406                 | 8.1                 |  |
| 250                                      | 376                       | 940             | 1068            | 628             | 1109            | 643            | 4804  | 189                     | 66                | 16              | 35              | 335             | 641   | 16.8 | 531                 | 10.6                |  |
| 300                                      | 310                       | 952             | 985             | 589             | 1200            | 725            | 4756  | 205                     | 79                | 18              | 65              | 358             | 725   | 19.4 | 602                 | 12 0                |  |
| 350                                      | 287                       | 900             | 910             | 533             | 1240            | 810            | 4680  | 240                     | 89                | 26              | 80              | 375             | 810   | 22.6 | 695                 | 13 9                |  |
| 400                                      | 280                       | 849             | 860             | 483             | 1262            | 870            | 4604  | 242                     | 94                | 22              | 85              | 425             | 868   | 25.3 | 821                 | 16 4                |  |
| 450                                      | 252                       | 760             | 840             | 450             | 1225            | 950            | 4477  | 261                     | 110               | 28              | 65              | 485             | 949   | 29 5 | 1008                | 20 2                |  |
| 500                                      | 232                       | 758             | 760             | 410             | 1240            | 1007           | 4407  | 264                     | 119               | 37              | 82              | 500             | 997   | 32.0 | 1093                | 21 9                |  |

TABLE B-11

## NUMBER OF PARTICLES IN SIEVE RANGE WITH INCREASING DRUM REVOLUTIONS

| NO<br>OF<br>REV. | NUMBER OF PARTICLES <sup>a</sup> |                 |                 |                 |                  |                 |                 |                 |
|------------------|----------------------------------|-----------------|-----------------|-----------------|------------------|-----------------|-----------------|-----------------|
|                  | SAMPLE CA1                       |                 |                 |                 | SAMPLE RD7       |                 |                 |                 |
|                  | 1½ IN.-<br>1 IN.                 | 1 IN.-<br>¾ IN. | ¾ IN.-<br>½ IN. | ½ IN.-<br>⅜ IN. | 1½ IN.-<br>1 IN. | 1 IN.-<br>¾ IN. | ¾ IN.-<br>½ IN. | ½ IN.-<br>⅜ IN. |
| 0                | 36x                              | 80+             | 210             | 584             | 43x              | 93+             | 283             | 884             |
| 50               | 25x                              | 10x, 55+        | 7x, 190         | 400             | 26x, 1+          | 17x, 62+, 3     | 30+, 178        | 5+, 467         |
| 100              | 19x                              | 14x, 54+        | 6x, 8+, 169     | 2x, 3+, 350     | 28x              | 13x, 58+, 5     | 2x, 26+, 170    | 10+, 370        |
| 150              | 18x                              | 14x, 42+        | 9x, 23+, 140    | 1x, 5+, 310     | 14x              | 24x, 49+, 2     | 4x, 44+, 149    | 9+, 323         |
| 200              | 19x                              | 10x, 42+        | 8x, 36+, 113    | 1x, 5+, 310     | 13x              | 25x, 43+, 1     | 5x, 46+, 128    | 15+, 302        |
| 250              | 13x                              | 15x, 25+        | 5x, 33+, 109    | 5x, 4+, 234     | 12x              | 25x, 34+        | 4x, 45+, 121    | 22+, 280        |
| 300              | 13x                              | 14x, 22+        | 8x, 34+, 86     | 4x, 10+, 226    | 10x              | 28x, 30+        | 4x, 46+, 107    | 27+, 248        |
| 350              | 10x                              | 13x, 15+        | 11x, 39+, 77    | 7x, 15+, 252    | 10x              | 28x, 26+        | 5x, 42+, 99     | 20+, 232        |
| 400              | 10x                              | 13x, 14+        | 5x, 32+, 65     | 6x, 8+, 185     | 9x               | 26x, 26+        | 5x, 47+, 85     | 16+, 224        |
| 450              | 6x                               | 16x, 9+         | 7x, 30+, 23     | 12x, 29+, 146   | 8x               | 25x, 21+        | 4x, 45+, 79     | 10+, 205        |
| 500              | 6x                               | 14x, 6+         | 10x, 25+, 22    | 11x, 31+, 134   | 8x               | 24x, 21+        | 6x, 42+, 70     | 14+, 201        |

<sup>a</sup> x = particles originating in 1½-1 range, + = particles originating in 1-¾ range

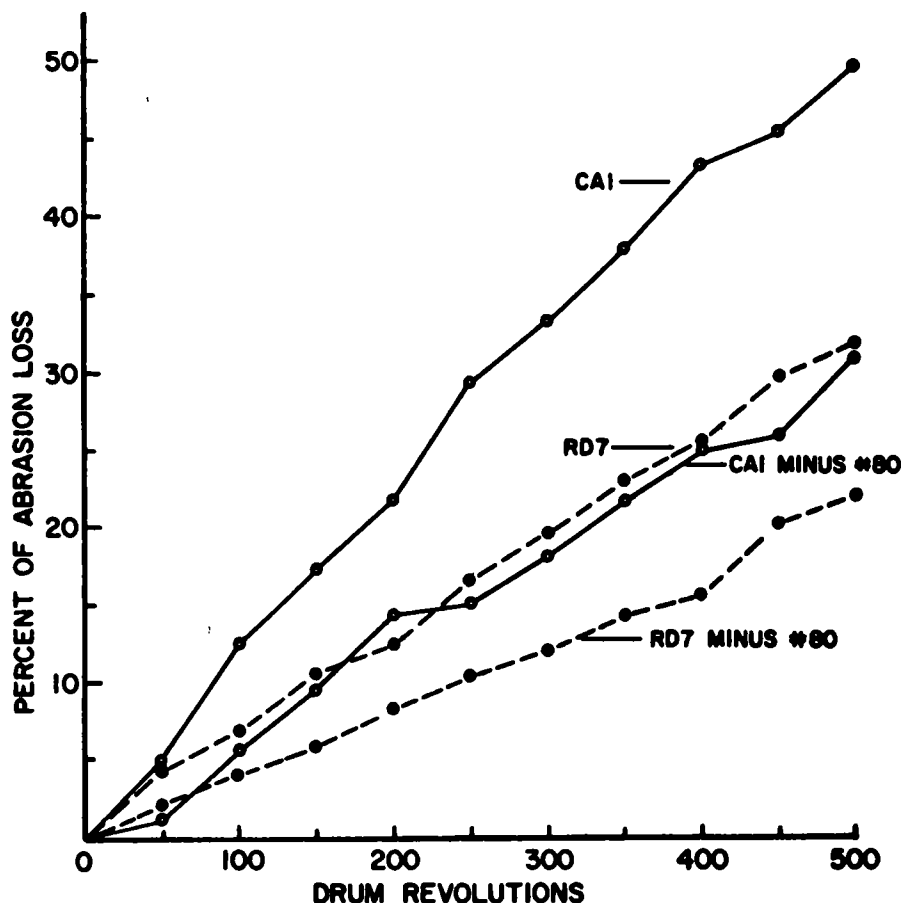


Figure B-2. Abrasion loss vs drum revolutions.

particular fraction versus the number of drum revolutions. The upper two curves pertain to the total number of marked aggregate pieces from the 1½-in.-to-1-in. fraction that could be recognized within the 1½-in.-to-¾-in. range. In the process of examining the marked pieces, each piece was included in the count that originated from the largest fraction; i.e. those that had an X or a discernable portion of an X remaining. There was no problem of the X being removed entirely by abrasion, but only by the reduction in particle size through abrasion of the surface or by fracture of the particle. Owing to breakage, it was possible to get an increase in the number of particles which originated in the 1½-to-1-size fraction. The information used to obtain Figure B-3 is presented in Table B-9.

It can be noted for sample CA1 that breakage did occur, as the total number increased suddenly from 36 to 43 in the first few hundred cycles. In the case of RD7, no increase in number is observed, however. This suggests a contrasting mechanism of abrasion in these two examples. In RD7 the abrasion occurs by attrition of material from the surface until the particles are small enough to pass beyond the lowest size fraction used for this comparison (the ¾-in. sieve). This appears to happen quite suddenly, as suggested by the drop from 43 to 37 or 38 at about 450 revolutions. Up to this point the total number was fairly constant.

In CA1 a breaking of particles is suggested by the increase in the number of particles. This is quite possible as a particle 1½ in. in size can divide several times and still be retained by the ¾-in. sieve. The mechanism of abrasion for this sample is probably a combination of breaking of particles and surface attrition.

The CA1 aggregate looks like a poor material in regard to abrasion resistance because it has large coarse crystals well within the upper sand size range. The aggregate is not accepted by the Indiana Highway Commission because of its high abrasion loss. In view of the extreme abrasion loss of this aggregate, it is suggested that breakage during Los Angeles abrasion is not common for acceptable aggregates, but that surface abrasion of the particles is the primary mechanism for abrasion of carbonate aggregates in the range of 35 percent or less LA loss. It may well be that the fracture phenomenon of coarse limestones yields the additional amount of particle size reduction beyond the normal surface wear to make the aggregate not acceptable as an engineering material.

The lower two curves in Figure B-3 relate the number of particles remaining in the 1½-in.-to-1-in.-size fraction to the number of revolutions. In both curves the number decreases sharply in the first 100 to 150 revolutions. An interesting observation is that RD7 tends to approach a

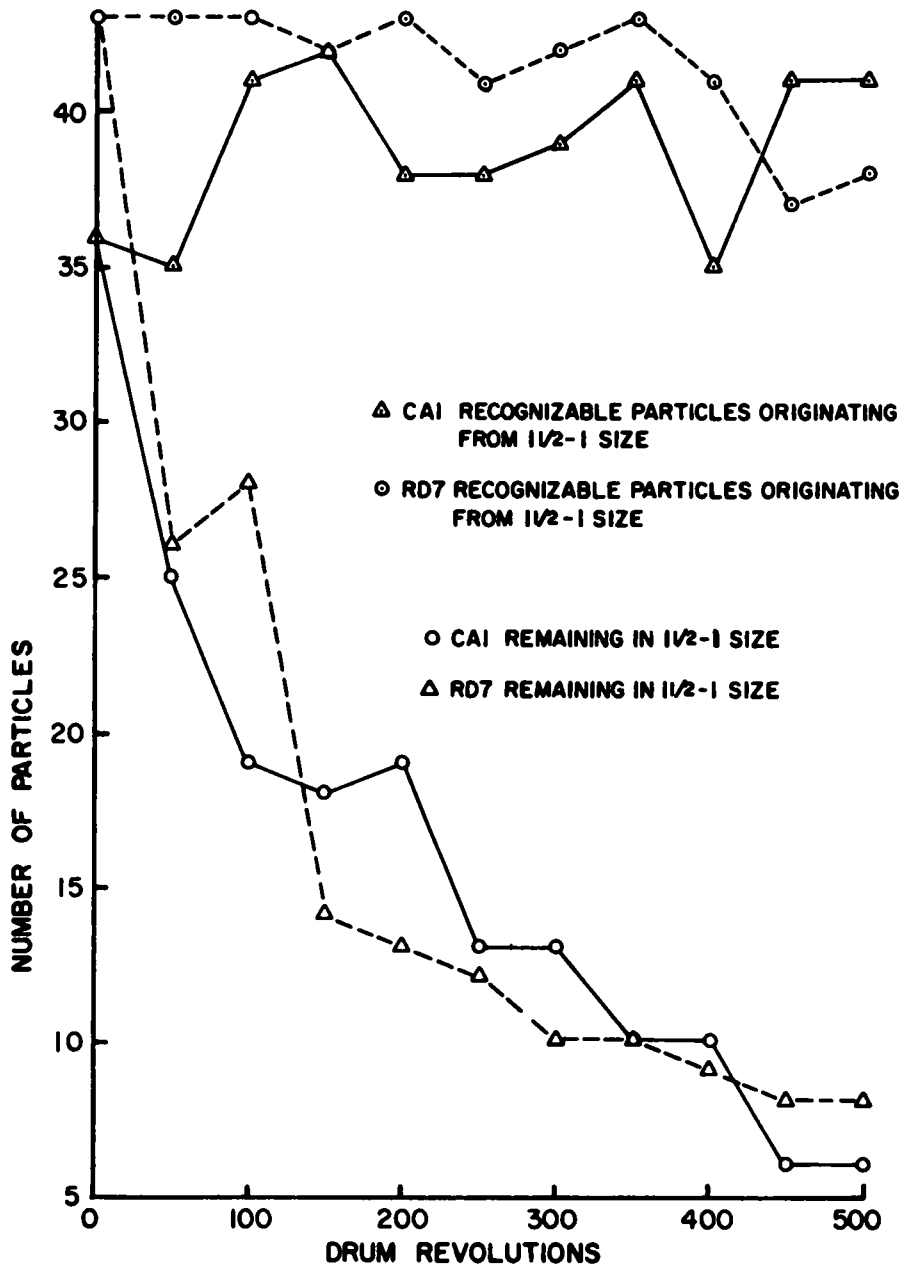


Figure B-3 Reduction in number of aggregate particles with increasing drum revolutions

constant number of particles retained in the 1 1/2-to-1 size in the latter stages of the test. The trend in CA1 is less obvious because the particle number may be continuing to decrease with increasing revolutions. For RD7, as least, it can be stated that the number does become fairly constant. It is suggested that the fine material present in the drum at this time is supplying a cushioning effect for the larger particles and in effect is preventing further abrasion. Apparently the other sizes continue to abrade, because the total abrasion loss does increase. One might suggest that these few remaining particles are stronger than the rest, but the cushioning phenomenon seems to be a more reasonable explanation.

Figures B-4 through B-9 show the progressive abrasion of the 1 1/2-in.-to-1-in.-size fraction of aggregate CA1. It can be observed that the angular shape of the particles persists through 100 revolutions at least. In the RD7 sample the angular corners were lost at an earlier stage. The persistence of angular corners suggests that more breakage of the CA1 aggregate occurred, thus maintaining angular shapes longer than in the case of the RD7 aggregate.

Following Los Angeles abrasion testing, the grain-size distribution was determined on the abraded samples for a considerable number of samples. Included were samples from the previously discussed Indiana quarry study, as



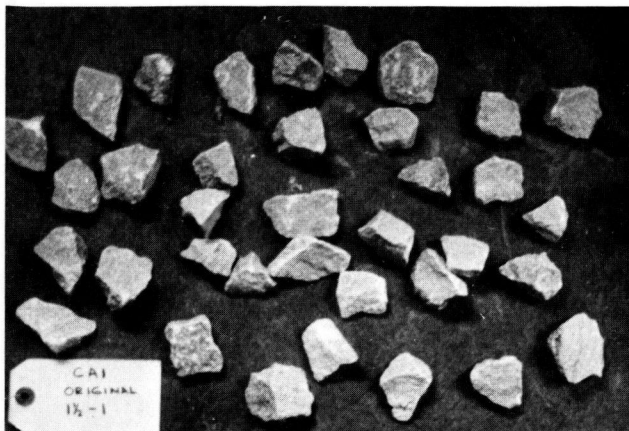


Figure B-4. Aggregate CA1, 1½-to-1-in. fraction, original.



Figure B-5. Aggregate CA1, 1½-to-1-in. fraction after 50 drum revolutions.



Figure B-6. Aggregate CA1, 1½-to-1-in. fraction after 100 drum revolutions.



Figure B-7. Aggregate CA1, 1½-to-1-in. fraction after 200 drum revolutions.

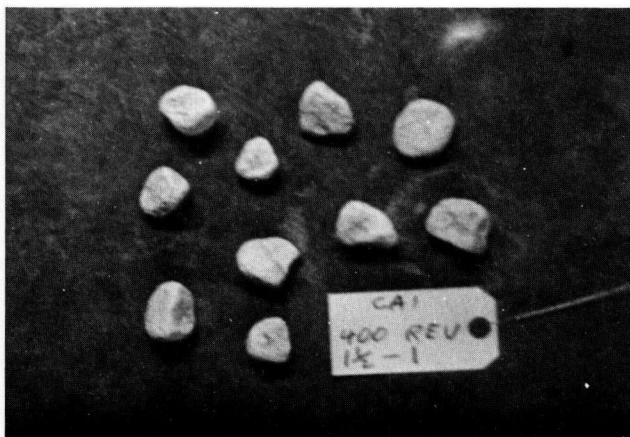


Figure B-8. Aggregate CA1, 1½-to-1-in. fraction after 400 drum revolutions.

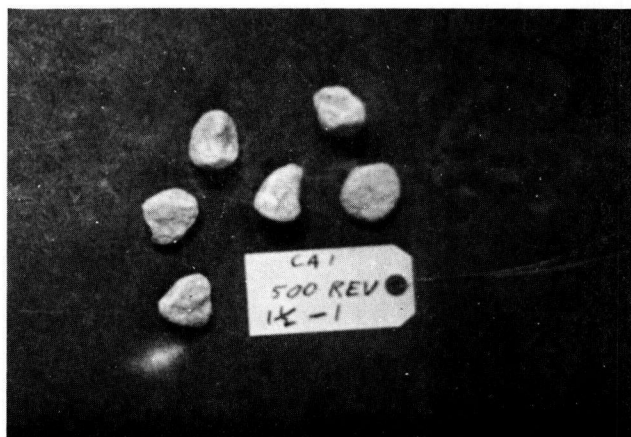


Figure B-9. Aggregate CA1, 1½-to-1-in. fraction after 500 drum revolutions.

well as many samples from other geographical areas. In essence, grain-size analysis became a standard terminal step for the Los Angeles abrasion test in the final year of the Phase II testing program.

Owing to the large number of tests involved in this gradation analysis, statistical analysis of the data was required. The results are discussed in detail in the following section. A general analysis of the data is presented here, however, because of the close connection with the previous analysis on aggregate crushing.

In this connection, Table B-12 gives the Indiana quarry study Los Angeles abrasion and final gradation after testing. Two values for the fine material are given, the minus No. 80 and the minus No. 80 +  $\Delta$  value. The quantity  $\Delta$  is the difference between the original weight of the sample, expressed as a percent, and the total weight of the sieved material following the test, also on the percent basis. Therefore,  $\Delta$  is a measure of the material lost during the test, usually escaping in the form of dust particles. This amount has been added to the minus No. 80 portion, under the assumption that the loss material would normally fall within this size range.

Figure B-10, showing Los Angeles value versus minus No. 80 +  $\Delta$ , indicates an increase in the production of fine material with increasing abrasion loss. There also is a general concentration of data for samples from the same quarry zone; for example, RD or RG. This would seem to indicate that each specific rock ledge has a unique relation-

ship between abrasion and the amount of fine production. The relation is of a directly proportional nature, but varies from rock unit to rock unit. This could possibly be an identifying or distinguishing characteristic of various rock units.

Table B-13 is a fairly complete list of the samples that were sieved following Los Angeles abrasion testing. Only the samples from the single quarry study in Indiana are omitted. The rock names also are included in the table, with representatives from the three major genetic rock groups.

The data from Table B-12 are plotted in Figure B-11. As in previous plots, an apparent relationship between Los Angeles abrasion and the minus No. 80 +  $\Delta$  fraction is indicated. A response of increased fine production with increased abrasion loss is suggested.

A considerable difference is apparent between the carbonate aggregates and the coarse-grained igneous aggregates. In the latter case, an increase in the amount of fines with increasing Los Angeles abrasion is indicated, but the increase is not as considerable as for carbonate rocks. This suggests that igneous rocks with high Los Angeles abrasion

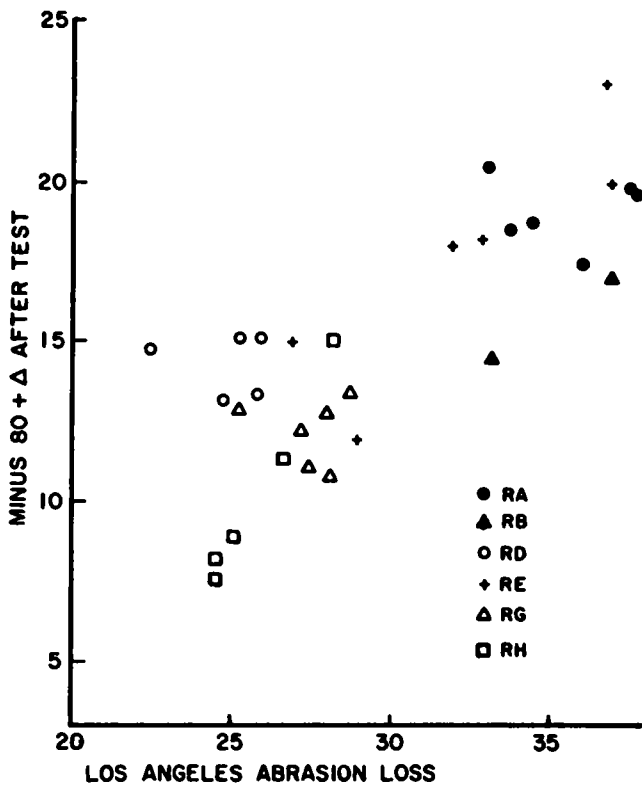


Figure B-10 Production of fines versus Los Angeles abrasion loss; Indiana quarry study

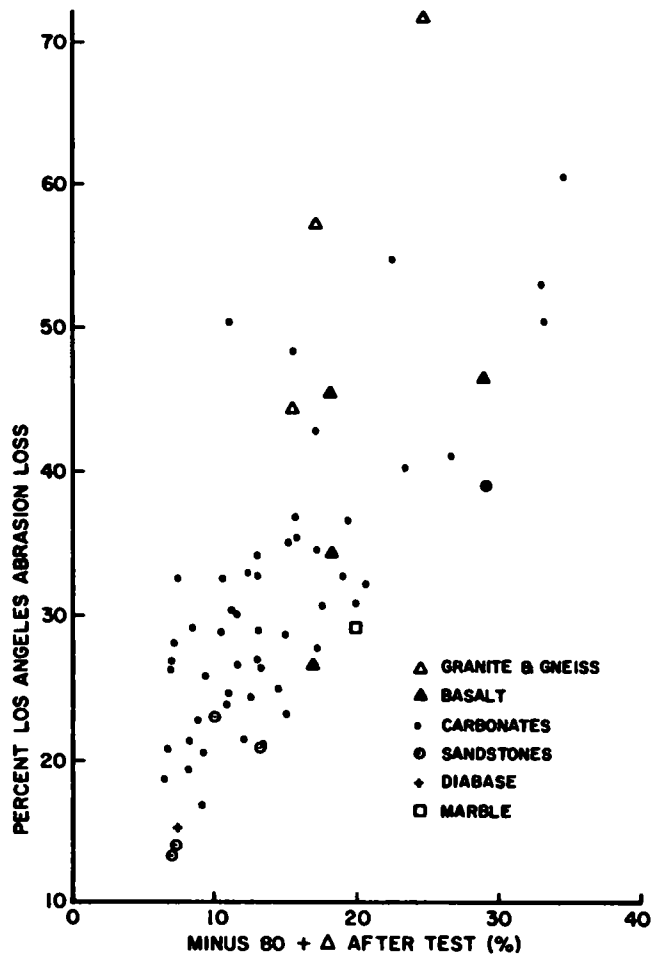


Figure B-11. Production of fines versus Los Angeles abrasion loss; all states

TABLE B-12  
SIEVE ANALYSIS FOLLOWING LOS ANGELES ABRASION TESTING, INDIANA QUARRY STUDY

| SAMPLE | SIZE FRACTION (%) |         |         |         |         |       |       |        |        |        |        |        | L.A. ABRASION VALUE (%) |        |        |        |        |        |        |        |        |                      |                   |       |
|--------|-------------------|---------|---------|---------|---------|-------|-------|--------|--------|--------|--------|--------|-------------------------|--------|--------|--------|--------|--------|--------|--------|--------|----------------------|-------------------|-------|
|        | 3/4 IN.           |         | 1/2 IN. |         | 3/8 IN. |       | NO. 4 |        | NO. 8  |        | NO. 10 |        |                         | NO. 20 |        | NO. 40 |        | NO. 60 |        | NO. 80 |        | MINUS NO. 80 + Δ (%) | Δ = 100-TOTAL (%) | TOTAL |
|        | 1/2 IN.           | 3/4 IN. | 3/8 IN. | 1/2 IN. | 3/8 IN. | NO. 4 | NO. 8 | NO. 10 | NO. 20 | NO. 40 | NO. 60 | NO. 80 |                         | NO. 10 | NO. 20 | NO. 40 | NO. 60 | NO. 80 | NO. 10 | NO. 20 | NO. 40 |                      |                   |       |
| RA 1   | 5.1               | 14.4    | 26.9    | 15.0    | 2.4     | 5.7   | 7.7   | 1.5    | 3.9    | 13.8   | 96.4   | 3.6    | 17.4                    | 36.2   |        |        |        |        |        |        |        |                      |                   |       |
| RA 2   | 6.9               | 15.4    | 25.2    | 13.9    | 1.9     | 3.5   | 8.2   | 2.2    | 2.8    | 17.1   | 97.3   | 2.7    | 19.8                    | 37.6   |        |        |        |        |        |        |        |                      |                   |       |
| RA 3   | 7.9               | 18.6    | 26.2    | 11.3    | 2.0     | 4.3   | 7.0   | 1.4    | 2.9    | 14.2   | 95.8   | 4.2    | 18.4                    | 33.9   |        |        |        |        |        |        |        |                      |                   |       |
| RA 4   | 6.4               | 13.4    | 24.2    | 15.5    | 2.5     | 7.0   | 6.9   | 1.4    | 3.0    | 15.5   | 95.8   | 4.2    | 19.7                    | 37.7   |        |        |        |        |        |        |        |                      |                   |       |
| RA 5   | 9.0               | 17.0    | 25.7    | 12.8    | 2.1     | 7.2   | 1.0   | 2.4    | 2.4    | 15.8   | 95.4   | 4.6    | 20.4                    | 33.2   |        |        |        |        |        |        |        |                      |                   |       |
| RA 6   | 8.4               | 15.0    | 26.8    | 12.1    | 2.2     | 7.2   | 4.7   | 1.4    | 2.6    | 15.2   | 96.5   | 3.5    | 18.7                    | 34.5   |        |        |        |        |        |        |        |                      |                   |       |
| RB 1   | —                 | —       | —       | —       | —       | 9.1   | 3.2   | 0.9    | 2.8    | 12.2   | —      | —      | —                       | 29.8   |        |        |        |        |        |        |        |                      |                   |       |
| RB 2   | —                 | —       | —       | —       | —       | 5.6   | 2.6   | 0.9    | 1.6    | 7.4    | —      | —      | —                       | 31.2   |        |        |        |        |        |        |        |                      |                   |       |
| RB 3   | —                 | —       | —       | —       | —       | 7.3   | 2.8   | 2.9    | 3.2    | —      | —      | —      | —                       | 36.9   |        |        |        |        |        |        |        |                      |                   |       |
| RB 4   | —                 | —       | —       | —       | —       | 9.6   | 6.6   | 0.9    | 3.3    | 15.5   | —      | —      | —                       | 33.3   |        |        |        |        |        |        |        |                      |                   |       |
| RB 5   | 8.1               | 16.2    | 27.1    | 12.7    | 2.3     | 7.6   | 7.5   | 1.4    | 2.6    | 13.5   | 99.0   | 1.0    | 14.5                    | 37.0   |        |        |        |        |        |        |        |                      |                   |       |
| RB 6   | 8.9               | 15.8    | 22.3    | 13.8    | 2.0     | 7.3   | 7.2   | 1.6    | 4.2    | 13.8   | 96.9   | 3.1    | 17.0                    | 31.2   |        |        |        |        |        |        |        |                      |                   |       |
| RC 1   | —                 | —       | —       | —       | —       | 2.8   | 1.1   | 0.3    | 1.1    | 6.1    | —      | —      | —                       | 20.3   |        |        |        |        |        |        |        |                      |                   |       |
| RC 2   | —                 | —       | —       | —       | —       | 8.9   | 5.3   | 0.6    | 2.5    | 12.2   | —      | —      | —                       | 30.7   |        |        |        |        |        |        |        |                      |                   |       |
| RC 3   | —                 | —       | —       | —       | —       | 7.2   | 2.3   | 0.8    | 1.7    | 9.3    | —      | —      | —                       | 34.0   |        |        |        |        |        |        |        |                      |                   |       |
| RC 4   | —                 | —       | —       | —       | —       | 5.1   | 2.9   | 0.9    | 4.9    | 5.5    | —      | —      | —                       | 28.2   |        |        |        |        |        |        |        |                      |                   |       |
| RC 5   | —                 | —       | —       | —       | —       | 7.0   | 4.2   | 0.6    | 1.8    | 12.3   | —      | —      | —                       | 26.7   |        |        |        |        |        |        |        |                      |                   |       |
| RC 6   | —                 | —       | —       | —       | —       | 5.2   | 4.5   | 1.0    | 1.8    | 10.3   | —      | —      | —                       | 24.7   |        |        |        |        |        |        |        |                      |                   |       |
| RD 1   | 10.8              | 23.8    | 28.9    | 10.1    | 2.5     | 6.9   | 0.7   | 1.6    | 1.4    | 11.5   | 98.2   | 1.8    | 13.3                    | 22.5   |        |        |        |        |        |        |        |                      |                   |       |
| RD 2   | 11.0              | 17.9    | 32.1    | 12.7    | 1.9     | 6.8   | 1.4   | 0.4    | 1.1    | 13.5   | 98.8   | 1.2    | 14.7                    | 25.9   |        |        |        |        |        |        |        |                      |                   |       |
| RD 3   | 7.4               | 20.5    | 29.3    | 15.4    | 3.4     | 6.6   | 1.8   | 0.6    | 1.5    | 12.8   | 99.3   | 0.7    | 13.5                    | 24.0   |        |        |        |        |        |        |        |                      |                   |       |
| RD 4   | 9.6               | 25.1    | 28.5    | 10.4    | 2.4     | 5.8   | 1.5   | 0.8    | 1.3    | 11.2   | 96.6   | 3.4    | —                       | 25.3   |        |        |        |        |        |        |        |                      |                   |       |
| RD 5   | 10.7              | 16.3    | 32.6    | 13.2    | 1.8     | 7.1   | 1.6   | 0.6    | 0.9    | 13.1   | 97.9   | 2.1    | 15.2                    | 26.0   |        |        |        |        |        |        |        |                      |                   |       |
| RD 6   | 10.2              | 20.8    | 28.8    | 11.5    | 2.6     | 7.0   | 2.0   | 0.4    | 1.5    | 11.9   | 96.7   | 3.3    | 15.2                    | 36.3   |        |        |        |        |        |        |        |                      |                   |       |
| RE 1   | 6.5               | 11.5    | 28.9    | 15.4    | 3.3     | 5.8   | 2.6   | 0.7    | 1.3    | 17.7   | 93.7   | 6.3    | 24.0                    | 35.5   |        |        |        |        |        |        |        |                      |                   |       |
| RE 2   | —                 | —       | —       | —       | —       | 10.4  | 3.2   | 0.4    | 1.4    | 17.6   | —      | —      | —                       | 33.0   |        |        |        |        |        |        |        |                      |                   |       |
| RE 3   | 7.1               | 10.4    | 30.1    | 16.7    | 2.8     | 10.0  | 1.6   | 2.0    | 1.0    | 18.1   | 99.8   | 0.2    | 18.3                    | 37.0   |        |        |        |        |        |        |        |                      |                   |       |
| RE 4   | —                 | —       | —       | —       | —       | 9.8   | 3.1   | 0.7    | 1.9    | 15.0   | —      | —      | —                       | 32.0   |        |        |        |        |        |        |        |                      |                   |       |
| RE 5   | 5.7               | 15.6    | 28.5    | 15.3    | 2.6     | 9.3   | 1.8   | 1.2    | 1.0    | 16.5   | 98.5   | 1.5    | 18.0                    | 36.9   |        |        |        |        |        |        |        |                      |                   |       |
| RE 6   | 7.5               | 8.6     | 28.1    | 16.3    | 2.3     | 10.0  | 2.5   | 0.5    | 1.1    | 20.1   | 97.0   | 3.0    | 23.1                    | 31.4   |        |        |        |        |        |        |        |                      |                   |       |
| RF 1   | —                 | —       | —       | —       | —       | 5.6   | 2.5   | 0.5    | 1.6    | 5.7    | —      | —      | —                       | 30.9   |        |        |        |        |        |        |        |                      |                   |       |
| RF 2   | —                 | —       | —       | —       | —       | 6.4   | 2.2   | 0.5    | 2.6    | 6.7    | —      | —      | —                       | 29.1   |        |        |        |        |        |        |        |                      |                   |       |
| RF 3   | —                 | —       | —       | —       | —       | 8.8   | 3.6   | 0.7    | 4.9    | 5.5    | —      | —      | —                       | 28.6   |        |        |        |        |        |        |        |                      |                   |       |
| RF 4   | —                 | —       | —       | —       | —       | 12.2  | 5.6   | 0.8    | 5.5    | 3.6    | —      | —      | —                       | 30.4   |        |        |        |        |        |        |        |                      |                   |       |
| RF 5   | —                 | —       | —       | —       | —       | 10.1  | 4.7   | 0      | 1.9    | 11.4   | —      | —      | —                       | 28.1   |        |        |        |        |        |        |        |                      |                   |       |
| RF 6   | —                 | —       | —       | —       | —       | 8.4   | 4.5   | 0.8    | 3.2    | 6.3    | —      | —      | —                       | 27.4   |        |        |        |        |        |        |        |                      |                   |       |
| RG 1   | 6.8               | 19.8    | 29.0    | 13.2    | 3.7     | 9.1   | 3.5   | 0.1    | 3.6    | 6.4    | 95.2   | 4.8    | 11.2                    | 27.4   |        |        |        |        |        |        |        |                      |                   |       |
| RG 2   | 8.9               | 17.3    | 27.6    | 14.6    | 3.4     | 10.1  | 4.1   | 0.5    | 2.8    | 7.5    | 96.8   | 3.2    | 10.7                    | 25.3   |        |        |        |        |        |        |        |                      |                   |       |
| RG 3   | 14.6              | 15.5    | 28.5    | 13.6    | 1.8     | 8.8   | 2.5   | 0.8    | 1.0    | 11.3   | 98.4   | 1.6    | 12.9                    | 28.1   |        |        |        |        |        |        |        |                      |                   |       |
| RG 4   | 8.5               | 19.1    | 27.9    | 13.0    | 3.2     | 10.2  | 2.8   | 1.4    | 1.1    | 9.9    | 97.1   | 2.9    | 12.8                    | 28.8   |        |        |        |        |        |        |        |                      |                   |       |
| RG 5   | 5.2               | 20.9    | 30.1    | 11.8    | 3.2     | 9.6   | 3.2   | 0.8    | 1.8    | 8.8    | 95.4   | 4.6    | 13.4                    | 27.2   |        |        |        |        |        |        |        |                      |                   |       |
| RG 6   | 9.9               | 19.8    | 27.4    | 12.6    | 3.1     | 8.9   | 3.0   | 0.6    | 2.5    | 8.3    | 96.1   | 3.9    | 12.2                    | 24.5   |        |        |        |        |        |        |        |                      |                   |       |
| RH 1   | 11.2              | 19.8    | 29.1    | 12.2    | 3.1     | 9.3   | 3.5   | 0.9    | 2.6    | 5.9    | 97.6   | 2.4    | 8.3                     | 25.1   |        |        |        |        |        |        |        |                      |                   |       |
| RH 2   | 11.2              | 21.5    | 27.7    | 12.4    | 2.1     | 7.6   | 3.0   | 1.4    | 4.1    | 5.6    | 96.6   | 3.4    | 9.0                     | 24.4   |        |        |        |        |        |        |        |                      |                   |       |
| RH 3   | 10.0              | 21.8    | 28.7    | 12.4    | 2.7     | 8.4   | 3.5   | 1.0    | 3.8    | 5.3    | 97.6   | 2.4    | 7.7                     | 26.6   |        |        |        |        |        |        |        |                      |                   |       |
| RH 4   | —                 | —       | —       | —       | —       | —     | —     | —      | —      | —      | —      | —      | —                       | 28.2   |        |        |        |        |        |        |        |                      |                   |       |
| RH 5   | 11.8              | 20.7    | 26.6    | 11.7    | 2.5     | 6.9   | 3.3   | 0.6    | 4.4    | 6.0    | 94.5   | 5.5    | 11.5                    | 26.6   |        |        |        |        |        |        |        |                      |                   |       |
| RH 6   | 10.6              | 17.0    | 27.4    | 12.9    | 3.4     | 8.6   | 1.7   | 1.2    | 2.0    | 12.4   | 97.2   | 2.8    | 15.2                    | 28.2   |        |        |        |        |        |        |        |                      |                   |       |

TABLE B-13

 PRODUCTION OF FINES VERSUS  
 LOS ANGELES ABRASION LOSS, ALL STATES

| SAMPLE       | ROCK TYPE        | L.A.               |                 |                  | SAMPLE          | ROCK TYPE | L.A.               |                 |                 |
|--------------|------------------|--------------------|-----------------|------------------|-----------------|-----------|--------------------|-----------------|-----------------|
|              |                  | ABRASION VALUE (%) | MINUS NO 80 (%) | MINUS NO. 80 + Δ |                 |           | ABRASION VALUE (%) | MINUS NO 80 (%) | MINUS NO 80 + Δ |
| Ga 2         | Granite          | 71.5               | 16.9            | 22.3             | Okla 2 (D2)     | Sandstone | 38.7               | 25.5            | 27.1            |
| Ga 3         | Gneiss           | 44.5               | 12.9            | 15.5             | Okla 3 (E-2)    | Limestone | 34.4               | 16.4            | 17.2            |
| Ga 4         | Gneiss           | 45.6               | 14.7            | 19.1             | Okla 4 (H-2)    | Limestone | 21.1               | 11.1            | 13.0            |
| Ga. 9        | Gneiss           | 57.2               | 13.9            | 17.2             | Pa 1 (I-1)      | Limestone | 24.1               | 7.4             | 12.3            |
| Ga 10        | Limestone        | 23.9               | 9.3             | 10.7             | Pa. 3 (II-1)    | Limestone | 25.2               | 5.7             | 6.7             |
| Idaho 93     | Basalt           | 26.3               | 14.0            | 16.9             | Pa 4 (II-2)     | Limestone | 26.5               | 6.8             |                 |
| Idaho LT 117 | Basalt           | 29.7               | 11.6            | 17.1             | Pa. 5 (III-1)   | Limestone | 22.5               | 8.7             | 8.7             |
| Idaho LT 126 | Basalt           | 34.2               | 16.2            | 18.1             | Pa. 6 (III-2)   | Limestone | 27.9               | 7.1             |                 |
| Idaho LT 102 | Basalt           | 46.5               | 24.2            | 27.1             | Pa. 7 (IV-1)    | Graywacke | 21.1               | 12.2            | 13.2            |
| Ill 2        | Dolomite         | 26.7               | 12.8            | 13.1             | Pa 8 (IV-2)     | Sandstone | 13.5               | 7.2             | 7.7             |
| Ill 8        | Limestone        | 28.7               | 11.3            | 13.2             | Pa 9 (V-1)      | Quartzite | 14.0               | 7.1             | 7.6             |
| Ind. 3       | Dolomite         | 27.8               | 14.1            | 15.1             | Pa. 10 (V-2)    | Dolomite  | 26.2               | 10.0            | 13.3            |
| Ind 4        | Dolomite         | 32.6               | 17.9            | 18.8             | Pa. 11 (VI-1)   | Diabase   | 14.9               | 7.0             | 7.7             |
| Ind. 5       | Dolomite         | 32.1               | 20.0            | 20.4             | Pa. 12 (VI-2)   | Dolomite  | 23.3               | 14.1            | 14.9            |
| Ind. 7       | Dolomite         | 36.4               | 19.3            | 19.4             | Pa. 13 (VIII-1) | Marble    | 28.7               | 18.8            | 19.9            |
| Ind. 8       | Dolomite         | 22.3               | 12.4            | 13.0             | Pa. 14 (VIII-2) | Limestone | 18.6               | 6.5             | 0.0             |
| Ind. 9       | Dolomite         | 30.5               | 17.2            | 17.8             | Pa. 15 (IX-1)   | Limestone | 16.5               | 9.3             | 9.3             |
| Ind. 11      | Dolomite         | 21.7               | 11.5            | 12.1             | Pa. 16 (IX-2)   | Dolomite  | 24.4               | 9.4             | 11.0            |
| Ind. 12      | Dolomite         | 25.1               | 14.0            | 14.6             | Pa 17 (X-1)     | Limestone | 20.5               | 8.1             | 9.3             |
| Mo 1         | Limestone        | 28.6               | 14.1            | 15.0             | Pa. 18 (X-2)    | Limestone | 21.6               | 7.8             | 8.2             |
| Mo 2         | Limestone        | 60.6               | 30.9            | 34.2             | Pa. 20 (XII-2)  | Limestone | 19.6               | 6.7             | 8.1             |
| Mo 3         | Limestone        | 42.9               | 14.5            | 15.3             | Wis 1           | Dolomite  | 54.6               | 18.5            | 22.5            |
| Mo 4         | Limestone        | 78.9               | 39.6            | 44.3             | Wis. 2          | Dolomite  | 31.1               | 19.3            | 19.8            |
| Mo. 5        | Limestone        | 48.4               | 11.6            | 13.6             | Wis 3           | Dolomite  | 50.3               | 32.6            | 33.2            |
| Mo. 7        | Limestone        | 28.4               | 9.6             | 10.5             | Wis. 4          | Dolomite  | 61.8               | 45.3            | 45.6            |
| Mo. 8        | Sandstone        | 23.0               | 8.5             | 10.0             | Wis. 5          | Dolomite  | 52.9               | 29.6            | 31.6            |
| Mo. 9        | Dolomite         | 33.0               | 9.5             | 12.6             | Wis. 6          | Dolomite  | 40.9               | 24.5            | 26.5            |
| Mo. 13       | Limestone        | 25.9               | 6.4             | 9.3              | Fla 1           | Limestone | 50.5               | 12.2            | 12.9            |
| Mo. 14       | Limestone        | 40.3               | 21.0            | 23.4             | Fla. 2          | Limestone | 30.0               | 10.5            | 11.5            |
| Mo. 18       | Limestone        | 32.3               | 9.3             | 10.6             | Fla. 3          | Limestone | 34.0               | 11.2            | 13.0            |
| Mo. 21       | Limestone        | 26.5               | 8.9             | 11.7             | Fla. 4          | Limestone | 32.5               | 7.5             | 7.4             |
| Mo. 23       | Limestone        | 30.4               | 8.0             | 11.1             | Fla. 5          | Limestone | 29.1               | 8.4             | 8.5             |
| Mo. 24       | Limestone        | 35.0               | 13.1            | 15.3             | Fla. 6          | Limestone | 32.7               | 12.0            | 12.9            |
| Okla 1 (B2)  | Cherty limestone | 20.9               | 5.8             | 6.5              | Fla. 7          | Limestone | 36.2               | 15.4            | 15.9            |
|              |                  |                    |                 |                  | Fla 8           | Limestone | 35.6               | 13.9            | 15.9            |

loss produce less fine material than do carbonate rocks with a comparable high abrasion loss.

Several other features of the plot are of interest. The point with coordinates 12.9 and 50.5 represents a limestone aggregate from Florida that is of particular concern. An incredibly small amount of fine production is indicated for an aggregate with a high abrasion loss. Indeed, all of the samples from Florida yield a scarcity of fines as compared to other aggregates in Table B-11. This may be due to the higher percentage of quartz grains contained in these aggregates. At any rate, the Florida samples plot on the left side of the band of points because of their low fine production.

Another interesting relationship is shown by the samples identified as sandstones. Actually they are graywacke sandstones containing a considerable amount of fine-size matrix material. In general they appear to produce a greater amount of fines for a particular abrasion loss than do the carbonate rocks. The fine-grained particles of this aggregate

are released during abrasion and may constitute a special problem as far as degradation is concerned.

Two peripheral areas encountered during the testing program may have supplied useful information concerning aggregate degradation but could not be explored in depth because of the limits of time and personnel. These areas were wet Los Angeles abrasion testing and repetitive load testing. The considerable efforts expended in the extensive study in thin-section analysis, Los Angeles abrasion, and freeze-thaw testing precluded the possibility of any other extensive involvements.

Several representative aggregate types were chosen for wet Los Angeles abrasion testing. Three carbonate aggregates with different rock textures—two basalts, one sound the other quite unsound; and a coarse-grained or phaneritic gneiss—were selected for testing. The carbonate aggregates consisted of a fine-grained limestone, a coarse-grained limestone, and an extremely poor argillaceous dolomite that was a known degrading material. Of the two basalts one was a sound unweathered material with a good service record;

the other was an altered surface-stained aggregate that was reported as a degrading material. The gneiss was a sound granite gneiss with phaneritic grains aligned in bands of quartz, feldspar, and ferromagnesian minerals.

The results of these wet Los Angeles tests were not conclusive because of the limited sample number. If time had allowed, considerably more tests would have been run and perhaps all 150 or so samples on hand could have been tested, but this was quite impossible. Wet Los Angeles tests are particularly time consuming because the Los Angeles drum has to be made watertight in advance of testing and the abraded material is messy and difficult to remove from the drum after the test.

The limited results (Table B-14) suggest that the presence of water had a profound effect on the altered basalt and the weathered argillaceous dolomite. The addition of water increased the abrasion loss considerably for these two aggregates, but had considerably less effect on the other aggregates. The effect on the granite gneiss was quite small.

The data from these limited tests suggest that highly argillaceous and/or weathered carbonates, and altered basalts, are more affected by the addition of water during Los Angeles abrasion testing than are durable appearing carbonates, gneisses, and basalts. They also suggest that the presence of argillaceous and altered material in the aggregate is more important than the average grain size in determining loss in this wet abrasion test.

The repetitive load test was selected as a laboratory test to augment the data obtained from freeze-thaw and Los Angeles abrasion testing. The repetitive load test was chosen primarily because Aughenbaugh et al. (1963, and 1966) suggested that the results of this test more closely approximated the results of field compaction degradation than did other laboratory load tests. The kneading compactor test was also considered during the planning stage, because the movement of the aggregate during this test is much like that during field compaction. In the repetitive load test, however, the mechanism of loading is different from field conditions, because the aggregate pieces are forced together on point-to-surface contact and are reduced in size by crushing and not by mutual attrition. Aughenbaugh et al. report, however, that the kneading compactor results are quite erratic as compared with field compaction degradation, perhaps because of boundary conditions of the kneading compactor steel mold. As only a limited study could be made in this general area, it was decided to use the repetitive load test.

TABLE B-14

## WET LOS ANGELES ABRASION DATA

| AGGREGATE                          | LOS ANGELES ABRASION LOSS (%) |                          |
|------------------------------------|-------------------------------|--------------------------|
|                                    | GRADING B                     | GRADING B +<br>50% WATER |
| Fine-grained limestone             | 32.0                          | 22.0                     |
| Coarse-grained limestone           | 48.9                          | 41.7                     |
| Weathered argillaceous<br>dolomite | 50.3                          | 73.2                     |
| Sound basalt                       | 16.0                          | 16.4                     |
| Altered basalt                     | 22.0                          | 36.3                     |
| Granite gneiss                     | 41.7                          | 49.3                     |

Three samples were run in the repetitive loading device. In each case, 10,000 25-psi load applications were made at the rate of about three per second. Three aggregates (fine-grained limestone, coarse-grained limestone, and altered basalt) were selected from the samples used for wet Los Angeles abrasion tests.

Following the test, the samples were sieved over the same series of sieves used in earlier Los Angeles abrasion tests. The results (Table B-15) indicate that minimal breakdown occurred for the three samples. The aggregates do suffer breakdown in the same relative amounts in this test as they do in Los Angeles abrasion; that is, altered basalt, fine-grained limestone, and coarse-grained limestone, in increasing order of loss. Nevertheless, the mechanisms for wear by the two tests are somewhat different.

The results of this test are too limited to make any suggestions other than that Los Angeles abrasion values may well be directly correlative with the breakdown under repetitive loading. Considerably more tests would be required to substantiate such a relationship.

The other engineering test results are considered in the over-all statistical comparison in the following section. Freeze-thaw testing was considered to be a successful endeavor in the program, but the sodium sulfate testing was somewhat of a failure. Test results obtained in the Purdue University laboratory were compared to those submitted earlier and considerable differences were noted. In recent discussions with highway officials (Kiel, 1966) it was learned that reproducibility within a single laboratory may be possible using the sodium sulfate test but between labora-

TABLE B-15

## SIEVE ANALYSIS FOLLOWING REPETITIVE LOAD TESTING

| SAMPLE                   | SIZE FRACTION (%)      |                 |                 |                 |                  |                 | L.A. ABRASION VALUE (%) |      |
|--------------------------|------------------------|-----------------|-----------------|-----------------|------------------|-----------------|-------------------------|------|
|                          | ¾ IN.-<br>½ IN.        | ½ IN.-<br>¾ IN. | ¾ IN.-<br>NO. 4 | NO. 4-<br>NO. 8 | NO. 8-<br>NO. 10 | MINUS<br>NO. 10 | DRY                     | WET  |
|                          | Fine-grained limestone | 45.3            | 48.5            | 3.5             | 1.2              | 0.1             | 0.5                     | 32.0 |
| Coarse-grained limestone | 45.2                   | 48.7            | 3.8             | 1.1             | 0.1              | 1.0             | 48.9                    | 41.7 |
| Altered basalt           | 43.1                   | 48.9            | 7.1             | 0.4             | —                | 0.3             | 22.0                    | 36.3 |

ories it is much more difficult. The solubility relationships of the sodium sulfate solutions are such at the soaking temperatures (room temperature) that fluctuations of a few degrees alter the solubility of the sodium sulfate drastically (Lange, 1949, p 1261).

## RESULTS OF STATISTICAL ANALYSIS

### General

In this study of aggregate textures, engineering and laboratory tests, and aggregate degradation, a long and rather exhaustive list of properties and measurements has been amassed for the samples. A total of 21 possible variables is included in the list of measured or calculated parameters pertaining to the aggregates. This necessitates analysis of the data by statistical methods with the aid of a high-speed electronic computer.

In addition to the considerable number of variables that were ultimately compared to each other, the comparison of certain pairs of variables also was accomplished. The variables that seemed to be most closely related were given individual attention. Table B-16 lists the parameters that were compared. The paired parameters are given first,

TABLE B-16  
VALUES COMPARED IN STUDY OF  
VARIOUS CATEGORIES OF ROCKS

#### *Carbonate rocks:*

1. Los Angeles abrasion loss vs degradation value.
2. Los Angeles abrasion loss vs freeze-thaw value.
3. Degradation value vs freeze-thaw value.
4. Los Angeles abrasion loss vs mean grain size.
5. Los Angeles abrasion loss vs standard deviation of mean grain size
6. Los Angeles abrasion loss vs log of mean grain size
7. Los Angeles abrasion loss vs log of standard deviation of mean grain size.
8. Los Angeles abrasion loss vs remaining variable measured as independent variables
9. All variables in turn treated as the dependent variable, vs remaining variables by replacement-deletion process.
10. Los Angeles abrasion loss vs the log of all other variables as independent variables.
11. Los Angeles abrasion loss vs other variables on the state-by-state basis

#### *Phaneritic igneous and metamorphic rocks:*

1. Los Angeles abrasion loss vs mean grain diameter.
2. Los Angeles abrasion loss vs standard deviation of the mean grain diameter.
3. Los Angeles abrasion loss vs freeze-thaw value.
4. Los Angeles abrasion loss vs degradation value.
5. Los Angeles abrasion loss vs all other variables as independent variables.
6. All variables in turn treated as the dependent variable vs the remaining variables by the replacement-deletion process.

#### *Basaltic rocks:*

1. Los Angeles abrasion loss vs degradation value.
2. Los Angeles abrasion loss vs all other variables as independent variables.
3. All variables in turn treated as the dependent variable vs the remaining variables by the replacement-deletion process.

followed by the over-all grouping. They have been subdivided on the basis of rock type because of the inherent differences. Multiple correlation and regression analyses were run on all the listed comparisons using a BIMD 29 program deck.

### Carbonate Rocks

The results from the paired variables for carbonate rocks are given in Table B-17. The first column gives the variables considered. In the last column, the equations for the first two comparisons are presented in the form of examples to indicate how the equations can be obtained for the remaining comparisons. The cumulative  $R^2$  value is a measure indicating how much the total variation is being reduced. A value of 1 000 would indicate that 100 percent of the variation is satisfied by the regression. The  $F_{calc}$  value when compared to an  $F_{tab}$  value indicates the level of significance given in the second last column. Partial correlation coefficients also are given. This measure was described previously. Using degradation vs Los Angeles abrasion loss as an example, the partial correlation coefficient shows that an inverse relationship exists between the two variables with a strong degree of correlation. In like manner for the average grain size vs Los Angeles abrasion loss comparison, a direct—but not significant—relationship is suggested. Krumbein and Imbrie (1963) suggest that  $\pm 0.2$  be the minimum value considered to have any significance.

Table B-17 indicates that the degradation value and Los Angeles loss are strongly correlative and have an inverse relationship; that is, as the abrasion loss increases the degradation value decreases or the aggregate becomes less resistant to degradation. It also shows that freeze-thaw loss and Los Angeles abrasion are strongly correlative in a direct manner, or as abrasion loss increases freeze-thaw loss also increases. Interestingly enough, the degradation value and freeze-thaw value are not correlative at a significant level, with considerably less than 95 percent level for the standard deviation. These two comparisons are discussed further in the discussion of the over-all correlation of carbonate properties and also in the analysis of the state-by-state basis. Suffice it to say at this point that the correlation is only of a marginal nature.

The last four entries in Table B-17 explore the relationships between the logarithm of grain size and powers thereof with Los Angeles abrasion and a similar comparison between the logarithm of standard deviation and abrasion. The logarithmic transform was used in an attempt to equalize the variances for the variable giving no variable an advantage because of extreme values of greater numerical spread. For the last four entries it is apparent from both the partial correlation coefficient and the  $F_{calc}$  value that the relationship is slight if at all. A stronger correlation is shown before the logarithmic transform was applied.

Following the paired comparisons, Los Angeles abrasion as the dependent variable was compared to all of the other parameters for which sufficient data were available. Two comparisons were made—one in which the maximum number of variables was used, which eliminated some samples; the second in which several variables were dropped

TABLE B-17  
DATA COMPARISON FOR CARBONATES AGGREGATES

| VARIABLES                                    | REGRES-<br>SION<br>COEFF | NO<br>OF<br>SAM-<br>PLES | INTER-<br>CEPT | CUM<br>R <sup>2</sup> | F <sub>calc</sub> | PARTIAL<br>CORR<br>COEFF. | LEVEL<br>OF<br>SIGN<br>(%) | EQUATION                   |
|--|--------------------------|--------------------------|----------------|-----------------------|-------------------|---------------------------|----------------------------|----------------------------|
| 1. DGVALvsLA                                 | -0.1165                  | —                        | 9.43960        | 0.37670               | 59.8370           | -0.61377                  | 99+                        | DGVAL= 9.4396-0.11065 LA   |
| 2. DGVALvsLA+(LA) <sup>2</sup>               | -0.21184                 | —                        | 10.98670       | 0.37670               | 59.8370           | -0.37637                  | 99+                        | DGVAL=10.9867-0.21184 LA   |
|  | +0.00134                 | —                        | —              | 0.40100               | 32.8050           | 0.19743                   | —                          | +0.00134 (LA) <sup>2</sup> |
| 3. FTvsLA                                    | -0.20843                 | —                        | -3.75110       | 0.34900               | 43.9570           | 0.59075                   | 99+                        |                            |
| 4. FTvs(LA) <sup>2</sup> (LA)                | -0.07089                 | —                        | 0.88150        | 0.34900               | 53.7320           | 0.27830                   | 99+                        |                            |
| 5. DGVALvsFT                                 | 0.12327                  | 83                       | 3.75320        | 0.03060               | 2.5602            | 0.17500                   | 75+                        |                            |
| 6. DGVALvsFT+(FT) <sup>2</sup>               | 0.56460                  | 83                       | 3.12290        | 0.03060               | 2.5602            | 0.30230                   | —                          |                            |
|  | -0.01740                 | —                        | —              | 0.09540               | 4.2187            | -0.25850                  | —                          |                            |
| 7. AVSIZvsLA                                 | 0.00407                  | 94                       | 0.02312        | 0.05050               | 4.8916            | 0.22470                   | 90+                        |                            |
| 8. AVSIZvsLA+(LA) <sup>2</sup>               | 0.00713                  | 94                       | -0.02690       | 0.05050               | 4.8916            | 0.10710                   | —                          |                            |
|  | -0.00004                 | —                        | —              | 0.05270               | 2.5290            | -0.04800                  | 90+                        |                            |
| 9. STDEVvsLA                                 | 0.00177                  | 94                       | -0.01713       | 0.06470               | 6.3719            | 0.35450                   | 95+                        |                            |
| 10. STDEVvs(LA) <sup>2</sup> +LA             | -0.00006                 | 94                       | 0.08500        | 0.07009               | 6.9345            | 0.07540                   | —                          |                            |
|  | 0.00017                  | —                        | —              | 0.07010               | 3.4299            | -0.00260                  | 90+                        |                            |
| 11. LAvsLOGSIZ                               | 3.14300                  | 93                       | 28.90000       | 0.02440               | 2.2776            | 0.15620                   | 75+                        |                            |
| 12. LAvs(LOGSIZ)<br>+LOGSIZ                  | 1.61765                  | 93                       | 29.32300       | 0.02769               | 2.5919            | 0.05930                   | 50+                        |                            |
|  | 0.58976                  | —                        | —              | 0.02785               | 1.2889            | 0.01240                   | —                          |                            |
| 13. LAvsLOG(STDEV)                           | 2.55043                  | 93                       | 29.30710       | 0.01510               | 1.3960            | 0.12290                   | 75                         |                            |
| 14. LAvsLOG(STDEV) <sup>2</sup><br>+LOG(STD) | 5.35080                  | 93                       | 29.78940       | 0.03930               | 3.7192            | 0.19200                   | 75                         |                            |
|  | -4.85560                 | —                        | —              | 0.05140               | 2.4380            | -0.11240                  | —                          |                            |

Legend DGVAL = degradation value  
LA = percent loss in Los Angeles abrasion  
FT = percent loss in freezing and thawing  
AVSIZ = average grain size  
STDEV = standard deviation of grain size  
LOGSIZ = log<sub>10</sub> of average grain size

to maximize the sample size. This situation occurred because not all samples had complete data available on them.

Figure B-12 is a cluster diagram of the simple correlation coefficients for the comparison using maximum sample number and 13 variables. This diagram shows all the interrelationships among the variables. It can be observed that strong correlations exist between Los Angeles abrasion, freeze-thaw loss, and degradation value. A marginal relationship between Los Angeles abrasion loss and average size is shown.

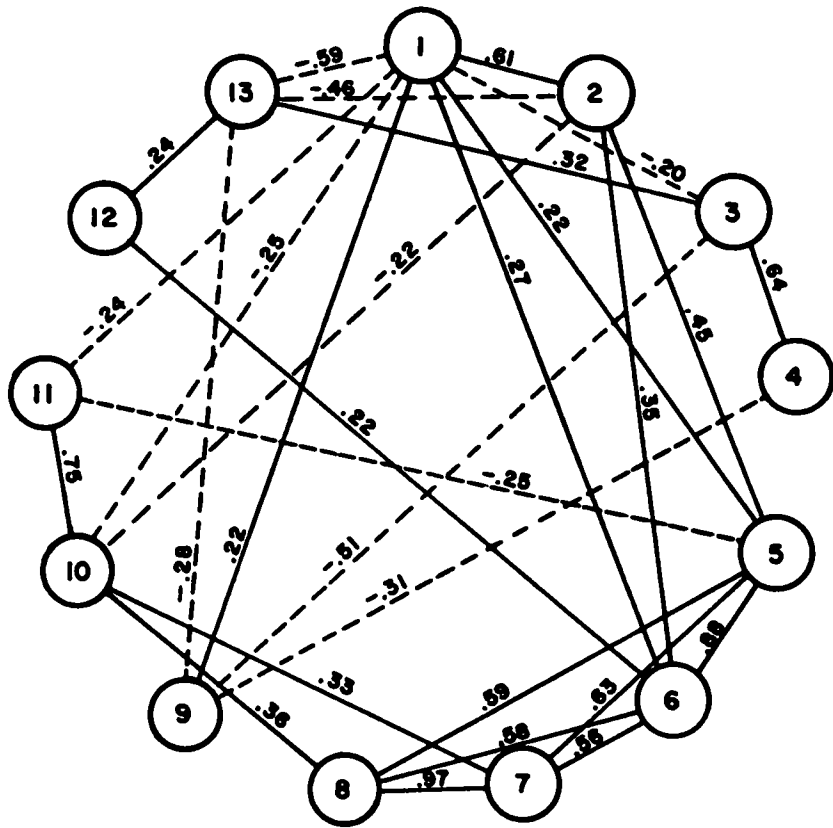
Figure B-13 is a cluster diagram of the partial correlation coefficients for the same 13 variables. The number of contributing variables is shown. The number of contributing variables is reduced to six by eliminating all partial correlations less than  $\pm 0.2$  in keeping with the statement by Krumbein and Imbrie (1963). It can be observed that freeze-thaw loss and degradation value are most significant. Grain diameter, grain roundness, and grain interlock are quite marginal and have the reverse relationship (sign), as would be expected. In fact, average size has reversed in sign from Figure B-12 to Figure B-13. Standard deviation has the anticipated sign, but has a marginal value. Figure B-13 indicates that freeze-thaw and degradation value are the truly significant factors in determining Los Angeles abrasion. In the analysis, 61.7 percent of the variation in Los Angeles abrasion loss is accounted for.

As an interesting sidelight, freeze-thaw, degradation

value, and freeze-thaw along with degradation value were deleted in turn from the variables compared. In this process, no other variables reached the significant level and with freeze-thaw and degradation value deleted only standard deviation remained with a partial correlation coefficient of +0.23.

The cluster diagram of the simple correlation coefficients for the second carbonate comparison (Los Angeles abrasion vs 16 variables) is shown as Figure B-14. Three variables have been added to the list in Figure B-12—specific gravity, percent absorption, and insoluble residue. Again, the interrelationships among variables are shown. As before, the Los Angeles abrasion loss is correlative with freeze-thaw loss and degradation value. A marginal relationship with void content is shown with the sense one would expect (as voids increase, abrasion loss increases). Standard deviation is related in a similar manner as before. A direct correlation between percent absorption and abrasion is noted and is related in the manner expected (abrasion loss increases with increased absorption). Insoluble residue, although a marginal value, has the reverse sign, as would be expected. As shown, the relationship suggests that abrasion loss would increase with decreasing insoluble content. The relationship was also noted among the partial correlation coefficients and is discussed further in a subsequent paragraph.

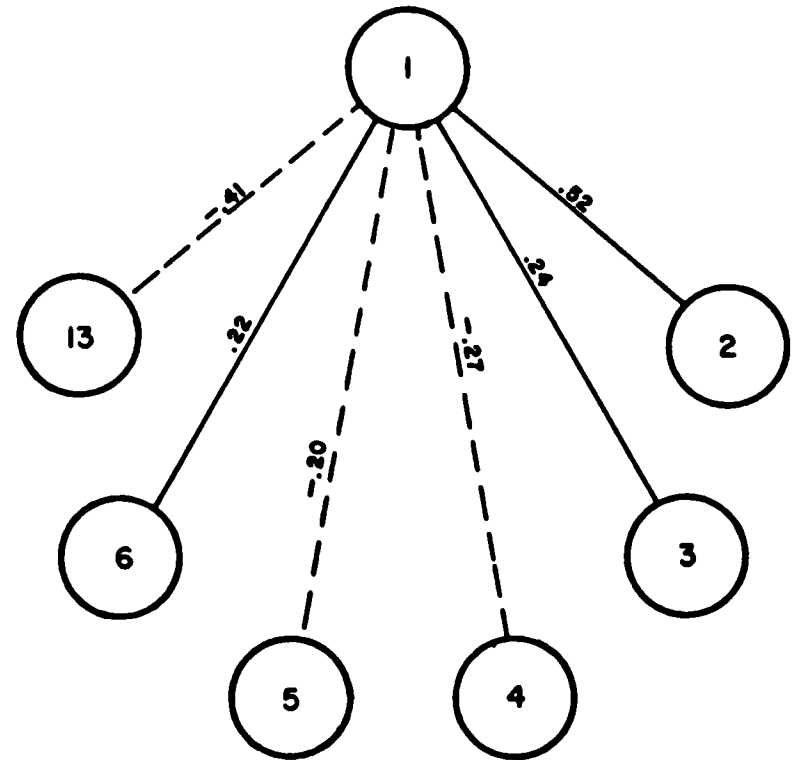
Figure B-15 shows the partial correlation coefficients for



**SAMPLE SIZE = 72**

- 1. Los Angeles Abrasion
- 2. Freeze-Thaw Loss
- 3. Grain Interlock Number - Highest Number Indicates Best Interlock
- 4. Grain Roundness Number - Highest Number Indicates Most Rounded
- 5. Average Grain Size (mm)
- 6. Standard Deviation Of Grain Size (mm)
- 7. Average Matrix Size (mm)
- 8. Standard Deviation Of Matrix (mm)
- 9. Percent Voids
- 10. Percent Matrix
- 11. Matrix Diameter / Grain Diameter
- 12. Maximum Diameter / Minimum Diameter
- 13. Degradation Evaluation - Highest Numbers Indicate Best Materials

Figure B-12. Cluster diagram of simple correlation coefficients of carbonate samples, 13 variables.

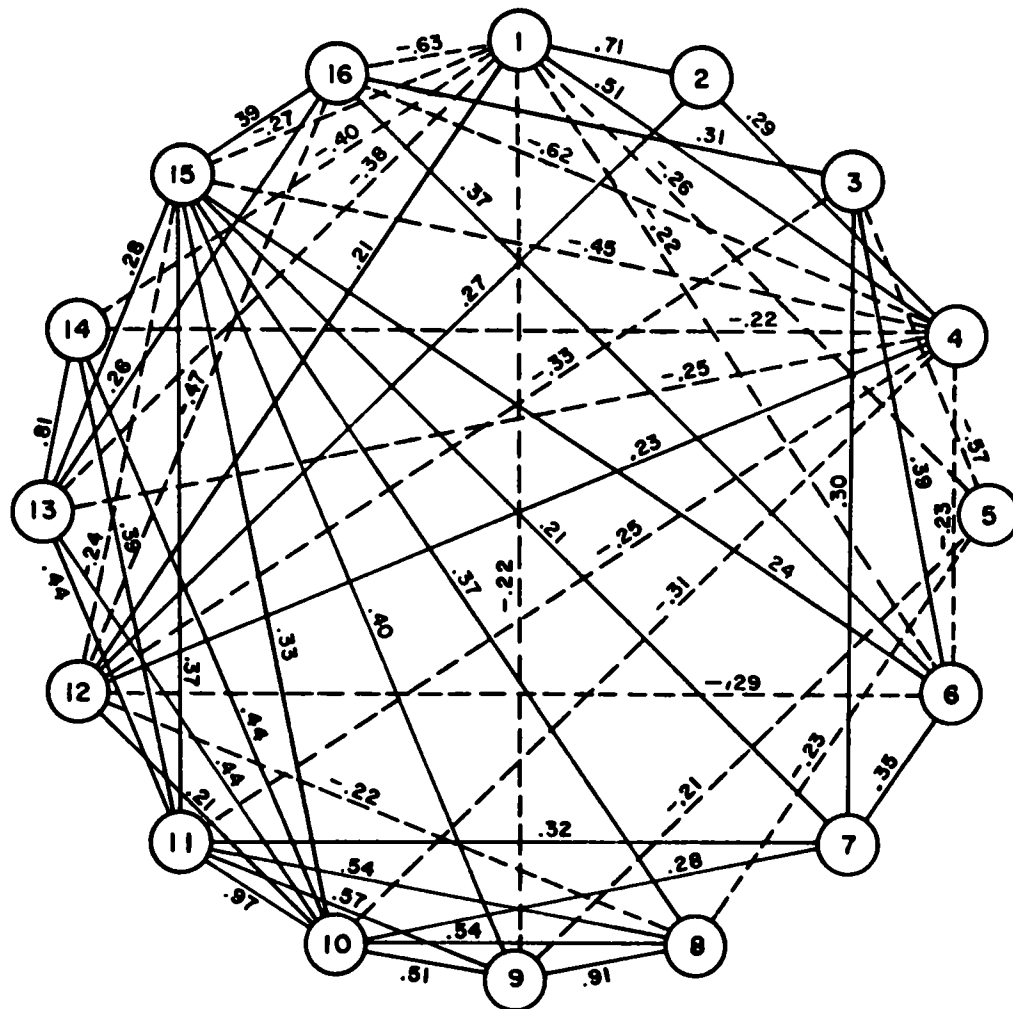


**SAMPLE SIZE = 72**

- 1. Los Angeles Abrasion
- 2. Freeze - Thaw Loss
- 3. Grain Interlock Number - Highest Number Indicates Best Interlock
- 4. Grain Roundness Number - Highest Number Indicates Most Rounded
- 5. Average Grain Size (mm)
- 6. Standard Deviation Of Grain Size (mm)
- 13. Degradation Evaluation - Highest Numbers Indicate Best Materials

Figure B-13 Cluster diagram of partial correlation coefficients, Los Angeles vs 13 variables (carbonates).

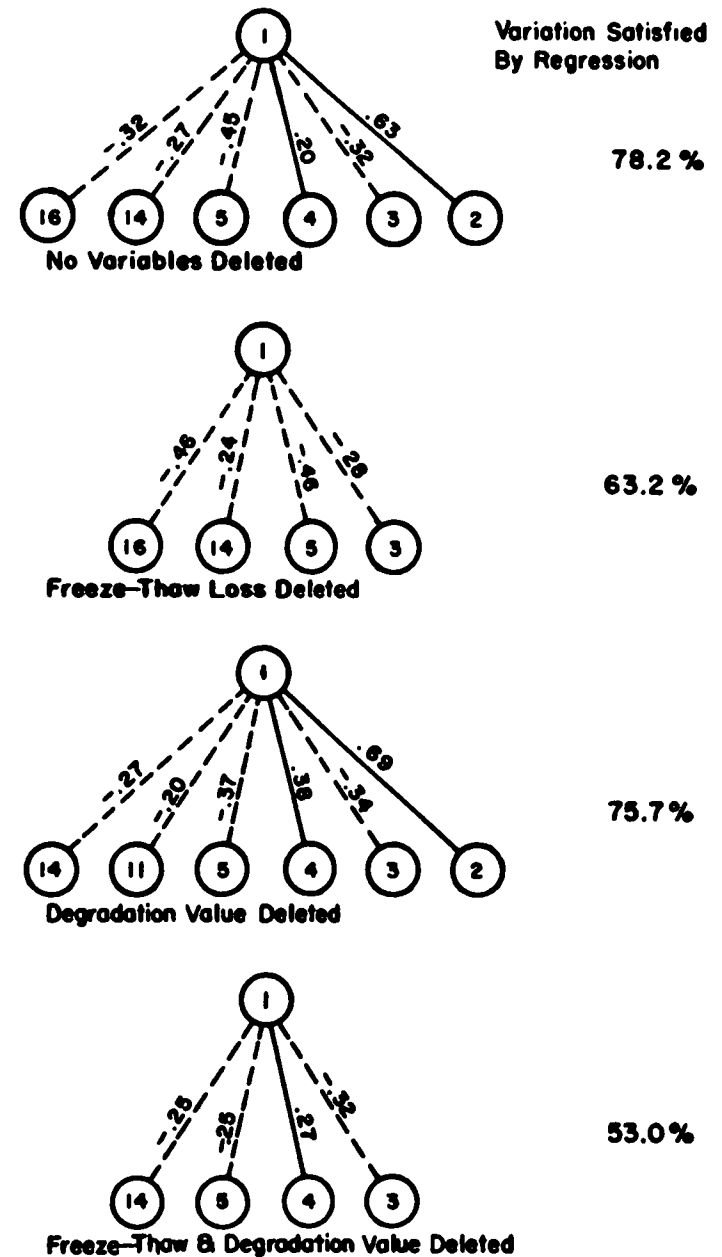




SAMPLE SIZE = 51

- |                              |  |
|------------------------------|--|
| 1. Los Angeles Abrasion      | 9. Standard Deviation Of Grain Size (mm) |
| 2. Freeze-Thaw Loss          | 10. Average Matrix Size (mm)             |
| 3. Specific Gravity          | 11. Standard Deviation Of Matrix (mm)    |
| 4. Percent Absorption        | 12. Percent Voids                        |
| 5. Percent Insoluble Residue | 13. Percent Matrix                       |
| 6. Grain Interlock Number    | 14. Matrix Diameter/Grain Diameter       |
| 7. Grain Roundness Number    | 15. Maximum Diameter/Minimum Diameter    |
| 8. Average Grain Size (mm)   | 16. Degradation Evaluation               |

Figure B-14. Cluster diagram of simple correlation coefficients of carbonates, 16 variables.



LEGEND: Some As Figure B-13. SAMPLE SIZE = 51

Figure B-15 Cluster diagrams of partial correlation coefficients of carbonates, Los Angeles abrasion vs 16 variables.

the 16-variable comparison of carbonates in the form of four cluster diagrams. The first diagram is with no variables deleted, the second with freeze-thaw loss deleted, the third with degradation value deleted, and the fourth with freeze-thaw and degradation value omitted. To the right is shown how much of the variation is accounted for in the different diagrams.

The insoluble residue correlation has gained strength over the simple correlation comparison and persists through the four diagrams. This relationship has appeared before (West et al, 1964), but not in such a persistent manner. The problem is compounded by the fact that not all insoluble residue material is argillaceous. In this study the

compositions of the clay-size fraction of the insoluble residues were determined to be primarily illite and quartz, but an analysis of the size distribution of the insolubles and the composition of the coarse fraction was not ascertained. This may be a fruitful area for future research.

The primary purpose for including Figure B-15 is to show the change in variation that is accounted for by regression analysis when the most important variables are deleted. Only one new variable (matrix deviation) appears, and then in most marginal fashion. This shows that the degradation value, for example, does not so overshadow the variation that other important comparisons are neglected.

The data for the regression analyses of Los Angeles abrasion loss vs 13 variables and Los Angeles abrasion loss vs 16 variables are given in Table B-18.

From the data of Table B-18, a regression equation can be written for each of the analyses. These equations are as follows:

Equation 1, 13 variables:

$$\begin{aligned} \text{LA} (\%) = & 42.31703 + 0.14147 (\text{FTHAW} \% \times 10) \\ & - 2.05111 (\text{DEGVL}) \\ & - 0.08329 (\text{M/GR} \times 10) - 1.32558 \\ & (\text{GROND}) + 1.10867 (\text{GLOCK}) \\ & + 0.26818 (\% \text{ Voids}) + 1.99127 (\text{STDEV} \\ & (\text{mm}) \times 10) \\ & - 2.13336 (\text{AVSIZ}(\text{mm}) \times 10) - 0.04288 \\ & (\text{PCTMT} \%) \\ & + 5.17268 (\text{MTDEV}(\text{mm}) \times 10) \\ & - 3.70730 (\text{AVMAT}(\text{mm}) \times 10) \\ & - 0.03190 (\text{MX/MIN} \times 10) \end{aligned} \quad (\text{B-1})$$

Equation 2, 16 variables:

$$\begin{aligned} \text{LA} (\% \times 10) = & 674.38252 + 0.63955 (\text{FTHAW} \% \\ & \times 10) \\ & - 16.73956 (\text{DEGVL}) - 2.64634 \\ & (\text{M/GR} \times 10) \\ & - 2.11892 (\text{INRES} \%) - 7.96084 \\ & (\text{SP.G} \times 10) - 2.94186 \\ & (\text{Voids} \%) + 14.18393 (\text{ABSORP} \\ & \%) + 4.19544 (\text{AVSIZ}(\text{mm}) \times 10) \\ & - 1.58470 (\text{MX/MIN} \times 10) \\ & - 48.91929 (\text{MTDEV}(\text{mm}) \times 10) \\ & - 36.85741 (\text{AVMAT}(\text{mm}) \times 10) \\ & + 0.36391 (\text{PCTMT} \%) + 1.41558 \\ & (\text{GLOCK}) - 1.63205 (\text{GROND}) \\ & + 0.38023 (\text{STDEV}(\text{mm}) \times 10) \end{aligned} \quad (\text{B-2})$$

The  $F$  values indicate that all variables are significant at the 95 percent confidence level and the  $R^2$  value indicates the contribution of each with regard to the reduction in sums of squares or taking the variation into account. The two equations can be used to predict the Los Angeles abrasion loss when the other variables are known.

The replacement and deletion of variables process in the computer program was used to make the other variable, in turn, the dependent variable (replace Los Angeles abrasion loss). The results served to confirm the relationships between the variables. Los Angeles abrasion was most highly

TABLE B-18

REGRESSION ANALYSIS  
OF CARBONATE AGGREGATES

| AGGR NO   | VARIABLE NAME    | REGRESSION COEFF | PARTIAL CORR COEFF | F VALUE | $R^2$   |
|---|------------------|------------------|--------------------|---------|---------|
| (a) LOS ANGELES ABRASION LOSS VS 13 VARIABLES; $N=76$ |                  |                  |                    |         |         |
| 2   | FRHAW            | 0.14147          | 0.51595            | 44.03   | 0.37300 |
| 13  | DEGVL            | -2.05111         | -0.41074           | 36.07   | 0.49706 |
| 11  | M/GR             | -0.08329         | -0.11401           | 25.24   | 0.51263 |
| 4   | GROND            | -1.32558         | -0.27620           | 20.11   | 0.53121 |
| 3   | GLOCK            | 1.10867          | 0.24166            | 16.86   | 0.54637 |
| 9   | VOIDS            | 0.26818          | 0.18342            | 14.51   | 0.55792 |
| 6   | STDEV            | 1.99127          | 0.22306            | 12.68   | 0.56631 |
| 5   | AVSIZ            | -2.13336         | -0.20083           | 12.84   | 0.60527 |
| 10  | PCTMT            | -0.04288         | -0.08363           | 11.29   | 0.60640 |
| 8   | MTDEV            | 5.17268          | 0.17095            | 10.09   | 0.60823 |
| 7   | AVMAT            | -3.70730         | -0.15774           | 9.41    | 0.61790 |
| 12  | MX/MIN           | -0.03190         | 0.01454            | 8.49    | 0.61798 |
| 1   | LOSABR-DEPENDENT |                  |                    |         |         |
| Intercept=42.31703                                    |                  |                  |                    |         |         |
| (b) LOS ANGELES ABRASION LOSS VS 17 VARIABLES; $N=51$ |                  |                  |                    |         |         |
| 2   | FTHAW            | 1.66308          | 0.63955            | 50.95   | 0.50980 |
| 16  | DEGVL            | -16.73956        | -0.32202           | 38.22   | 0.61430 |
| 14  | M/GR             | -2.64634         | -0.26742           | 33.16   | 0.67920 |
| 5   | INRES            | -2.11892         | -0.44775           | 30.71   | 0.72760 |
| 3   | SP G             | -7.96084         | -0.31528           | 26.71   | 0.74800 |
| 12  | VOIDS            | -2.94186         | -0.15293           | 23.15   | 0.75946 |
| 4   | ABSORP           | 14.18393         | 0.20380            | 20.15   | 0.76638 |
| 8   | AVSIZ            | 4.19544          | 0.04809            | 17.38   | 0.76805 |
| 15  | MX/MIN           | -1.58470         | -0.04468           | 15.34   | 0.77100 |
| 11  | MTDEV            | -48.91929        | -0.18476           | 13.61   | 0.77289 |
| 10  | AVMAT            | -36.85740        | 0.17133            | 12.64   | 0.78097 |
| 13  | PCTMT            | 0.36391          | 0.07061            | 11.35   | 0.78183 |
| 6   | GLOCK            | 1.41558          | 0.04018            | 10.21   | 0.78203 |
| 7   | GROND            | -1.63205         | -0.03924           | 9.24    | 0.78240 |
| 9   | STDEV            | 0.38023          | 0.00509            | 8.39    | 0.78240 |
| 1   | LOSABR-DEPENDENT |                  |                    |         |         |
| Intercept=674.3852                                    |                  |                  |                    |         |         |

| Legend | Variable | Description                            |
|--------|----------|--|
|        | LOSABR   | = percent loss, Los Angeles abrasion   |
|        | FTHAW    | = percent loss in freezing and thawing |
|        | SP G     | = specific gravity                     |
|        | INRES    | = percent insoluble residue            |
|        | GLOCK    | = grain interlock number               |
|        | GROND    | = grain roundness number               |
|        | AVSIZ    | = average grain size                   |
|        | STDEV    | = standard deviation of grain size     |
|        | AVMAT    | = average matrix deviation             |
|        | MTDEV    | = matrix size deviation                |
|        | VOIDS    | = percent voids                        |
|        | PCTMT    | = percent matrix                       |
|        | M/GR     | = matrix diameter/grain diameter.      |

correlative with degradation value, and as such is its best estimator. Space limitations preclude presentation here of the remaining data for the other variables as the dependent variable.

A logarithmic transform of all the data of the Los Angeles abrasion loss vs 12 variables comparison was made for the sake of completeness. This transform was utilized for the same reason as in the paired comparisons, to reduce the variances of the variables and put them on an equal basis in this regard. Figure B-16 is a cluster diagram of the partial correlation coefficients. It can be observed that no real improvement in correlation has occurred, but instead the degradation value comparison has been reduced. Grain interlock number and grain roundness number are improved somewhat by the transform, but in general no variables are strongly favored by the transform. By and large, the same relative position is maintained as for the nontransformed data.

As a final analysis of the carbonate aggregates, Los Angeles abrasion as the dependent variable was compared to the other variables on the state-by-state basis. Only data from Missouri, Illinois, Pennsylvania, and Virginia were analyzed because of the small sample sizes for the other states. Even for the states studied, the variables had to be reduced in number because the sample size must be two greater than the number of variables. Cluster diagrams for the partial correlation coefficient are shown as Figures B-17, B-18, B-19, and B-20 for Missouri, Illinois, Pennsylvania, and Virginia, respectively. The sample sizes are such that little more can be added to the statements made earlier about the analysis of the states combined. The relationships between freeze-thaw, degradation value, and Los Angeles abrasion still hold and the remaining relationships are somewhat sporadic.

### Phaneritic Igneous and Metamorphic Rocks

The results of the paired variable comparisons for igneous and metamorphic rocks are given in Table B-19. The column listings are similar to those of Table B-17, as previously explained.

The results given in Table B-19 indicate that the average grain size is a good predictor of Los Angeles abrasion loss for coarse-grained igneous and metamorphic rocks. The standard deviation of grain size is suitable for comparison, however. As in previous comparisons, degradation value and Los Angeles abrasion loss have a strong inverse correlation.

A correlation and regression analysis of the data also was made. Serious limitations were placed on this analysis because of the small sample size (13) and the results are not very meaningful. A cluster diagram of the simple correlation coefficients is shown in Figure B-21. The usual correlation between Los Angeles abrasion loss and freeze-thaw value is shown. The relationship between Los Angeles abrasion loss and degradation value on the one hand and average size on the other are in reverse of their usual sense. This suggests that too few data are available particularly in light of the results given in Table B-19, which indicate contrary results. The partial correlation coefficients are merely ramifications of the simple correlation values and as such are equally misleading. This comparison of partial correlation coefficients has been deleted for this purpose.

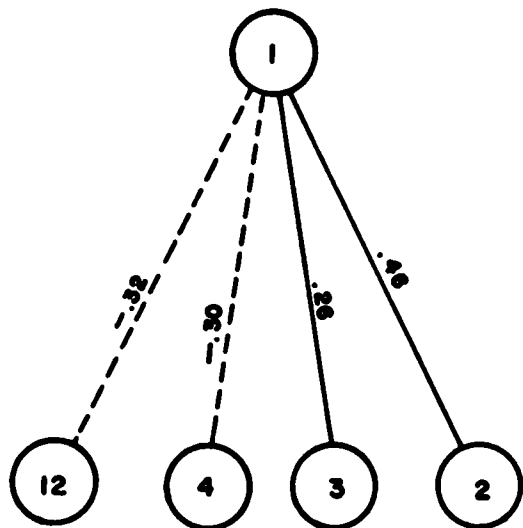
An equation for the phaneritic igneous and metamorphic rocks can be obtained in like fashion to that obtained for the carbonate rocks. Only average size and the freeze-thaw value are significant at the 95 percent level. With these limitations of significance and the questionable relationship of average grain size and degradation value with Los Angeles abrasion loss, it would be misleading to present the

TABLE B-19

### DATA COMPARISON FOR CRYSTALLINE IGNEOUS AND METAMORPHIC ROCKS

| VARIABLES                                   | N  | REGRES-<br>SION<br>COEFF.     | INTER-<br>CEPT    | R <sup>2</sup>             | F<br>VALUE                 | PARTIAL<br>CORR.<br>COEFF   | LEVEL<br>OF<br>SIGNIF-<br>ICANCE<br>(%) | EQUATION   |
|---|----|-------------------------------|-------------------|----------------------------|----------------------------|-----------------------------|---|--|
| 1. AVSIZvsLA                                | 14 | 0.01010                       | 0.06996           | 0.4955                     | 11.786                     | 0.7039                      | 99+                                     | AVSIZ=0.06996+0.0101 (LA)                              |
| 2. AVSIZvs(LA)+(LA) <sup>2</sup>            | 14 | 0.00906<br>0.00001            | 0.08580<br>—      | 0.4955<br>0.4958           | 11.786<br>5.408            | 0.1965<br>0.0238            | —<br>95+                                | AVSIZ=0.0858+0.00906 (LA)<br>+0.0001 (LA) <sup>2</sup> |
| 3. STDEVvsLA                                | 14 | 0.00476                       | 0.17390           | 0.1547                     | 2.196                      | 0.3933                      | 75+                                     |  |
| 4. STDEVvsLA+(LA) <sup>2</sup>              | 14 | 0.01016<br>-0.00007           | 0.09190<br>—      | 0.1547<br>0.1653           | 2.196<br>1.089             | 0.2027<br>-0.1122           | —<br>50+                                |  |
| 5. DEGvsLA                                  | 14 | -0.20891                      | 12.28126          | 0.7679                     | 39.707                     | -0.8763                     | 99+                                     |  |
| 6. DEGvsLA+(LA) <sup>2</sup>                | 14 | -0.34320<br>0.00170           | 14.32370<br>—     | 0.7679<br>0.7849           | 39.707<br>20.072           | -0.5735<br>0.2707           | —<br>99+                                |  |
| 7. DEGvsLA+LA <sup>3</sup> +LA <sup>2</sup> | 14 | 0.86130<br>0.00030<br>-0.0310 | 2.37420<br>—<br>— | 0.7679<br>0.7849<br>0.8584 | 39.707<br>21.112<br>20.199 | 0.4478<br>0.5843<br>-0.5609 | —<br>—<br>99+                           |  |

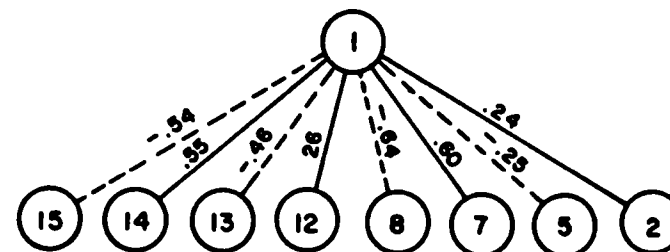
Legend LA = percent loss by Los Angeles abrasion  
 AVSIZ = average grain diameter  
 STDEV = standard deviation of grain diameter  
 DEG = degradation evaluation



1. Los Angeles Abrasion
2. Log Of Freeze-Thaw
3. Log Of Grain Interlock Number
4. Log Of Grain Roundness Number
5. Log Of Average Grain Size
6. Log Of Standard Deviation Of Grain Size
7. Log Of Average Matrix Size
8. Log Of Standard Deviation Of Matrix Size
9. Log Of Percent Matrix
10. Log Of Matrix Diameter - Grain Diameter Ratio
11. Log Of Maximum Diameter/Minimum Diameter
12. Log Of Degradation Value

**SAMPLE SIZE = 59**

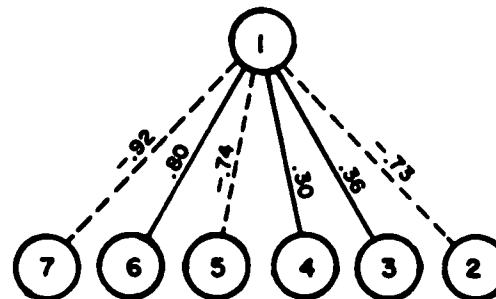
Figure B-16. Cluster diagram of partial correlation coefficients of carbonates, Los Angeles abrasion vs log of 12 variables.



1. Los Angeles Abrasion
2. Specific Gravity
3. Percent Absorption
4. Percent Insoluble Residue
5. Grain Interlock Number
6. Grain Roundness Number
7. Average Grain Size (mm)
8. Standard Deviation Of Grain Size
9. Average Matrix Size
10. Matrix Deviation
11. Percent Voids
12. Percent Matrix
13. Matrix Diameter/Grain Diameter
14. Maximum Diameter/Minimum Diameter
15. Degradation Evaluation

**SAMPLE SIZE = 18**

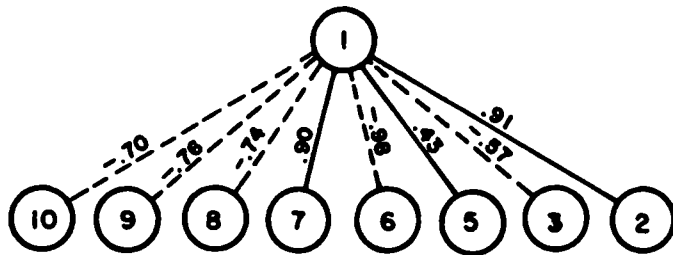
Figure B-17. Cluster diagram of partial correlation coefficients, Missouri carbonates



1. Los Angeles Abrasion
2. Freeze-Thaw Loss
3. Percent Insoluble Residue
4. Grain Interlock Number
5. Grain Roundness Number
6. Average Grain Size (mm)
7. Degradation Evaluation

**SAMPLE SIZE = 9**

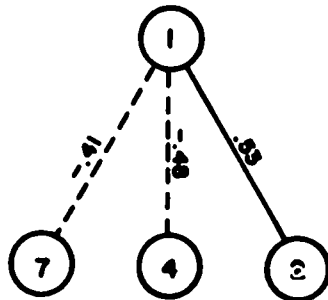
Figure B-18 Cluster diagram of partial correlation coefficients, Illinois carbonates



- |                           |                                     |
|---------------------------|-------------------------------------|
| 1. Los Angeles Abrasion   | 6. Grain Roundness Number           |
| 2. Freeze-Thaw Loss       | 7. Average Grain Size               |
| 3. Specific Gravity       | 8. Standard Deviation Of Grain Size |
| 4. Percent Absorption     | 9. Percent Matrix                   |
| 5. Grain Interlock Number | 10. Degradation Evaluation          |

**SAMPLE SIZE = 12**

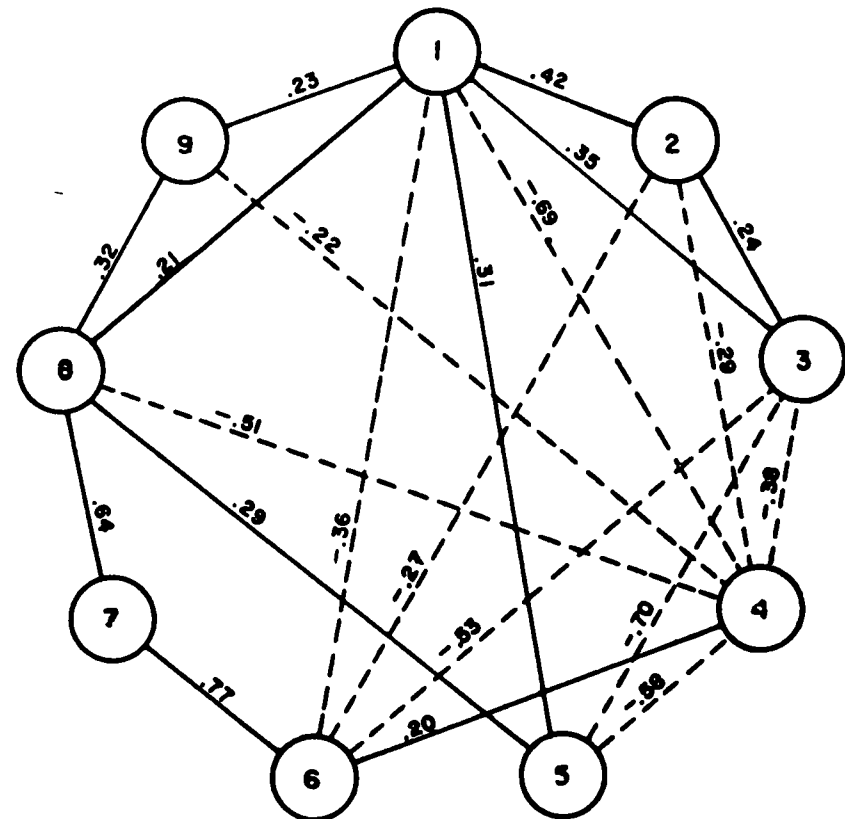
Figure B-19 Cluster diagram of partial correlation coefficients, Pennsylvania carbonates



- |                         |                           |
|-------------------------|---------------------------|
| 1. Los Angeles Abrasion | 5. Grain Interlock Number |
| 2. Freeze-Thaw Loss     | 6. Grain Roundness Number |
| 3. Specific Gravity     | 7. Average Grain Size     |
| 4. Percent Absorption   | 8. Degradation Evaluation |

**SAMPLE SIZE = 10**

Figure B-20. Cluster diagram of partial correlation coefficients, Virginia carbonates.



- |  |
|--|
| 1. Los Angeles Abrasion                |
| 2. Freeze-Thaw Loss                    |
| 3. Percent Absorption                  |
| 4. Average Grain Size                  |
| 5. Average Matrix Grain Size           |
| 6. Percent Matrix                      |
| 7. Matrix Diameter / Grain Diameter    |
| 8. Maximum Diameter / Minimum Diameter |
| 9. Degradation Evaluation              |

**SAMPLE SIZE = 11**

Figure B-21 Cluster diagram of simple correlation coefficients, crystalline igneous and metamorphic rocks.

equation at this point and thereby add some credibility to it. Therefore, it is not supplied herein.

As a final effort, the replacement and deletion of variables was performed with each variable in turn being considered the dependent variable. With freeze-thaw loss as the dependent variable, the analysis looked somewhat more in keeping with previous results. A positive correlation value was obtained between freeze-thaw and (1) Los Angeles abrasion loss and (2) average grain size. A negative correlation value was obtained between freeze-thaw and degradation value. This merely indicates the fickle nature of this analysis with so few samples and shows its general unreliability.

The over-all conclusion for these phaneritic igneous and metamorphic aggregates has changed little since the end

of Phase I. Average grain size is a good predictor of Los Angeles abrasion loss. Freeze-thaw values also are good predictors.

#### Basalts

The analysis of basalts was hindered somewhat by the same situation as in the phaneritic igneous and metamorphic aggregates; that is, a paucity of samples (only nine). The results were meaningful to a certain degree, but from the negative point of view.

A paired comparison between Los Angeles abrasion loss and degradation value was made first. The results indicated that a direct relationship exists between the two variables; that is, as abrasion loss increases, degradation value increases. This is contrary to the relationship between abrasion loss and degradation for carbonates and for phaneritic igneous-metamorphic rocks. In actuality it indicates that no strong relation exists between them and that too few samples are presented. The suggestion that no relationship exists between Los Angeles abrasion loss and degradation value is in keeping with the findings in Phase I in regard to basalt aggregates.

A correlation and regression analysis also was run using Los Angeles abrasion as the dependent variable and the others as independent variables. The independent variables used were specific gravity, grain interlock number, grain roundness number, average size, percent matrix, and degradation value. The only reasonable result of the group of simple and partial correlations was the inverse relationship between grain roundness number and degradation value. This indicates that as the grains become rounder (high numbers) the degradation value gets smaller (more prone to degradation). The interlock relationship has the correct relationship (sign) with degradation (directly related) but has a partial correlation less than 0.2.

As a summary of the analysis of basalts it can be said that Los Angeles abrasion is not a generally applicable predictor of basalt degradation. Textural measurements such as roundness and interlock may be somewhat applicable. Chemical degradation plays the major role here and the best tool for investigation is petrography. The presence of volcanic glass, and the minerals palagonite and chlorophaeite indicate an unstable chemical relationship that may give rise to chemical degradation. This was suggested by work done in Idaho (Day, 1962) and borne out by petrographic studies in Phase I (West et al., 1964).

#### Comparison with Field Compaction Degradation Data

The final problem undertaken was to ascertain, if possible, how the degradation of the various carbonate aggregates compared with existing field degradation tests. It was not possible to field test all the aggregates accumulated for this study, because field degradation tests are long and tedious so that only a few aggregate sources can be investigated. As an example, Aughenbaugh et al. (1963) were able to examine a limit of four aggregate sources in their two-year field study of compaction degradation. At this rate, the numerous samples in this present study, which were made necessary through the national scope of the problem, could not be realistically evaluated in the field.

TABLE B-20

#### CARBONATE AGGREGATES IN DESCENDING ORDER OF LOS ANGELES ABRASION LOSS

| L.A  | DESIG.  | DGVAL | L.A  | DESIG.  | DGVAL |
|------|---------|-------|------|---------|-------|
| 78.9 | Mo 4    | 4     | 29.1 | Fla 5   | 7     |
| 66.8 | Ill. 4  | 3     | 29.0 | Iowa 5  | 3     |
| 61.8 | Wis 4   | 3     | 28.9 | Mo 11   | 8     |
| 60.2 | Mo 2    | 4     | 28.7 | Pa 13   | 8     |
| 54.5 | Wis 1   | 3     | 28.7 | Ill 5   | 4     |
| 53.0 | Mo 20   | 2     | 28.6 | Mo 1    | 7     |
| 52.9 | Wis. 4  | 4     | 28.4 | Mo. 7   | 8     |
| 50.5 | Fla. 1  | 4     | 28.2 | Vir. 23 | 8     |
| 50.3 | Wis. 3  | 4     | 27.9 | Pa. 6   | 8     |
| 48.4 | Mo 5    | 7     | 27.8 | Ind 3   | 6     |
| 46.0 | Mo. 6   | 4     | 26.7 | Ill 8   | 4     |
| 44.0 | Mo. 12  | 7     | 26.5 | Pa. 4   | 8     |
| 43.7 | Mo 10   | 4     | 26.5 | Mo. 21  | 7     |
| 43.0 | Iowa 3  | 3     | 26.4 | Ill 9   | 6     |
| 42.9 | Mo 3    | 7     | 26.1 | Mo. 13  | 8     |
| 38.7 | Okla. 2 | 3     | 26.1 | Pa 10   | 5     |
| 37.6 | Ill 6   | 3     | 25.7 | Ill. 7  | 5     |
| 36.4 | Ind. 8  | 5     | 25.2 | Pa 3    | 9     |
| 36.2 | Fla 7   | 5     | 24.4 | Pa. 16  | 7     |
| 36.0 | Iowa    | 7     |      | Ind 12  |       |
| 36.0 | Mo. 22  | 4     | 24.1 | Pa. 1   | 8     |
| 35.7 | N.Y. 1  | 7     | 24.1 | N.Y. 3  | 6     |
| 35.6 | Fla. 8  | 5     | 23.3 | Pa 12   | 8     |
| 35.0 | Mo 24   | 4     | 23.0 | Mo 8    | 9     |
| 35.0 | Iowa 1  | 3     | 23.0 | N.Y. 2  | 7     |
| 35.0 | Ill 12  | 8     | 22.8 | Vir 1   | 8     |
| 34.6 | Mo. 15  | 7     | 22.3 | Pa 5    | 8     |
| 34.0 | Fla 3   | 5     | 22.3 | Ind. 7  | 9     |
| 33.4 | Okla 3  | 4     |      | Ind. 11 |       |
| 33.0 | Mo. 9   | 6     | 20.9 | Okla. 1 | 9     |
| 32.9 | Mo 16A  | 7     | 20.5 | Pa 17   | 8     |
| 32.7 | Fla 6   | 5     | 20.5 | Pa. 18  | 8     |
|      | Ind. 4  |       | 19.7 | Vir. 20 | 9     |
| 32.5 | Mo. 16  | 6     | 19.6 | Pa 20   | 6     |
| 32.5 | Fla. 4  | 5     | 19.3 | N.Y. 7  | 9     |
| 32.3 | Mo. 18  | 7     | 19.2 | Vir. 21 | 9     |
| 32.1 | Ind. 5  | 5     | 19.0 | Vir. 7  | 9     |
| 31.1 | Wis 2   | 6     | 18.6 | Pa 14   | 8     |
| 31.0 | Mo. 19  | 7     | 18.0 | Pa. 19  | 8     |
| 30.5 | Ill. 3  | 4     | 17.0 | Vir. 28 | 9     |
| 30.5 | Ind. 9  | 5     | 16.5 | Pa. 15  | 9     |
| 30.4 | Mo 23   | 7     | 16.2 | Vir. 8  | 9     |
| 29.5 | Ill. 1  | 5     | 16.1 | Vir. 17 | 9     |
| 29.2 | Fla. 2  | 7     | 15.5 | Vir. 31 | 9     |

In the case of the carbonate aggregates, it was possible to compare the results to the data obtained in Aughenbaugh's study (1963). The three carbonate quarries studied by Aughenbaugh were resampled for comparisons. These are listed as Ind. 4, Ind. 11, and Ind. 12. In Table B-20 all the carbonates examined in this research program are listed in order of decreasing Los Angeles abrasion value. In Aughenbaugh's study, Ind. 11 normally degraded the least, with Ind. 12 next and Ind. 4 degrading the most. This is also their order in Los Angeles abrasion loss. The three Indiana samples have been added to the list in Table B-20. In the Aughenbaugh study, Ind. 4 produced about 1.5 percent fines using a steel-wheel roller. This being the case, the maximum allowable Los Angeles abrasion may well be put in the low 40 percent range for base and sub-base material. It can be observed in Table B-20 that abrasions above 40 are normally in the 3-to-5 degradation range, indicating poor to marginal material.

The freeze-thaw values for Ind. 4, Ind. 11, and Ind. 12 are 1.3, 0.7, and 1.6, respectively. Again, Ind. 11, which degrades the least, has the lowest freeze-thaw loss, but the other samples are interchanged. Ind. 12 has the greatest freeze-thaw loss and intermediate degradation by field measurement, whereas the reverse is true for Ind. 4. Ind. 12 is a banded, argillaceous dolomite and its higher freeze-thaw loss is not unexpected. The previous analysis has shown that both freeze-thaw and Los Angeles loss are highly correlative with the supplied degradation value. This may only mirror the preconceived ideas of the aggregate suppliers that abrasion and soundness loss indicate degradation properties. However, the fact remains that Los Angeles abrasion is a useful measure and that freeze-thaw value generally confirms it in comparison to field compaction degradation.

## APPENDIX C

### INDIANA QUARRY PROBLEM

#### STATEMENT OF PROBLEM

Sampling of rock in quarries and of crushed rock from mills or stockpiles for use in testing various characteristics of aggregates has long been a thorny problem. One aspect of the problem is that of representation; that is, of obtaining a sample that is representative of the finished product and that can be tested to determine how that product will react in service. Consideration of the many obviously possible variables in a simple operation indicates the complexity of the problem or representation.

In the quarry, one problem faced was the possible variation in lithology in three dimensions. The manner in which the rock is shot and how it breaks and falls undoubtedly varies from place to place or even from time to time in the same place. The broken rock is also picked up according to some pattern by the loading equipment, which varies in type and size, and then is transported in a truck or other conveyance to a mill where the rock is discharged in a variety of ways into a primary crusher of one kind or another. By this time the relatively ordered natural arrangement of lithologies in the quarry probably has been disrupted by mixing.

In the crushing mill, further mixing may be brought about by variations in layout and type of equipment. For example, the rock being processed may or may not be temporarily stored in a bin or pile after primary crushing. Such storage insures a constant supply of material for the secondary crusher, thus smoothing out any irregularities

in the quantity delivered to the mill from the quarry. Consequently, storage of this type is relatively common in crushing plants.

Also, the number of different size gradations produced by a mill may determine whether or not large fragments must be recycled through a crusher or are included as part of a large-size gradation. By the time the finished product of crushed stone is binned or piled for sale, the probability of mixing has increased over the probable mixing prior to delivery at the mill.

Quarries may contain rock possessing different physical characteristics, and these rocks of different physical characteristics may be quarried simultaneously. If so, and if mixing takes place as previously suggested, what physical characteristics does the finished product possess? In addition to mixing is there a possibility that soft or weakly consolidated rock is unable to withstand the rigors of quarrying and milling processes and is so reduced in size as to be screened out into the finest?

Thus, evaluation of the rock in a quarry or from a crushing mill is a complex problem surfeited with variables. Sampling of the quarry or mill product needs close study to insure that the knowledge gained from the samples bears some pertinent relationship to the knowledge needed to judge the probable performance of the crushed rock in use.

Originally the Indiana quarry study was divided into two parts that involved two or more quarries. The first part was to be a limited study of a quarrying operation in-

volving dissimilar rocks. By applying statistical methods, an attempt was to be made to determine procedures for processing representative samples for testing. Evolution of a basis for better and more standard sampling techniques giving better representation of bulk quarry production was the goal, with the possibility of accumulating data for the evaluation of natural aggregate mixing and beneficiation in quarrying and crushing operations as a subsidiary of the goal.

The second part of the study was to relate details of the geological units, of quarrying and crushing operations, of stockpiling, and of any other discovered factor, to final aggregate quality. This part of the study was to relate these factors individually and collectively in one or more quarries known to produce stone of marginal quality in order to gain some insight into possible preconstruction quality control, as well as an assessment of confidence to be placed on assumed uniformity of aggregate as emplaced.

Consideration was given to many quarries, and visits were made to those few that seemed to possess rock of the desired physical characteristics. However, after examining several quarries it became apparent that a greater number of samples would be needed to measure statistically the many variables involved in either part of the quarry problem than available time and equipment would permit processing. It appeared that economies in effort were needed and that detailed analysis of a single ideal quarry and mill would give definitive results relating geology, mixing, natural beneficiation, milling, and stockpiling to the final product available. In addition, sampling techniques could be tested. Such a quarry and mill had been found and could be used for the purposes of this part of the total project. Approval to modify the approach in this manner, using a single quarry for this portion of the study, was obtained and the research proceeded in that manner.

#### QUARRY AND MILL SELECTION

The quarry selected for concentrated study is located geologically in flat-lying sedimentary rocks lacking complicated or discontinuous sedimentary and deformational structures but possessing obvious variations in lithologies in the vertical direction. The major lithologic differences are relatively easy to identify in small fragments without elaborate preparation; thus fragments of individual lithologies can be identified and separated out of samples taken at different stages of processing as a means of measuring possible natural mixing and beneficiation. The quarry face is low and extensive enough to examine and to sample at several convenient places without interfering with operations. The entire vertical thickness of the face is shot at one time. The mill also can be sampled at two stages with convenience and safety and without interfering with operations.

The quarry studied in detail utilizes rock from three limestone formations of Meramecian (Mississippian) age. These are, from oldest to youngest, the Harrodsburg Limestone, the Salem Limestone, and the St. Louis Limestone. For each of these formations in Indiana, high loss in Los Angeles abrasion has been recorded in at least sev-

eral localities for selected portions of these rock units. It is a rare circumstance of the total geologic environment to find these three formations in a single quarry, and even rarer that they yield an aggregate product sufficiently low in abrasion to be classified as class A stone according to Indiana highway specifications (less than 40% loss in Los Angeles abrasion) as is the case in this quarry. The Harrodsburg unit immediately below the floor of the quarry becomes fairly coarse-grained, thus increasing its abrasion loss and making it relatively unsuitable for aggregate production.

The Harrodsburg Limestone is the lowest and oldest formation in the quarry. Only the top 10.9 to 11.9 ft of the formation, in beds 5 to 18 in. thick, is exposed in the quarry. This unit is gray to dark gray rock composed of fossilized and fragmented echinoderms and bryozoans whose remains chiefly are between 1/8 mm and 1 mm in diameter. Both the fragments and the material that binds them together consist of the mineral calcite (calcium carbonate). The Harrodsburg contains minor quantities of chert, disseminated argillaceous material, and thin shale layers, the amount of the non-chert impurities appears to increase upward in the rock at this place.

The Harrodsburg in the face of the study quarry is divisible into three horizontally disposed parts, each measured to be between 3.0 and 4.4 ft in thickness. Each of these parts contains lithologies that are common to all, thus it is not possible to identify pieces of crushed Harrodsburg as originating from a particular place within the formation in this quarry.

The Salem Limestone, the middle formation in position and age in the study quarry, is a very light gray to light tan rock unit. The Salem varies from the underlying Harrodsburg only in subtle ways. The entire thickness of the formation is exposed in the quarry and varies from 10.4 to 11.3 ft. Like the Harrodsburg, the Salem is composed of fragmented, fossilized remains of crinoids and bryozoans but, unlike the Harrodsburg, the Salem contains specimens of the foraminifer *Endothyra baileyi* (Hall), which also are made of the mineral calcite. The organic debris in the Salem is smaller than that of the Harrodsburg and gives much evidence of deposition by currents. Minor very thin shale in layers or associated with stylolites, plus rather persistent thin layers of chert in lenses and nodules in the lowest foot or two of the Salem, constitute the apparent impurities in the formation.

The Salem is divisible into two horizontally disposed parts in the study quarry; the upper part is a single bed that varies from 3.5 to 4.4 ft in thickness and the lower part is in beds from 2 to 4 ft in thickness. The lower and thicker part is fairly homogeneous in lithology, but the upper part varies laterally and vertically from rock that is identical to the lower part to rock that is composed of silt-sized calcite lacking obvious fossilized organic debris. It is not possible to identify pieces of crushed Salem as originating from a particular place within the formation at this quarry.

Only the lowest 8.7 to 10.1 ft of the St. Louis Limestone is quarried and crushed. An additional thickness of weathered St. Louis is stripped off and discarded, along



with the Pleistocene till overlying the bedrock. Division of the St. Louis into three small horizontally disposed parts is possible only on an arbitrary basis and was based on convenience in sampling; for example, some of the vertical changes in lithologies are gradational or take place within beds rather than between beds. Because of repetition of lithologies within the St. Louis, it is not possible to identify pieces of crushed St. Louis as originating from a particular place with the formation in this quarry. The individual parts of the St. Louis that were sampled vary from 2.2 to 4.4 ft in thickness.

The lowest part of the quarried St. Louis consists of tan, wavy laminated, lithographic limestone overlain by a shale layer, which in turn is overlain by a limestone breccia. The top of this part of the St. Louis is a layer made of the same material as the matrix of the breccia. The breccia fragments characteristically are tan lithographic limestone in a slightly coarser-grained, greenish, argillaceous limestone matrix, but locally the fragments are dense, dark, blue-gray limestone and the matrix locally is tan lithographic limestone. In this part of the St. Louis there are vertical and lateral variations in lithologies.

The middle part of the quarried St. Louis varies vertically in lithologies that are more persistent in lateral directions than the part that is below. The lowest lithology in the middle part is tan to gray, very fine- to coarse-grained, heterogeneous limestone made of varying but minor quantities of fossil fragments and fine-size calcite crystals. Locally thick black shale or a shaly interval is present above and (or) below this rock, and lenticular chert or lenticular coarse-grained replacement quartz is present within this rock. Next above is similar rock with similar impurities at similar places, but which has the added attribute of being locally laminated. The top of this part of the St. Louis characteristically is dark gray to tan lithographic limestone that locally is faintly laminated; streaks of shale or quite thick lenses or pods of shale also are found locally within this rock.

The top of the quarried St. Louis has a basal lithographic limestone indistinguishable from other lithographic limestones in the formation. However, it is separated from lower rock by a bedding plane and grades upward within a bed to limestone of coarser crystal size. The remaining beds of this part of the St. Louis are bluish-gray, dense, fine- to medium-grained limestone.

It should be noted that there is a general reduction in grain size upward from the Harrodsburg, through the Salem, and into the St. Louis. This change in grain size is a reflection of the change in constituent calcite grains from chiefly debris of skeletons of marine organism upward to chiefly chemically precipitated material with intercalations and lenses of organic debris ranging downward to exceedingly fine sizes.

The rock in the study quarry was sampled chiefly at four different places; the samples were collected from the subdivisions of the three formations previously described. Each quarry sample is from one of the subdivisions and consists of rock broken from the quarry face to provide equal representation in the sample of all the rock in the subdivision at a place; the samples are as close to channel

samples as is possible to obtain with a geologic hammer. At three of the sampling places (Locations 1 to 3) pairs of samples were taken at different times from each of the eight subdivisions. At the fourth sampling place (Location 4) a "double" sample was taken from each subdivision. Each of the single samples weighed at least 50 lb and double samples were on the order of 100 lb in weight.

It was not considered feasible to sample the pile of shot quarry rock at the toe of the face or in the trucks when loaded for transport to the crushing mill. Observation of piles of newly shot quarry rock at different times showed that the method of shooting caused mixing of some degree. The practice in this quarry is to shoot the bottom 5 ft or so of the face first with a heavier load than above, and to time-delay shoot the lightly loaded upper part. This practice causes the rock in the lower part of the face to be shot outward before, and slightly farther than, the rock in the rest of the face. After the face is shot, the rock is picked up by diesel-powered shovels and dropped into trucks; the shovels usually operate back-and-forth along paths perpendicular to the quarry face.

At the mill, the trucks dump the rock into the primary crusher. Two samples were obtained from the intermittent output of the primary crusher. The rock from the primary crusher is fed onto a belt, which in turn drops the rock on the top of an open-air temporary storage pile of conical shape. A steady flow of rock is vibrated out of the center of the bottom of the temporary storage cone onto a belt that feeds the secondary crusher. The outflow from the temporary storage cone was sampled 14 times.

After going through the secondary crusher, the rock is screened into the sizes required for the gradations being manufactured. The undersized pieces are fed into a hammermill for manufacture of agricultural lime and the oversized pieces are then returned to the secondary crusher for reprocessing. This particular mill is arranged to produce two size gradations at the same time; during the period of sampling for this project the pairs of products consisted of Indiana No. 4's and No. 11's, No. 9's and No. 11's, and "large" and "small" No. 9's (Indiana numbered sizes for coarse aggregate used in highway construction). The point of sampling was at the end of the troughs from the final screen to the top of the closed storage bins. Because of the vagaries in the production, two samples of No. 4's, twelve samples of No. 9's, and ten samples of No. 11's were obtained as a result of 14 trips to the troughs. Table C-1 gives an abbreviated listing of the Indiana coarse aggregate number designation.

The sets of samples from the mill were taken in sequence, starting with the point sampled nearest to the beginning of the crushing process and ending with the product sampled with the smallest size gradation. Samples were taken with a scoop shovel held under the outfall at the point being sampled; in the restricted space under the primary crusher this was a sloppy and hazardous task. Several shovelfuls were needed for each sample. One set of samples consisted of pairs of samples taken in sequence at each stage of production that was sampled.

The finished crushed limestone is drawn from the storage

TABLE C-1  
 ABBREVIATED SUMMARY OF TABULATED SIZES OF COARSE AGGREGATES

| AGGR<br>CLASS | TOTAL PASSING SIEVE WITH SQUARE OPENINGS (%) |       |       |       |       |      |      |       |
|---------------|--|-------|-------|-------|-------|------|------|-------|
|               | 1½ IN  | 1 IN  | ¾ IN  | ½ IN  | ⅜ IN  | NO 4 | NO 8 | NO 30 |
| 4             | 100  | 70-90 | 40-70 | 10-30 | —     | 0-5  | 0-2  | —     |
| 9             |  |       | 100   | 65-90 | —     | 0-10 | —    | 0-2   |
| 11            |  |       |       | 100   | 75-95 | 5-20 | 0-5  | —     |

Source "Workbook for In-Service Training School for Highway Inspector Supervisors" (Feb 1966)

bin in the mill and is trucked to the stockpiles. The stockpiles are wedge-shaped in longitudinal section and are elongated. The trucks dump their loads on top of the piles and the stone is picked up for sale at the thick end. Each of six existing stockpiles was sampled once for this study; representation of material in stockpiles sampled for physical characteristics possibly is worthy of greater and more systematic study. The six samples taken were obtained from the working faces of the piles by scooping up material with a shovel along an inverted "V" path.

#### PROCESSING AND TESTING OF SAMPLES

The quarry samples consisted of pieces of rock in a wide range of sizes; these samples were crushed in a laboratory jaw crusher, mixed, and sieved for the correct gradation and weight for testing for physical characteristics

Samples taken from the mill and stockpiles were treated variously. The samples or splits from the original samples were sieved to remove pieces smaller than No. 3 mesh, which proved to be too small to identify with reliability, and then washed. Samples taken before the secondary crusher weighed in excess of 40 lb each and contained a wide range of sizes, chiefly large, these samples were not split into smaller portions. The size of samples taken after the final screening depended on the size gradation being produced. The samples of Indiana No. 9 and larger gradations all weighed in excess of 35 lb and samples of smaller gradations weighed in excess of 15 lb (see Table C-1 for clarification of Indiana aggregate grading designations)

Samples taken of the finished product were repeatedly mixed and split by quartering, using conventional methods, until they had been reduced to contain about 1,000 pieces larger than No. 3 mesh for lithologic identification. After lithologic separation, the samples with gradations greater than that of the No. 11 gradation were crushed if necessary, mixed, and sieved for the correct gradation and weight necessary for testing for physical characteristics.

Gradations as small as, or smaller than, No. 11 were not processed further because they were too small to use in the Los Angeles B test.

Little difficulty was experienced in identifying the pieces of crushed rock of the mill and stockpile samples as having originated in one of the three formations in the quarry. Identifications were made using a low-power, large-field

magnifier mounted on a stand and fitted with a built-in source of reflected incandescent light.

Originally it was anticipated that some fragments, such as shale or chert, would not be recognizable as coming from a particular formation; thus an "unknown" category was used. This category was discarded after a few samples had been processed, because only a piece or so, representing an insignificant proportion of a rare sample, could not be identified. Only a rare piece of shale was found that was not associated with carbonate material identifiable as coming from a particular formation. The chert in the Harrodsburg and in the Salem was formed by the silicification of the carbonate rocks in these formations. Thus each piece of chert found in the Harrodsburg and the Salem at this particular quarry displays relict carbonate structures that serve to identify its origin. The origin of the chert in the St. Louis cannot be stated as dogmatically, but all of the chert *per se* observed in the St. Louis in this quarry lacks observable relict carbonate structures and the large replacement quartz crystals also found in the St. Louis are not duplicated in the Harrodsburg and Salem units. There is, therefore, only a slight possibility of confusing the formational origin of the cherts and shales.

There is some possibility of confusing pieces from the top part of the Harrodsburg with Salem pieces, and *vice versa*. Resolution of this possible confusion in the study quarry rests upon color differences; the upper part of the Harrodsburg is distinctly gray and the Salem is distinctly tan in cast. Color differences also serve to distinguish between texturally similar rocks in the upper part of the Salem and in the St. Louis. Patches of rock composed of silt-sized calcite exist in both formations, and differentiations are made on the basis of the tan cast in the Salem and a green cast to the confusable parts of the St. Louis.

On the other hand, similarities in color of rock exist between the Salem and the St. Louis and between the Harrodsburg and the St. Louis. Parts of both the Salem and the St. Louis have a tan color or cast, and differentiation must be based on a larger proportion of grains of sand size in the Salem than in the St. Louis and on recognition of the larger grains as fragments of fossils. Parts of both the Harrodsburg and the St. Louis are dark gray or bluish-gray, and differentiation here also is based on a larger proportion of grains, which are fossil fragments, of sand size in the Harrodsburg than in the St. Louis. In both of these cases errors of identification are

possible because all formations are known to contain small lenses of rock that are exactly like the adjacent formation. This is not known to be the case in the study quarry, but as these bodies are only a few inches thick and a few feet in diameter, it would be easy to miss such a body in the quarry face.

To gain some idea as to the constancy of identification of formational origin, the thoroughness of sample mixing, and the accuracy in splitting samples where this was necessary, 8 of the 46 samples were examined for formational distribution more than once. In the case of three samples, the same portions were examined for formational distribution two different times. Opposite quarters of the final split of four samples were examined for formational distribution in one sample. The results of this work show that constancy of identification of formational origin probably was achieved.

The Los Angeles abrasion test, B grading (ASTM, 1965), was used as the basis for comparing the aggregate samples. The B grading test is performed using the standard Los Angeles abrasion drum with a single shelf, 11 steel spheres as the charge, 500 drum revolutions, and 5,000 gm of sample. The aggregate sample consists of 2,500 gm between 1 in. and  $\frac{3}{4}$  in. in size and 2,500 gm between  $\frac{3}{4}$  in. and  $\frac{1}{2}$  in. in size as determined by standard sieves with square openings. Following the test the samples were sieved over the No. 12 sieve and their loss was calculated as a percent of the original weight minus the weight retained on the No. 12 sieve in respect to the original weight.

Care was taken in advance of testing to insure that the entire sample was processed to obtain the correctly sized portion for testing. If more than 2,500 gm were obtained for each size grouping, the samples were split to allow a representative portion to be tested.

#### VARIATION IN LOS ANGELES ABRASION LOSS

Following laboratory testing, an analysis of variance (AOV) calculation was made of the quarry data. The Los Angeles abrasion values obtained for the eight divisions (A through H) of the quarry face were used for this purpose.

Analysis of variance tests are used to ascertain if significant differences are present between successive groups of data. In this case the AOV calculation was used to test for significant differences in the Los Angeles abrasion values for each horizontal rock unit across the quarry and also for differences between rock units from top to bottom in the quarry. Table C-2 gives the abrasion value results of the two samples taken at each location.

The AOV calculations, presented in a following section, show that only an insignificant difference in Los Angeles abrasion loss occurs among samples of each rock unit when sampled across the quarry. On the contrary, a significant difference does exist among the various units (A through H) when compared collectively using their respective abrasion values. This indicates that a significant change in Los Angeles abrasion accompanies the change in lithologic appearance as expressed by various bedding units of the

TABLE C-2

#### PERCENT LOSS, LOS ANGELES ABRASION, QUARRY SAMPLES

| TOP OF QUARRY |      |      |      |
|---------------|------|------|------|
| H             | 24.5 | 25.1 | 24.4 |
|               | 28.1 | 26.6 | 28.2 |
| G             | 27.4 | 28.2 | 25.3 |
|               | 28.1 | 28.8 | 27.2 |
| F             | 31.4 | 30.9 | 29.1 |
|               | 27.8 | 29.2 | 28.1 |
| E             | 36.3 | 35.5 | 33.0 |
|               | 37.0 | 32.0 | 36.9 |
| D             | 24.7 | 22.5 | 25.9 |
|               | 24.0 | 25.3 | 26.0 |
| C             | 20.3 | 30.7 | 34.0 |
|               | 24.6 | 28.2 | 26.7 |
| B             | 31.2 | 29.8 | 31.2 |
|               | 36.9 | 33.3 | 37.0 |
| A             | 36.2 | 37.6 | 33.9 |
|               | 37.7 | 33.2 | 34.5 |

#### BASE OF QUARRY

quarry. This change in lithology, of course, was the basis for dividing the quarry face into the eight horizontal units described previously.

#### DURABILITY OF ROCK FORMATIONS DURING PROCESSING

As previously stated under "Quarry and Mill Selection," it was possible to divide the in-progress samples into the three basic units, the Harrodsburg (A, B, and C), the Salem (D and E), and the St. Louis formations (F, G, and H). This was done on the basis of the unique combination of lithologic features, discussed previously, that each stratigraphic unit possessed.

To ascertain what if any changes occurred during the processing of the aggregate, samples were taken at several stages during the operation. Three locations were used initially: (1) directly after primary crushing at the base of the primary jaw crusher, (2) at the base of the surge pile that precedes secondary crushing, and (3) after secondary crushing and sieving where the finished product has been prepared.

For the first location, the base of the primary crusher, only two samples were obtained. This sampling operation was deemed to be a dangerous maneuver and was discouraged by the plant superintendent. It entailed sampling below the primary jaw crusher, which is dangerous because rocks fly about during dumping and crushing.

The bulk of the samples were obtained at the other two locations—the base of the surge pile and after the final sizing of the aggregate. Therefore, the beginning point for rock processing that could be measured with any degree of certainty and safety was the base of the surge pile.

In choosing the surge pile base as the beginning point it was recognized that some mixing of the rock particles

that could not be determined by testing had occurred prior to this point. Mixing during blasting, transportation, primary crushing, and surging to form the pile may have been significant, but this portion had to be neglected.

The samples taken at the surge pile base (designated P for progress sample) were divided into three formational groups—Harrodsburg, Salem, and St. Louis. The percentage of each constituent group was ascertained on a weight basis.

The samples taken after the final sieving consisted of the two sizes of aggregates being made on the particular day of sampling. Fortunately, Ind. No. 9 and No. 11 were being made on all the days that sampling was carried out. These were also divided according to their formational group and the weight percentage of each was determined.

An AOV test was applied in two different ways to determine what if any changes had occurred during processing. In the first analysis (analysis A), using one formation at a time, the percentage contributed by that formation to one sample group was compared to its contribution to the other groups. For example, the percentage of Harrodsburg in the P samples was compared to its percentage in the No. 9 and No. 11 size samples. Then the Salem and St. Louis formations were compared in the same manner. The basic data used in the AOV calculations in analysis A are given in Table C-3.

The results indicate a significant reduction in the percentage of Harrodsburg material between the P samples and the No. 9 and the No. 11 samples. However, no significant change occurred in the Salem and St. Louis percentages relative to the total variance. This suggests that the less durable Harrodsburg material decreased in percentage of representation in the sizes retained on screens during processing. The AOV calculations are presented in a subsequent section of this appendix.

In the second application of the analysis of variances (analysis B) the calculation was used to determine the contribution of the three formational units in the P samples, the No. 9 samples and the No. 11 samples. For

example, the percentage of Harrodsburg, Salem, and St. Louis fragments in the P samples was analyzed to see which predominated. The same was done in turn for the No. 9 and the No. 11 samples. The basic data for the AOV calculations in analysis B are given in Table C-4.

For the P samples, it was found that the Harrodsburg was the major percentage contributor, followed by the Salem and the St. Louis in that order. A statistically important difference is noted. For the No. 9 samples, the St. Louis is the major contributor, with Harrodsburg second and Salem last; again this order is statistically significant. In the No. 11 samples, the same order as in the P samples (Harrodsburg most abundant, St. Louis intermediate, followed by Salem) is recorded, but the order is not statistically significant. The AOV calculations also are presented in a subsequent section of this appendix.

These results suggest that the percentage of Harrodsburg decreased between the P and the No. 9 samples. The No. 11, being of a smaller size, maintained a higher percentage of the less durable Harrodsburg material, although no statistically significant value was obtained. Interestingly enough, the order of formational percentages in the P samples is not the same as in the quarry face. This suggests that mixing in the quarry, including blasting and handling prior to crushing, was not complete. A complete listing of mill samples, with abrasion values and formational percentages, is given in later sections of this appendix.

A further comparison of the aggregate processing data was made using a multiple regression and correlation analysis. This statistical analysis, explained in Chapter Two, is used to ascertain the contribution of several variables in determining the value of remaining variables.

In this analysis, the Los Angeles abrasion loss values of the P samples were compared to the relative amounts of the three formational units present in each sample. Both simple correlation and partial correlation analyses were made. The procedure was then repeated for the No. 9 samples. The No. 11 size, however, was too small to test using the B grading, Los Angeles abrasion, and these

TABLE C-3  
ANALYSIS OF VARIANCE DATA OF FORMATIONAL PERCENTAGES, ANALYSIS A

| SALEM FORMATION (%) |              |               | ST LOUIS FORMATION (%) |              |                | HARRODSBURG FORMATION (%) |              |                |
|---------------------|--------------|---------------|------------------------|--------------|----------------|---------------------------|--------------|----------------|
| P SAMPLES           | NO 9 SAMPLES | NO 11 SAMPLES | P SAMPLES              | NO 9 SAMPLES | NO. 11 SAMPLES | P SAMPLES                 | NO 9 SAMPLES | NO. 11 SAMPLES |
| 25.1                | 28.5         | 37.5          | 39.0                   | 38.5         | 46.4           | 35.9                      | 33.0         | 16.1           |
| 22.7                | 23.4         | 37.0          | 32.3                   | 30.9         | 22.8           | 45.0                      | 45.8         | 40.2           |
| 19.8                | 23.4         | 31.3          | 45.2                   | 38.8         | 37.3           | 35.0                      | 42.8         | 31.3           |
| 33.3                | 27.3         | 36.7          | 33.3                   | 32.0         | 28.3           | 33.3                      | 40.7         | 35.0           |
| 19.3                | 21.4         | 28.3          | 29.8                   | 44.5         | 30.4           | 50.8                      | 34.2         | 41.3           |
| 24.6                | 23.9         | 27.6          | 31.4                   | 46.8         | 31.0           | 44.0                      | 29.2         | 41.4           |
| 23.9                | 27.4         | 36.4          | 21.4                   | 36.9         | 23.6           | 54.7                      | 35.6         | 40.0           |
| 25.4                | 28.2         | 29.1          | 34.0                   | 63.6         | 34.5           | 40.7                      | 8.1          | 36.4           |
| 32.7                | 29.9         | 21.8          | 48.4                   | 57.7         | 50.9           | 19.0                      | 12.4         | 27.3           |
| 20.2                | 32.1         | 28.8          | 31.0                   | 35.8         | 36.5           | 48.8                      | 32.1         | 34.6           |
| 43.3                |              |               | 47.7                   |              |                | 8.8                       |              |                |
| 29.5                |              |               | 31.4                   |              |                | 39.1                      |              |                |

TABLE C-4

## ANALYSIS OF VARIANCE DATA OF FORMATIONAL PERCENTAGES, ANALYSIS B

| P SAMPLES |      |               |       | NO. 9 SAMPLES |        |      |               |       | NO. 11 SAMPLES |        |      |               |       |              |
|-----------|------|---------------|-------|---------------|--------|------|---------------|-------|----------------|--------|------|---------------|-------|--------------|
| SAMPLE    |      | LITHOLOGY (%) |       |               | SAMPLE |      | LITHOLOGY (%) |       |                | SAMPLE |      | LITHOLOGY (%) |       |              |
| NO.       | SIZE | ST LOUIS      | SALEM | HARRODS-BURG  | NO.    | SIZE | ST. LOUIS     | SALEM | HARRODS-BURG   | NO.    | SIZE | ST. LOUIS     | SALEM | HARRODS-BURG |
| 1         | P    | 39.0          | 25.1  | 35.9          | 7      | 9    | 38.5          | 28.5  | 33.0           | 3      | 11   | 46.4          | 37.5  | 16.1         |
| 4         | P    | 32.3          | 22.7  | 45.0          | 13     | 9    | 30.9          | 23.4  | 45.8           | 5      | 11   | 22.8          | 37.0  | 40.2         |
| 9         | P    | 45.2          | 19.8  | 35.0          | 16     | 9    | 33.8          | 23.4  | 42.8           | 8      | 11   | 37.3          | 31.3  | 31.3         |
| 10        | P    | 33.3          | 33.3  | 33.3          | 19     | 9    | 32.0          | 27.3  | 40.7           | 11     | 11   | 28.3          | 36.7  | 35.0         |
| 15        | P    | 29.8          | 19.3  | 50.8          | 22     | 9    | 44.5          | 21.4  | 34.2           | 14     | 11   | 30.4          | 28.3  | 41.3         |
| 18        | P    | 31.4          | 24.6  | 44.0          | 25     | 9    | 46.8          | 23.9  | 29.2           | 17     | 11   | 31.0          | 27.6  | 41.4         |
| 21        | P    | 21.4          | 23.9  | 54.7          | 28     | 9    | 36.9          | 27.4  | 35.6           | 20     | 11   | 23.6          | 36.4  | 40.0         |
| 24        | P    | 34.0          | 25.4  | 40.7          | 31     | 9    | 63.6          | 28.2  | 8.1            | 23     | 11   | 34.5          | 29.1  | 36.4         |
| 27        | P    | 48.4          | 32.7  | 19.0          | 33     | 9    | 57.7          | 29.2  | 12.4           | 26     | 11   | 50.9          | 21.8  | 27.3         |
| 30        | P    | 31.0          | 20.2  | 48.8          | 39     | 9    | 35.8          | 32.1  | 32.1           | 29     | 11   | 36.5          | 28.8  | 34.6         |
| 32        | P    | 47.7          | 43.4  | 8.8           |        |      |               |       |                |        |      |               |       |              |
| 34        | P    | 31.4          | 29.5  | 39.1          |        |      |               |       |                |        |      |               |       |              |

samples were not run. The simple correlation and partial correlation cluster diagrams are shown in Figure C-1.

For the P samples the simple correlation analysis indicates a strong negative relationship between the percentage of St. Louis and the percentage of Harrodsburg constituents present. This suggests that in a statistically significant number of samples a decrease in St. Louis percentage was matched by an increase in Harrodsburg percentage and *vice versa*. Inasmuch as the third contributing factor, the percentage of Salem, did not change (statistically) during this comparison, the simple situation of one constituent increasing independently and thereby decreasing the other two would not explain the findings.

The reasons suggested for this negative correlation between Harrodsburg and St. Louis are two in number. First, these units are at extreme positions in the quarry, with the Harrodsburg at the quarry bottom and the St. Louis at the top. Therefore, material coming from the quarry could well contain more Harrodsburg with less Salem and St. Louis material present, in that order, or indeed more St. Louis, with lesser amounts of Salem and Harrodsburg, respectively. The effect of blasting is such that the lower ledges are thrown farther from the quarry face than are the upper layers, which tend to drop more nearly straight down.

The second explanation may lie in the Harrodsburg material itself. It appeared during field investigations that when blasted the Harrodsburg broke into larger pieces on the average than did the other units. In the event that one of these larger pieces was transported to the jaw crusher, a considerable influx of rock from the Harrodsburg would end up in the subsequent sample. In the quarry itself there were nearly equal amounts of each formational unit, however.

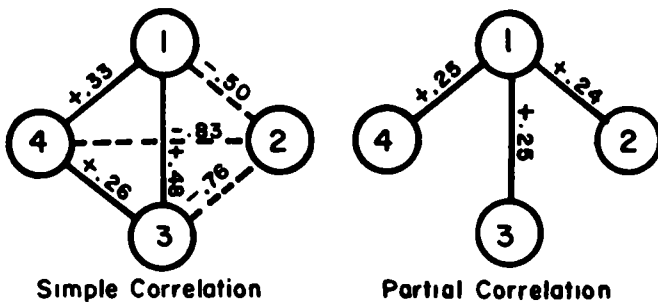
The strong negative correlation ( $-0.50$ ) between Los Angeles abrasion loss and Harrodsburg percentage merits some discussion. On the face of it, this suggests that as the percentage of Harrodsburg increases, the abrasion loss

decreases, or, indeed, that the Harrodsburg has a lower average Los Angeles abrasion loss than do the other contributors. This is not necessarily the case, as the average abrasion loss for Harrodsburg in the quarry is 32.0 percent as compared to 29.9 percent and 27.7 percent for the Salem and the St. Louis, respectively. However, the abrasion loss of the Harrodsburg may change drastically after initial processing and the weak material is removed. Yet it is doubtful that the Harrodsburg could have been beneficiated so drastically by primary crushing alone, so that this relationship between Los Angeles abrasion loss and percentage of Harrodsburg is not fully explainable.

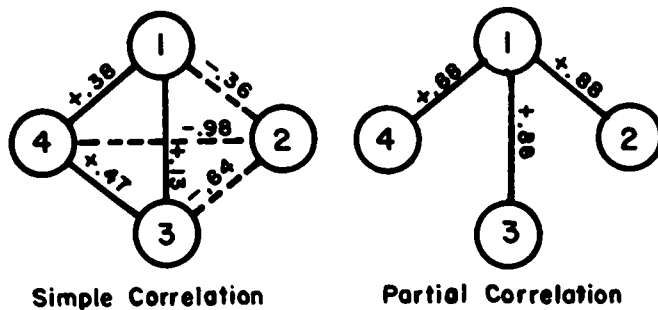
Referring to the No. 9 sample simple correlation analysis in Figure C-1, it can be observed that the negative correlation between Harrodsburg and St. Louis, which was prevalent in the P samples, has increased to  $-0.98$ . Processing appears to have accentuated the association of lesser amounts of Harrodsburg and greater amounts of St. Louis, and *vice versa*. This information coupled with previous suggestions that the Harrodsburg has decreased in percent contribution from the P samples to No. 9 samples (during processing), it appears that the Harrodsburg is removed most readily and that the St. Louis is most durable. In the P sample the difference in relative amounts is probably due to blasting and loading. This relationship has been modified by aggregate processing to form the No. 9 samples.

The negative correlation between Los Angeles abrasion loss and Harrodsburg percentage has decreased to  $-0.36$  from the  $-0.50$  level of the P samples. The answer for this relationship may lie in the fact that weaker material is selectively removed from the Harrodsburg, thus leaving a basically stronger material behind. This thesis could be tested by picking only Harrodsburg pieces from the No. 9 samples, running an abrasion test on them alone and comparing this value to the original in-quarry value. Time and testing restrictions did not allow for doing this.

Following the correlation of data, regression analysis



### IN-PROGRESS (P) SAMPLES



### NUMBER 9 SAMPLES

- Legend:**
1. Percent Loss, Los Angeles Abrasion.
  2. Percent Harrodsburg Formation.
  3. Percent Salem Formation.
  4. Percent St. Louis Formation.

Figure C-1 Cluster diagrams of correlation coefficients in aggregate processing study

was made of both P sample and No. 9 sample data. The two equations obtained were:

#### P Sample

$$LA = -511.61 + 5.34\% \text{ Harrod.} + 5.38\% \text{ St. Louis,} \\ \text{with } R^2 = 32.1\%$$

#### No. 9 Sample

$$LA = -1391.4 + 14.19\% \text{ St. Louis} + 14.13\% \text{ Harrod.} \\ + 14.24\% \text{ Salem, with } R^2 = 88.3\%$$

For the P sample, only 32.1% of the variation is accounted for by the three rock percentages, a rather poor situation. This shows that considerable variation occurs in

the system which is not accounted for by the various rock percentages. However, for the No. 9 sample, 88.3% of the variation in abrasion loss is accounted for by the rock percentages. This value is considerably better than for the P samples and it is useful as a predicting equation for the Los Angeles abrasion loss. To ascertain a Los Angeles abrasion loss for a No. 9 sample the equation can be used if the rock percentages are known. In this case, 88.3% of the possible variation is taken into account by the three rock percentages.

The poor regression values for the P samples, in contrast to excellent ones for the No. 9 samples, yielded an interesting situation. It suggests that for rocks of nearly uniform size (No. 9's) the variation is less than for a poorly sorted hodge-podge of sizes as in the P samples. Another possible explanation is that the rock percentages of the P samples were ascertained prior to crushing of the large cobble-size pieces that composed a considerable fraction of these samples. The Los Angeles abrasion test was run after crushing using the B grading size. The rock percentages in the B size may have differed substantially from the original percentages in the P sample. Several analyses were made of the crushed material after this problem was recognized and the findings indicated an important shift of percentages (up to 10%) occurred from the initial samples to the B gradations samples. The No. 9 sample, however, required no crushing to make the B grading and it was assumed that no change occurred in the rock percentage contributions

### DETAILED QUARRY DESCRIPTION AND ANALYSIS OF QUARRY SAMPLE DATA

A detailed description of the rock units sampled for physical testing is given in Table C-5. The relationship between the numbered samples collected for physical testing is given in Table C-6. Table C-7 gives the analysis of variance of abrasion losses for quarry face samples.

### DETAILED DATA—MILL AND STOCKPILE SAMPLES

Table C-8 gives the abrasion resistance and the proportions of the formational units in the mill and stockpile samples.

### ANALYSIS OF QUARRY AGGREGATE DURING PROCESSING

The analysis of variance of the mill samples, formation by formation, is given in Table C-9. Also, the analysis of variance of the mill samples according to individual size gradation is given in Table C-10.

TABLE C-5

DESCRIPTION OF ROCK UNITS SAMPLED FOR PHYSICAL TESTING,  
INDIANA QUARRY STUDY

| ROCK UNIT              | DESCRIPTION  | RANGE OF THICKNESS (FT)                  |
|------------------------|--|--|
| Overburden             | St. Louis limestone and Pleistocene till   | Not measured                             |
| St. Louis limestone    |  |  |
| H                      | Tan lithographic limestone grading upward through unit to bluish-gray dense limestone of coarser crystal size. Transition from lithographic to coarser limestone takes place within a bed. Locally contains minor chert.   | 3.0 to 3.8                               |
| G                      | Dark gray to tan, dense and brittle lithographic limestone that locally is faintly laminated and contains shaly streaks or thick lenses of shale. Gray dense limestone that weathers to tan. Grain size heterogeneous and grains consist of calcite crystals and fossil fragments. Locally rock contains chert or coarser replacement quartz, is laminated, and is capped by 1 or 2 in. of black shale.  |  |
| F                      | Rock similar to above, but lacks chert and laminations and is locally shaly at the base. Rock is similar to matrix of breccia described below. Grayish-tan lithographic or slightly coarser limestone breccia fragments in a matrix of greenish-gray soft argillaceous limestone. Breccia is variable in thickness and lenses laterally into lithographic limestone. Tan, dense, and wavyly laminated lithographic limestone topped by a shale parting.  | 3.4 to 4.4                               |
|                        | Range of thickness of quarried St. Louis   | <u>2.2 to 2.3</u><br><u>8.7 to 10.4</u>  |
| Salem limestone:       |  |  |
| E                      | Fossil fragmental limestone of light tan to light tannish-gray color. Basically a single bed composed primarily of fragmented and fossilized remains of echinoderms and bryozoans, all bound together by small calcite crystals. Fragments range in size from 0.1 to 1.0 mm, but chiefly are less than 0.5 mm. Unit is terminated at the base by thin shale and has local and irregular hazy carbonaceous streaks.   | 3.5 to 4.4                               |
| D                      | Fossil fragmental limestone of very light tannish-gray to light tan color. Beds of 2- to 4-ft thickness are composed of the fossil <i>Endothyra</i> and fragmented and fossilized echinoderms and bryozoans bound together by calcite crystals. Fragments average about 0.5 mm, are in greater abundance than in rock above, and are found in laminations and other sedimentary structures. Rock is locally cherty (silicified limestone) in lower third and especially in lowest ½ ft. Beds are separated by thin shales that pass laterally into stylolites. |  |
|                        | Range of thickness of quarried Salem   | <u>6.3 to 7.5</u><br><u>10.4 to 11.3</u> |
| Harrodsburg limestone: |  |  |
| C                      | Gray dense limestone in beds 0.4 to 0.8 ft thick. Rock is composed of fragmented and fossilized echinoderms and bryozoans averaging between 0.5 to 1.0 mm in size. Top ½ ft is argillaceous and shaly and unit is slightly cherty (silicified limestone).  | 3.5 to 3.7                               |
| B                      | Dark gray limestone very similar to unit C above except for dispersed argillaceous material in wavy streaks and for wavy shale partings.   | 3.0 to 4.0                               |
| A                      | Very dark gray limestone very similar to Unit B above except for a few nodules of chert (silicified limestone) and is very shaly in top ½ ft.  | <u>3.7 to 4.4</u>                        |
|                        | Range of thickness of quarried Harrodsburg   | <u>10.4 to 11.9</u>                      |
| All                    | Range of thickness of quarried rock  | <u>30.9 to 32.1</u>                      |

TABLE C-6  
RELATIONSHIP BETWEEN NUMBERED SAMPLES\* COLLECTED FOR PHYSICAL TESTING

| ROCK UNIT             | LOCATION 1 |                | LOCATION 2 |                | LOCATION 3 |                | LOCATION 4 |                |
|-----------------------|------------|----------------|------------|----------------|------------|----------------|------------|----------------|
|                       | SAMPLE NO  | THICKNESS (FT) | SAMPLE NO  | THICKNESS (FT) | SAMPLE NO. | THICKNESS (FT) | SAMPLE NO  | THICKNESS (FT) |
| St Louis limestone    |            |                |            |                |            |                |            |                |
| H                     | S65-RH1    | 3.0            | S65-RH2    | 3.5            | S65-RH3    | 3.0            | S66-RH8    | 3.8            |
| H                     |            |                | S65-RH5    | 3.5            | S65-RH6    | 3.0            |            |                |
| G                     | S65-RG1    | 3.4            | S65-RG2    | 4.4            | S65-RG3    | 4.2            | S66-RG8    | 4.3            |
| G                     | S65-RG4    | 3.4            | S65-RG5    | 4.4            | S65-RG6    | 4.2            |            |                |
| F                     | S65-RF1    | 2.3            | S65-RF2    | 2.2            | S65-RF3    | 2.3            | S66-RF8    | 2.3            |
| F                     | S65-RF4    | 2.3            | S65-RF5    | 2.2            | S65-RF6    | 2.3            |            |                |
| All                   |            | 8.7            |            | 10.1           |            | 9.5            |            | 10.4           |
| Salem limestone       |            |                |            |                |            |                |            |                |
| E                     | S65-RE1    | 4.1            | S65-RE2    | 3.5            | S65-RE3    | 3.5            | S66-RE8    | 4.4            |
| E                     | S65-RE4    | 4.1            | S65-RE5    | 3.5            | S65-RE6    | 3.5            |            |                |
| D                     | S65-RD1    | 6.3            | S65-RD2    | 7.5            | S65-RD3    | 7.0            | S66-RD8    | 6.9            |
| D                     | S65-RD4    | 6.3            | S65-RD5    | 7.5            | S65-RD6    | 7.0            |            |                |
| All                   |            | 10.4           |            | 11.0           |            | 10.5           |            | 11.3           |
| Harrodsburg limestone |            |                |            |                |            |                |            |                |
| C                     | S65-RC1    | 3.5            | S65-RC2    | 3.5            | S65-RC3    | 3.6            | S66-RC8    | 3.7            |
| C                     | S65-RC4    | 3.5            | S65-RC5    | 3.5            | S65-RC6    | 3.6            |            |                |
| B                     | S65-RB1    | 4.0            | S65-RB2    | 3.0            | S65-RB3    | 3.0            | S66-RB8    | 3.0            |
| B                     | S65-RB4    | 4.0            | S65-RB5    | 3.0            | S65-RB6    | 2.0            |            |                |
| A                     | S65-RA1    | 4.4            | S65-RA2    | 4.4            | S65-RA3    | 4.3            | S66-RA8    | 3.7            |
| A                     | S65-RA4    | 4.4            | S65-RA5    | 4.4            | S65-RA6    | 4.3            |            |                |
| All                   |            | 11.9           |            | 10.9           |            | 10.9           |            | 10.4           |
| Quarry                |            | 31.0           |            | 32.0           |            | 30.9           |            | 32.1           |

\* Key Example S65-RH1, S = sampled by Smith, 65 = 1965, year sampled, R = quarry designation, H = rock unit H, 1 = first sample taken in rock unit

TABLE C-8  
ABRASION RESISTANCE AND PROPORTIONS  
OF FORMATIONAL UNIT IN MILL  
AND STOCKPILE SAMPLES

| SAMPLE NO | LOSS, LOS ANGELES ABRASION, B GRADING (%) | FORMATIONAL COMPOSITION (% WT) |       |             | SAMPLE NO | LOSS, LOS ANGELES ABRASION, B GRADING (%) | FORMATIONAL COMPOSITION (% WT) |       |             |
|-----------|---|--------------------------------|-------|-------------|-----------|---|--------------------------------|-------|-------------|
|           |   | ST LOUIS                       | SALEM | HARRODSBURG |           |   | ST LOUIS                       | SALEM | HARRODSBURG |
| ML 1-P    | 25.4                                      | 39.0                           | 25.1  | 35.9        | ML 31-9   | 26.8                                      | 63.6                           | 28.2  | 8.1         |
| ML 4-P    | 26.6                                      | 32.3                           | 22.7  | 45.0        | ML 33-9   | 28.7                                      | 57.7                           | 29.9  | 12.4        |
| ML 9-P    | 26.8                                      | 45.2                           | 19.8  | 35.0        | ML 29-9   | —   | 35.8                           | 32.1  | 32.1        |
| ML 10-P   | 25.8                                      | 33.3                           | 33.3  | 33.3        | ML 3-11   | —   | 46.4                           | 37.5  | 16.1        |
| ML 15-P   | 27.3                                      | 29.8                           | 19.3  | 50.8        | ML 5-11   | —   | 22.8                           | 37.0  | 40.2        |
| ML 18-P   | 26.2                                      | 31.4                           | 23.6  | 44.0        | ML 8-11   | —   | 37.3                           | 31.3  | 31.3        |
| ML 21-P   | 28.0                                      | 21.4                           | 24.6  | 44.0        | ML 11-11  | —   | 28.3                           | 36.7  | 35.0        |
| ML 21-P   | 28.0                                      | 21.4                           | 23.9  | 54.7        | ML 14-11  | —   | 30.4                           | 28.3  | 41.3        |
| ML 24-P   | 27.4                                      | 34.0                           | 25.4  | 40.7        | ML 17-11  | —   | 31.0                           | 27.6  | 41.4        |
| ML 27-P   | 29.9                                      | 48.4                           | 32.7  | 19.0        | ML 20-11  | —   | 23.6                           | 36.4  | 40.0        |
| ML 30-P   | 22.6                                      | 31.0                           | 20.2  | 48.8        | ML 23-11  | —   | 34.5                           | 29.1  | 36.4        |
| ML 32-P   | 29.0                                      | 47.7                           | 43.4  | 8.8         | ML 26-11  | —   | 50.9                           | 21.8  | 27.3        |
| ML 34-P   | 27.5                                      | 31.4                           | 29.5  | 39.1        | ML 29-11  | —   | 36.5                           | 28.8  | 34.6        |
| ML 7-9    | 27.0                                      | 38.5                           | 28.5  | 33.0        | ML 35-x   | —   | 34.0                           | 38.4  | 27.6        |
| ML 13-9   | 26.5                                      | 30.9                           | 23.4  | 45.8        | ML 36-x   | —   | 29.1                           | 67.9  | 3.0         |
| ML 16-9   | 26.8                                      | 33.8                           | 23.4  | 42.8        | ST 1-53   | —   | 21.7                           | 51.1  | 27.2        |
| ML 19-9   | —   | 32.0                           | 27.3  | 40.7        | ST 2-11   | —   | 31.8                           | 27.3  | 40.9        |
| ML 22-9   | 27.9                                      | 44.5                           | 21.4  | 34.2        | ST 2-11   | —   | 28.3                           | 32.6  | 39.1        |
| ML 25-9   | 25.3                                      | 46.8                           | 23.9  | 29.2        | ST 3-4    | —   | 40.2                           | 32.3  | 27.6        |
| ML 28-9   | 24.7                                      | 36.9                           | 27.4  | 35.6        | ST 4-5    | —   | 39.0                           | 39.0  | 22.0        |



TABLE C-7  
ANALYSIS OF VARIANCE OF ABRASION LOSSES FOR QUARRY FACE SAMPLES

| ROCK UNIT   | LOCATION 1   | LOCATION 2       | LOCATION 3 | $x_j$ | $\bar{x}_j$ |
|-------------|--------------|------------------|------------|-------|-------------|
| H           | R<br>24.5    | $x_{.j}$<br>25.1 | 24.4       | 156.9 | 26.1        |
|             | 28.1 * =52.6 | 26.6 =51.7       | 28.3 =52.6 |       |             |
| G           | 27.4         | 28.2             | 25.3       | 165.0 | 27.5        |
|             | 28.1 =55.5   | 28.8 =57.0       | 27.2 =52.5 |       |             |
| F           | 31.4         | 30.9             | 29.1       | 176.5 | 29.4        |
|             | 27.8 =59.2   | 29.2 =60.1       | 28.1 =57.8 |       |             |
| E           | 36.3         | 35.5             | 33.0       | 210.7 | 35.1        |
|             | 37.0 =73.3   | 32.0 =67.5       | 36.9 =69.9 |       |             |
| D           | 24.7         | 22.5             | 25.9       | 148.4 | 24.7        |
|             | 24.0 =48.7   | 25.3 =47.8       | 26.0 =51.9 |       |             |
| C           | 20.3         | 30.7             | 34.0       | 164.5 | 27.4        |
|             | 24.6 =44.9   | 28.2 =58.9       | 26.7 =60.7 |       |             |
| B           | 31.2         | 29.8             | 31.2       | 199.4 | 33.2        |
|             | 26.9 =68.1   | 33.3 =63.1       | 37.0 =68.2 |       |             |
| A           | 36.2         | 37.6             | 33.9       | 213.1 | 35.5        |
|             | 37.7 =73.9   | 33.2 =70.8       | 34.5 =68.4 |       |             |
| Harrodsburg | x            | 476.2            | 476.9      | 481.4 | x =1434.5   |

\* Missing sample L A value calculated by standard procedure, Cochran L. Cox, 2nd Ed, p 80

|                          | ss  | df           | ms                       | F                          | H              |
|--------------------------|---|--------------|--------------------------|----------------------------|----------------|
| Col means ( $S_c$ )      | $\frac{\sum x_i^2}{r} - \frac{x^2}{rcn}$  | $c-1$        | $\frac{S_c}{c-1}$        | $F_{(c)(r)} = \frac{1}{4}$ | $\sigma^2 = 0$ |
| Row means ( $S_r$ )      | $\frac{\sum x_j^2}{rn} - \frac{x^2}{rcn}$   | $r-1$        | $\frac{S_r}{r-1}$        | $F_{2,r} = \frac{2}{4}$    | $r^2 = 0$      |
| Interaction              | $S_i - S_c - S_r = S_i$   | $(c-1)(r-1)$ | $\frac{S_i}{(c-1)(r-1)}$ | $F_{3,i} = \frac{3}{4}$    | $i^2 = 0$      |
| Subtotal ( $S_s$ )       | $\frac{\sum \sum x_{ij}^2}{n} - \frac{x^2}{rcn}$  | $rc-1$       |                          |                            |                |
| Within $S_s - S_r = S_w$ |   | $rc(n-1)$    | $\frac{S_w}{rc(n-1)}$    |                            |                |
| Total ( $S_t$ )          | $\sum \sum x_{ij}^2 - \frac{x^2}{rcn}$  | $rcn-1$      |                          |                            |                |
| Columns (i)              | $\frac{\sum x_i^2}{n} - \frac{x^2}{rcn} = \frac{685,946.01}{16} - \frac{2,057,790.25}{48} = 42871.63 - 42870.63 = 1.00$ |              |                          |                            |                |
| Rows (j)                 | $\frac{\sum x_j^2}{cn} - \frac{x^2}{rcn} = \frac{261,644.13}{6} - 42870.63 = 43607.36 - 42870.63 = 736.73$              |              |                          |                            |                |
| Subtotal                 | $\frac{\sum x_j^2}{r} - \frac{x^2}{rcn} = \frac{87,438.27}{2} - 42870.63 = 43719.14 - 42870.63 = 848.51$                |              |                          |                            |                |

Interaction = 110.78

Within = 973.09 - 848.51 = 124.58

$\sum \sum x_{ij}^2 - \frac{x^2}{rcn} = 43843.72 - 43870.63 = 973.09$

|                |        |    |        |                     |      |                        |
|----------------|--------|----|--------|---------------------|------|------------------------|
| Col. means     | 1.00   | 2  | 0.5    | 0.5/5.19 = 0.096    | 3.40 | $\sigma^2 = 0$ (true)  |
| Row means      | 736.73 | 7  | 105.25 | 105.25/5.19 = 20.28 | 2.42 | $\sigma^2 = 0$ (false) |
| Interaction    | 110.78 | 14 | 7.91   | 7.91/5.19 = 1.524   | 2.13 | $\sigma^2 = 0$ (true)  |
| Subtotal       | 848.51 | 23 |        |                     |      |                        |
| Within (error) | 124.58 | 24 | 5.19   |                     |      |                        |
| Total          | 973.09 |    |        |                     |      |                        |

TABLE C-9  
ANALYSIS OF VARIANCE OF MILL SAMPLES,  
BY FORMATION, INDIANA QUARRY AGGREGATE  
DURING PROCESSING

| PROPORTION OF ST LOUIS FORMATION<br>IN THE MILL SAMPLES (%) |                       |                       |
|---|-----------------------|-----------------------|
| TYPE P<br>SAMPLE  | TYPE 9<br>SAMPLE      | TYPE 11<br>SAMPLE     |
| 39 0  | 38 5                  | 46 4                  |
| 32 3  | 30.9                  | 22 8                  |
| 45 2  | 33 8                  | 37.3                  |
| 33 3  | 32 0                  | 28 3                  |
| 29 8  | 44 5                  | 30.4                  |
| 31 4  | 46 8                  | 31 0                  |
| 21 4  | 36 9                  | 23 6                  |
| 34 0  | 63 6                  | 34.5                  |
| 48 4  | 57.7                  | 50 9                  |
| 31 0  | 35 8                  | 36.5                  |
| 47 7  |                       |                       |
| 31 4  |                       |                       |
| $x_i = 424.9$   | $420.5$               | $341.7$               |
| $x_i^2 = 180540.01$   | $176820.25$           | $116758.89$           |
| $\frac{12}{15045.00}$                                       | $\frac{10}{17682.02}$ | $\frac{10}{11675.89}$ |
| $\Sigma x_{ij}^2 = 46980.89$                                |                       |                       |
| $\frac{\Sigma x_i^2}{ni} = 44402.92$                        |                       |                       |
| ss  | df                    | MS                    |
| $44402.92 - 44037.70 = 365.22$                              | 2                     | 182.61                |
| $= 2577.97$   | 29                    | 101.49                |
| $46980.89 - 44037.70 = 2943.19$                             |                       |                       |

| PROPORTION OF SALEM FORMATION<br>IN THE MILL SAMPLES (%) |                      |                      |
|--|----------------------|----------------------|
| TYPE P<br>SAMPLE   | TYPE 9<br>SAMPLE     | TYPE 11<br>SAMPLE    |
| 25 1   | 28 5                 | 37 5                 |
| 22 7   | 23 4                 | 37 0                 |
| 19 8   | 23 4                 | 31 3                 |
| 33 3   | 27.3                 | 36 7                 |
| 19 3   | 21 4                 | 28 3                 |
| 24 6   | 23 9                 | 27 6                 |
| 23.9   | 27 4                 | 36.4                 |
| 25 4   | 28 2                 | 29 1                 |
| 32 7   | 29 9                 | 21.8                 |
| 30 2   | 32 1                 | 28 8                 |
| 43 4   |                      |                      |
| 29 5   |                      |                      |
| $x_i = 319.9$  | $265.5$              | $314.5$              |
| $x_i^2 = 102336.01$                                      | $70490.25$           | $98910.25$           |
| $\frac{12}{8528.00}$                                     | $\frac{10}{7049.02}$ | $\frac{10}{9891.02}$ |
| $\Sigma x_{ij}^2 = 26364.57$                             |                      |                      |
| $\frac{\Sigma x_i^2}{ni} = 25468.06$                     |                      |                      |
| ss   | df                   | MS                   |
| $25468.06 - 25306.38 = 161.68$                           | 2                    | 80.59                |
| $= 896.51$   | 29                   | 30.91                |
| $26364.57 - 25306.38 = 1057.99$                          | 31                   |                      |

| PROPORTION OF HARRODSBURG FORMATION<br>IN THE MILL SAMPLES (%) |                      |                       |
|--|----------------------|-----------------------|
| TYPE P<br>SAMPLE   | TYPE 9<br>SAMPLE     | TYPE 11<br>SAMPLE     |
| 35 9   | 33.0                 | 16 1                  |
| 45 0   | 45 8                 | 40.2                  |
| 35 0   | 42 8                 | 31.3                  |
| 33 3   | 40 7                 | 35.0                  |
| 50 8   | 34.2                 | 41.3                  |
| 44 0   | 29 2                 | 41.4                  |
| 54 7   | 35.6                 | 40 0                  |
| 40 7   | 8.1                  | 36 4                  |
| 19.0   | 12.4                 | 27.3                  |
| 48 8   | 32 1                 | 34.6                  |
| 8 8  |                      |                       |
| 39.1   |                      |                       |
| $x_i = 455.8$  | $313.9$              | $343.6$               |
| $x_i^2 = 207753.64$  | $98533.21$           | $118060.96$           |
| $\frac{12}{17312.80}$  | $\frac{10}{9853.32}$ | $\frac{10}{11806.10}$ |
| $\Sigma x_{ij}^2 = 42793.00$                                   |                      |                       |
| $\frac{\Sigma x_i^2}{ni} = 38972.22$                           |                      |                       |
| ss   | df                   | MS                    |
| $38972.22 - 35607.40 = 3364.82$                                | 2                    | 1682.41               |
| $42743.00 - 35607.40 = 7135.60$                                | 31                   | 133.41                |
| $= 3770.78$  | 29                   | 130.03                |

TABLE C-10  
ANALYSIS OF VARIANCE OF MILL SAMPLES,  
BY INDIVIDUAL SIZE GRADATION, INDIANA  
QUARRY AGGREGATE DURING PROCESSING

| IN-PROGRESS (P) SAMPLES (%)   |  |           |                                |                    |
|---|--|-----------|--------------------------------|--------------------|
| SAMPLE  | ST.  |           | HARRODS-                       |                    |
|   | LOUIS  | SALEM     | BURG                           |                    |
| 1-P   | 39.0   | 25.1      | 35.9                           |                    |
| 4-P   | 32.3   | 22.7      | 45.0                           |                    |
| 9-P   | 45.2   | 19.8      | 35.0                           |                    |
| 10-P  | 33.3   | 33.3      | 33.3                           |                    |
| 15-P  | 29.8   | 19.3      | 50.8                           |                    |
| 18-P  | 31.4   | 24.6      | 44.0                           |                    |
| 21-P  | 21.4   | 23.9      | 54.7                           |                    |
| 24-P  | 34.0   | 25.4      | 40.7                           |                    |
| 27-P  | 48.4   | 32.7      | 19.0                           |                    |
| 30-P  | 31.0   | 20.2      | 48.8                           |                    |
| 32-P  | 47.2   | 43.4      | 8.8                            |                    |
| 34-P  | 31.4   | 29.5      | 39.1                           |                    |
| H: $\sigma_e^2 = 0$   |  |           |                                |                    |
| $x_j =$   | 424.9  | 319.9     | 455.1                          | $x = 1199.9$       |
| $x_j^2 =$   | 180540.01  | 102336.01 | 207116.01                      | $x^2 = 1439760.01$ |
| $\Sigma \Sigma x_{ij}^2 = 44001.99$ $\Sigma x_{ij}^2 = 489992.03$               |  |           |                                |                    |
| Col.  | $\frac{\Sigma x_j^2}{r} - \frac{x^2}{rc} = \frac{489992.03}{12} - \frac{1439760.01}{36} = 839.6$ |           |                                |                    |
| Residue = $S_r - S_c = S_r = 3169.4$  |  |           |                                |                    |
| Total = $\Sigma \Sigma x_{ij}^2 - \frac{x^2}{rc} = 44001.99 - 39993.0 = 4009.0$ |  |           |                                |                    |
| ss  | df   | MS        | $F_{calc}$                     | $F_{tab}$          |
| 839.6   | 2  | 419.8     | 4.37                           | 3.32 (95%)         |
| 3169.4  | 33   | 96.04     | Sign. 95%                      |                    |
| 4009.0  |  |           | $\therefore \sigma_e^2 \neq 0$ |                    |

| NO 9 SAMPLES (%)  |   |        |                                |                           |
|---|---|--------|--------------------------------|---------------------------|
| SAMPLE  | ST.   |        | HARRODS-                       |                           |
|   | LOUIS   | SALEM  | BURG                           |                           |
| 7-9   | 38.5  | 28.5   | 33.0                           |                           |
| 13-9  | 30.9  | 23.4   | 45.8                           |                           |
| 16-9  | 33.8  | 23.4   | 42.8                           |                           |
| 19-9  | 32.0  | 27.3   | 40.7                           |                           |
| 22-9  | 44.5  | 21.4   | 34.2                           |                           |
| 25-9  | 46.8  | 23.9   | 29.2                           |                           |
| 28-9  | 36.9  | 27.4   | 35.6                           |                           |
| 31-9  | 63.6  | 28.2   | 8.1                            |                           |
| 33-9  | 57.7  | 29.9   | 12.4                           |                           |
| 39-9  | 35.8  | 32.1   | 32.1                           |                           |
| H: $\sigma_e^2 = 0$   |   |        |                                |                           |
| $x_j =$   | 420.6   | 265.5  | 313.9                          | $x = 1000.0$              |
|   |   |        |                                | $x^2 = 1000000.0$         |
|   |   |        |                                | $\frac{x^2}{n} = 3333.33$ |
| $\Sigma \Sigma x_{ij}^2 = 37158.13$ $\Sigma x_{ij}^2 = 345927.82$                 |   |        |                                |                           |
| Col.  | $\frac{\Sigma x_j^2}{r} - \frac{x^2}{rc} = 34592.78 - 33333.33 = 1259.45$ |        |                                |                           |
| Residue = $S_r - S_c = S_r = 2565.35$   |   |        |                                |                           |
| Total = $\Sigma \Sigma x_{ij}^2 - \frac{x^2}{rc} = 37158.13 - 33333.33 = 3824.80$ |   |        |                                |                           |
| ss  | df  | MS     | $F_{calc}$                     | $F_{tab}$                 |
| 1259.45   | 2   | 629.72 | 6.63                           | 3.32 (95%)                |
| 2565.35   | 27  | 95.01  | Sign. 95%                      |                           |
| 3824.80   |   |        | $\therefore \sigma_e^2 \neq 0$ |                           |

| NO. 11 SAMPLES (%)  |   |       |                             |                            |
|---|---|-------|-----------------------------|----------------------------|
| SAMPLE  | ST  |       | HARRODS-                    |                            |
|   | LOUIS   | SALEM | BURG                        |                            |
| 3-11  | 46.4  | 37.5  | 16.1                        |                            |
| 5-11  | 22.8  | 37.0  | 40.2                        |                            |
| 8-11  | 37.3  | 31.3  | 31.3                        |                            |
| 11-11   | 28.3  | 36.7  | 35.0                        |                            |
| 14-11   | 30.4  | 28.3  | 41.3                        |                            |
| 17-11   | 31.0  | 27.6  | 41.4                        |                            |
| 20-11   | 23.6  | 36.4  | 40.0                        |                            |
| 23-11   | 34.5  | 29.1  | 36.4                        |                            |
| 26-11   | 50.9  | 21.8  | 27.3                        |                            |
| 29-11   | 36.5  | 28.8  | 34.6                        |                            |
| H: $\sigma_e^2 = 0$   |   |       |                             |                            |
| $x_j =$   | 341.7   | 314.5 | 343.6                       | $x = 999.8$                |
|   |   |       |                             | $x^2 = 999600.04$          |
|   |   |       |                             | $\frac{x^2}{n} = 33320.00$ |
| $\Sigma \Sigma x_{ij}^2 = 34928.34$ $\Sigma x_{ij}^2 = 333730.10$                 |   |       |                             |                            |
| Col.  | $\frac{\Sigma x_j^2}{r} - \frac{x^2}{rc} = 33373.01 - 33320.00 = 53.10$ |       |                             |                            |
| Residue = $S_r - S_c = S_r = 1555.33$   |   |       |                             |                            |
| Total = $\Sigma \Sigma x_{ij}^2 - \frac{x^2}{rc} = 34928.34 - 33320.00 = 1608.34$ |   |       |                             |                            |
| ss  | df  | MS    | $F_{calc}$                  | $F_{tab}$                  |
| 53.0  | 2   | 26.51 | 0.46                        | 3.32 (95%)                 |
| 1555.33   | 27  | 57.60 | Not sign.                   |                            |
|   |   |       | $\therefore \sigma_e^2 = 0$ |                            |

## APPENDIX D

## DATA COLLECTED DURING PHASE I

| DESIGNATION | DESCRIPTION  | L A<br>VALUE,<br>500<br>CYCLES | ABSORP-<br>TION<br>(%)         | BULK<br>SP G.<br>SAT. S D.     | SULFATE<br>SOUND-<br>NESS<br>(%) | FREEZE-<br>THAW<br>RATIO | USE                           | GENERAL<br>PERFORM-<br>ANCE                    |
|-------------|--|--------------------------------|--------------------------------|--------------------------------|----------------------------------|--------------------------|-------------------------------|--|
| Alaska 1    | Alluvium, reworked glacial outwash mixture of igneous and metamorphic schists                                | 18.5                           | Coarse<br>0.26<br>Fine<br>1.01 | Coarse<br>2.78<br>Fine<br>2.63 | —                                | 0.04                     | Concrete and aggregate borrow | Very good                                      |
| Alaska 2    | Bedrock; micaceous chlorite schist   | 42-52                          | 1.08                           | 2.65                           | 2                                | 0.04                     | Subbase embankment            | Poor; degrades                                 |
| Alaska 3    | Precambrian schist; washed alluvium composed of siliceous micaceous schist with some quartz, dredge tailings | 46                             | 1.2                            | 2.65                           | 1.21                             | —                        | Crushed aggregate base        | Degrades, minus 200 increases 2.5% of original |

| DESIGNATION | ROCK<br>TYPE     | DESCRIPTION  | L.A VALUE,<br>500 CYCLES | SAND<br>EQUIVALENT | INTENDED USE  |
|-------------|------------------|--|--------------------------|--------------------|---|
| Arizona 1   | Quartzite gravel | Extremely hard; often breaks with conchoidal fracture                                    | 20%                      | 28                 | 4-in thick aggregate base, ¾-in. open-graded specifications   |
| Arizona 2   | Andesite gravel  |  | —                        | —                  | —   |
| Arizona 3   | Basalt gravel    | Somewhat weathered Tertiary basalt   | C grading<br>25-27%      | 44                 | Open-graded asphaltic concrete in two 2-in. lifts   |
| Arizona 4   | Scoria           | Intermediate between dense basalt and porous cinders                                     | C grading<br>29%         | 70                 | ¾-in open-graded base 4 in. thick   |
| Arizona 5   | Volcanic cinder  | From late Tertiary cinder cones. Cinders are red and contain few basalt fragments        | C grading<br>38%         | Variable<br>9-89   | Aggregate base placed in 4-in. lifts by pneumatic-tired rollers   |
| Arizona 6   | Granite gravel   | Precambrian intrusive  | C grading<br>24%         | 76                 | Aggregate base crushed to 3-in open-graded specifications   |
| Arizona 7   | Diabase          | Occurs as sills or dikes and is often weathered to exfoliated boulders and a coarse sand | C grading<br>22%         | —                  | Select material of 3-in minus size under a 4-in base-course and 2.5-in. asphaltic concrete pavement           |
| Arizona 8   | Tuff             | Late Tertiary age, poorly cemented waterlaid volcanic ash                                | —                        | —                  | Select material and imported borrow. Placed in 3- to 4-in. lifts and compacted with grid or pneumatic rollers |
| Arizona 9   | Limestone        | Hard crystalline Jurassic age limestone  | C grading<br>20%         | —                  | ¾-in open-graded aggregate base course 4 in. thick  |

| DESIGNATION                           | TYPE OF MATERIAL | PETROGRAPHIC DESCRIPTION   | REMARKS   |
|---------------------------------------|------------------|--|---|
| Corps 1<br>(Corps of Eng., Vicksburg) | Gravel           | Composed of crushed conglomerate plus limestone, coarse-grained granites and sandstones, vein quartz, schists, phyllites, and some basic igneous rocks | Fines develop repeatedly when stockpiled, hence the gravel is an obvious degrader. Montmorillonite clay in the matrix of the conglomerate is thought to cause the problem |

| DESIGNATION | DESCRIPTION OF GRAVEL  | L. A. VALUE, 500 CYCLES | SPECIFIC GRAVITY                         | ABSORPTION (%) | SULFATE SOUNDNESS      | SAND EQUIVALENT | DURABILITY FACTOR |      | R VALUE |
|-------------|--|-------------------------|--|----------------|------------------------|-----------------|-------------------|------|---------|
|             |  |                         |  |                |                        |                 | COARSE            | FINE |         |
| Cal. 1      | Composed of sandstone, meta-sandstone, chert, quartzite, vein quartz, plus meta-volcanics and ultrabasic schists               | 30.8                    | —  | —              | Occasionally 10%       | 42              | 48                | 41   | 80      |
| Cal. 2      | Composed of hornblende, andesite, basalt, vesicular basalt, and obsidian   | 24.4                    | S.S.D. 2.69                              | 1.5            | 4.3                    | —               | —                 | —    | —       |
| Cal. 3      | Composed mostly of quartz, some metamorphics, volcanics, metamorphosed sandstone, and sandstone                                | 36.6                    | O.D. 2.68                                | —              | 0.5 avg                | 56              | 87                | 89   | —       |
| Cal. 4      | Composed of andesite, granite, volcanic sandstone, andesite tuff, meta-volcanic basalt   | 36.2                    | S.S.D. 2.59                              | 2.2            | 6.0 avg.               | —               | —                 | 75   | —       |
| Cal. 5      | Composed mostly of sandstone, with quartzite, quartz, chert, and igneous rocks   | 20.0                    | No. 4 2.74 (O.D.)<br>No. 4 2.69 (S.S.D.) | 1.2            | 1.4 avg.               | 40              | 59                | 66   | 82      |
| Cal. 6      | Composed of sandstone, granite, ultrabasics, meta-volcanics, quartzite, and shale  | 26.8                    | No. 4 2.63 (O.D.)<br>No. 4 2.46 (S.S.D.) | 2.8            | 5.0 avg<br>14.7% shale | 68              | 50                | 63   | —       |
| Cal. 7      | Composed of granitic rocks, gneiss, schist, meta-sandstone, meta-volcanics, quartz, and limestone                              | 31.0                    | —  | —              | —                      | 47              | 67                | 77   | —       |
| Cal. 8      | Composed of granitic rocks, volcanics, anorthosite, and gneiss   | —                       | —  | —              | Occasionally 10%       | 30              | 65                | 66   | 79      |
| Cal. 9      | Composed of leuco-granite, gneiss, meta-volcanics, quartz, porphyritic granite, gneissic granite, mica schist, quartz diorite  | —                       | —  | —              | —                      | 72              | 76                | 80   | —       |
| Cal. 10     | Composed mostly of granitic rocks, with basalt, schist, quartzite, and rhyolite (calcite coating on most of sample)            | 26.6                    | No. 4 2.63 (O.D.)<br>No. 4 2.56 (S.S.D.) | 0.8            | 2.8 avg                | 43              | 82                | 70   | —       |
| Cal. 11     | Composed of granitic rocks, quartz, volcanics and meta-volcanics, schists, quartzite, sandstone, gabbro, ultrabasics, hornfels | —                       | —  | —              | —                      | 48              | 74                | 79   | —       |
| Cal. 12     | Composed of volcanic (mostly andesite with some basalts and rhyolite) granitics, siltstone, and sandstone                      | —                       | —  | —              | Occasionally 10%       | —               | 78                | 79   | —       |

| DESIGNATION | DESCRIPTION OF GRAVEL  | L A<br>VALUE,<br>500<br>CYCLES | SP GR,<br>OVEN DRIED       | ABSORP-<br>TION<br>(%) | SULFATE<br>SOUND-<br>NESS<br>(WEIGHTED EQUIVA-<br>AVG %) | SAND<br>LENT | PLASTICITY<br>LL-PL-PI | DURABILITY<br>FACTOR |      | R<br>VALUE |
|-------------|--|--------------------------------|----------------------------|------------------------|--|--------------|------------------------|----------------------|------|------------|
|             |  |                                |                            |                        |  |              |                        | COARSE               | FINE |            |
| Cal. 13     | Coarse—ultrabasics, fine—ultrabasics and traces of quartz  | 21.8                           | <No. 4 2.70<br>>No. 4 2.71 | 3.5                    | 41.4   | 24           | 32-21-11               | 20                   | 22   | 79         |
| Cal. 14     | Coarse—ultrabasics; fine—ultrabasics, serpentinized ultrabasics, quartz  | 22.8                           | <No. 4 2.78<br>>No. 4 2.75 | 2.3                    | 17.7   | 34           | 28-21-7                | 42                   | 21   | 75         |
| Cal. 15     | Coarse—sandstone; fine—sandstone, quartz   | 33.1                           | <No. 4 2.70<br>>No. 4 2.49 | 3.0                    | 50.4   | 17           | 22-16-6                | 21                   | 22   | 58         |
| Cal. 16     | Coarse—ultrabasics; fine—ultrabasics, serpentine, quartz, trace of calcite   | 25.6                           | <No. 4 2.87<br>>No. 4 2.84 | 1.4                    | 25.9   | 41           | 25-20-5                | 35                   | 30   | 80         |
| Cal. 17     | Coarse—volcanics, ultrabasics, sandstone; fine—volcanics, sandstone, quartz  | 24.2                           | <No. 4 2.69<br>>No. 4 2.60 | 1.3                    | 11.8   | 37           | NP                     | 60                   | 45   | 80         |
| Cal. 18     | Ultrabasics  | 19.6                           | <No. 4 2.84<br>>No. 4 2.76 | 1.7                    | 22.7   | 28           | 22-18-4                | 56                   | 34   | 82         |
| Cal. 19     | Sandstone and pebbly sandstone, altered ultrabasics and meta-volcanics, hornfels   | 39.6                           | <No. 4 2.61<br>>No. 4 2.44 | 4.0                    | 50.9   | 22           | 26-18-8                | 12                   | 25   | 55         |
| Cal. 20     | Coarse—sandstone, shale, ultrabasics, chert, fine—fragments of same material plus grains of quartz and calcite and trace of pyrite | 35.4                           | <No. 4 2.60<br>>No. 4 2.73 | 2.0                    | 35.4   | 20           | 22-14-8                | 12                   | 23   | 24         |
| Cal. 21     | Diabase, gabbroic, with some ultrabasics, and siltstone  | 20.6                           | <No. 4 2.65<br>>No. 4 2.44 | 4.0                    | 13.2   | 33           | 24-22-2                | 63                   | 40   | 84         |
| Cal. 22     | Sandstone and meta-sandstone, ultrabasics, volcanics   | 28.0                           | <No. 4 2.70<br>>No. 4 2.60 | 2.0                    | 23.5   | 37           | NP                     | 46                   | 33   | 80         |
| Cal. 23     | Mostly sandstone and meta-sandstone, some chert, siliceous rocks, ultrabasics, and schists   | 34.0                           | <No. 4 2.70<br>>No. 4 2.55 | 2.6                    | 27.4   | 28           | NP                     | 40                   | 27   | 78         |
| Cal. 24     | Mostly sandstone and meta-sandstone, some ultrabasics, chert, quartz, meta-igneous   | 30.0                           | <No. 4 2.69<br>>No. 4 2.53 | 2.5                    | 16.5   | 37           | NP                     | 46                   | 31   | 81         |
| Cal. 25     | Cherty shale, chert and siliceous rocks, shale, siliceous tuff; trace of sandstone and organics                                    | 26.4                           | <No. 4 2.68<br>>No. 4 2.45 | 3.5                    | 22.2   | 18           | 39-25-14               | 19                   | 21   | 56         |
| Cal. 26     | Sheared sandstone, meta-sandstone  | 59.4                           | <No. 4 2.61<br>>No. 4 2.42 | 3.6                    | 44.2   | 59           | NP                     | 28                   | 27   | 80         |
| Cal. 27     | Sandstone and meta-sandstone, chert, some vein quartz, basics, meta-igneous  | 28.4                           | <No. 4 2.69<br>>No. 4 2.58 | 1.8                    | 8.5  | 79           | NP                     | 40                   | 31   | 81         |
| Cal. 28     | Sandstone, chert and vein quartz, ultrabasics, meta-volcanics, siltstone, glaucophane schist                                       | 27.8                           | <No. 4 2.75<br>>No. 4 2.61 | 1.6                    | 7.4  | 24           | NP                     | 53                   | 31   | 81         |
| Cal. 29     | Weathered granite  | 61.4                           | <No. 4 2.64<br>>No. 4 2.45 | 2.6                    | 14.6   | 62           | NP                     | 34                   | 36   | 75         |
| Cal. 30     | Granites, biotite, hornblende, quartz  | —                              | <No. 4 2.75                | —                      | 8.0  | 59           | NP                     | —                    | 34   | 69         |

| DESIGNATION | TYPE OF MATERIAL | L. A. LOSS (%) | BULK S P. GR. | ABSORPTION |
|-------------|------------------|----------------|---------------|------------|
| Del. 1      | Stone            | 25.04          | 2.85          | 0.37       |
| Del. 2      | Stone            | 21.98          | 2.86          | 0.62       |
| Del. 3      | —                | 28.82          | 2.82          | 0.48       |
| Del. 4      | Stone            | 26.74          | 2.72          | 0.63       |
| Del. 5      | Gravel           | 28.74          | 2.61          | 1.19       |
| Del. 6      | Gravel           | —              | 2.63          | 0.29       |
| Del. 7      | Gravel           | 35.62          | 2.55          | 1.96       |

| DESIGNATION | DESCRIPTION  | MgSO <sub>4</sub>       |                    | BULK SP. GR. | ABSORPTION (%) | FREEZE-THAW (%) LOSS |
|-------------|--|-------------------------|--------------------|--------------|----------------|----------------------|
|             |  | L. A. VALUE, 500 CYCLES | LOSS, 5 CYCLES (%) |              |                |                      |
| D.C. 1      | Gravel of Pliocene age, 68% quartz, 22% chert, 5% quartzite, 5% sandstone  | 33                      | 0.6                | 2.57         | 1.3            | 41                   |
| D.C. 2      | Gravel of Pliocene age, 65% quartz, 22% chert, 6% quartzite, 7% sandstone  | 35                      | 0.5                | 2.59         | 1.1            | 37                   |
| D.C. 3      | Sand sample  | —                       | —                  | —            | —              | —                    |
| D.C. 4      | Crushed-stone aggregate composed of propylite with occurrence of talc and serpentine of Paleozoic age. Black to dark green moderately dense serpentized basic rock   | 18                      | 7.4                | 2.57         | 2.1 avg        | 68                   |
| D.C. 5      | Gravel of Pliocene age, 65% quartz, 9% sandstone, 4% quartzite, 22% chert  | B A<br>35 39            | 5.4<br>14.4        | 2.57         | 1.1<br>1.3     | 48                   |
| D.C. 6      | Gravel of recent alluvial deposits; 30% quartz, 32% sandstone, 22% quartzite, 10% chert, 6% misc rocks   | A<br>34                 | 0.6                | 2.63         | 0.9            | —                    |
| D.C. 7      | Crushed-stone aggregate composed of dark, fine- to medium-grained, hard, dense, hornblende, which grades in part into hornblende schist. Hornblende, plagioclase, and quartz are most common. Pyrite locally is common, as are veinlets of calcite. In general, rock appears fresh and durable | 27*<br>20               | 3.0*<br>0.4        | 3.07         | 0.4            | 79                   |

\* Test on combined sample

| DESIGNATION | AGGREGATE TYPE    | PETROGRAPHIC INFORMATION   | L.A. VALUE, 500 CYCLES         | BULK SP. GR.                   | ABSORPTION (%)             | SULFATE SOUNDNESS, 5 CYCLES (%) |
|-------------|-------------------|--|--------------------------------|--------------------------------|----------------------------|---------------------------------|
| Fla. 1      | Quartz gravel     | Stream gravels containing quartz of various gradations   | 37.6–<br>42.5                  | 2.60                           | 0.5–<br>1.0                | —                               |
| Fla. 2      | Quartz gravel     | Stream gravels containing quartz of various gradations   | 35.5–<br>41.4                  | 2.65                           | 0.5–<br>1.0                | —                               |
| Fla. 3      | Crushed limestone | Marine Pliocene limestone 10–15 ft thick   | 25.6–<br>32.5                  | 2.58                           | 1.5                        | —                               |
| Fla. 4      | Quartz gravel     | Stream gravels containing quartz of various gradations   | 38.6–<br>44.5                  | 2.62–<br>2.64                  | 0.3–<br>0.4                | —                               |
| Fla. 5      | Crushed limestone | Limerock of late Oligocene age; commonly dense hard cream-colored rock. In this location the formation is about 100 ft thick | 34.0–<br>42.0                  | 2.50                           | 3.5                        | 25.8                            |
| Fla. 6      | Crushed limestone | Same formation as Fla. 5, but at this location hardness varies. 91–98% CaCO <sub>3</sub> , with the remainder chiefly silica | 28.0–<br>44.2                  | 2.39–<br>2.53                  | 5                          | 14.1–<br>18.4                   |
| Fla. 7      | Crushed limestone | Pleistocene age formation; 95% carbonate   | 29.0–<br>44.2<br>22.5–<br>45.7 | 2.54–<br>2.56<br>2.25–<br>2.42 | 2.6–<br>3.7<br>4.6–<br>5.4 | 11.2                            |

| DESIGNATION | DESCRIPTION  | L.A. VALUE,<br>500 CYCLES | BULK<br>SP. GR. | ABSORPTION<br>(%) | SOUNDNESS<br>(%) | COMMENTS   |
|-------------|--|---------------------------|-----------------|-------------------|------------------|--|
| Ga. 1       | Quartz monzonite   | 60                        | —               | —                 | —                | Always fails, 60% L A loss limit   |
| Ga. 2       | Slightly foliated migmatite gneiss                                       | 59 avg.                   | 2.62            | 0.45 avg.         | 3.4              | Frequently exceeds 60% limit   |
| Ga. 3       | Injected biotite gneiss and mica schist contact zone                     | 46.1 avg.                 | 2.70            | 0.50 avg.         | 2.8              | May fail test when predominance of schist is encountered                                     |
| Ga. 4       | Gneissic biotite granite   | 40.7 avg.                 | —               | 0.76 avg.         | —                | Consistently satisfactory  |
| Ga. 5       | Biotite granite  | 42.3                      | 2.62            | 0.69              | 3.7              | Only recently added to list and not yet used   |
| Ga. 6       | Gneiss   | 41-50.1<br>46.3 avg.      | 2.61            | 0.44              | 2.3              | Sometimes makes class A, sometimes class B stone   |
| Ga. 7       | Augen gneiss (porphyritic granite gneiss)                                | 38.7 avg.                 | 2.61            | 0.54 avg.         | —                | Recently opened but satisfactory   |
| Ga. 8       | Injected biotite granite gneiss  | 37-47<br>43.9 avg.        | 2.61            | 0.43 avg.         | —                | Always has been a satisfactory stone   |
| Ga. 9       | Mica schist and granite gneiss, one unaltered, one showing decomposition | 55.4<br>46.0              | 2.65            | 0.61<br>0.51      | —                | No difficulty in base course, but iron stains concrete. No longer used as concrete aggregate |
| Ga. 10      | Limestone; typically dark in color with veined white calcite             | 22.0 avg.                 | 2.67            | 0.50              | 7.5              | Extensively used without known failures  |
| Ga. 11      | Ordovician age limestone   | 25.4 avg.                 | 2.71            | 0.66              | —                | Used in north Georgia; no trouble except for occasional shaly beds                           |
| Ga. 12      | Relatively pure Ordovician limestone                                     | 25.5 avg.                 | 2.72            | 0.40 avg.         | —                | Class A aggregate, of cement grade   |

| DESIGNATION | ROCK TYPE                 | L.A. VALUE,<br>500 CYCLES | SPECIFIC GRAVITY |        |          | ABSORPTION<br>(%) | INTENDED<br>USE                           | COMMENTS   |
|-------------|---------------------------|---------------------------|------------------|--------|----------|-------------------|---|--|
|             |                           |                           | BULK<br>DRY      | S.S.D. | APPARENT |                   |   |  |
| Haw. 1      | Basalt cobbles            | 15.8                      | 2.70             | 2.77   | 2.89     | 3.2               | Concrete and asphaltic concrete aggregate | Very dense, obviously no trouble involved              |
| Haw. 2      | Cinders from aa lava flow | 31.2                      | 2.40             | 2.49   | 2.65     | 3.86              | Access roads                              | Probably less suitable material in sender's estimation |

| DESIGNATION | ROCK TYPE                | L.A. VALUE,<br>500 CYCLES | SPECIFIC<br>GRAVITY            | ABSORPTION<br>(%)     | SAND EQUIV           |                          | SODIUM<br>SULFATE<br>LOSS<br>(%) | COMMENTS                   |
|-------------|--------------------------|---------------------------|--------------------------------|-----------------------|----------------------|--------------------------|----------------------------------|----------------------------|
|             |                          |                           |                                |                       | ORIGI-<br>NAL        | AFTER<br>FREEZE-<br>THAW |                                  |                            |
| Idaho 1     | Slightly altered basalt  | 24.0 avg.                 | —                              | —                     | 58<br>66             | 63<br>69                 | —                                | Susceptible to degradation |
| Idaho 2     | Basalt                   | 27.0 avg.                 | 2.87 avg.                      | 1.3 coarse aggregates | 56<br>63<br>85       | 61<br>44<br>67           | —                                | Susceptible to degradation |
| Idaho 3     | Basalt, weathered basalt | 22.0 avg.                 | coarse<br>2.83<br>fine<br>2.98 | 1.3 avg.              | 63<br>80<br>78<br>79 | 38<br>65<br>52<br>69     | 1.2                              | Susceptible to degradation |
| Idaho 4     | Basalt                   | 18.0 avg.                 | 2.84 avg.                      | 1.25 avg.             | 72<br>78<br>72<br>70 | 69<br>45<br>39<br>53     | —                                | Susceptible to degradation |
| Idaho 5     | Basalt                   | 21.8 avg.                 | 2.81 avg.                      | 19.0                  | 72                   | 50                       | —                                | Susceptible to degradation |

**Petrographic Descriptions**

Idaho No 1 Both poor and intermediate material was submitted from the quarry. Poor material—dark minerals altered to smectite-chlorite. Intermediate material—not entirely altered. Rock composition based on thin-section analysis: plagioclase 37%, pyroxene 25%, magnetite 5%, chlorophacite-smectite 13%, iddingsite 5%, palagonite 15%.

Idaho No 2 Several degrees of altered material were represented.

Thin section No 1—plagioclase 35%, aegite 6%, magnetite 2%, and interstitial material (glass) 56%, which is almost entirely altered to palagonite.

Thin section No 2—plagioclase 39%, aegite 15%, magnetite 2%, and interstitial material 44%, which is predominantly charged with illmenite, plagioclase, aegite, and possibly olivine.

Idaho No 3 Thin-section analysis yields plagioclase 39%, aegite 20%, olivine 3%, magnetite 8%, smectite 13%, and palagonite 18%.



| DESIGNATION | 500 CYCLES       | SPECIFIC GRAVITY | ABSORPTION (%) | SULFATE SOUNDNESS | REMARKS                         |
|-------------|------------------|------------------|----------------|-------------------|---------------------------------|
| III 1       | 29               | 2.63             | 1.0-1.5        | 9%                | High L.A. loss                  |
| III. 2      | 30               | 2.60             | 1.5-2.0        | 30%               | High L.A. and soundness loss    |
| III. 3      | 25               | 2.55             | 2.5            | Mid. 30's         | High soundness                  |
| III. 4      | 50               | 2.42             | 4.0            | 15-20             | High soundness                  |
| III. 5      | —                | —                | —              | Very high         | Turns to mush in soundness test |
| III. 6      | 32, 50<br>49, 35 | —                | —              | —                 | —                               |
| III. 7      | 23-24            | 2.6-2.65         | 1.5            | 5-6               | —                               |
| III. 8      | 30               | 2.60             | 1.5-2.0        | 30                | Rejected on basis of soundness  |
| III. 9      | 28-35            | —                | —              | 15-30             | —                               |
| III 10      | 30               | 2.6-2.7          | 1.8-2.0        | 1.5-2.0           | Best stone in the state         |
| III. 11     | 50               | 2.35-2.40        | 4.5-5.0        | 35-39             | Poor                            |
| III. 12     | 35               | 2.66             | 0.7            | 10                | Good                            |

| DESIGNATION | SPECIFIC GRAVITY       |       |                  |                | FREEZE-THAW LOSS (%)    |                       | COMPOSITION (%) |      |                  |                                |                                |                         |                       | COMMENT      |
|-------------|------------------------|-------|------------------|----------------|-------------------------|-----------------------|-----------------|------|------------------|--------------------------------|--------------------------------|-------------------------|-----------------------|--------------|
|             | L.A. VALUE, 500 CYCLES | S S D | CORR FOR ABSORP. | ABSORPTION (%) | IOWA ALCOHOL "A FREEZE" | IOWA WATER "C FREEZE" | CAO             | MGO  | LOSS ON IGNITION | FE <sub>2</sub> O <sub>3</sub> | AL <sub>2</sub> O <sub>3</sub> | SiO <sub>2</sub> (DIFF) | TOTAL CO <sub>2</sub> |              |
| Iowa 1      | 32                     | 2.678 | 2.607            | 2.70           | 31                      | 6.9                   | 38              | 9.2  | 39.1             | 0.4                            | 3.4                            | 9.9                     | 86.3                  | Questionable |
| Iowa 2      | 36                     | 2.674 | 2.637            | 1.37           | 3.8                     | 0.5-2.0               | 45.6            | 6.9  | 43.4             | 0.3                            | 0.5                            | 3.3                     | 95.7                  | Good         |
| Iowa 3      | 43                     | 2.623 | —                | 3.50           | 60.0                    | 3.0-7.0               | 28.4            | 15.7 | 39.5             | 2.0                            | 1.1                            | 13.3                    | 83.6                  | Questionable |
| Iowa 4      | 41                     | 2.650 | 2.622            | 1.07           | 12.0                    | 1.0-2.0               | 54.0            | 1.2  | 43.7             | 0.1                            | —                              | 1.0                     | 98.6                  | Good         |
| Iowa 5      | 29                     | 2.672 | 2.640            | 1.18           | 30.0                    | 10.0                  | 42.0            | 3.0  | 38.0             | 0.6                            | 1.8                            | 14.5                    | 83.1                  | Questionable |

| DESIGNATION | TYPE OF MATERIAL  | L.A. VALUE, 500 CYCLES    | SP. GRAVITY |      | ABSORPTION | FREEZE-THAW RATIO | COMMENTS  |
|-------------|-------------------|---------------------------|-------------|------|------------|-------------------|---|
|             |                   |                           | S S D       | DRY  |            |                   |   |
| Kans. 1     | Limestone         | B grading<br>33.0         | 7.60        | 2.51 | 3.64       | 0.97              | PI 1 to 4 Used with 5% crushed sandstone in road base. Least susceptible to degradation of those supplied |
| Kans. 2     | Chert<br>source 1 | D grading<br>21.5         | 2.59        | —    | 1.41       | 0.96              | Used with 10% binder soil. Intermediate degradation   |
|             |                   | C grading<br>20.0         |             |      |            |                   |   |
| Kans. 3     | Limestone         | C grading<br>20.3         | 2.56        | —    | 1.51       | 0.96              | Used in granular subbase. Intermediate degradation  |
|             |                   | D grading<br>28.9         | 2.61        | 2.55 | 2.37       | 0.97              |   |
| Kans. 4     | Limestone         | C grading<br>31.1         | 2.54        | 2.46 | 3.17       | 0.99              | Used in 8-in. detour section. Intermediate degradation  |
| Kans. 5     | Limestone         | A grading<br>31.9<br>45.4 | 2.38        | 2.25 | 6.03       | 0.94              | Used with 12% sand added and as 100% crushed limestone. Most susceptible                                  |

| DESIG-NATION | DESCRIPTION    | COMPOSITION (%) |                    | COMMENTS                      |
|--------------|----------------|-----------------|--------------------|-------------------------------|
|              |                | SHALE           | INCRUSTED MATERIAL |                               |
| Mich. 1      | Glacial gravel | 8.4             | 7.2                | Suspected of some degradation |
| Mich. 2      | Glacial gravel | 0.0             | 12.5 avg.          | Suspected of some degradation |
| Mich. 3      | Glacial gravel | No data         | No data            | Suspected of some degradation |

| DESIG-NATION | DESCRIPTION   | L. A. VALUE, 500 CYCLES | SP. GR | MG              |                       | COMMENTS   |
|--------------|---|-------------------------|--------|-----------------|-----------------------|--|
|              |   |                         |        | ABSORP-TION (%) | SULFATE, 5 CYCLES (%) |  |
| Miss. 1      | Chert gravel, most of which is not badly weathered      | 17.46                   | 2.57   | 1.75            | 3.850                 | Very good record in concrete structures and pavements                                |
| Miss. 2      | 98% chert gravel, of which 65% is weathered and unsound | 17.57                   | 2.392  | 2.98            | 3.741                 | Has been used with success, but petrographic lab claims it is too unsound to use     |
| Miss. 3      | 100% chert gravel of which 58% is weathered and unsound | 15.32                   | 2.524  | 1.64            | 3.502                 | Degradation of the three samples submitted has not been a problem under manipulation |

| DESIG-NATION | ROCK TYPE        | L. A. VALUE, 500 CYCLES | SP. GR | ABSORP-TION (%) | FRENCH COEFF. | SOUNDNESS, 16 CYC ALCOHOL FREEZE-THAW | COMMENTS      |
|--------------|------------------|-------------------------|--------|-----------------|---------------|---------------------------------------|---------------|
|              |                  |                         |        |                 |               |                                       |               |
| Mo. 1        | Limestone        | 30                      | 2.65   | 0.6             | —             | Slightly flaking                      | Hard material |
| Mo. 2        | Limestone        | 43                      | 2.63   | 1.8             | —             | Some unsoundness                      | Soft material |
| Mo. 3        | Limestone        | 36                      | 2.62   | 0.7             | —             | Sound                                 | Hard material |
| Mo. 4        | Limestone        | 46                      | 2.55   | 2.0             | —             | Slight chipping                       | Soft material |
| Mo. 5        | Limestone        | 33                      | 2.65   | 0.8             | —             | Sound                                 | Hard material |
| Mo. 6        | Limestone        | 46                      | 2.58   | 1.2             | —             | Very slight flaking                   | Soft material |
| Mo. 7        | Limestone        | 27                      | 2.60   | 1.3             | —             | Slight flaking                        | Hard material |
| Mo. 8        | Quartz sandstone | —                       | —      | —               | —             | —                                     | Hard material |
| Mo. 9        | Dolomite         | —                       | —      | —               | —             | —                                     | —             |
| Mo. 10       | Limestone        | —                       | 2.62   | 0.8             | 5.4           | —                                     | Soft material |
| Mo. 11       | Dolomite         | —                       | —      | —               | —             | —                                     | —             |
| Mo. 12       | Limestone        | 35                      | 2.65   | 0.5             | —             | Slight flaking                        | Hard material |
| Mo. 13       | Limestone        | 25                      | 2.67   | 0.6             | —             | Some flaking                          | Hard material |
| Mo. 14       | Limestone        | 42                      | 2.40   | 3.5             | —             | Some flaking                          | Soft material |
| Mo. 15       | Dolomite         | 30                      | 2.54   | 3.0             | —             | Considerable flaking                  | Hard material |
| Mo. 16       | Dolomite         | 38                      | 2.45   | 4.0             | —             | Considerable flaking                  | Soft material |
| Mo. 16a      | Dolomite         | 28                      | 2.66   | 0.7             | —             | Slight flaking                        | Hard material |
| Mo. 17       | Limestone        | —                       | 2.55   | 1.3             | 7.8           | —                                     | Hard material |
| Mo. 18       | Limestone        | —                       | 2.52   | 2.1             | 6.6           | —                                     | Soft material |
| Mo. 19       | Limestone        | 31                      | 2.46   | 2.7             | 8.0           | —                                     | Hard material |
| Mo. 20       | Limestone        | 53                      | 2.35   | 6.0             | 4.5           | —                                     | Soft material |
| Mo. 21       | Limestone        | 27                      | 2.66   | 0.7             | 9.1           | —                                     | Hard material |
| Mo. 22       | Limestone        | 36                      | 2.58   | 1.2             | 7.0           | —                                     | Soft material |
| Mo. 23       | Limestone        | —                       | ~2.55  | ~1.3            | ~7.8          | —                                     | Hard material |
| Mo. 24       | Limestone        | —                       | ~2.52  | ~2.1            | ~6.6          | —                                     | Soft material |

| DESIG-NATION | ROCK TYPE           | L. A. VALUE, 500 CYCLES | DEVAL ABRASION | SP GR | FREEZE-THAW WEIGHT LOSS, 25 CYCLES (%) | Na <sub>2</sub> SO <sub>4</sub> LOSS (%) | MgSO <sub>4</sub> LOSS (%) | COMMENTS                                   |
|--------------|---------------------|-------------------------|----------------|-------|--|--|----------------------------|--|
|              |                     |                         |                |       |  |  |                            |  |
| N.Y. 1       | Dolomite            | 31.8                    | 3.5            | 2.72  | 0.0                                    | 0.0                                      | 0.5                        | Good material                              |
| N.Y. 2       | Limestone           | 21.3                    | 3.4            | 2.72  | 0.0                                    | 0.0                                      | 3.0                        | No problems                                |
| N.Y. 3       | Limestone           | 20.3                    | 2.3            | 2.66  | 0.0                                    | 0.4                                      | 1.4                        | May yield some plastic fines               |
| N.Y. 4       | Limestone           | 23.0                    | 4.7            | 2.68  | 2.4                                    | 0.1                                      | 0.3                        | May yield some plastic fines               |
| N.Y. 5       | Dolomite            | 20.9                    | 2.6            | 2.80  | 0.3, 3.0                               | 0.3                                      | 0.6                        | One of the better stones in the state      |
| N.Y. 6       | Diabase (trap)      | 26.1                    | 2.4            | 2.85  | 0.6                                    | 0.6                                      | 0.7                        | Very good material                         |
| N.Y. 7       | Limestone           | 20.2                    | 2.5            | 2.70  | 1.0                                    | 0.0                                      | 0.4                        | Good material                              |
| N.Y. 8       | Graywacke sandstone | 32.2                    | 2.5            | 2.60  | 3.7                                    | 17.6                                     | 14.8                       | Accepted on the basis of geologic evidence |
| N.Y. 9       | Graywacke sandstone | 27.8                    | 4.8            | 2.64  | 6.6                                    | 27.8<br>19.2                             | 16.2<br>14.6               | Similar to N.Y. 8, but of better quality   |

| DESIG-NATION | DESCRIPTION | L. A. VALUE, 500 CYCLES | SP. GR. S. D. | ABSORPTION (%) | SHALE (%) | SODIUM SULFATE (%) | COMMENTS   |
|--------------|-------------|-------------------------|---------------|----------------|-----------|--------------------|--|
| N D 1        | Gravel      | A grading<br>23.0       | 2.63<br>2.68  | 2.0<br>1.9     | 0.13<br>— | 2.5<br>3.1         | Washed gravel used in Portland cement concrete with good performance |

| DESIG-NATION | DESCRIPTION  | L. A. VALUE, 500 CYCLES |        | SP. GR. |      | ABSORPTION (%) |      | NESS LOSS (%) | SOFT PIECES (%) | SHALE (%) | COAL (%) | CHERT (%) | REMARKS                               |
|--------------|--|-------------------------|--------|---------|------|----------------|------|---------------|-----------------|-----------|----------|-----------|---------------------------------------|
|              |  | SIZE D                  | SIZE B | COARSE  | FINE | COARSE         | FINE |               |                 |           |          |           |                                       |
| Ohio 1       | Glacial sand and gravel                            | 27.6                    | —      | 2.43    | 2.32 | 3.50           | 5.20 | 18.2          | 0.6             | 2.4       | 0.0      | 0.1       | Suspected of degradation              |
| Ohio 2       | Glacial gravel composed of limestone and sandstone | 11.2                    | 26.8   | 2.60    | 2.43 | 1.20           | 1.70 | 14.3          | 10.3            | 0.0       | 0.1      | 0.1       | Sandstone more unsound than limestone |

| DESIG-NATION | GEOLOGIC DESCRIPTION   | L. A. VALUE, 500 CYCLES | SPEC. GR. (S. S. D.) | ABSORPTION (%) | DEGRADATION RATING   |
|--------------|--|-------------------------|----------------------|----------------|--|
| Okla. 1      | Mixture of chert and limestone   | 23.4                    | 2.607                | 0.3            | Excellent  |
| Okla. 2      | Dusty, crusher-run calcareous sandstone; gray, massively bedded  | 43.8                    | —                    | —              | Poor; excessive production of fines  |
| Okla. 3      | Dusty, crusher-run limestone; generally massively bedded white stone that weathers to an almost pure white | 44.8                    | —                    | —              | Excessive fine production and a tendency toward increased plasticity index |
| Okla. 4      | Crushed limestone; massively bedded, hard, gray, cherty material in place                                  | 27.0                    | —                    | —              | Good   |

| DESIGNATION | TYPE OF MATERIAL | L A. VALUE, 500 CYCLES | SPECIFIC GRAVITY, LE CHAT-ELIER | Na <sub>2</sub> SO <sub>4</sub> LOSS (%) | LL    | SAND EQUIVALENT | ORE. P NO 20 | DEGRADATION, H | COMMENTS  |
|-------------|------------------|------------------------|---------------------------------|--|-------|-----------------|--------------|----------------|---|
| Ore. 1      | Quarry           | 20.0                   | 2.74                            | 1.4                                      | 22 np | 65.9            | 28.4         | 8.9            | Fails specifications; failed rapidly as base  |
| Ore. 2      | Quarry           | 11.8                   | 2.74                            | 0.2                                      | 22 np | 75.6            | 16.1         | 1.6            | Meets specifications; no service record   |
| Ore. 3      | Quarry           | 20.0                   | 2.70                            | 0.2                                      | 20 np | 63.3            | 23.3         | 4.8            | Fails specifications; considerable patching in road material  |
| Ore. 4      | Pit              | 22.7                   | 2.82                            | 0.2                                      | 19 np | 84.2            | 15.8         | 0.4            | Meets specifications; used in asphalt paving and bases with good service record   |
| Ore. 5      | Pit              | 17.2                   | 2.74                            | 0.2                                      | 20 np | 69.8            | 16.6         | 0.7            | Meets specifications; all types of work have good service record  |
| Ore. 6      | Gravel bar       | 19.0                   | 2.78                            | 0.2                                      | 20 np | 78.0            | 11.9         | 0.5            | Meets specifications, all types of work have good service record  |
| Ore. 7      | Quarry           | 23.6                   | 2.94                            | 4.6                                      | 22 np | 43.0            | 21.0         | 5.5            | Fails specifications, very poor service records in all types of work  |
| Ore. 8      | Quarry           | 11.8                   | 2.85                            | 0.2                                      | 21 np | 79.5            | 10.5         | 0.6            | Meets specifications, all types of work with fair service record  |
| Ore. 9      | Quarry           | 11.8                   | 2.79                            | 0.2                                      | 20 np | 84.8            | 16.8         | 2.0            | Meets specifications, first use base and pavement had considerable failure in 2 years. Degraded sand layer under pavement |
| Ore. 10     | Quarry           | 14.5                   | 2.88                            | 0.2                                      | 23 np | 71.3            | 17.3         | 0.4            | Meets specifications; all phases of work have good service record   |

| DESIGNATION | ROCK TYPE                       | L A. VALUE, 500 CYCLES | SP. GR. | ABSORPTION (%) | SODIUM SULFATE SOUNDNESS | COMMENTS                               |
|-------------|---------------------------------|------------------------|---------|----------------|--------------------------|--|
| Penn. 1     | Limestone                       | 20.5                   | 2.63    | 0.76           | —                        | Degradation unnoticeable               |
| Penn. 2     | Dolomite                        | 33.0                   | 2.53    | 0.80           | 6.35                     | Some degradation under rolling         |
| Penn. 3     | Limestone                       | 17.6                   | 2.67    | 0.40           | —                        | Excellent material                     |
| Penn. 4     | Limestone                       | 23.8                   | 2.67    | 0.66           | —                        | Excellent material                     |
| Penn. 5     | Limestone                       | 14 avg.                | 2.66    | 0.96           | —                        | Good material                          |
| Penn. 6     | Limestone                       | 13 avg.                | 2.67    | 0.66           | —                        | Good material                          |
| Penn. 7     | Graywacke sandstone             | 26.8                   | 2.68    | 0.78           | —                        | Poor material in regard to degradation |
| Penn. 8     | Red sandstone                   | 16.9                   | 2.66    | 0.80           | —                        | Very little breakdown                  |
| Penn. 9     | Quartzite                       | 18.0                   | 2.66    | 1.22           | —                        | Excellent, hard                        |
| Penn. 10    | Slightly metamorphosed dolomite | 27.5                   | 2.67    | 0.78           | —                        | Good service but tendency to plate     |
| Penn. 11    | Diabase                         | 7.1 avg.               | 2.99    | 0.50           | —                        | Little or no crushing                  |
| Penn. 12    | Dolomite                        | 16.0 avg.              | 2.83    | 0.44           | —                        | —                                      |
| Penn. 13    | Calcareous marble               | 17 avg.                | 2.86    | 0.30           | —                        | Good material                          |
| Penn. 14    | Carbonaceous limestone          | 13 avg.                | 2.65    | 0.50           | —                        | Good material                          |
| Penn. 15    | Limestone                       | 14.0                   | 2.78    | 0.40           | —                        | Best material in district              |
| Penn. 16    | Dolomite                        | 22.5                   | 2.66    | 0.62           | —                        | Softest material in district           |
| Penn. 17    | Limestone                       | 20.5                   | 2.66    | 1.08           | —                        | —                                      |
| Penn. 18    | Limestone                       | 20.5                   | 2.72    | 0.15           | —                        | —                                      |
| Penn. 19    | Limestone                       | 18.0                   | 2.66    | 0.42           | 1.5                      | —                                      |
| Penn. 20    | Limestone                       | 24.8                   | 2.69    | 0.80           | 1.4                      | —                                      |

| DESIGNATION | DESCRIPTION    | L A. VALUE, 500 CYCLES | ABSORPTION (%) | FRAC-TURED FACE COUNT | SOLUBLE SALTS (%) | COMMENTS |
|-------------|----------------|------------------------|----------------|-----------------------|-------------------|----------|
| Utah 1      | Terrace gravel | —                      | —              | —                     | —                 | —        |
| Utah 2      | Terrace gravel | 40.0                   | 1.42           | 78                    | 1.8               | —        |
| Utah 3      | Terrace gravel | 38.0                   | 1.57           | 75                    | 1.9               | —        |
| Utah 4      | Terrace gravel | 39.6                   | 1.40           | 80                    | 1.7               | —        |
| Utah 5      | Terrace gravel | 39.6                   | 1.40           | 80                    | 1.7               | —        |
| Utah 6      | Terrace gravel | 37.6                   | 1.18           | 75                    | 1.3               | —        |

| DESIGNATION | L. A. ABRASION           | SP. GR | ABSORPTION (%) | DESIGNATION | L.A. ABRASION            | SP GR | ABSORPTION (%) |
|-------------|--------------------------|--------|----------------|-------------|--------------------------|-------|----------------|
| Vir. 1      | A 23.6, B 22.8<br>C 23.3 | 2.74   | 0.34           | Vir. 17     | A 18.7, B 16.1<br>C 19.3 | 2.81  | 0.39           |
| Vir. 2      | A 32.3, B 29.9           | 2.72   | 1.11           | Vir. 18     | B 16.2                   | 2.71  | 0.37           |
| Vir. 3      | C 28.1                   | 2.67   | 0.33           | Vir. 19     | A 20.7, B 20.4           | 2.72  | 0.13           |
| Vir. 4      | A 23.3, B 19.8           | 2.82   | 0.30           | Vir. 20     | B 19.7, C 18.6           | 2.70  | 0.19           |
| Vir. 5      | A 38.8, B 37.0<br>C 40.0 | 2.63   | 0.23           | Vir. 21     | B 19.2, C 21.0           | 2.78  | 0.19           |
| Vir. 6      | A 40.1, B 42.2           | 2.69   | 0.34           | Vir. 22     | A 19.8, B 18.6           | 2.59  | 0.51           |
| Vir. 7      | A 19.0, B 19.0           | 2.85   | 0.23           | Vir. 23     | A 31.1, B 28.2           | 2.80  | 0.23           |
| Vir. 8      | C 27.8                   | 2.79   | 0.38           | Vir. 24     | B 38.9, C 44.1           | 2.63  | 0.16           |
| Vir. 9      | A 25.4, B 30.4<br>C 32.7 | 2.62   | 0.60           | Vir. 25     | B 18.2                   | 2.77  | 0.35           |
| Vir. 10     | B 17.5                   | 2.71   | 0.30           | Vir. 26     | B 17.4, C 19.0           | 2.69  | 0.47           |
| Vir. 11     | A 20.6, B 19.5           | 2.76   | 0.51           | Vir. 27     | A 20.0, B 20.9<br>C 28.0 | 3.03  | 0.30           |
| Vir. 12     | B 21.6                   | 2.82   | 0.27           | Vir. 28     | A 17.6, B 17.0           | 2.76  | 0.50           |
| Vir. 13     | A 20.5, B 19.0           | 2.73   | 0.26           | Vir. 29     | A 24.9, B 22.5<br>C 22.5 | 2.71  | 0.47           |
| Vir. 14     | B 23.6                   | 2.81   | 0.44           | Vir. 30     | A 21.4, B 20.2           | 2.76  | 0.60           |
| Vir. 15     | A 26.2, B 25.9<br>C 20.7 | 2.67   | 0.33           | Vir. 31     | A 15.9, B 15.5           | 2.76  | 0.59           |
| Vir. 16     | B 30.2, C 26.1           | 2.70   | 0.26           | Vir. 32     | A 15.5, B 16.0           | 2.97  | 0.54           |
|             |                          |        |                | Vir. 33     | B 25.2, C 27.2           | 2.79  | 0.16           |
|             |                          |        |                | Vir. 34     | B 13.6                   | 2.94  | 0.16           |

| DESIGNATION | TYPE OF MATERIAL | L.A. VALUE, 500 CYCLES | SP GR | ABSORPTION (%) | FREEZE-THAW LOSS <sup>a</sup> , IOWA A FREEZE (%) | SODIUM SULFATE SOUNDNESS | DEGRADATION EVALUATION      |
|-------------|------------------|------------------------|-------|----------------|---|--------------------------|-----------------------------|
| Wis. 1      | Dolomite         | 40                     | 2.58  | 2.98           | 18.4  | 70.4 <sup>b</sup>        | Poor                        |
| Wis. 2      | Dolomite         | 54                     | 2.43  | 4.38           | 3.8   | 27.2 <sup>b</sup>        | Fair                        |
| Wis. 3      | Dolomite         | 25                     | 2.79  | 0.67           | 1.6   | 11.0 <sup>b</sup>        | Good                        |
| Wis. 4      | Quartzite        | 50                     | —     | —              | —   | 5.1 <sup>c</sup>         | —                           |
| Wis. 5      | Dolomite         | 41                     | 2.72  | 1.64           | —   | 16.8 <sup>d</sup>        | —                           |
| Wis. 6      | Igneous gravel   | 30                     | 2.67  | 0.94           | —   | —                        | —                           |
| Wis. 7      | Dolomite         | 43                     | 2.54  | 3.7            | —   | —                        | Poor                        |
| Wis. 8      | Dolomite         | 49                     | 2.44  | 4.1            | —   | —                        | Good                        |
| Wis. 9      | Dolomite         | 46                     | —     | —              | —   | 7.6 <sup>c</sup>         | Borderline, excessive fines |
| Wis. 10     | Dolomite         | 48                     | 2.66  | 1.9            | —   | —                        | Poor, substandard           |
| Wis. 11     | Dolomite         | 42-69                  | —     | —              | —   | 7.6 to 30.1              | Marginal and questionable   |
| Wis. 12     | Dolomite         | 32                     | 2.56  | 3.0            | —   | —                        | Poor, substandard           |

<sup>a</sup> Alcohol-water mixture, Iowa 1956 Specifications  
<sup>b</sup> 8 Cycles, AASHTO T 104-45

<sup>c</sup> 5 Cycles, AASHTO T 104-51.  
<sup>d</sup> 8 Cycles, AASHTO T 104-57

| DESIGNATION | TYPE OF DEPOSIT | L. A. VALUE, 500 CYCLES | SAND EQUIVALENT   | R VALUE | LL      | NP | Na <sub>2</sub> SO <sub>4</sub> SOUNDNESS LOSS (%) | COMMENTS  |
|-------------|-----------------|-------------------------|-------------------|---------|---------|----|--|---|
| Wyom. 1     | Gravel pit      | B-52.8                  | 53                | 79      | LL 27.0 | NP | 10.8   | Rejected because of degradation                     |
| Wyom. 2     | Gravel pit      | B-30.3                  | —                 | —       | LL 18.0 | NP | 13.38  | Fails sulfate test; rejected because of degradation |
| Wyom. 3     | Gravel pit      | B-27.1                  | Spec gravity 2.65 |         |         |    | —  | Considered a good pit                               |

# APPENDIX E

## LABORATORY TEST DATA OBTAINED AT PURDUE UNIVERSITY DURING PHASE I

| DESIGNATION | ROCK TYPE               | DEGRA-DATION NUMBER | GRAIN SHAPE NUMBER | GRAIN INTERLOCK NUMBER | GRAIN SIZE (MM) |           | COMMENTS                             |
|-------------|-------------------------|---------------------|--------------------|------------------------|-----------------|-----------|--------------------------------------|
|             |                         |                     |                    |                        | AVG.            | VARIATION |                                      |
| Idaho 1     | Slightly altered basalt | 4                   | 2                  | 5                      | 0.10            | 0.75-0.03 | Considerably altered; volcanic glass |
| Idaho 2     | Basalt                  | 3                   | 2                  | 5                      | 0.35            | 1.5-0.15  | Considerably altered; volcanic glass |
| Idaho 3     | Basalt                  | 3                   | —                  | —                      | —               | —         | —                                    |
| Idaho 4     | Basalt                  | 3                   | —                  | —                      | —               | —         | —                                    |
| Idaho 5     | Basalt                  | 3                   | —                  | —                      | —               | —         | —                                    |

| DESIGNATION | ROCK TYPE | INSOLUBLE RESIDUE (%)         | D.T.A.   | X-RAY TOTAL SAMPLE                                       | DEGRA-DATION NUM-BER | CALC. CALC. VOIDS (%) | CALC. DEG OF SATUR. (%) | GRAIN SHAPE NUM-BER | GRAIN INTER-LOCK NUMBER | GRAIN SIZE (MM) |             |
|-------------|-----------|-------------------------------|--|--|----------------------|-----------------------|-------------------------|---------------------|-------------------------|-----------------|-------------|
|             |           |                               |  |  |                      |                       |                         |                     |                         | AVG.            | VARIATION   |
| III 1       | Limestone | 3.2                           | Calcite  | Calcite  | 5                    | 4.78                  | 70                      | 5                   | 6                       | 0.47            | 1.7-0.1     |
| III. 2      | Dolomite  | Bed No 1 6.6<br>Bed No. 2 9.5 | Bed No 1—dolomite, some calcite<br>Bed No. 2—calcite | Bed No. 1—dolomite, quartz, calcite<br>Bed No. 2—calcite | 4                    | 10.2                  | 43                      | 4                   | 7                       | 0.27            | 4.0-0.1     |
| III. 3      | Limestone | 19.30                         | Calcite, some dolomite                               | Calcite, some dolomite                                   | 4                    | 8.82                  | 71                      | 6                   | 1                       | 0.25            | 2.0-0.05    |
| III 4       | Dolomite  | 3.6                           | Dolomite   | Dolomite, some calcite                                   | 3                    | 18.3                  | 51                      | 4                   | 4                       | 0.63            | 2.5-0.05    |
| III. 5      | Limestone | 22.0                          | Dolomite, calcite                                    | Calcite, plus dolomite                                   | —                    | —                     | —                       | 4                   | 4                       | 0.008           | 0.025-0.004 |
| III 6       | Limestone | 4.9                           | Calcite  | Calcite  | 3                    | —                     | —                       | 7                   | 3                       | 2.25            | 4.5-0.1     |
| III. 7      | Limestone | 6.5                           | Calcite and quartz                                   | Calcite  | 7                    | 4.78                  | 81                      | 5                   | 5                       | 1.50            | 3.0-0.2     |
| III. 8      | Limestone | 15.6                          | Calcite  | Calcite  | 4                    | 5.87                  | 74                      | 7                   | 4                       | 1.0             | 5.0-0.1     |
| III. 9      | Limestone | 39.2                          | Calcite, quartz                                      | Calcite, quartz  | 6                    | —                     | —                       | 2                   | 1                       | 0.1             | 0.5-0.015   |
| III. 10     | Dolomite  | 3.7                           | Dolomite   | Dolomite   | 8                    | 8.78                  | 56                      | 2                   | 7                       | 0.15            | 0.25-0.001  |
| III. 11     | Dolomite  | 12.7                          | Dolomite   | Dolomite, some calcite                                   | 2                    | 21.0                  | 51                      | 4                   | 4                       | 0.20            | 1.0-0.02    |
| III. 12     | Dolomite  | 4.9                           | Calcite  | Calcite  | 6                    | 2.94                  | 61                      | —                   | —                       | —               | —           |

| DESIGNATION | ROCK TYPE | INSOLUBLE RESIDUE (%) | D.T.A.   | X-RAY TOTAL SAMPLE | DEGRA-DATION NUM-BER | CALC. CALC. VOIDS (%) | CALC. DEG OF SATUR. (%) | GRAIN SHAPE NUM-BER | GRAIN INTER-LOCK NUMBER | GRAIN SIZE (MM) |             |
|-------------|-----------|-----------------------|----------|--------------------|----------------------|-----------------------|-------------------------|---------------------|-------------------------|-----------------|-------------|
|             |           |                       |          |                    |                      |                       |                         |                     |                         | AVG.            | VARIATION   |
| Iowa 1      | Dolomite  | 11.1                  | Dolomite | Dolomite, quartz   | 3                    | 8.42                  | 84                      | 2                   | 4                       | 0.03            | 0.058-0.015 |
| Iowa 2      | Dolomite  | 5.3                   | —        | Dolomite           | 7                    | 7.39                  | 48                      | 2                   | 7                       | 0.035           | 0.07-0.017  |
| Iowa 3      | Dolomite  | 23.3                  | —        | Dolomite, quartz   | 3                    | 11.6                  | 76                      | 3                   | 4                       | 0.020           | 0.070-0.005 |
| Iowa 4      | Limestone | 2.3                   | —        | Calcite            | 7                    | 3.68                  | 76                      | 7                   | 2                       | 0.15            | 0.60-0.10   |
| Iowa 5      | Limestone | 7.5                   | —        | Calcite            | 3                    | 2.94                  | 99                      | 6                   | 1                       | 0.30            | 1.5-0.10    |

| DESIGNATION | ROCK TYPE | INSOLUBLE RESIDUE (%) | D.T.A. | X-RAY TOTAL SAMPLE                    | DEGRADATION NUMBER | CALC. VOIDS (%) | CALC. DEG. OF SATUR. (%) |
|-------------|-----------|-----------------------|--------|---------------------------------------|--------------------|-----------------|--------------------------|
| Kans. 1     | Limestone | 13.7                  | —      | Calcite, some quartz, little dolomite | 8                  | 7.70            | 99                       |
| Kans. 2     | Chert     | —                     | —      |                                       | 7                  | 4.53            | 81                       |
| Kans. 3     | Limestone | 2.88                  | —      | Calcite, little quartz and dolomite   | 5                  | 6.26            | 97                       |
| Kans. 4     | Limestone | 5.80                  | —      | Calcite, some quartz, little dolomite | 5                  | 9.55            | 82                       |
| Kans. 5     | Limestone | 22.09                 | —      | Calcite, some quartz, little dolomite | 3                  | 17.3            | 78                       |

| DESIGNATION | ROCK TYPE | INSOLUBLE RESIDUE (%) | D.T.A. | X-RAY TOTAL SAMPLE               | DEGRADATION NUMBER | CALC. VOIDS (%) | CALC. DEG. OF SATUR. (%) | GRAIN SHAPE NUMBER | GRAIN INTERLOCK NUMBER | GRAIN SIZE (MM) |             |
|-------------|-----------|-----------------------|--------|----------------------------------|--------------------|-----------------|--------------------------|--------------------|------------------------|-----------------|-------------|
|             |           |                       |        |                                  |                    |                 |                          |                    |                        | AVG             | VARIATION   |
| Mo. 1       | Limestone | 4.3                   | —      | Calcite with little dolomite     | 7                  | 3.31            | 48                       | 4                  | 6                      | 0.12            | 3.0-0.015   |
| Mo. 2       | Dolomite  | 2.2                   | —      | Dolomite                         | 3                  | 9.48            | 49                       | 4                  | 6                      | 0.13            | 0.75-0.005  |
| Mo. 3       | Limestone | 4.0                   | —      | Calcite plus dolomite            | 7                  | 8.77            | 21                       | 5                  | 8                      | 0.75            | 2.0-0.02    |
| Mo. 4       | Dolomite  | 5.3                   | —      | Dolomite                         | 3                  | 12.31           | 41                       | 3                  | 3                      | 0.02            | 0.75-0.04   |
| Mo. 5       | Limestone | 1.6                   | —      | Calcite                          | 7                  | 3.31            | 63                       | 6                  | 7                      | 0.07            | 2.0-0.02    |
| Mo. 6       | Dolomite  | 2.9                   | —      | Dolomite                         | 3                  | 10.87           | 28                       | 2                  | 4                      | 0.035           | 0.06-0.01   |
| Mo. 7       | Limestone | 8.2                   | —      | Calcite                          | 8                  | 5.88            | 57                       | 4                  | 5                      | 0.26            | 0.45-0.05   |
| Mo. 8       | Dolomite  | 4.5                   | —      | —                                | —                  | —               | —                        | —                  | —                      | —               | —           |
| Mo. 9       | Sandstone | 41.1                  | —      | Dolomite                         | —                  | —               | —                        | —                  | —                      | —               | —           |
| Mo. 10      | Limestone | 0.8                   | —      | Calcite                          | —                  | —               | —                        | —                  | —                      | —               | —           |
| Mo. 11      | Dolomite  | 13.4                  | —      | Dolomite plus quartz             | —                  | —               | —                        | —                  | —                      | —               | —           |
| Mo. 12      | Limestone | 3.2                   | —      | Calcite                          | 7                  | 2.94            | 45                       | 5                  | 7                      | 0.15            | 0.7-0.05    |
| Mo. 13      | Limestone | 3.8                   | —      | Calcite                          | 8                  | 2.20            | 73                       | 6                  | 0.20                   | 4               | 1.5-0.05    |
| Mo. 14      | Dolomite  | 10.9                  | —      | Dolomite                         | 3                  | 18.6            | 44                       | 1                  | 0.014                  | 4               | 0.02-0.005  |
| Mo. 15      | Dolomite  | 20.2                  | —      | Dolomite                         | 7                  | 13.68           | 54                       | 4                  | 0.035                  | 5               | 0.06-0.010  |
| Mo. 16      | Dolomite  | 33.8                  | —      | Dolomite plus quartz             | 3                  | 17.21           | 55                       | 2                  | 0.008                  | 4               | 0.020-0.005 |
| Mo. 16a     | Dolomite  | 2.6                   | —      | Dolomite                         | —                  | —               | —                        | —                  | —                      | —               | —           |
| Mo. 17      | Limestone | 7.2                   | —      | Calcite, little dolomite         | 7                  | 7.34            | 45                       | —                  | —                      | —               | —           |
| Mo. 18      | Dolomite  | 32.1                  | —      | Calcite plus dolomite            | —                  | —               | —                        | —                  | —                      | —               | —           |
| Mo. 19      | Dolomite  | 12.0                  | —      | Calcite plus dolomite            | 7                  | 11.35           | 57                       | 3                  | 0.01                   | 5               | 0.02-0.006  |
| Mo. 20      | Dolomite  | 35.3                  | —      | Calcite plus dolomite and quartz | 2                  | 18.35           | 73                       | 6                  | 0.25                   | 3               | 3.0-0.008   |
| Mo. 21      | Limestone | 3.4                   | —      | Calcite                          | 7                  | 2.94            | 63                       | 6                  | 0.23                   | 5               | 0.75-0.004  |
| Mo. 22      | Limestone | 9.6                   | —      | Calcite                          | 4                  | 6.62            | 46                       | 5                  | 0.25                   | 4               | 0.7-0.015   |
| Mo. 23      | Limestone | 7.6                   | —      | Calcite, little dolomite         | —                  | —               | —                        | —                  | —                      | —               | —           |
| Mo. 24      | Limestone | 47.2                  | —      | Calcite                          | —                  | —               | —                        | —                  | —                      | —               | —           |

| DESIG-NATION | ROCK TYPE           | INSOL-UBLE RESI-DUE (%) | D T A | X-RAY TOTAL SAMPLE      | DEGRA-DATION NUM-BER | CALC. VOIDS (%) | CALC DEG OF SATUR. (%) | GRAIN SHAPE NUM-BER | GRAIN INTER-LOCK NUMBER | GRAIN SIZE (MM) |             |
|--------------|---------------------|-------------------------|-------|-------------------------|----------------------|-----------------|------------------------|---------------------|-------------------------|-----------------|-------------|
|              |                     |                         |       |                         |                      |                 |                        |                     |                         | AVG.            | VARIATION   |
| N Y 1        | Dolomite            | 2.21                    | —     | Dolomite                | 7                    | —               | —                      | 3                   | 6                       | 0.090           | 0.175-0.040 |
| N Y 2        | Limestone           | 14.48                   | —     | Calcite, some quartz    | 7                    | —               | —                      | 5                   | 7                       | 0.025           | 0.045-0.015 |
| N Y 3        | Limestone           | 18.87                   | —     | Calcite, some quartz    | 6                    | —               | —                      | 7                   | 6                       | 0.380           | 2.0-0.010   |
| N Y 4        | Limestone           | —                       | —     | —                       | —                    | —               | —                      | —                   | —                       | —               | —           |
| N Y 5        | Dolomite            | 6.19                    | —     | Dolomite                | 9                    | —               | —                      | 2                   | 7                       | 0.060           | 0.20-0.04   |
| N.Y. 6       | Diabase             | —                       | —     | —                       | 9                    | —               | —                      | 3                   | 6                       | 0.50            | 1.0-0.10    |
| N.Y. 7       | Limestone           | 42.41                   | —     | Calcite plus quartz     | 9                    | —               | —                      | 4                   | 7                       | 0.020           | 0.05-0.007  |
| N Y 8        | Graywacke sandstone | 97.14                   | —     | Quartz                  | 4                    | —               | —                      | 5                   | 7                       | 0.035           | 0.085-0.010 |
| N.Y 9        | Graywacke sandstone | 89.66                   | —     | Quartz, little dolomite | 4                    | —               | —                      | 4                   | 6                       | 0.085           | 0.250-0.010 |

| DESIG-NATION | ROCK TYPE                       | DEGRA-DATION NUM-BER | GRAIN SHAPE NUM-BER | GRAIN INTER-LOCK NUM-BER | GRAIN SIZE (MM) |             | ROCK COMPOSITION   |
|--------------|---------------------------------|----------------------|---------------------|--------------------------|-----------------|-------------|--|
|              |                                 |                      |                     |                          | AVG             | VARIATION   |  |
| Ore 1        | Lithic graywacke                | 2                    | 6                   | 7                        | 0.09            | 0.4-0.05    | Clastic sedimentary rock composed of basalt pieces which are highly altered to palagonite or chlorophaeite |
| Ore 2        | Lithic graywacke                | 7                    | 5                   | 7                        | 0.05            | 1.5-0.010   | Clastic sedimentary rock composed of basalt pieces but not as badly altered as Ore 1                       |
| Ore 3        | Limestone (insol residue 30.7%) | 3                    | 7                   | 6                        | 0.075           | 0.10-0.035  | Calcite and quartz   |
| Ore. 4       | Basalt                          | 8                    | 2                   | 6                        | 0.175           | 1.5-0.10    | Plagioclase and pyroxene only slightly altered   |
| Ore 5        | Basalt                          | 8                    | 2                   | 6                        | 0.20            | 0.75-0.02   | Plagioclase and pyroxene only slightly altered   |
| Ore. 6       | Basalt                          | 8                    | 2                   | 6                        | 0.08            | 0.75-0.01   | Plagioclase and pyroxene only slightly altered   |
| Ore 7        | Basalt                          | 2                    | 2                   | 7                        | 0.20            | 0.75-0.04   | Plagioclase and pyroxene with some alteration material and volcanic glass                                  |
| Ore 8        | Basalt                          | 4                    | 4                   | 6                        | 0.15            | 0.25-0.08   | Plagioclase and pyroxene with brown alteration material and volcanic glass                                 |
| Ore 9        | Basalt                          | 2                    | 2                   | 5                        | 0.03            | 0.175-0.010 | Plagioclase and pyroxene somewhat altered, volcanic glass present  |
| Ore. 10      | Basalt                          | 8                    | 2                   | 6                        | 0.15            | 0.30-0.060  | Plagioclase and pyroxene present with slight alteration but little volcanic glass                          |



| DESIGNATION | ROCK TYPE                       | INSOLUBLE RESIDUE (%) | D.T A                 | X-RAY TOTAL SAMPLE                               | DEGRADATION NUMBER | CALC VOIDS (%) | CALC DEG. OF SATUR (%) | GRAIN SHAPE NUMBER | GRAIN INTER-LOCK NUMBER | GRAIN SIZE (MM) |            |
|-------------|---------------------------------|-----------------------|-----------------------|--|--------------------|----------------|------------------------|--------------------|-------------------------|-----------------|------------|
|             |                                 |                       |                       |  |                    |                |                        |                    |                         | AVG             | VARIATION  |
| Penn 1      | Limestone                       | 7.67                  | Calcite               | Calcite, little quartz                           | 8                  | 3.68           | 54                     | 7                  | 6                       | 1               | 4.0-0.40   |
| Penn. 2     | Dolomite                        | 8.35                  | —                     | Dolomite plus calcite                            | 4                  | 7.72           | 26                     | 2                  | 6                       | 0.015           | 0.3-0.005  |
| Penn 3      | Limestone                       | 21.40                 | —                     | Calcite, some quartz                             | 9                  | 2.21           | 48                     | 6                  | 4                       | 0.20            | 4.0-0.10   |
| Penn 4      | Limestone                       | 49.41                 | —                     | Calcite and quartz                               | 8                  | 2.21           | 79                     | —                  | —                       | —               | —          |
| Penn. 5     | Limestone                       | 8.29                  | Calcite               | Calcite, little quartz                           | 8                  | 2.94           | 86                     | 2                  | 6                       | 0.025           | 3.0-0.01   |
| Penn 6      | Limestone                       | 6.75                  | —                     | Calcite, little quartz and illite                | 8                  | 2.57           | 68                     | 2                  | 7                       | 0.050           | 0.17-0.02  |
| Penn. 7     | Graywacke sandstone             | —                     | Quartz, clay minerals | Quartz, some illite, little calcite and chlorite | 4                  | —              | —                      | 4                  | 6                       | 0.130           | 0.25-0.03  |
| Penn 8      | Red sandstone                   | —                     | Mica, clay, quartz    | Muscovite, illite quartz, some calcite           | 8                  | —              | —                      | 6                  | 6                       | 0.040           | 0.125-0.01 |
| Penn. 9     | Quartzite                       | —                     | —                     | —  | 8                  | —              | —                      | —                  | —                       | —               | —          |
| Penn. 10    | Slightly metamorphosed dolomite | 30.34                 | —                     | Dolomite plus quartz and calcite                 | 5                  | 7.00           | 29                     | 3                  | 8                       | 0.065           | 0.25-0.015 |
| Penn 11     | Diabase                         | —                     | —                     | —  | 9                  | —              | —                      | 3                  | 6                       | 0.50            | 1.5-0.1    |
| Penn. 12    | Dolomite                        | 6.61                  | —                     | Dolomite   | 8                  | 1.42           | 88                     | 3                  | 7                       | 0.060           | 0.75-0.010 |
| Penn 13     | Calcareous marble               | 19.64                 | —                     | Calcite, some dolomite, considerable quartz      | 8                  | 0.3            | 99                     | 5                  | 7                       | 1.0             | 2.0-0.1    |
| Penn. 14    | Carbonaceous limestone          | 28.91                 | Calcite plus organics | Calcite, some quartz                             | 8                  | 2.94           | 45                     | 4                  | 5                       | 0.08            | 0.5-0.04   |
| Penn 15     | Limestone                       | 6.81                  | Calcite               | Calcite  | 9                  | 3.16           | 35                     | 3                  | 7                       | 0.01            | 0.06-0.005 |
| Penn 16     | Dolomite                        | 16.42                 | —                     | Dolomite, some quartz                            | 7                  | 7.36           | 22                     | 4                  | 6                       | 0.06            | 0.7-0.01   |
| Penn. 17    | Limestone                       | 11.91                 | —                     | Calcite, little quartz                           | 8                  | 3.31           | 86                     | 4                  | 7                       | 0.025           | 3.0-0.02   |
| Penn. 18    | Limestone                       | 10.08                 | Calcite plus organics | Calcite  | 8                  | 0.29           | 99                     | 3                  | 7                       | 0.015           | 1.75-0.007 |
| Penn. 19    | Limestone                       | 52.55                 | Calcite               | Calcite plus quartz                              | 8                  | 2.57           | 43                     | 5                  | 6                       | 0.065           | 0.75-0.005 |
| Penn. 20    | Limestone                       | 27.36                 | Calcite               | Calcite plus quartz                              | 6                  | 1.84           | 99                     | 5                  | 6                       | 0.22            | 0.75-0.030 |

| DESIGNATION | ROCK TYPE           | GRAIN SHAPE NUMBER | GRAIN INTERLOCK NUMBER | GRAIN SIZE (MM) |             |
|-------------|---------------------|--------------------|------------------------|-----------------|-------------|
|             |                     |                    |                        | AVG.            | VARIATION   |
| Vir 1       | Marble              | 4                  | 7                      | 0.20            | 0.7-0.125   |
| Vir. 2      | Gneiss              | 5                  | 7                      | 0.30            | 0.7-0.1     |
| Vir 3       | Granite             | 4                  | 7                      | 0.60            | 2.0-0.1     |
| Vir. 4      | Dolomite            | 3                  | 6                      | 0.045           | 0.664-0.020 |
| Vir 5       | Granite             | 5                  | 7                      | 0.75            | 1.75-0.15   |
| Vir. 6      | Granite             | 5                  | 7                      | 0.30            | 1.0-0.08    |
| Vir 7       | Dolomite            | 3                  | 7                      | 0.01            | 0.25-0.05   |
| Vir 8       | Quartz diorite      | 5                  | 7                      | 0.60            | 1.0-0.1     |
| Vir. 9      | Gneiss              | 5                  | 8                      | 0.50            | 2.25-0.30   |
| Vir. 10     | Basalt              | 3                  | 7                      | 0.20            | 0.5-0.01    |
| Vir 11      | Gneiss              | 5                  | 8                      | 0.50            | 2.25-0.30   |
| Vir. 12     | Dolomite            | 4                  | 7                      | 0.05            | 0.07-0.02   |
| Vir. 13     | Limestone           | 2                  | 7                      | 0.20            | 0.125-0.005 |
| Vir 14      | Dolomite            | 2                  | 6                      | 0.175           | 0.25-0.035  |
| Vir. 15     | Granite             | 6                  | 6                      | 0.70            | 1.0-0.2     |
| Vir. 16     | Dolomite            | —                  | —                      | —               | —           |
| Vir 17      | Dolomite            | 4                  | 7                      | 0.10            | 0.25-0.025  |
| Vir. 18     | Limestone           | 3                  | 7                      | 0.06            | 0.25-0.025  |
| Vir. 19     | Limestone           | 6                  | 6                      | 0.04            | 1.0-0.02    |
| Vir. 20     | Limestone           | 4                  | 7                      | 0.015           | 0.04-0.005  |
| Vir. 21     | Dolomite            | 3                  | 7                      | 0.08            | 0.10-0.02   |
| Vir 22      | Quartzite           | 5                  | 7                      | 0.50            | 1.0-0.2     |
| Vir. 23     | Limestone           | 3                  | 7                      | 0.017           | 0.03-0.005  |
| Vir 24      | Gneiss              | 4                  | 6                      | 0.50            | 2.0-0.20    |
| Vir 25      | Limestone           | 4                  | 8                      | 0.025           | 0.10-0.008  |
| Vir 26      | Limestone           | 7                  | 6                      | 0.15            | 0.6-0.10    |
| Vir 27      | Diabase             | 2                  | 7                      | 0.40            | 1.0-0.15    |
| Vir 28      | Limestone           | 3                  | 7                      | 0.020           | 0.035-0.006 |
| Vir. 29     | Limestone           | 6                  | 6                      | 0.30            | 1.5-0.03    |
| Vir. 30     | Dolomite            | 3                  | 6                      | 0.012           | 0.25-0.005  |
| Vir. 31     | Dolomite            | 5                  | 8                      | 0.05            | 0.1-0.02    |
| Vir. 32     | Diabase             | 3                  | 6                      | 0.30            | 0.75-0.10   |
| Vir. 33     | Granite             | 5                  | 8                      | 0.40            | 3.0-0.50    |
| Vir. 34     | Graywacke sandstone | 5                  | 6                      | 0.025           | 0.2-0.005   |

| DESIGNATION | ROCK TYPE       | INSOLUBLE RESIDUE (%) | D T A    | X-RAY TOTAL SAMPLE  | DEGRADATION NUMBER | CALC VOIDS (%) | CALC DEG. OF SATUR (%) | GRAIN SHAPE NUMBER | GRAIN INTER-LOCK NUMBER | GRAIN SIZE (MM) |             |
|-------------|-----------------|-----------------------|----------|---------------------|--------------------|----------------|------------------------|--------------------|-------------------------|-----------------|-------------|
|             |                 |                       |          |                     |                    |                |                        |                    |                         | AVG             | VARIATION   |
| Wis 1       | Dolomite        | —                     | —        | —                   | 3                  | 12.28          | 61                     | —                  | —                       | —               | —           |
| Wis. 2      | Dolomite        | —                     | —        | —                   | 4                  | 18.3           | 56                     | —                  | —                       | —               | —           |
| Wis 3       | Dolomite        | —                     | —        | —                   | 8                  | 2.8            | 66                     | —                  | —                       | —               | —           |
| Wis 4       | Quartzite       | —                     | —        | —                   | —                  | —              | —                      | —                  | —                       | —               | —           |
| Wis 5       | Dolomite gravel | —                     | —        | —                   | —                  | —              | —                      | —                  | —                       | —               | —           |
| Wis 6       | Igneous gravel  | —                     | —        | —                   | —                  | —              | —                      | —                  | —                       | —               | —           |
| Wis 7       | Dolomite        | 19.0                  | Dolomite | Dolomite and quartz | 3                  | 14.1           | 64                     | 4                  | 4                       | 0.065           | 0.75-0.030  |
| Wis. 8      | Dolomite        | 6.4                   | Dolomite | Dolomite and quartz | 6                  | 17.9           | 54                     | 3                  | 6                       | 0.075           | 0.15-0.030  |
| Wis 9       | Dolomite        | 7.6                   | Dolomite | Dolomite and quartz | 4                  | —              | —                      | 4                  | 5                       | 0.15            | 0.25-0.07   |
| Wis 10      | Dolomite        | 9.0                   | Dolomite | Dolomite and quartz | 3                  | 8.4            | 59                     | 3                  | 5                       | 0.07            | 0.12-0.03   |
| Wis. 11     | Dolomite        | 5.0                   | Dolomite | Dolomite and quartz | 4                  | —              | —                      | 4                  | 5                       | 0.10            | 0.25-0.02   |
| Wis. 12     | Dolomite        | 19.0                  | Dolomite | Dolomite and quartz | 3                  | 12.6           | 59                     | 4                  | 5                       | 0.06            | 0.175-0.020 |

## APPENDIX F

### SEMI-QUANTITATIVE ANALYSIS OF CARBONATE INSOLUBLES

|        |                               |                        |
|--------|-------------------------------|------------------------|
| Legend | x Trace to small amount       | xxxxx Large amount     |
|        | xx Small amount               | F *—Probably feldspar  |
|        | xxx Moderate amount           | S *—Probably sepiolite |
|        | xxxx Moderate to large amount |                        |

| DESIGNATION     | MONTMOR-<br>ILLONITE | CHLORITE | VERMIC-<br>ULITE | ILLITE | HYDRO-<br>BIOTITE | KAOLINITE | QUARTZ | FELDSPARS<br>AND/OR<br>SEPIOLITE |
|-----------------|----------------------|----------|------------------|--------|-------------------|-----------|--------|----------------------------------|
| Ill 1           |                      |          |                  | XX     | X                 | X         | XXXX   | X                                |
| Ill. 2 (bed 1)  | x                    |          | x                | X      |                   |           | XXX    | X                                |
| Ill. 2 (bed 2)  |                      |          | x                | XX     |                   |           | XXXXX  |                                  |
| Ill 3           |                      |          |                  | X      | X                 |           | XXXXX  | X                                |
| Ill 4 (bed 2)   |                      |          |                  | X      | X                 |           | XXXXX  |                                  |
| Ill. 5          |                      |          |                  | X      |                   |           | XXXXX  |                                  |
| Ill 6           |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Ill. 7          |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Ill 8           |                      |          |                  | X      |                   | X         | XXXXX  | X                                |
| Ill 9           |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Ill. 11         |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Iowa 1 (bed 2)  |                      |          | x                | XX     |                   |           | XXXXX  | X                                |
| Iowa 2 (bed 10) |                      |          | x                | X      |                   |           | XXXX   | X                                |
| Iowa 3 (bed 3)  |                      |          |                  | XXXX   |                   |           | XXX    |                                  |
| Iowa 4 (bed 4)  |                      |          | x                | X      |                   |           | XXXXX  | X                                |
| Iowa 5 (bed 6)  |                      |          | x                | XX     |                   |           | XXXXX  | X                                |
| Mo 1            |                      |          | x                | X      |                   |           | XXXXX  | xx S *                           |
| Mo 2            |                      |          | x                | X      |                   |           | XXXX   |                                  |
| Mo 3            |                      |          | x                | XX     |                   |           | XXXX   |                                  |
| Mo 4            |                      |          |                  | XX     | X                 |           | XXXXX  |                                  |
| Mo 5            |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Mo 6            |                      |          |                  | XX     | X                 |           | XXXXX  |                                  |
| Mo 7            |                      |          |                  | XX     |                   | X         |        |                                  |
| Mo 8            |                      |          |                  | X      | X                 |           | XXXXX  | x F *                            |
| Mo 9            |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Mo. 10          |                      |          | x                | XX     |                   |           | XXXXX  | X                                |
| Mo 11           |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Mo. 12          |                      |          |                  | XX     | X                 |           | XXXXX  |                                  |
| Mo 13           |                      |          | x                | XX     |                   |           | XXXXX  | x F                              |
| Mo 14           |                      |          | x                | XX     |                   |           | XXXXX  |                                  |
| Mo 15           |                      |          | x                | XX     |                   |           | XXXXX  | X                                |
| Mo 16           |                      |          | x                | X      |                   |           | XXXXX  | xx F                             |
| Mo 16a          |                      |          | x                | X      |                   |           | XXXXX  | x F                              |
| Mo 17           |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Mo 18           |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Mo 19           |                      |          | x                | X      |                   |           | XXXXX  | x F                              |
| Mo 20           |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Mo. 21          |                      |          | x                | X      |                   |           | XXXXX  | x F                              |
| Mo 22           |                      | x        |                  | XX     |                   | X         | XXXXX  | x F                              |
| Mo 23           |                      |          |                  | XX     | X                 |           | XXXXX  | F                                |
| Mo. 24          |                      |          |                  | X      | X                 |           | XXXXX  | x F                              |
| N.Y. 1          |                      |          |                  | X      |                   |           | XXXXX  |                                  |
| N.Y. 2          |                      |          | x                | XX     |                   | X         | XXXX   |                                  |
| N.Y. 3          |                      |          | x                |        | X                 |           | XXXXX  |                                  |
| N.Y. 5          |                      |          |                  | X      | X                 |           | XXXXX  | xx                               |
| N.Y. 7          |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| N.Y. 8          |                      |          |                  | XX     | X                 |           | XXXXX  | F                                |
| N.Y. 9          |                      |          |                  | XXXX   |                   | X         | XXXX   | x F                              |
| Penn 1          |                      |          | x                |        |                   |           | XXXXX  |                                  |
| Penn 2          |                      |          | x                |        |                   |           | XXXXX  |                                  |
| Penn 3          |                      |          |                  | X      |                   |           | XXXX   | x S                              |
| Penn 4          |                      |          | x                | X      |                   |           | XXXXX  |                                  |
| Penn 5          |                      |          |                  | XX     |                   |           | XXXXX  | X                                |
| Penn. 6         |                      |          |                  | XX     |                   |           | XXXXX  | X                                |
| Penn. 10        |                      | x        |                  | XX     |                   | X         | XXXXX  | xx F                             |
| Penn. 12        |                      |          |                  | XXX    |                   |           | XXXX   | xx F                             |
| Penn. 14        |                      |          | x                | X      |                   |           | XXXXX  | x F                              |
| Penn. 15        | xx                   |          |                  | XX     |                   |           | XXXXX  |                                  |
| Penn 16         |                      |          | x                | X      |                   |           | XXXXX  | x S                              |
| Penn 17         |                      |          |                  | XXX    |                   | xxx       | XXXX   | x S                              |
| Penn. 18        |                      |          |                  | X      |                   | X         | XXXX   | x S                              |
| Penn. 19        |                      |          |                  | X      |                   |           | XXXXX  | xx S                             |
| Penn. 20        |                      |          | xx               | XX     |                   |           | XXXX   |                                  |
| Wis 1 (bed 1)   |                      |          | x                | XX     |                   |           | XXXX   | xx F                             |
| Wis. 1 (bed 2)  |                      |          |                  | XX     | XX                |           | XXXXX  | X                                |
| Wis 1 (bed 3)   |                      |          |                  | XXX    |                   |           | XXXX   | xx F                             |
| Wis. 2 (bed 1)  |                      |          | x                | XX     |                   |           | XXXX   | xx F                             |
| Wis 2 (bed 2)   |                      |          | x                | X      |                   |           | XXXXX  | x F                              |
| Wis. 3 (bed 1)  |                      |          |                  | X      | X                 |           | XXXXX  | xx F                             |
| Wis. 3 (bed 2)  |                      |          | x                | X      |                   |           | XXXXX  | xx F                             |
| Wis. 4 (bed 1)  |                      |          | x                | X      |                   |           | XXXXX  | xx F                             |
| Wis. 4 (bed 2)  |                      |          | xx               | XX     |                   |           | XXXXX  | xx F                             |
| Wis. 5 (bed 1)  |                      |          | x                | XXX    |                   |           | XXXXX  | xx F                             |
| Wis. 5 (bed 2)  |                      |          | x                | XXX    |                   |           | XXXXX  | xx F                             |
| Wis. 6 (bed 1)  |                      |          | xx               | XXX    |                   |           | XXXXX  | xx F                             |
| Wis 6 (bed 2)   |                      |          |                  | XXXXX  | XX                |           | XXXXX  | xx F                             |

# APPENDIX G

## SUMMARY OF DATA ON AGGREGATE SAMPLES, PHASE II

Legend LA = Los Angeles abrasion loss, F-T = freeze-thaw loss, SPG = specific gravity, ABS = percent absorption, INS = percent insoluble residue, GL = grain interlock number, GN = grain roundness number, AVSIZ = average size (mm), STDEV = standard deviation of average size (mm), AVMAT = average matrix size (mm), SDMAT = standard deviation of average matrix size (mm), VOID = percent voids, MTRX = percent matrix, M/G = matrix diameter/grain diameter, MX/MIN = maximum diameter/minimum diameter, DV = degradation value

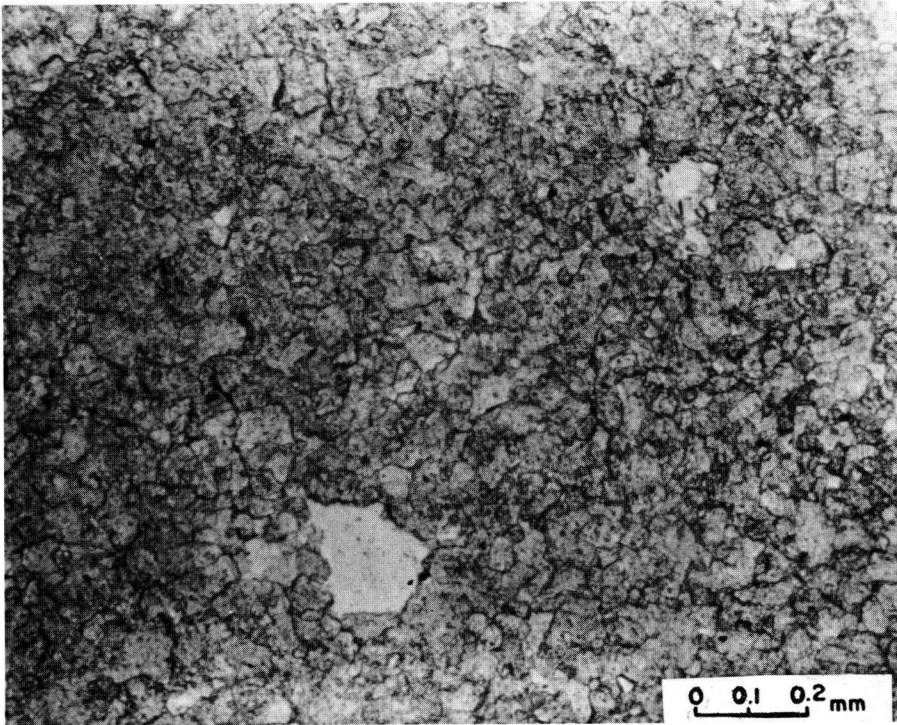
| SAMPLE     | ROCK NAME | LA   | F-T  | SPG  | ABS | INS  | GL | GN | AVSIZ | STDEV | AVMAT | SDMAT | VOID | MTRX | M/G   | MX/MN | DV |
|------------|-----------|------|------|------|-----|------|----|----|-------|-------|-------|-------|------|------|-------|-------|----|
| Fla 1      | Limestone | 50.5 | 7.2  | 2.34 | 5.4 | —    | —  | —  | 0.428 | 0.411 | .246  | .178  | 17.6 | 44.7 | 0.900 | 1.750 | 4  |
| Fla 2      | Limestone | 29.2 | 2.6  | —    | —   | —    | —  | —  | 0.281 | 0.140 | .228  | .201  | 17.6 | 46.3 | 1.042 | 1.436 | 7  |
| Fla. 3     | Limestone | 34.0 | 3.4  | —    | —   | —    | —  | —  | 0.006 | 0.004 | .099  | .065  | 5.2  | 86.5 | 9.999 | 1.372 | 5  |
| Fla 4      | Limestone | 32.5 | 2.7  | —    | —   | —    | —  | —  | 0.765 | 0.348 | .584  | .456  | 23.3 | 44.8 | 1.101 | 1.770 | 5  |
| Fla. 5     | Limestone | 29.1 | 1.2  | 2.58 | 1.5 | —    | —  | —  | 0.131 | 0.082 | .166  | .143  | 26.1 | 62.2 | 1.732 | 1.591 | 7  |
| Fla. 6     | Limestone | 32.7 | 1.2  | 2.54 | 2.7 | —    | —  | —  | 0.014 | 0.026 | .039  | .039  | 5.8  | 55.6 | 3.880 | 1.708 | 5  |
| Fla 7      | Limestone | 36.2 | 2.9  | —    | —   | —    | —  | —  | 0.014 | 0.010 | .050  | .047  | 17.8 | 57.2 | 4.659 | 1.494 | 5  |
| Fla. 8     | Limestone | 35.6 | 1.7  | 2.50 | 3.5 | —    | —  | —  | 0.009 | 0.006 | .033  | .038  | 29.1 | 46.9 | 4.683 | 1.408 | 5  |
| Ga 1       | Granite   | 54.5 | 2.3  | —    | —   | —    | —  | —  | 0.736 | 0.504 | .280  | .153  | —    | 1.9  | 0.628 | 1.785 | 4  |
| Ga 2       | Granite   | 71.5 | 1.1  | 2.62 | 0.5 | —    | —  | —  | 0.854 | 0.487 | —     | —     | —    | —    | —     | 1.700 | 7  |
| Ga. 3      | Gneiss    | 44.5 | 0.7  | 2.70 | 0.5 | —    | —  | —  | 0.790 | 0.906 | .281  | .103  | —    | 2.6  | 0.385 | 1.769 | 6  |
| Ga. 4      | Gneiss    | 45.6 | 2.4  | —    | 0.8 | —    | —  | —  | 0.270 | 0.223 | —     | —     | —    | —    | —     | 1.929 | 8  |
| Ga 7       | Gneiss    | 41.7 | 2.9  | 2.61 | 0.5 | —    | —  | —  | 0.738 | 0.494 | .203  | .068  | —    | 2.0  | 0.393 | 1.822 | 7  |
| Ga 9       | Gneiss    | 57.2 | 0.6  | 2.65 | 0.6 | —    | —  | —  | 0.394 | 0.220 | .232  | .082  | —    | 3.7  | 0.760 | 1.784 | 5  |
| Ga 10      | Limestone | 23.9 | 1.0  | 2.67 | 0.5 | —    | —  | —  | 0.023 | 0.015 | .034  | .019  | —    | 49.8 | 1.844 | 1.524 | 7  |
| III. 1     | Limestone | 29.5 | 1.4  | 2.63 | 1.2 | 3.2  | 6  | 5  | 1.333 | 1.173 | .793  | .573  | —    | 41.3 | 1.492 | 2.975 | 5  |
| III. 2     | Dolomite  | —    | —    | —    | —   | —    | —  | —  | 0.343 | 0.488 | .665  | .488  | 0.9  | 63.0 | 3.290 | 1.971 | —  |
| III. 3 PE  | Limestone | 30.5 | 3.1  | 2.55 | 2.5 | 19.3 | 1  | 6  | 0.029 | 0.024 | .048  | .049  | 6.5  | 55.9 | 2.196 | 1.465 | 3  |
| III. 3 PA  | —         | —    | —    | —    | —   | —    | —  | —  | 0.017 | 0.012 | .047  | .035  | 7.4  | 68.0 | 3.181 | 1.374 | —  |
| III. 4 A 1 | Dolomite  | 66.8 | 11.8 | 2.42 | 4.0 | 3.6  | 4  | 4  | 0.980 | 1.564 | .185  | .244  | —    | 17.1 | 0.391 | 1.964 | 3  |
| III. 4 A 1 | —         | —    | —    | —    | —   | —    | —  | —  | 0.084 | 0.043 | .043  | .023  | —    | 11.7 | 0.626 | 1.404 | —  |
| III. 4 B 1 | —         | —    | —    | —    | —   | —    | —  | —  | 0.093 | 0.042 | .028  | .012  | —    | 23.6 | 0.402 | 1.459 | —  |
| III. 4 B 2 | —         | —    | —    | —    | —   | —    | —  | —  | 0.051 | 0.027 | .025  | .012  | —    | 13.3 | 0.642 | 1.498 | —  |
| III. 4 APE | —         | —    | —    | —    | —   | —    | —  | —  | 0.773 | 1.032 | .304  | .170  | 3.2  | 28.5 | 0.657 | 1.644 | —  |
| III. 5     | Limestone | 28.7 | 1.8  | —    | —   | 22.0 | 4  | 4  | 0.010 | 0.008 | .024  | .014  | —    | 68.8 | 2.875 | 1.462 | 4  |
| III. 5 PE  | —         | —    | —    | —    | —   | —    | —  | —  | 0.012 | 0.009 | .050  | .044  | —    | 87.4 | 7.492 | 1.975 | —  |
| III. 6     | Limestone | 37.8 | 3.2  | —    | —   | 4.9  | 3  | 7  | 1.614 | 1.149 | .400  | .298  | —    | 21.8 | 0.430 | 1.949 | 3  |
| III. 6 PA  | —         | —    | —    | —    | —   | —    | —  | —  | 1.150 | 0.727 | .348  | .130  | —    | 1.0  | 0.494 | 1.845 | —  |
| III. 6 PE  | —         | —    | —    | —    | —   | —    | —  | —  | 0.728 | 0.477 | .446  | .275  | —    | 1.6  | 0.569 | 1.778 | —  |
| III. 7     | Limestone | 25.7 | 1.2  | 2.62 | 1.5 | 6.5  | 5  | 5  | 0.385 | 0.300 | .082  | .115  | —    | 29.5 | 0.420 | 2.423 | 5  |
| III. 7 PE  | —         | —    | —    | —    | —   | —    | —  | —  | 0.272 | 0.186 | .122  | .074  | —    | 17.1 | 0.831 | 2.211 | —  |
| III. 7 PA  | —         | —    | —    | —    | —   | —    | —  | —  | 0.409 | 0.272 | .135  | .113  | —    | 18.0 | 0.877 | 2.877 | —  |
| III. 8     | Limestone | 26.7 | 0.8  | 2.60 | 1.7 | 15.6 | 4  | 7  | 0.039 | 0.023 | .024  | .016  | —    | —    | —     | 1.448 | 4  |
| III. 9     | Limestone | 26.4 | 2.8  | —    | —   | 39.2 | 1  | 2  | 0.061 | 0.050 | .035  | .019  | —    | 51.1 | 1.378 | 3.586 | 6  |
| III. 9 PA  | Dolomite  | —    | —    | —    | —   | —    | —  | —  | 0.054 | 0.043 | .027  | .025  | —    | 55.4 | 1.429 | 3.048 | —  |
| III. 11    | —         | 51.6 | 7.2  | 2.37 | 4.7 | 12.7 | 4  | 4  | 0.032 | 0.019 | .052  | .058  | 17.1 | 42.3 | 1.975 | 1.386 | 2  |
| III. 11 PE | —         | —    | —    | —    | —   | —    | —  | —  | 0.040 | 0.028 | .077  | .077  | —    | 65.8 | 2.509 | 1.518 | —  |
| III. 12    | Dolomite  | 35.0 | —    | 2.66 | 0.7 | 4.9  | —  | —  | 0.003 | 0.002 | —     | —     | —    | —    | —     | 1.667 | 8  |
| Ind 3      | Dolomite  | 27.8 | 1.0  | —    | —   | —    | 6  | 7  | 0.052 | 0.029 | .116  | .070  | —    | 66.2 | 1.666 | 1.443 | 6  |
| Ind. 4     | Dolomite  | 32.6 | 1.3  | —    | —   | —    | 6  | 8  | 0.137 | 0.074 | .061  | .021  | 9.7  | 3.8  | 1.582 | 0.604 | 5  |
| Ind. 5     | Dolomite  | 32.1 | 0.8  | —    | —   | —    | 5  | 7  | 0.036 | 0.019 | .018  | .009  | 10.6 | 9.7  | 1.218 | 0.597 | 5  |
| Ind 7      | Dolomite  | 22.3 | 0.6  | —    | —   | —    | 6  | 6  | 0.110 | 0.074 | .081  | .065  | 5.0  | 12.8 | 1.061 | 1.499 | 9  |
| Ind. 8     | Dolomite  | 30.5 | 0.6  | —    | —   | —    | 5  | 6  | 0.026 | 0.018 | .015  | .010  | 12.5 | 14.1 | 0.761 | 1.450 | 5  |
| Ind. 9     | Dolomite  | 36.4 | 1.2  | —    | —   | —    | 6  | 6  | 0.029 | 0.019 | .016  | .011  | 11.4 | 9.4  | 0.719 | 1.429 | 5  |
| Ind. 11    | Dolomite  | 21.7 | 0.7  | —    | —   | —    | 7  | 5  | 0.093 | 0.061 | .038  | .013  | 7.2  | 1.5  | 1.440 | 0.549 | 8  |

|          |             |      |      |      |     |      |   |   |       |       |      |      |      |      |       |       |   |
|----------|-------------|------|------|------|-----|------|---|---|-------|-------|------|------|------|------|-------|-------|---|
| Iowa 12  | Dolomite    | 35.0 | 5.0  | 2.68 | 2.7 | 11.0 | 4 | 2 | 0.036 | 0.016 | .022 | .011 | 11.3 | 10.3 | 0.771 | 1.539 | 3 |
| Iowa 28  | Dolomite    | 36.0 | 2.6  | 2.67 | 1.4 | 5.3  | 7 | 2 | 0.043 | 0.024 | .024 | .014 | 6.8  | 13.5 | 0.761 | 1.728 | 7 |
| Iowa 33  | Dolomite    | 43.0 | —    | 2.62 | 3.5 | 23.3 | 4 | 3 | 0.27  | 0.011 | .018 | .026 | —    | 22.5 | 0.839 | 1.481 | 3 |
| Iowa 43  | Limestone   | 41.0 | —    | 2.65 | 1.1 | 2.3  | 2 | 7 | 0.206 | 0.117 | .095 | .082 | —    | 26.5 | 0.702 | 1.786 | 7 |
| Iowa 57  | Limestone   | 29.0 | 6.5  | 2.67 | 1.2 | 7.5  | 1 | 6 | 0.008 | 0.008 | .031 | .012 | 12.2 | 65.0 | 5.335 | 1.489 | 3 |
| Mo. 1    | Limestone   | 28.6 | 0.6  | 2.65 | 0.6 | 4.3  | 6 | 4 | 0.207 | 0.260 | .164 | .118 | —    | 54.9 | 1.347 | 2.162 | 7 |
| Mo. 2 A  | Dolomite    | 60.6 | 4.6  | 2.63 | 1.8 | 2.2  | 6 | 4 | 0.202 | 0.138 | .161 | .092 | —    | 33.7 | 1.183 | 1.698 | 3 |
| Mo. 3    | Limestone   | 42.9 | 1.0  | 2.63 | 0.7 | 4.0  | 8 | 5 | 0.702 | 0.473 | .276 | .214 | —    | 19.5 | 0.674 | 1.925 | 7 |
| Mo. 4    | Dolomite    | 78.9 | 22.1 | 2.55 | 2.0 | 5.3  | 3 | 3 | 0.033 | 0.014 | .024 | .012 | —    | 37.3 | 0.951 | 1.464 | 3 |
| Mo. 5    | Limestone   | 48.4 | 1.4  | 2.66 | 0.8 | 1.6  | 7 | 6 | 0.134 | 0.095 | .144 | .096 | —    | 52.7 | 1.430 | 1.828 | 7 |
| Mo. 6    | Dolomite    | 46.0 | —    | 2.58 | 1.2 | 2.9  | 4 | 2 | 0.033 | 0.013 | .026 | .008 | 14.3 | 3.9  | 0.949 | 1.426 | 3 |
| Mo. 7    | Limestone   | 28.4 | 1.2  | 2.60 | 1.3 | 8.2  | 5 | 4 | 0.196 | 0.189 | .189 | .200 | —    | 58.6 | 1.596 | 1.928 | 8 |
| Mo. 8    | Dolomite    | 23.0 | 1.2  | —    | —   | 4.5  | — | — | 0.148 | 0.130 | —    | —    | —    | —    | —     | 2.891 | 8 |
| Mo. 9    | Sandstone   | 33.0 | —    | —    | —   | 1.1  | — | — | 0.021 | 0.011 | .025 | .016 | —    | 25.0 | 1.567 | 1.517 | 4 |
| Mo. 10   | Limestone   | 43.7 | —    | 2.62 | 0.8 | 0.8  | — | — | 1.015 | 0.726 | .322 | .178 | —    | 12.6 | 0.511 | 1.780 | 4 |
| Mo. 11   | Dolomite    | 28.9 | —    | —    | —   | 13.4 | — | — | 0.018 | 0.010 | .012 | .007 | —    | 10.1 | 0.865 | 1.446 | 3 |
| Mo. 12   | Limestone   | 44.0 | —    | 2.65 | 0.5 | 3.1  | 7 | 5 | 0.176 | 0.158 | .078 | .046 | —    | 33.3 | 0.849 | 1.990 | 7 |
| Mo. 13   | Limestone   | 26.1 | 1.0  | 2.67 | 0.5 | 3.8  | 4 | 6 | 0.147 | 0.123 | .310 | .265 | —    | 73.4 | 2.891 | 1.780 | 8 |
| Mo. 14   | Limestone   | 40.3 | 0.8  | 2.40 | 3.5 | 10.9 | 4 | 1 | 0.009 | 0.004 | .007 | .004 | —    | 32.7 | 0.892 | 1.503 | 3 |
| Mo. 15   | Dolomite    | 34.6 | —    | 2.54 | 3.0 | 20.2 | 5 | 4 | 0.047 | 0.018 | .021 | .015 | —    | 11.3 | 0.586 | 1.407 | 7 |
| Mo. 16   | Dolomite    | 32.5 | —    | 2.45 | 4.0 | 33.8 | 4 | 2 | 0.007 | 0.003 | .016 | .007 | —    | 40.2 | 3.115 | 1.497 | 3 |
| Mo. 16 A | Dolomite    | 32.9 | —    | 2.66 | 0.7 | 2.6  | — | — | 0.042 | 0.015 | .020 | .004 | —    | 7.2  | 0.598 | 1.357 | 7 |
| Mo. 17   | Limestone   | —    | —    | 2.55 | 1.3 | 7.2  | — | — | 0.206 | 0.208 | .291 | .220 | —    | 70.8 | 2.508 | 1.911 | 7 |
| Mo. 18   | Dolomite    | 32.3 | —    | 2.52 | 2.1 | 32.1 | — | — | 0.094 | 0.072 | .095 | .075 | —    | 37.5 | 1.304 | 1.454 | 7 |
| Mo. 19   | Dolomite    | 31.0 | —    | 2.46 | 2.7 | 12.0 | 5 | 3 | 0.014 | 0.009 | .018 | .009 | —    | 40.8 | 1.580 | 1.499 | 7 |
| Mo. 20   | Dolomite    | 53.0 | —    | 2.35 | 6.0 | 35.3 | 3 | 6 | 0.021 | 0.010 | .024 | .011 | —    | 54.8 | 1.420 | 1.403 | 2 |
| Mo. 21   | Limestone   | 26.5 | 1.8  | 2.66 | 0.7 | 3.4  | 5 | 6 | —     | —     | —    | —    | —    | —    | —     | —     | 7 |
| Mo. 22   | Limestone   | 36.0 | 4.2  | 2.58 | 1.2 | 9.6  | 4 | 5 | 0.273 | 0.175 | .188 | .160 | —    | 53.5 | 0.850 | 1.358 | 4 |
| Mo. 23   | Limestone   | 30.4 | 4.3  | —    | —   | 7.6  | — | — | 0.012 | 0.008 | .014 | .009 | —    | 44.7 | 1.574 | 1.481 | 7 |
| Mo. 24   | Limestone   | 35.0 | 0.0  | —    | —   | 47.2 | — | — | 0.026 | 0.017 | .041 | .029 | —    | 56.0 | 1.758 | 1.726 | 4 |
| N.Y. 1   | Dolomite    | 35.7 | 0.8  | 2.72 | —   | 2.2  | 6 | 3 | 0.113 | 0.054 | .039 | .008 | —    | 1.5  | 0.413 | 1.529 | 7 |
| N.Y. 2   | Limestone   | 23.0 | 0.3  | 2.72 | —   | 14.5 | 7 | 5 | 0.032 | 0.036 | .055 | .038 | —    | 72.9 | 2.979 | 2.091 | 7 |
| N.Y. 3   | Limestone   | 24.1 | 0.8  | 2.66 | —   | 18.9 | 6 | 7 | 0.650 | 0.699 | .896 | .772 | —    | 69.9 | 2.458 | 2.061 | 6 |
| N.Y. 5   | Dolomite    | 18.0 | 0.5  | 2.80 | —   | 6.2  | 7 | 2 | —     | —     | —    | —    | —    | —    | —     | —     | — |
| N.Y. 6   | Diabase     | 12.5 | —    | 2.85 | —   | —    | 6 | 3 | 0.408 | 0.482 | .833 | .756 | —    | 68.1 | 2.847 | 2.183 | 9 |
| N.Y. 7   | Limestone   | 19.3 | 0.6  | 2.70 | —   | 42.4 | 7 | 4 | 0.028 | 0.022 | .012 | .006 | —    | 11.2 | 0.773 | 1.907 | 9 |
| N.Y. 8   | Graywacke   | 21.9 | —    | 2.60 | —   | 97.2 | 7 | 5 | 0.047 | 0.025 | .126 | .101 | —    | 72.0 | 3.265 | 1.407 | 4 |
| N.Y. 9   | Graywacke   | 24.6 | 1.2  | 2.64 | —   | 89.7 | 6 | 4 | 0.100 | 0.046 | .072 | .032 | —    | 26.7 | 1.007 | 1.669 | 4 |
| Okla. 1  | Chert       | 20.9 | 0.9  | 2.61 | 0.3 | —    | — | — | 0.053 | 0.065 | .063 | .055 | —    | 63.5 | 2.008 | 1.902 | 9 |
| Okla. 2  | Sandstone   | 38.7 | 4.0  | —    | —   | —    | — | — | 0.055 | 0.034 | .057 | .038 | 10.7 | 47.0 | 1.803 | 1.862 | 3 |
| Okla. 3  | Limestone   | 33.4 | 2.7  | —    | —   | —    | — | — | 0.172 | 0.143 | .308 | .251 | 16.1 | 55.8 | 2.808 | 1.744 | 4 |
| Okla. 4  | Limestone   | 21.1 | 0.6  | —    | —   | —    | — | — | 0.158 | 0.144 | .191 | .131 | 0.5  | 61.6 | 1.794 | 1.841 | 8 |
| Ore. 1   | Lithicwacke | 16.0 | —    | 2.74 | —   | —    | 7 | 6 | 0.118 | 0.084 | .095 | .058 | —    | 37.4 | 1.088 | 1.500 | 2 |
| Ore. 2   | Lithicwacke | 13.3 | —    | 2.74 | —   | —    | 7 | 5 | 0.111 | 0.115 | .057 | .040 | —    | 33.8 | 0.651 | 1.540 | 7 |
| Ore. 3   | Limestone   | 20.6 | —    | 2.70 | —   | 30.7 | 6 | 7 | 0.005 | —     | —    | —    | —    | —    | —     | —     | 3 |
| Ore. 4   | Basalt      | 21.4 | —    | 2.82 | —   | —    | 6 | 2 | 0.073 | 0.079 | —    | —    | —    | —    | —     | 2.955 | 8 |
| Ore. 5   | Basalt      | 21.1 | —    | 2.84 | —   | —    | 6 | 2 | 0.115 | 0.126 | .065 | .039 | —    | 37.6 | 1.012 | 2.168 | 8 |
| Ore. 6   | Basalt      | 22.0 | —    | 2.78 | —   | —    | 6 | 2 | 0.032 | 0.031 | —    | —    | —    | —    | —     | 1.602 | 8 |
| Ore. 7   | Basalt      | 25.0 | —    | 2.94 | —   | —    | 7 | 2 | 0.128 | 0.111 | .071 | .043 | —    | 33.8 | 1.043 | 2.125 | 2 |
| Ore. 8   | Basalt      | 14.6 | —    | 2.85 | —   | —    | 6 | 4 | 0.281 | 0.193 | —    | —    | —    | —    | —     | 2.814 | 4 |
| Ore. 9   | Basalt      | 16.8 | —    | 2.79 | —   | —    | 5 | 2 | 0.014 | 0.013 | .015 | .009 | —    | 51.3 | 1.738 | 2.311 | 2 |
| Ore. 10  | Basalt      | 17.4 | —    | 2.88 | —   | —    | 6 | 2 | 0.061 | 0.037 | .092 | .072 | —    | 72.4 | 2.972 | 2.372 | 8 |
| Penn. 1  | Limestone   | 24.1 | 0.9  | 2.63 | 0.8 | 7.7  | 6 | 7 | —     | —     | —    | —    | —    | —    | —     | —     | 8 |
| Penn. 2  | Dolomite    | —    | —    | 2.53 | 0.8 | 8.4  | 6 | 2 | 0.068 | 0.052 | .278 | .204 | 10.8 | 75.3 | 5.578 | 1.529 | 4 |
| Penn. 3  | Limestone   | 25.2 | 0.6  | 2.67 | 0.4 | 21.4 | 4 | 6 | —     | —     | —    | —    | —    | —    | —     | —     | 9 |
| Penn. 4  | Limestone   | 26.5 | 0.2  | 2.67 | 0.7 | 49.4 | — | — | 0.461 | 0.532 | .532 | .402 | —    | 53.3 | 1.543 | 1.623 | 8 |
| Penn. 5  | Limestone   | 22.3 | 0.6  | 2.66 | 1.0 | 8.3  | 6 | 2 | 0.095 | 0.194 | .228 | .130 | —    | 77.7 | 3.619 | 1.676 | 8 |
| Penn. 6  | Limestone   | 27.9 | 0.6  | 2.67 | 0.7 | 6.8  | 7 | 2 | 0.043 | 0.024 | .107 | .071 | —    | 71.3 | 3.101 | 1.502 | 8 |

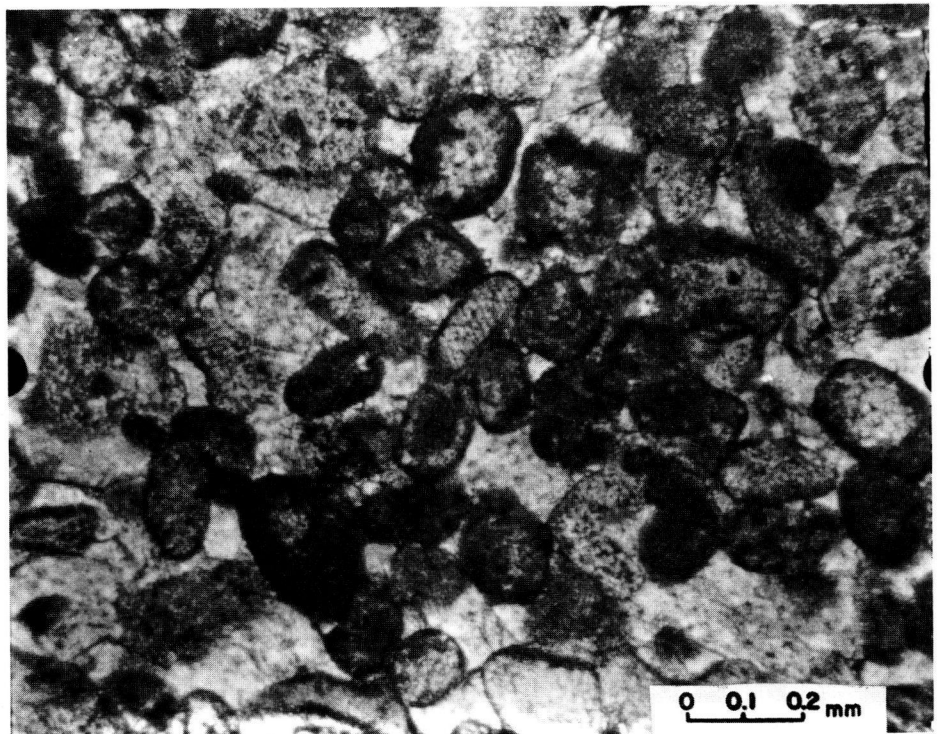
| SAMPLE   | ROCK<br>NAME | LA   | F-T  | SPG  | ABS | INS  | GL | GN | AVSIZ | STDEV | AVMAT | SDMAT | VOID | MTRX | M/G   | MX/MN | DV |
|----------|--------------|------|------|------|-----|------|----|----|-------|-------|-------|-------|------|------|-------|-------|----|
| Penn. 7  | Graywacke    | 21.1 | —    | 2.68 | 0.8 | —    | 6  | 4  | 0.125 | 0.062 | .105  | .062  | —    | 44.2 | 1.237 | 1.549 | 5  |
| Penn. 8  | Sandstone    | 13.5 | 0.3  | 2.66 | 0.8 | —    | 6  | 6  | 0.034 | 0.019 | .026  | .023  | —    | 40.2 | 1.049 | 1.591 | 8  |
| Penn. 9  | Quartzite    | 14.0 | 0.2  | 2.66 | 1.2 | —    | —  | —  | —     | —     | —     | —     | —    | —    | —     | —     | 8  |
| Penn. 10 | Dolomite     | 26.1 | 0.3  | 2.67 | 0.8 | 30.3 | 8  | 3  | 0.092 | 0.051 | 134   | 085   | —    | 56.2 | 1.891 | 1.516 | 5  |
| Penn. 11 | Diabase      | 14.9 | 0.3  | 2.99 | 0.5 | —    | 6  | 3  | 0.519 | 0.399 | —     | —     | —    | —    | —     | 1.913 | 9  |
| Penn. 12 | Dolomite     | 23.3 | 0.3  | 2.83 | 0.4 | 6.6  | 7  | 3  | 0.054 | 0.039 | —     | —     | —    | —    | —     | 1.557 | 8  |
| Penn. 13 | Marble       | 28.7 | 0.4  | 2.86 | 0.3 | 19.6 | 7  | 5  | 0.618 | 0.398 | 200   | 042   | —    | 2.2  | 0.496 | 1.626 | 8  |
| Penn. 14 | Limestone    | 18.6 | 0.5  | 2.65 | 0.5 | 28.9 | 5  | 4  | 0.047 | 0.043 | 043   | .030  | —    | 64.2 | 1.953 | 2.285 | 8  |
| Penn. 15 | Limestone    | 16.5 | 0.3  | 2.78 | 0.4 | 6.8  | 7  | 3  | 0.002 | —     | —     | —     | —    | —    | —     | —     | 9  |
| Penn. 16 | Dolomite     | 24.4 | 0.7  | 2.66 | 0.6 | 16.4 | 6  | 4  | 0.138 | 0.134 | .565  | 388   | —    | 77.0 | 6.478 | 1.592 | 7  |
| Penn. 17 | Limestone    | 20.5 | 0.4  | 2.66 | 1.1 | 11.9 | 7  | 4  | 0.117 | 0.074 | .366  | .264  | —    | 67.1 | 4.544 | 1.693 | 8  |
| Penn. 18 | Limestone    | 20.5 | 0.5  | 2.72 | 0.2 | 10.1 | 7  | 3  | 0.013 | 0.012 | .039  | .028  | —    | 76.3 | 4.288 | 1.610 | 8  |
| Penn. 19 | Limestone    | 18.0 | —    | 2.66 | 0.4 | 52.5 | 6  | 5  | 0.118 | 0.065 | 088   | .043  | —    | 42.5 | 1.120 | 1.564 | 8  |
| Penn. 20 | Limestone    | 19.6 | 0.6  | 2.69 | 0.8 | 27.4 | 6  | 5  | 0.192 | 0.185 | .190  | .130  | —    | 60.9 | 1.810 | 1.820 | 6  |
| Vir. 1   | Marble       | 22.8 | 1.2  | 2.74 | 0.3 | —    | 7  | 4  | 0.184 | 0.131 | .133  | .139  | —    | 13.4 | 1.756 | 2.336 | 8  |
| Vir. 5   | Granite      | 27.0 | 0.5  | 2.63 | 0.2 | —    | 7  | 5  | 0.459 | 0.305 | —     | —     | —    | —    | —     | 1.670 | 7  |
| Vir. 6   | Granite      | 42.2 | 2.0  | 2.69 | 0.3 | —    | 7  | 5  | 0.438 | 0.318 | .207  | .074  | —    | 3.5  | 0.759 | 1.705 | 6  |
| Vir. 7   | Dolomite     | 19.0 | 0.6  | 2.85 | 0.2 | —    | 7  | 3  | 0.015 | 0.021 | .021  | .010  | —    | 33.2 | 2.114 | 1.657 | 9  |
| Vir. 9   | Gneiss       | 30.4 | 1.4  | 2.62 | 0.6 | —    | 8  | 5  | 0.205 | 0.181 | .083  | .052  | —    | 12.7 | 0.807 | 2.057 | 8  |
| Vir. 11  | Gneiss       | 19.5 | 0.6  | 2.76 | 0.5 | —    | 8  | 5  | 0.118 | 0.139 | —     | —     | —    | 1.0  | —     | 1.800 | 9  |
| Vir. 17  | Dolomite     | 16.1 | 0.3  | 2.81 | 0.4 | —    | 7  | 4  | 0.070 | 0.045 | .059  | .037  | —    | 17.2 | 1.169 | 1.608 | 9  |
| Vir. 18  | Limestone    | 16.2 | 0.4  | 2.71 | 0.4 | —    | 7  | 3  | 0.058 | 0.037 | .066  | .034  | —    | 17.8 | 1.525 | 1.649 | 9  |
| Vir. 20  | Limestone    | 19.7 | 0.2  | 2.70 | 0.2 | —    | 7  | 4  | 0.008 | 0.006 | .040  | .023  | —    | 78.9 | 6.239 | 1.473 | 9  |
| Vir. 21  | Dolomite     | 19.2 | 0.4  | 2.78 | 0.2 | —    | 7  | 3  | 0.126 | 0.054 | .148  | .088  | —    | 34.4 | 1.526 | 1.422 | 9  |
| Vir. 22  | Quartzite    | 18.6 | 2.7  | 2.59 | 0.5 | —    | 7  | 5  | 0.418 | 0.266 | .410  | .284  | —    | 11.3 | 1.325 | 1.410 | 9  |
| Vir. 23  | Limestone    | 28.2 | 0.5  | 2.80 | 0.2 | —    | 7  | 3  | 0.007 | 0.003 | .018  | .090  | —    | 63.5 | 3.603 | 1.544 | 8  |
| Vir. 27  | Diabase      | 20.9 | 0.3  | 3.03 | 0.3 | —    | 7  | 2  | 0.436 | 0.353 | —     | —     | —    | —    | —     | 1.920 | 9  |
| Vir. 28  | Limestone    | 17.0 | 0.5  | 2.76 | 0.5 | —    | 7  | 3  | 0.009 | 0.005 | .021  | .007  | —    | 34.5 | 3.263 | 1.637 | 9  |
| Vir. 31  | Dolomite     | 15.5 | 1.0  | 2.71 | 0.6 | —    | 8  | 5  | 0.119 | 0.119 | .224  | .178  | —    | 71.2 | 2.627 | 1.690 | 9  |
| Vir. 32  | Diabase      | 16.0 | 0.1  | 2.76 | 0.5 | —    | 6  | 3  | 0.240 | 0.224 | —     | —     | —    | —    | —     | 1.812 | 9  |
| Vir. 34  | Greenstone   | 13.6 | 1.0  | 2.94 | 0.2 | —    | 6  | 5  | 0.017 | 0.015 | .020  | .016  | —    | 28.6 | 1.482 | 2.268 | 9  |
| Vir. 38  | Argillite    | 23.3 | 0.5  | 2.78 | 0.3 | —    | —  | —  | 0.040 | 0.023 | .015  | .007  | —    | 23.6 | 0.814 | 2.208 | 6  |
| Wis. 1   | Dolomite     | 54.5 | 8.4  | 2.54 | 3.7 | 16.5 | 4  | 4  | 0.091 | 0.048 | —     | —     | 11.4 | —    | —     | 1.492 | 3  |
| Wis. 2   | Dolomite     | 31.1 | 3.0  | 2.44 | 4.1 | 7.0  | 6  | 3  | 0.179 | 0.097 | —     | —     | —    | —    | —     | 1.469 | 6  |
| Wis. 3   | Dolomite     | 50.3 | 1.4  | —    | —   | 6.8  | 5  | 4  | —     | —     | —     | —     | —    | —    | —     | —     | —  |
| Wis. 4   | Dolomite     | 61.8 | 10.6 | 2.66 | 1.9 | 9.2  | 5  | 3  | 0.100 | 0.052 | —     | —     | —    | —    | —     | 1.447 | 3  |
| Wis. 5   | Dolomite     | 52.9 | 4.0  | —    | —   | 4.0  | 5  | 4  | 0.144 | 0.078 | —     | —     | —    | —    | —     | 1.550 | 4  |
| Wis. 6   | Dolomite     | 40.9 | 2.2  | 2.56 | 3.0 | 22.3 | 5  | 4  | 0.097 | 0.051 | —     | —     | —    | —    | —     | 1.409 | 3  |

## APPENDIX H

### AGGREGATE PHOTOMICROGRAPHS



*Figure H-1. Photomicrograph of aggregate Illinois 8.*



*Figure H-2. Photomicrograph of aggregate Iowa 4-3.*

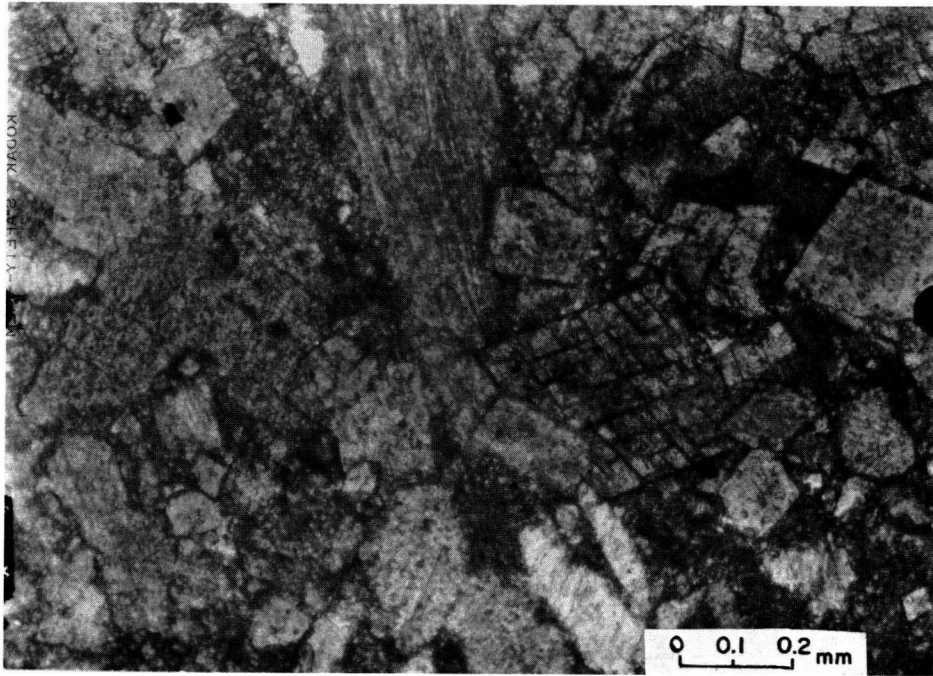


Figure H-3. Photomicrograph of aggregate Missouri 2A.

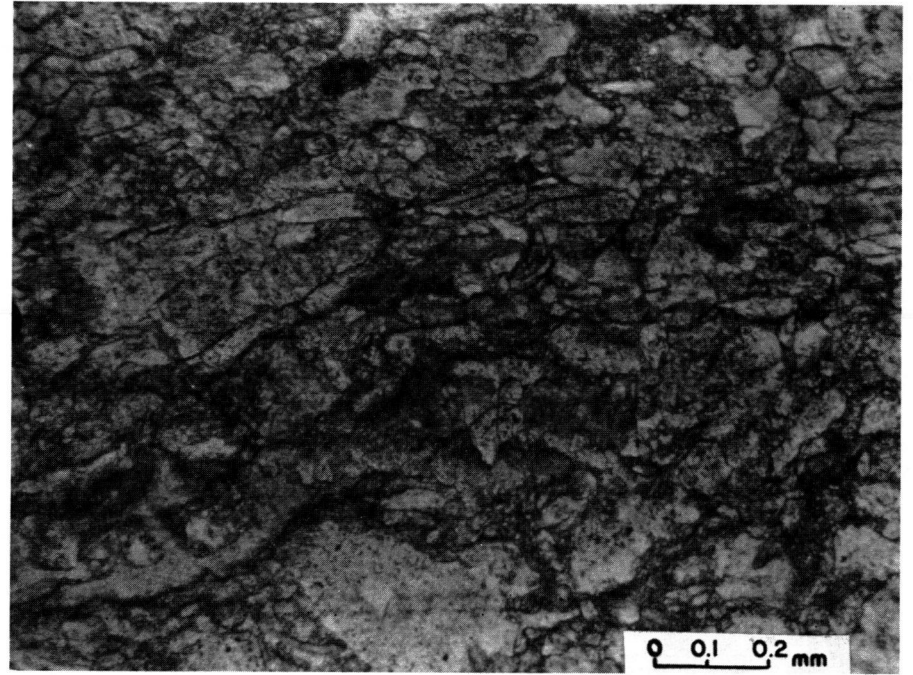
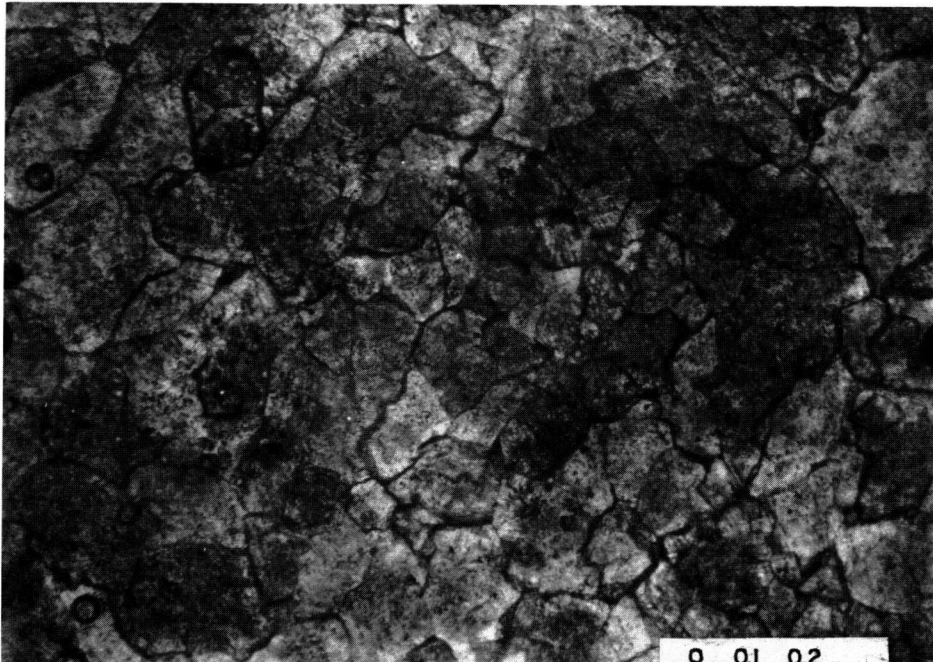


Figure H-4. Photomicrograph of aggregate Missouri 12.





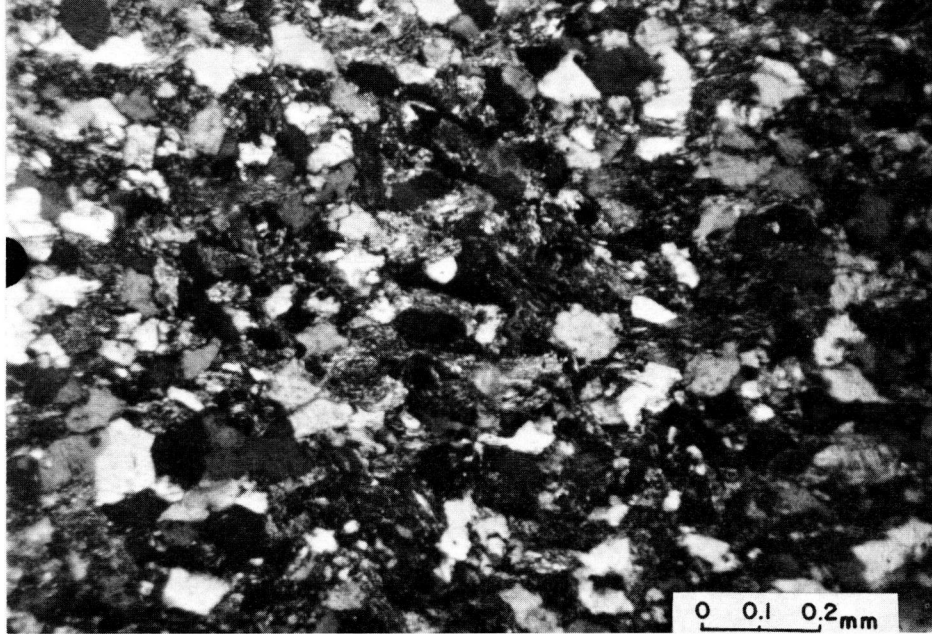


Figure H-7. Photomicrograph of aggregate New York 9.



Figure H-8. Photomicrograph of aggregate Georgia 2.

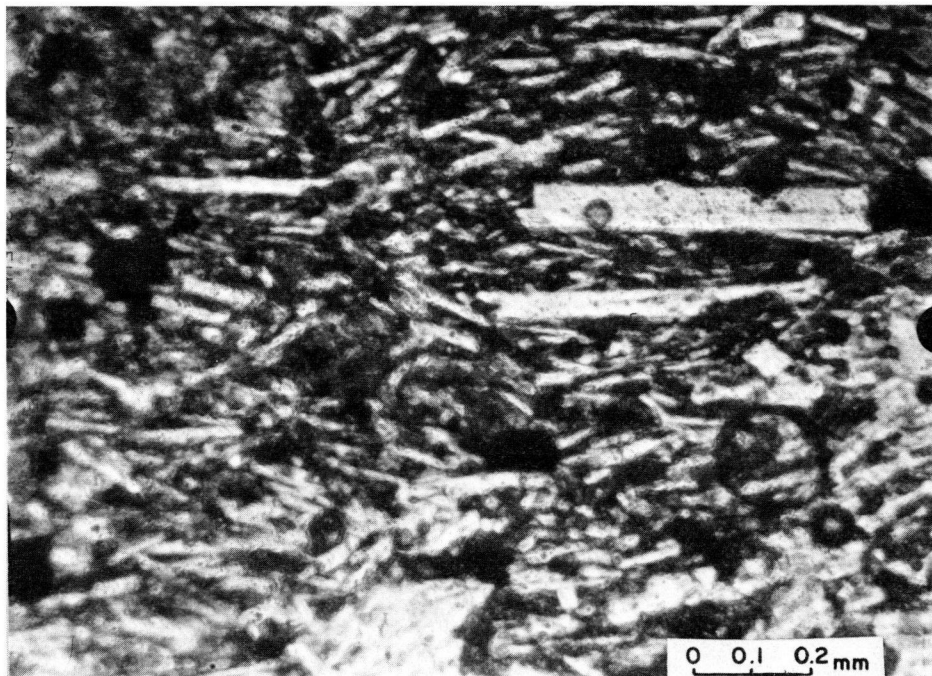


Figure H-9. Photomicrograph of aggregate Oregon 4.

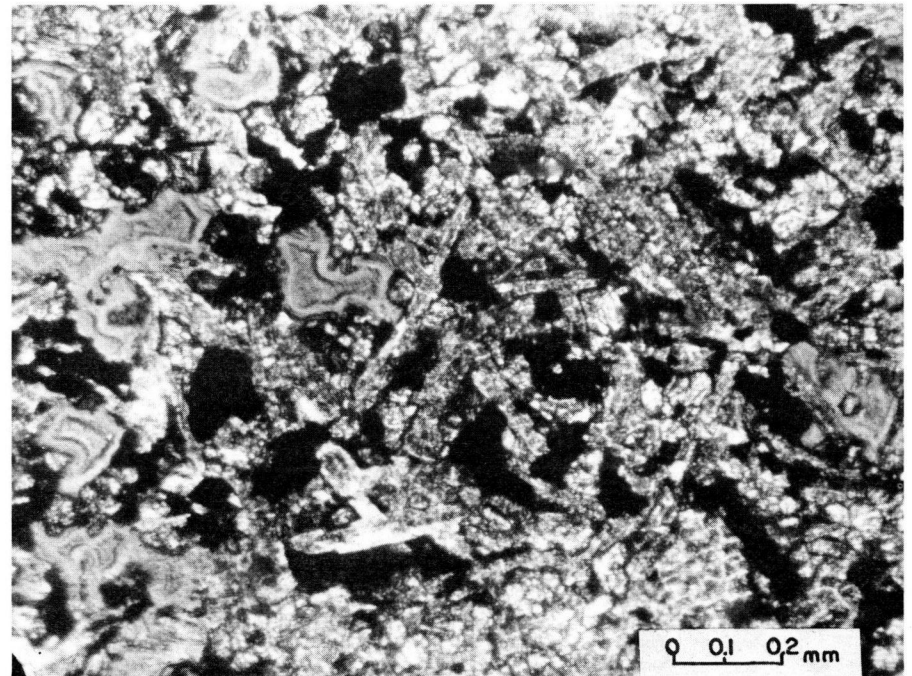


Figure H-10. Photomicrograph of aggregate Oregon 7.

## APPENDIX I

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**THE DIVISION OF ENGINEERING** is one of the eight major Divisions into which the National Research Council is organized for the conduct of its work. Its membership includes representatives of the nation's leading technical societies as well as a number of members-at-large. Its Chairman is appointed by the Council of the Academy of Sciences upon nomination by the Council of the Academy of Engineering.

**THE HIGHWAY RESEARCH BOARD**, organized November 11, 1920, as an agency of the Division of Engineering, is a cooperative organization of the highway technologists of America operating under the auspices of the National Research Council and with the support of the several highway departments, the Bureau of Public Roads, and many other organizations interested in the development of transportation. The purpose of the Board is to advance knowledge concerning the nature and performance of transportation systems, through the stimulation of research and dissemination of information derived therefrom.

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