NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 46

EFFECTS OF DIFFERENT METHODS OF STOCKPILING AND HANDLING AGGREGATES

HIGHWAY RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 46

EFFECTS OF DIFFERENT METHODS OF STOCKPILING AND HANDLING AGGREGATES

BY MILLER-WARDEN ASSOCIATES
RALEIGH, NORTH CAROLINA

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

SUBJECT CLASSIFICATION.
MINERAL AGGREGATES
CONSTRUCTION

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES—NATIONAL ACADEMY OF ENGINEERING 1967

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.

This report is one of a series of reports issued from a continuing research program conducted under a three-way agreement entered into in June 1962 by and among the National Academy of Sciences-National Research Council, the American Association of State Highway Officials, and the U. S. Bureau of Public Roads. Individual fiscal agreements are executed annually by the Academy-Research Council, the Bureau of Public Roads, and participating state highway departments, members of the American Association of State Highway Officials.

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 an effectual dissemination of findings and their application in the formulation of policies, procedures, and practices in the subject problem area.

NCHRP Project 10-3 FY '65
NAS-NRC Publication 1580
Library of Congress Catalog Card Number: 67-62903

FOREWORD

By Staff

Highway Research Board

Highway engineers have for many years been concerned about the problems of segregation and degradation of aggregates during the handling and construction procedures. It has been generally accepted that the problems exist, but little information was available on the extent or degree of variation in the gradation of aggregates between the time of production and the actual use in the road. This report contains the findings and recommendations on aggregate gradation variation resulting from field investigations of stockpiling and base course construction procedures. A segregation index has also been developed for rating the different stockpiling methods. The information contained in the report will be of particular interest to highway construction and materials engineers as well as aggregate producers. It should be helpful in evaluating some of the current aggregate handling practices and acceptance specifications.

It has been well established that the quality and gradation of the aggregates used greatly influence the performance of highways and structures. Aggregate gradation also has an effect on the proportion of bitumen or portland cement required in pavement mixtures to assure the construction of high quality pavements. For these reasons it is important that aggregates are within specified gradation limits at the time they are incorporated into the highway or structure. However, it is not always possible or practical to test materials and make acceptance decisions just prior to construction. It then becomes necessary to produce and stockpile the aggregates ahead of actual use. The accompanying handling operations often contribute to segregation and degradation, thus changing the gradation of the material as it goes into the finished product.

Miller-Warden Associates (now a division of Materials Research and Development, Inc.) first investigated segregation effects of stockpiling using coarse aggregate consisting of limestone. A segregation index was developed for rating the relative amount of segregation resulting from different stockpiling procedures for the one type and gradation of aggregate. An interim report of this initial phase of the study was published as *NCHRP Report 5*.

The second phase of the investigation, reported herein, involved both uncrushed gravel and a different crushed limestone gradation in a further evaluation of segregation as related to various stockpiling techniques, plus a measure of degradation caused by routine handling, spreading, and compaction methods for base courses. During this phase of the project, six full-scale stockpiles were built and the degree of segregation determined. To measure aggregate degradation, six dense-graded aggregate base courses were constructed using crushed limestone from two sources with significantly different Los Angeles abrasion loss histories.

In general, information contained in this report confirms the trends indicated by the earlier phase of the project. Methods of minimizing segregation during stockpiling are discussed. The amount of degradation of the particular aggregates used and base course construction procedures investigated was much lower than

anticipated. Possible explanations of this aspect of the findings are given in the report, along with suggestions for further research to clarify the findings. The report also contains considerable background information on related factors such as sample size, reliability, and statistical concepts.

Research conducted under this project and NCHRP Project 10-2, "Evaluation of Construction Control Procedures," is providing a more thorough understanding of the problem of aggregate handling and gradation specifications. The findings will contribute to the development of practical approaches for improving quality control in highway construction. Related publications in the NCHRP series are Reports No. 5 and 34.

CONTENTS

FIGURES

TABLES

EFFECTS OF DIFFERENT METHODS OF STOCKPILING AND HANDLING AGGREGATES

SUMMARY

The purpose of this investigation was to measure the effects of several different methods of stockpiling and handling on aggregate properties. As a result of these studies the following major items were accomplished.

Six full-scale stockpiles (three with crushed stone and three with uncrushed gravel) were constructed to compare with results from similar stockpiling methods obtained in initial HR 10-3 studies and published in *NCHRP Report 5*. Those methods selected for continuing study had initially produced relatively high, intermediate and low values of segregation (variation). The overall variance of the gradation of the aggregate from the output of these stockpiles was measured in terms of Hudson $\bar{A}$ and the percentages passing the standard sieves. Throughout the initial and continuation studies, segregation was minimized when the stockpiles were formed by spreading the aggregate in thin layers and reclaiming with a front-end loader. Coned or tent piles produced such extensive segregation that quality of the resulting product would be adversely affected. In addition, an excessive number of test increments would be required to find average values of gradation measurements with an acceptable degree of accuracy. Stockpiles built with dump trucks by tightly joining successive loads produced acceptable levels of variation and also proved to be the most economical method of construction.

To measure aggregate degradation six field test sections of North Carolina stabilized aggregate base course (three with a soft aggregate, and three with a hard aggregate) were constructed by several routine methods for handling, spreading and compacting aggregate bases. The degradation effects from each variable were evaluated by mathematical and statistical means. The very small amount of degradation produced by techniques employed during the handling and construction of dense-graded aggregates was deemed to be of no practical importance. This leads to the belief that a soft aggregate can be used without excessive degradation, providing the proper design is used.

A system was employed whereby each gradation in both segregation and degradation studies is expressed in terms of a single number called Hudson $\bar{A}$. This value is related to the surface area and voidage of an aggregate and expresses the relative coarseness of an aggregate gradation.

A segregation index was obtained by dividing the overall gradation variance, σ^2_o, by within-batch variance, σ^2_b. This index can be applied to Hudson $\bar{A}$ or to the percentages passing individual sieves and tested for statistical significance by use of the F-test.

A degree of variation was obtained by dividing the overall variance, σ^2_o, by the maximum theoretical variance, σ^2_{max}, multiplied by 100. D of V is therefore an expression of the percentage of complete segregation.

A mathematical model was developed for predicting the standard deviation

that will result from several combinations of variables; namely, aggregate type, gradation, and method of stockpile construction.

A system employing analysis of variance techniques was developed to determine the significance of gradation changes resulting from different types of spreading and compacting equipment.

Sources contributing to overall variability were extensively investigated and quantified. These sources included testing error, σ^2_t, sampling error, σ^2_s, batch-to-batch variance, σ^2_l, within-batch variance, σ^2_b, and actual or inherent variance, σ^2_a.

An equation was adapted for the purpose of estimating the total sample weight required. These tests indicate that the total weight of larger maximum size coarse aggregate for gradation tests should be greater than that specified by AASHO standards if acceptable accuracy is to be obtained.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

THE NEED

The deleterious effects of SEGREGATION * caused by handling, transporting, and STOCKPILING of AGGREGATES are well known, although no generally accepted engineering basis has been developed for comparing the effects caused by one method with those caused by another. Segregation and its resulting variations in gradation have caused considerable nonuniformity in many materials and products, and create a condition for substandard performance. These segregation effects also have resulted in much wasted time, effort, and money in designing different types of paving mixtures with aggregate samples that were not representative of those available for construction. The nonrepresentative samples are often due to failure to secure a sufficient number of test increments to correctly represent the actual condition of variability in an aggregate stockpile, particularly when the aggregate is highly segregated.

Likewise, the mechanism of DEGRADATION has been held responsible for untold difficulties which necessitated the readjustment of aggregate blends or changes in other materials proportions to compensate for increases in the finer size fractions. In the case of aggregate bases, it is not at all uncommon to scarify a compacted base and blend in a coarse sand to bring the mixture into grading specifications when field tests have indicated excessive degradation.

Most highway and materials engineers can recall specific instances where aggregate segregation or degradation has presented design and construction problems that could have been avoided had proper care been used in handling and subsequent sampling of the material. The results of these difficulties are ultimately reflected in the performance or cost of the roadway. A constantly fluctuating gradation makes accurate control virtually impossible, and may result in widely varying properties of some finished products. Further, it has been well established that bitumen demand or concrete mix proportions are influenced by the coarseness or fineness of an aggregate material. Engineers have long recognized these difficulties and have formulated strong opinions about the deficiencies of certain operating procedures, but not until this research study was undertaken had a definite rating scale been assigned to the various methods commonly used for aggregate stockpiling. The numbers in the scale rate one stockpiling procedure against another, with the lower number being best, whereas the least desirable or more variable procedures result in a large SEGREGATION INDEX, S, or DEGREE OF VARIATION, D of V.

The combination of these two mechanisms, segregation and degradation, should have a marked influence on the preparation of highway specifications. However, few specification writers have spelled out firm guidelines which will alleviate or minimize these undesirable effects. Many specifications are rather ambiguous in defining the specific procedures to be used in handling and stockpiling aggregates and simply state that procedures to be used should minimize segregation. Although some specifications are more definitive, many of the required procedures have not been quantitatively evaluated from an engineering standpoint and are based largely on the experience or opinions of those responsible for preparing the specifications. This does not necessarily provide the optimum conditions from either the cost or operations viewpoint. Thus, there is a need for documented factual information on the pertinent factors related to both segregation and degradation of highway con-

* In each section, key words are printed in small capitals at their first appearance. An explanation of these words is given in Appendix E.

struction aggregates under normal practical operating conditions.

Segregation is defined as the tendency of larger particles to separate from a mass of particles of different sizes, under certain conditions. This segregation may be brought about by the methods of mixing, transporting, handling, or storing the aggregate wherein there is a condition created that favors nonrandom distribution of the aggregate sizes.

When a bed of particles of different sizes is shaken or vibrated, as when aggregates are shipped by rail, there is a tendency for the larger particles to move to the top of the bed, but only under extreme conditions will the degree of segregation from this cause be great enough to cause major problems.

The degree of segregation which occurs when a stream or mass of aggregate flows because of the action of gravity can be very large and may approach the arrangement shown in Fig. A-4C (Appendix A). When a stream of aggregate slides down a chute, the large particles can roll more easily than the small ones, and due to their faster motion will be thrown farther from the end of the chute.

When a falling stream, or small mass of aggregate, is brought to rest, mutual collisions between small and large particles exert forces which, on the average, tend to distribute the large particles around the lower outer portion of the resulting cone. If more aggregate falls in the same place, so that the size of the cone is increased, the surface of the cone forms an inclined plane down which large particles can roll and slide more easily than small ones. This results in a further migration of coarse particles toward the periphery of the base of the cone. As the cone is made still larger, portions of the outer layer may slide along slip planes parallel to the ANGLE OF REPOSE; this action further concentrates coarse particles near the base of the pile.

It is commonly assumed that aggregates degrade in proportion to the number of times they are stockpiled, transported, manipulated, or otherwise handled. The amount of degradation has also been thought to be in relation to the hardness of the particular aggregate in question, although there is poor correlation between test values resulting from the more common methods of measuring aggregate hardness or tendency toward degradation and actual roadway performance. It was evident that additional knowledge of the magnitude of degradation resulting from various normal construction operations was needed to properly assess these effects.

These problems are not new. Engineers for many years have been concerned with the establishment of guidelines for handling and stockpiling aggregates, but only in the past two years or so has an organized effort been made to systematically define the related problems involved and to quantitatively develop and evaluate various alternate solutions.

BACKGROUND

The initial phase of NCHRP Project 10-3, initiated in October 1963, involved construction of eleven full-scale stockpiles of various types. Due to the limited funds available, these initial studies were confined to an investigation of the relative amount of segregation resulting from the more commonly employed stockpiling procedures, using only one type and gradation of aggregate. These studies were completed and an interim report (*NCHRP Report 5*) was published in mid-1964. As a part of this work, a segregation index, *S*, was developed for rating the relative amount of segregation resulting from different stockpiling procedures. This value is based on a ratio of certain statistical VARIANCES which are explained in detail in subsequent sections of this report.

A summary of the HR 10-3 results is provided in Figure 1. The stockpiles have been listed in order of increasing *S*-values, with the lower values indicating the more desirable methods of construction.

Although many data on segregation were obtained, it was not possible to evaluate degradation, or to determine if the patterns of segregation found in the stockpiles would be equally applicable to other aggregate types and gradations. The desirability of continuing studies of segregation was evident, and the problem of measuring degradation remained unanswered. Because the initial funding was not sufficient to include these other areas of study, additional money was allocated for additional studies that would broaden the scope of the original effort. The continuation phase was started in November 1964.

This report presents the findings of the continuation phase of the study and ties in the initial research efforts. To provide continuity, frequent reference is made to the initial studies and several summary tables, charts and graphs based on the original research are provided so that comparisons can be made between the two phases of the study.

RESEARCH APPROACH

This section presents details of the approach developed by the research agency in analyzing project objectives and in planning construction activities.

Project Objectives

Some of the presently used methods of stockpiling and handling of aggregates may result in segregation, degradation, or may otherwise adversely affect the behavior of the various elements of the completed highway. Handling in this context is defined as including any of the steps that may be used in excavating, quarrying, crushing, screening, loading, transporting, reloading, dumping, mixing, spreading and compacting, and otherwise moving, treating or processing of aggregates. As indicated in the previous section, initial research studies had fulfilled some of the objectives relating to stockpiling but did not go into the matter of degradation.

In accordance with the Project Statement, the research efforts for the project were directed to the following objectives:

1. To find the effects of stockpiling (including storing) on the properties of a wide range of aggregates.

SUMMARY OF STOCKPILE TESTS

Relative Rating in Order of Increased Segregation

Stockpile Number	Type of Pile	Method of Construction	Method of Reclaiming	Required Number of Samples*
1	Flat-Mixed	Crane Bucket	FE Loader	8
10	Ramped	Rubber-Tired Dozer	FE Loader	9
3	Flat-Layered	Crane Bucket	FE Loader	10
11	Flat-Mixed	Rubber-Tired Dozer	FE Loader	11
9	Truck Dumped	Dump Trucks	FE Loader	13
6	Flat-Layered	FE Loader	FE Loader	19
8	Tiered(Bermed)	Crane Bucket	FE Loader	32
5	Coned-Tent	Portable Conveyor	FE Loader	35
7	Single Cone	Crane Bucket	FE Loader	55
2	Double Cone	Crane Bucket	FE Loader	67
4	Single Cone	Crane Bucket	Crane Bucket	67

NOTE The required number of samples was calculated at a 95 percent confidence level and a desired accuracy of ± .05 Ā. This column shows that the number of samples must be increased as the variability of the aggregate gradation increases.

SEGREGATION INDEX OF STOCKPILING METHODS

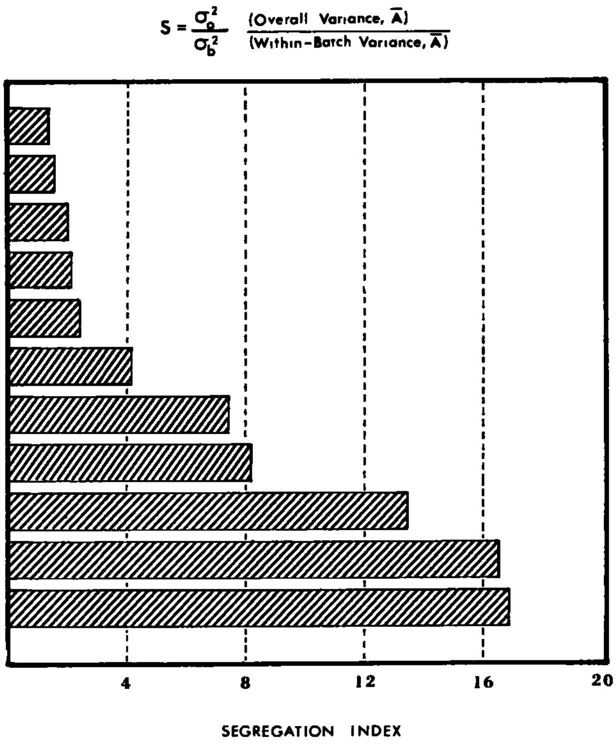


Figure 1. Summary of initial stockpile tests.

2. To find the effects of handling on the properties of a wide range of aggregates.

3. To establish from the results of this study suggested procedures for stockpiling and handling different aggregates.

Further analysis of the project objectives indicated that two distinct phases of field experimentation would be required, because it was not believed practicable to attempt to measure both segregation and degradation within a stockpile due to the difficulty of separating the effects of each factor. Thus, a working plan was developed to separately measure segregation and degradation and covers the following field experiments:

1. A further evaluation of three stockpiling methods employed in Project 10-3 which had produced low, intermediate and high levels of segregation in order to determine:

(a) The effect of a rounded gravel versus crushed stone having essentially the same gradation; and

(b) The effect of gradation using the same (crushed stone) aggregate type, as was used in Project 10-3.

2. Measuring the amount of degradation that would occur as a result of normal handling, mixing, spreading and compacting operations when using a typical hard (low Los Angeles loss) and soft (high Los Angeles loss) crushed stone having essentially the same gradation.

The field work was therefore divided into two parts and is presented accordingly—one part involved aggregate segregation (stockpiling); the other, aggregate degradation (base construction).

A secondary objective of both parts was to develop methodology and research tools appropriate to the solution of these problems.

Segregation Studies

The initial segregation studies involved a single aggregate and a single gradation and were done at a single quarry location. A significant accomplishment resulting from these studies included the development of the "segregation index," and the evaluation of the relative efficiency of stockpiling methods.

To better define the limitations of the original findings, this research investigation was broadened to include another gradation range and another type of aggregate; namely, a rounded gravel and a larger sized crushed stone. Fifteen hundred tons of aggregate, a typical working pile on highway construction, was planned for the construction of each of four stockpiles by the following methods:

1. Single-cone pile built with clambucket.
2. Cast-and-spread pile built with clambucket.
3. Truck-dumped pile.
4. Flat-mixed pile built with rubber-tired dozer. (Lack of funds precluded construction of this stockpile.)

Also, it was planned to obtain a minimum of 50 dupli-

cate random increments of 25 to 30 lb (100 test portions) from each stockpile.

This research plan provided the additional data on the effects of stockpiling methods, aggregate type, and aggregate gradation.

Degradation Studies

There are essentially two types of degradation, chemical and mechanical, which present construction and maintenance problems.

Chemical decomposition comes about through alteration of the mineral constituents making up the aggregate particles and is usually the result of using an unstable aggregate that will decompose, disintegrate, or otherwise be changed by chemical or freeze-thaw action into a material which may have a detrimental effect on the performance of the pavement structure. This type of degradation was not within the scope of the project objectives, and was not studied in the course of the work reported herein.

The continuing research investigation was concerned with measuring the mechanical degradation of aggregate caused by friction, impact, and/or pressure forces. Mechanical degradation is defined as the grinding, shattering or breaking process that reduces the rock to smaller fragments that have the same mineral composition as the original rock. This is of special concern to the engineer, particularly in the construction and maintenance of aggregate base courses. The kneading action of heavy traffic loads may, in some cases, create additional fines approaching clay and silt sizes.

Ekse and Morris (*34*)* suggest that such degradation of base course aggregates will result in "(1) reduction of angularity and interlock of the coarser particles and (2) some 'lubrication' of the coarser particles by increasing amounts of fine material distributed through the aggregate under moist conditions." The net effect is to reduce the stability of the base course and cause failure of the pavement layers supported by the base. Even if the stability of the base is not directly affected, creation of excess fines may make the base frost-susceptible.

Laboratory tests (Los Angeles and Deval abrasion) have been devised to provide an indication of this tendency of some aggregates to degrade when subjected to mechanical action. However, the results of these tests do not always correlate well with actual performance.

The objectives of this part of the study did not include an evaluation of test methods, but rather were concerned with measuring the amount of mechanical degradation that occurred when normal handling and construction techniques (mixing, spreading, and compaction) were employed with a commonly used type of mechanically stabilized base.

The research agency believed that this objective could be best accomplished through the construction and evaluation of field test sections built by the methods used for routine highway construction. Variables would include different spreading and compacting procedures using two aggregates of widely varying abrasive characteristics.

Six test sections, each 100 ft long by 10 ft wide, were selected to compare the degradation of a hard aggregate (Los Angeles abrasion loss about 12%) and a soft aggregate (Los Angeles abrasion loss about 50%). The sections were to be built in pairs using the same construction technique for each pair, the variable being a soft aggregate in one lane and a hard aggregate in the adjacent lane. A minimum of 50 replicated test increments for each condition were planned to determine changes in the average percentage of each size fraction as the aggregate passed through the different stages of preparation and construction.

The aggregate selected met North Carolina Standard Specifications for No. 8 stone. This material was selected for several reasons; namely, (1) a good service record extending over many years, (2) the sources were conveniently located and readily available, and (3) the wide spread of Los Angeles abrasion loss appeared quite desirable.

Research Tools

It was initially planned that several additional statistical tools would be explored for interpretation and analysis of the data acquired. Some of these concepts involved statistical relationships that had not been previously used in this type of data analysis. Others were based on the more conventional approaches used throughout several segments of industry.

A discussion of the interpretation and application of these concepts is provided in Chapter Two.

* Italic numbers refer to items in the Bibliography, Appendix G.

CHAPTER TWO

STATISTICAL TOOLS FOR DATA ANALYSIS

It is obviously beyond the scope of this report to present a textbook on statistics—nor is it necessary. On the other hand, certain statistical concepts have been used as tools for the definition and measurement of variability. These statistical concepts are essential to the breaking down of variability into its components so that the causes of variation can be identified, and estimates made of their relative size. The pertinent statistical fundamentals are briefly re-

viewed in this chapter and a more detailed explanation is provided in Appendix A.

THE NORMAL DISTRIBUTION CONCEPT

A substantial portion of the analysis and presentation of the data is based on the concept of a normal distribution. This means that for each group of test data an average value, $\overline{X}$, has been determined and the pattern of variability has been shown in relation to the distribution about the average. One of the properties of the NORMAL DISTRIBUTION CURVE is that, regardless of its shape, a definite percentage of the total area beneath the curve is defined by vertical lines spaced a definite number of STANDARD DEVIATION (σ) units from the centerline of the curve which represents the average value, $\overline{X}$. By determining the standard deviation of gradation test results, for example, an estimate of the percentage of results that will be contained within given limits can be calculated.

Vertical lines located one standard deviation ($1\ \sigma$) on either side of the average will include approximately 68 percent of all test values, $\pm 2\sigma$ units will include about 95 percent of all test values, and $\pm 3\sigma$ units will include 99+ percent of all test values.

SIGMA (σ), then, is a means of expressing variation as a numerical value. For convenience, the VARIANCE (σ^2), which is the square of the standard deviation, is used instead of σ in some parts of this report because variances can be added and subtracted directly, whereas standard deviations cannot.

Accordingly, in this report both standard deviation and variance have been used as the measures of variability. A relatively small value of either of these PARAMETERS indicates that essentially all measurements lie close to the average; a relatively large value indicates that the measurements deviate from the average over a wider range.

CONSTRUCTION OF MODEL

Variation in aggregate gradation results from a combination of many different factors, usually called variance components. For a complete analysis of the test data, it is essential to know the magnitude of each of these influencing factors.

Earlier statistical studies made in connection with NCHRP Project 10-2 included the design of a model showing the sources of the overall variations in gradation expected among random samples of aggregate taken at a point in the process flow from the source to the point where the aggregate was incorporated into the product or construction. It was concluded that the OVERALL VARIANCE, σ^2_o, of the gradation of aggregate samples taken from the same LOT such as a stockpile, aggregate base section, railroad car, or bin, may be conveniently broken down into the following four basic components:

1. σ^2_a, the inherent variance resulting from the random arrangement of particles in a mixture.
2. σ^2_t, a variance due to testing errors.*
3. σ^2_s, a variance due to sampling errors.*
4. σ^2_l, the batch-to-batch variation within the LOT.

$$\sigma^2_o = \sigma^2_a + \sigma^2_t + \sigma^2_s + \sigma^2_l \tag{1}$$

The Pythagorean diagram showing the relationship of these variances, and scaled roughly to the average size of the components of variance, is shown as Figure A-2. The magnitude of the individual components of variation must be known or estimated so that corrective action can be applied in the proper place for maximum effectiveness.

COMPONENTS OF VARIANCE

Because the data presented in the following chapters make use of statistical terms that may be unfamiliar to the reader, a brief explanation of their meaning is given here. For those who wish a more detailed discussion, it is suggested that Appendix A be consulted, as well as some of the statistical references given in the bibliography.

The major statistical parameters used are as follows:

1. *Theoretical maximum variance.* This is a limiting value which can never be exceeded and is designated herein as σ^2_{max}. It is derived from the binomial theorem as $P(100 - P)$, where P is the average percent passing a given sieve, and is represented by the black and white spots in Figure A-4D, depicting complete segregation.

2. *Inherent variance.* This is a variance due to the random distribution of particles within an aggregate mass and is identified as σ^2_a in this report. It is a basic variation in gradations that cannot be eliminated or reduced by process control. It is extremely important because it provides a minimum limiting value which must be considered when statistical methods are employed to determine the size of a sample or test portion for a predetermined degree of accuracy.

3. *Testing error.* The variance due to TESTING ERROR (σ^2_t) is the within-test portion variance due to the lack of REPEATABILITY of the test procedure. This is not an error in the sense of someone using the wrong technique, but is an error due to the random variations associated with any test procedure. Testing error was determined by repeatedly having the same operator, using the same equipment, run the same test portion a second time, and determining the difference between the two runs.

4. *Experimental error.* The sum of the variances due to inherent variation and testing error ($\sigma^2_a + \sigma^2_t$) is called EXPERIMENTAL ERROR (σ_e). This value is important because it is this combined variance that affects repeatability and REPRODUCIBILITY of an aggregate gradation test on *duplicate* test portions. When a precision statement is to be written, this experimental error must be used as the basis. In both the HR 10-2 and 10-3 studies, only repeatability was measured.

5. *Sampling error.* The sampling error (σ^2_s) is a result of the combined effects of all other within-batch variations not due to inherent variance or testing error. The method of calculating this value is shown in Table 1 as $\sigma^2_s = \sigma^2_b - (\sigma^2_a + \sigma^2_t)$.

6. *Within-batch variance.* The within-batch variance

* These are not errors in the sense of someone making a mistake; they are random variations associated with the sampling and testing procedure.

TABLE 1

SUMMARY OF VARIANCES

VARIANCE	DESIGNATION	CAUSE	HOW ESTIMATED	EQUATION
Theoretical maximum	σ^2_{max}	Complete segregation	Computed	$\sigma^2_{max} = P(100 - P)$
Inherent (within-test portion)	σ^2_a	Inherent	Computed	$\sigma^2_a = \frac{P(100 - P)\bar{g}}{454\ W}$
Testing error (between tests)	σ^2_t	Testing error	By experiment	$\sigma^2_t = \frac{\Sigma(X_1 - X_2)^2}{2n}$
Sampling error (among increments)	σ^2_s	Sampling error	By difference	$\sigma^2_s = \sigma^2_b - (\sigma^2_a + \sigma^2_t)$
Within-batch	σ^2_b	Multiple (sum of σ^2_a, σ^2_t, σ^2_s)	By experiment	$\sigma^2_b = \frac{\Sigma(X_A - X_B)^2}{2n}$
Batch-to-batch (within lot)	σ^2_l	Segregation	By difference	$\sigma^2_l = \sigma^2_o - \sigma^2_b$
Overall	σ^2_o	Sum of variances	By experiment	$\sigma^2_o = \frac{\Sigma X^2 - (\Sigma X)^2/n}{n - 1}$

(σ^2_b) is the sum of the sampling and experimental errors and is found by taking two test portions or increments from suitably separated points within the same batch, performing a gradation test on each increment and statistically determining the difference between the two runs. Because in most cases the nonuniformity represented by this variance will be corrected by subsequent mixing, it does not necessarily affect the quality of construction.

7. *Batch-to-batch variance.* The batch-to-batch, or within-lot variance (σ^2_l) is of real significance because it can cause actual differences in the performance of different batches. The size of this variance depends almost entirely on the combined effects of the methods of handling, transporting, and stockpiling aggregates, and the resulting degree of segregation.

8. *Overall variance.* The total overall variance among test portions taken from a LOT is symbolized by ($\sigma^2_o = \sigma^2_a + \sigma^2_t + \sigma^2_s + \sigma^2_l$). Obviously, this is the largest and most important variance of all because it contains the total of the other variances. This variance is the most significant consideration in the writing of realistic specifications, in the establishment of optimum sampling plans, and in determining the number of test portions required to obtain a desired degree of accuracy.

9. *Summary of variances.* The summary of variances in Table 1 is given for the benefit of the reader who does not wish to study this subject in depth. A more detailed explanation, together with the methods of calculation, is given in Appendix A.

GRADATION PARAMETERS

The research agency considered many methods of data analysis and presentation. Obviously, a simple comparison of gradation variations from point to point in both the stockpiling and degradation studies does not present a complete picture. This statement is in no way meant to disparage the value of such comparisons, as the gradation parameters are a fundamental part of the more sophisticated techniques which have been subsequently developed. It is to say, however, that a look beyond gradation *per se* is essential for making significant comparisons and evaluations.

It was apparent that additional "gauges" had to be developed to properly evaluate gradation changes as they affect bitumen content, mix proportions, freeze-thaw characteristics, and roadway performance. The usual listing of percentages passing the various sieves, used alone, was inadequate for this purpose. Consequently, other parameters were devised; namely, HUDSON $\bar{A}$, a gradation parameter, and DEGREE OF VARIATION (D of V) and SEGREGATION INDEX (S), which are measures of relative variability. Accordingly, this section presents a discussion of the meaning and application of these recently developed research tools.

Hudson $\bar{A}$

To measure and assess the effects of changes in gradation by the use of statistical methods, it is desirable to describe the gradation by a single number rather than a multiplicity of percentages. The FINENESS MODULUS (FM), originated by Abrams, is such a parameter and is useful when dealing with aggregates for portland cement concrete. However, the FM was intentionally designed to exclude the influence of the minus No. 200 fraction of the aggregate on the gradation. This makes the FM unsuitable for use when dealing with aggregates for bituminous concrete or when other aggregate mixtures contain a significant quantity of minus No. 200 material.

The UNIFORMITY COEFFICIENT (C_u) is another parameter that is useful in characterizing the properties of a gradation. This characteristic is defined as the ratio of the particle diameter at the 60 percent finer point to that at the 10 percent finer point on the gradation curve. Unfortunately, this parameter is difficult to derive and interpret.

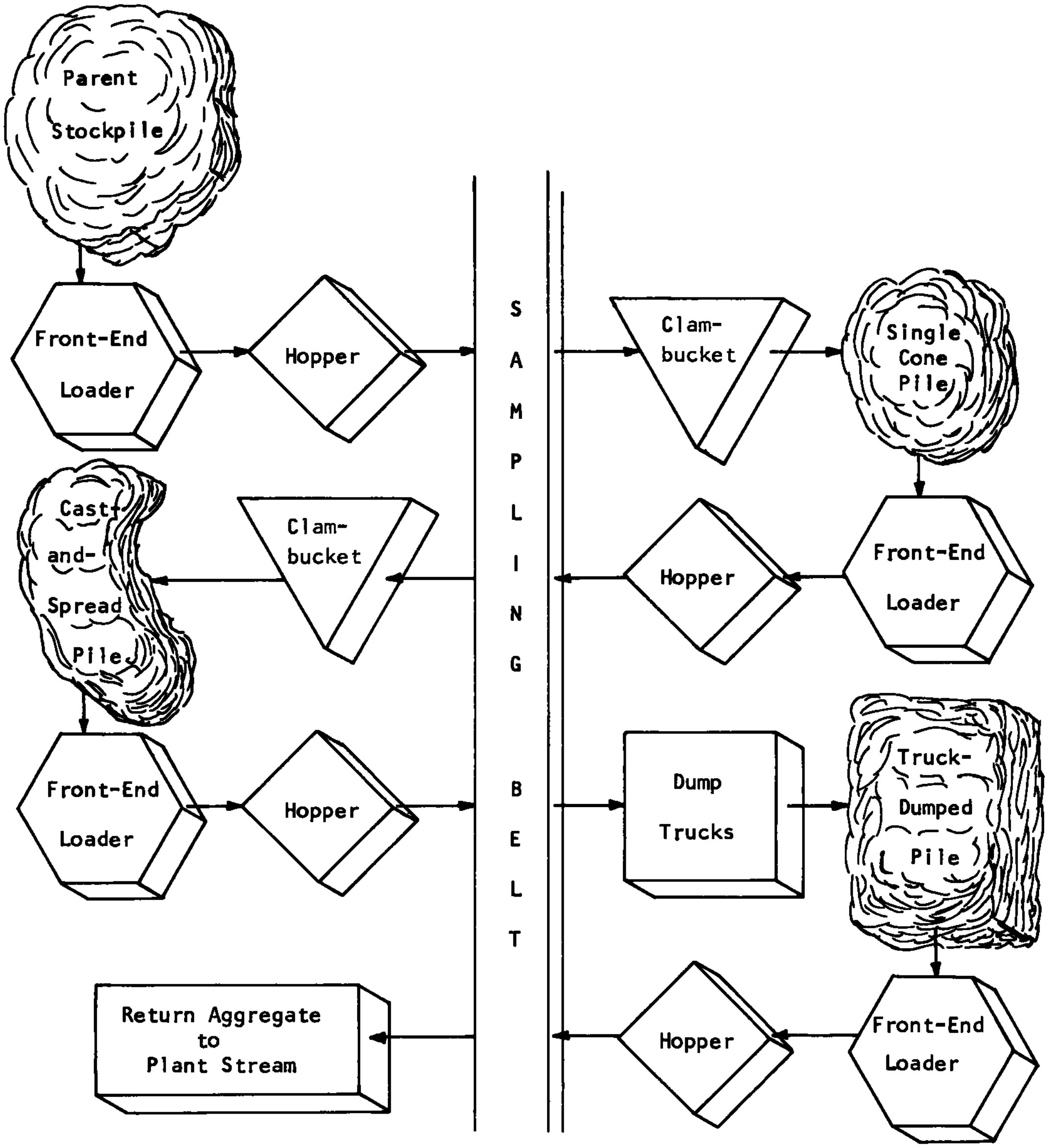


Figure 2. Flow sheet for stockpile tests at Gresham's Lake quarry (1½ in.-⅜ in. crushed stone).

METHOD OF STOCKPILING

Single-coned.—In both cases, the aggregate from the routine production stream was first fed into a hopper and then passed across a conveyor belt so that the initial samples of the raw or parent material could be secured. The material was allowed to flow off the end of the conveyor belt. As a sufficient pile accumulated, it was picked up with a clambucket and the single-coned pile was constructed. For this pile, each bucket of material was deposited at the apex so that maximum coning action would occur (Figs. 5 and 8), as was the case in the initial studies. The single-coned piles were reclaimed with a front-end loader and the aggregate again was passed across the conveyor belt.

Cast-and-spread.—The cast-and-spread piles were built simultaneously with the breakdown of the single-coned piles. Aggregate from the cone pile was passed across the conveyor belt, picked up with the clambucket and a cast-and-spread pile constructed. The bucket was gradually opened as the crane turned through an arc, so that the aggregate was spread in a thin layer. Each clambucket was emptied over a length of about 15 ft.

The cast-and-spread pile built at Gresham's Lake covered an arc of about 180° and the bottom of the pile had an average width of 23 ft. The height was 10 ft and the peak of the arc had a measured length of 106 ft. The angle of repose at each end of the pile was approximately 35°. These dimensions fall into better perspective by examining Figures 11 and 6. Due to mechanical difficulties, it was necessary to change clambuckets about midway through the construction of this pile. The replacement bucket had

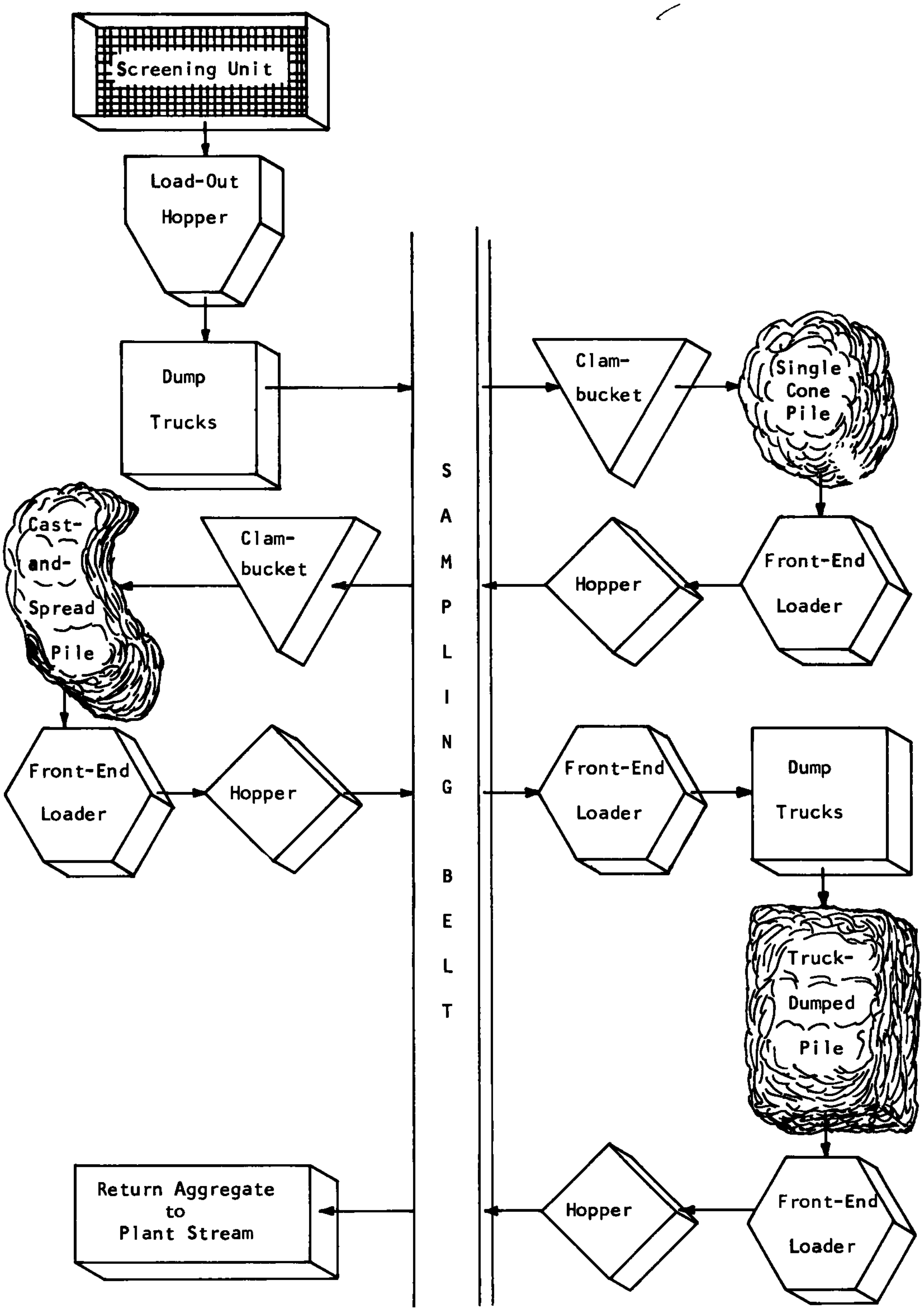


Figure 3. Flow sheet for stockpile tests at H. T. Campbell Sons gravel plant (1 in.-No. 4 uncrushed gravel).

a capacity of 1½ cu yd, whereas the first bucket had a capacity of only 1 cu yd. It is believed that this change had no bearing on the results obtained.

In the case of the gravel stockpile, the area available for construction of the cast-and-spread pile was not as great as desired. Consequently, the aggregate was spread through an arc of only 90° (Fig. 9). This resulted in a pile that was somewhat higher and wider than the previ-

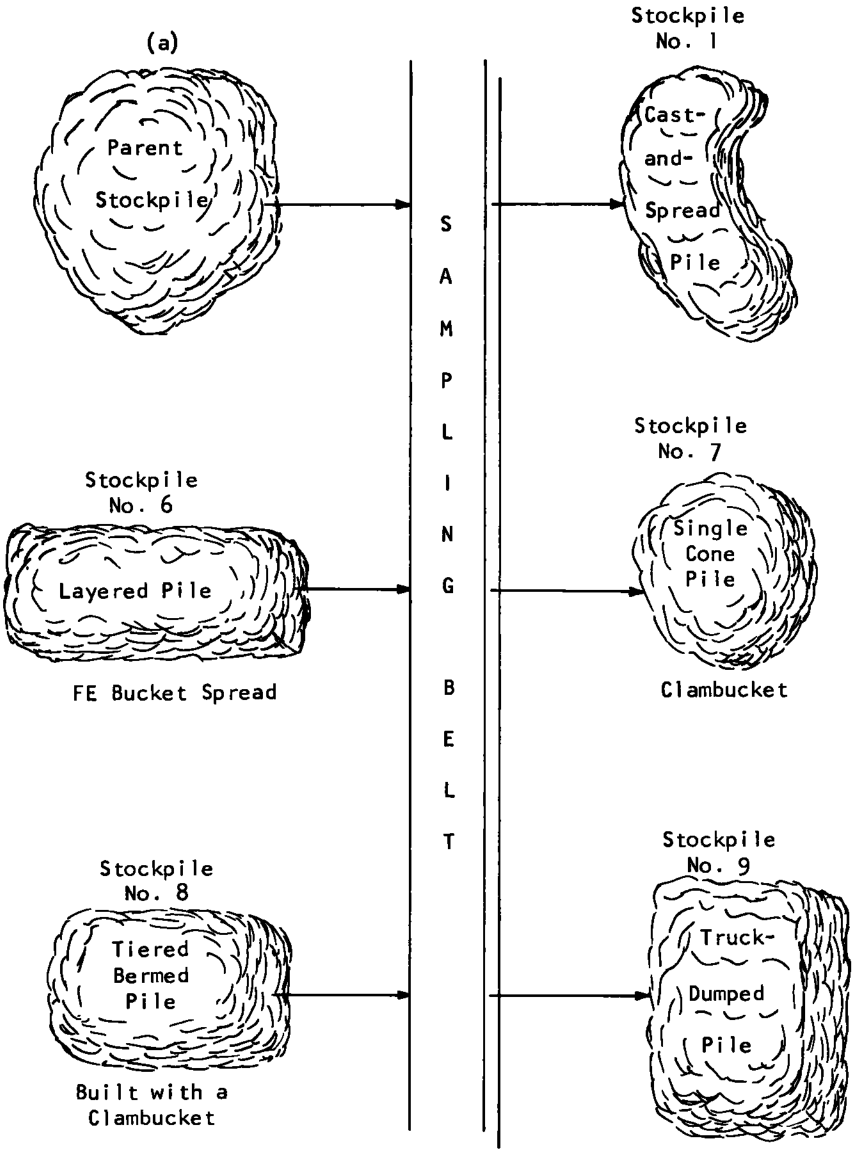


Figure 4. Flow sheet for stockpile tests at Princeton (N.C.) quarry (1 in.-No. 4 crushed stone).

ously constructed cast-and-spread piles. This gravel pile measured 100 ft on the outside radius, 30 ft on the inside radius; one end had a radius of 18 ft and the other end a radius of 13 ft. The average height of the pile was approximately 13 ft, with a width at the base of approximately 45 ft (note Fig. 11).

Truck-dumped pile.—The aggregate used for construction of the cast-and-spread pile for both the stone and the gravel was picked up by front-end loader, passed across the conveyor belt for sampling, and then used for construction of the truck-dumped pile. The aggregate was loaded directly into dump trucks and a stockpile was constructed by dumping each load tightly against the preceding load for a height of one load.

In the case of the crushed stone, the stockpile contained 86 truckloads and measured 106 ft long by 63 ft wide by 4.5 ft high (Fig. 7). The gravel stockpile contained 60 truckloads and measured 54 ft wide by 73 ft long, with an average height of 4.5 ft (Fig. 10). In both cases the aggregate was reclaimed with a front-end loader and again passed across the sampling belt. Both aggregates were returned to their normal process stream upon completion of these stockpiles.

Sampling Considerations

Throughout these studies, RANDOM SAMPLES have been used as a basis for analysis. This means that every portion of the LOT had an equal or known chance for inclusion in the SAMPLE. This section explains the system which was employed for TEST PORTION selection in order to obtain unbiased results.

Figure 5. Single-cone pile built with clambucket; Gresham's Lake quarry (1½ in.-⅜ in. crushed stone).

Figure 6. Cast-and-spread pile built with clambucket; Gresham's Lake quarry (1½ in.-⅜ in. crushed stone).

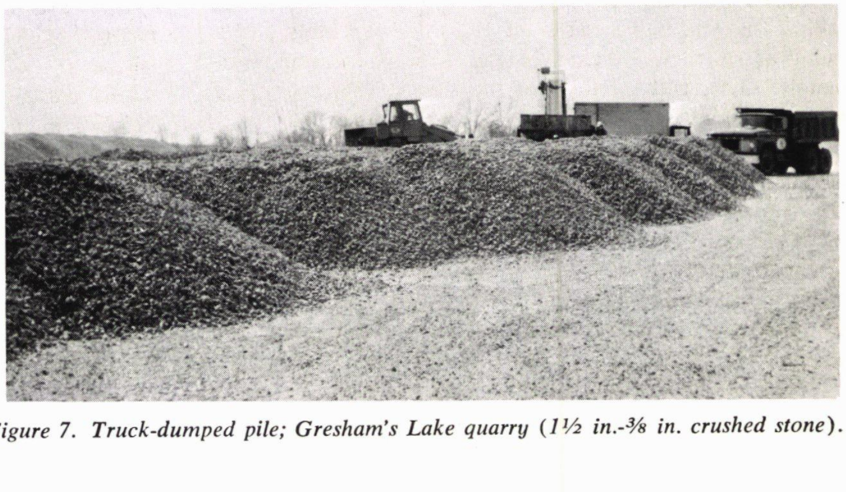


Figure 7. Truck-dumped pile; Gresham's Lake quarry (1½ in.-⅜ in. crushed stone).

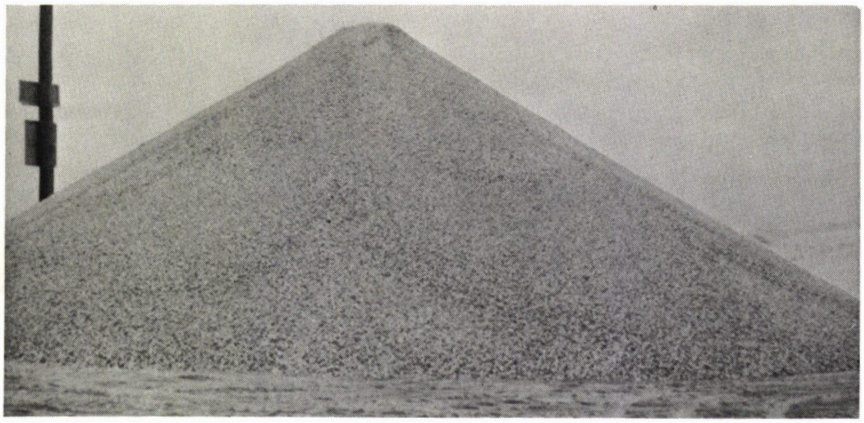


Figure 8. Single-cone pile built with clambucket; Campbell Co. (1 in.-No. 4 uncrushed gravel).

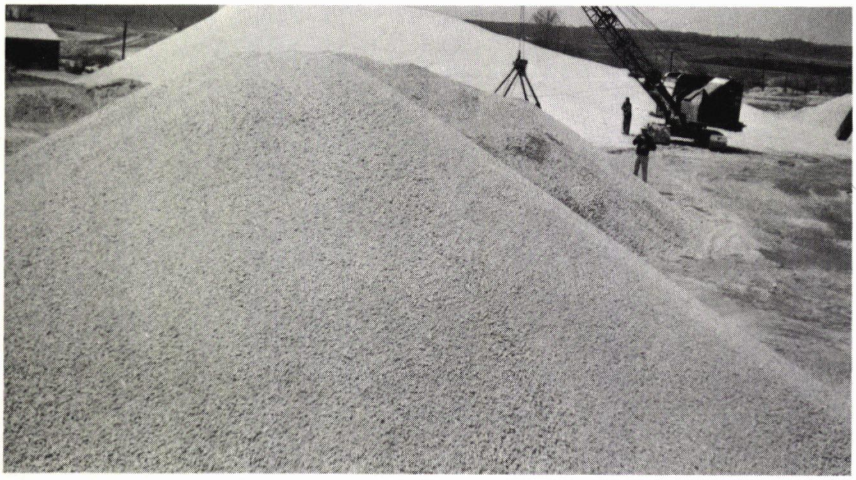


Figure 9. Cast-and-spread pile built with clambucket; Campbell Co. (1 in.-No. 4 uncrushed gravel).

Figure 10. Truck-dumped pile; Campbell Co. (1 in.-No. 4 uncrushed gravel).

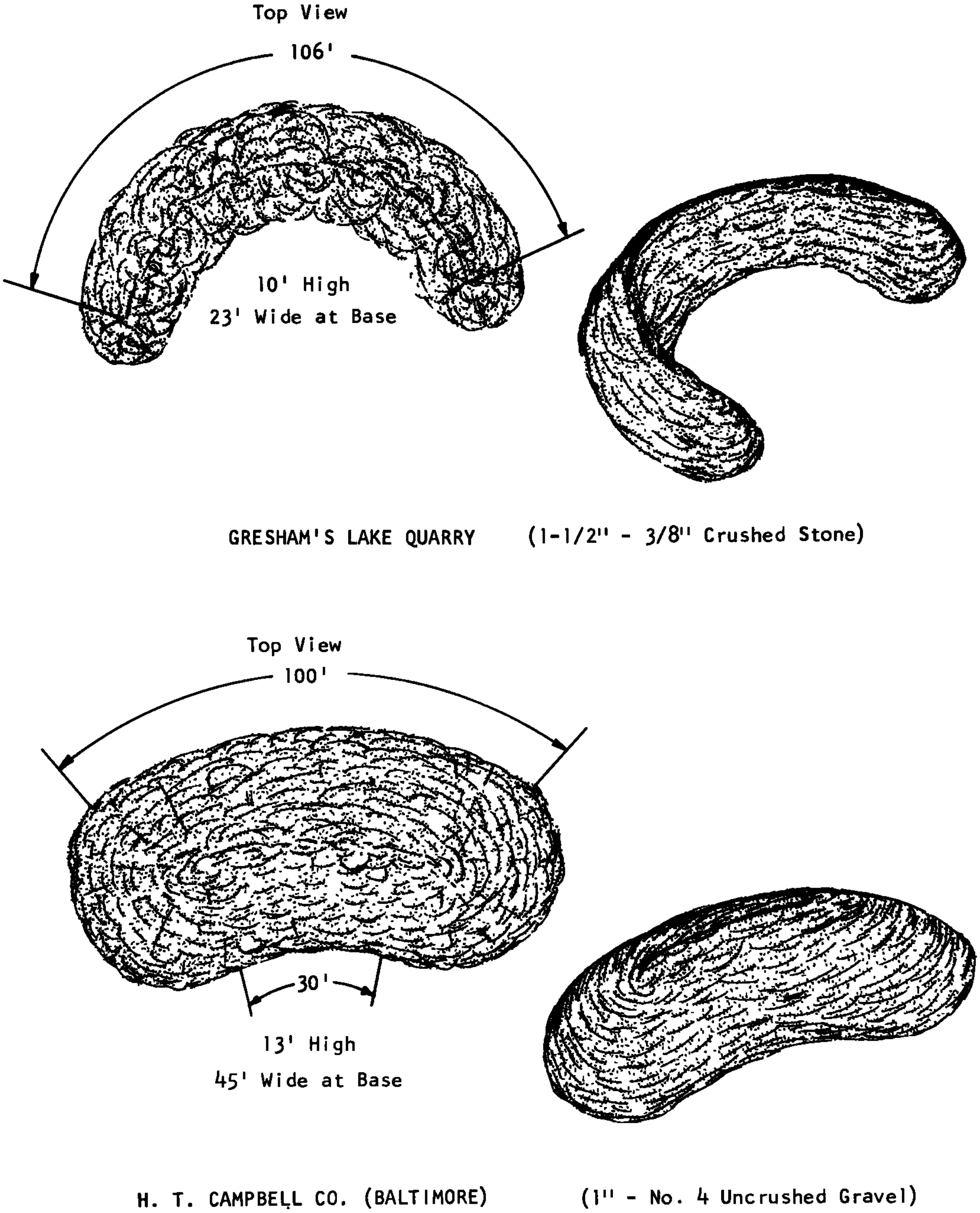


Figure 11. General configuration of cast-and-spread stockpiles.

The method of choosing test portions is an important factor in statistical studies of this type because it determines what use can be made of the sample data. The use of a random sampling procedure is mandatory if the resulting data are to have statistical validity. It has been found that subjective methods of choosing samples usually lead to biased samples, primarily due to subconscious or conscious preferences of the inspector or technician making the selections.

The following points in relation to random sampling were considered in these studies:

1. The overall LOT which the sample represented was defined (a given stockpile or test section).
2. The SAMPLING PLAN was so designed that every portion within the LOT had a known chance of being chosen for the sample.

SAMPLING PLAN

All samples were secured using a sampling plan as shown in Table 2. The only variation from strictly random procedure resulted when a brief breakdown made it impossible

TABLE 2

STRATIFIED RANDOM SAMPLING PLAN [a]

SAMPLE NO.	HOUR	RANDOM NO.	×60	TIME [b]	SAMPLE NO.	HOUR	RANDOM NO.	×60	TIME [b]
1	1	0.02	1	7:31	31	6	0.04	2	1:02
2		0.26	15	7:45	32		0.38	23	1:23
3		0.32	19	7:49	33		0.46	28	1:28
4		0.62	37	8:07	34		0.51	31	1:31
5		0.93	56	8:26	35		0.59	36	1:36
6		0.97	59	8:29	36		0.86	52	1:52
7	2	0.10	6	8:36	37	7	0.33	20	2:20
8		0.21	12	8:42	38		0.45	27	2:27
9		0.63	38	9:08	39		0.46	28	2:28
10		0.68	41	9:11	40		0.50	30	2:30
11		0.73	44	9:14	41		0.58	35	2:35
12		0.79	48	9:18	42		0.88	53	2:53
13	3	0.31	18	9:48	43	8	0.23	14	3:14
14		0.45	27	9:57	44		0.54	32	3:32
15		0.52	31	10:01	45		0.69	41	3:41
16		0.65	39	10:09	46		0.77	47	3:47
17		0.71	43	10:13	47		0.95	57	3:57
18		0.93	56	10:26	48		0.99	59	3:59
19	4	0.31	18	10:48	49	9	0.03	2	4:02
20		0.41	25	10:55	50		0.17	10	4:10
21		0.48	29	10:59	51		0.25	15	4:15
22		0.51	31	11:01	52		0.48	29	4:29
23		0.56	34	11:04	53		0.50	30	4:30
24		0.60	36	11:06	54		0.70	42	4:42
25	5	0.07	4	11:34	55	10	0.00	0	5:00
26		0.47	29	11:59	56		0.40	24	5:24
27		0.57	34	12:04	57		0.66	40	5:40
28		0.70	42	12:12	58		0.68	42	5:42
29		0.76	45	12:15	59		0.77	47	5:47
30		0.88	53	12:23	60		0.90	54	5:54

[a] 50 to 60 sample increments, 8- to 10-hr work day.
[b] 7:30 assumed starting time.

to secure TEST INCREMENTS at the scheduled time in one isolated incident. When construction operations were resumed following the breakdown, the plan was modified to insure the taking of the planned number of increments.

The particular plan used is known as a STRATIFIED RANDOM SAMPLING PLAN. This means that an equal number of test increments were taken during each time element (hour). It was decided initially that six REPLICATED test portions would be taken per hour. Six random numbers were then selected for each hour's operation and placed in ascending numerical order. Each number was multiplied by 60 to determine the exact minute within each 1-hour period for securing the test increment.

SAMPLE ACQUISITION

In the case of the crushed stone, all aggregate test increments were secured from the sampling belt. The procedure was similar to that followed in the initial 10-3 studies, which has proved to be satisfactory (Figs. 12, 13, and 14). Each time the belt was stopped, two test increments were removed. These increments, weighing approximately 25 lb, were separated by a distance of some 10 to 12 ft on the belt.

In the case of the gravel stockpile construction, this procedure could not be followed because of certain operational difficulties. The main problem here was that the conveyor belt employed was too narrow and the aggregate on a rather lengthy section of the belt would have to be removed to get a test increment of the required size. Consequently, test increments were obtained by cutting a flowing stream of aggregate with a pan (Fig. 15). The aggregate batches were loaded by a front-end loader into a large dump truck. The truck body was then raised to an angle of approximately 30° to 40° and the feeder gate at the rear opened so that a uniform stream would flow from the truck body. This closely simulated the rate of flow and the size of the aggregate stream feeding the sampling belt from the hopper at the other two locations (Princeton and Gresham's Lake). Two sample containers were passed through the flowing stream of aggregate (representing a single batch) in rapid succession, so that two increments for determining within-batch variance were secured. The time interval between replicated test portions permitted the

Figure 12. Templates used to define sample boundary on belt.

Figure 13. Aggregate removed from sample area on belt.

Figure 14. Fines brushed from sample area on belt.

Figure 15. Method of obtaining test increments from uncrushed gravel piles.

flow of a volume of aggregate equal to that required to cover approximately a 12-ft section of belt. All test increments were transferred to the testing laboratory of the research agency for gradation analysis.

DEGRADATION STUDIES

Variables

This part of the study was designed so that the relationships among the types of aggregate, methods of spreading, and methods of compaction could be established.

AGGREGATES

Both aggregates employed for these test sections were produced to meet specifications for North Carolina No. 8 stone, grading as follows:

Sieve Size	Total % Passing
1½ in.	100
1 in.	80–95
½ in.	60–75
No. 4	40–55
No. 10	28–43
No. 40	15–27
No. 200	5–12

This material is used extensively throughout the State for base course construction of secondary, primary, and Interstate highways. It is put down in layers 3 to 5 in. thick for a total depth of up to 20 in. Most secondary or light-duty roads, however, are constructed with a base thickness of 6 in. (one lift) to 8 in. (two lifts), so the construction conditions in the case of the test sections is realistic in terms of normal highway practice. The North Carolina standard specifications for this aggregate are quite detailed. To aid in understanding and interpreting the results, these specifications are given in Appendix C.

Both aggregates were produced to meet North Carolina standard specifications for stabilized base course. They were selected for this study as representative of relatively hard and soft aggregates on the basis of Los Angeles abrasion loss and specific gravity.

Hard stone.—The aggregate used for construction of Sections 1-D, 2-D, and 3-D (Fig. 16) was produced at the Teer quarry in Durham, N. C. It is identified geologically as traprock, and has a Los Angeles abrasion loss ranging from a low of about 7% to a high of about 17%, with an average of about 12%. The specific gravity of the parent aggregate varies from 2.78 to 2.80. Crushing does not produce a sufficient quantity of fines, so the aggregate is blended with overburden material to meet gradation requirements.

Soft stone.—The aggregate used for construction of Sections 1-G, 2-G, and 3-G (Fig. 16) was produced at Gresham's Lake quarry, located approximately 8 miles north of Raleigh, N. C., and was transported to Durham for this construction. This aggregate is identified geologically as a granite having a Los Angeles abrasion loss ranging from a low of about 42% to a high of about 62%, with an average value of about 50%. The specific gravity ranges from 2.62 to 2.74, dependent on the location within the quarry. When this material is crushed, it usually produces sufficient fines and it normally is not necessary to combine any added material to meet gradation requirements.

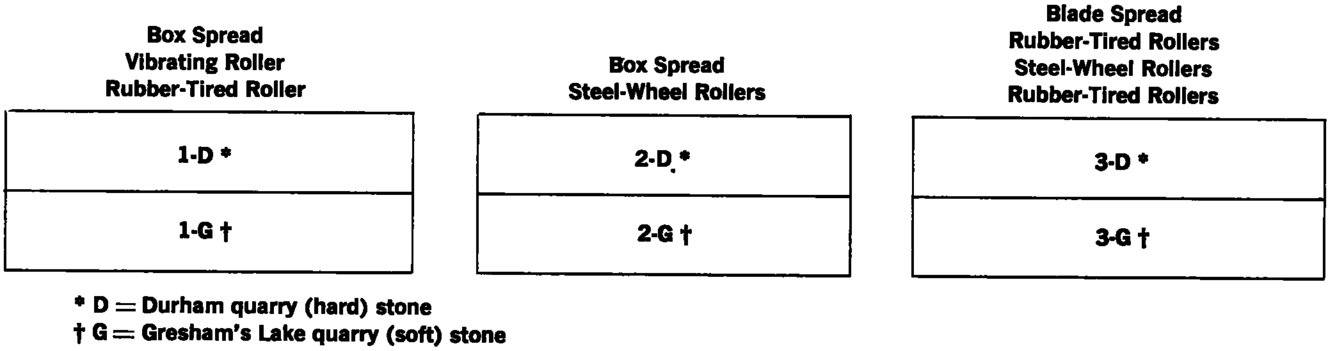


Figure 16. Identification and equipment used on degradation test sections.

METHOD OF SPREADING

Spreader box.—Sections 1-D, 2-D, 1-G, and 2-G (Fig. 16) were spread with a mechanical spreader used for routine base and pavement construction in North Carolina. This machine (Fig. 17) is a rubber-tired spreader for either aggregate base or bituminous mixtures. It was set to provide an uncompacted thickness of approximately 6½ in. When compacted, the thickness measured approximately 5½ in.

Blade spreading.—Sections 3-D and 3-G were spread with a motor grader (Fig. 18). Although this method of spreading generally is not used on an extensive basis in heavy-duty highway construction, it is often assumed to be more conducive to degradation and was therefore selected as one of the variables. Conditions of these test sections were such that it was relatively easy to obtain a uniform thickness with the blade spreading. In addition, it appeared that considerable additional mixing took place as the material was worked back and forth in an effort to obtain a uniform thickness of spread.

METHOD OF COMPACTION

Section 1; vibrating steel-wheel and rubber-tired roller.—Sections 1-D and 1-G were compacted with the vibrating steel-wheel roller (Fig. 19), followed by the rubber-tired roller (Fig. 20). The vibrating steel-wheel roller weighed 12,000 lb and made three passes over the material before the rubber-tired roller was brought into action. The rubber-tired roller weighed 14,600 lb and had five wheels in front and four wheels in back. Tire pressure was maintained at approximately 70 psi. Section 1-D was compacted to 94.6% of the maximum laboratory density obtained by AASHO Method T-99; Section 1-G was compacted to 102.9% of maximum laboratory density.

During the course of this construction, an expert soils engineer with some 35 years experience with this type of base construction in North Carolina served as advisor on the field operations. Compactive effort was terminated, based on his visual inspection, when it appeared that maximum density had been reached. Subsequent density measurements confirmed that the cut-off point had been properly selected. This same system is employed on routine highway construction throughout the area where this research was conducted.

Section 2; three-wheel roller.—Sections 2-D and 2-G were compacted with a three-wheel (steel) roller (Fig. 21) that weighed 21,200 lb. It was not practicable to determine the exact number of passes which this roller made over each section because of the multitude of construction items that were taking place simultaneously. These two sections, however, were compacted to 96.3% and 104.1%, respectively, of maximum laboratory density.

Section 3; rubber-tired and three-wheel roller.—In Sections 3-D and 3-G, the material which had been previously spread by the motor grader was compacted with the rubber-tired roller, followed by the three-wheel steel-wheel roller, and finally the rubber-tired roller. In this case, 96.3% of laboratory density was obtained in Section 3-D and 102.7% of laboratory density was obtained in Section 3-G.

Construction of Test Sections

FLOW OF MATERIAL

In brief, the aggregate was passed across a feeder belt for initial sampling, passed through the pug mill mixer, where the water was added, discharged onto a truck load-out belt, transported to the test section site, and spread by box spreader or motor grader. The sections were then compacted as described previously.

Figure 22 shows the flow of aggregate from the parent pile through the various handling and processing operations to the end point. The hard aggregate was picked up by front-end loader from the quarry working pile and loaded onto dump trucks. The trucks deposited the aggregate into a feeder pile at the end of the pug mill feeder belt. The soft aggregate was dumped directly from the transport dump trucks, as they arrived on the project site, onto the feeder pile.

The mixer was a 2-ton continuous-type pug mill 9 ft long, 5 ft wide, and 3 ft deep, and was a twin-shaft, counter-rotating type (Fig. 23). The aggregate stayed in the pug mill approximately 9 sec from point of entry to point of discharge. Spray bars located at the top edge added water during mixing.

To help the reader better visualize the field operations, additional photographs show the conveyor and mixer assembly for preparing base course aggregate (Fig. 24), the

area used for construction of degradation test sections (Fig. 25), the base course aggregate spread by mechanical spreader (Fig. 26), the technicians removing test increments (Fig. 27), the 50 test increments secured from each section (Fig. 28), and the holes from which test increments were removed (Fig. 29).

CONFIGURATION

Each test section was 100 ft long by 10 ft wide and the base material was spread to produce an average compacted thickness of approximately 5½ in. The base was constructed on a hard-surfaced roadway (Fig. 25) so that all fines within the sampling area could be recovered for gradation analysis. Prior to construction of the test sections the roadway was swept clean and barricades were erected to prevent its use by local traffic. Individual sections were constructed in accordance with Figure 16, as previously outlined. The D or G following each number indicates that either Durham quarry (hard) or Gresham's quarry (soft) stone was used in the particular section involved.

Sampling Considerations

SAMPLING PLAN

To eliminate bias, as discussed previously under "Segregation Studies (Stockpiling)—Sampling Considerations," all test increments were taken in accordance with a random sampling plan. The aggregate entering into and discharged from the pug mill was sampled on the basis of a random time element. The sampling plan used for this purpose was given previously as Table 2. The aggregate was picked up by a front-end loader, discharged into a hopper, and passed across a conveyor belt for initial sampling. This belt discharged into the pug mill, from which the material was deposited on a second belt, which dumped into trucks. When the master switch was pulled, both belts and pug

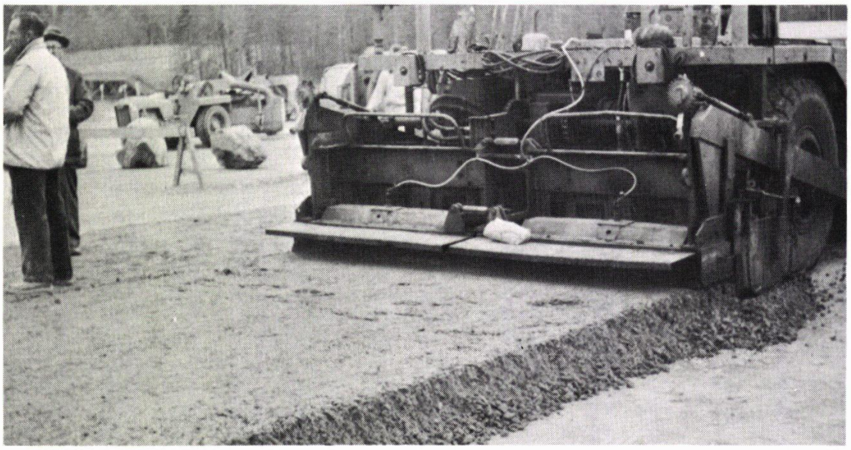


Figure 17. Base course test section spread by mechanical spreader.

Figure 18. Base course test section spread by motor grader.

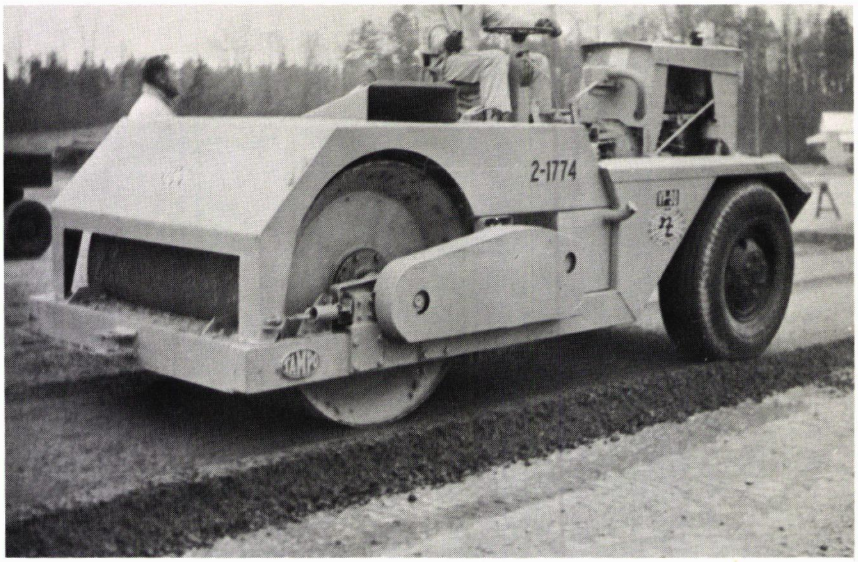


Figure 19. Vibrating roller used in compacting test sections.

Figure 20. Rubber-tired roller used in compacting test sections.

Figure 21. Steel-wheel roller used in compacting test sections.

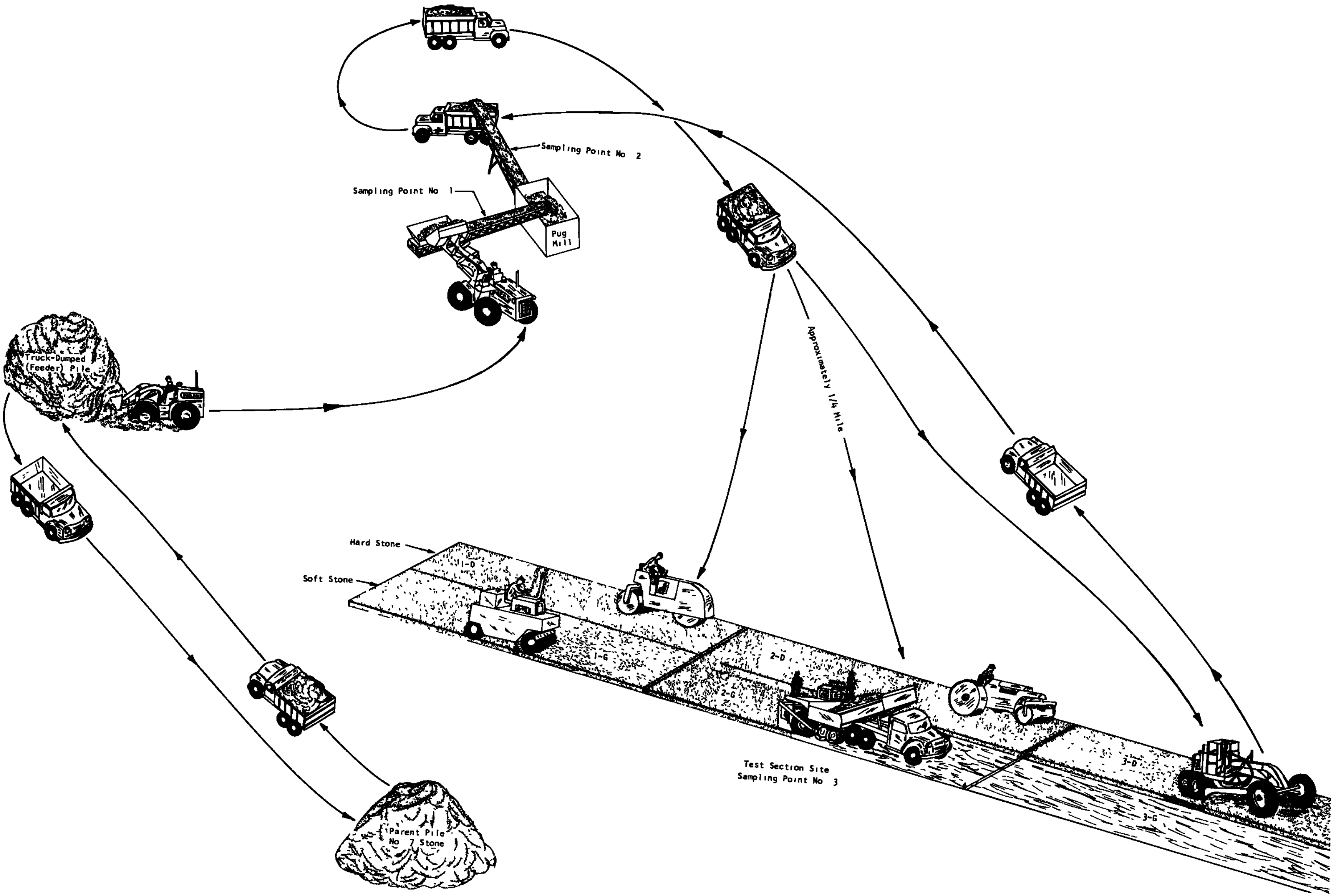


Figure 22. Flow sheet for construction of degradation test sections.

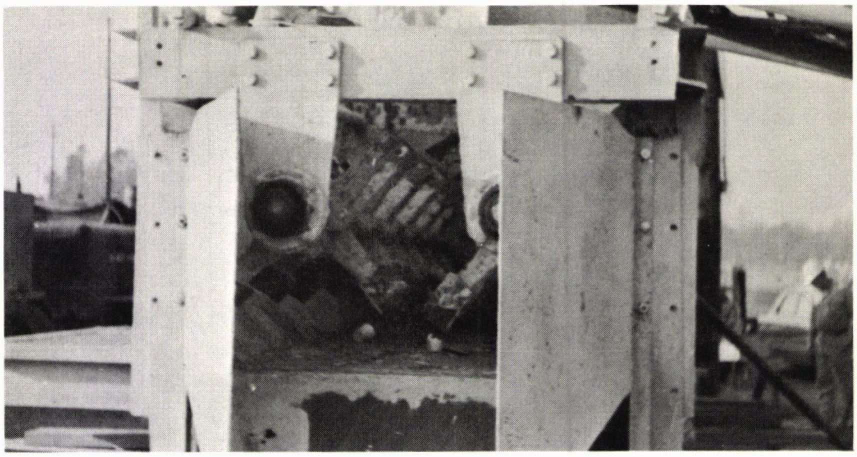


Figure 23. Discharge end (top) and input (bottom) to pug mill used for mixing base course aggregate.

Figure 24. Conveyor and mixer assembly for preparing base course aggregate.

Figure 25. Area used for construction of degradation test sections.

Figure 26. Base course aggregate spread by mechanical spreader.

Figure 27. Technicians removing test increments.

Figure 28. Fifty test increments secured from each section.

Figure 29. Random pattern of test increment holes (see Fig. 30).

mill stopped so that before-mixing and after-mixing samples were acquired at the same time.

The roadway samples were also taken in accordance with a random sampling plan, although in this case the randomization was developed in terms of location, as shown in Figure 30.

The individual points on this sampling plan were located by using a table of random numbers similar to Table 3. Two columns of random numbers were selected for various locations, with each pair of numbers being used to determine a single test portion location. For example, if the numbers 0.967 and 0.696 were provided as a starting point, the length of the section (100 ft) would be multiplied by 0.967 and the width (10 ft) by 0.696, so that this particular test portion would be located 96.7 ft (lengthwise) from the southeast corner and 6.96 ft from the right-hand edge of the lane. All other test portions were located in a similar manner. A total of 25 replicated test portions was removed from each section. The replications were taken so that within-batch variation, σ^2_b, as well as between-batch variation, σ^2_l, could be determined. Chapter Two provides an explanation of the significance of these terms and how they fit into the overall evaluation.

SAMPLE ACQUISITION

Belt samples were secured by defining a specific area of the belt and then removing all material within this area. A total of four test portions was taken, two from the belt feeding the raw material into the pug mill and two from the belt leading from the pug mill discharge to truck loadout. The two sampling points on each belt were approximately 10 ft apart. Sufficient material was removed at each sampling point to produce a test portion weighing approximately 25 lb. Each portion was placed in a cotton

CHAPTER FOUR

PRESENTATION OF DATA

Inasmuch as the field experiments had different objectives, the data presented in this section are divided into two major parts—one concerned with stockpiling results and the other with degradation results.

As previously indicated, the raw data for both the initial and the continuation phases are available on special request (see Appendix H). The data presented in this chapter, however, are given in summary form as a series of tables, charts, and graphs which describe the relationships of various statistical and engineering parameters. An effort has been made to present the more familiar comparisons first and gradually lead into the more complex, statistical relationships. In the event the reader does not desire to delve into unfamiliar statistical analysis of the data, he may simply examine the gradation charts for evidence of changes in gradation at the various sampling points. He should be cautioned, however, that additional comparisons are necessary to have a complete understanding of the results obtained.

Prior to examination of the detailed results, several observations of a general nature may aid in an overall understanding of both phases of the study.

In research work of this type, it is not always possible to accurately predict the final outcome or even the pattern of test values that will be obtained. In these studies, the stockpiling results followed, more or less, the pattern expected as a result of the earlier Princeton quarry investigation; however, the degradation results departed considerably from those anticipated.

This, of course, does not diminish their value but may indicate a need for even more exhaustive tests covering other materials and conditions before absolute conclusions can be drawn.

Consider first the stockpiling investigation. Previous studies at the Princeton quarry of Nello L. Teer Company had established a pattern of segregation for several different stockpiling methods. Those methods which were selected for continuing study (on the basis of the initial work) were believed to offer the most desirable, the least desirable, and an intermediate level of stockpiling efficiency. In the absence of more extensive data to either confirm or refute these trends, it was expected that a somewhat similar pattern would result as other aggregates or gradations, or both, were evaluated by the same methods. Although the general trend was confirmed, there appeared to be slightly more departure from a clear-cut pattern than was obtained in the earlier work. This leads to the belief that not only the stockpiling method, but also aggregate type, gradation, and unknown factors may have a more significant influence on the results than was previously anticipated.

The degradation results failed to confirm the usual belief that there is continual degradation as the aggregate is handled, spread, compacted, or otherwise subjected to abrasive or pressure forces, particularly aggregates having a high Los Angeles abrasion loss. With these preconceived ideas in mind, it was anticipated that a substantial increase in fines (especially minus No. 200) would be shown as the base course aggregate went through the various mixing, spreading, and compacting operations. Although a slight build-up of fines was indicated from point to point, the amount of breakdown or degradation was substantially less than was expected. In addition, the difference in degradation between the very hard and very soft aggregate was virtually nil. Possible reasons for the lack of difference are given later in this chapter.

Most of the work used as a basis for the current report is a continuation of studies initially conducted under the same NCHRP project. Because the initial results were published as a separate report (*NCHRP Report 5*), there is little need to repeat this material in its entirety. It is believed desirable, however, to provide a summary table of results obtained at the Princeton quarry, where eleven full-scale stockpiles were constructed and evaluated. This should help the reader in understanding and comparing results obtained on the later work.

SUMMARY OF INITIAL STOCKPILING STUDIES (PRINCETON QUARRY)

Details of the accomplishments of the initial 10-3 investigation have been published in *NCHRP Report 5*, "Effects of Different Methods of Stockpiling and Handling Aggregates—Interim Report." For convenience, a rating of the various stockpiling methods evaluated is provided in summary form. The basis for this rating system is the segregation index, S, obtained by dividing the overall variance, σ^2_o of Hudson $\bar{A}$, by the within-batch variance, σ^2_b of this value. It should be especially noted that in the initial studies an *average* within-batch variance was obtained and used for calculating S. Because of the sampling scheme used for this early work, it was not possible to determine a separate σ^2_b for each stockpile. As experience was gained through the progressive steps involved in the research, a realization of the need and value of a different approach to measuring within-batch variance became apparent. Consequently, later work was carried out using a different sampling pattern, which did provide individual σ^2_b values for each stockpiling method. The net effect of the two different approaches was that the initial S results appeared to follow a more definite pattern, because the overall variance was divided by a constant, whereas in the continuation studies the within-batch variance changed from stockpile to stockpile. However, the later system is

believed to provide a more realistic and practical basis for comparison.

Table 4 provides a summary of the construction methods used and the results obtained in terms of segregation index for the initial work accomplished at the Princeton quarry.

STOCKPILING DATA

This section presents the gradation curves, tables, charts, and graphs which indicate the relationships among different methods studied and among the various parameters obtained.

Average Gradation of Stockpile Aggregate

The average grading of aggregate used at each of the three stockpiling sites is given in Table 5. It can be seen that two of the aggregates (Princeton and Baltimore) have basically the same gradation, whereas the third (Gresham's Lake quarry) is considerably coarser. Differences in these gradations should be carefully noted, as there is an indication that maximum size and relative proportions have an effect on stockpiling results.

Aggregate Grading Charts

To the highway engineer, aggregate grading charts may have more meaning than some of the other data, because most engineers are acquainted with their use in the interpretation of gradations. First, the average gradation and standard deviation of each stockpiling method was found; second, the $\pm 2\sigma_0$ limits were applied to the average to produce the gradation limits indicated by the width of the black bands. These limits correspond to the theoretical limits that would include 95 percent of all test values obtained under similar conditions. One can readily compare variability from one pile to another by comparing the width of the $\pm 2\sigma_0$ gradation bands, because as variability increases the width of the band increases. Also, the changing slope of the lines provides an indication as to the relative amount of aggregate between adjacent sieves.

TABLE 4

SEGREGATION INDEX [a] OF STOCKPILING METHODS

STOCKPILE NO.	STOCKPILE TYPE	CONSTRUCTION METHOD [b]	n	SEGREGATION INDEX [c]	F-TABLE VALUE, 95%	¾ IN.	⅜ IN.	NO. 4	NO. 8
1 [d]	Flat-mixed	Clamshell bucket	46	1.35	1.48	1.71	1.36	0.37	0.21
10	Ramped	Rubber-tired dozer	74	1.59 [e]	1.42	1.39	2.06	2.11	1.99
3	Flat-layered	Clamshell bucket	52	1.96 [e]	1.48	2.67	2.28	0.43	0.60
11	Flat-mixed	Rubber-tired dozer	66	2.10 [e]	1.42	1.33	1.82	3.40	10.68
9 [d]	Truck-dumped	Dump trucks	73	2.30 [e]	1.42	2.62	3.34	1.12	1.11
6	Flat-layered	FE loader	50	4.05 [e]	1.48	4.10	5.01	1.61	2.43
8	Tiered (bermed)	Clamshell bucket	75	7.37 [e]	1.42	6.63	7.10	3.43	4.23
5	Coned tent	Portable conveyor	64	8.10 [e]	1.42	5.22	13.31	3.92	1.98
7 [d]	Single cone	Clamshell bucket	58	13.36 [e]	1.48	12.13	17.52	6.14	1.54
2	Double cone	Clamshell bucket	66	16.48 [e]	1.42	12.75	15.64	7.11	10.86
4	Single cone	Clamshell bucket	65	16.86 [e]	1.42	17.93	27.46	4.71	1.53

[a] Listed in order of increased segregation (Princeton quarry) based on the ratio of σ^2_0/σ^2_b (= overall variance/within-batch variance); $n = 96$ for average σ^2_b, assumed to be the same for all stockpiles.
[b] All stockpiles reclaimed with front-end loader except Stockpile No. 4, which was reclaimed with clamshell bucket.
[c] Based on $\bar{\bar{A}}$.
[d] Selected for further comparison and evaluation studies in the continuation phase.
[e] Significant difference.

TABLE 5

AVERAGE AGGREGATE GRADING

SIEVE SIZE	PERCENT PASSING: PRINCETON (1 IN.-NO. 4 CRUSHED STONE)	GRESHAM'S LAKE (1½ IN.-⅜ IN. CRUSHED STONE)	BALTIMORE (1 IN.-NO. 4 UNCRUSHED GRAVEL)
1½ in.	100	100	100
1 in.	—	67.1	—
¾ in.	80.4	27.6	80.3
⅜ in.	15.2	6.9	28.6
No. 4	1.8	4.6	5.5
No. 8	0.6	3.9	2.4

There are three groups of grading charts included at this point: Princeton quarry (1-in.-No. 4 crushed stone) (Figs. 31, 32, 33, and 34); Gresham's Lake (1½-in.-⅜-in. crushed stone) (Figs. 35, 36, 37, 37a, and 38); and Baltimore (1-in.-No. 4 uncrushed gravel) (Figs. 39, 40, 41, and 42). The order of presentation is that in which the field work was performed.

Considering each group of grading charts individually, the following observations are made:

1. At Princeton quarry (1 in.-No. 4 crushed stone)

there was little change in gradation between the parent pile and the cast-and-spread pile. The single-cone pile showed a slight tendency toward degradation, which leveled off as the aggregate was used in the construction of subsequent piles. The comparatively wide band representing the single-cone pile clearly shows the greater variability (segregation) found in this pile. This variability is decreased as the aggregate is later used for construction of the truck-dumped pile.

2. Considering the Gresham's Lake (1½ in.-⅜ in. crushed stone) charts, it is noted that this is essentially a one-size aggregate and is coarser than the other aggregates studied. Material drawn from the parent pile showed a comparatively low standard deviation at all size levels. Upon construction of the single-cone pile, the standard deviation of all sizes approximately doubled, but then decreased to the original level when the aggregate was spread in thin layers in the cast-and-spread pile, then showed another sharp increase as the material was used in the construction of the truck-dumped pile.

Two aggregate grading charts (Figs. 37 and 37a) are shown for the cast-and-spread pile. These charts are based on the total data (100 increments) and the first 60 increments, respectively. With the exception of Figure 37, all other charts, graphs, tables, etc., for the cast-and-spread pile were determined on the basis of the data contained in Figure 37a. Fifty replicated test portions (100 individual increments) were taken to represent this pile. Upon plotting the points for the $\bar{A}$ charts shown in a subsequent subsection, it was immediately apparent that the average level and variability experienced a marked change at a certain point in the construction process. This occurred at 1:00 PM, after approximately 60 test increments had been taken. This change in grading and its ramifications are discussed in the section on "Graphical Presentation of Hudson $\bar{A}$ Values." Both gradation charts are shown so that the reader may be aware of the effect of an ASSIGNABLE CAUSE on stockpiling efficiency. Mistaken conclusions could be drawn unless (a) the total data are shown, and (b) that portion of the data affected by the assignable cause is then removed from consideration in subsequent comparisons and interpretations.

There is evidence of statistically significant increases and decreases in the average gradation found in these and several other stockpiles, but this obviously does not indicate an increase in particle size and may or may not indicate a decrease. All stockpiles were constructed under practical conditions at quarry sites and it was not always possible to cleanly separate the stockpiled aggregate from the underlying material on which it was constructed. In spite of the front-end loader operator being continually cautioned against letting his bucket drop into this underlying material, it was observed several times that some contamination did occur. A slight amount of the increase in minus No. 8 material may be attributed to this cause. Most of the increase in fineness, however, is presumably due to degradation. Particularly with the Gresham's Lake aggregate, the very weak point and sharp corners of the coarser particles were apparently broken away during initial handling for construction of the cone pile. During subsequent handling, the gradation of the coarser particles remained fairly constant.

3. Considering the Baltimore charts (1 in.-No. 4 uncrushed gravel), it is apparent that the variability showed a substantial increase between the parent pile and the single-cone pile. The variability was decreased during subsequent construction of the cast-and-spread and truck-dumped piles, and in the latter case returned to the level of the parent material. The variability of the parent aggregate in this case is much greater than at either of the other two locations. This greater variability is also evident in the piles subsequently constructed from this aggregate and may be attributed to the rounded particle shape of the uncrushed gravel with the increased tendency toward segregation.

Graphical Presentation of Hudson $\bar{A}$ Values

This section presents, in graphical form, plots of the Hudson $\bar{A}$ values obtained at each stockpiling location. Points on the graphs for the Princeton quarry (1 in.-No. 4 crushed stone) represent a single $\bar{A}$ value, whereas points on the graphs for the Gresham's Lake quarry (1½ in.-⅜ in. crushed stone) and Baltimore (1 in.-No. 4 uncrushed gravel) represent the average of the two (A and B) replicate test portions. Because $\bar{A}$ is a measure of relative coarseness, these charts are particularly valuable as a means of showing changes in gradation from point to point or from time to time. If the gradation remained fairly constant, the points would fall, more or less, in a straight line. Points widely separated (on the vertical scale) mean that there is considerable variation in gradation.

The dashed centerline represents the average $\bar{A}$ value, while the two outer dashed lines define the $\pm 2\sigma_0$ limits, which should include 95 percent of individual test values obtained under similar conditions. In all cases the $\pm 2\sigma_0$ lines are drawn on the basis of the standard deviation of individual test increments, but it should be remembered that each point on the Gresham's Lake and Baltimore charts is an average of two replicate increments, as previously described.

Each individual chart should be examined, keeping in mind the type of stockpile which it represents. Figs. 43, 44, 45, and 46 present the sequential $\bar{A}$ values from the Princeton quarry. Note especially the Princeton single-cone pile (Fig. 44). In this case the front-end loader began reclaiming the pile on one outer edge and worked straight through, keeping an even working face as the pile was depleted. Test increments were randomly secured throughout the breakdown of this pile. The fact that coarser particles were predominant on the outer edges of the pile is evident by the relatively low $\bar{A}$ values at the beginning and again at the completion of breaking this pile down. This trend is also true in the single-cone piles constructed at Gresham's Lake and at Baltimore (Figs. 48 and 52), although the trend is not quite as pronounced.

It will be recalled that construction of the three piles represented herein at Princeton quarry was not a sequential

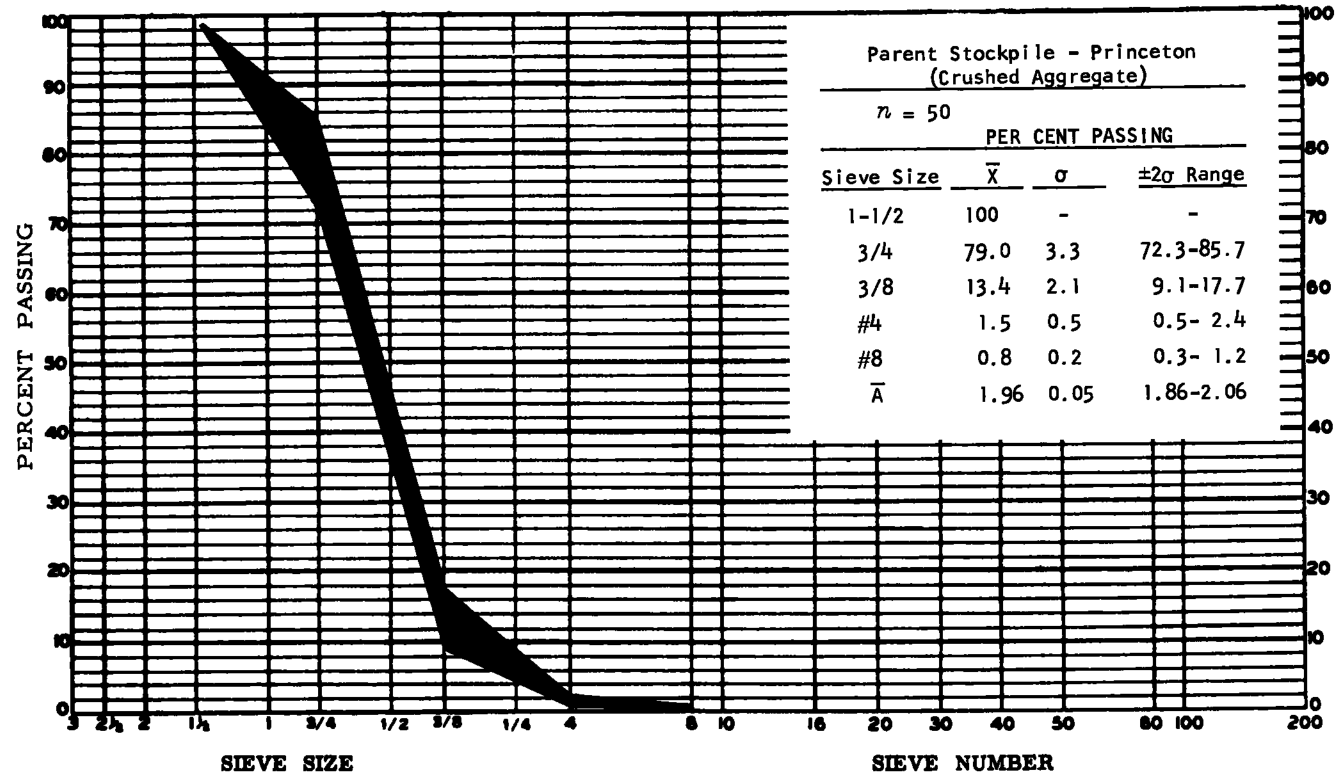


Figure 31. Aggregate grading chart, parent stockpile, Princeton (crushed) aggregate.

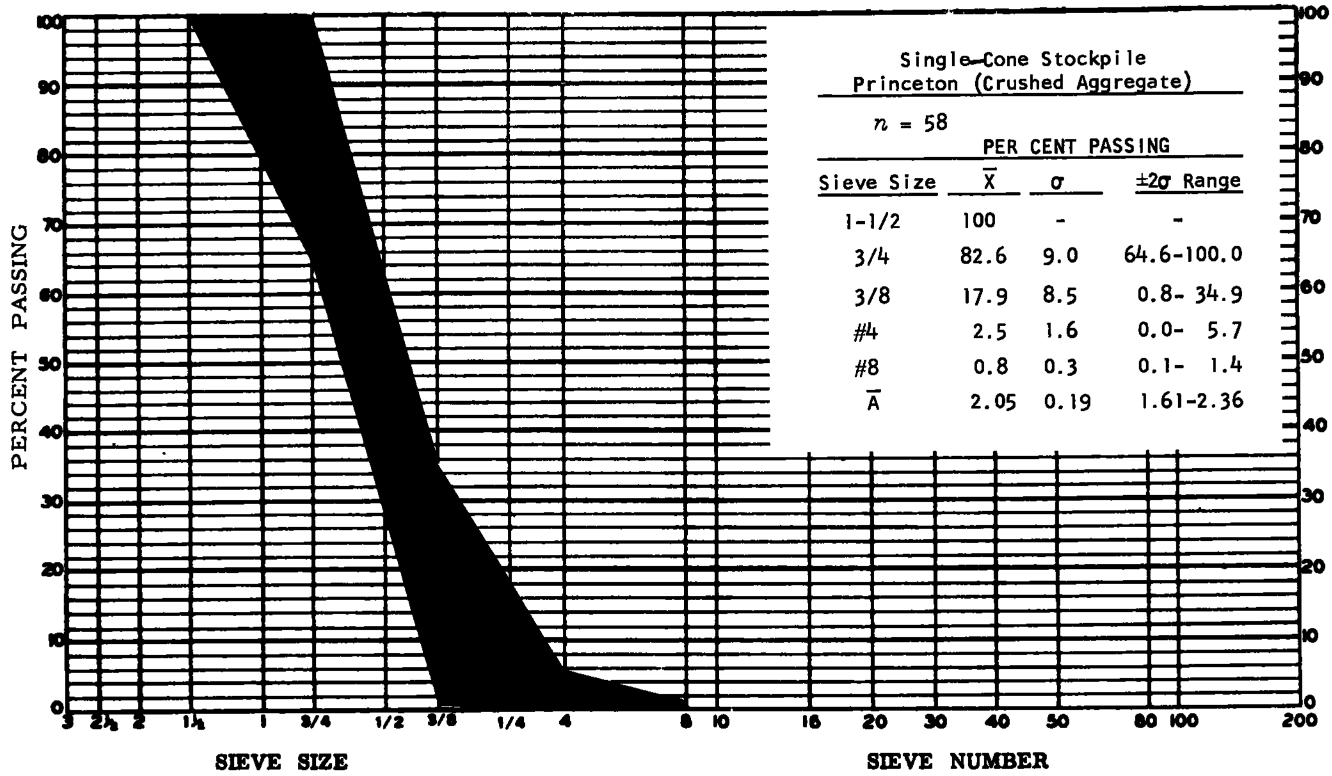
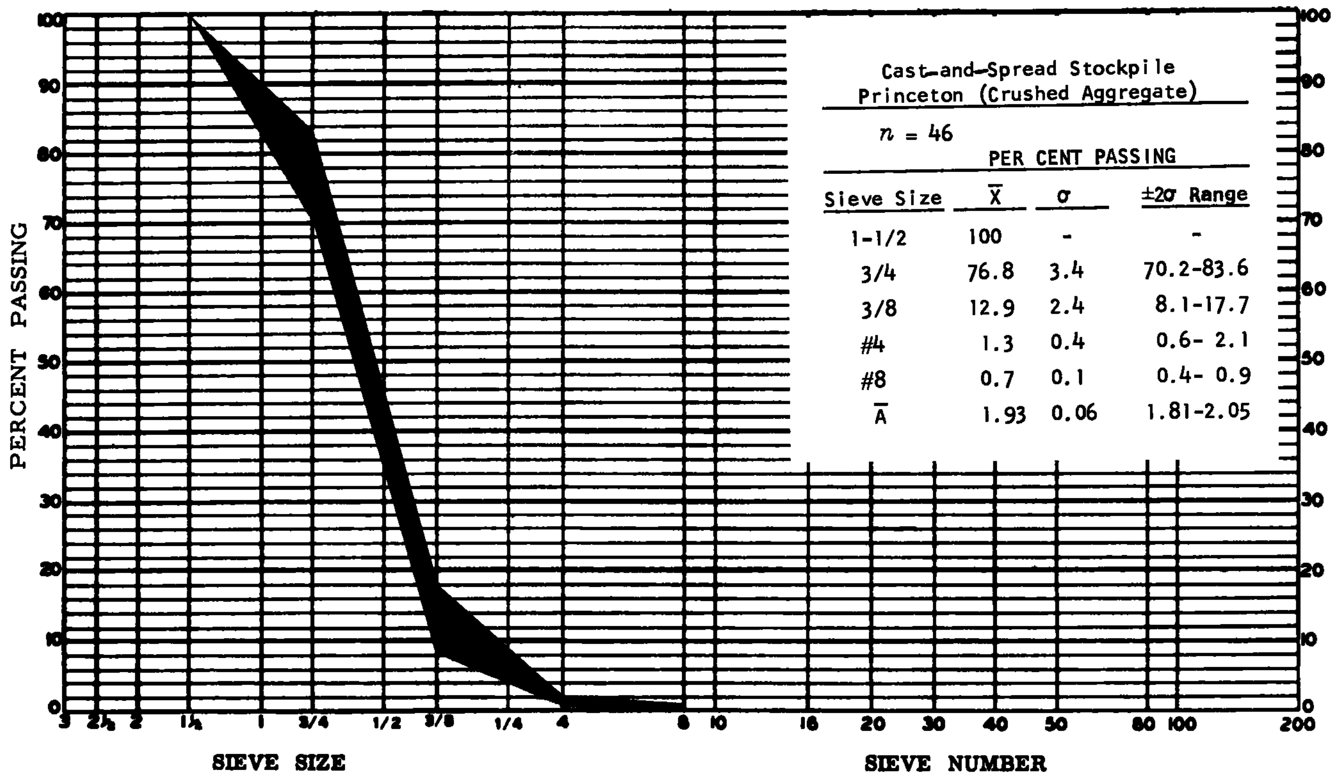
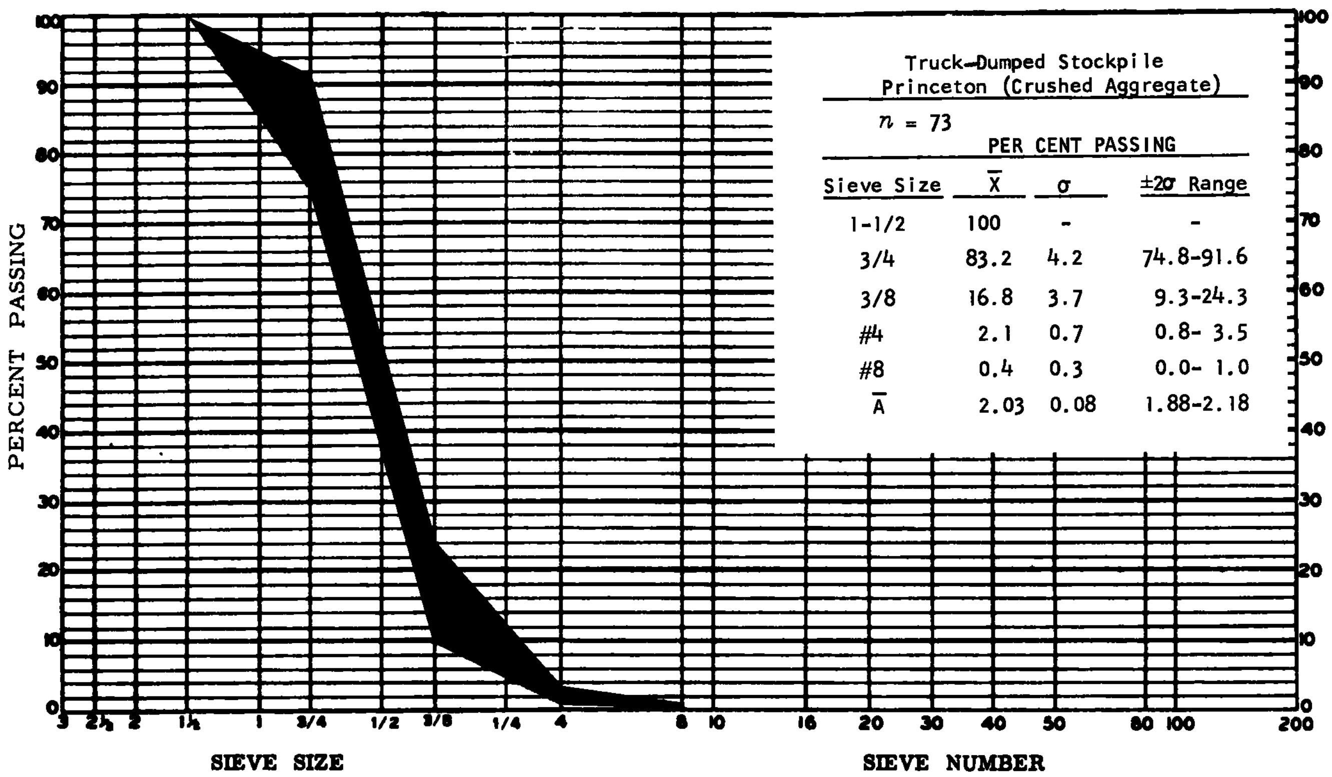


Figure 32. Aggregate grading chart, single~~-cone~~ stockpile, Princeton (crushed) aggregate.



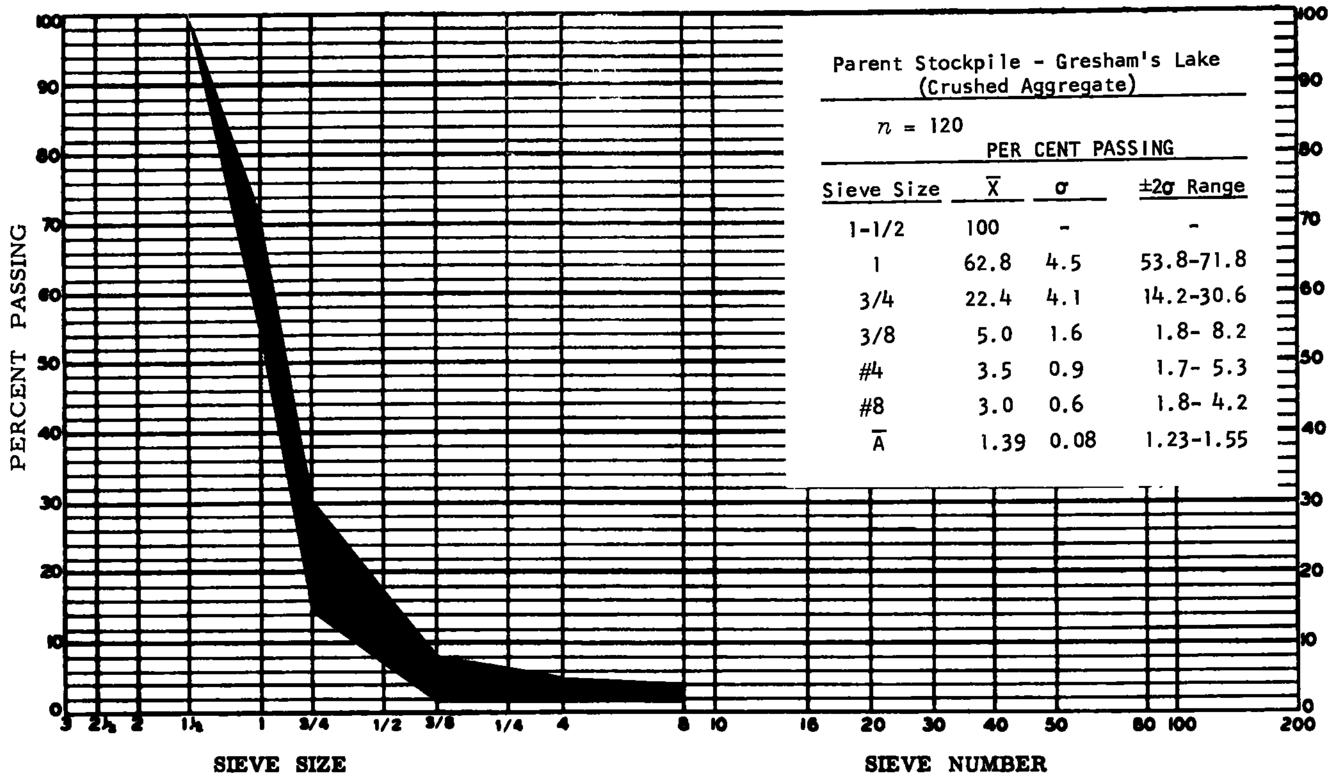
Sieve Size	$\bar{X}$	σ	$\pm 2\sigma$ Range
1-1/2	100	-	-
3/4	76.8	3.4	70.2-83.6
3/8	12.9	2.4	8.1-17.7
#4	1.3	0.4	0.6- 2.1
#8	0.7	0.1	0.4- 0.9
$\bar{A}$	1.93	0.06	1.81-2.05

Figure 33. Aggregate grading chart, cast-and-spread stockpile, Princeton (crushed) aggregate.



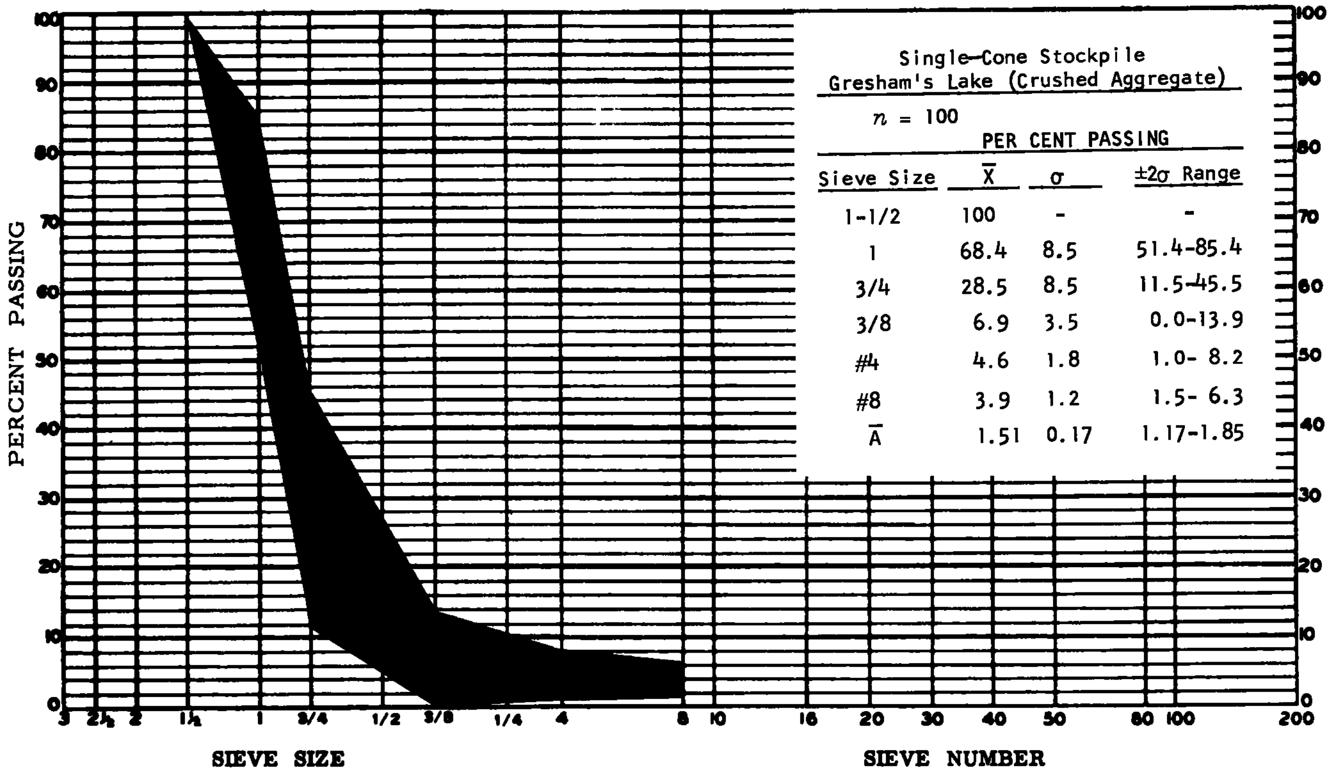
Sieve Size	$\bar{X}$	σ	$\pm 2\sigma$ Range
1-1/2	100	-	-
3/4	83.2	4.2	74.8-91.6
3/8	16.8	3.7	9.3-24.3
#4	2.1	0.7	0.8- 3.5
#8	0.4	0.3	0.0- 1.0
$\bar{A}$	2.03	0.08	1.88-2.18

Figure 34. Aggregate grading chart, truck-dumped stockpile, Princeton (crushed) aggregate.



Sieve Size	$\bar{X}$	σ	±2σ Range
1-1/2	100	-	-
1	62.8	4.5	53.8-71.8
3/4	22.4	4.1	14.2-30.6
3/8	5.0	1.6	1.8- 8.2
#4	3.5	0.9	1.7- 5.3
#8	3.0	0.6	1.8- 4.2
$\bar{A}$	1.39	0.08	1.23-1.55

Figure 35. Aggregate grading chart, parent stockpile, Gresham's Lake (crushed) aggregate.



Sieve Size	$\bar{X}$	σ	±2σ Range
1-1/2	100	-	-
1	68.4	8.5	51.4-85.4
3/4	28.5	8.5	11.5-45.5
3/8	6.9	3.5	0.0-13.9
#4	4.6	1.8	1.0- 8.2
#8	3.9	1.2	1.5- 6.3
$\bar{A}$	1.51	0.17	1.17-1.85

Figure 36. Aggregate grading chart, single-cone stockpile, Gresham's Lake (crushed) aggregate.

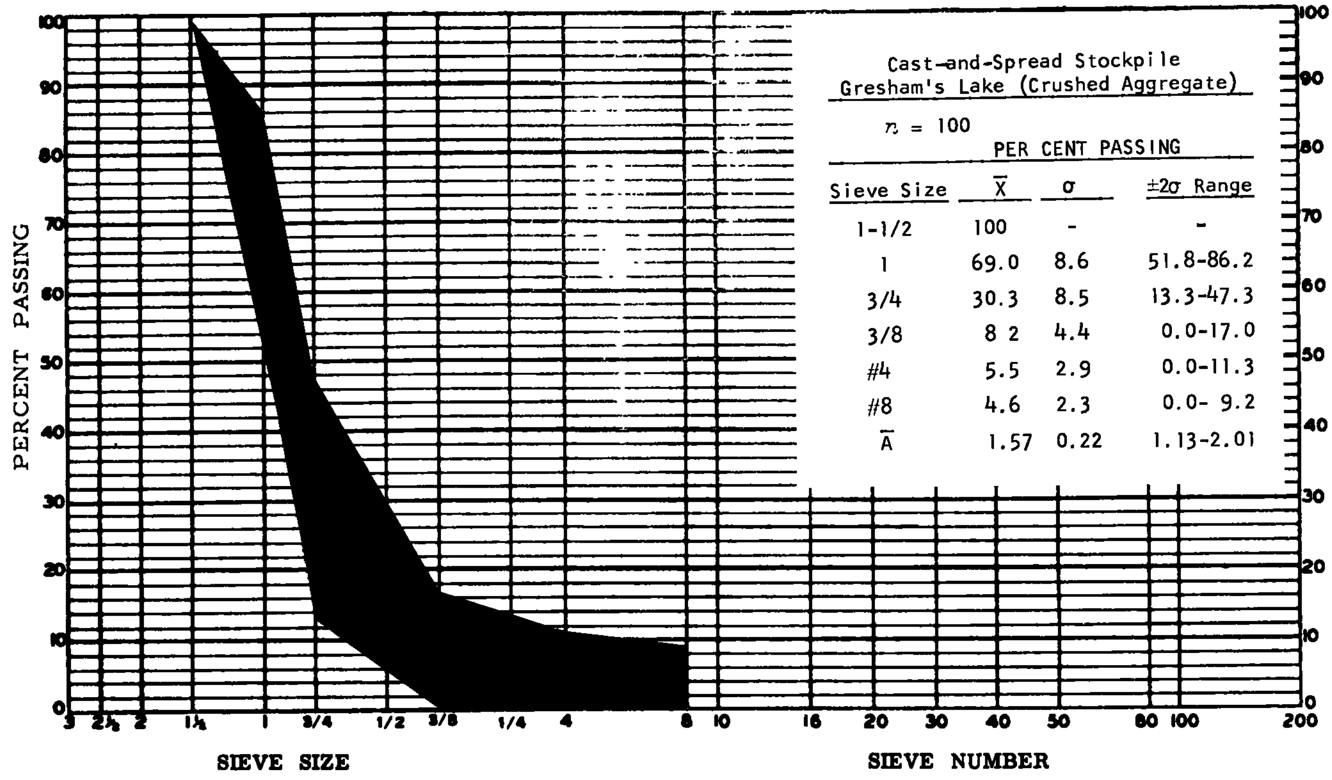


Figure 37. Aggregate grading chart, cast-and-spread stockpile, Gresham's Lake (crushed) aggregate.

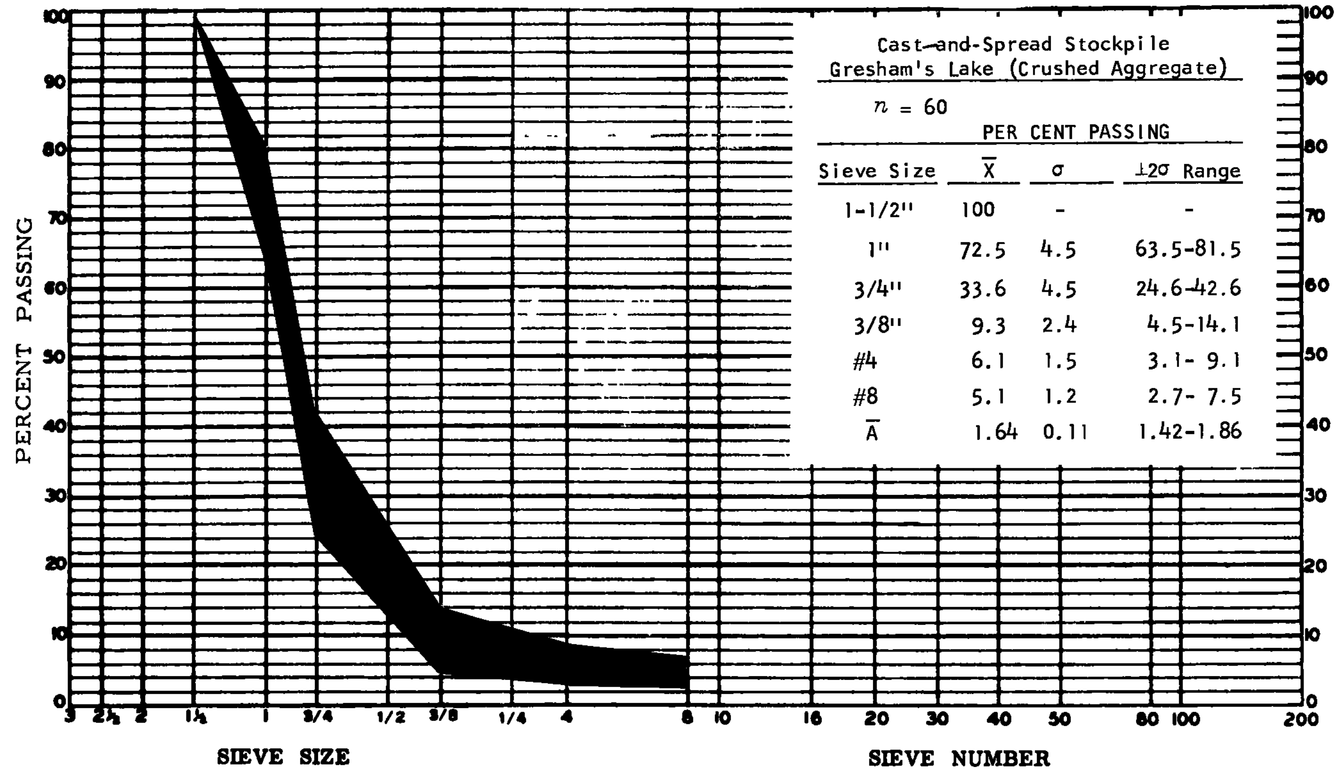
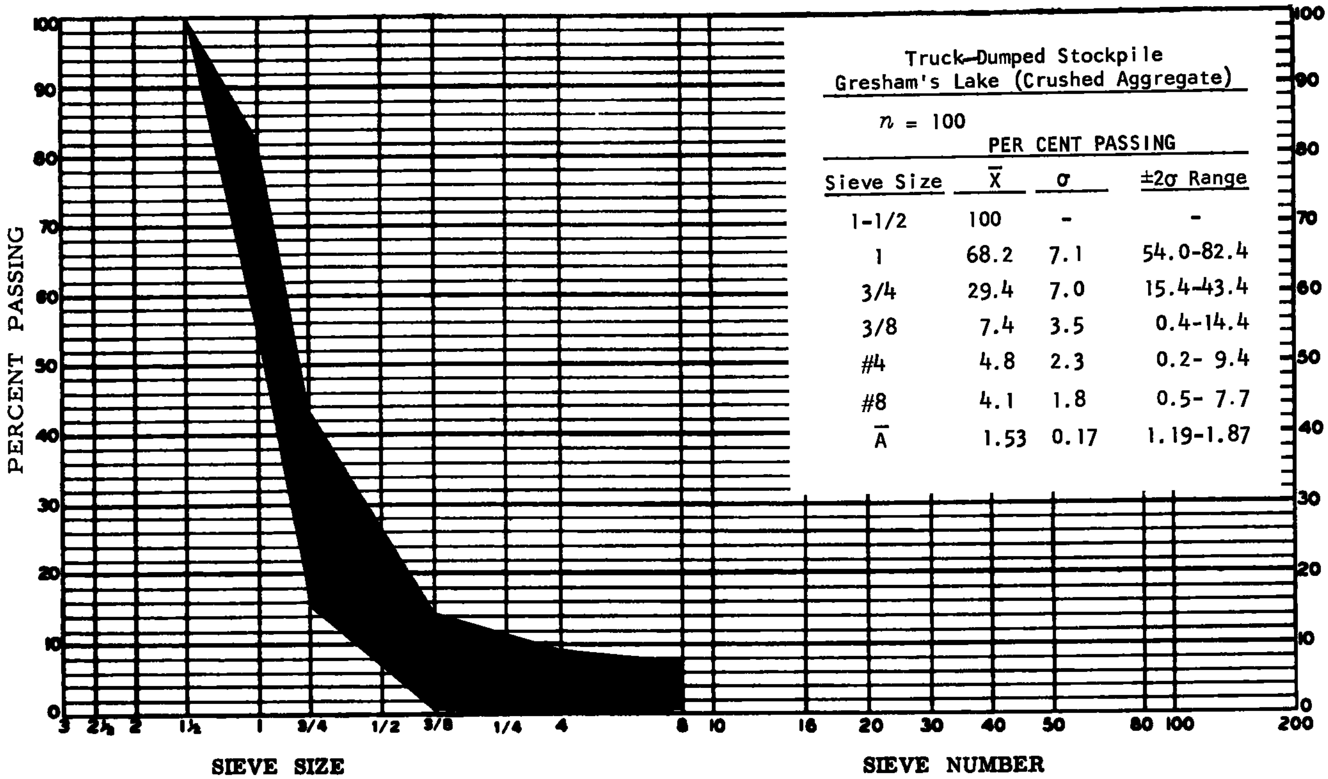
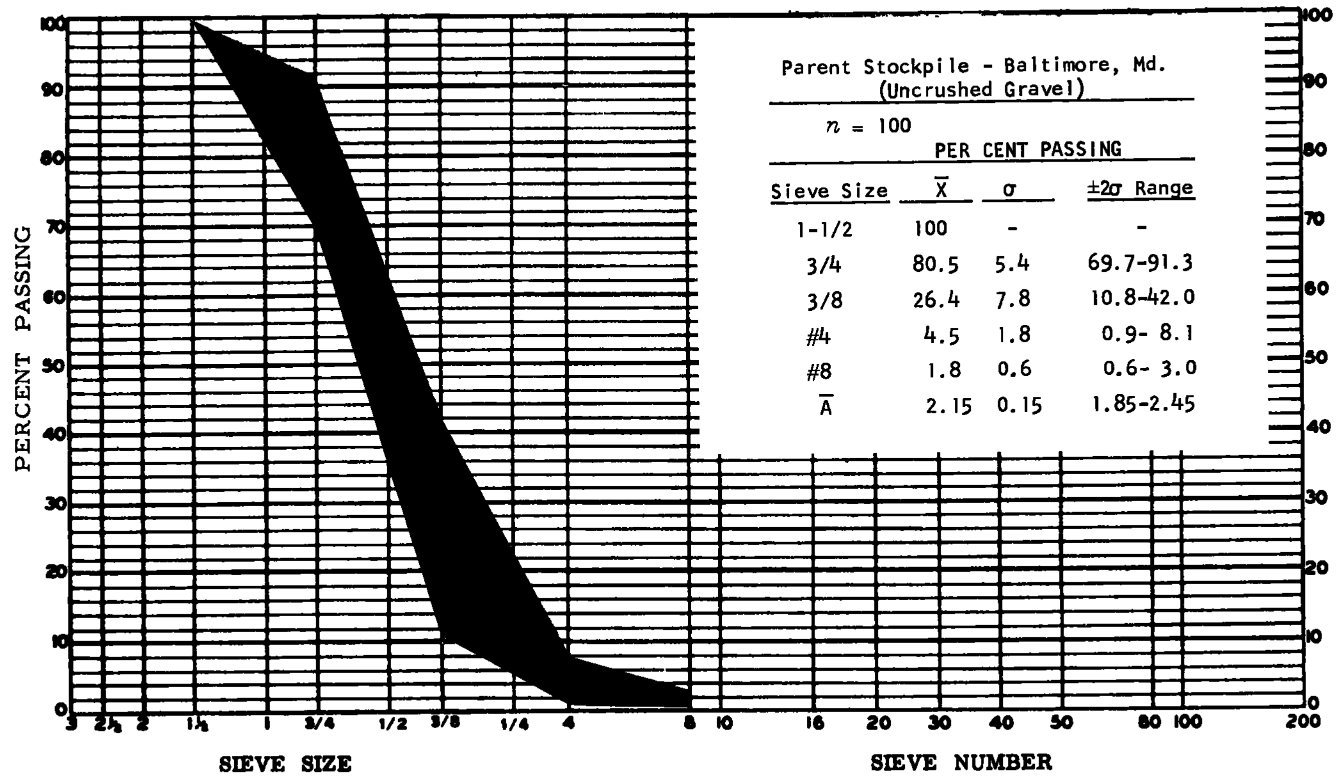


Figure 37a. Aggregate grading chart, cast-and-spread stockpile, Gresham's Lake (crushed) aggregate.



Sieve Size	$\bar{X}$	σ	$\pm 2\sigma$ Range
1-1/2	100	-	-
1	68.2	7.1	54.0-82.4
3/4	29.4	7.0	15.4-43.4
3/8	7.4	3.5	0.4-14.4
#4	4.8	2.3	0.2- 9.4
#8	4.1	1.8	0.5- 7.7
$\bar{A}$	1.53	0.17	1.19-1.87

Figure 38. Aggregate grading chart, truck-dumped stockpile, Gresham's Lake (crushed) aggregate.



Sieve Size	$\bar{X}$	σ	$\pm 2\sigma$ Range
1-1/2	100	-	-
3/4	80.5	5.4	69.7-91.3
3/8	26.4	7.8	10.8-42.0
#4	4.5	1.8	0.9- 8.1
#8	1.8	0.6	0.6- 3.0
$\bar{A}$	2.15	0.15	1.85-2.45

Figure 39. Aggregate grading chart, parent stockpile, Baltimore (uncrushed) gravel.

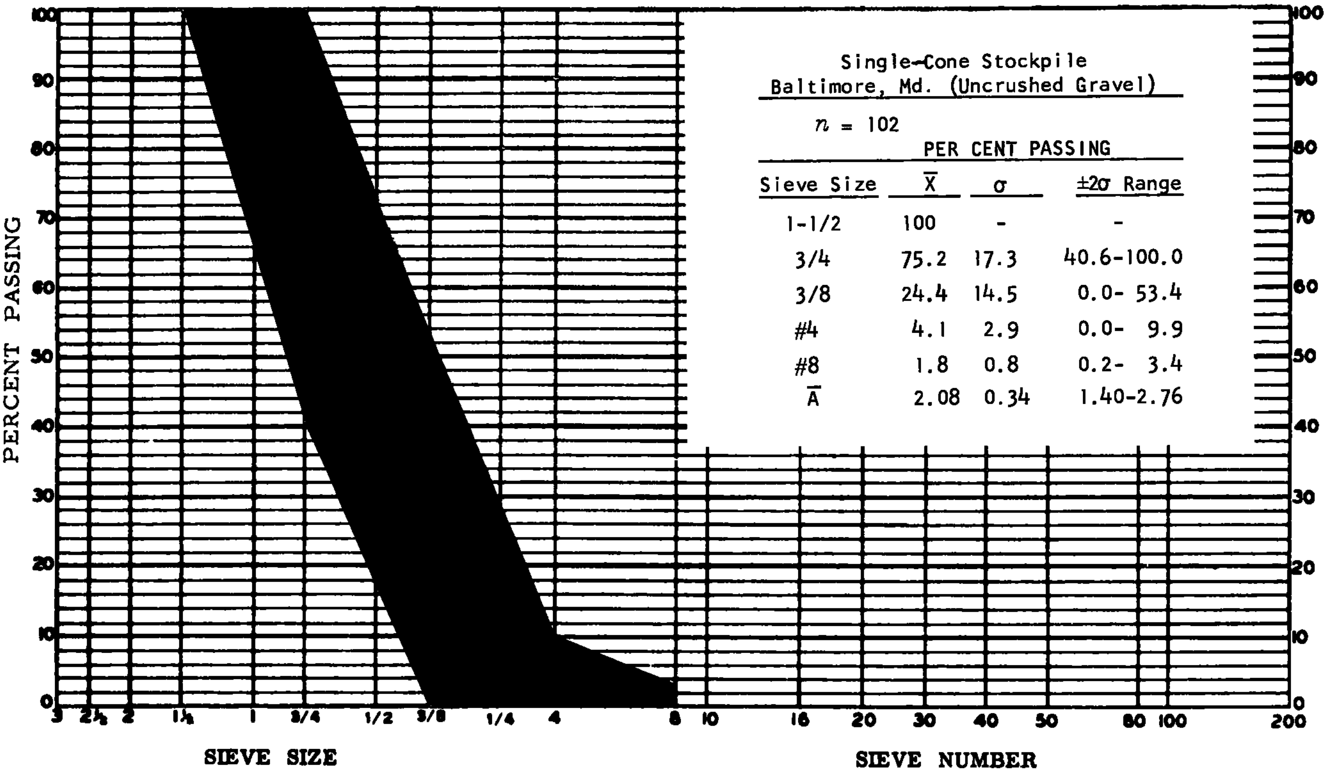


Figure 40. Aggregate grading chart, single-cone stockpile, Baltimore (uncrushed) gravel.

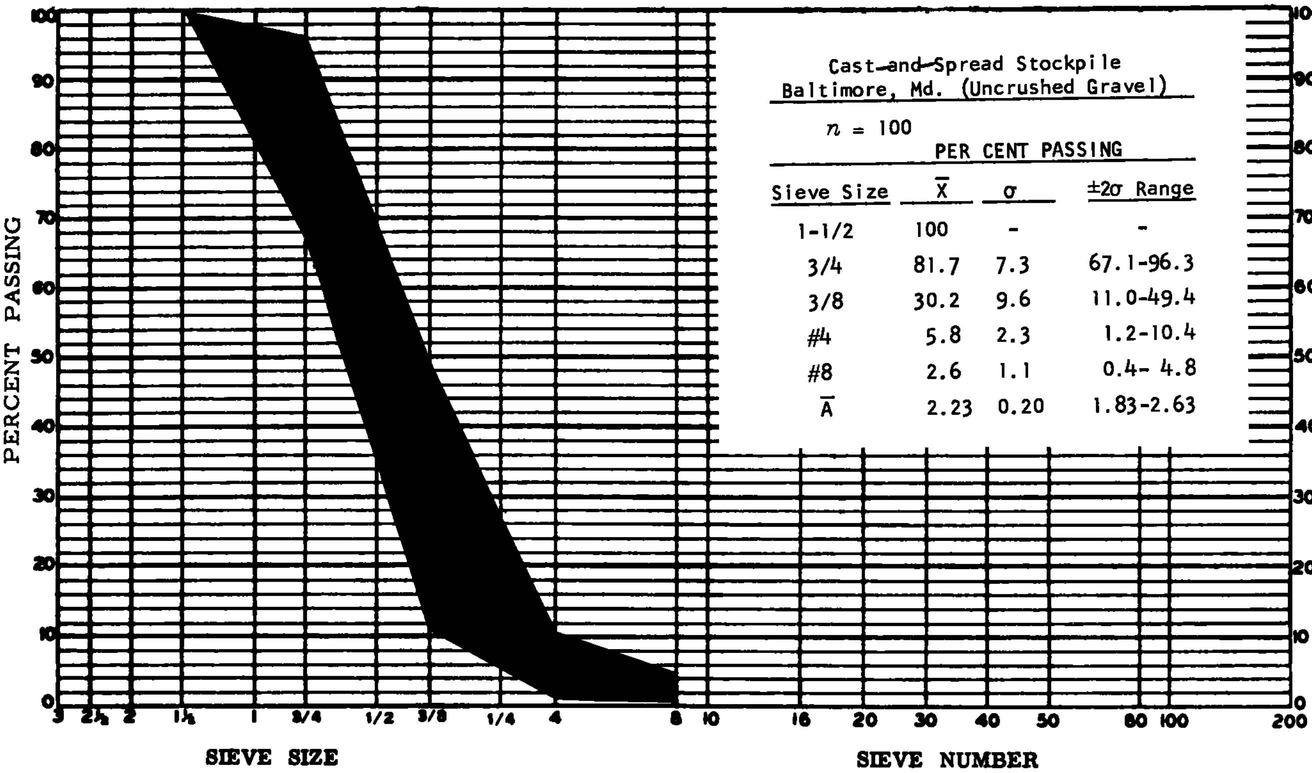


Figure 41. Aggregate grading chart, cast-and-spread stockpile, Baltimore (uncrushed) gravel.

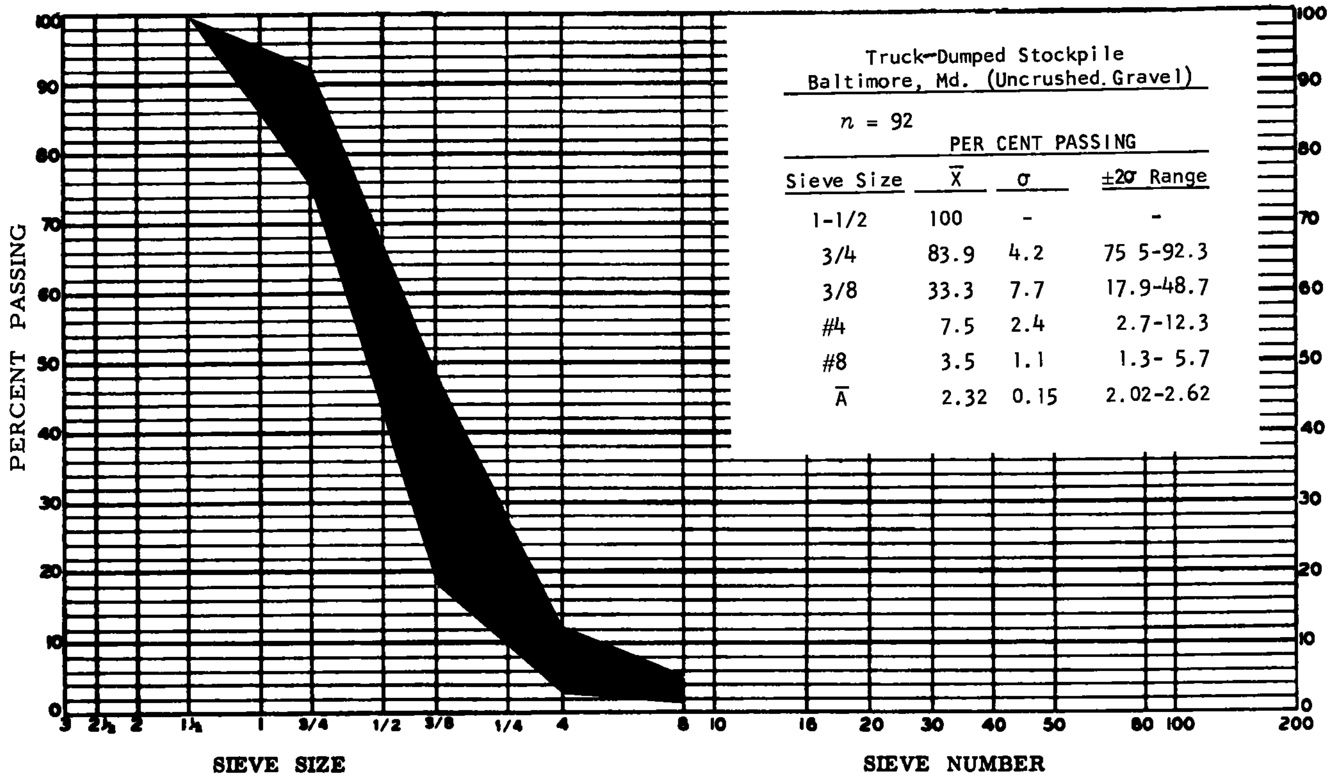


Figure 42. Aggregate grading chart, truck-dumped stockpile, Baltimore (uncrushed) gravel.

operation as was the case at the other two locations. There is, therefore, no reason for the condition of segregation in one pile to be reflected in another for the Princeton data.

Moving to the Gresham's Lake and Baltimore data, note first Figure 47 for the Gresham's Lake parent pile. This material was used for construction of the cone pile represented in Figure 48. This cone pile was depleted in the usual manner of beginning on one side and working straight through the pile such that the coarser particles are evident at the beginning and particularly at the end of the breakdown. This is a normal pattern of variation for a cone pile, as the coarser particles on the surface have a tendency to tumble to the outer perimeter. The lower $\bar{A}$ values for test increments taken in the afternoon (after 2:00 PM) indicate this area of coarseness. Moving to Figure 49 for the Gresham's cast-and-spread pile, this same area of coarseness is reflected in the corresponding portion of this pile, which was built with the coarser particles.

When these graphs were drawn, this trend toward coarseness on one side of the pile was immediately noticed. To verify this observation, the *t*-test of significance was performed. This test indicates whether or not a statistically significant difference exists between two means. The test is made using

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{\sigma^2_1}{n_1} + \frac{\sigma^2_2}{n_2}}} \qquad (4)$$

in which

$\bar{X}_1$, $\bar{X}_2$ = average level of $\bar{A}$ for cast-and-spread stockpile before 1:00 PM and after 1:00 PM, respectively;

σ^2_1, σ^2_2 = variance of $\bar{A}$ for cast-and-spread stockpile before 1:00 PM and after 1:00 PM, respectively; and

n_1, n_2 = number of test increments from cast-and-spread stockpile before 1:00 PM and after 1:00 PM, respectively.

The test verified that a significant difference at the 95% confidence level did exist (4.14 calculated vs table value of 2.00) between the average level of test increments taken before 1:00 PM in the cast-and-spread and those taken after 1:00 PM. This specific time has no importance except that it is the approximate point where the aggregate began to be coarser. The tests have further shown that the first 60 to 70 test increments from each of these two piles are from the same statistical population, whereas the latter 30 to 40 test increments are from a different population. This means that the greater variability of the coarse side of the coned pile was carried over to the same relative point in the cast-and-spread pile. This, in effect, has produced two different conditions of average level, $\bar{X}$, and variability, σ.

This condition might have been avoided had the crane operator distributed the coarser material over the entire surface of the pile rather than concentrating the coarse

aggregate on one end. These observations should have special value to those who wish to use this method of stockpile construction because it emphasizes that, for any condition of high segregation to be corrected, the aggregate must be spread in thin layers over a relatively wide area of the pile.

As previously stated, the gradation curves, segregation index, and degree of variation have been determined on the basis of using the data from the first 60 test increments only, because it is definitely shown that bias exists in the last 40 increments; i.e., an assignable cause has been identified which would cause mistaken conclusions if not removed. Again, for the reader's ease of comparison and understanding, the cast-and-spread plot (Fig. 49) includes the points for the total number of test portions taken. Through subsequent mixing and handling these variations have been decreased, as is shown in Figure 50, representing the truck-dumped pile.

Examination of the graphs for the Baltimore uncrushed gravel (Figs. 51, 52, 53, and 54) reveals a greater RANGE of $\bar{A}$ values than was found at either of the other locations. Note particularly the graph for the single-cone pile (Fig. 52), where $\bar{A}$ reaches a low of 1.3 and a high of almost 2.8. In this same graph, the coarser material at the base of the pile is reflected by the lower values at the beginning and at the end of the reclaiming operation. Moving to Figures 53 and 54, it can be seen that the variability decreases as the aggregate is used for the construction of the cast-and-spread pile and decreases still further in the truck-dumped pile. In both of these cases the test increments assume a more or less random distribution.

It appears that some of the high level of variability found in the single-cone piles could be averaged out if the piles were broken down by continually moving around the circumference as the aggregate is loaded. The more common practice is to begin loading on one side of the pile and work straight through. However, in general, levels of segregation in stockpiles appeared to have little or no influence on the stockpiles subsequently built from that material when the proper construction techniques were employed. This observation is confirmed by examination of Figure 55, which shows the level of standard deviation for the ¾-in. size and Hudson $\bar{A}$ for each stockpile.

Variability Measures—Variance and Standard Deviation

This part of the project was concerned entirely with measuring aggregate gradation variability resulting from combinations of different stockpile construction techniques, aggregate types, and gradations. One of the statistical tools used for this purpose is the standard deviation, σ, which is a measure of dispersion of individual test values about their average. If the individual values are closely grouped about the average, the standard deviation will have a small numerical value. A more detailed explanation of standard deviation has been given in Chapter Two.

The square of the standard deviation is the variance, σ^2, which can be treated mathematically by adding or subtracting directly, whereas standard deviations cannot.

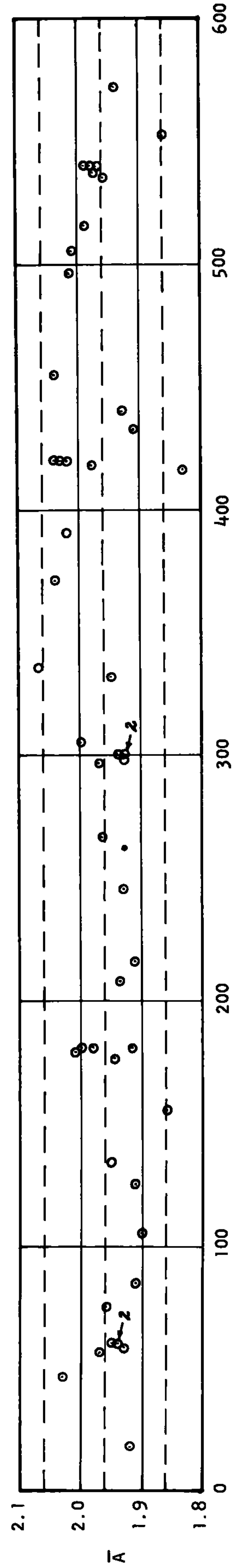


Figure 43. Hudson $\bar{A}$ values for parent stockpile, Princeton (1 in.-No. 4 crushed stone) aggregate; $\bar{X} = 1.96$, $N = 50$, $\sigma(\bar{A}) = 0.05$.

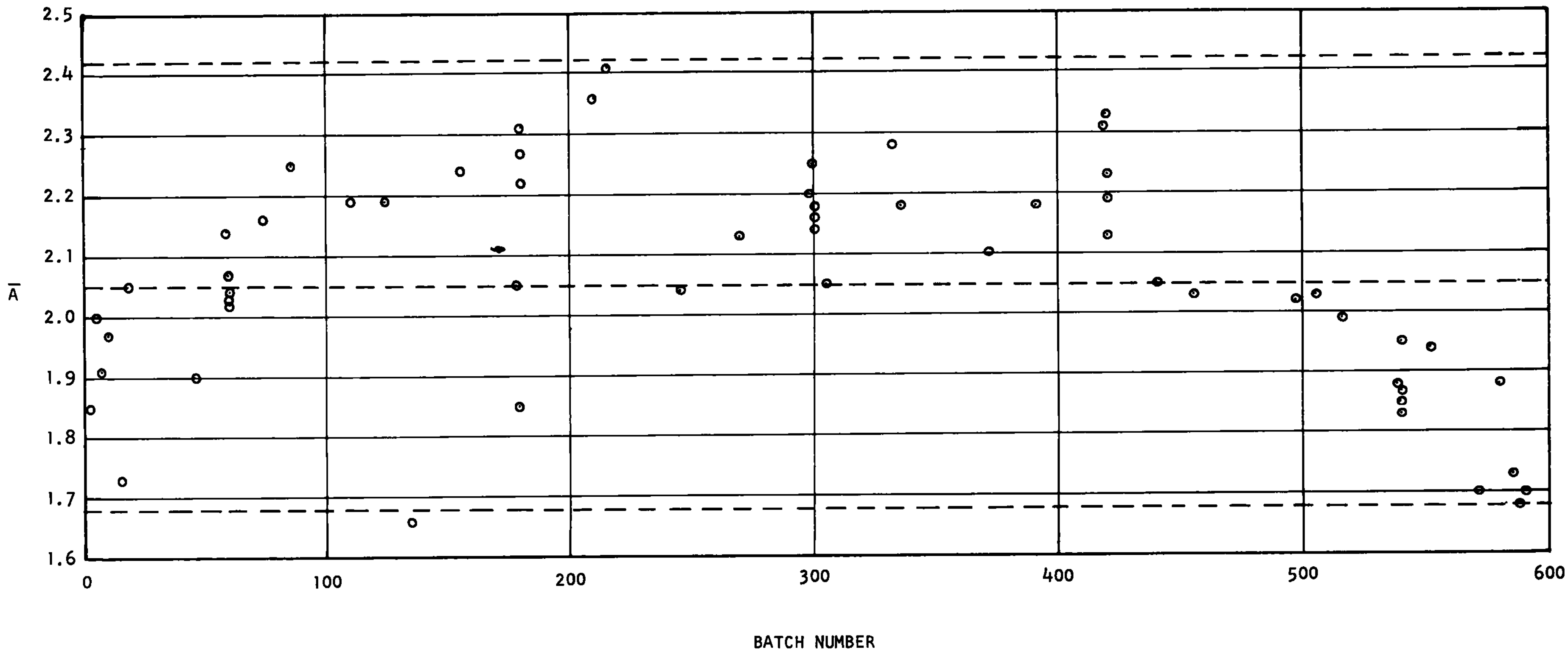


Figure 44. Hudson $\overline{A}$ *values for single-cone stockpile, Princeton (1 in.-No. 4 crushed stone) aggregate;* $\overline{X} = 2.05$, $N = 58$, $\sigma(\overline{A}) = 0.19$.

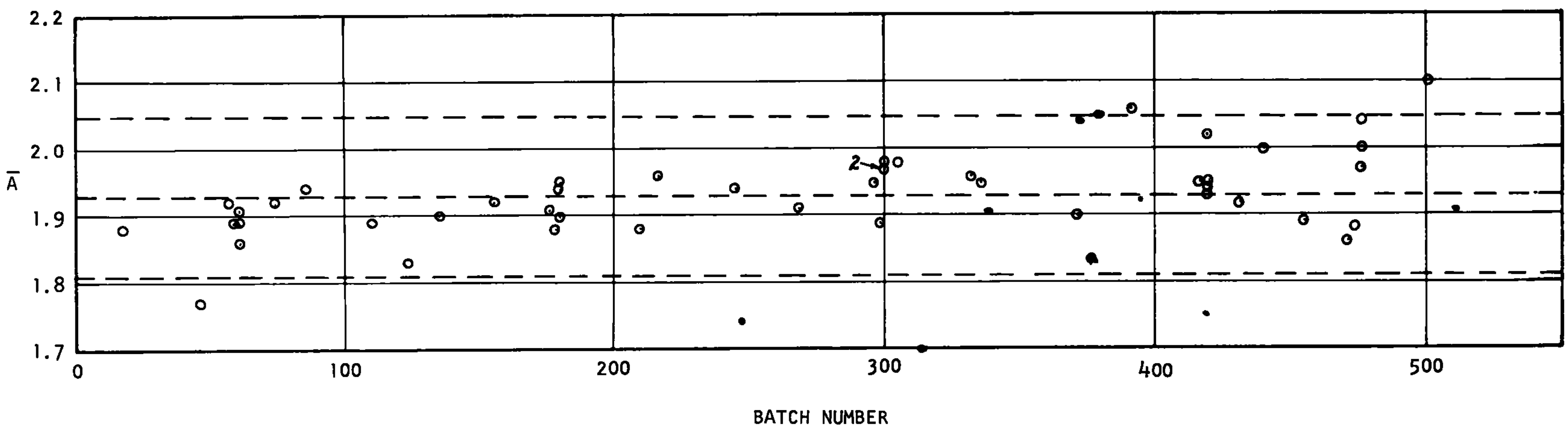


Figure 45. Hudson $\overline{A}$ *values for cast-and-spread stockpile, Princeton (1 in.-No. 4 crushed stone) aggregate;* $\overline{X} = 1.93$, $N = 46$, $\sigma(\overline{A}) = 0.06$.

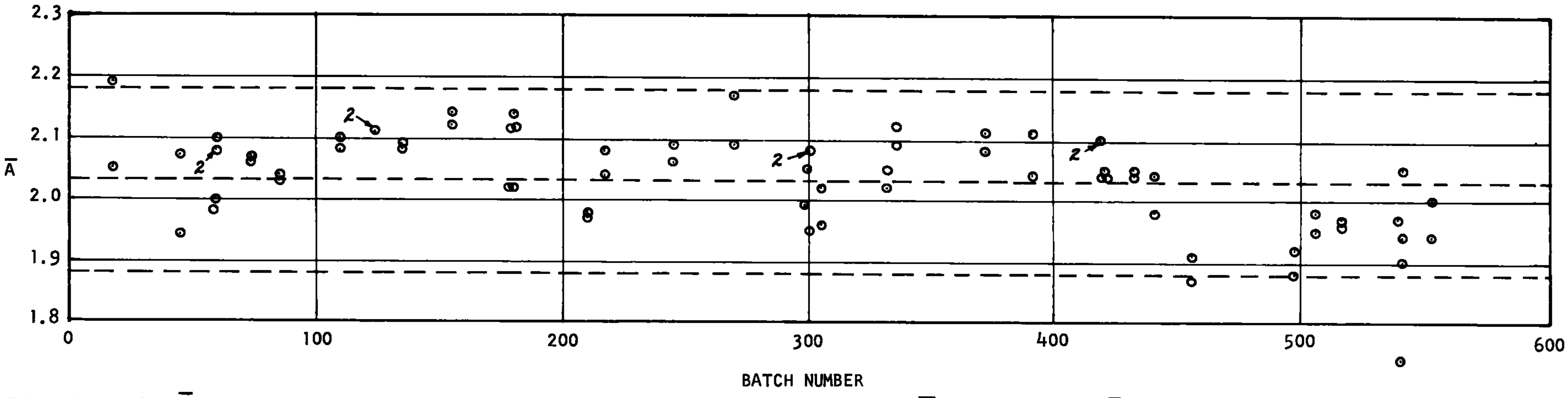


Figure 46. Hudson $\bar{A}$ *values for truck-dumped stockpile, Princeton (1 in.-No. 4 crushed stone) aggregate;* $\bar{X} = 2.03$, $N = 73$, $\sigma(\bar{A}) = 0.08$.

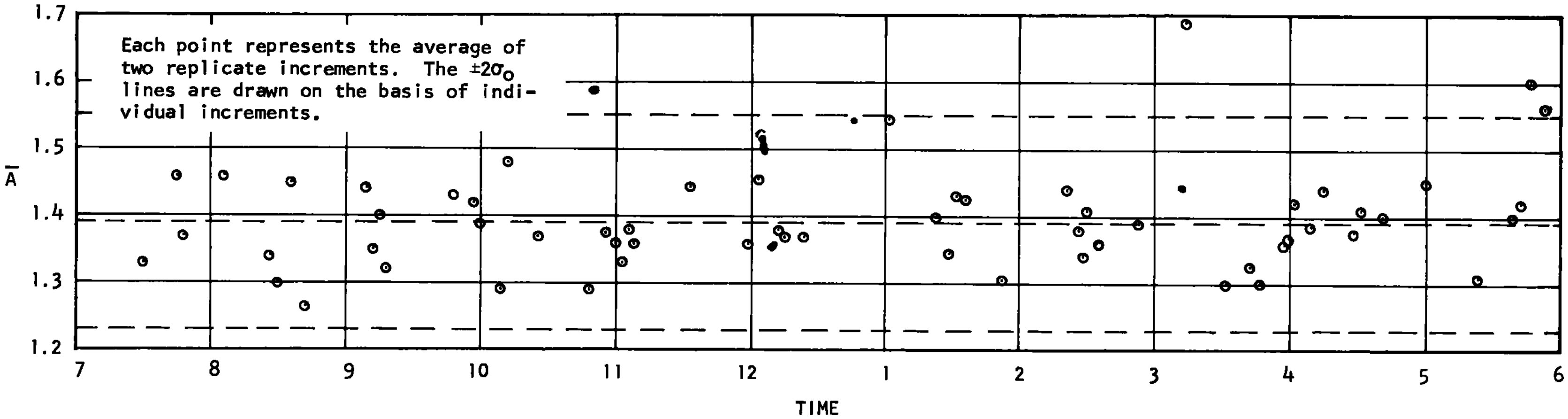


Figure 47. Batch-to-batch variation of Hudson $\bar{A}$ *values for parent stockpile, Gresham's Lake (1½ in.-⅜ in. crushed stone) aggregate;* $\bar{X} = 1.39$, $N = 120$, $\sigma(\bar{A}) = 0.08$.

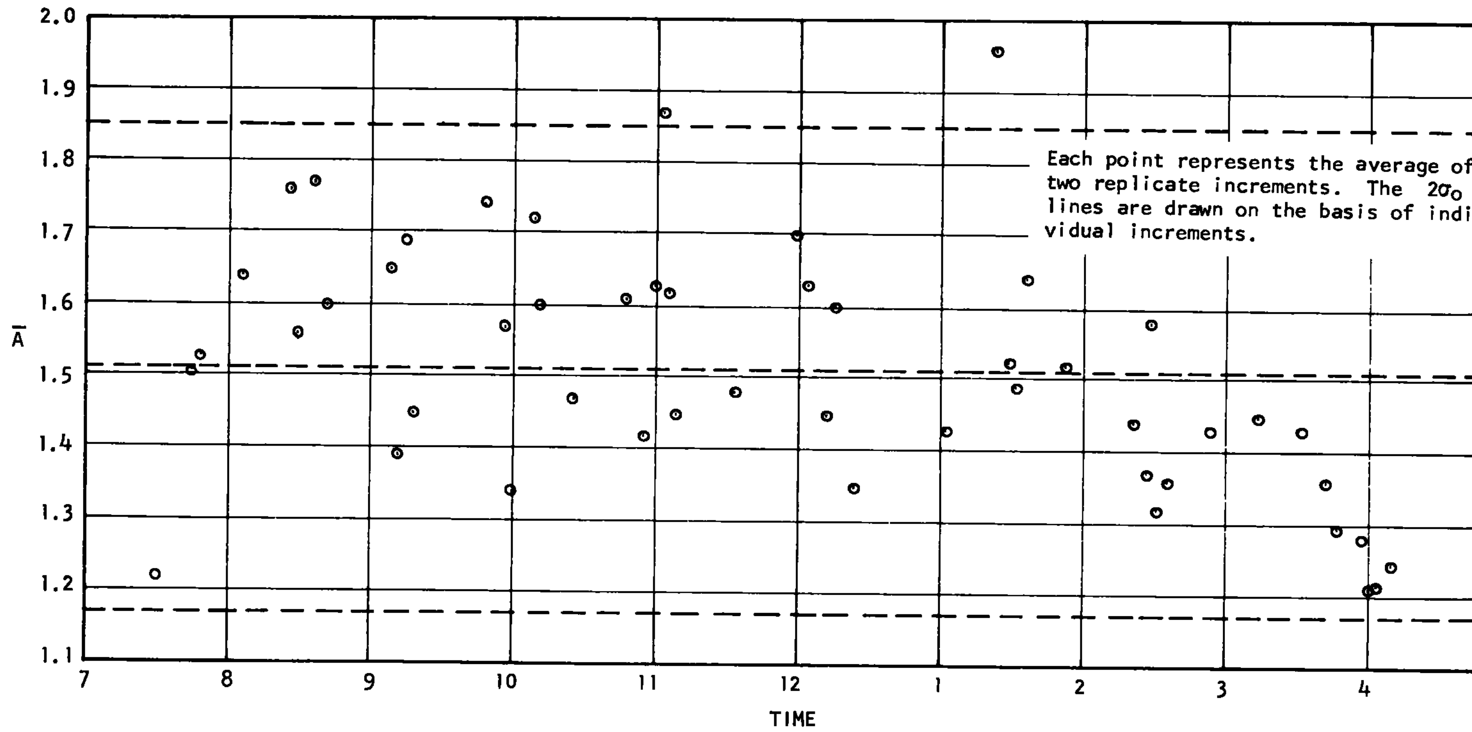


Figure 48. Batch-to-batch variation of Hudson $\bar{A}$ values for single-cone stockpile, Gresham's Lake (1½ in.-⅜ in. crushed stone) aggregate; $\bar{X} = 1.$ $N = 100$, $\sigma(\bar{A}) = 0.17$.

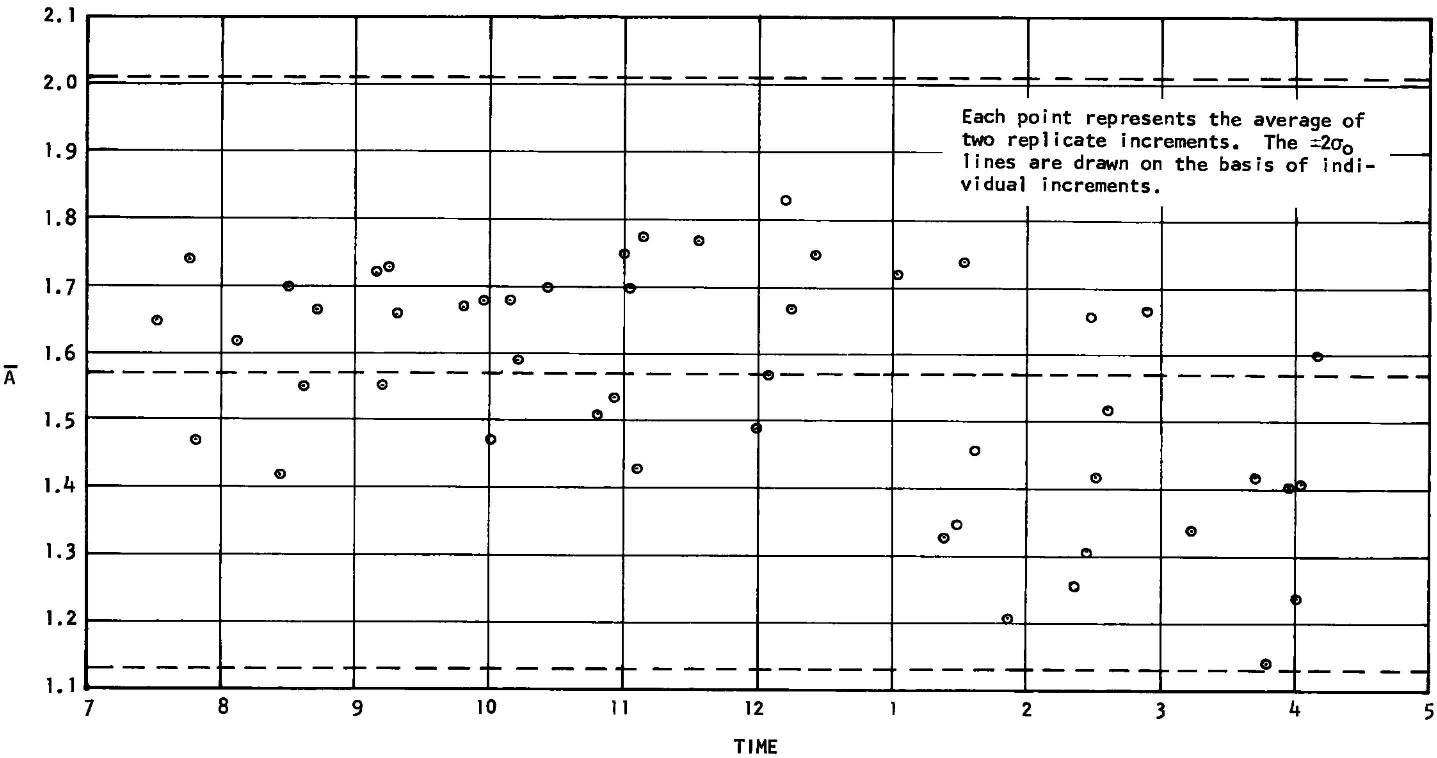


Figure 49. Batch-to-batch variation of Hudson $\bar{A}$ values for cast-and-spread stockpile, Gresham's Lake (1½ in.-⅜ in. crushed stone) aggregate; $\bar{X} = 1.57$, $N = 100$, $\sigma(\bar{A}) = 0.22$.

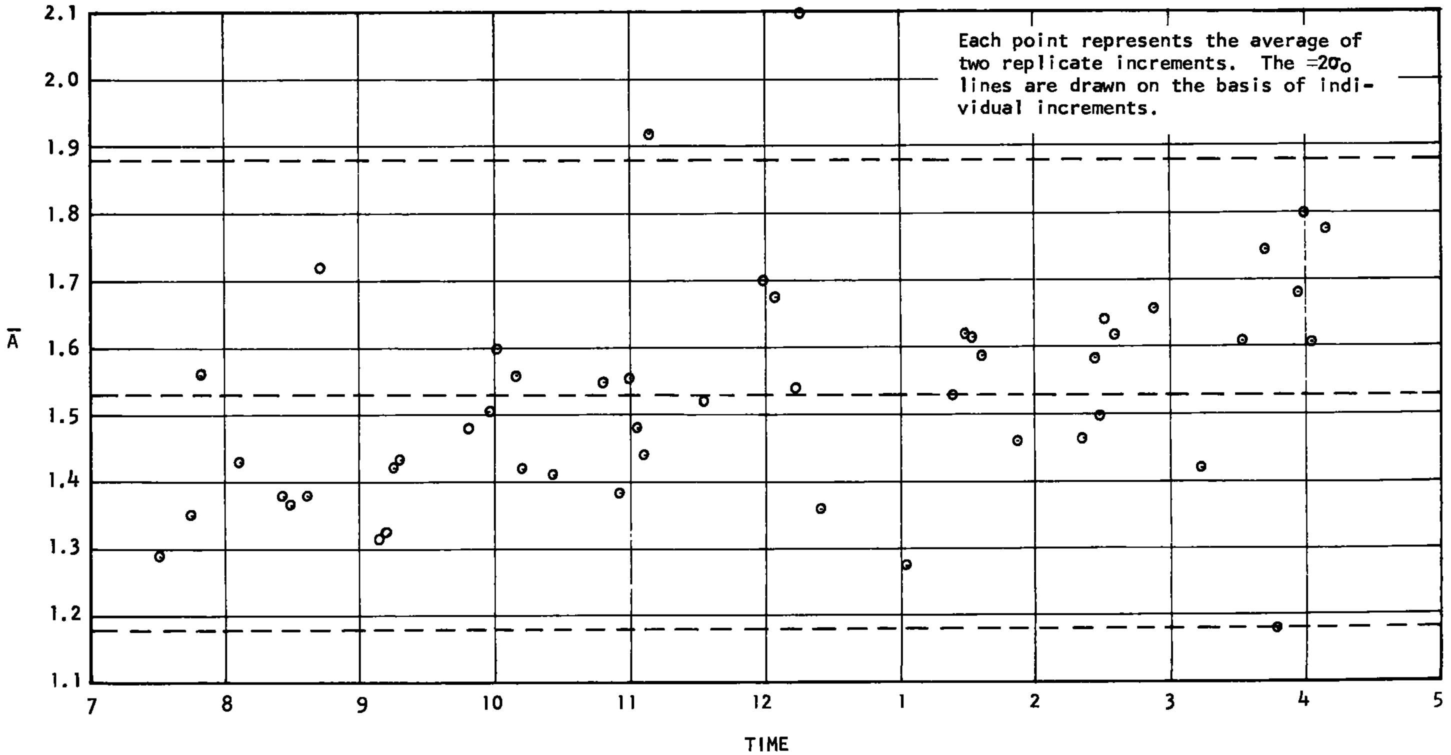


Figure 50. Batch-to-batch variation of Hudson $\overline{A}$ values for truck-dumped stockpile, Gresham's Lake (1½ in.-⅜ in. crushed stone) aggregate, $\overline{X} = 1.53$, $N = 100$, $\sigma(\overline{A}) = 0.17$.

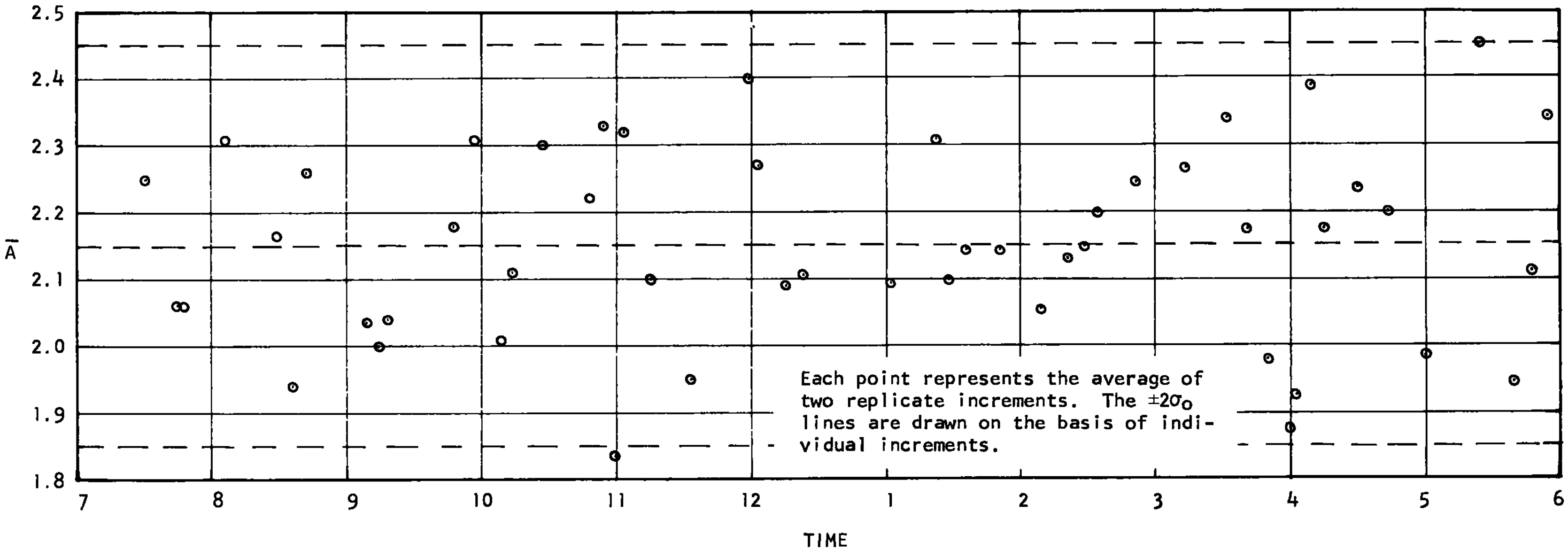


Figure 51. Batch-to-batch variation of Hudson $\overline{A}$ values for parent stockpile, Baltimore (1 in.-No. 4 uncrushed gravel) aggregate; $\overline{X} = 2.15$, $N = 100$, $\sigma(\overline{A}) = 0.15$.

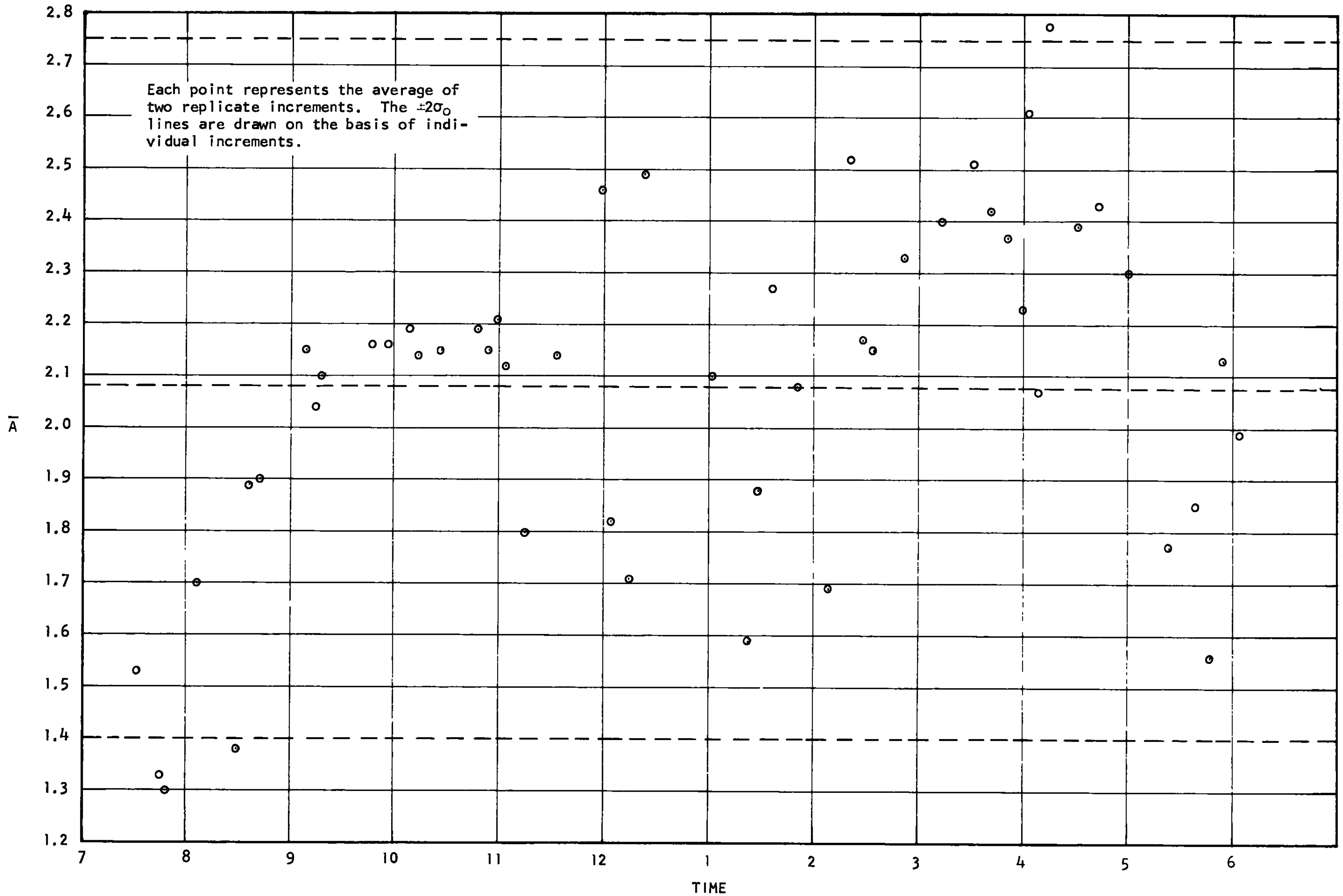


Figure 52. Batch-to-batch variation of Hudson Ā values for single-cone stockpile, Baltimore (1 in.-No. 4 uncrushed gravel) aggregate; $\overline{X} = 2.08$, $N = 102$, $\sigma(\overline{A}) = 0.34$.

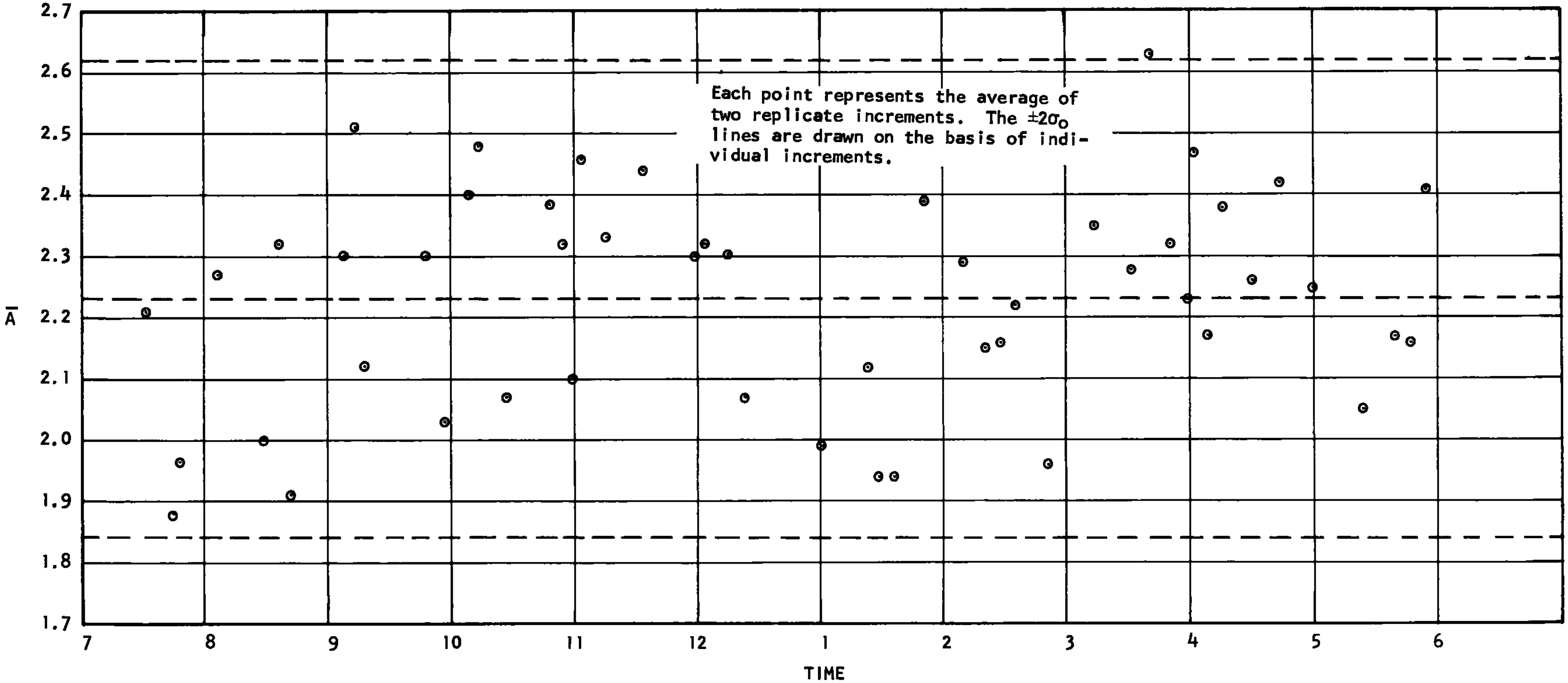


Figure 53. Batch-to-batch variation of Hudson $\bar{A}$ values for cast-and-spread stockpile, Baltimore (1 in.-No. 4 uncrushed gravel) aggregate; $\bar{X} = 2.23$, N = 100, $\sigma(\bar{A}) = 0.20$.

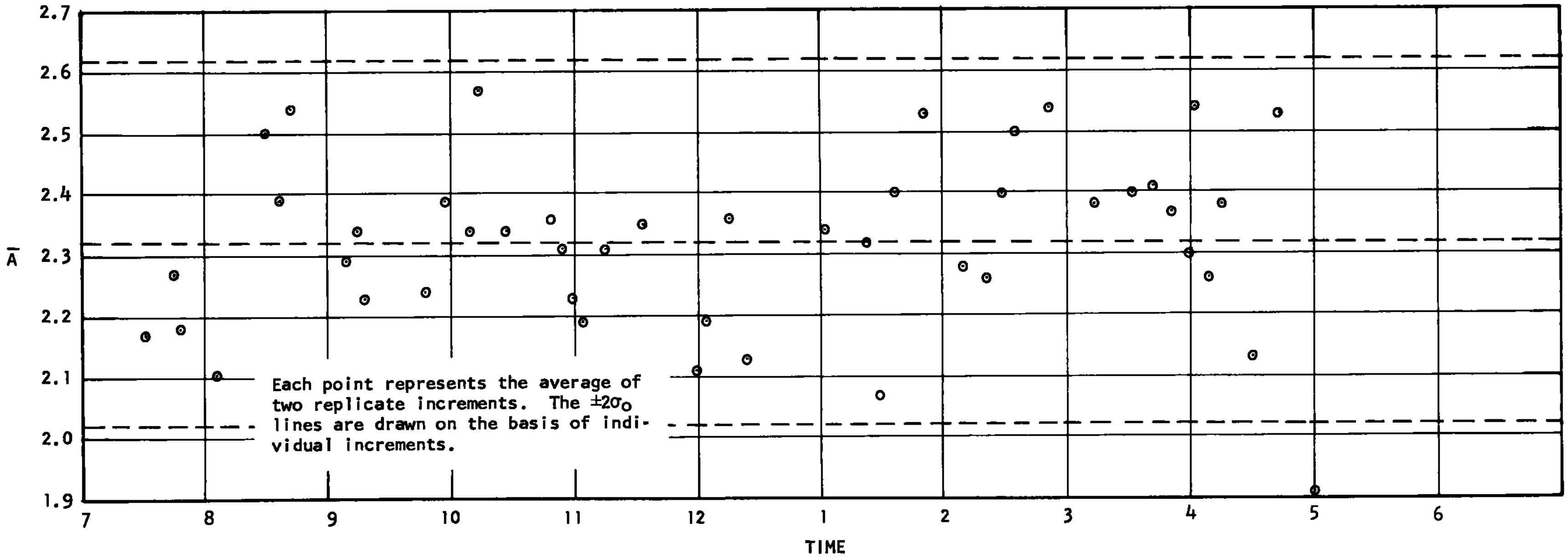


Figure 54. Batch-to-batch variation of Hudson $\bar{A}$ values for truck-dumped stockpile, Baltimore (1 in.-No. 4 uncrushed gravel) aggregate; $\bar{X} = 2.32$, N = 92, $\sigma(\bar{A}) = 0.15$.

Inasmuch as each method of presentation has advantages, the data are listed in both terms.

Table 6 provides a summary of both the overall standard deviation and the overall variance. The mathematical relationship between these values and the average value of the percent passing a sieve is somewhat involved, but, in brief, percentages of the order of 50% tend to have the highest variability. This table indicates the magnitude of variability of each size fraction. The lower numbers indicate lesser variability (greater uniformity) and, consequently, a more desirable condition.

These data confirm the variability levels shown in the aggregate grading charts presented earlier in this chapter.

Segregation Index

This section presents certain comparisons of data in terms of segregation index. As previously discussed in Chapter Two, the segregation index, S, is simply a ratio between overall variance (σ^2_o) and within-batch variance (σ^2_b) that shows the pattern of variation of gradation. Although the percentage passing any one sieve size could be used as a basis for this comparison, Hudson $\bar{A}$ has been selected because it includes the combined effects of all the different size fractions. Inasmuch as most of the aggregates employed for these studies contained a substantial portion of ¾-in. material, an additional comparison is also made on this size fraction. It will be noted that the pattern of segregation is the same, whether $\bar{A}$ or the percentage smaller than ¾ in. is used. These data are first presented in graphical form (Figs. 56 and 57), followed by Table 7, which gives individual S-values for each sieve size as well as Hudson $\bar{A}$.

Aggregate from all three sources shows essentially the same relative pattern of segregation for the three stockpiling methods investigated.

As previously discussed, S can be high if the overall variance (σ^2_o) is high in relation to the within-batch variance (σ^2_b). Conversely, S will be low if σ^2_o is low in relation to σ^2_b. Had it not been for the relatively high σ^2_b values from the gravel stockpiles, the resulting S-values would have been considerably higher.

It should be noted that the segregation index values used in this report were calculated from the computer print-out data prior to rounding the σ^2_o and σ^2_b values. Had S been calculated after rounding, slightly different values would have resulted. The values were rounded to eliminate any sense of false security in the degree of accuracy of the data. This rounding was done in accordance with the procedure outlined in ASTM STP 15-C, Part 2.

Table 7 lists all segregation index values and also indicates the values which are statistically significant. The values so marked show a ratio between overall variance, σ^2_o, and within-batch variance, σ^2_b, greater than could have been due to chance. This means that a relatively high batch-to-batch variation exists. In other words, a condition of segregation is present to such an extent that

TABLE 6

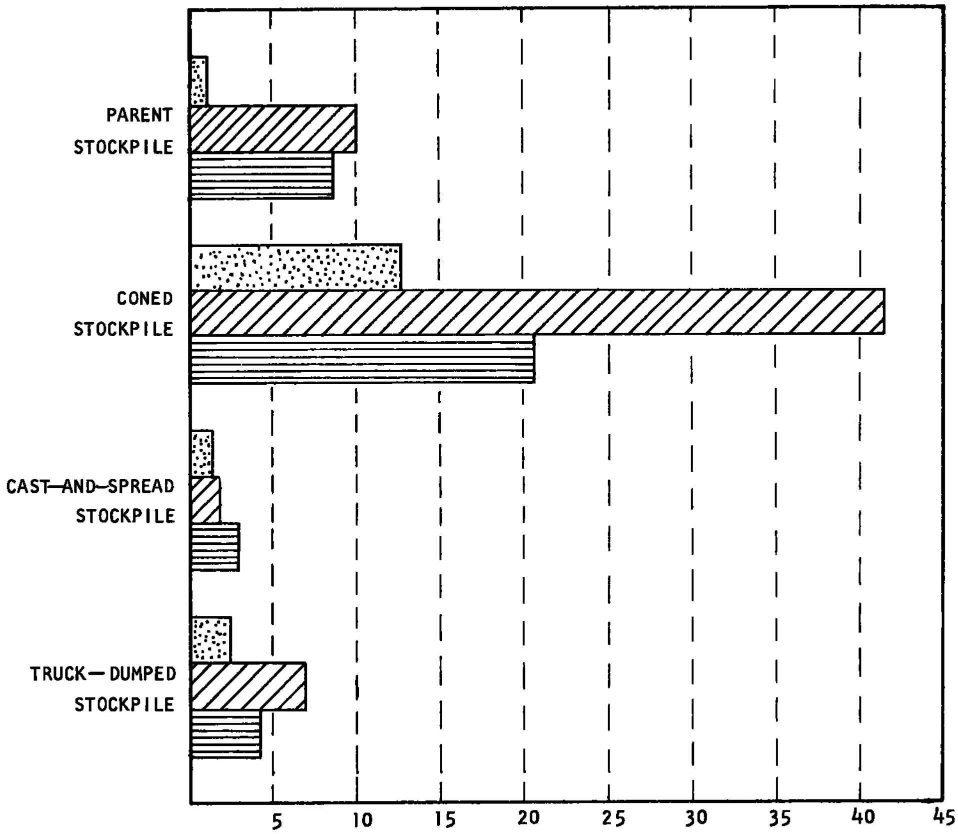
OVERALL STANDARD DEVIATION,[a] σ_o, AND OVERALL VARIANCE,[a] σ^2_o

			VARIABILITY MEASURES															
			1-INCH			¾-INCH			⅜-INCH			NO. 4			NO. 8			HUDSON $\bar{A}$	
STOCKPILE	AGGREGATE	n[b]	% PASS.	σ_o	σ^2_o	% PASS.	σ_o	σ^2_o	% PASS.	σ_o	σ^2_o	% PASS.	σ_o	σ^2_o	% PASS.	σ_o	σ^2_o	σ_o	σ^2_o
Parent pile	Cr. stone,[c] 1″-#4	50	—	—	—	79	3.3	11.1	13	2.1	4.5	1	0.5	0.2	1	0.2	0.04	0.051	0.003
	Cr. stone,[d] 1½″-⅜″	120	63	4.5	20.4	22	4.1	16.6	5	1.6	2.6	4	0.9	0.8	3	0.6	0.40	0.078	0.006
	Gravel,[e] 1″-#4	100	—	—	—	81	5.4	28.9	26	7.8	60.0	5	1.8	3.3	2	0.6	0.40	0.150	0.022
Single cone	Cr. stone,[c] 1″-#4	65	—	—	—	83	9.0	81.3	18	8.5	73.0	3	1.6	2.5	1	0.3	0.10	0.190	0.035
	Cr. stone,[d] 1½″-⅜″	100	68	8.5	73.1	28	8.5	71.8	7	3.5	12.4	5	1.8	3.4	4	1.2	1.60	0.171	0.029
	Gravel,[e] 1″-#4	102	—	—	—	75	17.3	300.8	24	14.5	211.5	4	2.9	8.2	2	0.8	0.70	0.336	0.113
Cast and spread	Cr. stone,[c] 1″-#4	46	—	—	—	77	3.4	11.5	13	2.4	5.7	1	0.4	0.2	1	0.1	0.02	0.059	0.004
	Cr. stone,[d] 1½″-⅜″	60	73	4.5	19.9	34	4.5	20.2	9	2.4	5.6	6	1.5	2.3	5	1.2	1.4	0.113	0.012
	Gravel,[e] 1″-#4	100	—	—	—	82	7.3	53.0	30	9.6	92.3	6	2.3	5.2	3	1.1	1.10	0.196	0.038
Truck-dumped	Cr. stone,[c] 1″-#4	73	—	—	—	83	4.2	17.5	17	3.7	13.9	2	0.7	0.5	1	0.3	0.10	0.077	0.006
	Cr. stone,[d] 1½″-⅜″	100	68	7.1	50.6	29	7.0	48.8	7	3.5	12.1	5	2.3	5.2	4	1.8	3.20	0.175	0.030
	Gravel,[e] 1″-#4	92	—	—	—	84	4.2	17.8	33	7.7	59.5	8	2.4	5.7	4	1.1	1.30	0.151	0.023

[a] Of percent passing. [b] Number of gradation tests. [c] Princeton, N.C., quarry. [d] Gresham's Lake quarry. [e] Baltimore gravel processing plant.

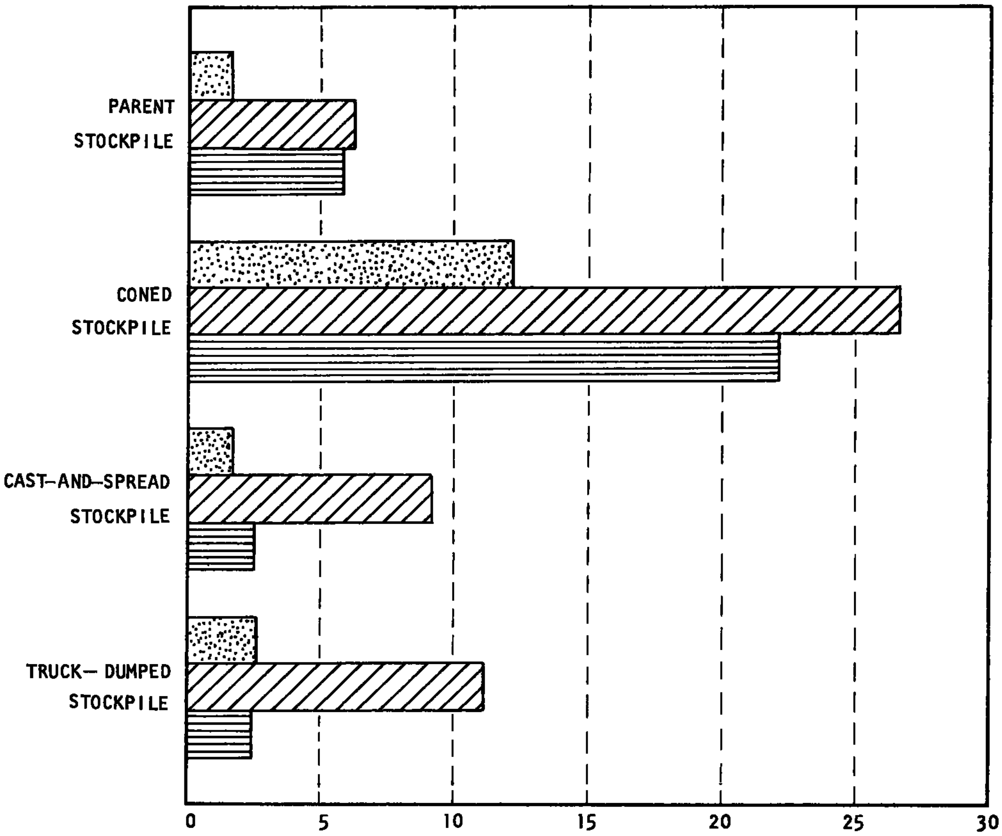
Sieve Size	Parent (Source) Stockpile →	Single-Cone Stockpile →	Cast-and-Spread Stockpile →	Truck-Dumped Stockpile
	Standard Deviation			
3/4 In. Baltimore	5.4	17.3	7.3	4.2
3/4 In. Gresham's	4.1	8.5	4.5	7.0
$\bar{A}$, Baltimore	0.150	0.336	0.196	0.151
$\bar{A}$, Gresham's	0.078	0.171	0.113	0.175

Figure 55. Standard deviation for the ¾-in. size and Hudson $\bar{A}$ for each stockpile.



	PRINCETON (1" - #4 Crushed Stone)	GRESHAM'S LAKE (1-1/2" - 3/8" Crushed Stone)	BALTIMORE (1" - #4 Gravel)
PARENT STOCKPILE	1.0	10.0	8.5
CONED STOCKPILE	13.4	41 4	20.5
CAST—AND—SPREAD STOCKPILE	1.3	1.9	2.8
TRUCK—DUMPED STOCKPILE	2.3	6.8	4.1

Figure 56. Segregation index, based on $\bar{A}$, for segregation studies.



	PRINCETON (1" - #4 Crushed Stone)	GRESHAM'S LAKE (1-1/2" - 3/8" Crushed Stone)	BALTIMORE (1" - #4 Gravel)
PARENT STOCKPILE	1.6	6.2	5.8
CONED STOCKPILE	12.1	26.6	22.1
CAST-AND-SPREAD STOCKPILE	1.7	9.1	2.5
TRUCK-DUMPED STOCKPILE	2.6	11.1	2.4

Figure 57. Segregation index, based on ¾-in. values, for segregation studies.

TABLE 7

SEGREGATION INDEX

STOCKPILE	AGGREGATE	n	F-TABLE VALUE, 95%	SEGREGATION INDEX $\bar{A}$	1-IN.	¾-IN.	⅜-IN.	NO. 4
Parent (starting)	Cr. stone,[a] 1"-#4	50	1.48	1.00	—	1.6*	1.1	0.6
	Cr. stone,[b] 1½"-⅜"	120	1.36	10.00*	3.7*	6.2*	13.7*	11.0*
	Gravel,[c] 1"-#4	100	1.39	8.50*	—	5.8*	8.5*	9.0*
Single cone (clambucket)	Cr. stone,[a] 1"-#4	65	1.42	13.36*	—	17.9*	27.5*	4.7*
	Cr. stone,[b] 1½"-⅜"	100	1.39	41.43*	16.8*	26.9*	42.6*	34.1*
	Gravel,[c] 1"-#4	102	1.39	20.54*	—	22.1*	15.5*	13.6*
Cast and spread (clambucket)	Cr. stone,[a] 1"-#4	46	1.48	1.35	—	1.7*	1.4	0.4
	Cr. stone,[b] 1½"-⅜"	60	1.39	1.91*	4.1*	9.1*	27.5*	20.1*
	Gravel,[c] 1"-#4	100	1.39	2.81*	—	2.6*	3.1*	2.7*
Truck-dumped	Cr. stone,[a] 1"-#4	73	1.42	2.30*	—	2.6*	3.3*	1.1
	Cr. stone,[b] 1½"-⅜"	100	1.39	6.82*	13.3*	11.2*	5.4*	4.3*
	Gravel,[c] 1"-#4	92	1.40	4.11*	—	2.4*	4.5*	3.8*

* Statistically significant difference. [a] Princeton quarry. [b] Gresham's Lake quarry. [c] Baltimore gravel plant.

it may have an influence on the quality of the finished work.

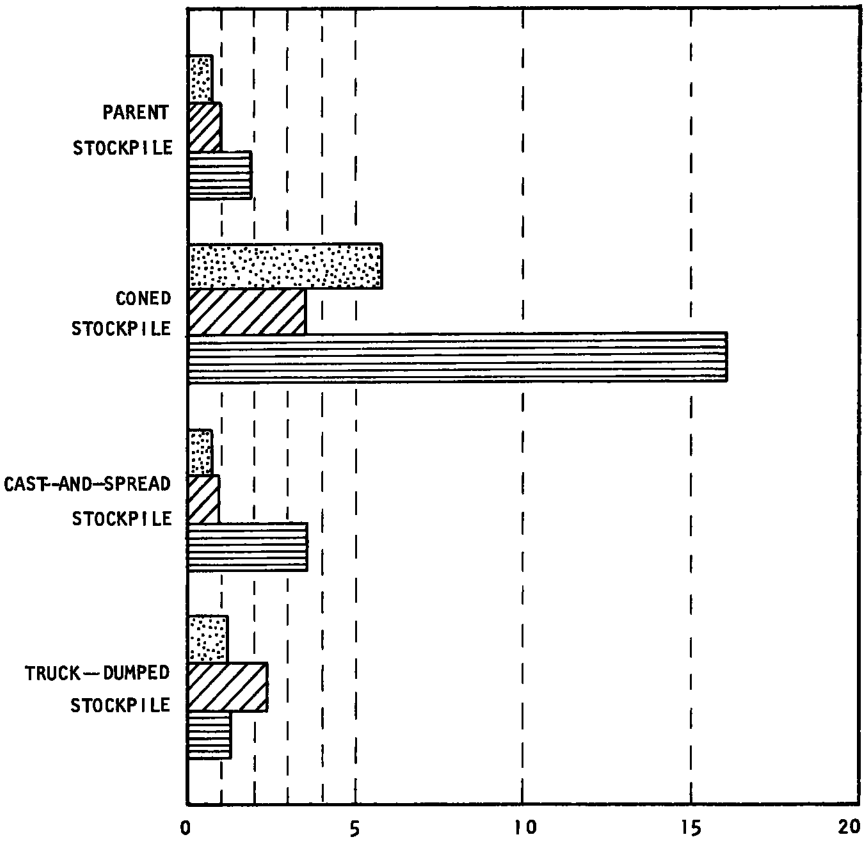
A segregation index for the minus No. 8 material is not given because it has no practical significance, due to the very small proportion of aggregate involved.

The general trend of these data substantiate the trends shown in earlier sections of this chapter. In comparing the Princeton quarry results with those obtained on the uncrushed gravel from Baltimore, the greater tendency toward segregation of the gravel is evident by the higher *S*-values. Likewise, in comparing the Princeton quarry (1 in.-No. 4) results with the Gresham's Lake (1½ in.-⅜ in.) results, it is obvious that the larger maximum size aggregate used in the latter case results in higher *S*-values.

Degree of Variation (D of V)

The degree of variation (D of V) of the ¾-in. size from each stockpile is shown graphically in Figure 58 and is tabulated for all sizes through the minus No. 4 in Table 8. The meaning and application of this parameter has been previously discussed in Chapter Two; however, for the sake of convenience, a brief review is given here.

D of V is a comparison between overall variance actually obtained and the maximum theoretical variance possible to obtain on a given sieve size. The resulting number can be thought of as a percentage of the maximum possible segregation. Obviously, the higher values for D of V indicate more segregation at that particular point.



	PRINCETON (1" - #4 Crushed Stone)	GRESHAM'S LAKE (1-1/2" - 3/8" Crushed Stone)	BALTIMORE (1" - #4 Gravel)
PARENT STOCKPILE	0.7	1.0	1.9
CONED STOCKPILE	5.8	3.5	16.1
CAST-AND-SPREAD STOCKPILE	0.7	0.9	3.6
TRUCK-DUMPED STOCKPILE	1.2	2.4	1.3

Figure 58. Degree of variation, based on ¾-in. values, for segregation studies.

Because the denominator in the equation for calculating D of V requires that a definite percentage be used, Hudson $\bar{A}$ is not appropriate for this purpose. Only the D of V values based on passing ¾ in. and ⅜ in. are believed to have significant meaning, because of the small amount of aggregate passing the No. 4 and No. 8 sieves. Considering the ¾-in. size fraction for each of the aggregates, maximum values were obtained in the cone pile in all cases. These values also confirm the trends shown by the data previously presented as to the effects of stockpiling method, aggregate type, and gradation.

Summary Table

For ease of comparison, all of the stockpiling data previously presented have been summarized in Table 9. In addition, the within-batch variance and standard deviation are shown so that one parameter can be easily compared with another. The data are listed in the order of stockpile construction. Arranging the data in this manner provides an opportunity for observing the change in various statistical parameters from pile to pile.

All of these data show the same general trend, as follows:

1. The cone method of construction results in maximum values of segregation (variability), while the cast-and-spread method minimizes the segregation (variation) values.
2. Uncrushed gravel aggregate has a greater tendency toward segregation than crushed stone.
3. The larger maximum size crushed aggregate has a greater tendency toward segregation than does the smaller size.

Model for Predicting Segregation

It is apparent that segregation is a result of a combination of several variables. Mainly these are method of construction; aggregate type and gradation; and, to a lesser degree, certain process variables such as equipment operator techniques, type and condition of equipment, and differences in configuration of stockpiles. There also are other undetermined variables of a minor nature. With this knowledge in mind, a mathematical model has been developed which provides a comparison of actual measured values of standard deviation with predicted values.

This system begins with a determination of the mean value of standard deviation that includes the sum total of all effects from stockpiling method, aggregate type, and gradation. It then theorizes that each variable has an effect, either positive or negative, on the mean. Mathematical values for these effects are calculated and distributed in the equation for comparison with the measured value. The general equation is

$$\sigma_{ijk} = m + p_i + g_j + s_k + e_{ijk} \qquad (5)$$

in which

σ = predicted standard deviation;
m = adjusted mean of standard deviation;
p = effect from stockpiling method;
g = effect from gradation;
s = effect from aggregate type;
e = error from unidentified sources; and
i,j,k = number of repetitions of variable.

This comparison can be made on the standard deviation of either $\bar{A}$ or any individual sieve size. The research agency has elected to use the standard deviation of the ¾-in. sieve as a basis for the comparisons shown in Table 10 and Figure 59.

These comparisons of experimental and predicted values indicate that there are unknown factors, not included in the model, which significantly affect the relative amount of segregation. For the predicted values to more closely approximate the actual values, it would be necessary to obtain many more data using other gradations and aggregate types. The method of least squares was used to develop the mathematical model (Eq. 5) for determining the predicted values. Details on the use of Eq. 5 are given in Appendix D.

A specific value was determined for each of the factors which influence segregation. These values are of different magnitudes and, depending on whether they tend to increase or decrease segregation, will have a positive or negative value. These values are listed below in descending order. It can be seen that the cone method of stockpile con-

TABLE 8

DEGREE OF VARIATION $= \dfrac{\sigma^2_o}{\bar{P}(100 - \bar{P})} \times 100$

SIEVE SIZE	GRESHAM'S LAKE 1½ IN.-⅜ IN. CRUSHED STONE: PARENT PILE	CONED PILE	CAST-&-SPREAD PILE	TRUCK-DUMPED PILE	BALTIMORE 1 IN.-NO. 4 UNCRUSHED GRAVEL: PARENT PILE	CONED PILE	CAST-&-SPREAD PILE	TRUCK-DUMPED PILE	PRINCETON (INITIAL WORK) 1 IN.-NO. 4 CRUSHED STONE: PARENT PILE	CONED PILE	CAST-&-SPREAD PILE	TRUCK-DUMPED PILE
1 In.	1.2	3.3	1.0	2.3	—	—	—	—	—	—	—	—
¾ In.	1.0	3.5	0.9	2.4	1.9	16.1	3.6	1.3	0.7	5.8	0.7	1.2
⅜ In.	0.6	1.9	0.7	1.9	3.2	11.6	4.4	2.7	0.4	4.9	0.5	1.0
No. 4	0.3	0.7	0.4	1.1	0.7	2.2	0.9	0.9	0.1	1.3	0.2	0.2

TABLE 9

SUMMARY OF STATISTICAL DATA, SEGREGATION STUDY

		PRINCETON QUARRY (1"-#4 CRUSHED STONE)				GRESHAM'S LAKE QUARRY (1½"-⅜" CRUSHED STONE)				BALTIMORE (1"-#4 UNCRUSHED GRAVEL)			
SIEVE SIZE	PARAMETER	STARTING PILE	CONED PILE	C & S PILE	TRUCK-DUMPED PILE	STARTING PILE	CONED PILE	C & S PILE	TRUCK-DUMPED PILE	STARTING PILE	CONED PILE	C & S PILE	TRUCK-DUMPED PILE
	n*	50	58	46	73	120	100	60	100	100	102	100	92
	W†	27.2	22.1	25.3	25.6	38.2	38.9	36.6	35.8	37.9	34.1	35.2	35.1
$\bar{A}$	$\bar{A}$	1.96	2.05	1.93	2.03	1.39	1.51	1.64	1.53	2.15	2.08	2.23	2.32
	σ^2_a	0.003	0.035	0.004	0.006	0.006	0.029	0.012	0.030	0.022	0.113	0.038	0.023
	σ_a	0.05	0.19	0.06	0.08	0.08	0.17	0.11	0.18	0.15	0.34	0.19	0.15
	σ^2_b	0.003	0.003	0.003	0.003	0.001	0.001	0.006	0.004	0.003	0.005	0.014	0.006
	σ_b	0.05	0.05	0.05	0.05	0.03	0.03	0.08	0.06	0.05	0.07	0.12	0.08
	S	1.0	13.5	1.5	2.3	10.0	41.4	1.9	6.8	8.5	20.5	2.8	4.1
1 In.	$\bar{X}$	—	—	—	—	62.8	68.4	72.5	68.2	—	—	—	—
	σ^2_a	—	—	—	—	20.36	73.08	19.93	50.62	—	—	—	—
	σ_a	—	—	—	—	4.5	8.5	4.5	7.1	—	—	—	—
	σ^2_b	—	—	—	—	5.54	4.28	4.90	3.80	—	—	—	—
	σ_b	—	—	—	—	2.4	2.1	2.2	2.0	—	—	—	—
	S	—	—	—	—	3.7	16.8	4.1	13.3	—	—	—	—
	D of V	—	—	—	—	1.2	3.3	1.0	2.3	—	—	—	—
¾ In.	$\bar{X}$	79.0	82.6	76.8	83.2	22.4	28.5	33.6	29.4	80.5	75.2	81.7	83.9
	σ^2_a	11.12	81.30	11.49	17.52	16.61	71.77	20.19	48.84	28.88	300.77	53.00	17.80
	σ_a	3.3	9.0	3.4	4.2	4.1	8.5	4.5	7.0	5.4	17.3	7.3	4.2
	σ^2_b	6.70	6.70	6.70	6.70	2.69	2.67	2.21	4.35	5.00	13.62	20.82	7.41
	σ_b	2.6	2.6	2.6	2.6	1.6	1.6	1.5	2.1	2.2	3.7	4.6	2.7
	S	1.6	12.1	1.7	2.6	6.2	26.9	9.1	11.2	5.8	22.1	2.6	2.4
	D of V	0.7	5.6	0.6	1.2	1.0	3.5	0.9	2.4	1.9	16.1	3.6	1.3
⅜ In.	$\bar{X}$	13.4	17.9	12.9	16.8	5.0	6.9	9.3	7.4	26.4	24.4	30.2	33.3
	σ^2_a	4.52	72.99	5.68	13.90	2.61	12.35	5.61	12.11	60.95	211.49	92.32	59.53
	σ_a	2.1	8.5	2.4	3.7	1.6	3.5	2.4	3.5	7.8	14.5	9.6	7.7
	σ^2_b	4.16	4 16	4.16	4.16	0.19	0.29	0.20	2.24	7.15	13.62	29.98	13.21
	σ_b	2.0	2.0	2.0	2.0	0.4	0.5	0.5	1.5	2.7	3.7	5.5	3.6
	S	1.1	17.5	1.4	3.3	13.7	42.6	27.5	5.4	8.5	15.5	3.1	4.5
	D of V	0.4	5.1	0.5	1.0	0.6	1.9	0.7	1.9	3.2	11.6	4.4	2.7
No 4	$\bar{X}$	1.5	2.5	1.3	2.1	3.5	4.6	6.1	4.8	4.5	4.1	5.8	7.5
	σ^2_a	0.24	2.46	0.15	0.45	0.77	3.41	2.31	5.22	3.25	8.17	5.22	5.68
	σ_a	0.5	1.6	0.4	0.7	0.9	1.8	1.5	2.3	1.8	2.9	2.3	2.4
	σ^2_b	0.40	0.40	0.40	0.40	0.07	0.10	0.12	1.09	0.36	0.60	1.94	1.50
	σ_b	0.6	0.6	0.6	0.6	0.3	0.3	0.3	1.1	0.6	0.8	1.4	1.2
	S	0.6	6.2	0.4	1.1	11.0	34.1	20.1	4.8	9.0	13.6	2.7	3.8
	D of V	0.2	1.0	0.1	0 2	0.3	0.7	0.4	1.1	0.7	2.1	0.9	0.9

* Number of test portions.
† Average weight of test portions, in pounds

TABLE 10

COMPARISONS OF STANDARD DEVIATIONS, ACTUAL VS PREDICTED, ¾-IN. SIZE

STOCKPILE TYPE	STANDARD DEVIATION, σ_o 1"-#4 CRUSHED STONE ACTUAL	PREDICTED	1½"-⅜" CRUSHED STONE ACTUAL	PREDICTED	1"-#4 UNCRUSHED GRAVEL ACTUAL	PREDICTED
Cone	9.0	10.8	8.5	12.0	17.3	14.9
Cast and spread	3.4	4.3	4.5	5.4	7.3	8.4
Truck-dumped	4.2	4.4	7.0	5.5	4.2	8.4

struction has the greatest effect on increasing segregation, whereas the cast-and-spread method has the greatest effect on decreasing segregation. The effects of aggregate type and gradation lie between these extreme values. The average from all effects, m, was found to be 9.08, and

$p_1 = 4.34$ (cone method of stockpile construction);
$s_2 = 2.03$ (uncrushed gravel aggregate);
$g_2 = 0.566$ (coarse-graded aggregate);
$g_1 = -0.566$ (fine-graded aggregate);
$s_1 = -2.03$ (crushed stone);
$p_3 = -2.13$ (truck-dumped method);
$p_2 = -2.19$ (cast-and-spread method)

Figure 58 shows graphically the relationship between actual and predicted values of sigma. If it were possible to make an exact prediction, all points would fall on the dashed 45° line, which has been drawn to illustrate perfect correlation.

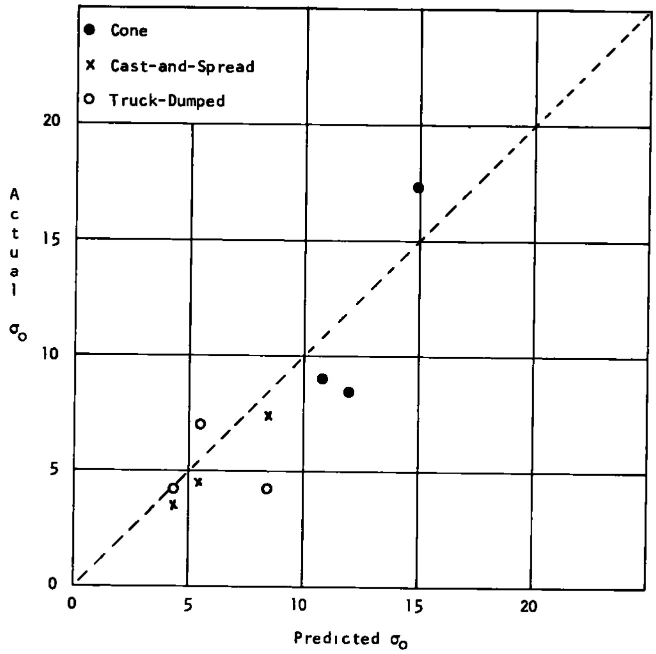


Figure 59. Actual vs predicted standard deviations, ¾-in. size from all sources. Dashed line represents perfect correlation.

Comparative Construction Costs

Tables 11 and 12 present a comparison of costs associated with the various construction methods studied. Table 12 gives the data obtained from the initial 10-3 studies; Table 11, the data from the later studies. It will be noted that the truck-dumped method has again proved to be the most economical procedure for stockpile construction. The stockpile built with uncrushed gravel indicated a unit cost of $0.28 per ton, whereas the Gresham's Lake (1½ in.-⅜ in. crushed stone) indicated a unit cost of $0.42 per ton. It should be remembered that different aggregate quantities were involved at each of the three locations. Therefore, a direct comparison of construction time in each case would be misleading. At the Princeton quarry, approximately 1,500 tons; at the Gresham's Lake quarry, approximately 1,115 tons; and at the Campbell plant in Baltimore, approximately 1,050 tons of aggregate were used. The stockpiling price as shown represents actual construction cost (number of hours times equipment cost per hour), as there were no charges for use of the aggregates. These cost data are a byproduct of the main research effort.

In actual practice, the use of truck-dumped methods could provide even lower cost figures if the aggregate were loaded by gravity from a storage hopper directly into the truck body. In such case, the cost would be at an absolute minimum, as there would be no extra loading charges involved. This is a common practice when aggregates are hauled from a quarry. All unit cost figures would vary according to the particular construction operation involved, condition of equipment, skill of operator, equipment rental rate, and quantity of aggregate involved.

Stockpiles included under the scope of this investigation were limited to a height of material contained in one truckload (approximately 4½ ft). With a hard aggregate not subject to excessive degradation, it may be practicable to build similar piles to a substantial height by permitting the trucks to haul over the preceding loads to discharge their contents.

The additional data acquired in the continuation studies

TABLE 11

COMPARATIVE COSTS OF STOCKPILE CONSTRUCTION

STOCKPILE TYPE	STOCKPILE LOCATION	CONSTRUCTION METHOD	CONSTRUCTION TIME (HR)	TOTAL COST ($)	COST PER TON ($)[a]	SEGREGATION INDEX[b]
Single cone	Gresham's Lake	Clambucket	11.00	713	0.64	41.40
	Baltimore Gravel	Clambucket	13.50	645	0.62	20.50
Cast & spread	Gresham's Lake	Clambucket	8.00	518	0.46	21.80
	Baltimore Gravel	Clambucket	8.75	418	0.40	2.80
Truck-dumped	Gresham's Lake	Dump trucks[c]	7.25	470	0.42 to 0.00[e]	6.80
	Baltimore Gravel	Dump trucks[d]	6.00	287	0.28 to 0.00[e]	4.10

[a] Construction cost only. [b] Based on $\bar{A}$. [c] Loaded by conveyor belt. [d] Loaded by front-end loader
[e] Equal to or less than $0.34 if aggregate is delivered to stockpile site in trucks

confirmed the trend initially developed that the truck-dumped procedure will provide a relatively low segregation index.

Summary and Interpretation of Stockpiling Data

The initial and continuation studies have quantified for the first time the effects on segregation of commonly used procedures for stockpiling so that it is now possible to recommend specific methods to minimize the undesirable effects. This investigation confirms the belief that those methods which produce cone piles will result in a high level of segregation; that uncrushed gravel aggregate has a greater tendency toward segregation than does crushed stone; and, that the larger maximum size aggregate tends to segregate more than the smaller sizes.

An examination of all the mathematical and statistical parameters presented in the preceding sections of this chapter confirms these observations. Both the aggregate grading charts and the charts showing the plot of Hudson $\bar{A}$ clearly show the higher variability of the coned piles, as well as the influence of aggregate size and type. Likewise, the tables of variance, standard deviation, segregation index, and degree of variation support the aforementioned observations.

The relative effect of each variable is quantified by the use of a mathematical model for predicting segregation. The model has disclosed that the cone method of stockpile construction has a greater influence on segregation than any of the other variables investigated. Other factors, in order of their relative effect, include uncrushed gravel aggregate, coarse-graded aggregate, fine-graded aggregate, crushed stone, truck-dumped method, and cast-and-spread method.

TABLE 12

INITIAL STOCKPILING STUDIES AT PRINCETON QUARRY

STOCKPILE NO.	STOCKPILE TYPE	CONSTRUCTION METHOD	CONSTRUCTION TIME (HR)	TOTAL COST ($)	COST PER TON ($)[a]	SEGREGATION INDEX[b]
1	Flat-mixed	Clambucket	10.25	758	0.50	1.35
2	Double cone	Clambucket	10.25	758	0.50	16.48
3	Flat-layered	Clambucket	6.75	500	0.33	1.96
4	Single cone	Clambucket	10.25	758	0.50	16.86
5	Coned-tent	Portable conveyor	11.00	817	0.54	8.10
6	Flat-layered	Front-end loader	13.00	959	0.64	4.05
7	Single cone	Clambucket	11.00	817	0.54	13.36
8	Tiered (bermed)	Clambucket	13.00	959	0.64	7.37
9	Truck-dumped	Dump trucks[c]	7.00	517	0.34[d]	2.30
10	Ramped	Rubber-tired dozer	11.00	808	0.54	1.59
11	Flat-mixed	Rubber-tired dozer	9.25	683	0.45	2.10

[a] Construction cost only. [b] Based on $\bar{A}$. [c] Loaded by conveyor belt. [d] Equal to or less than $0.34 if aggregate is delivered to stockpile site in trucks.

The mixing action resulting from the cast-and-spread method has produced smaller values for practically all statistical parameters. This can be seen in the aggregate grading charts and in the tables for segregation index and degree of variation. The truck-dump method of construction continues to be the most economical and practical method of stockpiling, as indicated by the segregation index and by Tables 11 and 12, showing comparative costs of stockpile construction.

A number of different measures and comparisons of variability have been presented. The segregation index values indicated a range from about 1 to 41, whereas the degree of variation ranged from less than 1 to about 16. Hudson $\bar{A}$ values ranged from 1.2 to 2.7. There is no assurance that any of these methods, used alone, will present a complete picture of the pattern and amount of segregation in the various types of stockpiles. Each method of analysis was designed to measure and compare some particular aspect of the data. Consequently, the relationships between the various parameters must be understood for each to fulfill its intended purpose.

It should be realized that this research activity has been in an almost unexplored area with respect to the behavior of aggregates in bulk. Although general trends have been observed and their effects estimated, there undoubtedly remain many causes of variation which have not been identified or evaluated.

In summary, the data show that the largest amount of segregation is found in the coned piles, regardless of aggregate type or gradation. The variation in gradation in this type of stockpile is of sufficient magnitude to probably require readjustment of bitumen content or of concrete mix proportions from batch to bach. Further, the uncrushed gravel will cause a higher level of segregation than does a comparable crushed stone; the larger maximum size causes higher levels of segregation than do the smaller sizes; the described statistical parameters serve as a valuable aid in interpreting the results of tests; and the mathematical model can be used to predict segregation resulting from many combinations of variables.

Logical questions that will arise from a review of the data may include: What effect do the variations have on the road or in mix design or in the writing of realistic specifications? It would not be possible to provide complete answers to these questions on the basis of this research study and, as a matter of fact, such answers extend beyond the scope of the current effort.

DEGRADATION

Data derived from the degradation studies are presented in this section as a series of tables, charts, and graphs. The same statistical parameters by which the stockpiling methods were evaluated are used in the analysis of the data. The variables that are compared are the Hudson $\bar{A}$ value, which characterizes the entire gradation range, and the percent of the base material passing the No. 200 sieve, which is significantly associated with the performance of this type of aggregate base construction. The segregation index and degree of variation are also shown, although their significance is of secondary importance from the viewpoint of degradation.

Aggregate grading charts showing the average gradation and the $\pm 2\sigma$ limits are presented for each sampling point in the flow of aggregates used in the test section construction. In addition, analysis of variance has been used to determine the source and magnitude of those factors which could have contributed to degradation.

A complete description of test section construction details is given in Chapter Three, but for the convenience of the reader a brief summary is given in the following.

Two base course aggregates—a hard stone (Durham quarry, average L.A. 12%) and a soft stone (Gresham's Lake quarry, average L.A. 50%)—were used to construct six test sections using conventional methods and equipment. The sections were constructed by identical methods in pairs, with the variable in each pair being hard versus soft stone. Sections 1-D and 1-G were spread with a box spreader and compacted with a vibrating steel-wheel roller and a rubber-tired roller. Sections 2-D and 2-G were spread with a box spreader and compacted with a three-wheel steel roller. Sections 3-D and 3-G were spread with a motor grader and compacted with a rubber-tired roller.

In each case the base course aggregate was brought directly from the pug mill mixer by dump truck to be spread by the described method, so any differences between sections constructed with the same aggregate should be the result of differences between spreading and compacting procedures.

Average Gradation of Aggregates Used in Degradation Study

The average gradations given in Table 13 are of special interest because the results indicate that their close approximation of the maximum density curves in each case may have minimized degradation. Both aggregates were produced to meet North Carolina specifications for No. 8 stone, a gradation which has given excellent performance

TABLE 13

AVERAGE GRADATIONS FROM DEGRADATION STUDIES

	TOTAL PERCENT PASSING	
SIEVE SIZE	DURHAM QUARRY (HARD STONE)	GRESHAM'S LAKE QUARRY (SOFT STONE)
1½ in.	100	100
¾ in.	79.2	78.2
⅜ in.	58.6	48.5
No. 4	45.9	36.0
No. 8	37.5	29.6
No. 16	29.7	23.4
No. 30	21.9	18.7
No. 50	14.2	12.6
No. 100	8.6	7.5
No. 200	4.7	3.9

over a number of years. The balance of plus No. 4 to minus No. 4 provides a cushion of fines around the coarser particles and tends to prevent the breakdown that is believed to occur with point-to-point contact.

These gradings represent the overall average of tests from each of the five locations sampled: (1) before mixing, (2) after mixing, (3) Test Section No. 1, (4) Test Section No. 2, and (5) Test Section No. 3.

These average gradings have been plotted on aggregate grading charts in Figures 60 and 61. The area enclosed by the solid lines represents the average grading $\pm 2\sigma_0$ limits; the dashed line represents a maximum density gradation curve.

It has been well established that the theoretical absolute relative maximum density is obtained when a grading plots as a straight line having a slope of 0.45 on a log-log scale. However, studies have shown that there is little practical difference in density between gradations having slopes from about 0.35 to 0.52. The maximum density curve shown in Figure 60 has a slope of 0.35; that in Figure 61 has a slope of 0.48. These slopes were selected to correspond to the approximate average grading in each case.

Aggregate Grading Charts

The aggregate grading charts presented in this section are similar to those presented in the previous section on segregation. Again, they are designed to show the average gradation and the $\pm 2\sigma_0$ limits. The range indicated by the width of the gradation band will include 95 percent of all test values obtained under similar conditions. These curves show changes in gradation of the aggregate from the parent stockpile, after processing by the pug mill mixer, and after compaction in the various test sections. These curves are of special value to the engineer because the width of the gradation band is an indication of variability, with the wider bands being more variable.

The Durham quarry (hard stone) curves (Figs. 62, 63, 64, 65, and 66) are presented first, followed by the Gresham's Lake (soft stone) gradation curves (Figs. 67, 68, 69, 70, and 71). Each curve is an average of all test portions taken at the particular sampling location indicated.

Three significant characteristics of these curves should be noted: (1) the slope of each group of curves is essentially the same; (2) variability is greatest near the point where 50% of the aggregate passes a given sieve; and (3) there is essentially no difference between the degradations of the hard and soft aggregates.

The last observation came as quite a surprise. Although the cushioning effect of the fines was known in a general way, it was not anticipated that degradation differences between Los Angeles abrasion losses of 12 and 50 would be so completely obliterated. There were no statistically significant gradation changes at any size level between these two aggregates.

This perhaps fails to confirm a generally accepted belief, but certainly appears to point toward minimizing degradation by proper gradation design. Further, it causes one to wonder if reported values of degradation on many construction projects may not be distorted by improper or inadequate sampling procedures.

Degradation Results

Figure 72 indicates the average level of each gradation size, bounded by the 95% confidence limit. It will be noted that a single vertical line, drawn through each sieve size chart, will be common to each sampling location at the given confidence level. This means that a single gradation could be selected which would be appropriate to describe the aggregate at every sampling point. In other words, there was apparently no appreciable degradation of either stone.

The basis for selection of these aggregates was discussed in Chapter One. The lack of degradation is probably due to the close approach to the maximum density curve for this type of aggregate.

Variables Affecting Degradation

Degradation resulting from aggregate processing and handling can usually be attributed to a combination of several variables. These variables will include not only the effects of different characteristics of the individual aggregates concerned, but also the effects from the handling, mixing, and compaction equipment. Each of these will produce a specific amount of degradation, although in many cases its total effect is virtually insignificant.

One of the most useful statistical tools to detect and measure the magnitude of these variation sources is a method of extracting single degree of freedom contrasts (a specialized case of analysis of variance, ANOV). In this procedure, the ratio of variances of the items being tested is compared with an appropriate value from Snedecor's F table. If the calculated value exceeds the value from the table, a difference greater than could be due to chance alone is said to exist. In the case of these studies, this means that the items tested which showed significance are contributors to the measured degradation (although the magnitude of total degradation is very small).

It has been concluded that the two most important indicators of gradation changes in base course aggregates are the Hudson $\bar{A}$ and the minus No. 200 material. Consequently, these two values have been selected for an ANOV, wherein tests of significance are made to compare changes in the average value of $\bar{A}$ and minus No. 200 as the aggregate was processed and compacted. The mechanics of making these comparisons are given in Tables 14, 15, 16, and 17. The purpose of this ANOV is to show whether or not there are statistically significant differences among the variables, individually, or combinations of the variables. Variables which were compared include the following:

- Source—Durham (hard) vs Gresham's (soft) stone.
- Sources vs spreading method.
- Sources and spreading method vs compaction method.
- Sources $\times$ sources vs spreading method.

Average Gradation
Durham (Hard) Stone

	PER CENT PASSING		
Sieve Size	$\overline{X}$	σ	±2σ Range
1-1/2	100	-	-
3/4	79.2	3.9	71.4-87.0
3/8	58.6	4.4	49.8-67.4
#4	45.9	3.6	38.7-53.1
#8	37.5	2.9	31.7-43.3
#16	29.7	2.3	25.1-34.3
#30	21.9	1.8	18.3-25.5
#50	14.2	1.4	11.4-17.0
#100	8.6	0.9	6.8-10.4
#200	4.7	0.6	3.5- 5.9

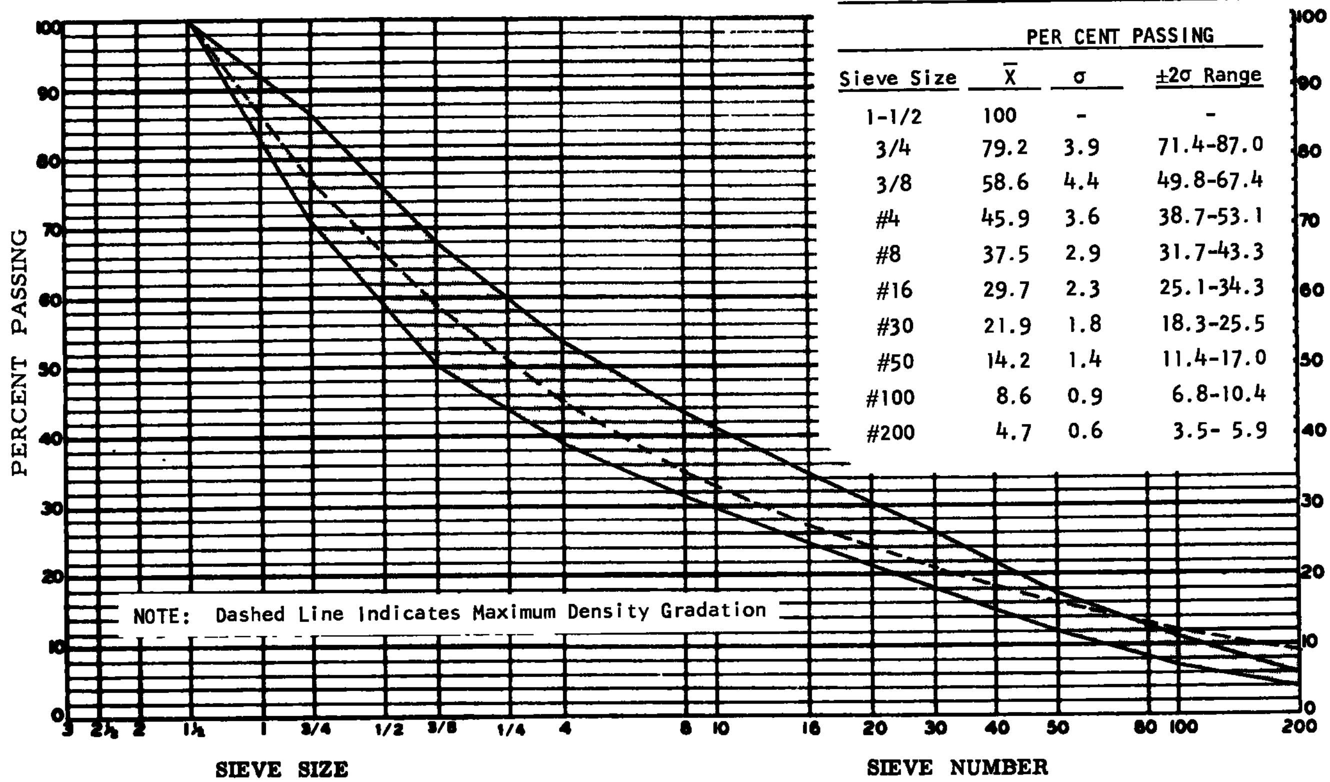


Figure 60. Aggregate grading chart, Durham (hard) stone, parent pile.

Average Gradation
Gresham's Lake (Soft) Stone

	PER CENT PASSING		
Sieve Size	$\overline{X}$	σ	±2σ Range
1-1/2	100	-	-
3/4	78.2	4.1	70.0-86.4
3/8	48.5	5.0	38.5-58.5
#4	36.0	4.0	28.0-44.0
#8	29.6	3.2	23.2-36.0
#16	23.4	2.5	18.4-28.4
#30	18.7	2.0	14.7-22.7
#50	12.6	1.3	10.0-15.2
#100	7.5	0.8	7.5- 9.1
#200	3.9	0.5	2.9- 4.9

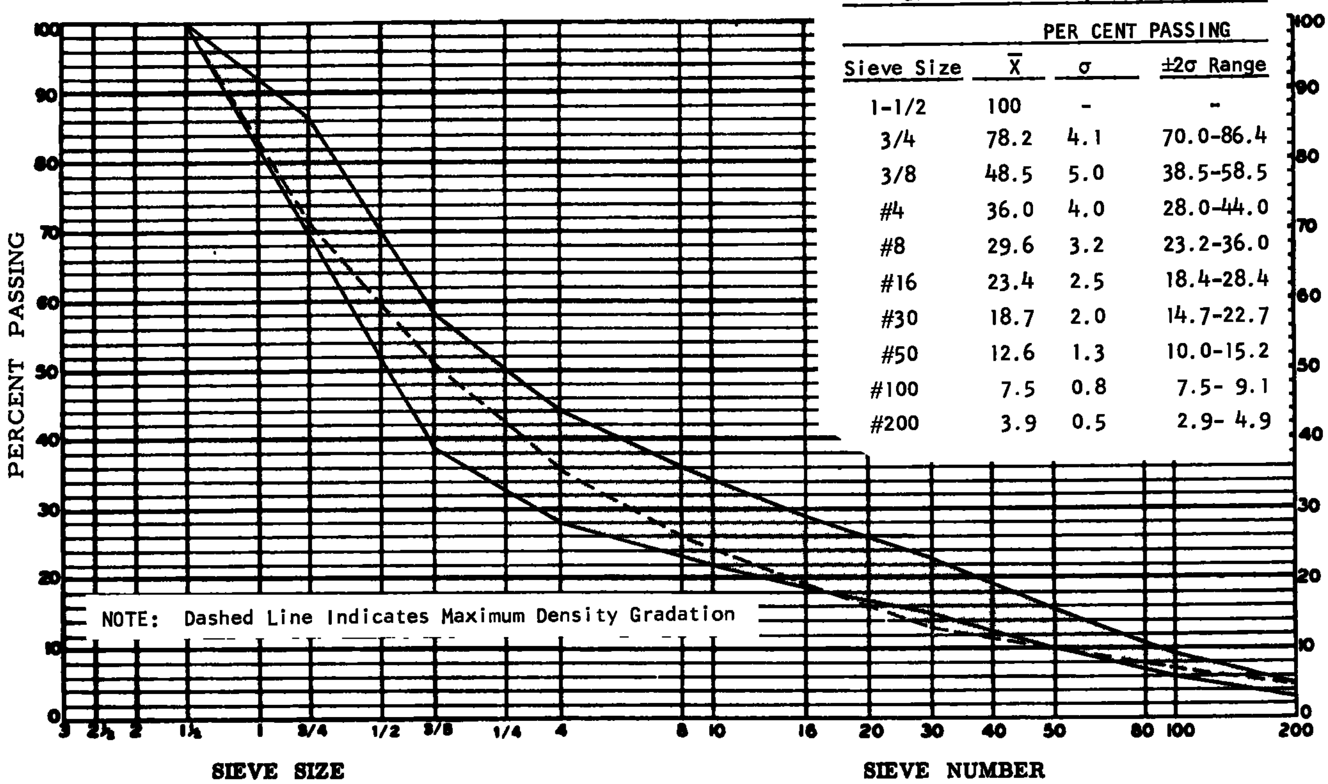
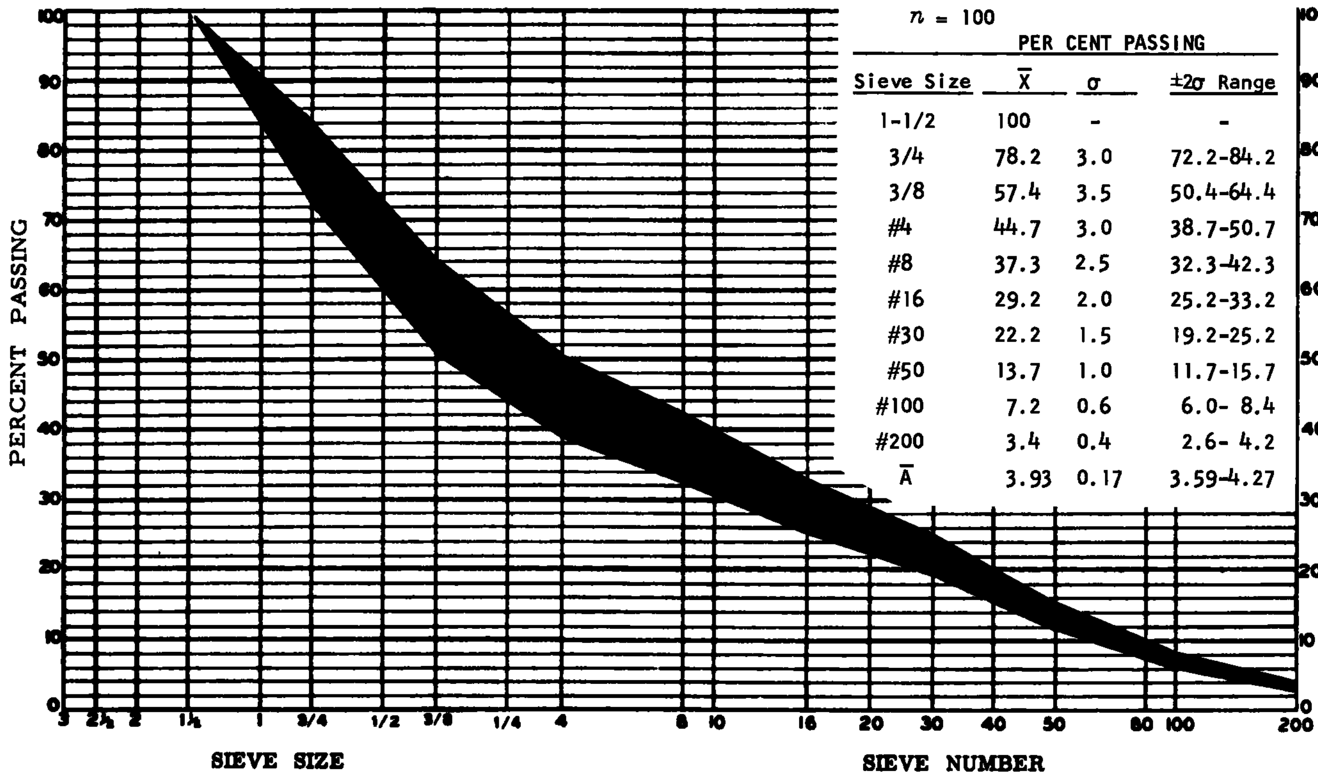


Figure 61. Aggregate grading chart, Gresham's Lake (soft) stone, parent pile.

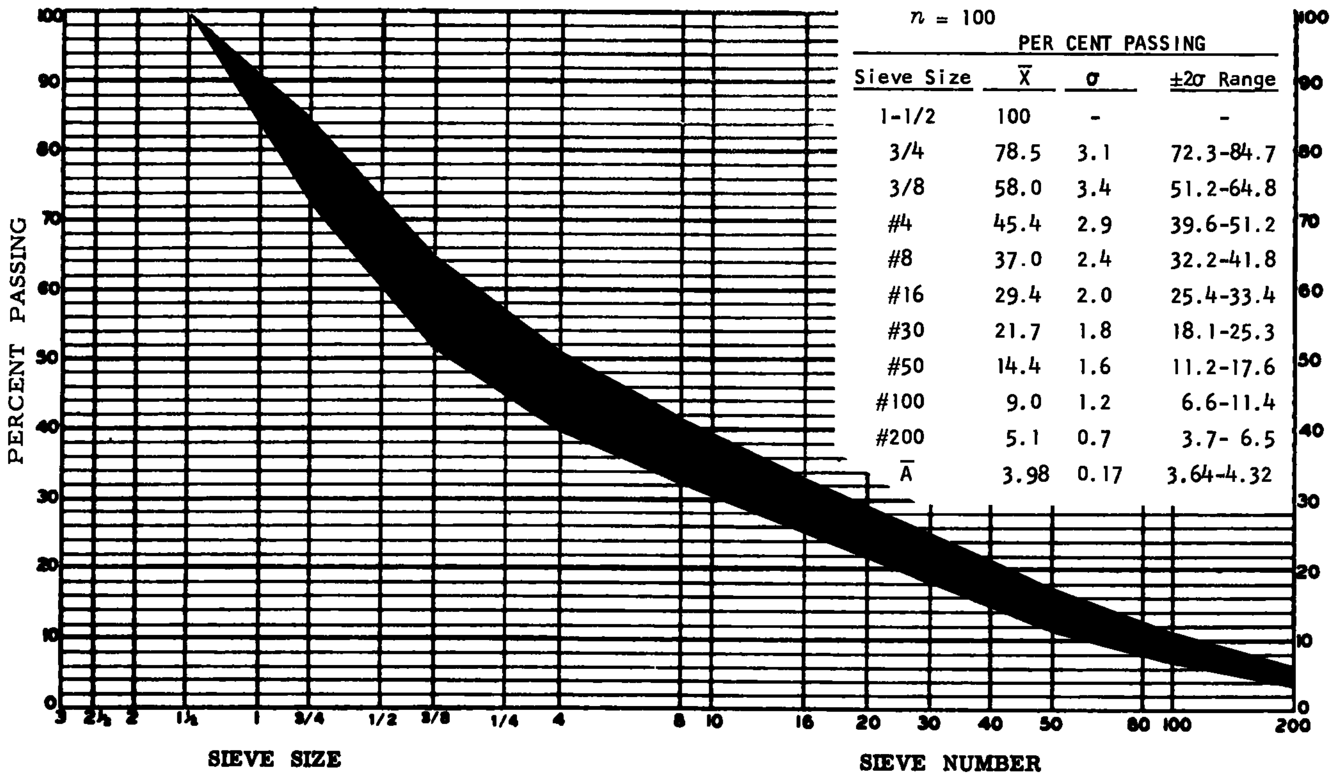


Belt - Before Mixing
Durham Stone (Hard Stone)

n = 100

Sieve Size	PER CENT PASSING $\bar{X}$	σ	$\pm 2\sigma$ Range
1-1/2	100	-	-
3/4	78.2	3.0	72.2-84.2
3/8	57.4	3.5	50.4-64.4
#4	44.7	3.0	38.7-50.7
#8	37.3	2.5	32.3-42.3
#16	29.2	2.0	25.2-33.2
#30	22.2	1.5	19.2-25.2
#50	13.7	1.0	11.7-15.7
#100	7.2	0.6	6.0- 8.4
#200	3.4	0.4	2.6- 4.2
$\bar{A}$	3.93	0.17	3.59-4.27

Figure 62. Aggregate grading chart, Durham (hard) stone, belt before mixing.

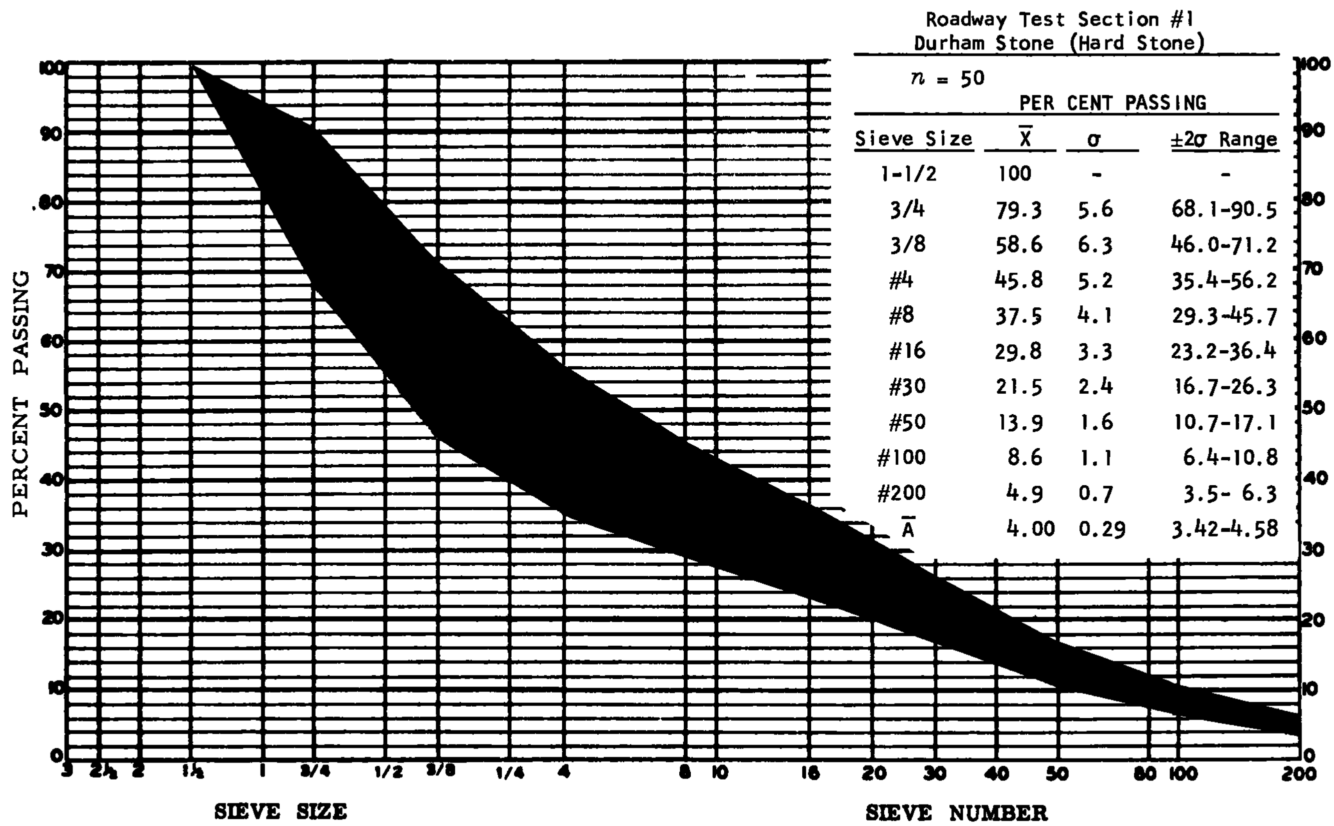


Belt - After Mixing
Durham Stone (Hard Stone)

n = 100

Sieve Size	PER CENT PASSING $\bar{X}$	σ	$\pm 2\sigma$ Range
1-1/2	100	-	-
3/4	78.5	3.1	72.3-84.7
3/8	58.0	3.4	51.2-64.8
#4	45.4	2.9	39.6-51.2
#8	37.0	2.4	32.2-41.8
#16	29.4	2.0	25.4-33.4
#30	21.7	1.8	18.1-25.3
#50	14.4	1.6	11.2-17.6
#100	9.0	1.2	6.6-11.4
#200	5.1	0.7	3.7- 6.5
$\bar{A}$	3.98	0.17	3.64-4.32

Figure 63. Aggregate grading chart, Durham (hard) stone, belt after mixing.

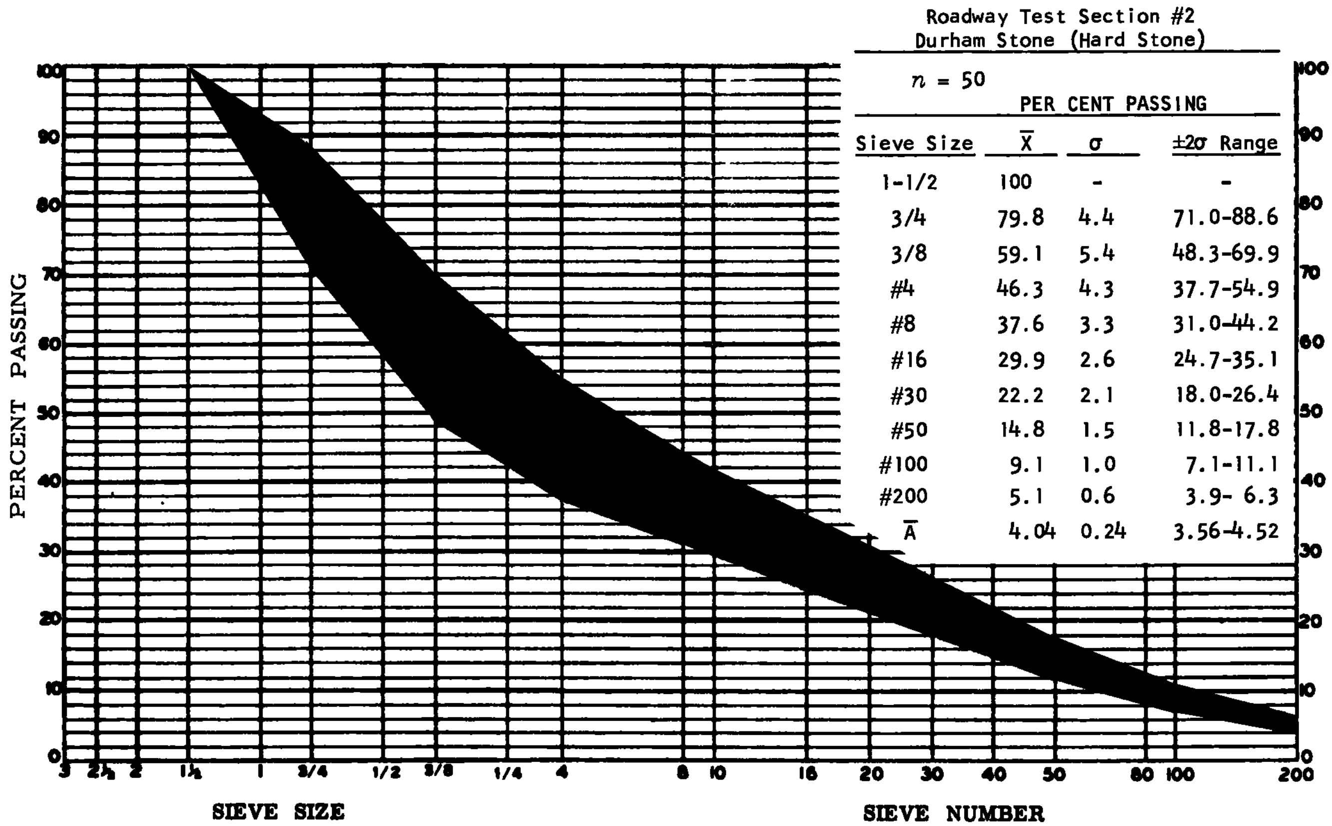


Roadway Test Section #1
Durham Stone (Hard Stone)

n = 50

Sieve Size	$\bar{X}$	σ	±2σ Range
	PER CENT PASSING		
1-1/2	100	-	-
3/4	79.3	5.6	68.1-90.5
3/8	58.6	6.3	46.0-71.2
#4	45.8	5.2	35.4-56.2
#8	37.5	4.1	29.3-45.7
#16	29.8	3.3	23.2-36.4
#30	21.5	2.4	16.7-26.3
#50	13.9	1.6	10.7-17.1
#100	8.6	1.1	6.4-10.8
#200	4.9	0.7	3.5- 6.3
$\bar{A}$	4.00	0.29	3.42-4.58

Figure 64. Aggregate grading chart, Durham (hard) stone, roadway test section 1.

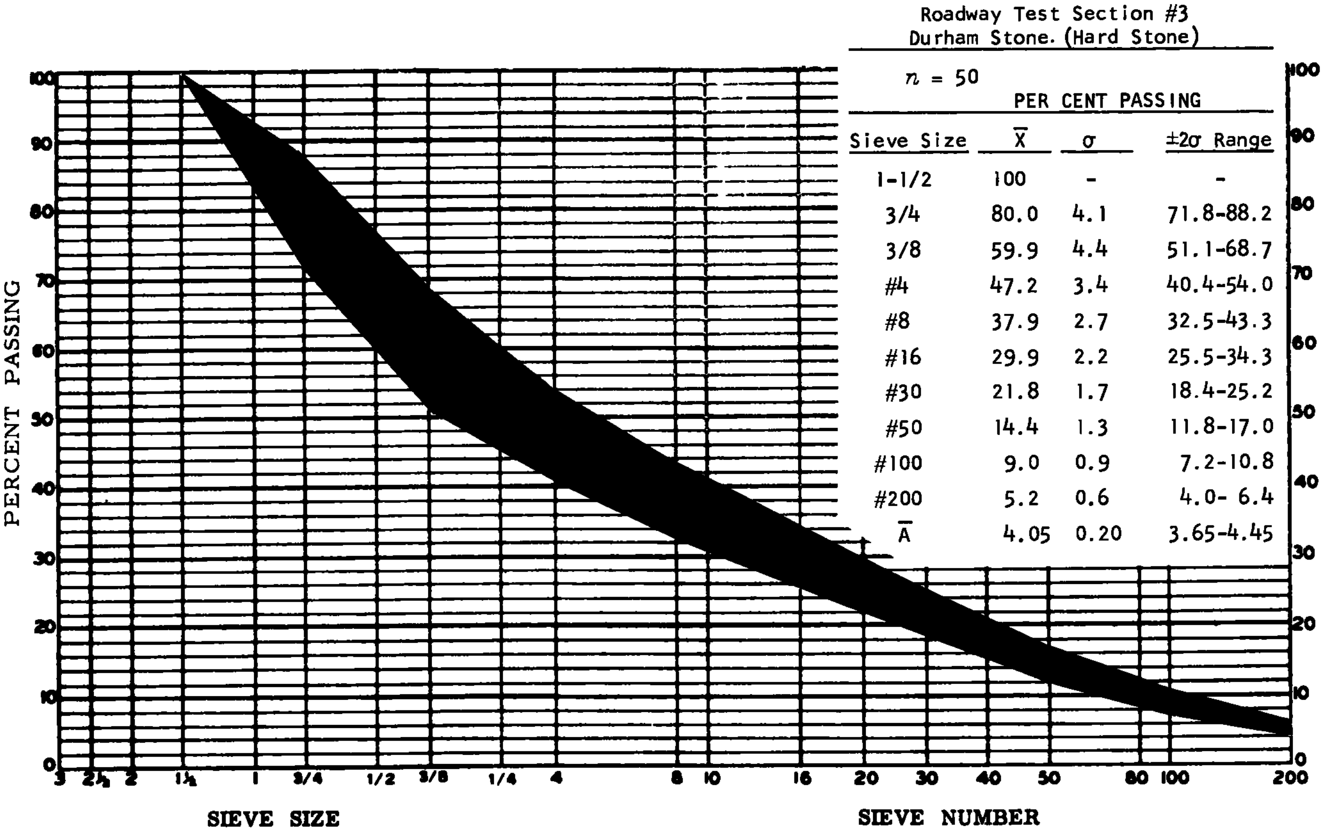


Roadway Test Section #2
Durham Stone (Hard Stone)

n = 50

Sieve Size	$\bar{X}$	σ	±2σ Range
	PER CENT PASSING		
1-1/2	100	-	-
3/4	79.8	4.4	71.0-88.6
3/8	59.1	5.4	48.3-69.9
#4	46.3	4.3	37.7-54.9
#8	37.6	3.3	31.0-44.2
#16	29.9	2.6	24.7-35.1
#30	22.2	2.1	18.0-26.4
#50	14.8	1.5	11.8-17.8
#100	9.1	1.0	7.1-11.1
#200	5.1	0.6	3.9- 6.3
$\bar{A}$	4.04	0.24	3.56-4.52

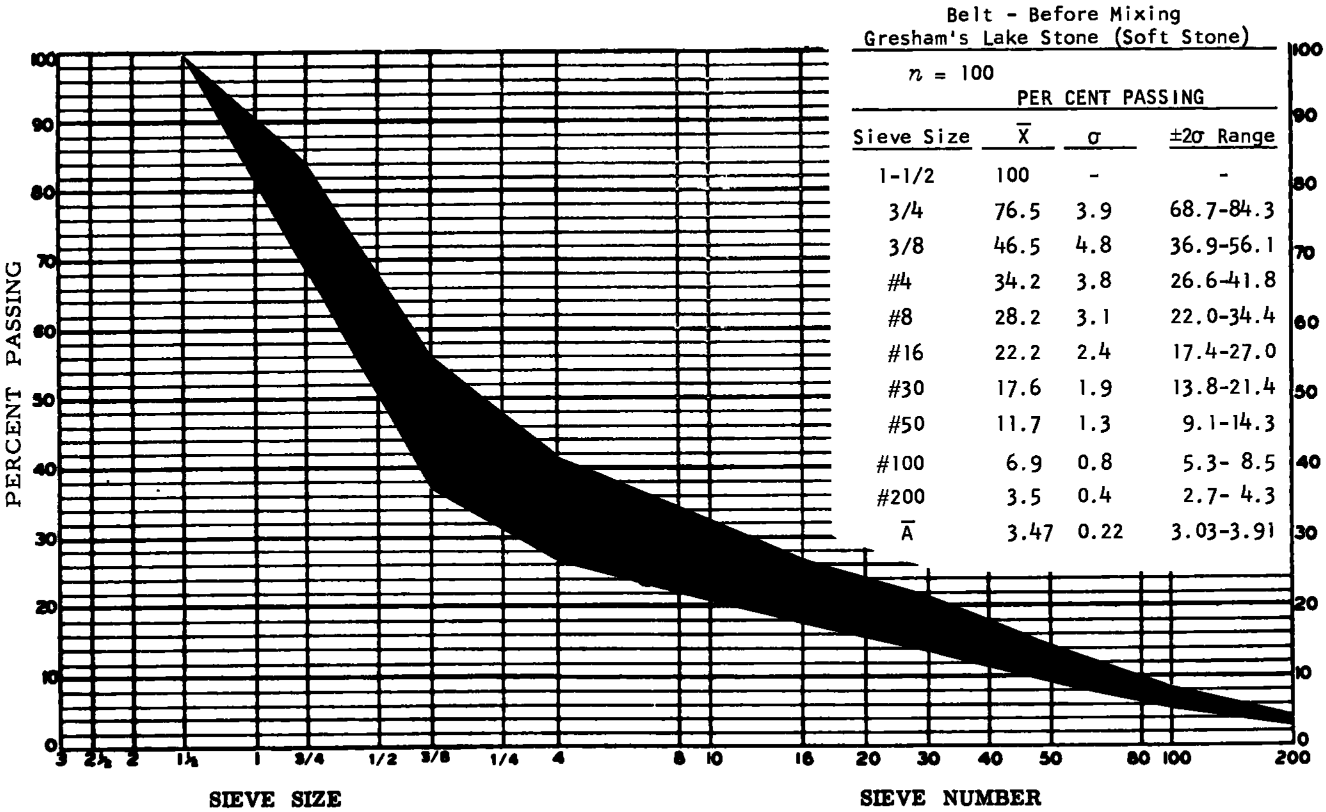
Figure 65. Aggregate grading chart, Durham (hard) stone, roadway test section 2.



n = 50

Sieve Size	$\bar{X}$	σ	$\pm 2\sigma$ Range
	PER CENT PASSING		
1-1/2	100	-	-
3/4	80.0	4.1	71.8-88.2
3/8	59.9	4.4	51.1-68.7
#4	47.2	3.4	40.4-54.0
#8	37.9	2.7	32.5-43.3
#16	29.9	2.2	25.5-34.3
#30	21.8	1.7	18.4-25.2
#50	14.4	1.3	11.8-17.0
#100	9.0	0.9	7.2-10.8
#200	5.2	0.6	4.0- 6.4
$\bar{A}$	4.05	0.20	3.65-4.45

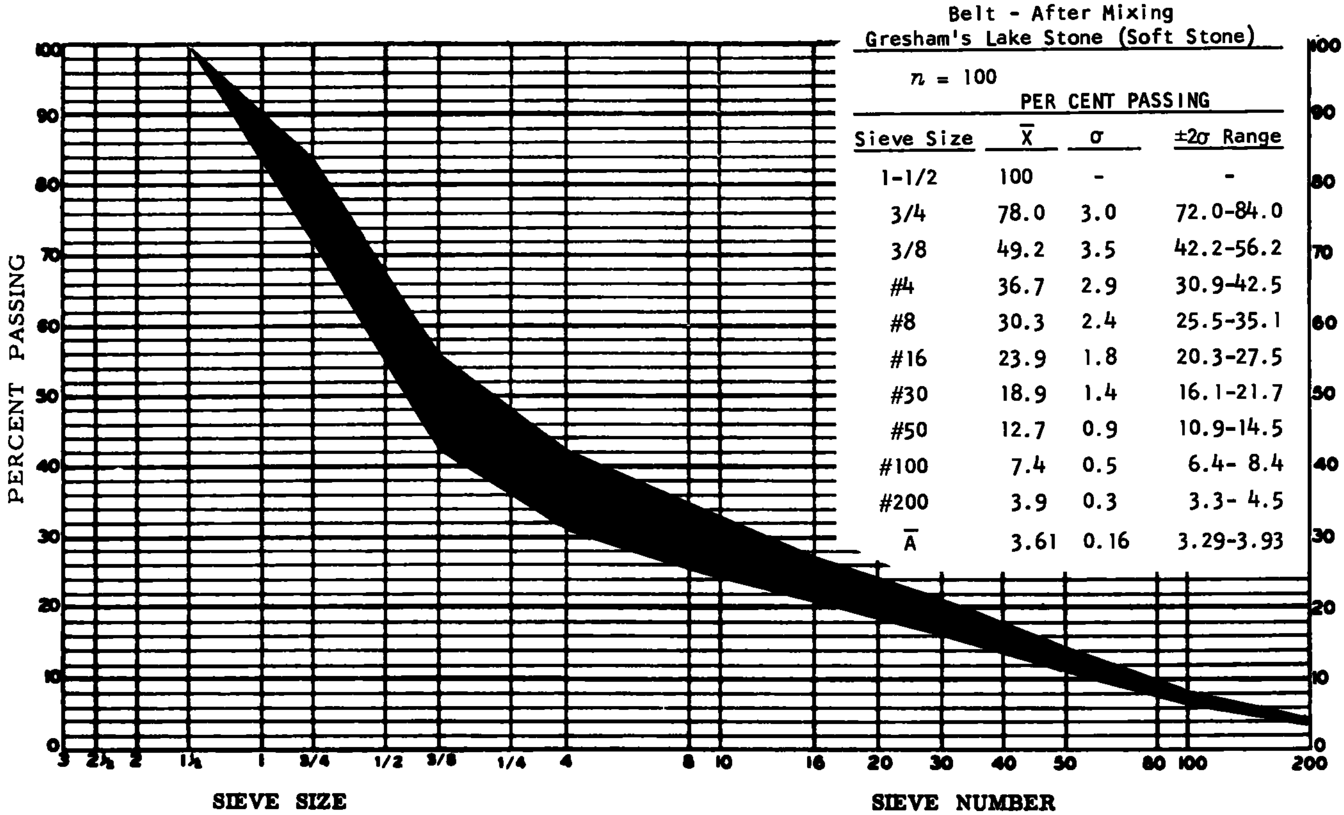
Figure 66. Aggregate grading chart, Durham (hard) stone, roadway test section 3.



n = 100

Sieve Size	$\bar{X}$	σ	$\pm 2\sigma$ Range
	PER CENT PASSING		
1-1/2	100	-	-
3/4	76.5	3.9	68.7-84.3
3/8	46.5	4.8	36.9-56.1
#4	34.2	3.8	26.6-41.8
#8	28.2	3.1	22.0-34.4
#16	22.2	2.4	17.4-27.0
#30	17.6	1.9	13.8-21.4
#50	11.7	1.3	9.1-14.3
#100	6.9	0.8	5.3- 8.5
#200	3.5	0.4	2.7- 4.3
$\bar{A}$	3.47	0.22	3.03-3.91

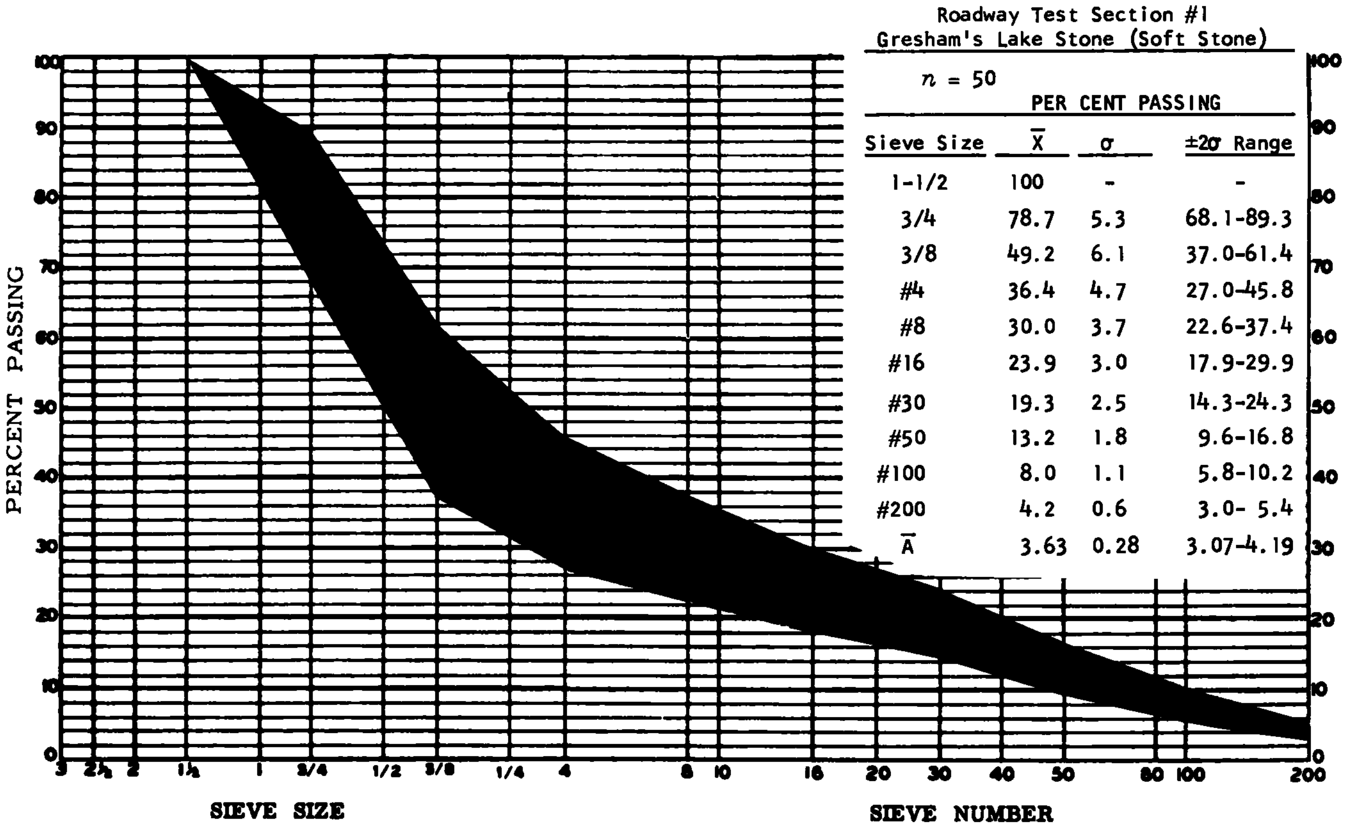
Figure 67. Aggregate grading chart, Gresham's Lake (soft) stone, belt before mixing.



n = 100

Sieve Size	$\bar{X}$	σ	$\pm 2\sigma$ Range
	PER CENT PASSING		
1-1/2	100	-	-
3/4	78.0	3.0	72.0-84.0
3/8	49.2	3.5	42.2-56.2
#4	36.7	2.9	30.9-42.5
#8	30.3	2.4	25.5-35.1
#16	23.9	1.8	20.3-27.5
#30	18.9	1.4	16.1-21.7
#50	12.7	0.9	10.9-14.5
#100	7.4	0.5	6.4- 8.4
#200	3.9	0.3	3.3- 4.5
$\bar{A}$	3.61	0.16	3.29-3.93

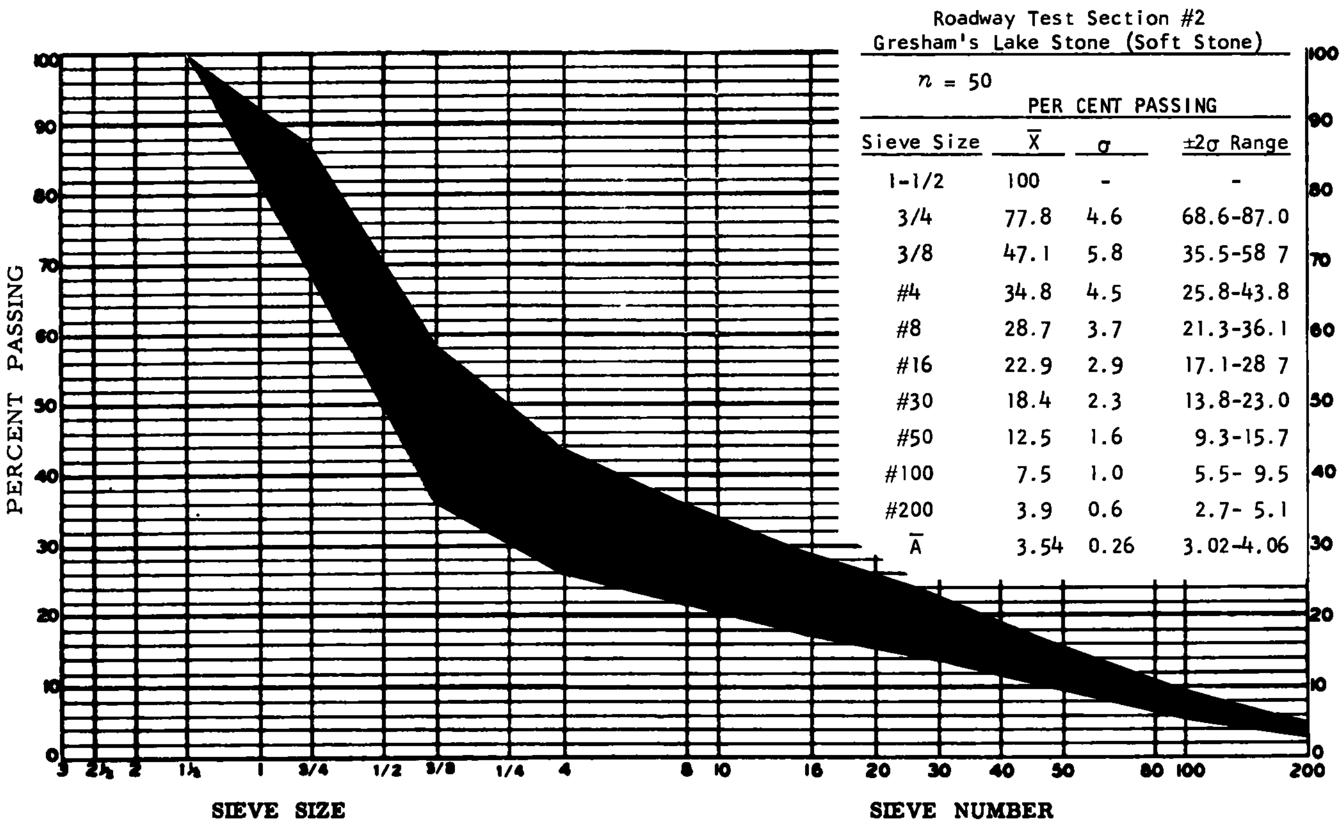
Figure 68. Aggregate grading chart, Gresham's Lake (soft) stone, belt after mixing.



n = 50

Sieve Size	$\bar{X}$	σ	$\pm 2\sigma$ Range
	PER CENT PASSING		
1-1/2	100	-	-
3/4	78.7	5.3	68.1-89.3
3/8	49.2	6.1	37.0-61.4
#4	36.4	4.7	27.0-45.8
#8	30.0	3.7	22.6-37.4
#16	23.9	3.0	17.9-29.9
#30	19.3	2.5	14.3-24.3
#50	13.2	1.8	9.6-16.8
#100	8.0	1.1	5.8-10.2
#200	4.2	0.6	3.0- 5.4
$\bar{A}$	3.63	0.28	3.07-4.19

Figure 69. Aggregate grading chart, Gresham's Lake (soft) stone, roadway test section 1.

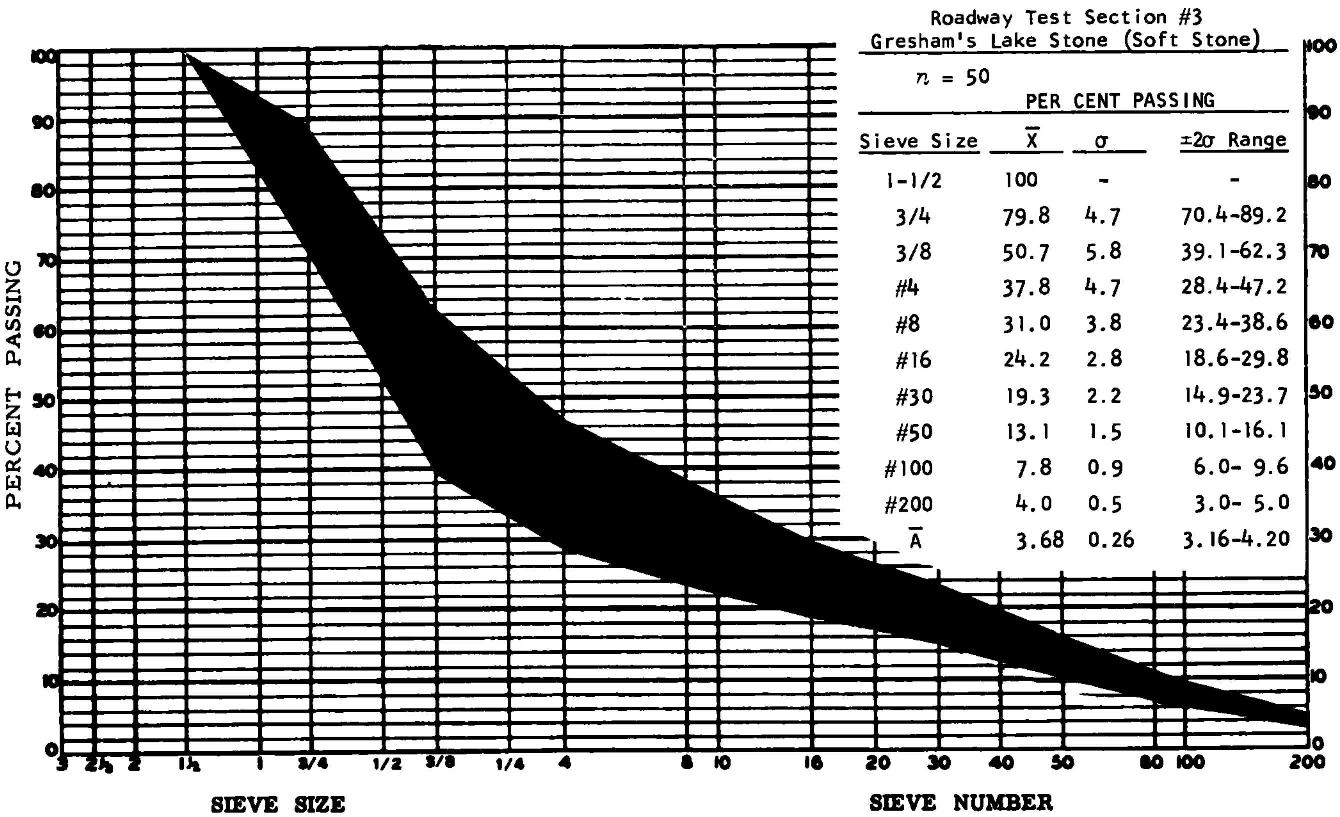


Roadway Test Section #2
Gresham's Lake Stone (Soft Stone)

n = 50

	PER CENT PASSING		
Sieve Size	$\overline{X}$	σ	$\pm2\sigma$ Range
1-1/2	100	-	-
3/4	77.8	4.6	68.6-87.0
3/8	47.1	5.8	35.5-58 7
#4	34.8	4.5	25.8-43.8
#8	28.7	3.7	21.3-36.1
#16	22.9	2.9	17.1-28 7
#30	18.4	2.3	13.8-23.0
#50	12.5	1.6	9.3-15.7
#100	7.5	1.0	5.5- 9.5
#200	3.9	0.6	2.7- 5.1
$\overline{A}$	3.54	0.26	3.02-4.06

Figure 70. Aggregate grading chart, Gresham's Lake (soft) stone, roadway test section 2.



Roadway Test Section #3
Gresham's Lake Stone (Soft Stone)

n = 50

	PER CENT PASSING		
Sieve Size	$\overline{X}$	σ	$\pm2\sigma$ Range
1-1/2	100	-	-
3/4	79.8	4.7	70.4-89.2
3/8	50.7	5.8	39.1-62.3
#4	37.8	4.7	28.4-47.2
#8	31.0	3.8	23.4-38.6
#16	24.2	2.8	18.6-29.8
#30	19.3	2.2	14.9-23.7
#50	13.1	1.5	10.1-16.1
#100	7.8	0.9	6.0- 9.6
#200	4.0	0.5	3.0- 5.0
$\overline{A}$	3.68	0.26	3.16-4.20

Figure 71. Aggregate grading chart, Gresham's Lake (soft) stone, roadway test section 3.

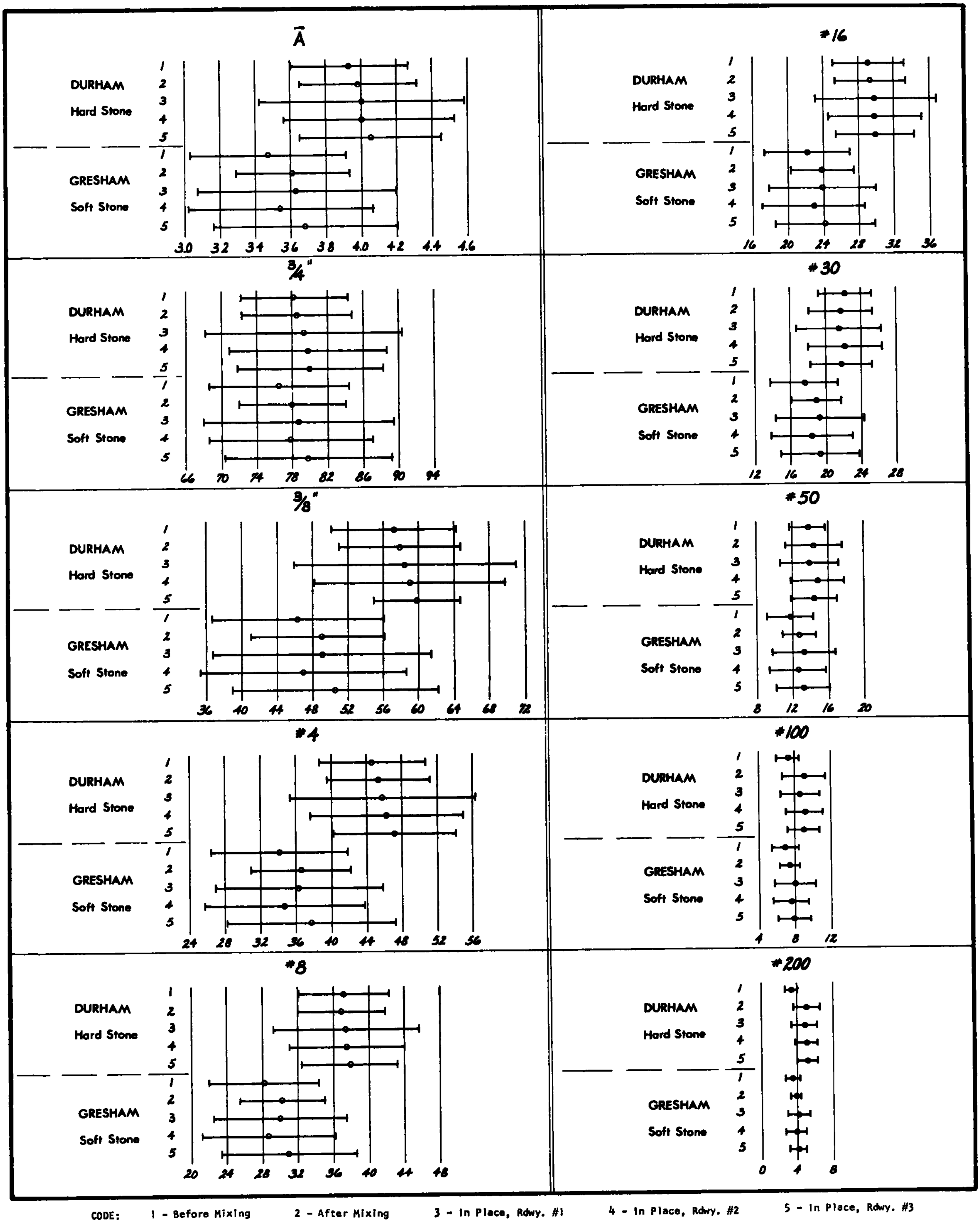


Figure 72. Confidence limits, degradation test sections.

- Source × source and spreading method vs compaction method.
- Pug mill vs test sections.
- Source × road vs pug mill.
- Belt vs all combined factors.
- Source × belt vs all combined factors.
- Belt vs pug mill × source.

In comparing the acquired data, statistically significant differences were found to exist between the two aggregate sources, between before and after pug mill mixing for both aggregate sources, and between several combinations of combined effects of the variables. Further examination of the data indicates that these apparent differences have no practical significance even though they satisfy the criteria of being statistically different. For example, it is most unlikely that a change of 1% in minus No. 200 content would be the difference between good and poor performance, unless a borderline material were involved; likewise, it is unlikely that a change of 0.1 in $\bar{A}$ would make any material difference in base course performance. Obviously, there is a level which, if exceeded, could adversely affect performance. These data, however, do not indicate that any such level has been reached or even approached. There is no way to define mathematically the answer to the resultant effect on performance of slight variations. This answer must be obtained by evaluations and correlations with respect to performance under traffic after a period of several climatic cycles.

Based on experience of the research agency engineering staff, however, the relatively small amount of degradation that did take place would not cause a measurable effect in roadway service.

The analysis showed that the experimental method and data analysis could detect minute changes in gradation so small as not to be important from a practical point of view. The overall study has proved the ability to accurately measure the degradation effect from each piece of equipment, aggregate type, and process operation, or of any variable considered individually or in combination with others. The statistical techniques employed for this purpose not only permit these effects to be quantified but also allow determination of a specific level of confidence on the results obtained.

Although this particular study did not disclose a detrimental degree of aggregate degradation, the fact that a very precise system of evaluation has been developed is, in itself, a worthwhile contribution.

Variability Measures—Variance and Standard Deviation

The significance and use of the variance and standard deviation as tools for measuring variability have been previously discussed in Chapter Two. They are used here to show the variations in gradation of the aggregate at the different points in the process stream.

Tables 18 and 19 give the same basic data. Table 18 is in terms of standard deviation and Table 19 is in terms of variance. The two methods of presentation are used for the convenience of both engineers and statisticians who may wish to undertake further analysis of these data. Past experience has shown that some engineers have a better understanding of standard deviation, whereas the statistician and others prefer the use of variance as a measure of variability.

The tables are set up to show the changes in variability of the percentages passing the various sieves as the base course aggregate passes from point to point during the process of construction of the test sections.

Slightly more variability was found in the test section samples for both hard and soft stone than was found in the samples taken before the aggregate was spread on the road. The spreading process has caused a slight increase in segregation. It also appears that the variability in section 1 was further increased to a slight degree because of the compaction procedure employed (a combination of rubber-tired and vibrating steel-wheel rolling).

Segregation Index

The data given in Table 20 are not directly related to the degradation study, but are included to show the relative amount of segregation of the base material at the sampling points in the process stream. These data are shown in terms of the segregation index, *S*, which is the ratio of the overall variance, σ^2_o, to the within-batch variance, σ^2_b. The Gresham's Lake aggregate (soft stone) indicated somewhat higher *S* values in test sections 1 and 3. Otherwise, the values remained reasonably constant from point to point for both the hard and the soft aggregate. The fact that the larger sieve sizes showed higher *S* values indicates that the larger particles were most affected by the spreading and compaction procedures. Data for the Hudson $\bar{A}$ values are shown in Figure 73.

The significance of the relative difference in *S* values is not clear with respect to degradation. For example, *S* for the soft stone in section 1 is 5.7, but is only 2.3 for section 2. The higher value is due to a low within-batch variance of Hudson $\bar{A}$ in section 1, as the overall variance, σ^2_o, for $\bar{A}$ in each case is nearly the same. There was no visible difference between the two sections, nor do the average gradations indicate any substantial differences.

The segregation index values based on $\bar{A}$ probably have the most usefulness because they include the effects from all the different sieve sizes.

Degree of Variation

As was the case in presenting the segregation index data, the values of the relative degree of variation given in Table 21 are not directly related to the degradation studies, but are included to show differences in the base mixture with respect to segregation. These values are a measure of the actual overall variation compared with the maximum theoretical variation. There is some evidence of increased segregation after the aggregate was processed through the pug mill and after spreading and compaction. It will be noted that the highest D of V is found in test section 1, where the aggregate was spread by a box spreader

TABLE 14

ANALYSIS OF VARIANCE FOR MINUS NO. 200, TEST SECTIONS DEGRADATION STUDY, METHOD OF EXTRACTING SINGLE df CONTRASTS

SOURCE (1) SPREADER (2) COMPACTOR (3)	SOURCE G VS D	1 VS 2	1 & 2 VS 3	SOURCE × 1 VS 2	SOURCE × 1 & 2 VS 3	ROAD VS PUG MILL	SOURCE × ROAD VS PUG MILL	BELT VS ALL	SOURCE × BELT VS ALL	AVERAGE CHARACTER-ISTIC	TOTAL
1 G Box 1 (VR)	1	1	1	1	1	2	2	2	2	4.19	209.5
2 G Box 2 (S)	1	−1	1	−1	1	2	2	2	2	3.86	193.0
3 G Bl 3 (RSR)	1	0	−2	0	−2	2	2	2	2	4.05	202.5
4 D Box 1 (VR)	−1	1	1	−1	−1	2	−2	2	−2	4.85	242.5
5 D Box 2 (S)	−1	−1	1	1	−1	2	−2	2	−2	5.06	253.0
6 D Bl 3 (RSR)	−1	0	−2	0	2	2	−2	2	−2	5.21	260.5
7 D Belt	−1	0	0	0	0	0	0	−5	5	3.41	341.0
8 G Belt	1	0	0	0	0	0	0	−5	−5	3.47	347.0
9 D Pug	−1	0	0	0	0	−3	3	2	−2	5.06	506.0
10 G Pug	1	0	0	0	0	−3	−3	2	2	3.85	385.0
Totals	266.0	6.0	28.0	27.0	23.0	49.0	61.0	106.40	574.0		
(Totals)^2	70,756	36	784	729	529	2,401	3,721	1,132,096	329,476		
Divisor	700	200	600	200	600	3,000	3,000	7,000	7,000		
Sum of squares	101.08	0.18	1.31	3.65	0.88	0.80	1.24	161.73	47.07		

G = Gresham's Lake (soft) stone; D = Durham (hard) stone.

TABLE 15

ANALYSIS OF VARIANCE FOR MINUS NO. 200, TEST SECTIONS DEGRADATION STUDY, METHOD OF EXTRACTING SINGLE df CONTRASTS

SOURCE (1) SPREADER (2) COMPACTOR (3)	SOURCE G VS D	1 VS 2	1 & 2 VS 3	SOURCE × 1 VS 2	SOURCE × 1 & 2 VS 3	BELT VS PUG MILL	BELT VS AFTER COMPACTION	BELT VS PUG MILL	BELT VS AFTER × SOURCE	AVERAGE CHARACTER-ISTIC	TOTAL
1 G Box 1 (VR)	−1	1	1	−1	−1	0	4	0	−4	4.19	209.5
2 G Box 2 (S)	−1	−1	1	1	−1	0	4	0	−4	3.86	193.0
3 G Bl 3 (RSR)	−1	0	−2	0	2	0	4	0	−4	4.05	202.5
4 D Box 1 (VR)	1	1	1	1	1	0	4	0	4	4.85	242.5
5 D Box 2 (S)	1	−1	1	−1	1	0	4	0	4	5.06	253.0
6 D Bl 3 (RSR)	1	0	−2	0	−2	0	4	0	4	5.21	260.5
7 D Belt	1	0	0	0	0	−1	0	−1	0	3.41	341.0
8 G Belt	−1	0	0	0	0	−1	0	1	0	3.47	347.0
9 D Pug	1	0	0	0	0	1	−6	1	−6	5.06	506.0
10 G Pug	−1	0	0	0	0	1	−6	−1	6	3.85	385.0
Totals	266.0	6.0	28.0	27.0	23.0	203.0	98.0	127.0	122.0		
(Totals)^2	70,756	36	784	729	529	41,209	9,604	16,129	14,884		
Divisor	700	200	600	200	600	400	12,000	400	12,000		
Sum of squares	101.08	0.18	1.31	3.65	0.88	103.02	0.80	40.32	1.24		

G = Gresham's Lake (soft) stone; D = Durham (hard) stone.

TABLE 16

ANALYSIS OF VARIANCE FOR HUDSON $\bar{A}$, TEST SECTIONS DEGRADATION STUDY, METHOD OF EXTRACTING SINGLE df CONTRASTS

	SOURCE (1) SPREADER (2) COMPACTOR (3)	SOURCE G VS D	1 VS 2	1 & 2 VS 3	SOURCE × 1 VS 2	SOURCE × 1 & 2 VS 3	BELT VS PUG MILL	BELT VS AFTER COMPACTION	BELT VS PUG MILL	BELT VS AFTER × SOURCE	AVERAGE CHARACTER-ISTIC	TOTAL
1	G Box 1 (VR)	−1	1	1	−1	−1	0	4	0	−4	3.629	181.45
2	G Box 2 (S)	−1	−1	1	1	−1	0	4	0	−4	3.535	176.75
3	G Bl 3 (RSR)	−1	0	−2	0	2	0	4	0	−4	3.678	183.90
4	D Box 1 (VR)	1	1	1	1	1	0	4	0	4	3.998	199.90
5	D Box 2 (S)	1	−1	1	−1	1	0	4	0	4	4.038	201.90
6	D Bl 3 (RSR)	1	0	−2	0	−2	0	4	0	4	4.053	202.65
7	D Belt	1	0	0	0	0	−1	0	−1	0	3.933	393.30
8	G Belt	−1	0	0	0	0	−1	0	1	0	3.472	347.20
9	D Pug	1	0	0	0	0	1	−6	1	−6	3.983	398.30
10	G Pug	−1	0	0	0	0	1	−6	−1	6	3.609	360.90
Totals		145.85	2.70	13.10	6.70	6.10	18.70	31.00	8.70	1.10		
(Totals)²		21,272.2225	7.2900	171.6100	44.8900	37.2100	349.6900	961.0000	75.6900	1.2100		
Divisor		700	200	600	200	600	400	12,000	400	12,000		
Sum of squares		30.3888	0.0365	0.2860	0.2245	0.0620	0.8742	0.0801	0.1892	0.0001		

G = Gresham's Lake (soft) stone; D = Durham (hard) stone.

TABLE 17

ANALYSIS OF VARIANCE FOR HUDSON $\bar{A}$, TEST SECTIONS DEGRADATION STUDY, METHOD OF EXTRACTING SINGLE df CONTRASTS

	SOURCE (1) SPREADER (2) COMPACTOR (3)	SOURCE G VS D	1 VS 2	1 & 2 VS 3	SOURCE × 1 VS 2	SOURCE × 1 & 2 VS 3	ROAD VS PUG MILL	SOURCE × ROAD VS PUG MILL	BELT VS ALL	SOURCE × BELT VS ALL	AVERAGE CHARACTER-ISTIC	TOTAL
1	G Box 1 (VR)	1	1	1	1	1	2	2	2	2	3.629	181.45
2	G Box 2 (S)	1	−1	1	−1	1	2	2	2	2	3.535	176.75
3	G Bl 3 (RSR)	1	0	−2	0	−2	2	2	2	2	3.678	183.90
4	D Box 1 (VR)	−1	1	1	−1	−1	2	−2	2	−2	3.998	199.90
5	D Box 2 (S)	−1	−1	1	1	−1	2	−2	2	−2	4.038	201.90
6	D Bl 3 (RSR)	−1	0	−2	0	2	2	−2	2	−2	4.053	202.65
7	D Belt	−1	0	0	0	0	0	0	−5	5	3.933	393.30
8	G Belt	1	0	0	0	0	0	0	−5	−5	3.472	347.20
9	D Pug	−1	0	0	0	0	−3	3	2	−2	3.983	398.30
10	G Pug	1	0	0	0	0	−3	−3	2	2	3.609	360.90
Totals		145.85	2.70	13.10	6.70	6.10	15.50	12.50	109.00	31.00		
(Totals)²		21,272.2225	7.2900	171.6100	44.8900	37.2100	240.2500	156.2500	11,881.0000	961.0000		
Divisor		700	200	600	200	600	3,000	3,000	7,000	7,000		
Sum of squares		30.3888	0.0365	0.2860	0.2245	0.0620	0.0801	0.0521	1.6973	0.1373		

G = Gresham's Lake (soft) stone; D = Durham (hard) stone.

TABLE 18

STANDARD DEVIATIONS FOR DEGRADATION AGGREGATES

SIEVE SIZE	DURHAM QUARRY AGGREGATE (HARD STONE) BELT	PUG MILL	TEST SECT. 1	TEST SECT. 2	TEST SECT. 3	GRESHAM'S LAKE AGGREGATE (SOFT STONE) BELT	PUG MILL	TEST SECT. 1	TEST SECT. 2	TEST SECT. 3
¾ In.	3.0	3.1	5.6	4.5	4.1	3.9	3.0	5.3	4.6	4.7
⅜ In.	3.5	3.4	6.3	5.4	4.4	4.8	3.5	6.1	5.8	5.8
No. 4	3.0	2.9	5.2	4.3	3.4	3.8	2.9	4.7	4.5	4.7
No. 8	2.6	2.5	4.1	3.3	2.7	3.1	2.4	3.8	3.7	3.8
No. 16	2.0	2.0	3.3	2.7	2.2	2.4	1.8	3.0	2.9	2.8
No. 30	1.5	1.8	2.4	2.1	1.7	1.9	1.4	2.5	2.3	2.2
No. 50	1.0	1.6	1.6	1.5	1.3	1.3	0.9	1.8	1.6	1.5
No. 100	0.6	1.2	1.1	1.0	0.9	0.8	0.5	1.1	1.0	0.9
No. 200	0.4	0.8	0.7	0.6	0.5	0.4	0.3	0.6	0.6	0.5
$\bar{A}$	0.17	0.17	0.29	0.24	0.20	0.22	0.16	0.28	0.26	0.26

TABLE 19

VARIANCES FOR DEGRADATION AGGREGATES

SIEVE SIZE	DURHAM QUARRY AGGREGATE (HARD STONE) BELT	PUG MILL	TEST SECT. 1	TEST SECT. 2	TEST SECT. 3	GRESHAM'S LAKE AGGREGATE (SOFT STONE) BELT	PUG MILL	TEST SECT. 1	TEST SECT. 2	TEST SECT. 3
¾ In.	9.10	9.78	30.85	19.76	16.84	15.46	8.88	28.55	21.34	21.96
⅜ In.	12.47	11.78	39.38	29.40	19.63	23.37	12.27	37.65	33.90	33.87
No. 4	9.18	8.52	27.25	18.37	11.82	14.67	8.26	22.22	20.11	22.34
No. 8	6.50	5.99	16.90	10.58	7.19	9.60	5.70	14.05	13.91	14.46
No. 16	3.89	3.83	10.68	7.01	4.70	5.88	3.27	9.24	8.37	7.91
No. 30	2.21	3.13	5.68	4.40	3.02	3.69	2.02	6.17	5.28	4.81
No. 50	0.95	2.59	2.68	2.15	1.60	1.65	0.87	3.12	2.43	2.20
No. 100	0.40	1.43	1.24	0.92	0.78	0.59	0.29	1.27	0.95	0.81
No. 200	0.13	0.56	0.53	0.37	0.36	0.17	0.08	0.40	0.31	0.24
$\bar{A}$	0.029	0.167	0.288	0.240	0.198	0.049	0.161	0.284	0.264	0.264

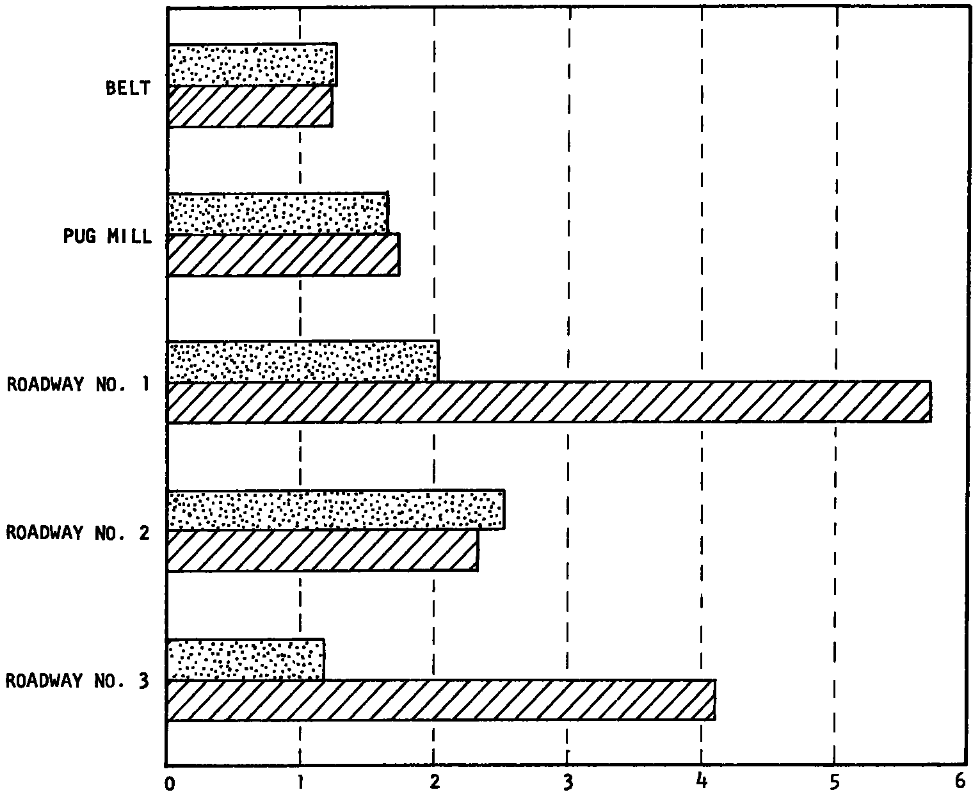
TABLE 20

SEGREGATION INDEX AT VARIOUS SAMPLING POINTS, DEGRADATION STUDY

SIEVE SIZE	SEGREGATION INDEX, σ^2_o/σ^2_b BELT HARD [a]	BELT SOFT [b]	PUG MILL HARD [a]	PUG MILL SOFT [b]	ROADWAY 1 HARD [a]	ROADWAY 1 SOFT [b]	ROADWAY 2 HARD [a]	ROADWAY 2 SOFT [b]	ROADWAY 3 HARD [a]	ROADWAY 3 SOFT [b]
$\bar{A}$	1.26	1.23	1.65	1.73	2.02	5.71	2.52	2.33	1.18	4.12
¾ In.	1.4	1.1	1.3	2.2	2.2	2.1	2.8	2.0	1.0	2.8
⅜ In.	1.2	1.2	1.6	1.9	2.1	5.4	2.8	2.5	1.1	4.7
No. 4	1.2	1.3	1.7	1.6	2.0	5.3	2.7	2.4	1.1	4.7
No. 8	1.2	1.3	1.7	1.5	2.1	5.4	2.3	2.3	1.4	4.7
No. 16	1.2	1.3	1.6	1.5	1.9	5.6	2.1	2.2	1.4	4.2
No. 30	1.1	1.3	2.1	1.5	1.9	5.9	2.1	2.2	1.7	3.9
No. 50	1.2	1.2	3.3	1.5	1.9	6.0	2.1	2.1	2.0	3.7
No. 100	1.7	1.3	4.0	1.4	2.1	6.3	2.1	2.1	2.6	3.5
No. 200	2.2	1.4	4.3	1.3	2.4	5.7	2.3	2.2	3.6	3.4

[a] Hard stone, Durham quarry aggregate

[b] Soft stone, Gresham's Lake quarry aggregate



	DURHAM (Hard Stone)	GRESHAM'S (Soft Stone)
BELT	1.26	1.23
PUG MILL	1.65	1.73
ROADWAY NO. 1	2.02	5.71
ROADWAY NO. 2	2.52	2.33
ROADWAY NO. 3	1.18	4.12

Figure 73. Segregation index based on $\bar{A}$, for degradation studies.

TABLE 21

DEGREE OF VARIATION, DEGRADATION STUDIES

SIEVE SIZE	DURHAM QUARRY AGGREGATE (HARD STONE)					GRESHAM'S LAKE AGGREGATE (SOFT STONE)				
	BELT	PUG MILL	TEST SECT. 1	TEST SECT. 2	TEST SECT. 3	BELT	PUG MILL	TEST SECT. 1	TEST SECT. 2	TEST SECT. 3
¾ In.	0.5	0.6	1.9	1.2	1.1	0.9	0.5	1.7	1.2	1.4
⅜ In.	0.5	0.5	1.6	1.2	0.8	0.9	0.5	1.5	1.4	1.4
No. 4	0.4	0.3	1.1	0.7	0.5	0.7	0.4	1.0	0.9	1.0
No. 8	0.3	0.3	0.7	0.5	0.3	0.5	0.3	0.7	0.7	0.7
No. 16	0.2	0.2	0.5	0.3	0.2	0.3	0.2	0.5	0.5	0.4
No. 30	0.1	0.2	0.3	0.3	0.2	0.3	0.1	0.4	0.4	0.3
No. 50	0.1	0.2	0.2	0.2	0.1	0.2	0.1	0.3	0.2	0.2
No. 100	0.1	0.2	0.2	0.1	0.1	0.1	0.04	0.2	0.2	0.1
No. 200	0.05	0.1	0.1	0.1	0.1	0.1	0.02	0.1	0.1	0.1

and compacted with both a rubber-tired and a vibrating steel-wheel roller. For ease of comparison, D of V for the ¾-in. size is presented graphically in Figure 74.

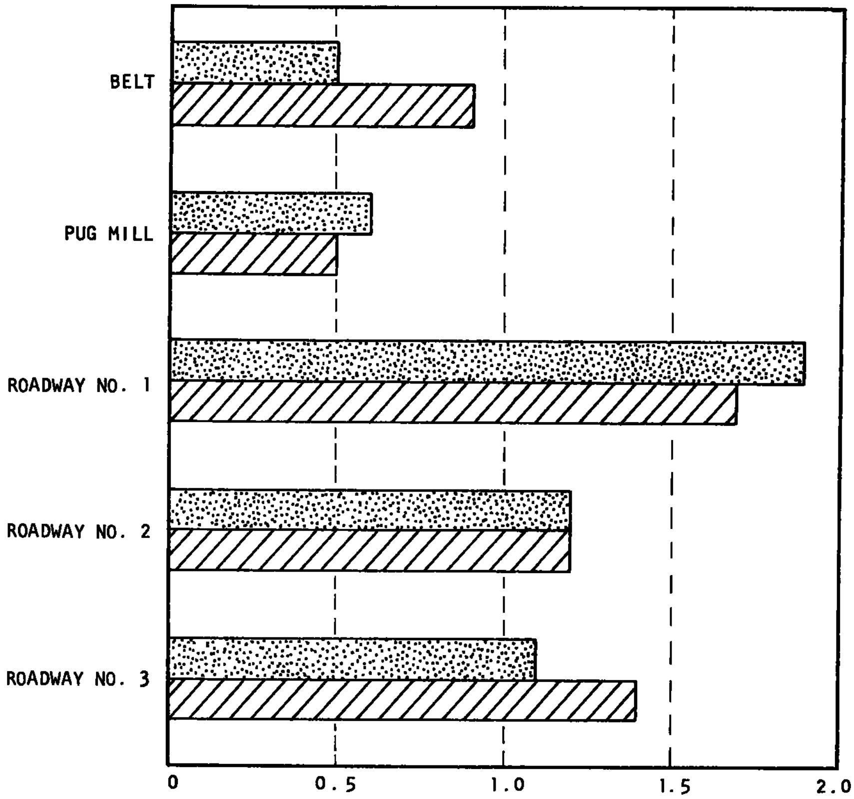
Summary Table

Table 22 is a summary of pertinent statistics from the degradation studies and permits comparisons among these various parameters. The basic data given in this table were used to calculate segregation index and degree of variation as presented in the two preceding sections of this chapter. This assembly of data provides an opportunity to compare easily the change in gradation and measures of variability from point to point as the aggregate goes through the various construction steps. One segment of data not included elsewhere is the average weight, $\overline{W}$, of the sample increment taken at each location.

It can be seen that the average level, $\overline{X}$, of each sieve size remains fairly constant from point to point, which means that there is no degradation of any consequence.

Interpretation of Degradation Data

It will be noted that there is little progressive breakdown of the aggregate, as commonly assumed, from point to point in the process of base construction. In the light of prior assumption, the minimal degradation shown by the test results may be surprising to many engineers. Admittedly, substantially more degradation would have occurred



	DURHAM (Hard Stone)	GRESHAM'S (Soft Stone)
BELT	0.5	0.9
PUG MILL	0.6	0.5
ROADWAY NO. 1	1.9	1.7
ROADWAY NO. 2	1.2	1.2
ROADWAY NO. 3	1.1	1.4

Figure 74. Degree of variation, based on ¾-in. values, for degradation studies.

TABLE 22

SUMMARY OF STATISTICAL DATA, DEGRADATION STUDY

SIEVE SIZE	PARAMETER	BELT HARD [a]	BELT SOFT [b]	PUG MILL HARD [a]	PUG MILL SOFT [b]	ROADWAY 1 HARD [a]	ROADWAY 1 SOFT [b]	ROADWAY 2 HARD [a]	ROADWAY 2 SOFT [b]	ROADWAY 3 HARD [a]	ROADWAY 3 SOFT [b]
	n *	100	100	100	100	50	50	50	50	50	50
	$\bar{W}$ **	29.0	34.5	30.0	32.0	23.3	26.4	26.8	29.6	22.7	24.1
$\bar{A}$	$\bar{A}$	3.93	3.47	3.98	3.61	4.00	3.63	4.04	3.54	4.05	3.68
	σ^2_o	0.029	0.049	0.028	0.026	0.083	0.080	0.058	0.070	0.039	0.070
	σ_o	0.17	0.22	0.17	0.16	0.29	0.28	0.24	0.26	0.20	0.26
	σ^2_b	0.023	0.040	0.017	0.015	0.041	0.014	0.023	0.030	0.033	0.017
	σ_b	0.15	0.20	0.13	0.12	0.20	0.12	0.15	0.17	0.18	0.13
¾ In.	$\bar{X}$	78.2	76.5	78.5	78.0	79.3	78.7	79.8	77.8	80.0	79.8
	σ^2_o	9.10	15.46	9.78	8.88	30.85	28.55	19.76	21.34	16.84	21.96
	σ_o	3.0	3.9	3.1	3.0	5.6	5.3	4.5	4.6	4.1	4.7
	σ^2_b	6.57	13.59	7.35	4.05	14.75	7.22	7.05	10.95	17.69	7.82
	σ_b	2.6	3.7	2.7	2.0	3.8	2.7	2.7	3.3	4.2	2.8
⅜ In.	$\bar{X}$	57.4	46.5	58.0	49.2	58.6	49.2	59.1	47.1	59.9	50.7
	σ^2_o	12.47	23.37	11.78	12.25	39.38	37.65	29.40	33.90	19.63	33.87
	σ_o	3.5	4.8	3.4	3.5	6.3	6.1	5.4	5.8	4.4	5.8
	σ^2_b	10.02	18.82	7.39	6.36	18.68	6.94	10.58	13.72	18.41	7.27
	σ_b	3.2	4.3	2.7	2.5	4.3	2.6	3.3	3.7	4.3	2.7
No. 4	$\bar{X}$	44.7	34.2	45.4	36.7	45.8	36.4	46.3	34.8	47.2	27.8
	σ^2_o	9.18	14.67	8.52	8.26	27.25	22.22	18.37	20.11	11.82	22.34
	σ_o	3.0	3.8	2.9	2.9	5.2	4.7	4.3	4.5	3.4	4.7
	σ^2_b	7.70	11.70	5.03	5.03	13.71	4.19	6.81	8.38	10.32	4.71
	σ_b	2.8	3.4	2.2	2.2	3.7	2.1	2.6	2.9	3.2	2.2
No. 8	$\bar{X}$	37.3	28.2	37.0	30.3	37.5	30.0	37.6	28.7	37.9	31.0
	σ^2_o	6.50	9.60	5.99	5.70	16.90	14.05	10.58	13.91	7.19	14.46
	σ_o	2.6	3.1	2.5	2.4	4.1	3.8	3.3	3.7	2.7	3.8
	σ^2_b	5.48	7.23	3.60	3.71	8.08	2.59	4.55	5.98	5.25	3.05
	σ_b	2.3	2.7	1.9	1.9	2.8	1.6	2.1	2.4	2.3	1.7
No. 16	$\bar{X}$	29.2	22.2	29.4	23.9	29.8	23.9	29.9	22.9	29.9	24.2
	σ^2_o	3.89	5.88	3.83	3.27	10.68	9.24	7.01	8.37	4.70	7.91
	σ_o	2.0	2.4	2.0	1.8	3.3	3.0	2.7	2.9	2.2	2.8
	σ^2_b	3.37	4.60	2.40	2.19	5.59	1.64	3.28	3.82	3.34	1.89
	σ_b	1.8	2.1	1.6	1.5	2.4	1.3	1.8	2.0	1.8	1.4
No. 30	$\bar{X}$	22.2	17.6	21.7	18.9	21.5	19.3	22.2	18.4	21.8	19.3
	σ^2_o	2.21	3.69	3.13	2.02	5.68	6.17	4.40	5.28	3.02	4.81
	σ_o	1.5	1.9	1.8	1.4	2.4	2.5	2.1	2.3	1.7	2.2
	σ^2_b	1.98	2.92	1.46	1.34	3.02	1.04	2.15	2.44	1.76	1.25
	σ_b	1.4	1.7	1.2	1.2	1.7	1.0	1.5	1.6	1.3	1.1
No. 50	$\bar{X}$	13.7	11.7	14.4	12.7	13.9	13.2	14.8	12.5	14.4	13.1
	σ^2_o	0.95	1.65	2.59	0.87	2.68	3.12	2.15	2.43	1.60	2.20
	σ_o	1.0	1.3	1.6	0.9	1.6	1.8	1.5	1.6	1.3	1.5
	σ^2_b	0.77	1.35	0.78	0.59	1.38	0.52	1.02	1.14	0.79	0.60
	σ_b	0.9	1.2	0.9	0.8	1.2	0.7	1.0	1.1	0.9	0.8
No. 100	$\bar{X}$	7.2	6.9	9.0	7.4	8.6	8.0	9.1	7.5	9.0	7.9
	σ^2_o	0.40	0.59	1.43	0.29	1.24	1.27	0.92	0.95	0.78	0.81
	σ_o	0.6	0.8	1.2	0.5	1.1	1.1	1.0	1.0	0.9	0.9
	σ^2_b	0.23	0.47	0.36	0.21	0.60	0.20	0.43	0.45	0.30	0.23
	σ_b	0.5	0.7	0.6	0.5	0.8	0.5	0.7	0.7	0.6	0.5
No. 200	$\bar{X}$	3.4	3.5	5.1	3.9	4.9	4.2	5.1	3.9	5.2	4.1
	σ^2_o	0.13	0.17	0.56	0.08	0.53	0.40	0.37	0.31	0.36	0.24
	σ_o	0.4	0.4	0.8	0.3	0.7	0.6	0.6	0.6	0.6	0.5
	σ^2_b	0.06	0.12	0.13	0.06	0.22	0.07	0.16	0.14	0.10	0.07
	σ_b	0.2	0.4	0.4	0.2	0.5	0.3	0.4	0.4	0.3	0.3

[a] Hard stone, Durham quarry aggregate.
[b] Soft stone, Gresham's Lake quarry aggregate

* Number of test portions
** Average weight of test portions (lbs)

had an aggregate been used containing a relatively small quantity of minus No. 8 material so that there was point contact among the larger aggregate particles. The objective here, however, was to use a well-designed base course material representative of good construction, rather than create a condition that would have artificially resulted in excessive degradation. Thus, North Carolina No. 8 base course aggregate, a commonly used material with a good performance record, was selected.

Although the stockpiling studies reported in the preceding section did not specifically include degradation effects, it was observed that the coarser fractions of the Gresham's Lake stone (1½ in.-⅜ in.) showed a reduction in size when the aggregate was drawn from the parent pile and used to construct the single-cone pile. For instance, the 1-in. portion showed an increase of about 10% (from 62.8 to 72.5) passing this sieve. This was apparently due to breaking off some of the fragile edges during initial handling and the aggregate later reached a fairly constant gradation.

The design of the base mixture was based on the theory that the gradation of the fractions of aggregate larger than the No. 4 sieve in base courses of this type should closely approximate the maximum density curve. However, the aggregate fraction passing the No. 4 sieve should be open-graded. To minimize degradation, it is important that large spaces between the particles in the coarse fraction be filled completely with the fine fraction. The reported percent density of each test section (based on one field test) confirmed the engineer's judgment as to when the maximum practicable density had been reached. The grading of the aggregate used in these tests closely approaches a maximum density curve, as was previously shown in Figures 60 and 61.

Nijboer (*70*) reports that a German investigator, Herrmann, has stated that the crushing of aggregate under traffic is dependent on the grading. He describes a maximum density grading that is subject to very little crushing under high stresses as "kornstabil," which term might be translated as "grainstable." This point seems to be of special interest when a stone of dubious quality is to be incorporated in a roadbed, because the crushing of the larger particles of aggregate could produce a grading which would not meet the requirements previously stated, thus leading to instability of the mixture.

In the case of the degradation data, the aggregate gradation charts (Figs. 62-71) are perhaps the most useful indicator of changes in gradation from point to point in the production stream. It can be seen that some slight amount of breakdown occurred as the aggregate passed from the parent pile through the pug mill and finally into the test sections. This degradation was not as great as had been anticipated and is, in fact, so small that it probably could not be detected by routine sampling or through any change of performance characteristics. A quick review shows that the change in percentage of minus No. 200 material in each case was as shown in Figure 75. Thus, it is seen that the hard stone actually had a greater increase in minus No. 200 material than did the soft stone.

Examination of the variability of test data for section 1, in the case of both the hard and soft aggregate, shows more variation in all sieve sizes than at any other point studied. This is apparently due to the vibrating or rubber-tired roller, or both, rearranging some of the aggregate particles. In any event, the variability is still not considered excessive.

The degree of variation and the segregation index are new terms for evaluation of variations in gradation. At this stage, no firm guidelines can be given for the interpretation and application of these values to the data. Rather, they must be used on a relative basis to rate one method against another. As additional experience is gained it may be possible to establish ratings of excellent, good, fair, poor, and unacceptable for both S and D of V.

In conclusion, Figure 72, showing 95% confidence

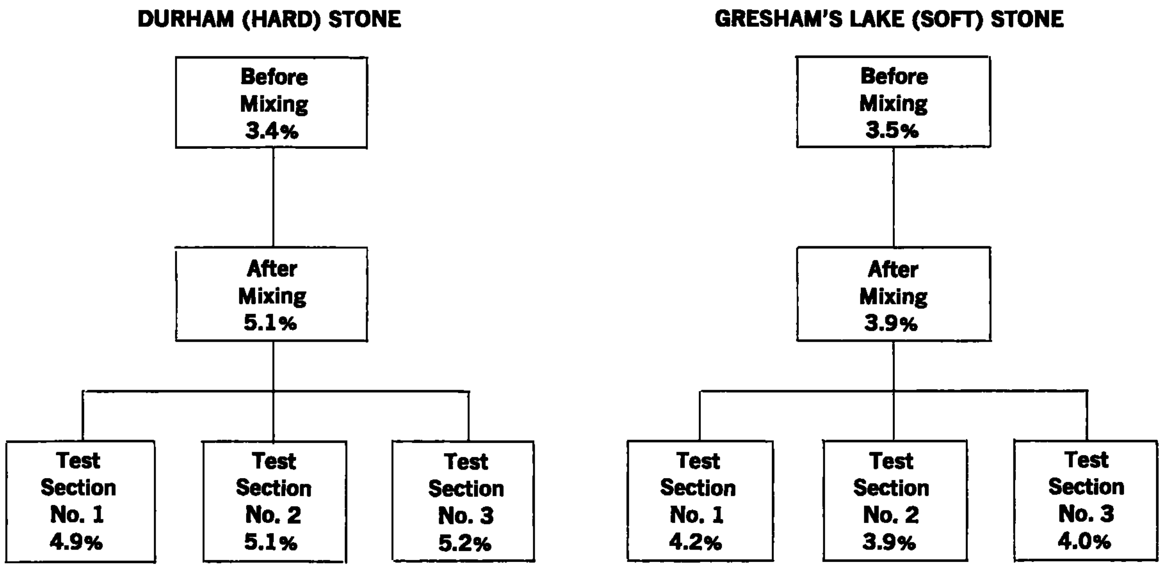


Figure 75. Change in percentage of minus No. 200 material in each aggregate of gradation studies.

limits, reveals that a single line drawn vertically through a common point on the chart for each individual sieve size and for $\bar{A}$ would intersect the confidence band for that size in every location sampled and tested. This means that a single percentage figure for the amount passing a given sieve would satisfy all locations. Therefore, none of the variations detected would have any significance from a practical point of view.

Results of these tests did not produce the degree of degradation that might have been anticipated, but they have served to show that, with a properly graded base material and carefully controlled construction practices, degradation should not present a major problem, even with an aggregate having a relatively large Los Angeles abrasion loss. Additional studies using an aggregate with a less dense gradation are needed to further evaluate degradation effects.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This chapter presents conclusions and recommendations on the results of different methods of stockpiling and handling as they affect the properties of aggregates and suggests procedures for minimizing the undesirable effects.

CONCLUSIONS

Segregation

Conclusions on relative segregation of aggregates are based on the construction of six full-scale stockpiles by three commonly used procedures (cone, cast-and-spread, and truck-dumped methods) using a crushed stone (1½-⅜ in.), and an uncrushed gravel (1 in.-No. 4). Test results from these stockpiles are combined with results obtained in the initial work involving the construction of eleven stockpiles. The continuation studies have confirmed and amplified the conclusions given in the interim report on the earlier Princeton quarry stockpiling investigation, as follows:

1. The largest amount of segregation was found in all types of coned or tent-shaped piles, regardless of aggregate type or gradation. The variation of gradation in this type of stockpile was of such magnitude as to increase the probability of having to readjust the bitumen content or the concrete mix proportions from batch to batch.

2. These studies have confirmed the common belief that, due to the particle shape of the uncrushed gravel, there is a much greater tendency for the larger aggregate particles to migrate down the face of a cone pile than was found in either of the crushed stone gradations. This is evident from examination of the data and was also noticeably visible during construction of the stockpile.

3. Both gradation and particle shape have an influence on the angle of repose of coned stockpiles. Similar piles constructed at each location produced the following results:

Aggregate	Angle of Repose (°)
1 in.-No. 4 crushed stone	34
1½ in.-⅜ in. crushed stone	35
1 in.-No. 4 uncrushed gravel	30

4. In all cases, segregation was minimized when an aggregate stockpile was formed by spreading the material in thin layers. This can be accomplished by casting with a clamshell bucket or, in the case of an aggregate not subject to degradation, by spreading with a rubber-tired bulldozer.

5. A segregated stockpile can be corrected using ordinary equipment and appropriate handling procedures.

6. The overall variance, σ^2_o, can be broken down into several component parts, which may include actual or inherent variance, σ^2_a, testing variance, σ^2_t, and sampling variance, σ^2_s. In addition, the between-batch variance, σ^2_l, and within-batch variance, σ^2_b, can be determined. Establishing the magnitude of these values leads to a greater insight and better understanding of the causes of variability as they apply to aggregates and permits corrective action to be applied at the place where it can be most effective.

7. The segregation index concept developed in the initial study has again proved to be a valuable research tool for indicating the pattern of segregation and can be tested for statistical significance by the use of the F table, which is found in statistical texts. The S value is found by comparing the overall variance (σ^2_o) of a gradation measurement with the within-batch variance (σ^2_b) of the same measurement. The within-batch variance is the sum of the inherent variance of the gradation (σ^2_a), the testing error (σ^2_t), and the sampling error (σ^2_s). In this work, these values, based on Hudson $\bar{A}$, range from a low of about 1 for the Princeton quarry parent pile to a high of about

41 for the Gresham's Lake coned pile. This is a relative scale for comparing one method with another and no absolute limits for evaluation have as yet been established.

8. The degree of variation is a new research parameter for expressing the actual variation as a percentage of the maximum possible variation. It is defined as

$$\frac{\sigma^2_o}{\sigma^2_{max}} \times 100 \qquad (6)$$

in which

σ^2_o = overall variance;
$\sigma^2_{max} = P\,(100\text{-}P)$; and
P = total percent passing a specific sieve.

It is particularly useful for comparing amounts of segregation among sieve sizes at different percentage levels. Values found in this study ranged from less than 1 in several instances to about 16 for the coned, rounded gravel stockpile.

9. The relative coarseness of an aggregate gradation can be expressed by Hudson $\bar{A}$, which is a single number reflecting the amount of material passing the ten standard sieves from 1½ in. through No. 200. This value is related to the surface area of the aggregate and is sufficiently sensitive to reflect changing requirements for mix proportions or asphalt content as the aggregate grading varies. In these studies, $\bar{A}$ values ranged from a low of 1.2 to a high of 2.7.

10. Further cost studies have confirmed that the most economical and acceptable method of forming and reclaiming stockpiles from aggregate delivered in trucks is to discharge the loads in such a way that they are tightly joined, and to reclaim the aggregate with a front-end loader. Subsequent studies have indicated stockpiling costs as low as $0.38 per ton for this method of construction. When the aggregate is not delivered in trucks, the least expensive acceptable results are obtained by forming the stockpile in layers with a clambucket and reclaiming the aggregate with a front-end loader.

11. In general, the results of these studies indicate that a large number of samples must be taken and individually tested to find the average value and limits of variation of gradation measurements with an acceptable degree of accuracy. Under good conditions ($\sigma_o = 4\%$), the percentage of an aggregate passing a ¾-in. sieve can be determined with an accuracy of about ± 4.5% and a degree of assurance of 95% by averaging the results of tests on five test portions of not less than 30 lb each.

12. If circumstances necessitate the construction of a coned pile, gradation variations can be minimized when the pile is reclaimed if the aggregate is loaded by continually moving around the circumference of the pile rather than starting on one side and working straight through.

13. A mathematical model can be used to predict the relative effect of each stockpiling variable on total segregation. This model is expressed by

$$\sigma_{predicted} = m + p + g + s + e \qquad (7)$$

in which

m = adjusted mean of standard deviation;
p = effect from stockpiling method;
g = effect from gradation;
s = effect from aggregate type; and
e = error from unidentified sources.

It is now possible to assign a numerical coefficient to each of the variables which affect segregation and in turn predict the approximate standard deviation which would result. This study has shown the variables to have a relative effect on segregation as follows, with the major contributing factor listed first and other factors listed in descending order: Cone method of construction; uncrushed gravel aggregate; crushed stone; truck-dumped method; and cast-and-spread method. The first three items tend to cause an increase in segregation; the last two tend to decrease segregation.

Degradation

The following conclusions are based on results of gradation tests made on samples from two aggregate base mixtures taken at various process points during construction of six test sections. Three compaction methods and two spreading methods were used to construct three test sections using a hard aggregate, and three equivalent sections using a soft aggregate. Although both materials meet North Carolina standard specifications for stabilized aggregate base course, they were selected for this study as relatively hard and soft aggregates on the basis of Los Angeles abrasion loss and specific gravity.

1. None of the construction procedures investigated with either the hard or the soft aggregate produced degradation (increase in minus No. 200) that could be considered injurious to the performance of the base in light of current knowledge.

2. The amount of degradation indicated by the precise sampling and testing procedures was substantially less with both the hard and soft aggregate than is customarily assumed, based on currently available information, when well-graded aggregate is employed.

3. It is possible that degradation was minimized by the use of an aggregate gradation which provided a cushion of fines around the coarse particles. This gradation approximates the maximum density curve and base mixtures of this design are widely and successfully used in North Carolina. This suggests that, with a properly designed mixture, a soft aggregate may be used for aggregate base construction without excessive degradation.

4. The Los Angeles abrasion test results of the hard and soft stone did not correlate with the amount of degradation measured.

5. The number of test portions secured from each sampling point (raw, mixed, compacted) provided sufficient accuracy to detect minute differences that are statistically significant but have no practical importance.

6. On the basis of the experimental data from the test sections, a minimum of five test portions would be required to assure a degree of accuracy of ± 1.0% of minus No. 200. Action decisions based on results of one or two tests would contain an extremely high element of risk (i.e., probability) of making the wrong decision.

7. The measured differences in degradation produced by

the variables (compaction and spreading) within a test section for either hard or soft stone were too small to be of practical importance, although there were statistically significant differences indicated.

8. A special method of extracting single degree of freedom contrasts provides an extremely sensitive means for measuring the significance of minute gradation changes and can be effectively used in similar type work. This method was used to evaluate the effects of changes in minus No. 200 and Hudson $\bar{A}$.

9. A statistically randomized method of sampling using the hoop method of sample acquisition proved to be an accurate method of obtaining representative test portions from a mechanically stabilized base.

RECOMMENDATIONS FOR FURTHER STUDIES

Analysis of the data indicates that continuing studies in the areas of both segregation and degradation would be beneficial to provide more positive evaluation of the trends developed up to this point.

A rating system for stockpiling efficiency has been devised which appears to be a reliable tool. From this system, a mathematical model has been subsequently developed to estimate the magnitude of the effect of aggregate type, gradation, and method of construction on variations in grading. In terms of a statistical universe, however, the volume of data on hand is relatively small. Consequently, the mathematical model based on these data contains a higher margin of error than is desirable. There is a definite need for additional stockpiling data to be acquired under conditions similar to those reported herein but involving a wider range of aggregate types and gradations. The additional data would be used to construct a more precise mathematical model from which reliable estimates of stockpiling efficiency could be made. The relative magnitude of these coefficients appears to have real meaning in assessing the effects of each variable, as the factors which contribute to segregation can be ranked according to their level. When sufficient data are accumulated, an estimate can be made of the effect of each stockpiling variable on segregation without actually constructing the pile. Such data would be particularly useful in optimizing cost considerations for stockpile construction versus the level of segregation that could be tolerated for a specific construction item.

It appears that as much as $0.20 to $0.25 per ton could be saved in aggregate handling costs by using the more economical truck-dumped method, without sacrificing level of performance in the end product. Additional stockpiling tests are needed to provide proof of the trends indicated in the current studies. On the basis of current work, the data corroborate those specifications which rule out cone methods of construction. Subsequent studies would probably be more fruitful if they included only cast-and-spread, truck-dumped, and tiered (bermed) methods.

Additional degradation data are essential for a better assessment of the effects of mixing, spreading, and compaction variables. Studies in this area should involve aggregates with a higher void content so that comparisons could be made to verify the minimizing effect of the designed gradation used in the initial tests. The methods and design of experiment employed in this report have proved adequate to make such comparisons accurately. Both crushed stone and gravel with varying degrees of hardness should be used in future studies.

It is entirely possible that aggregates currently prohibited from use in base construction because of being too soft may be used without detrimental effect in a properly designed grading. More than one-half of the State highway departments will not permit the use of an aggregate in a bituminous mixture if its Los Angeles abrasion loss exceeds 40%.

Because of the overlapping objectives of these two research areas, it is recommended that additional studies be planned to include both items in a single investigation. Such studies should produce data that would be helpful to aggregate producers, materials and testing engineers, as well as pavement design and construction engineers. These data can be used to minimize variations, which are ultimately reflected in pavement costs, from both a construction and maintenance viewpoint.

APPENDIX A

STATISTICAL CONCEPTS

The statistical concepts used for the analysis of these data have been developed in connection with two NCHRP projects (HR 10-2 and HR 10-3) with overlapping objectives. The material contained in this Appendix is presented in more detail in the HR 10-2 interim report (*NCHRP Report 34*). This is not an attempt to provide a textbook on statistics, but rather to present the fundamental concepts which are essential to an understanding of the methods of data presentation. Chapter Two presents a summary of these parameters and the following provides a more detailed description of their derivation and use.

NORMAL DISTRIBUTION CURVE

STATISTICS is a scientific method that deals with the analyses of averages, and VARIATION around averages, as found in numerical DATA. By the use of proper statistical techniques, certain inferences can be drawn from limited data that would not otherwise be possible. In addition, optimum sampling and testing schedules can be developed that eliminate unnecessary expenditures of money, time, and effort by requiring only the number of tests necessary to evaluate a particular condition. One application of statistics used in this report is the concept of the NORMAL DISTRIBUTION. One of the properties of the NORMAL DISTRIBUTION CURVE is that, regardless of its shape, a definite percentage of the total area beneath the curve is defined by vertical lines spaced a definite number of STANDARD DEVIATION (σ) units from the centerline of the curve which represents the average value, $\bar{X}$, as shown in Figure A-1.

The tails of the normal distribution curve approach the base line at approximately three standard deviation units on each side of the average. It should be noted, however, that about 68.2 percent of all possible test results would fall within $\pm 1\sigma$ limit from the average; 95 percent would fall within $\pm 2\sigma$ limits; and 99.7 percent of the results would fall within $\pm 3\sigma$ limits. Thus, under normal conditions, the number (or percentages) of measurements deviating from the average by any given amount can be predicted. When a very few samples are taken, this curve will often assume a shape other than that of a normal curve. This does not necessarily indicate that the parent distribution, consisting of all possible measurements, is not normally distributed.

In the case illustrated by Figure A-1, SIGMA (σ) = 2.3, so $\pm 3\sigma = \pm 6.9$ and about 100 percent of the values are included in the RANGE 55.1 to 68.9. If these numbers represented the percentage of an aggregate passing a certain sieve and the results of a large number of tests indicated that the standard deviation, σ, of the measurements was in fact 2.3, it could be expected that few future measurements would normally exceed this range. Obviously, if σ was smaller the range would be narrower, while a large value of σ would correspond to a wider range of variation.

Sigma, then, is a means of expressing variation as a numerical value. For convenience, the VARIANCE, σ^2, which is the square of the standard deviation, is used instead of σ as a measure of variability in some parts of this report because variances can be added, whereas standard deviations cannot be directly treated arithmetically.

Accordingly, in this report both the standard deviation and the variance have been selected as the measures of variability. A relatively small value of either of these PARAMETERS indicates that essentially all measurements lie close to the average, while a relatively large value indicates that the measurements deviate from the average over a wider range.

SIGNIFICANCE OF VARIABILITY

When actual variations are compared with specification limits, there are three possible conditions (Figure A-2), as follows:

(a) *A low variation with most results within specification limits.* This may indicate that the specifications are realistic and that the production process is in good control. However, if all results are within specification limits, the data may indicate that the sampling procedure is not entirely unbiased.

(b) *A relatively low variation with an average too close to the specification limit.* This may indicate that either the material production is offset with respect to the specification requirements, or that the specifications are offset with relation to current practice.

(c) *A high variation making it improbable that most results will fall within the specification limits most of the time.* This condition indicates that control needs to be tightened to reduce the variation to the uniformity required

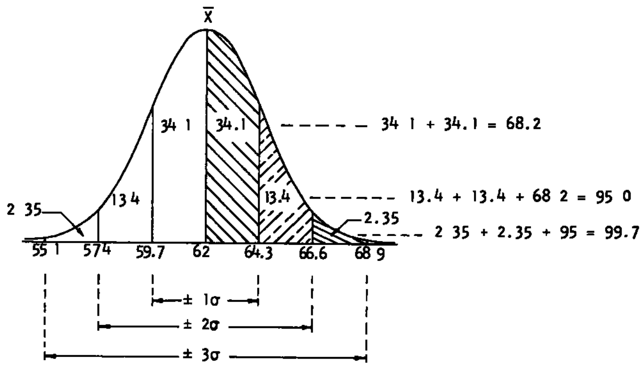


Figure A-1. Percentages of area within given sigma limits.

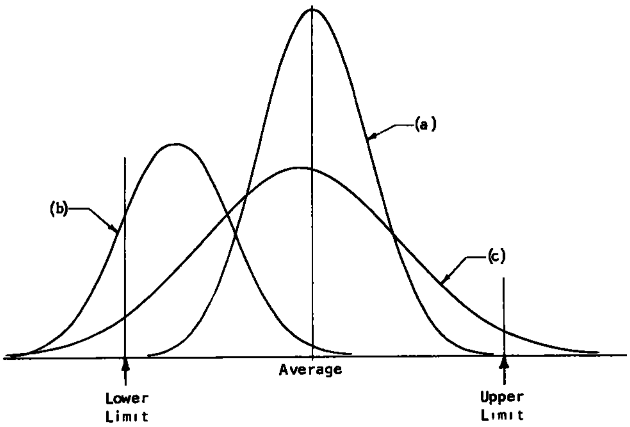


Figure A-2. Effect of variability.

by the specification or that the specification tolerances are not realistic and need to be broadened.

These relationships can be profitably applied to the construction control of aggregates and bituminous and portland cement concrete mixes, as well as to many other materials, processes, test methods, and operations used in highway construction. They may be used for two main purposes: (1) to rate the compliance of a given aggregate, material, or process, with the specification requirements; or (2) to compare specification requirements with the variability of typical operations. This method of presentation by use of the NORMAL CURVE assists in visualizing the pertinent relationships between operating tolerances and specification limits, and also provides a logical means for selecting the more fruitful areas for additional detailed study and research, for determining whether there is a necessity for administrative investigation or improved control, and/or for indicating the need for a specification rewrite.

In this report statistical methods based on the normal distribution curve have been used to analyze various problems, to treat the data, and to provide a means of measuring the relative sizes of the components of variation of the gradation of aggregates in both the degradation and segregation studies.

ANALYSIS OF VARIANCE

The means of isolating and measuring the relative magnitude of the individual components of variability is called ANALYSIS OF VARIANCE. The components to be isolated and defined will differ, depending on the system and on the objectives of the analysis. The statistical principles, however, are the same and, in general, involve a large number of replicate measurements on test portions selected in such a manner that the influence of other causes of variability is either eliminated or is capable of being otherwise estimated. Sometimes this involves some rather complicated interrelationships and occasionally some rather ingenious means of isolating and studying the individual components. The basic arithmetic, however, boils down to the fact that variances, σ^2, are additive.

Construction of Model

Early statistical studies made in connection with HR 10-2 included the design of a model showing the sources of the overall variations in gradation expected among random samples of aggregate taken at a point in the process flow from source to the point where the aggregate was incorporated into the product or construction. It was concluded that the OVERALL VARIANCE, σ^2_o, of the gradation of aggregate samples taken from the same LOT such as a section of pavement base, stockpile, railroad car, or bin, may be conveniently broken down into four basic components:

$$\sigma^2_o = \sigma^2_a + \sigma^2_t + \sigma^2_s + \sigma^2_l \qquad \text{(A-1)}$$

in which

σ^2_o = overall variance;
σ^2_a = the inherent variation resulting from the random arrangement of particles of different sizes in a mixture;
σ^2_t = a variance due to testing errors*;
σ^2_s = a variance due to sampling errors*; and
σ^2_l = the batch-to-batch variation within the LOT.

Figure A-3 shows the relationship of these variances, scaled roughly to the average size of the components of variance at the point of use. It shows how these components can be combined in various ways to construct a model germane to a given study.

During the HR 10-2 and 10-3 studies, research was directed to the evaluation of these variances, by both theoretical methods and by measurements on samples taken under practical operating conditions. The basic variance components and their pertinent combinations are discussed individually in the following.

Causes of Variation

INHERENT VARIANCES

Many of the basic concepts necessary for the understanding of the methods of evaluating the amount of segregation, or differences in gradation from point to point in a LOT of coarse aggregate are illustrated by the arrangements and equations in Figure A-4. If the white spots are thought of as particles of aggregate passing the openings of a given sieve, the arrangements shown can represent the conditions existing in a LOT of aggregate, such as a stockpile.

It may be thought that a well-mixed aggregate should have an ordered arrangement such as in Figure A-4A, so that selection of a sample increment of any size or from any part of the arrangement would always give nearly the same proportions of white and black spots, or the same percentage, *P*, of particles passing a given sieve. This is not the case, however, because condition A is an unnatural condition, which, if achieved, would disappear when the aggregate was moved or mixed. When particles of different sizes are thoroughly mixed they are almost completely randomized, as are the spots in Figure A-4B, and this is as

* These are not errors in the sense of someone making a mistake. They are random variations associated with the sampling and testing procedure

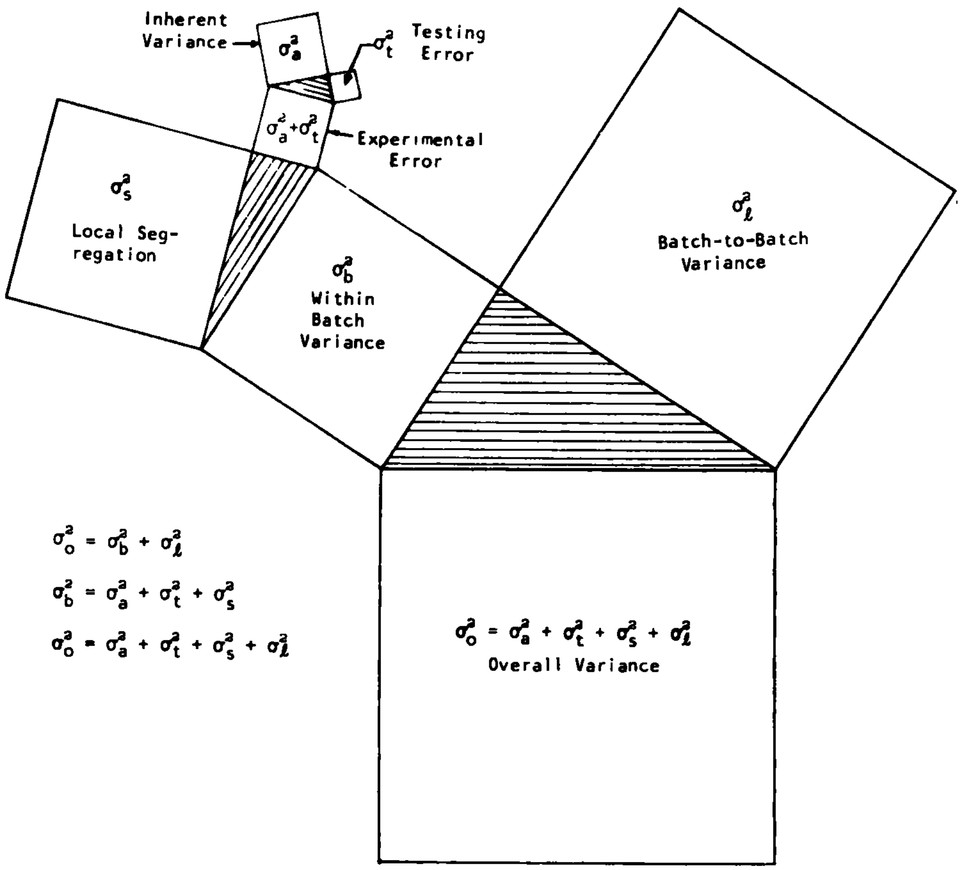


Figure A-3. Sources of variance.

nearly a uniform distribution of particles of different sizes as can be expected. It will be seen that if sample increments containing the same number of contiguous spots were selected from B, some increments would contain more white spots than others, or in the case of aggregates, the percentage, *P*, of small particles would be different. The measure of this difference is the variance, σ^2, and since the arrangement of B is truly random, it is possible to calculate the value of the variance under various conditions. Also, if a large number of increments is selected, it is possible to predict, from the normal distribution curve, the percentage of increments that will contain a certain number of white spots. One peculiarity of this random distribution is that the variance depends on the size of the increment, and a collection of large increments will have a smaller variance of the number of white spots than a collection of small increments. The arrangement of B is analogous to the condition existing when a LOT of particles of different sizes is mixed. No matter how thorough the mixing, samples consisting of increments of particles taken from the LOT will have different percentages of particles passing a given sieve. This variance, designated in this report as σ^2_a, is inherent, and can only be reduced by taking larger increments. For increments of equal size, the value of σ^2_a will vary with different gradations, and can be calculated from the binomial equation shown with Figure A-4B.

THEORETICAL OVERALL VARIANCE

Even this random distribution of particle sizes, as shown in Figure A-4B, is largely theoretical, and can only be attained under special conditions, as is the case with the theoretical maximum variance (σ^2_{max}) of a totally segregated condition illustrated by Figure A-4D. In real life, the condition existing in a LOT of coarse and fine particles is most nearly represented by a partly segregated condition illustrated by arrangement C. Here the variation in the proportion of white spots that represent the percentage of aggregate smaller than the openings in a given sieve, *P*, is symbolized by σ^2_o, the overall variance, which is made up of the inherent variance plus the variance due to segregation.

ACTUAL OVERALL VARIANCE

In the case of actual aggregates used in construction, the situation is different from the arrangement of spots of equal sizes shown in Figure A-4C in that the particles are of different sizes, consequently the distribution is not exactly binomial. However, the difference between the true average value of a measurement, such as the percentage passing a given sieve if the entire LOT was put through the sieve, and the percentage, *P*, of test portion passing this sieve can be expressed as the sum of two variances, one due to inherent variation and the other to segregation. If

the distribution were entirely binomial, as in the case of spots of equal size (Fig. A-4C), the first approximation of the total variance would be

$$\sigma^2_o = \frac{P(100-P)}{n} + P(100-P)k \qquad \text{(A-2)}$$

in which k is a coefficient that expresses the relative amount of segregation. When dealing with aggregates containing particles of many different sizes, the random component of the overall variance, σ^2_o, is called the inherent variance, σ^2_a, and is computed by

$$\sigma^2_a = \frac{P(100-P)\bar{g}}{454\, W} \qquad \text{(A-3)}$$

in which

- P = the percentage by weight of the aggregate passing a designated sieve;
- σ_a = the inherent standard deviation of P;
- $\bar{g}$ = the average particle weight of all particles retained on the designated sieve (in grams); and
- W = the total weight, in pounds, of the test portion of aggregate passed through the sieves.

Also, in the case of graded aggregates, there will be a different overall variance, σ^2_o, for the percentage passing each sieve. These variances are related by raising the quantity $P(100-P)$ to some power, t, so that

$$\sigma^2_o = \sigma^2_a + k[P(100-P)]^t \qquad \text{(A-4}a\text{)}$$

expresses the overall variance for the percentage of aggregate passing any sieve. Then,

$$(\sigma^2_o - \sigma^2_a) = k[P(100-P)]^t \qquad \text{(A-4}b\text{)}$$

and the amount of segregation of any particle size in the gradation is expressed by the coefficient k and the exponent t. The value of t depends on the range and distribution of particle sizes in the gradation and on possible interactions or additional factors which have not as yet been evaluated.

MATHEMATICAL EVALUATION OF VARIATION PARAMETERS

If y and x are substituted for $(\sigma^2_o - \sigma^2_a)$ and $P(100-P)$, respectively, Eq. A-4b is simplified to

$$y = k\,x^t \qquad \text{(A-4}c\text{)}$$

which in logarithmic form becomes

$$\log y = \log k + t \log x \qquad \text{(A-4}d\text{)}$$

The values of k and t are found by the method of least squares, using actual data, as in the following example:

But

$$\Sigma(\log y) = N(\log k) + t\,\Sigma(\log x) \qquad \text{(A-5)}$$

and

$$\Sigma(\log x)(\log y) = \log k\,\Sigma(\log x) + t\,\Sigma(\log x)^2 \qquad \text{(A-6)}$$

in which N is the number of sieve sizes. Substituting the summation values in Eqs. A-5 and A-6 and solving them simultaneously gives $t = 1.65239$ and $k = 0.00629$. This last value is a "coefficient of segregation," and Eq. A-4c becomes

$$y = 0.00629\, x^{1.65} \qquad \text{(A-7)}$$

and Eq. A-4b becomes

$$(\sigma^2_o - \sigma^2_a) = 0.00629\,[P(100-P)]^{1.65} \qquad \text{(A-8)}$$

From Eq. A-8 the relative segregation of any particle size can be calculated, provided the percentage of that size is known. For purposes of comparison, the variance or standard deviation of a fictitious size, at which exactly 50% of the total aggregate would pass the sieve, can be used. Then, by Eq. A-8, $\sigma^2_o - \sigma^2_a = 64.24$, and $\sqrt{\sigma^2_o - \sigma^2_a} = 8.02$.

GRAPHICAL EVALUATION OF VARIATION PARAMETERS

The value of t can also be obtained by plotting the dependent variable, $\sigma^2_o - \sigma^2_a$, on the ordinate, and $P(100-P)$ on the abscissa of logarithmic graph paper. If the "best line" drawn through the plotted points is considered to be the hypotenuse of a right triangle, the slope, t, can be found by dividing the scaled altitude by the scaled base.

A slightly more accurate method is to use selected points from the straight line. For example, if two points are (3500, 30) and (1000, 4), Eq. A-4c gives

$$30 = k(3500)^t \qquad \text{(A-9}a\text{)}$$

and

$$4 = k(1000)^t \qquad \text{(A-9}b\text{)}$$

Dividing Eq. A-9a by Eq. A-9b gives $(3.5)^t = 7.5$, from which, by the Ln3 scale of a Deci-Log slide rule, $t = 1.61$.

This basis of comparison is satisfactory if the overall variance is large with respect to the inherent variance.

PARTIAL VARIANCES

In the preceding discussion, Eq. A-4b was given in terms of σ^2_o and σ^2_a. However, there are other components in the

Sieve Size	Data Furnished			Data Derived					
	σ^2_a	σ^2_o	$\bar{X}$[a]	y	x	$\log y$	$\log x$	$\log y \times \log x$	$(\log x)^2$
¾ In.	4.0	26.4	82.3	22.4	1460	1.35025	3.16435	4.27266	10.01311
⅜ In.	2.25	57.0	31.7	54.8	2160	1.73878	3.33445	5.79787	11.11856
No. 4	0.5	6.6	5.3	6.1	500	0.78533	2.69897	2.11958	7.28444
No. 8	0.25	1.6	2.8	1.4	270	0.14613	2.43136	0.35529	5.91151
Σ						4.02049	11.62913	12.54540	34.32762

[a] Average percent passing.

overall variance, σ^2_o. As pointed out by Visman in his memorandum (*90*) defending the Manning equation, and in other articles (*91, 92, 93*):

> ". . . the influence of segregation and analytical error can be accounted for by adding the partial variances due to segregation and analysis to the sampling variance (σ^2_s), on the understanding that the three variances be mutually independent. For coal, this condition is fulfilled within a relatively wide interval.
>
> $$\sigma^2_{total} = \sigma^2_s + \sigma^2_{segr} + \sigma^2_{anal} \qquad \text{(A-9)}$$
>
> The partial variances can be estimated from an experiment based on the analysis of variance (three independent variables). In turn, the variance (σ^2_{segr}) due to segregation can be subjected to an analysis of variance, thus determining the partial variances due to macro-segregation and micro-segregation, respectively."

In the context of the segregation studies reported herein,

$$\sigma^2_o = \sigma^2_a + \sigma^2_t + \sigma^2_s + \sigma^2_l \qquad \text{(A-10)}$$

in which

σ^2_o = total variance of a percentage passing a given sieve;

σ^2_a = the inherent variance $= \dfrac{P(100 - P)\bar{g}}{454\,W}$;

σ^2_t = variance due to testing error;

σ^2_s = within-batch variance or "micro-segregation;"

σ^2_l = within-lot (batch-to-batch) variance or "macro-segregation."

The testing error, σ^2_t, has been found to be quite small and can usually be neglected. If it can be established that σ^2_s is independent, this variance can also be subtracted from σ^2_o to obtain values of k and t for σ^2_l, the variance that has the most significant effect on quality, as shown by

$$\sigma^2_o - (\sigma^2_a + \sigma^2_t + \sigma^2_s) = \sigma^2_l = k[P(100 - P)]^t \qquad \text{(A-11)}$$

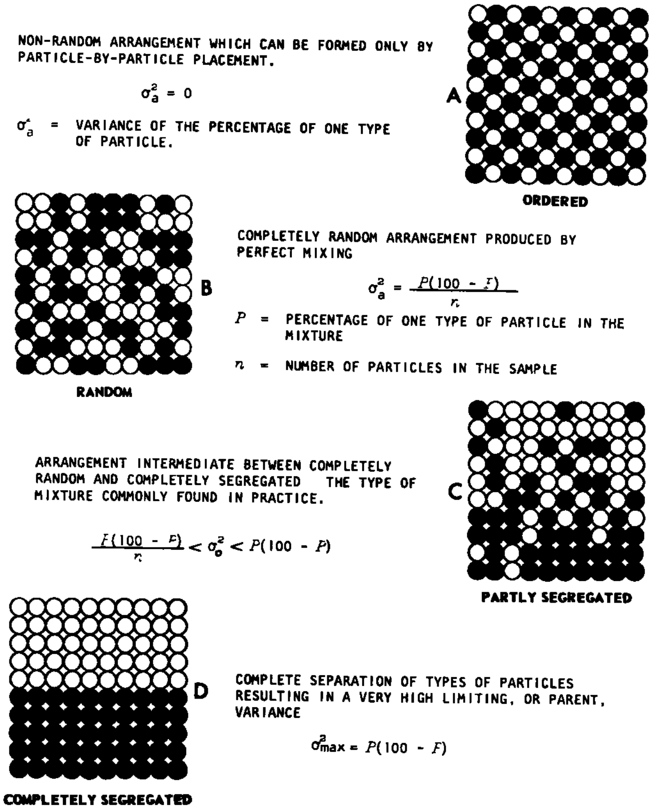


Figure A-4. Particle arrangements. The white and black spots represent particles, or groups of particles, having unlike characteristics in an infinite population of combinations of such particles. The different arrangements represent the degree of dispersal of like particles throughout the mixture.

Inherent Variance

An initial activity was to devise some method of estimating the inherent variance, σ^2_a, of the relative percentages of particle sizes due to the discrete nature and normal random distribution of aggregate particles.

Inasmuch as σ^2_a is caused by nonhomogeneity within the volume of aggregate actually tested, it is a basic variation in gradations that cannot be reduced by process control. Obviously, it would be impractical and uneconomical to modify any production process in an attempt to reduce the process level of variance below this inherent variance. Also, this basic variation must be considered when establishing numerical limits for gradation specifications. In addition, a method of estimating this variance is necessary to the development of a method of computing the minimum size of the sample or test portion required for a predetermined accuracy and degree of assurance.

As previously mentioned, this research agency has conducted two NCHRP projects (HR 10-2 and HR 10-3) with objectives that have some degree of overlap. Because the statistical concepts used for analysis of data in each case were essentially the same, close coordination was maintained between the two projects. The laboratory experimental work to study inherent variance, σ^2_a, is a typical example. This work was conducted in Lincoln, Nebr., in connection with one phase of the 10-2 project, although the results obtained are equally applicable to both projects. Results of this experiment are reported in detail in the HR 10-2 interim report (*NCHRP Report 34*) and are outlined in brief at this point.

Manning (*50*), Buslik (*27*), and Visman (*82, 83, 84*) have devised formulas for computing the theoretical value of σ^2_a, but the data with which the theoretical values have been compared do not appear to be entirely satisfactory for the purpose of establishing the validity of the formulas for aggregate control. Because of lack of suitable data and disagreement among values obtained by their theoretical equations, a special experiment was designed to measure the inherent variance of two typical commercial coarse aggregates. As far as can be determined through a search of the literature, this experiment is the most comprehensive study ever undertaken on inherent variance, using a practical aggregate gradation.

Briefly, the experiment consisted of making up a selected gradation with completely random particle arrangement as

in Figure A-4B, securing test increments in such a manner as to produce a zero sampling error, and running the gradation test. Because for all practical purposes the testing error was small enough to be ignored, the variation resulting was assumed to be due entirely to inherent variance.

The findings are in general agreement with equations based on the binomial distribution theory and, in particular, provide a reasonably good verification of Manning's equation. These raw data on which the findings are based (available on special request, see Appendix H) should have special significance to the future researcher wishing to study this subject in greater depth.

The theoretical inherent standard deviation with which the experimental values are compared is computed from

$$\sigma_a = \sqrt{\frac{P(100 - P)\bar{g}}{454\,W}} \qquad \text{(A-14)}$$

in which

P = the percentage by weight of the aggregate passing a designated sieve;
σ_a = the standard deviation of P;
$\bar{g}$ = the average particle weight,* in grams, of all particles larger than the openings in the designated sieve; and
W = the total weight,† in pounds, of all aggregate passed through the sieves.

Reasonable correlation between experimental and theoretical values of σ_a was obtained at the 95% confidence level, particularly with respect to the larger particles (¾ in.) in the gradation and when the weight of the test portion was in the order of 20 lb. On this basis, the values of σ_a obtained by the use of Eq. A-12 were considered to be a sufficiently accurate estimate and values of σ_a so computed are used in this report. To show the relative magnitude of this source of variability, average σ_a values corresponding to a sample weight, W, of about 25 lb are presented in Table A-1 for the various sieve sizes of the gradation used in this study (1½ in. to No. 8).

TABLE A-1

AVERAGE σ_a VALUES FOR $W = 25$ POUNDS

SIEVE SIZE	THEORETICAL INHERENT VARIABILITY, σ_a (% PASSING)
1½ In.	2.8
¾ In.	2.0
⅜ In.	1.4
No. 4	0.7
No. 8	0.6

Testing Error

The variance due to testing error, σ^2_t, is usually considered to be the between-test-portion variance due to the lack of repeatability of the test procedure, which may include effects of reducing increments to test portion size, or other preparatory work. Even when the same sample is passed through the same sieves, results may differ. Aggregate particles are usually of irregular shape, and during one test may be favorably positioned for passing through a sieve opening, whereas during another test the same particles may not be so oriented. With some types of shaking equipment, particles that have passed through the openings of one sieve may even return to that sieve after prolonged shaking.

Sources of variation between reported gradations, not usually considered a part of the testing error of the procedure, may include differences in sieving efficiency and actual errors, such as the loss of aggregate particles from the sample during testing, inaccurate weighing of groups of separated particles, or incorrect observations or calculations.

As used in this report, σ_t is a measure of the repeatability of the gradation test using the same test portion, the same equipment, and with the same operator. It is computed from

$$\sigma^2_t = \frac{\Sigma(X_1 - X_2)^2}{2n} \qquad \text{(A-13)}$$

in which

σ^2_t = variance due to lack of repeatability of the test;
X_1 = result of first test on test portion;
X_2 = result of second test on same portion; and
n = number of test portions (two measurements or tests were made on each test portion).

Because some aggregates are subject to degradation during sieving, σ^2_t was determined by retesting test portions taken at random from the various samples, rather than making multiple tests with the same test portion.

The retests were made under such conditions that the results were not biased by those originally obtained. A total of 61 retests were made on the three different aggregates involved (the test portion size varied from about 18 to 45 lb). The tests were all made by the same technicians, in the same laboratory, using the same sieving equipment.

The standard deviations of the percentages passing the various sieves are given in Table A-2.

Pooling data by combining variances yields a rounded figure for average standard deviation, $\bar{\sigma}_t$, of about 0.5% under these given conditions. This compares favorably with a pooled average value, $\bar{\sigma}_t$, of about 0.4% obtained in the HR 10-2 study.

* This value is the average particle weight of *all* particles of *all* material that would be retained on the designated sieve if there were no coarser sieves in the stack. It is not the average particle weight of merely that material passing the next larger sieve and retained on the designated sieve as is customarily visualized in gradation considerations.

† The *total* weight and not merely the weight of aggregate passing the designated sieve.

TABLE A-2

SUMMARY OF RESULTS OF SIEVING REPEATABILITY TESTS

STUDY	TYPE OF AGGREGATE	NO. OF TESTS, n	STANDARD DEVIATION,[a] σ_t						
			1 IN.	¾ IN.	½ IN.	⅜ IN.	NO. 4	NO. 8	$\bar{A}$
Degradation	1 In.-No. 4 crushed stone	21	—	0.3	0.3	0.4	0.7	1.3	0.026
Segregation	1½ In.-⅜ in. crushed stone	20	0.8	0.9	—	0.4	0.3	0.3	0.026
Segregation	1 In.-No. 4 uncrushed gravel	20	—	0.3	—	0.2	0.1	0.1	0.007
Weighted average among runs			0.8	0.6	0.3	0.3	0.5	0.8	0.021

[a] Percent passing sieves (Gilson).

Experimental Error

The sum of the variances due to inherent variation and testing error, $\sigma^2_a + \sigma^2_t$, has been called experimental error, σ_e. Because it is this combined variance that affects the repeatability and reproducibility of an aggregate gradation test on duplicate samples, the precision statement for this test must be based on this sum of variances.

Sampling Error

The source of the sampling error, σ^2_s, is the incomplete mixing of a small volume of aggregate, such as in a batch or unit of construction, so that the distribution of the particles of different sizes is not entirely random. As a result, an increment taken from one part of the batch will not show the same test values as one taken from another part of the batch. It is computed by first finding the total within-batch variance, σ^2_b, then subtracting the sum of the inherent variance and the testing error,

$$\sigma^2_s = \sigma^2_b - (\sigma^2_a + \sigma^2_t) \quad \text{(A-14)}$$

Within-Batch Variance

The within-batch variance is estimated by taking two test portions or increments from suitably separated points in the same batch, making the specified tests, and substituting the results in

$$\sigma^2_b = \frac{\Sigma(X_A - X_B)^2}{2n} \quad \text{(A-15)}$$

in which

σ^2_b = total within-batch variance;
X_A = test result on first increment;
X_B = test result on duplicate increment; and
n = number of paired increments (one-half the total number of increments).

In many instances, such as in the case of an aggregate for use in concrete, within-batch variance, σ^2_b, is of least practical importance, because the cause of this variance will be removed by further mixing. However, if the batch is sufficiently segregated, the sampling error, σ^2_s, may lead to misinterpretation of test results unless test portions are taken by collecting multiple increments of aggregate from different parts of the batch. The exercise of engineering judgment in interpreting the relative importance of within-batch variance for a given aggregate use can have much practical significance.

Batch-to-Batch Variance

The batch-to-batch, or within-lot, variance, σ^2_l, is the most significant, because it can cause actual differences in the performance of different batches.

The size of the variance depends almost entirely on the efficiency of the methods of handling, transporting, and storing aggregates, and the resulting degree of segregation. It is computed by difference, using

$$\sigma^2_l = \sigma^2_o - \sigma^2_b \quad \text{(A-16)}$$

Overall Variance

The total overall variance among test portions taken from a LOT is σ^2_o, which is equal to $\sigma^2_a + \sigma^2_t + \sigma^2_s + \sigma^2_l$, and is computed by

$$\sigma^2_o = \frac{\Sigma X^2 - \frac{(\Sigma X)^2}{n}}{n - 1} \quad \text{(A-17)}$$

in which

σ^2_o = total overall variance;
X = test result of an increment or test portion; and
n = number of measurements of test results.

It is this overall variance, σ^2_o, that directly affects the writing of practical specifications with realistic tolerances. The magnitude of σ^2_o also affects the sampling plan, because the number of test portions required to obtain a measured predetermined degree of assurance and accuracy is found from

$$n = \frac{t^2 \sigma^2_o}{\Delta^2} \quad \text{(A-18)}$$

in which

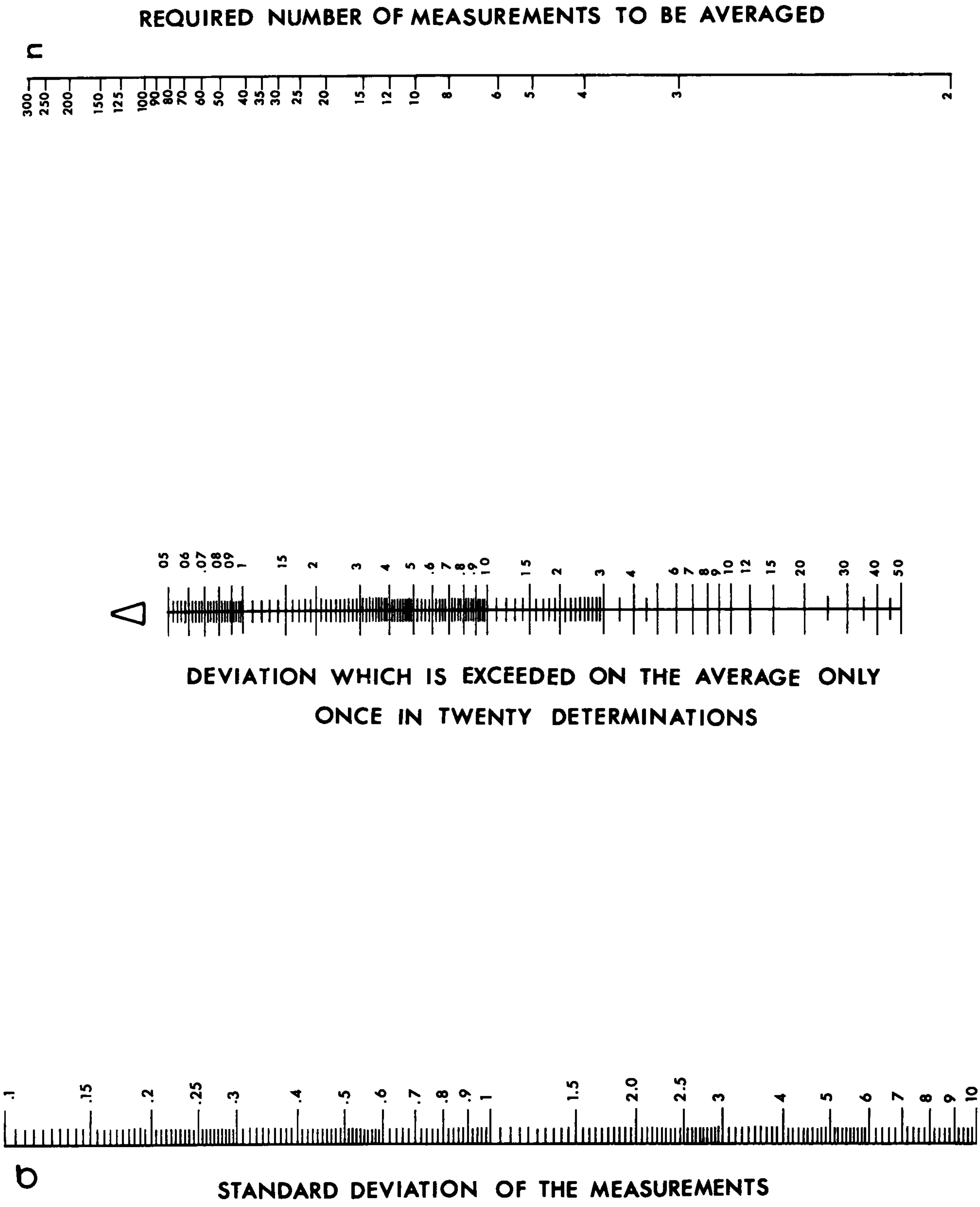


Figure A-5. Nomograph for estimating required number of measurements.

Use of Figure A-5.

The purpose of this nomograph is to furnish an approximate solution of

$$n = \left[\frac{t\sigma}{\Delta}\right]^2$$

where t depends on the number of degrees of freedom $(n - 1)$ associated with n.

1. To use, project a straight line from the standard deviation of the measurement on the left hand (σ) scale through the desired degree of accuracy on the center (Δ) scale. This line will intercept the right hand (n) scale at the approximate value of n indicated by the equation.

2. To obtain a more precise value of n, enter the t table with the number of degrees of freedom $(n - 1)$ associated with the chart value, and opposite this value find t in the column which has $t = 1.96$ opposite d.f. $= \infty$.

Insert this t in the equation and solve for n. Use this value of n to find a new t, and continue to iterate until the value of n found by solving the equation is nearly the same as the value of n used to find t.

n = number of test portions;
t = the desired degree of assurance, or probability of success in obtaining a correct answer, measured in standard deviation units from the center of the t distribution curve;
σ_0 = the overall standard deviation of the measurements; and
Δ = the maximum allowable difference between the computed average of the measurements and the true average.

For example, if it is known that the overall standard deviation of the percent by weight of aggregate passing the ¾-in. sieve is 4%, and it is desired to take enough test portions so that there is a 95% probability of obtaining an average value correct to ±1%, $n = \frac{(2.00)^2 \times (4)^2}{(1)^2} = 64$.

In the example, the value of $t = 2.00$ is for 60 degrees of freedom (d.f.) and 95% probability. This value of t must be found by iteration, because d.f. $= (n - 1)$, and n is initially unknown. To simplify computations and reduce the number of iteration trials, a nomograph has been devised (Fig. A-5; same as Fig. 3, *NCHRP Report 5*).

APPENDIX B

DATA ANALYSIS SUMMARIES

Each IBM 1410 computer printout sheet reproduced here presents a summary of the statistical parameters derived from an individual stockpile or test section constructed under the 10-3/1 continuation studies.

AVERAGE A = 1.394
VARIANCE OF A = .0060
STANDARD DEVIATION OF A = .0778
NUMBER OF TESTS = 120

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	22.40	16.613	4.076	18 19
3/8 "	5.03	2.613	1.616	32.12
No. 4	3.47	.765	.874	25.21
No. 8	2.96	.348	.590	19.94

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	42.8	15.6	27.1	1.41	4.40
3/8 "	13.2	2.3	10.9	1.77	5.35
No. 4	7.4	1.7	5.7	1.44	4.15
No. 8	5.4	1.6	3.8	1.01	3.39

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	2.690	1.640
3/8 "	.194	.440
No. 4	.066	.257
No. 8	.030	.173

WITHIN BATCH VARIANCE OF A = .0006
WITHIN BATCH STANDARD DEVIATION OF A = .0247

Figure B-1. Data analysis summary, Gresham's Lake stone (1½ in.-⅜ in.) from parent pile used for stockpiling studies (N.C. size No. 1).

AVERAGE A = 1.512
VARIANCE OF A = .0291
STANDARD DEVIATION OF A = .1706
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	28.46	71.767	8.471	29.76
3/8 "	6.89	12.346	3.513	50.97
No. 4	4.59	3.410	1.846	40.17
No. 8	3.90	1.548	1.244	31.86

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	48.5	9.4	39.0	-.30	-.52
3/8 "	19.2	1.8	17.3	.95	.73
No. 4	11.2	1.7	9.5	.99	1.05
No. 8	8.2	1.6	6.5	.68	.58

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	2.669	1.633
3/8 "	.293	.541
No. 4	.103	.321
No. 8	.052	.229

WITHIN BATCH VARIANCE OF A = .0007
WITHIN BATCH STANDARD DEVIATION OF A = .0276

Figure B-2. Data analysis summary, Gresham's Lake stone, single-cone stockpile.

AVERAGE A = 1.574
VARIANCE OF A = .0478
STANDARD DEVIATION OF A = .2188
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	30.30	72.202	8.497	28.03
3/8 "	8.24	19.779	4.447	53.94
No. 4	5.50	8.484	2.912	52.89
No. 8	4.61	5.136	2.266	49.05

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	61.3	7.7	53.6	.07	1.34
3/8 "	32.8	1.2	31.6	2.06	9.32
No. 4	21.6	1.0	20.6	2.27	10.33
No. 8	16.7	.9	15.8	2.14	9.56

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	3.707	1.925
3/8 "	1.166	1.079
No. 4	.419	.647
No. 8	.234	.483

WITHIN BATCH VARIANCE OF A = .0022
WITHIN BATCH STANDARD DEVIATION OF A = .0470

Figure B-3. Data analysis summary, Gresham's Lake stone, cast-and-spread stockpile. (Includes all 100 test increments, whereas the statistical calculations presented in the text are based on the first 60 increments).

AVERAGE A = 1.533
VARIANCE OF A = .0305
STANDARD DEVIATION OF A = .1748
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	29.37	48.842	6.988	23.79
3/8 "	7.36	12.110	3.480	47.27
No. 4	4.83	5.218	2.284	47.25
No. 8	4.06	3.170	1.780	43.82

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	47.2	11.8	35.3	.09	-.08
3/8 "	19.4	1.3	18.1	1.30	2.30
No. 4	13.4	1.0	12.4	1.58	3.47
No. 8	10.8	.9	9.9	1.54	3.54

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	4.353	2.086
3/8 "	2.245	1.498
No. 4	1.093	1.045
No. 8	.671	.819

WITHIN BATCH VARIANCE OF A = .0044
WITHIN BATCH STANDARD DEVIATION OF A = .0666

Figure B-4. Data analysis summary, Gresham's Lake stone, truck-dumped stockpile.

AVERAGE A = 2.152
VARIANCE OF A = .0225
STANDARD DEVIATION OF A = .1502
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	80.54	28.878	5.373	6.67
3/8 "	26.42	60.946	7.806	29.53
No. 4	4.48	3.254	1.804	40.21
No. 8	1.81	.392	.626	34.53

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	89.8	64.3	25.4	-.59	.30
3/8 "	41.7	11.1	30.6	.04	-1.07
No. 4	9.2	1.4	7.8	.52	-.61
No. 8	4.0	.3	3.7	.73	.81

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	5.002	2.236
3/8 "	7.149	2.673
No. 4	.360	.600
No. 8	.076	.276

WITHIN BATCH VARIANCE OF A = .0026
WITHIN BATCH STANDARD DEVIATION OF A = .0514

Figure B-5. Data analysis summary, Campbell uncrushed gravel (1 in.-No. 4), parent deposit (hopper storage).

AVERAGE A = 2.075
VARIANCE OF A = .1129
STANDARD DEVIATION OF A = .3361
NUMBER OF TESTS = 102

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	75.21	300.766	17.342	23.05
3/8 "	24.44	211.491	14.542	59.48
No. 4	4.10	8.172	2.858	69.59
No. 8	1.79	.662	.813	45.30

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	96.6	24.8	71.8	-1.16	.74
3/8 "	62.0	.8	61.2	.20	-.59
No. 4	11.9	.6	11.2	1.02	.45
No. 8	3.8	.6	3.2	.69	-.22

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	13.622	3.690
3/8 "	13.624	3.691
No. 4	.599	.774
No. 8	.081	.285

WITHIN BATCH VARIANCE OF A = .0055
WITHIN BATCH STANDARD DEVIATION OF A = .0741

Figure B-6. Data analysis summary, Campbell uncrushed gravel, single-cone stockpile.

AVERAGE A = 2.230
VARIANCE OF A = .0382
STANDARD DEVIATION OF A = .1956
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	81.66	52.999	7.280	8.91
3/8 "	30.16	92.323	9.608	31.85
No. 4	5.82	5.218	2.284	39.21
No. 8	2.58	1.133	1.064	41.26

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	96.0	60.3	35.6	-.75	.37
3/8 "	55.5	7.6	47.9	-.10	-.59
No. 4	13.3	1.4	11.9	.64	.62
No. 8	8.8	1.0	7.8	3.11	14.44

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	20.821	4.563
3/8 "	29.976	5.475
No. 4	1.935	1.391
No. 8	.444	.666

WITHIN BATCH VARIANCE OF A = .0135
WITHIN BATCH STANDARD DEVIATION OF A = .1165

Figure B-7. Data analysis summary, Campbell uncrushed gravel, cast-and-spread stockpile.

AVERAGE A = 2.321
VARIANCE OF A = .0228
STANDARD DEVIATION OF A = .1512
NUMBER OF TESTS = 92

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	83.91	17.799	4.218	5.02
3/8 "	33.34	59.528	7.715	23.13
No. 4	7.46	5.675	2.382	31.92
No. 8	3.53	1.310	1.144	32.37

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	91.3	71.0	20.3	-.61	.26
3/8 "	51.9	7.7	44.1	-.48	.58
No. 4	15.5	2.1	13.4	.61	.95
No. 8	7.7	1.5	6.2	1.42	2.72

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	7.413	2.722
3/8 "	13.214	3.635
No. 4	1.504	1.226
No. 8	.301	.549

WITHIN BATCH VARIANCE OF A = .0056
WITHIN BATCH STANDARD DEVIATION OF A = .0754

Figure B-8. Data analysis summary, Campbell uncrushed gravel, truck-dumped stockpile.

AVERAGE A = 3.933
VARIANCE OF A = .0285
STANDARD DEVIATION OF A = .1690
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	78.17	9.097	3.016	3.85
3/8 "	57.35	12.472	3.531	6.15
No. 4	44.69	9.183	3.030	6.78
No. 8	37.34	6.502	2.549	6.82
No. 16	29.23	3.885	1.971	6.74
No. 30	22.22	2.207	1.485	6.68
No. 50	13.71	.951	.975	7.11
No.100	7.19	.402	.634	8.81
No.200	3.41	.129	.359	10.50

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	86.4	68.8	17.6	.00	.38
3/8 "	66.9	48.3	18.6	.01	-.01
No. 4	52.8	37.0	15.7	.15	.07
No. 8	44.4	30.8	13.6	.20	.14
No. 16	34.9	24.2	10.7	.18	-.06
No. 30	26.4	18.5	7.9	.09	-.28
No. 50	16.5	11.6	4.9	.11	-.49
No.100	8.9	6.0	2.9	.24	-.62
No.200	4.3	2.7	1.5	.28	-.79

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	6.570	2.563
3/8 "	10.016	3.164
No. 4	7.697	2.774
No. 8	5.479	2.340
No. 16	3.374	1.836
No. 30	1.982	1.408
No. 50	.766	.875
No.100	.228	.477
No.200	.055	.234

WITHIN BATCH VARIANCE OF A = .0233
WITHIN BATCH STANDARD DEVIATION OF A = .1527

Figure B-9. Data analysis summary, Durham quarry aggregate from parent pile (hard stone for degradation studies) (N.C. size No. 8).

AVERAGE A = 3.983
VARIANCE OF A = .0279
STANDARD DEVIATION OF A = .1671
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	78.48	9.775	3.126	3.98
3/8 "	58.01	11.784	3.432	5.91
No. 4	45.40	8.520	2.918	6.42
No. 8	36.99	5.991	2.447	6.61
No. 16	29.37	3.829	1.956	6.66
No. 30	21.67	3.125	1.767	8.15
No. 50	14.42	2.585	1.608	11.15
No.100	8.96	1.433	1.197	13.35
No.200	5.06	.557	.746	14.74

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	91.2	72.1	19.0	.63	1.29
3/8 "	72.4	50.8	21.6	.75	1.88
No. 4	57.3	38.7	18.6	.64	1.61
No. 8	45.3	31.0	14.3	.16	.51
No. 16	37.1	25.3	11.7	.51	1.47
No. 30	27.9	17.9	9.9	.50	.50
No. 50	18.6	10.1	8.5	-.18	.17
No.100	11.5	5.5	5.9	-.52	.52
No.200	6.5	2.8	3.6	-.70	.84

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	7.350	2.711
3/8 "	7.394	2.719
No. 4	5.030	2.242
No. 8	3.601	1.897
No. 16	2.397	1.548
No. 30	1.457	1.207
No. 50	.778	.882
No.100	.364	.603
No.200	.134	.366

WITHIN BATCH VARIANCE OF A = .0173
WITHIN BATCH STANDARD DEVIATION OF A = .1318

Figure B-10. Data analysis summary, Durham quarry aggregate after pugmill mixing.

AVERAGE A = 3.998
VARIANCE OF A = .0827
STANDARD DEVIATION OF A = .2876
NUMBER OF TESTS = 50

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	79.30	30.846	5.553	7.00
3/8 "	58.57	39.384	6.275	10.71
No. 4	45.76	27.251	5.220	11.40
No. 8	37.53	16.904	4.111	10.95
No. 16	29.77	10.680	3.268	10.97
No. 30	21.48	5.677	2.382	11.08
No. 50	13.93	2.679	1.636	11.74
No.100	8.57	1.239	1.113	12.98
No.200	4.85	.533	.730	15.05

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	87.1	63.0	24.1	1.03	.62
3/8 "	67.8	38.8	29.0	-1.11	1.00
No. 4	52.7	28.8	23.8	-1.07	.92
No. 8	43.4	23.9	19.5	-1.13	1.22
No. 16	35.1	18.8	16.3	-1.17	1.63
No. 30	25.2	13.9	11.2	-1.01	1.20
No. 50	17.2	8.8	8.3	-.67	1.08
No.100	11.2	5.3	5.8	-.12	.98
No.200	6.7	3.1	3.6	.41	.91

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	14.748	3.840
3/8 "	18.682	4.322
No. 4	13.712	3.703
No. 8	8.078	2.842
No. 16	5.588	2.363
No. 30	3.016	1.736
No. 50	1.381	1.175
No.100	.596	.772
No.200	.217	.466

WITHIN BATCH VARIANCE OF A = .0413
WITHIN BATCH STANDARD DEVIATION OF A = .2032

Figure B-11. Data analysis summary, Durham quarry aggregate, section 1-D.

AVERAGE A = 4.038
VARIANCE OF A = .0576
STANDARD DEVIATION OF A = .2400
NUMBER OF TESTS = 50

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	79.82	19.760	4.445	5.56
3/8 "	59.12	29.401	5.422	9.17
No. 4	46.28	18.372	4.286	9.26
No. 8	37.58	10.584	3.253	8.65
No. 16	29.93	7.006	2.646	8.84
No. 30	22.17	4.400	2.097	9.46
No. 50	14.75	2.146	1.464	9.93
No.100	9.14	.921	.960	10.49
No.200	5.06	.373	.611	12.06

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	86.0	65.7	20.2	-1.20	1.21
3/8 "	66.5	44.1	22.4	-1.05	.48
No. 4	53.2	34.7	18.5	-.97	.27
No. 8	43.8	28.8	14.9	-.82	.31
No. 16	33.5	22.4	11.1	-.90	.34
No. 30	26.3	16.5	9.8	-.69	.35
No. 50	17.9	10.8	7.1	-.65	.43
No.100	11.3	6.5	4.8	-.61	.50
No.200	6.5	3.4	3.1	-.33	.27

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	7.048	2.654
3/8 "	10.578	3.252
No. 4	6.809	2.609
No. 8	4.549	2.132
No. 16	3.282	1.811
No. 30	2.147	1.465
No. 50	1.019	1.009
No.100	.430	.656
No.200	.160	.401

WITHIN BATCH VARIANCE OF A = .0226
WITHIN BATCH STANDARD DEVIATION OF A = .1504

Figure B-12. Data analysis summary, Durham quarry aggregate, section 2-D.

AVERAGE A = 4.053
VARIANCE OF A = .0392
STANDARD DEVIATION OF A = .1982
NUMBER OF TESTS = 50

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	79.96	16.841	4.103	5.13
3/8 "	59.90	19.629	4.430	7.39
No. 4	47.24	11.821	3.438	7.27
No. 8	37.92	7.193	2.682	7.07
No. 16	29.94	4.699	2.167	7.23
No. 30	21.78	3.017	1.737	7.97
No. 50	14.38	1.603	1.266	8.80
No.100	9.02	.783	.885	9.81
No.200	5.21	.356	.597	11.45

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	87.9	67.3	20.5	-.65	.76
3/8 "	67.4	48.3	19.0	-.41	-.31
No. 4	53.2	37.7	15.4	-.47	-.20
No. 8	42.9	30.9	11.9	-.35	-.29
No. 16	33.7	25.1	8.6	-.18	-.59
No. 30	25.1	18.2	6.8	-.04	-.84
No. 50	16.9	11.9	5.0	.11	-.82
No.100	10.9	7.4	3.5	.32	-.67
No.200	6.4	4.1	2.3	.42	-.66

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	17.691	4.206
3/8 "	18.413	4.291
No. 4	10.318	3.212
No. 8	5.251	2.291
No. 16	3.342	1.828
No. 30	1.756	1.325
No. 50	.788	.887
No.100	.298	.546
No.200	.098	.314

WITHIN BATCH VARIANCE OF A = .0334
WITHIN BATCH STANDARD DEVIATION OF A = .1827

Figure B-13. Data analysis summary, Durham quarry aggregate, section 3-D.

AVERAGE A = 3.472
VARIANCE OF A = .0488
STANDARD DEVIATION OF A = .2209
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	76.46	15.457	3.931	5.14
3/8 "	46.47	23.370	4.834	10.40
No. 4	34.24	14.670	3.830	11.18
No. 8	28.20	9.602	3.098	10.98
No. 16	22.16	5.876	2.424	10.93
No. 30	17.57	3.687	1.920	10.92
No. 50	11.74	1.651	1.285	10.94
No.100	6.87	.585	.765	11.12
No.200	3.47	.169	.412	11.84

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	85.7	63.3	22.4	-.57	.52
3/8 "	57.4	31.4	26.0	-.52	-.01
No. 4	43.0	22.2	20.8	-.55	.06
No. 8	34.9	19.4	15.4	-.49	-.24
No. 16	27.1	15.6	11.4	-.49	-.23
No. 30	21.3	12.6	8.7	-.46	-.23
No. 50	14.5	8.6	5.9	-.43	-.14
No.100	8.6	4.9	3.7	-.34	-.13
No.200	4.4	2.4	2.0	-.14	-.28

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	13.588	3.686
3/8 "	18.816	4.337
No. 4	11.701	3.420
No. 8	7.229	2.688
No. 16	4.597	2.144
No. 30	2.923	1.709
No. 50	1.348	1.161
No.100	.467	.683
No.200	.121	.348

WITHIN BATCH VARIANCE OF A = .0395
WITHIN BATCH STANDARD DEVIATION OF A = .1989

Figure B-14. Data analysis summary, Gresham's Lake aggregate from parent pile (soft stone for degradation studies) (N.C. size No. 8).

AVERAGE A = 3.609
VARIANCE OF A = .0259
STANDARD DEVIATION OF A = .1611
NUMBER OF TESTS = 100

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	78.00	8.883	2.980	3.82
3/8 "	49.16	12.248	3.499	7.11
No. 4	36.70	8.255	2.873	7.82
No. 8	30.31	5.703	2.388	7.87
No. 16	23.86	3.272	1.808	7.57
No. 30	18.92	2.015	1.419	7.50
No. 50	12.66	.871	.933	7.37
No.100	7.42	.288	.536	7.23
No.200	3.85	.079	.282	7.32

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	84.3	69.5	14.8	-.19	-.34
3/8 "	57.4	41.9	15.5	.17	-.57
No. 4	44.1	31.0	13.0	.33	-.41
No. 8	36.8	25.4	11.4	.37	-.28
No. 16	28.8	19.9	8.9	.38	-.09
No. 30	22.7	15.6	7.1	.38	.01
No. 50	15.1	10.3	4.8	.37	.06
No.100	8.8	6.0	2.7	.30	-.14
No.200	4.5	3.1	1.4	.19	-.09

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	4.054	2.013
3/8 "	6.362	2.522
No. 4	5.032	2.243
No. 8	3.712	1.926
No. 16	2.192	1.480
No. 30	1.339	1.157
No. 50	.593	.770
No.100	.206	.454
No.200	.055	.236

WITHIN BATCH VARIANCE OF A = .0149
WITHIN BATCH STANDARD DEVIATION OF A = .1223

Figure B-15. Data analysis summary, Gresham's Lake aggregate, after pug-mill mixture.

AVERAGE A = 3.629
VARIANCE OF A = .0804
STANDARD DEVIATION OF A = .2837
NUMBER OF TESTS = 50

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	78.70	28.545	5.342	6.78
3/8 "	49.18	37.650	6.135	12.47
No. 4	36.38	22.221	4.713	12.95
No. 8	29.99	14.050	3.748	12.49
No. 16	23.93	9.235	3.038	12.69
No. 30	19.27	6.167	2.483	12.88
No. 50	13.23	3.120	1.766	13.34
No.100	8.00	1.274	1.128	14.11
No.200	4.19	.397	.630	15.03

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	86.5	63.9	22.6	-.79	.06
3/8 "	59.1	34.5	24.6	-.47	-.35
No. 4	44.7	25.6	19.0	-.42	-.32
No. 8	36.7	21.5	15.2	-.40	-.30
No. 16	29.3	17.2	12.1	-.26	-.45
No. 30	23.6	13.7	9.8	-.18	-.53
No. 50	16.5	9.3	7.1	-.06	-.63
No.100	10.1	5.6	4.4	.00	-.88
No.200	5.3	2.9	2.3	.02	-1.04

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	7.216	2.686
3/8 "	6.942	2.634
No. 4	4.188	2.046
No. 8	2.589	1.609
No. 16	1.638	1.279
No. 30	1.041	1.020
No. 50	.518	.720
No.100	.202	.450
No.200	.066	.257

WITHIN BATCH VARIANCE OF A = .0143
WITHIN BATCH STANDARD DEVIATION OF A = .1197

Figure B-16. Data analysis summary, Gresham's Lake aggregate, section 1-G.

AVERAGE A = 3.535
VARIANCE OF A = .0699
STANDARD DEVIATION OF A = .2644
NUMBER OF TESTS = 50

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	77.81	21.344	4.620	5.93
3/8 "	47.07	33.898	5.822	12.36
No. 4	34.78	20.114	4.484	12.89
No. 8	28.71	13.907	3.729	12.98
No. 16	22.86	8.367	2.892	12.65
No. 30	18.38	5.278	2.297	12.49
No. 50	12.54	2.425	1.557	12.41
No.100	7.52	.950	.974	12.95
No.200	3.86	.313	.559	14.47

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	85.2	67.3	17.8	-.53	-.69
3/8 "	54.3	28.7	25.6	-.90	.35
No. 4	40.3	20.4	19.8	-.92	.47
No. 8	33.0	17.1	15.8	-.97	.46
No. 16	26.2	14.0	12.1	-.90	.26
No. 30	21.1	11.4	9.6	-.86	.19
No. 50	14.6	8.0	6.6	-.78	.04
No.100	9.0	4.8	4.2	-.57	-.19
No.200	4.8	2.4	2.4	-.30	-.46

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	10.946	3.308
3/8 "	13.724	3.704
No. 4	8.379	2.894
No. 8	5.979	2.445
No. 16	3.815	1.953
No. 30	2.444	1.563
No. 50	1.143	1.069
No.100	.446	.668
No.200	.137	.371

WITHIN BATCH VARIANCE OF A = .0303
WITHIN BATCH STANDARD DEVIATION OF A = .1743

Figure B-17. Data analysis summary, Gresham's Lake aggregate, section 2-G.

AVERAGE A = 3.678
VARIANCE OF A = .0697
STANDARD DEVIATION OF A = .2640
NUMBER OF TESTS = 50

SIEVE NUMBER	AVERAGE PERCENT PASSING	VARIANCE	STANDARD DEVIATION	COEFFICIENT OF VARIATION
1-1/2"	100.00	.000	.000	.00
3/4 "	79.84	21.961	4.686	5.86
3/8 "	50.73	33.866	5.819	11.47
No. 4	37.76	22.343	4.726	12.51
No. 8	30.97	14.459	3.802	12.27
No. 16	24.17	7.908	2.812	11.63
No. 30	19.29	4.811	2.193	11.36
No. 50	13.14	2.204	1.484	11.29
No.100	7.85	.806	.897	11.42
No.200	4.05	.242	.492	12.16

SIEVE NUMBER	MAXIMUM	MINIMUM	RANGE	SKEWNESS	KURTOSIS
1-1/2"	100.0	100.0	.0	.00	.00
3/4 "	87.8	68.4	19.4	-.46	-.51
3/8 "	59.8	37.8	21.9	-.49	-.66
No. 4	45.7	28.0	17.6	-.48	-.69
No. 8	37.3	23.1	14.2	-.51	-.67
No. 16	28.5	18.2	10.3	-.60	-.64
No. 30	22.7	14.5	8.1	-.59	-.57
No. 50	15.4	9.8	5.6	-.56	-.54
No.100	9.2	5.8	3.4	-.50	-.60
No.200	4.8	2.9	1.9	-.32	-.82

SIEVE NUMBER	WITHIN BATCH VARIANCE	WITHIN BATCH STANDARD DEVIATION
1-1/2"	.000	.000
3/4 "	7.817	2.796
3/8 "	7.268	2.696
No. 4	4.713	2.171
No. 8	3.046	1.745
No. 16	1.886	1.373
No. 30	1.251	1.118
No. 50	.604	.777
No.100	.227	.477
No.200	.070	.264

WITHIN BATCH VARIANCE OF A = .0168
WITHIN BATCH STANDARD DEVIATION OF A = .1298

Figure B-18. Data analysis summary, Gresham's Lake aggregate, section 3-G.

APPENDIX C

DEGRADATION STUDIES AGGREGATE SPECIFICATIONS

In the degradation studies reported herein the aggregate used met the North Carolina standard specifications * for "Aggregate for Non-Bituminous Flexible Type Bases," as follows:

. . . — 1.3 **Stabilized Aggregate Base Course.** (a) The stabilized aggregate shall consist of material meeting the requirements of Article — 1.2(a) and (b) herein, and when analyzed prior to spreading on the road, shall meet the grading requirements using AASHO Method T 88,† as follows:

Size No. 8

Sieve Designation	Percentage by Weight Passing
1½ inch	100
1 inch	80–95
½ inch	60–75
No. 4	40–55
No. 10	28–43
No. 40	15–27
No. 200	5–12

The material passing the No. 200 sieve shall be not more than two-thirds the percentage passing the No. 40 sieve.

(b) The fraction retained on the No. 4 sieve prior to spreading on the road shall meet the following requirements:

(1) Section 401-1.2(a) and (b).
(2) When tested in accordance with AASHO Method T 96, test grading A, it shall show a loss of not greater than 55 percent.
(3) The material passing the No. 40 sieve obtained from the above test, Paragraph (b)2, shall have a plasticity index not greater than 6, and a liquid limit not greater than 30, when tested in accordance with AASHO Methods T 89, T 90, T 91 and modification of the Liquid Limit Test described in — 1.1 (b), (1).
(4) When subjected to five alternations of the soundness test, AASHO Method T 104, using sodium sulphate, the weighted average loss shall not be more than 15 percent.

(c) The material passing the No. 4 sieve prior to spreading on the road shall meet the following requirements:

(1) The material passing the No. 10 sieve shall meet the grading requirements using AASHO Method T 88 as follows:

Sieve Designation	Percentage by Weight Passing
No. 10	100
No. 40	40–75
No. 200	12–35

(2) The material passing the No. 40 sieve shall have a plasticity index of not greater than 6, and a liquid limit of not greater than 25, when tested in accordance with AASHO T 89, T 90, T 91 and modification of the Liquid Limit Test described in — 1.1 (b), (1).
(3) The material passing the No. 200 sieve shall not be more than two-thirds the percentage passing the No. 40 sieve.
(4) The fraction passing the No. 10 sieve shall consist of a mixture of screenings or sand, silt, and clay, and it may occur as topsoil or sand clay meeting the requirements without admixture; or it may be deficient in one or more of the ingredients, coarse or fine sand or screenings, silt, or clay, in which case the required ingredient must be incorporated; or it may consist of crushed decomposed rock which shall meet the requirements stipulated in (1), (2) and (3) above.

(d) Components of Stabilized Aggregate Base Course:

(1) The "coarse material" shall consist of all material retained on the No. 4 sieve plus any screenings which occur naturally therewith during the crushing operation.
(2) The "added fines" shall consist of all material passing the No. 4 sieve less the screenings which are included in the "coarse material." The "added fines" shall have a plasticity index of not greater than 6 and a liquid limit of not greater than 25 when tested in accordance with AASHO Methods T 89, T 90, T 91 and modification of the Liquid Limit Test described in — 1.1(b), (1). Clay balls that will not pass the No. 4 sieve will not be permitted in the "added fines," unless such particles are reduced in size during the mixing operation so that they will pass the No. 4 sieve.
(3) The "coarse material" and the "added fines" shall each be prepared separately prior to being combined at the mixer and shall be so proportioned as to meet the final mix requirements.

(e) After the base course has been completed, that portion of the material which passes the No. 40 sieve shall have a plasticity index of not greater than 6 and a liquid limit of not greater than 25, when tested in accordance with AASHO Methods T 89, T 90, T 91 and modification of the Liquid Limit Test described in — 1.1(b), (1).

* Section 401.

† The percent passing the No 200 sieve was determined by the dry method rather than as specified by AASHO Method T-88 Spot checks were made to compare dry sieving versus washing results. The differences were not significant with the material being used The objective was to determine changes in gradation rather than specific quantities of fines.

APPENDIX D

DEVELOPMENT OF MATHEMATICAL MODEL

The mathematical model for depicting segregation, as given in Chapter Four (Eq. 5) was developed to compare actual versus predicted effects of stockpiling method, aggregate type, and gradation.

The first step in the development of the theoretical model required that the variables be arrayed so that quadratic equations could be formulated. It will be recalled that the variables included three stockpiling methods, two aggregate types, and two gradations. The stockpiling methods were coded as P_1 = coned, P_2 = cast-and-spread, P_3 = truck-dumped; the aggregate types were coded as S_1 = crushed stone and S_2 = uncrushed gravel; the gradations were coded G_1 = intermediate grading (Princeton and Baltimore) and G_2 = coarse grading (Gresham's Lake).

An average for the effect of each of the measured variables was then calculated to use in subsequent formulations.

Because the variability was greatest at the passing ¾-in. level, this point was selected for comparing actual versus predicted values. However, any other sieve size or $\bar{A}$ could have been used. Because there were eight unknowns and only six equations, it was necessary to let $p_1 + p_2 + p_3 = 0$; $s_1 + s_2 = 0$; and $g_1 + g_2 = 0$. The lower case letters are used to indicate predicted values, upper case to indicate measured values.

The following equations were then derived to predict each variable:

$$p_1 = \bar{P}_1 - \bar{G} \quad \text{(D-1)}$$

$$p_2 = \bar{P}_2 - \bar{G} \quad \text{(D-2)}$$

$$p_3 = \bar{P}_3 - \bar{G} \quad \text{(D-3)}$$

$$s_1 = \frac{G_1 + 2S_1 - 2G}{6} \quad \text{(D-4)}$$

$$s_2 = -s_1 \quad \text{(D-5)}$$

$$g_1 = \frac{2G_1 + S_1 - \cdot 2G}{6} \quad \text{(D-6)}$$

$$g_2 = g_1 \quad \text{(D-7)}$$

$$m = \frac{G - 3g_1 - 3s_1}{9} \quad \text{(D-8)}$$

in which

G = grand total of all standard deviations;
$\bar{G}$ = average of all standard deviations;
$\bar{P}_1, \bar{P}_2, \bar{P}_3$ = the average standard deviation resulting from each of the three methods of stockpile construction;
m = adjusted mean standard deviation.

Other symbols have meanings as previously defined. It can be seen that the theoretical or predicted values are based on the values actually measured.

Solution of Eqs. D-1 through D-8 provides specific values which indicate the relative effect of each variable on the adjusted mean in

$$\sigma_{\text{pred}} = m + p + g + s + e \quad \text{(D-9)}$$

in which e is an error constant resulting from unidentified sources, and p, g, and s are the effects of the particular stockpiling method, gradation, and aggregate type, respectively.

Substantially more data, obtained by repeating the stockpiling experiment several times, would be required to fully test the fit of the model and accurately evaluate the effects of the various factors.

APPENDIX E

GLOSSARY, SYMBOLS, AND ABBREVIATIONS

This listing presents explanations of statistical, mathematical, and technical terms as applied to quality control of highway construction, followed by commonly used symbols and abbreviations. In individual items, significant associated terms explained elsewhere in the glossary are capitalized.

ACCEPTANCE DECISION — A determination of acceptability of a MATERIAL, product, or process based on statistical or mathematical principles.

ACCURACY — The agreement between a measured value and a true value.

ADJACENT INCREMENTS — INCREMENTS which are not separated by like MATERIAL.

AGGREGATES (COARSE) — Certain specified GRADATIONS of mineral particles, usually larger than ¼ in. in size.

AGGREGATES (FINE) — Usually mineral particles, less than ¼ in. in size.

ALIQUOT — A part of a quantity which divides the quantity evenly, with no remainder; for example, ¼ or ⅒.

ALPHA RISK (α) — The PROBABILITY of rejecting good MATERIAL; also called Type 1 error.

ANALYSIS OF VARIANCE (ANOV) — A mathematical method of isolating causes of VARIATION.

ANGLE OF REPOSE — The slope formed by a free-flowing particulate matter when acted upon by the force of gravity.

ARRAY — An orderly arrangement of a group of numbers.

ASSIGNABLE CAUSE — A relatively large FACTOR, usually due to error or process change, which contributes to VARIATION and whose effects are of such importance as to justify time and money required for its identification.

ASYMPTOTE — A straight line that is continuously approached but never reached by a curved line.

ATTRIBUTE — A CHARACTERISTIC which is classified instead of measured.

AVERAGE ($\bar{X}$) — A measure of central value which usually refers to the arithmetic mean obtained by dividing the sum of n values by n.

BATCH — A UNIT or subdivision of a LOT, such as a mixer-truck load of concrete, or a square yard of subbase.

BETA RISK (β) —The PROBABILITY of accepting poor MATERIAL; also called a Type II error.

BIAS — A constant error, in one direction, which causes the AVERAGE of a number of measurements to be offset from the true value of the true measure of CENTRAL TENDENCY.

BIASING — Favoring one kind of result.

CELL BOUNDARIES — The upper and lower limits of a subgroup of numbers called a class.

CENTRAL TENDENCY — The property of many DATA to cluster about some single value.

CHARACTERISTIC — A measurable property of a MATERIAL, product, or type of CONSTRUCTION.

CLASS INTERVAL — A convenient subdivision of the total RANGE of a VARIABLE.

COEFFICIENT OF VARIATION (v) — The SIGMA of a group of measurements divided by their AVERAGE and multiplied by 100.

COMPONENTS OF VARIANCE — The individual VARIANCES that act cumulatively to produce the OVERALL VARIANCE.

CONFIDENCE INTERVAL — The RANGE that has a designated DEGREE OF ASSURANCE of including the true value upon repeated sampling.

CONFIDENCE LIMITS — The maximum and minimum values which define the CONFIDENCE INTERVAL.

CONSTANT — A number that remains the same throughout a series of calculations.

CONSTRUCTION — The end result of processing and placing MATERIALS or products in accordance with explicitly stated conditions; for example, a mile of finished concrete pavement.

CONSUMER'S RISK — The risk of accepting poor MATERIAL (see BETA RISK).

CONTIGUOUS — Having contact on most of one side.

CONTIGUOUS INCREMENTS — INCREMENTS that are in contact with each other.

CONTROL CHART — A graphic method of displaying DATA for the purpose of detecting ASSIGNABLE CAUSES of VARIATIONS in a repetitive process.

CORRELATION — A relationship which exists between two or more VARIABLES, and is often expressed as a RATIO known as the CORRELATION COEFFICIENT.

CORRELATION COEFFICIENT — A number having a value from -1 to $+1$ which shows the degree of relation between two VARIABLES; a value of zero indicates absence of CORRELATION.

DATA — Measurements collected for a planned purpose and suitable for the inference of conclusions.

DEFECT — An imperfection or fault which bars an item from acceptance.

DEGRADATION — Reduction in size of aggregate particles by accidental crushing or wear.

DEGREE OF ASSURANCE — The PROBABILITY that a CONFIDENCE INTERVAL has of including the true value; also called confidence coefficient or confidence level.

DEGREE OF SEGREGATION — A measure of the principal source of VARIATIONS in the GRADATION of AGGREGATE. It is computed by dividing the OVERALL VARIANCE by the maximum or parent VARIANCE.

DEGREES OF FREEDOM (d.f.) — The number of measurements (n) less the number of CONSTANTS derived from them. When only one AVERAGE has been taken, d.f. = $(n - 1)$; when only the VARIATION around group AVERAGES is determined, the DEGREES OF FREEDOM are the total number of measurements in the groups less the number of groups.

DISTRIBUTION — An arrangement of DATA which shows the FREQUENCY of occurrence of each successive individual measurement or RANGE of measurements.

ESTIMATOR ($\wedge$) — A function of the measurements on SAMPLES which provides a numerical estimate of a PARAMETER.

EXPERIMENTAL ERROR — The difference between measurements on two identically treated UNITS.

F-TEST — A method of comparing the RATIO of (1) the larger to the smaller SAMPLE VARIANCE to (2) a tabular value for the purpose of determining the PROBABILITY that the difference was due to chance.

FACTOR — A VARIABLE or ATTRIBUTE which may influence the CHARACTERISTIC being investigated.

FINENESS MODULUS (FM) — An empirical FACTOR obtained by adding the total percentages of a SAMPLE of the AGGREGATE retained on each of the STANDARD

SIEVES and dividing by 100. These sieves include the No. 100, No. 50, No. 30, No. 16, No. 8, No. 4, ⅜ in., ¾ in., 1½ in. and larger, increasing in the RATIO of 2 to 1.

FINES — Usually mineral particles which are less than 74 μ in size (passing a No. 200 STANDARD SIEVE).

FLOW SHEET — A diagram showing the movement of a product through a process.

FRAME — That group of objects about which inferences are to be made.

FREQUENCY — The number of times that a measurement falls within the limits of a CLASS INTERVAL.

GOODNESS OF FIT — Relationship of experimental measurements in a theoretical curve.

GRADATION — A general term used to describe the composition particle size of the AGGREGATE in a mixture; GRADATION is usually expressed as the PROPORTION (percent) of the AGGREGATE that will pass each of several sieves of different sizes.

HISTOGRAM — A type of bar chart which displays in terms of area the relative number of measurements of different classes; the width of the bar represents the CLASS INTERVAL, the height represents the number of measurements.

HUDSON ($\bar{A}$) — The term for a FACTOR which expresses the relative coarseness of an AGGREGATE GRADATION in a single number. It is found by summing the percentages passing the 1½ in., ¾ in., ⅜ in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 sieves and dividing by 100.

HYPOTHESIS (HYPOTHESES) — A statement of a possible but not certain truth.

INCREMENT — The smallest UNIT removed from a LOT during sampling.

INHERENT VARIANCE (σ_a) — A VARIANCE due to RANDOM or insignificant causes.

INTERACTION — The difference in the effect produced by one FACTOR when another FACTOR changes in value.

ITERATION — A method of finding a required value by means of successive estimates.

KURTOSIS — The flatness or peakedness of a DISTRIBUTION represented by a curve.

LEVELS — The values of a FACTOR which are included in an experiment.

LOT — An isolated quantity of MATERIAL from a single source. A measured amount of CONSTRUCTION assumed to be produced by the same process. When several true LOTS are combined, the result is a "grand LOT."

MATERIAL — A part, component, or ingredient such as portland cement or AGGREGATE, which when combined with other MATERIALS forms a product, such as concrete.

MEAN SQUARE — A sum of squares of measurements divided by associated DEGREES OF FREEDOM.

MEDIAN — The value in the middle of a RANKED ARRAY of an odd number of measurements, or the AVERAGE of the two central values in an even number of measurements.

MIDRANGE — One-half the sum of the minimum and maximum values in a group of measurements.

MODE — A typical value which occurs most often in an ARRAY of measurements.

NORMAL CURVE — A curve having a bell-shaped form which depends on values of X' and σ', and which shows the DISTRIBUTION of individual values of measured CHARACTERISTICS about their AVERAGE.

NORMAL DISTRIBUTION — A DISTRIBUTION represented by the NORMAL CURVE.

OVERALL VARIANCE (σ^2_o) — The sum of all RANDOM ERRORS and ASSIGNABLE CAUSES which may be expressed as the sum of several VARIANCES. It controls the number of measurements required for a desired ACCURACY and DEGREE OF ASSURANCE.

PARAMETER — A CONSTANT or coefficient that describes some CHARACTERISTIC of the DISTRIBUTION of a series of measurements.

PORTION — Any small part of a larger quantity.

PRECISION — The VARIANCE of repeated measurements of a CHARACTERISTIC.

PROBABILITY — The relative FREQUENCY of occurrence.

PROBABILITY DISTRIBUTION — A mathematical expression which makes possible the determination of the PROBABILITY that a VARIABLE will occur within a certain RANGE.

PROBABILITY SAMPLE — One in which every object in the FRAME has a known chance of inclusion.

PROCESS CONTROL — A method based on the application of STATISTICS used to regulate the uniformity of a MATERIAL, product, or process.

PRODUCER'S RISK — The PROBABILITY of having good MATERIAL rejected. (see ALPHA RISK).

PROPORTION — The relationship between four numbers in which the result of dividing the first by the second is the same as the result of dividing the third by the fourth; for example, 2 is to 6 as 3 is to 9.

QUARTERING — A method of reducing a SAMPLE to testing size. The MATERIAL is mixed and formed into a cone, and the cone is then flattened and separated cleanly into four parts. Two diagonally opposite parts are removed, the remaining MATERIAL is remixed, and the QUARTERING repeated until the remaining quarters are of the desired size.

RANDOM — Without aim or reason, depending entirely on chance. When a sampling process is said to be RANDOM, each item in the FRAME has an equal PROBABILITY of being chosen.

RANDOM ERRORS — Differences from the true value, due to chance, which behave as though chosen at RANDOM from a PROBABILITY DISTRIBUTION.

RANDOMNESS — A concept referring to a condition of complete disorder of individual measurements.

RANDOM NUMBER — A number selected from a table of RANDOM sampling numbers.

RANGE — The difference between the highest and lowest value in a group of measurements.

RANKED — Refers to measurements arranged in ascending order from smallest to largest.

RATIO — A fixed relation between two amounts, usually expressed as a fraction or a decimal obtained by dividing one number by the other.

REFUSAL — The end point of a GRADATION test at which no more AGGREGATE particles will pass through the sieve.

REGRESSION ANALYSIS — A method of investigating the relationship between two or more VARIABLES.

REJECT — An item or quantity of MATERIAL having CHARACTERISTIC values outside of acceptable limits.

REPEATABILITY — The RANGE within which repeated measurements are made by the same operator on the same apparatus; essentially, the PRECISION of the test.

REPLICATION — The repetition of an experiment.

REPRESENTATIVE — Serving as an example or specimen of a group of objects from a LOT of MATERIAL.

REPRESENTATIVE SAMPLE — A relatively small PORTION, having the same values of CHARACTERISTICS as the BATCH or LOT from which it is taken.

REPRODUCIBILITY — The RANGE within which check measurements by different operators on different apparatus should agree under definitely stated conditions.

RESIDUAL VARIATION — The VARIATION which remains in a set of DATA after the VARIATIONS due to known FACTORS and INTERACTIONS have been removed.

RIFFLING — A method of reducing the volume of a SAMPLE to testing size. The SAMPLE is poured into the hopper of a riffle. Chutes in the riffle divide the SAMPLE into two equal parts, and each part is directed into a separate pan. The contents of one pan are set aside, and the contents of the other are poured into the riffle hopper. The process is repeated until one pan contains the right amount of MATERIAL for testing.

SAMPLE — A small part of a LOT which represents the whole. A SAMPLE may be made up of one or more INCREMENTS or TEST PORTIONS.

SAMPLING ERROR (σ^2_s) — The VARIANCE between SAMPLES taken from the same BATCH.

SEGMENT — An arbitrary division of a LOT, which may be either real or imaginary.

SEGREGATION — Separation of portions of a mixture from the mass. In a stockpile consisting of a mixture of large and small particles of AGGREGATE, the large particles tend to segregate by separating from the mixture.

SEGREGATION INDEX (S) — A RATIO related to the degree to which a LOT is separated into unlike parts.

SEGREGATION VARIANCE (σ^2_l) — The VARIATION (VARIATION COMPONENT) which is entirely dependent on the method of transporting, handling, and STOCKPILING an AGGREGATE. This value is determined by difference between OVERALL VARIANCE and WITHIN-BATCH VARIANCE ($\sigma^2_l = \sigma^2_o - \sigma^2_b$).

SIGMA (σ) — A term used in STATISTICS to indicate the value calculated from the differences between the individual measurements in a group and their AVERAGE. Also called STANDARD DEVIATION.

SIGMA PRIME (σ') — The true value of SIGMA when all UNITS in a FRAME are considered.

SIGNIFICANT DIFFERENCE — A spread between two values too great to be due to chance alone, usually proved by a STATISTICAL test, as distinguished from a technically or economically meaningful difference.

SIGNIFICANT NUMBER — The smallest digit of a number that would have an effect on the ACCURACY of an answer determined by using that number.

SKEWNESS — Refers to a DISTRIBUTION that is not symmetrical.

SPACED SAMPLES — SAMPLES separated by some predetermined distance or volume.

SPECIFICATION — A descriptive statement of conditions of acceptability as to size, quality, performance, method, or other essential CHARACTERISTICS or ATTRIBUTES.

STANDARD DEVIATION — See SIGMA.

STANDARD SIEVES — Those screens used in AGGREGATE GRADATION analysis in which the size of the openings is successively halved as the sizes decrease. These sieves are as follows: 1½ in., ¾ in., ⅜ in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200.

STATISTIC — A summary value such as $\bar{X}$, σ, or R, computed from a group of measurements.

STATISTICAL ANALYSIS — A mathematical method of obtaining meaningful information from DATA.

STATISTICALLY — By means of STATISTICS.

STATISTICS — The science which deals with the treatment and analysis of numerical DATA; also a collection of numerical DATA.

STOCKPILING — Storage of AGGREGATES for later use in piles separated by bulkheads or intervening space.

SYSTEMATIC SAMPLES — SAMPLES taken at predetermined intervals of time, distance, or volume.

t DISTRIBUTION — A DISTRIBUTION slightly wider than the NORMAL CURVE used to estimate PROBABILITIES when only a small number of measurements is available.

t TEST — A method of testing a HYPOTHESIS regarding means.

TEST PORTION — The part of a SAMPLE actually tested; usually obtained by reducing the SAMPLE by QUARTERING, RIFFLING, or taking an ALIQUOT quantity.

TESTING ERROR (σ^2_t) — VARIATION caused by reducing a SAMPLE to a TEST PORTION and to the lack of REPEATABILITY of the test method.

TOLERANCE (Δ) — The permissible extreme deviation (Δ) of the measurement of a CHARACTERISTIC from a desired value.

TREATMENT — The particular set of conditions which will be applied to a unit in an experiment.

UNBIASED ESTIMATOR — One whose expected value is equal to the FRAME PARAMETER being estimated (see ESTIMATOR).

UNIFORMITY COEFFICIENT (C_u) — The RATIO of the diameter of the 60 percent finer point to that at the 10 percent finer point on the GRADATION curve.

UNIT — A small part of a LOT represented by a SAMPLE. It is assumed that VARIATIONS within the UNIT are due to chance and do not affect the performance of the LOT. A UNIT may be a square foot or square yard of pavement, a BATCH of concrete, or a ton of AGGREGATE.

VARIABLE — A measurement that can have a series of different values.

VARIABILITY — A tendency to be VARIABLE.

VARIANCE — The square of the SIGMA of the SAMPLE (σ^2) or of the true value $(\sigma')^2$.

VARIATION — Differences, due to any cause, in measured values of a measurable CHARACTERISTIC.

WITHIN-BATCH VARIANCE ($\sigma^2{}_b$) — A VARIANCE having a value that depends on the amount of difference of the measurements on two INCREMENTS taken from the same BATCH.

WITHIN-LOT VARIANCE ($\sigma^2{}_l$) — A VARIANCE having a value that depends on the amount of difference among INCREMENTS taken from different parts of a LOT.

SYMBOLS AND ABBREVIATIONS

$\bar{A}$ (HUDSON $\bar{A}$) — Symbol for a FACTOR which expresses the relative coarseness of an AGGREGATE GRADATION as a single number. It is found by summing the percentages passing the 1½ in., ¾ in., No. 4, No. 8, No. 16, No. 30, No. 50, No. 100, and No. 200 STANDARD SIEVES.

$\bar{\bar{A}}$ — Symbol for the AVERAGE of two or more values of $\bar{A}$.

ANOV — Abbreviation for ANALYSIS OF VARIANCE.

($\wedge$) — The caret, which is placed over a PARAMETER to indicate an estimate.

Δ (DELTA) — Symbol for degree of accuracy of the TOLERANCE, which is the maximum allowable difference between results to be obtained from the measurements and the true value.

d.f. — Abbreviation for DEGREES OF FREEDOM, a number associated with a MEAN SQUARE, and indicating the reliability of the MEAN SQUARE as an estimate for SIGMA PRIME.

d_2 — Symbol for the FACTOR given in Table II, Part 3, *ASTM STP 15-C*, which is a function of n and which is used to convert R to an estimate of σ.

i — An index which identifies an item in a series which is to be summed.

log — When placed before a number, indicates that the common, or Briggs, logarithm of the number is to be taken.

m — Symbol for the number of UNITS or measurements in a subgroup.

n — Symbol for the number of measurements, or subgroups, in a group.

P — Percent by weight of AGGREGATE passing a designated sieve.

R — Symbol for the RANGE, which is the difference between the largest and smallest number in a set of numbers.

$\bar{R}$ — Symbol for the AVERAGE of a number of RANGES.

Σ — Symbol indicating that values are to be totaled or summed.

$\sum_{i=1}^{n} X$ — Indicates that an entire series should be summed:

$$\sum_{i=1}^{n} X = (X_1 + X_2 + X_3 + \ldots X_n)$$

σ (SIGMA) — Symbol for the STANDARD DEVIATION, which is a measure of the dispersion of measurements from their AVERAGE and is an estimate of the true value σ'. It is the square root of the sum of the squares of the deviations from their AVERAGE, divided by their number less one; it may be calculated by

$$\sigma = \sqrt{\frac{\Sigma X^2 - (\Sigma X)^2/n}{n-1}}$$

σ' (SIGMA PRIME) — Symbol for the true value of SIGMA.

$\bar{\sigma}$ (SIGMA-BAR) — Symbol for the AVERAGE of two or more values of SIGMA.

$\sigma^2{}_a$ — Symbol for the INHERENT or actual VARIATION in a MATERIAL or product despite the closest practical control of VARIABLES.

$\sigma^2{}_b$ — Symbol for WITHIN-BATCH VARIANCE where a BATCH is some subdivision of a LOT such as a mixer-truck load of concrete or a load of subbase MATERIAL. The value depends largely on the method of collecting the SAMPLES and on the tools used.

$\sigma^2{}_l$ — Symbol for WITHIN-LOT VARIATION due to long-term SEGREGATION.

$\sigma^2{}_o$ — Symbol for OVERALL VARIANCE.

$\sigma^2{}_t$ — Symbol for VARIATION caused by reducing SAMPLE to testing size and that due to TESTING ERROR.

t — Symbol for a DISTRIBUTION slightly more spread out than a NORMAL DISTRIBUTION, used when only a limited number of measurements are available.

v — Symbol for COEFFICIENT OF VARIATION, which is a measure of relative PRECISION found by dividing the SIGMA of a set of values by their AVERAGE and multiplying by 100 to express as a percentage.

X — Symbol for an observed value of a measurable CHARACTERISTIC, or the AVERAGE of the m values in a subgroup.

$\bar{X}$ — Symbol for the AVERAGE, or arithmetical mean, found by dividing the sum of n measurements by n.

$\bar{\bar{X}}$ — Symbol for a grand AVERAGE, or the AVERAGE of AVERAGES.

z — Symbol for the distance from the centerline to a point on the base of the NORMAL DISTRIBUTION CURVE, expressed in SIGMA units.

APPENDIX F

SAMPLING PLANS

The schematic sampling plans shown in Figures F-1, F-2, and F-3 represent three possible schemes for securing unbiased samples. Many other variations of these plans are possible. The most appropriate plan depends on the sampling situation and on the information to be extracted from the measurements on the sample.

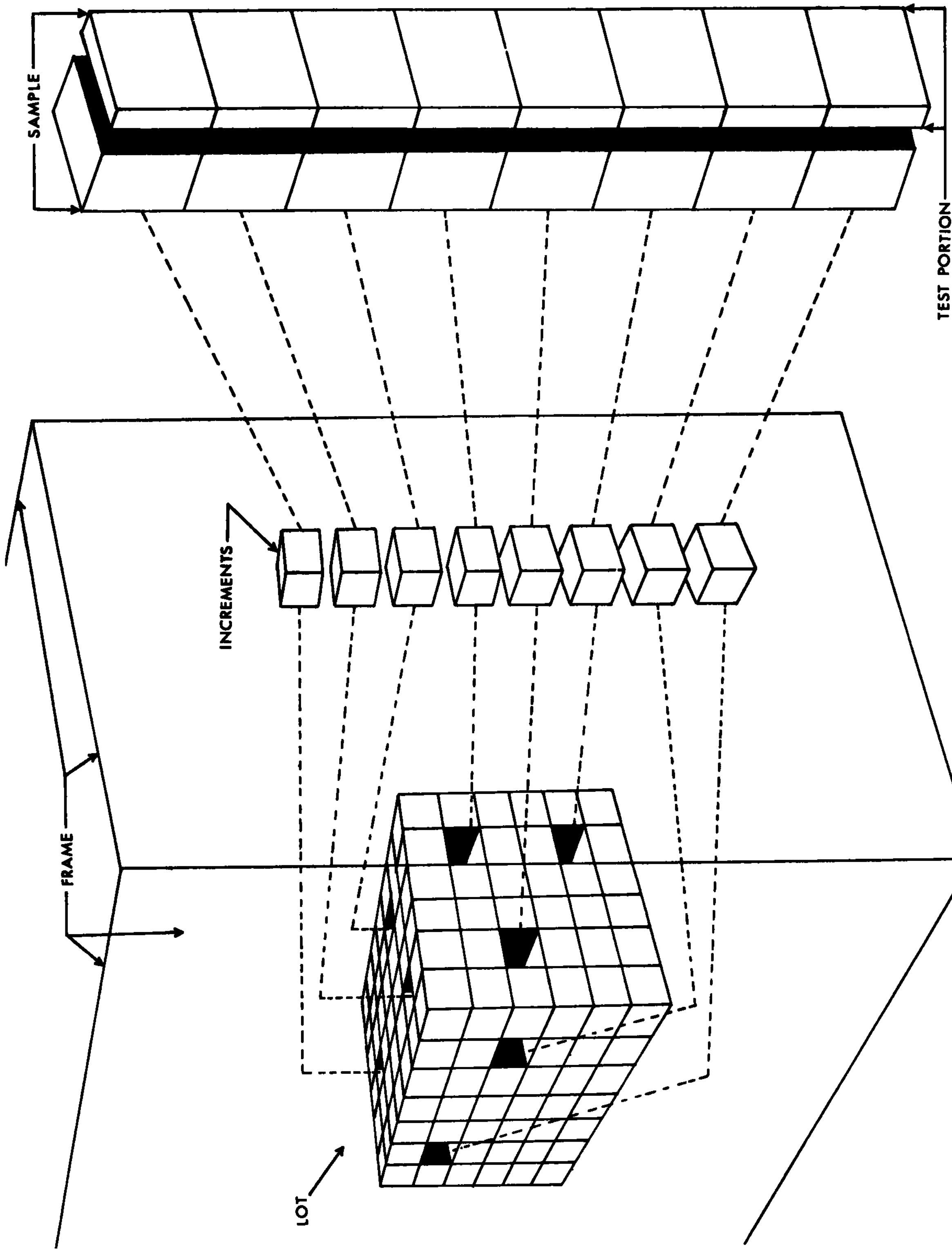


Figure F-1. Typical sampling plan for determining average gradation.

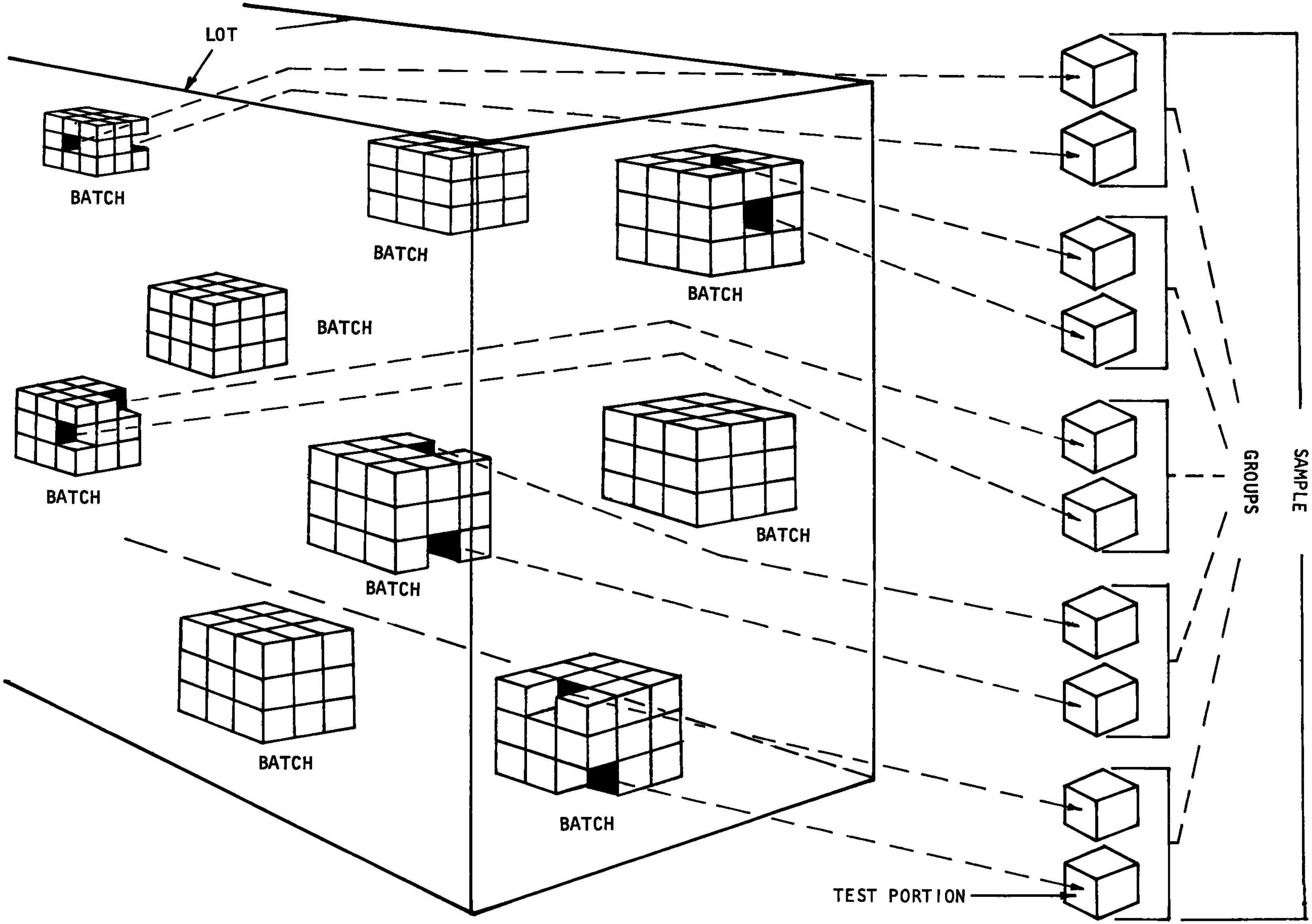


Figure F-2. Typical sampling plan for determining average gradation, within-lot variation, and within-batch variation.

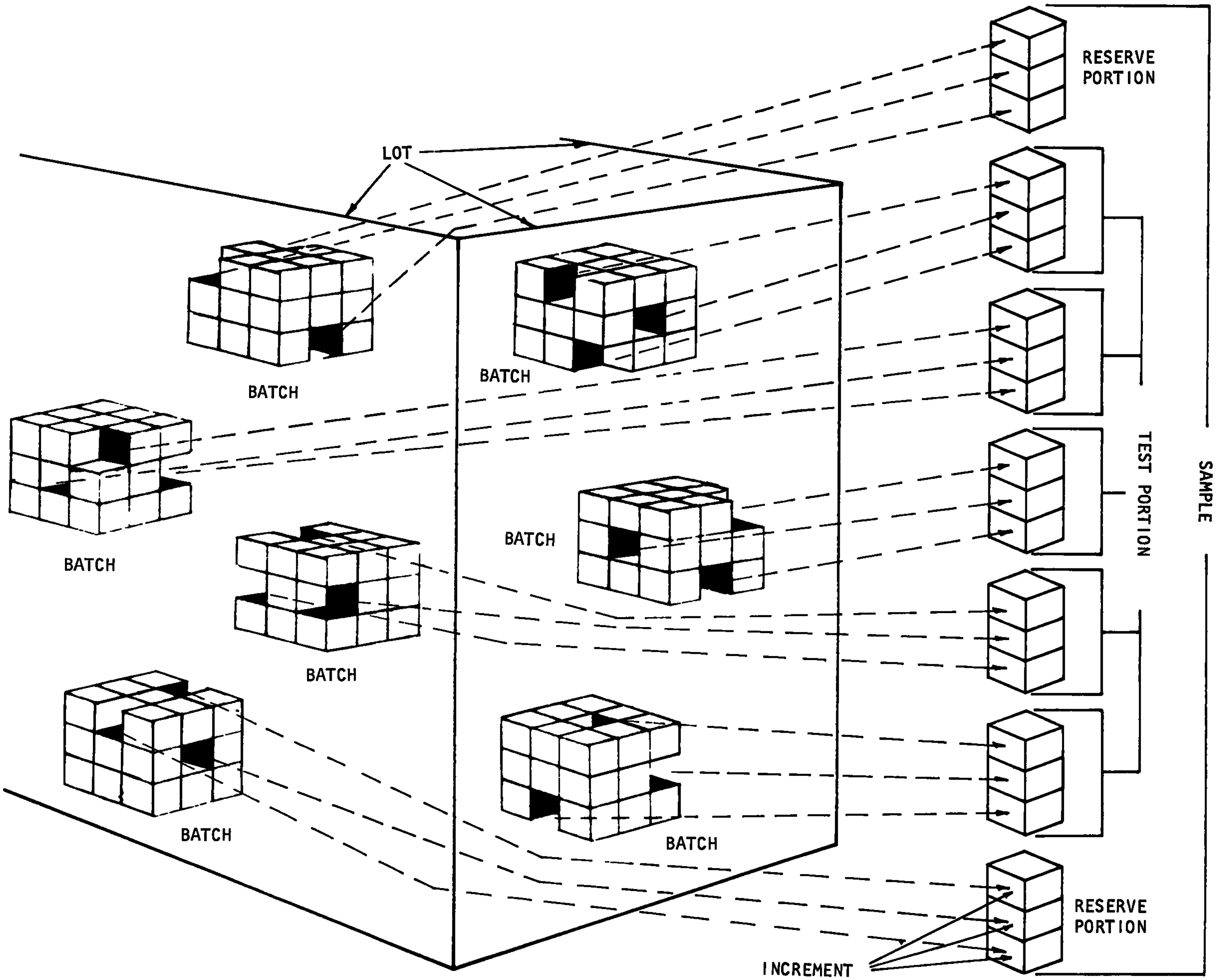


Figure F-3. Typical sampling plan for determining average gradation and within-lot variation for acceptance testing.

APPENDIX G

BIBLIOGRAPHY

1. ALLEN, E. P., "Petrography and Engineering Aspects of the Princeton Quarry of the Nello L. Teer Company." Report No. 1, pp. 1-5 (Oct. 1957) (unpublished).
2. ANDERSON, W. W., and SUTHERLAND, M. L., "The Variances of Reduction and Analysis—Symposium on Coal Sampling." *ASTM Spec. Pub. No. 162,* pp. 116-125 (June 1954).
3. ASTM Committee E-11 on Quality Control of Materials, "ASTM Manual on Quality Control of Materials." *ASTM STP 15-c* (Jan. 1951) pp. 1-136.
4. ASTM E-11. "Sampling Plans in ASTM Specifications." *ASTM Bull.* (July 1957) pp. 47-51.
5. ASTM STANDARD E 11-61. "Specification for Sieves for Testing Purposes (Wire Cloth Sieves, Round-Hole and Square-Hole Plate Screens or Sieves)."
6. ASTM STANDARD E 29-60 T. "Recommended Practices for Designating Significant Places in Specified Limiting Values (Tentative)."
7. ASTM STANDARD E 105-58. "Recommended Practice for Probability Sampling of Materials."
8. ASTM STANDARD E 122-58. "Recommended Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process."
9. ASTM STANDARD E 141-61. "Recommended Practice for Acceptance of Evidence Based on the Results of Probability Sampling."
10. ASTM STANDARD E 177-61 T. "Recommended Practice for Use of the Terms Precision and Accuracy as Applied to Measurement of a Property of a Material (Tentative)."
11. AUVIL, H. S., and GAYLE, J. B., "Physical Properties of Coke: Size and Its Measurement." *Bureau of Mines Report of Investigations 4735,* pp. 1-27 (Oct. 1950).
12. BAILEY, E. G., "Accuracy in Sampling Coal." *Jour. Ind. and Eng. Chem.,* pp. 161-178 (Mar. 1909).
13. BAKER, R. F., "A Study to Determine the Normal Variation in Aggregate Gradation by Asphalt Plants—Part 1." *Rep. No. EES-201-1,* Eng. Exper. Sta., Ohio State Univ. (Aug. 1962) pp. 1-41.
14. BEHRE, H. A., revised by HASSIALIS, M. D., "Sampling." *Handbook of Mineral Dressing,* TAGGART, A. F., Editor, Section 19, pp. 19-01-19-208 (1945).
15. BENSON, J. R., "The Grading of Aggregates for Bituminous Construction." *ASTM STP No. 83* (1948), pp. 117-133.
16. BERTHOLF, W. M., "The Analysis of Variance in a Sampling Experiment—Symposium on Bulk Sampling." *ASTM STP 114* (1951) pp. 36-45, 58-65.
17. BERTHOLF, W. M., "The Development of the Theoretical Basis of Coal Sampling—Symposium on Coal Sampling." *ASTM STP No. 162,* pp. 5-29 (June 1954).
18. BERTHOLF, W. M., and WEBB, W. L., "Tests of Geary-Jennings Sampler at Cabin Creek—Symposium on Coal Sampling." *ASTM STP No. 162,* pp. 83-112 (June 1954).
19. BERTHOLF, W. M., "The Effect of Increment Weight on Sampling Accuracy—Symposium on Bulk Sampling." *ASTM STP 242* (1958) pp. 27-43.
20. BICKING, C. A., "Observations on the Application of Statistical Techniques to ASTM Standards." ASTM Bull. (Sept. 1954) pp. 48-52.
21. BICKING, C. A., "Bibliography on Sampling of Raw Materials Products in Bulk." *Tappi* (Mar. 1964).
22. BICKING, C. A., "Bibliography on Sampling of Raw Materials and Products in Bulk." *Tappi,* Vol. 47, No. 5, pp. 147A-170A (May 1964).
23. BINGHAM, R. S., JR., "Bulk Sampling—A Common Sense Viewpoint." *Tappi,* Vol. 46, No. 5, pp. 288-296 (May 1963).
24. BRITISH STANDARDS INSTITUTION, "Methods for Sampling and Testing of Mineral Aggregates, Sands and Fillers." *British Standard* 812 (1960).
25. BROWN, R. L., "Student's Medal Competition, 1939—The Fundamental Principles of Segregation." *Inst. of Fuel,* pp. 15-19 (Oct. 1939).
26. BURMISTER, D. M., "The Grading-Density Relations of Granular Materials." *Proc. ASTM,* Vol. 38, Part II, pp. 587-601 (1938).
27. BUSLIK, D., "Mixing and Sampling with Special Reference to Multi-Sized Granular Material." *ASTM Bull. (TP92),* pp. 66-73 (Apr. 1950).
28. CLIVE, R., and SLATER, L., "Size Classification and Grading of Yorkshire Coals—Abstract of a Report on the Size Classification and Grading of Yorkshire Coal Made to the Yorkshire Coal-Owners by a Special Committee Appointed by the Yorkshire Advisory Committee on Research." *Trans. Inst. Mining Eng.,* Vol. 94, pp. 41-69 (1937-1938).
29. CORDON, W. A., "Size and Number of Samples and Statistical Considerations in Sampling." *ASTM STP 169* (1955) pp. 14-21.
30. CORYELI, R. L., SCHWERD, F. J., and PARENTE, E. J., "Tests of Accuracy of a Mechanical Coal Sampler—Symposium on Coal Sampling." *ASTM STP No. 162,* pp. 72-82 (June 1954).
31. CURRY, R. L., "Methods for Sampling and Determining Sieve Analysis of Aggregates Larger Than One and One-Half Inch Sieve." *Tech. Rep. No. 6-543,* U. S. Army Engineers, Waterways Experiment Station, Vicksburg, Miss., 30 pp. (May 1960).

32. DUNCAN, A. J., "Bulk Sampling: Problems and Lines of Attack." *Technometrics*, Vol. 4, No. 3 (1962).
33. DUNCAN, D. B., "Statistical Methods Applied to Highway Research Experimentation." *Proc. HRB*, Vol. 33, pp. 112-120 (1954).
34. ESKE, M., and MORRIS, H. C., "A Test for Production of Plastic Fines in the Process of Degradation of Mineral Aggregates." *ASTM STP No. 277*, pp. 122-126 (Oct. 1959).
35. FRITTS, S. S., "Law of Size Distribution." *Rock Products*, pp. 64-90 (May 1941).
36. GOODE, J. F., and LUFSEY, L. A., "A New Graphical Chart for Evaluating Aggregate Gradation." *Pub. Roads* (May 1962) pp. 13-26.
37. GRIFFIN, M. L., "A Mathematical View of Sampling, with Reference to the Degree of Accuracy to Be Obtained." *Jour. Soc. Chem. Ind.*, Vol. 28, pp. 192-194 (Feb. 1908).
38. GRUMELL, E. S., "A Decade of Sampling." *Trans. Am. Inst. of Mining and Metallurgical Eng.*, Vol. 139, pp. 11-48—Coal Div. (1940).
39. GRUMELL, E. S., and KING, J. G., "The Sampling of Coal and Coke." *Inst. of Fuel*, pp. 143-159 (Feb. 1933).
40. HARRA, G. W., "Degradation of Aggregates." *Pacific Builder and Eng.*, p. 86 (Sept. 1962).
41. HAZEN, S. W., JR., and BERKENKOTTER, R. D., "An Experimental Mine-Sampling Project Designed for Statistical Analysis." *Bur. of Mines Report of Investigations 6019*, pp. 1-111 (1962).
42. HEBDEN, J., and JOWETT, G. H., "The Accuracy of Sampling Coal." *Appl. Stat.*, Vol. 1, No. 2 (1952).
43. HEBLEY, H. F., "Coal Segregation Problems." *Fuel Engineers Appalachian Coals, Inc.*, Vol. 4, 15-18, pp. 63-71 (July 1936-Mar. 1937).
44. HOSKING, J. R., and SHERGOLD, F. A., "The Effect of Some Operating Conditions on the Efficiency of Separation of a Vibratory Screen," *Quarry Man. Jour.*, pp. 135-140 (Apr. 1962).
45. JOHNSON, E. E., "Sample Size for Specified Confidence Interval." *Ind. Qual. Control*, Vol. 20, pp. 40-41 (Dec. 1963).
46. JORDAN, J. P. R., "Problems Associated with Research on Aggregates." *Cement Lime and Gravel*, Vol. 37 (3), pp. 73-76 (Mar. 1962).
47. JOWETT, G. H., "The Accuracy of Systematic Sampling from Conveyor Belts." *Appl. Stat.*, Vol. 1, No. 1 (1952).
48. LACEY, P. M. C., "The Mixing of Solid Particles—The Application of Theory to Practice." *Chem. Age*, pp. 119-124 (Aug. 11, 1945).
49. LACEY, P. M. C., "The Mixing of Solid Particles—II. Some Practical Experiments." *Chem. Age*, pp. 145-148 (Aug. 18, 1945).
50. MANNING, A. B., "The Theory of Sampling Granular Material for the Determination of Size Distribution." *Inst. of Fuel*, pp. 153-155 (Dec. 1937).
51. MCKEEVER, H. J., "Gradation: Multi-Million Dollar Headache." *Roads and Streets* (Oct. 1963) p. 73.
52. MCPHERSON, A. T., "What Price Accurate Test Methods?" *ASTM Bull. No. 244* (Feb. 1960) pp. 7, 10, 14.
53. MILLER-WARDEN ASSOCIATES, "A Plan for Expediting the Use of Statistical Concepts in Highway Acceptance Specifications." *M-W Tech. Report No. 201*, Restyled 11-'63. (Prepared for Dept. of Commerce, Bureau of Public Roads, Office of Research and Development, Contract CPR 11-8718) (Aug. 1963) 122 pp.
54. MINOR, C. E., "Degradation of Mineral Aggregates." *ASTM STP No. 277*, pp. 109-121 (Oct. 1959).
55. MISKIMEN, T. A., and THURSTON, R. S., "Multilot Sampling—The Accuracies in Sampling of Large Coal Shipments by Application of the Variance Concept—Symposium on Coal Sampling." *ASTM STP No. 162*, pp. 129-136 (June 1954).
56. MITCHELL, D. R., "Segregation in the Handling of Coal." *Am. Inst. Mining and Metallurgical Eng. Tech. Pub. No. 864* (Class F, Coal Division, No. 86) pp. 1-24 (1937).
57. MITCHELL, D. R., "Coal Segregation Problems." *Fuel Engineers Appalachian Coals, Inc.*, Vol. 4, 15-18, pp. 46-62 (July 1936-Mar. 1937).
58. MURPHY, G., "Sampling of Materials." *ASTM Bull.* (May 1941) pp. 25-28.
59. NETTLETON, E. T., "Crushing, Sizing, Testing and Specifying Aggregates." *Rock Prod.* (Apr. 1939) pp. 45-46.
60. NETTLETON, E. T., "How Accurate are Sieve Tests?" *Rock Prod.* (Oct. 1939) pp. 45-46.
61. NETTLETON, E. T., "Human Error in Sampling." *Rock Prod.* (Nov. 1939) pp. 41-42 and 52.
62. NETTLETON, E. T., "Check Screens for Efficiency." *Rock Prod.* (Dec. 1939) pp. 35-36.
63. NETTLETON, E. T., "Breakage and Segregation." *Rock Prod.* (Feb. 1940) pp. 29-30 and 32.
64. NETTLETON, E. T., "Problem of Elongated Pieces." *Rock Prod.* (Apr. 1940) pp. 39-40.
65. NETTLETON, E. T., "How to Study Screen Efficiency." *Rock Prod.* (May 1940) pp. 44-45.
66. NETTLETON, E. T., "Specification Essentials." *Rock Prod.* (Nov. 1940) pp. 44, 50.
67. NETTLETON, E. T., "Fair Tolerances for Screening." *Rock Prod.* (Dec. 1940) pp. 29-30.
68. NETTLETON, E. T., "Accurate Sampling." *Rock Prod.* (June 1941) pp. 43-44.
69. NEVITT, N. G., "Aggregate Gradation." *Roads and Streets* (July 1962) pp. 127-128.
70. NIJBOER, L. W., *"Plasticity as a Factor in the Design of Dense Bituminous Road Carpets."* Elsevier (1948) 173 pp.
71. OLMSTEAD, F. R., "Avoiding Trouble in the Design and Control of Oil-Aggregate Mixtures." *Assn. Asphalt Paving Tech.*, Vol. 11, pp. 258-289 (1940).
72. PEAKES, G. L., "Fundamentals of a Test Method." *ASTM Bull.* (Jan. 1952) pp. 57-61.
73. PRICE, W. H., "Grading and Surface Area." *ASTM STP 169* (1955) pp. 274-283.
74. PROSCHAN, F., "Confidence and Tolerance Intervals

for the Normal Distribution." *Jour. Am. Stat. Assoc.*, Vol. 48, pp. 550-564 (1953).

75. PROUDLEY, C. E., "Sampling of Mineral Aggregates—Symposium on Mineral Aggregates." *ASTM STP 83* (1948) pp. 74-87.
76. PROUDLEY, C. E., "Techniques, Procedures and Practices of Sampling." *ASTM STP 169* (1955) pp. 7-13.
77. REINECKE, L., and CLARK, K. A., "The Sampling of Deposits of Road Stone and Gravel in the Field." *ASTM Proc.*, Vol. 18, Part 2, pp. 393-413 (1918).
78. SHERGOLD, F. A., and HOSKING, J. R., "Investigation of Test Procedures of Argillaceous and Gritty Rocks in Relation to Breakdown Under Traffic." *Roads and Road Constr.*, Vol. 41, No. 492, pp. 376-378 (Dec. 1963).
79. SHOOK, J. F., "Significance of Test Results Obtained from Random Samples." *Proc. ASTM*, Vol. 63 (1963).
80. SNYDER, N. H., revised by ARESCO, S. J., "Coal Sampling-Revision of Technical Paper 133." *Bur. of Mines Handbook*, pp. 1-16 (1957).
81. TOMLINSON, R. C., "Some Recent British Work on Coal Sampling—Symposium on Coal Sampling. *ASTM STP No. 162*, pp. 35-53 (June 1954).
82. VISMAN, J., "Tests on the Binomial Sampling Theory—Symposium on Coal Sampling." *ASTM STP No. 162*, pp. 141-151 (June 1954).
83. VISMAN, J., "Sampling to a Pre-Assigned Accuracy." *Report No. FRL 212*, Fuels Division, Canada Dept. of Mines and Tech. Surveys, Mines Branch, Ottawa, pp. 1-11 (Aug. 1955).
84. VISMAN, J., "Towards a Common Basis for the Sampling of Materials." *Res. Rep. R 93*, Dept. of Mines and Technical Surveys, Ottawa, pp. 1-39 (July 1962).
85. WEIDENBAUM, S. S., and BONILLA, C. F., "A Fundamental Study of Mixing of Particulate Solids." *Chem. Eng. Prog.*, Vol. 51, No. 1, pp. 27 J—36 J (Jan. 1955).
86. WEST, T. R., AUGHENBAUGH, N. B., JOHNSON, R. B., and LOUNSBURY, R. W., "Degradation of Aggregates." Interim Report, NCHRP Project 4-2 (not publ.) 111 pp. (Aug. 1964).
87. YOUDEN, W. J., "How to Evaluate Accuracy—Symposium on Quality of Observations." *Mat. Res. and Stand.*, Vol. 1, pp. 268-271, Disc., 275-277 (Apr. 1961).
88. "Screen Analysis of Coal (Other Than Pulverized Coal) for Performance and Efficiency Tests on Industrial Plant." *Brit. Stand. Spec. B.S. 1293*, pp. 1-54 (1946) (incorporating amendment issued Feb. 1954).
89. CHASTAIN, W. E., SR., and BURKE, J. E., "State Practices in the Use of Bituminous Concrete." *HRB Bull. 160*, pp. 1-107 (1957).
90. VISMAN, J., Unpublished memorandum on a paper entitled, "Mixing and Sampling with Special Reference to Multi-Sized Granular Material," by D. Buslik. *ASTM Bull., T.P. 92*, pp. 66-73 (Apr. 1950).
91. VISMAN, J., "Sampling of Coal and Washery Products." *Trans. of World Power Conf. 1947*, Sect. A2, pp. 430-441; *Chem. Abst.* 736b (1948); *Colliery Guardian* 175, 573 (1947).
92. VISMAN, J., "The Importance of Automatic Sampling—Potentialities and Applications." *Fuel in Sci. and Practice*, Vol. 29, pp. 101-105 (1950).
93. VISMAN, J., "A New Development in Coal Sampling." Preprint, Centre d'Etudes et Recherches des Charbonnages de France (CERCHAR).

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Highway Research Board
National Academy of Sciences
2101 Constitution Avenue
Washington, D.C. 20418

Rep. No.	Title
—*	A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research—Intermediate Report (Proj. 4-3(2)), 81 p., $1.80
1	Evaluation of Methods of Replacement of Deteriorated Concrete in Structures (Proj. 6-8), 56 p., $2.80
2	An Introduction to Guidelines for Satellite Studies of Pavement Performance (Proj. 1-1), 19 p., $1.80
2A	Guidelines for Satellite Studies of Pavement Performance, 85 p.+9 figs., 26 tables, 4 app., $3.00
3	Improved Criteria for Traffic Signals at Individual Intersections—Interim Report (Proj. 3-5), 36 p., $1.60
4	Non-Chemical Methods of Snow and Ice Control on Highway Structures (Proj. 6-2), 74 p., $3.20
5	Effects of Different Methods of Stockpiling Aggregates—Interim Report (Proj. 10-3), 48 p., $2.00
6	Means of Locating and Communicating with Disabled Vehicles—Interim Report (Proj. 3-4), 56 p. $3.20
7	Comparison of Different Methods of Measuring Pavement Condition—Interim Report (Proj. 1-2), 29 p., $1.80
8	Synthetic Aggregates for Highway Construction (Proj. 4-4), 13 p., $1.00
9	Traffic Surveillance and Means of Communicating with Drivers—Interim Report (Proj. 3-2), 28 p., $1.60
10	Theoretical Analysis of Structural Behavior of Road Test Flexible Pavements (Proj. 1-4), 31 p., $2.80
11	Effect of Control Devices on Traffic Operations—Interim Report (Proj. 3-6), 107 p., $5.80
12	Identification of Aggregates Causing Poor Concrete Performance When Frozen—Interim Report (Proj. 4-3(1)), 47 p., $3.00
13	Running Cost of Motor Vehicles as Affected by Highway Design—Interim Report (Proj. 2-5), 43 p., $2.80
14	Density and Moisture Content Measurements by Nuclear Methods—Interim Report (Proj. 10-5), 32 p., $3.00
15	Identification of Concrete Aggregates Exhibiting Frost Susceptibility—Interim Report (Proj. 4-3(2)), 66 p., $4.00
16	Protective Coatings to Prevent Deterioration of Concrete by Deicing Chemicals (Proj. 6-3), 21 p., $1.60
17	Development of Guidelines for Practical and Realistic Construction Specifications (Proj. 10-1,) 109 p., $6.00
18	Community Consequences of Highway Improvement (Proj. 2-2), 37 p., $2.80
19	Economical and Effective Deicing Agents for Use on Highway Structures (Proj. 6-1), 19 p., $1.20
20	Economic Study of Roadway Lighting (Proj. 5-4), 77 p., $3.20

* Highway Research Board Special Report 80

Rep. No.	Title
21	Detecting Variations in Load-Carrying Capacity of Flexible Pavements (Proj. 1-5), 30 p., $1.40
22	Factors Influencing Flexible Pavement Performance (Proj. 1-3(2)), 69 p., $2.60
23	Methods for Reducing Corrosion of Reinforcing Steel (Proj. 6-4), 22 p., $1.40
24	Urban Travel Patterns for Airports, Shopping Centers, and Industrial Plants (Proj. 7-1), 116 p., $5.20
25	Potential Uses of Sonic and Ultrasonic Devices in Highway Construction (Proj. 10-7), 48 p., $2.00
26	Development of Uniform Procedures for Establishing Construction Equipment Rental Rates (Proj. 13-1), 33 p., $1.60
27	Physical Factors Influencing Resistance of Concrete to Deicing Agents (Proj. 6-5), 41 p., $2.00
28	Surveillance Methods and Ways and Means of Communicating with Drivers (Proj. 3-2), 66 p., $2.60
29	Digital-Computer-Controlled Traffic Signal System for a Small City (Proj. 3-2), 82 p., $4.00
30	Extension of AASHO Road Test Performance Concepts (Proj. 1-4(2)), 33 p., $1.60
31	A Review of Transportation Aspects of Land-Use Control (Proj. 8-5), 41 p., $2.00
32	Improved Criteria for Traffic Signals at Individual Intersections (Proj. 3-5), 134 p., $5.00
33	Values of Time Savings of Commercial Vehicles (Proj. 2-4), 74 p., $3.60
34	Evaluation of Construction Control Procedures—Interim Report (Proj. 10-2), 117 p., $5.00
35	Prediction of Flexible Pavement Deflections from Laboratory Repeated-Load Tests (Proj. 1-3(3)), 117 p., $5.00
36	Highway Guardrails—A Review of Current Practice (Proj. 15-1), 33 p., $1.60
37	Tentative Skid-Resistance Requirements for Main Rural Highways (Proj. 1-7), 80 p., $3.60
38	Evaluation of Pavement Joint and Crack Sealing Materials and Practices (Proj. 9-3), 40 p., $2.00
39	Factors Involved in the Design of Asphaltic Pavement Surfaces (Proj. 1-8), 112 p., $5.00
40	Means of Locating Disabled or Stopped Vehicles (Proj. 3-4(1)), 40 p., $2.00
41	Effect of Control Devices on Traffic Operations (Proj. 3-6), 83 p., $3.60
42	Interstate Highway Maintenance Requirements and Unit Maintenance Expenditure Index (Proj. 14-1), 144 p., $5.60
43	Density and Moisture Content Measurements by Nuclear Methods (Proj. 10-5), 38 p., $2.00
44	Traffic Attraction of Rural Outdoor Recreational Areas (Proj. 7-2), 28 p., $1.40
45	Development of Improved Pavement Marking Materials—Laboratory Phase (Proj. 5-5), 24 p., $1.40
46	Effects of Different Methods of Stockpiling and Handling Aggregates (Proj. 10-3), 102 p., $4.60

THE NATIONAL ACADEMY OF SCIENCES is a private, honorary organization of more than 700 scientists and engineers elected on the basis of outstanding contributions to knowledge. Established by a Congressional Act of Incorporation signed by President Abraham Lincoln on March 3, 1863, and supported by private and public funds, the Academy works to further science and its use for the general welfare by bringing together the most qualified individuals to deal with scientific and technological problems of broad significance.

Under the terms of its Congressional charter, the Academy is also called upon to act as an official—yet independent—adviser to the Federal Government in any matter of science and technology. This provision accounts for the close ties that have always existed between the Academy and the Government, although the Academy is not a governmental agency and its activities are not limited to those on behalf of the Government.

THE NATIONAL ACADEMY OF ENGINEERING was established on December 5, 1964. On that date the Council of the National Academy of Sciences, under the authority of its Act of Incorporation, adopted Articles of Organization bringing the National Academy of Engineering into being, independent and autonomous in its organization and the election of its members, and closely coordinated with the National Academy of Sciences in its advisory activities. The two Academies join in the furtherance of science and engineering and share the responsibility of advising the Federal Government, upon request, on any subject of science or technology.

THE NATIONAL RESEARCH COUNCIL was organized as an agency of the National Academy of Sciences in 1916, at the request of President Wilson, to enable the broad community of U. S. scientists and engineers to associate their efforts with the limited membership of the Academy in service to science and the nation. Its members, who receive their appointments from the President of the National Academy of Sciences, are drawn from academic, industrial and government organizations throughout the country. The National Research Council serves both Academies in the discharge of their responsibilities.

Supported by private and public contributions, grants, and contracts, and voluntary contributions of time and effort by several thousand of the nation's leading scientists and engineers, the Academies and their Research Council thus work to serve the national interest, to foster the sound development of science and engineering, and to promote their effective application for the benefit of society.

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 highway transportation. The purposes of the Board are to encourage research and to provide a national clearinghouse and correlation service for research activities and information on highway administration and technology.