NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 100

RESEARCH NEEDS RELATING TO PERFORMANCE OF AGGREGATES IN HIGHWAY CONSTRUCTION

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **100**

RESEARCH NEEDS RELATING TO PERFORMANCE OF AGGREGATES IN HIGHWAY CONSTRUCTION

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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

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

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

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

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

The opinions and conclusions expressed or implied in these reports are those of the research agencies that performed the research. They are not necessarily those of the Highway Research Board, the National Academy of Sciences, the Bureau of Public Roads, the American Association of State Highway Officials, nor of the individual states participating in the Program.

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FOREWORD

By Staff
Highway Research Board

This report identifies 52 individual problems related to the performance of aggregates in highway construction and describes research needed to alleviate these problems The study effort consisted of a literature review, a workshop-conference involving 36 participants experienced in the various fields of aggregate use, and visits to parts of the country where aggregate problems are prevalent. Information contained in the report, particularly the detailed problem statements, will be of benefit to highway agencies, aggregate industry, and university personnel responsible for the planning of research programs Engineers concerned with portland cement concrete, bituminous mixtures, and aggregate base courses should also find the detailing of the aggregate-related problems in these areas of interest.

With the use of conventional design procedures, aggregates comprise more than 90 percent of the material required for the construction and maintenance of highway pavements. Highway consumption of sand, gravel, and crushed stone is nearing 1 billion tons per year and is expected to increase to about 1.5 billion tons annually by 1985, and total production for all uses will probably reach 4 billion tons annually by that time. Although nationally there is an abundant supply of conventional aggregates suitable for highway construction, there are localized areas, and in some cases regions, in which they are not economically available or are becoming depleted The problem is compounded because many of the existing sources are becoming unavailable through zoning restrictions, pollution control, and appreciating land values. In addition, there is an increasing need for aggregates with particular characteristics such as those which will provide high skid resistance and durability of pavement surface courses.

The over-all or general problem is that of determining what can be done about the current shortage of conventional aggregates in localized areas, the immediate need for aggregates with particular characteristics, and the long-range concern about the rapidly increasing consumption of aggregates as a national resource. There are a number of possible approaches to the alleviation of the problem, including:

1. Build roads with materials other than conventional aggregates.
2. Utilize available aggregates better.
3. Improve methods of handling and distribution of available aggregates
4. Produce synthetic aggregates as supplements for conventional aggregates.

Although all of the approaches are suitable subjects for research, the specific objective of the study undertaken jointly by Virginia Polytechnic Institute and the Pennsylvania State University was to formulate a comprehensive series of problem statements covering needed research in the highway aggregates field, the accomplishment of which, on a national basis, would provide the necessary background for better utilization of available supplies of conventional aggregates. In view of the fact that the unpublished knowledge and experience concerning aggregate performance is extensive, the researchers elected to depend heavily on information obtained during a two-day conference and follow-up field visits—involving people with experience in the fields of portland cement concrete, bituminous mixtures, and base courses and representing the major geographic regions of the United States and Canada—for the data collection phase of the study in preparation for the development of the detailed research needs.

It is recognized that all the research recommended in this report is not likely to be conducted within the next few years due to limitations of funds and needed research in other problem areas. There is also some question about the availability of facilities and talent necessary to accomplish the entire program in a few years However, the studies described in the report provide a framework for needed research in the mineral aggregates field that can be an effective guide for the selection of individual projects of national interest to be undertaken by highway agencies, such as state highway departments, the Bureau of Public Roads, or jointly through NCHRP, universities, and industry. The study also provides a basis for evaluation of the better utilization of conventional aggregates approach to a solution of the over-all aggregate problem in conjunction with such alternate approaches as improved methods of transportation of aggregates, production of synthetic aggregates, and the building of roads without aggregates.

CONTENTS

ACKNOWLEDGMENTS

The research reported herein was conducted at the Virginia Polytechnic Institute and The Pennsylvania State University under the general direction of Richard D. Walker, Professor of Civil Engineering (VPI), as Principal Investigator, together with Thomas D. Larson, Professor of Civil Engineering and Director of the Transportation Research Center, and Philip D. Cady, Assistant Professor of Civil Engineering, both of The Pennsylvania State University.

Special thanks are due to Frederick R. Allen and Harry J. Pence of Virginia Polytechnic Institute, and Hugh W. McGee and John Harmon of The Pennsylvania State University, who as Research Assistants were responsible for conducting the literature survey, analyzing the tape recordings made at the Workshop-Conference, and for considerable effort toward the writing of the research problem statements presented herein.

RESEARCH NEEDS RELATING TO PERFORMANCE OF AGGREGATES IN HIGHWAY CONSTRUCTION

SUMMARY To describe possible research studies that can be undertaken on a national basis to provide for the more efficient use of aggregate in the United States is the purpose of this project. A comprehensive series of research problem statements were formulated and separated into four general areas of study:

I. Portland Cement Concrete.
II. Bituminous Concrete and Related Materials.
III. Base Course and Shoulder Materials.
IV. General (involving at least two of the first three areas).

The formulation of the problem statements was based on an extensive literature review, a Workshop-Conference involving 36 consultant participants who are authorities in various fields of aggregates, and visits made to different parts of the United States and Canada as a follow-up program to the conference. Also, a priority rating procedure was developed.

A total of 52 statements were developed, 28 of which applied directly to the objective of the project. The remaining projects were considered to be important, although not directly related to the prime objectives. The estimated cost for the performance of all projects was $5,499,500. If only the first two priority projects in each of the four areas of study were funded, the cost is estimated to be $1,173,500.

Certain projects stand out as having great importance and this is reflected in the priority ratings. The priority one project of Study Area IV deals with highway safety through the implications of skid resistance. Base failures are an ever-increasing problem as heavier traffic volumes appear. Priority one project of Study Area III could give the key to the reasons for the failures and eventually result in large savings in maintenance cost. Many engineers thought the concrete D-line (deterioration line) problem was solved years ago, but indeed it persists in many states. The priority one item in Study Area II and its solution might cure this long-time problem. Similar comments could be made concerning all of the research problem statements that were formulated.

I. Portland Cement Concrete:

1. The Role of Aggregates in D-Line Cracking, $100,000.
2. Influence of Aggregate Particle Characteristics and Gradations on Properties of Fresh Concrete and Performance of Hardened Concrete, $118,000.

II. Bituminous Concrete and Related Materials:

1. Stripping of Asphalt Cement in Bituminous Mixtures and Identification of the Significant Aggregate Surface Properties that Influence Coating and Adhesion, $232,000.
2. Soundness of Aggregate Particles in Bituminous Mixtures, $163,000.

III. Base Course and Shoulder Materials:

1. The Relationship of Aggregate and Base Course Properties to Base Course Performance Under Varying Traffic Loads, $115,000.
2. Determination of the Causes of Change in Gradation for Aggregates Used in Highway Base Course Construction, $160,000.

IV. General:

1. Relating Aggregate Properties to Skid Resistance of Pavements, $223,000.
2. Determination of the Surface Characteristics of Aggregates Used in Highway Construction, $62,500.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

As sources of aggregates of known satisfactory performance are being depleted in many areas of the United States, ever-growing consumption will require that more use be made of aggregates that may not have a known service record. The situation is more serious near urban areas where many excellent aggregate sources are being zoned out of existence by being reserved for residential areas or other land uses. Conservation and water pollution control measures further complicate this problem in some areas where gravels are produced by dredging.

To make efficient use of aggregate sources without records of acceptable field performance, quantitative information is needed on the interaction between properties of the aggregate and performance in a particular environment. Progress in this area will aid the highway materials engineer in identifying new aggregates that can be used for specific purposes with normal processing, will point to methods of upgrading otherwise unacceptable aggregate supplies, and can lead to better construction practices which would make aggregate performance less critical.

The purpose of this project is to discover and describe areas of needed research which, undertaken on a national basis, would provide for the more efficient use of aggregate Accordingly, a comprehensive series of research problem statements has been formulated, having as its objective the development of procedures that a highway materials engineer may use to evaluate quantitatively the relevant properties of aggregates to be selected for a given class of use, in a given environment of service, and for a given level of performance. Additional project statements have been formulated which are less specifically directed to the objectives just described; their completion would, however, significantly contribute to the over-all efficient use of aggregate resources.

The approach taken in formulating project statements was a generally conservative one. This followed from the NCHRP Project Statement, from the Workshop-Conference and interview findings, from previous work (particularly *NCHRP Report 8*), and from the researchers' judgment, growing out of extensive experience in the field. Specifically, the following items were considered.

1 The recommended studies were to enable a highway materials engineer to quantitatively evaluate relevant properties of aggregate for selective use. Previous research has identified numerous aggregate properties without describing basic mechanisms and environmental considerations on which realistic evaluation methods could be based. Hence, known problems and approaches dominate the problem statements developed in this project.

2 Experts from the field (at the Workshop-Conference) stressed the need for re-directed studies of problems they felt were the critical ones, without being constrained by on-going efforts This conference was a "brain-storming" effort in which far-out approaches were rejected in favor of work on well-established needs.

3. *NCHRP Report 8* is concerned with the feasibility of using other than naturally occurring aggregates. It found no new processing methods and no "exotic" aggregates which are economical at present. In short, it points to the need for an evolutionary improvement of current practice.

All of the research problem statements are categorized into four general areas of study.

1. Portland cement concrete.
2. Bituminous concrete and related materials.
3. Base course and shoulder materials
4. General (involving at least two of the first three areas)

LITERATURE REVIEW

The initial step in accumulating the information necessary for formulating the research problem statements was a comprehensive review of the literature in each of the general areas of study. This review was used to help identify such things as the required properties of aggregates for specific uses, deleterious characteristics relative to specific uses, existing test methods that might be used to evaluate properties and deleterious characteristics, effect of environment, effect of different construction practices, and practical, available beneficiation processes. The literature review served as an important basis for a Workshop-Conference that was held to acquire the most significant inputs to the project. It also supplied important background material for each of the research problem statements.

No complete bibliography of the literature reviewed is included in this report The more significant references are listed with each problem statement.

WORKSHOP-CONFERENCE

Because the unpublished knowledge concerning aggregates and problems of their use is extensive, it was felt that authorities in the relevant areas should be consulted. It was further thought that the interaction between such individuals would produce better results than a long series of individual interviews Therefore, 36 highly qualified persons from the areas of portland cement concrete, bituminous concrete, and base courses, who represented the major geographical regions of the United States were invited to meet as consultants to this project. Together with representatives from the Highway Research Board and the Advisory Panel for the project, approximately 60 people participated in this endeavor.

The conference was held at the F. Donaldson Brown Continuing Education Center on the campus of Virginia Polytechnic Institute, in Blacksburg, Virginia, on Monday and Tuesday, March 18 and 19, 1968. With the exception of brief opening and closing general sessions, the two days were devoted to three simultaneous conferences in the three major areas previously mentioned

Notes and tape recordings of the conference were used as the major source of information for the research problem statements contained in this report. A summary of the conference, with a list of its participants, is given in Appendix B.

FOLLOW-UP VISITS

Field visits were made to critical geographic areas not represented in the Workshop-Conference to gain further first-hand knowledge of aggregate performance in highway construction Interviews were held with many highway materials engineers as well as other authorities who were not able to attend the conference. These visits provided the second most important source of information in the formulation of the research problem statements.

A summary of the visits appears in Appendix C.

FORMULATION OF RESEARCH PROBLEM STATEMENTS

Information gathered through the literature review, Workshop-Conference, and follow-up visits was carefully and thoroughly analyzed and, from a synthesis of this information, the research problem statements were drafted. A total of 52 statements are included in this report, 28 of which apply directly to the objective of the project.

The problem statements are divided into two basic priority categories, A and B, with the A category being subdivided into A_1 and A_2. The A category statements describe research areas in which findings would help fulfill the objectives of the project. Category B projects would produce useful information but are less clearly related to prime objective. A_1 priority is assigned to those problems in that class which have reasonable possibility of solution. A_2 priority indicates problems where sustained effort is indicated

A system of determining priorities within categories was developed and involved the following point count procedure:

A. Ease of solution (×1 *):
1. Improbable.
2. Possible, but not easy.
3. Probable, long time required.
4. Solution not too difficult.
5. Easily solved.

B. Value of solution (×3).
1. Very limited value.
2. Limited importance.
3. Need not immediate, important in future.
4. Immediate need, valuable.
5. Solves urgent problem, extremely valuable.

C Ease of implementation (×1):
1. Application very difficult.
2. Considerable correlative work required.
3. Some additional field work necessary.
4. Little additional field work required.
5. Solution very practical, easily applied.

D Geographical significance (×2):
1. Very limited application geographically.
2. Limited applicability.
3. Applicable in significant areas.
4. Extensive applicability.
5. Applicable everywhere

A priority number is chosen for each of the four criteria and multiplied by the weight factor shown. The total sum is then found. Thus, a problem for which the solution was not too difficult ($4 \times 1 = 4$), for which the need was not immediate but would be in the future ($3 \times 3 = 9$), which could be applied with little additional work ($4 \times 1 = 4$), and which would have extensive applicability ($4 \times 2 = 8$), would have a priority rating number of $4 + 9 + 4 + 8 = 25$. Intermediate values were used when needed. The higher the total value, the higher the priority of the prob-

* Indicates weighting factor

lem. The descriptions for the ratings under each of the four criteria were used only as guides in fixing numeric values, because they did not always exactly fit the research problem statement being examined.

The estimated cost of the research projects was computed using an approach developed by Bertram D. Tallamy Associates in their report for NCHRP Project 20-2, Research Needs in Highway Transportation (*NCHRP Report 55*). In their study a cost analysis of 48 completed NCHRP projects showed that each professional man-month of effort cost approximately $3,000, with a minimum "project initiation" cost of $25,000.

In pricing the research programs for this project the $3,000 per man-month figure was used, but project initiation costs were varied to reflect estimated capital equipment outlays or other project expenses

CHAPTER TWO

FINDINGS

CURRENT STATUS OF AGGREGATE RESEARCH

The total performance of a highway structure is intimately related to the performance of the aggregate used in its construction. This chapter presents background to the current status of knowledge and a framework for research that would help meet the needs of developing better test techniques, new beneficiation processes, and construction methods that are sensitive to aggregate properties

Scientific research concerning aggregate began in the early 1800's. Most of the early research concerned aggregates for use in portland cement concrete. As the uses for concrete multiplied, so did the problems associated with aggregate use. Essentially, the same thing occurred with asphalt and aggregates in the 1920's. Again, the problems concerning the use of aggregates with asphalt multiplied as fast as the growth of asphalt highway construction. It is therefore not contradictory to state that although a tremendous volume of research has been done, much yet needs to be accomplished

If there has been a persistent weakness in past research, it has been in the sense that it has lacked a generalized approach For example, much of the work on frost destruction of concrete in the 1940's was concerned with effects of air content, whereas precise control of other critical variables—the aggregate phase for example—was not maintained Alkali silica reactions were studied without generalizing this phenomenon of the other possible alkali reactions until problems of the carbonate reactions actually became critical. The effect of chlorides on concrete has been studied at great length without a consistent hypothesis having been developed Numerous freezing and thawing test methods have been developed that did not measure any fundamental property related to the mechanisms in question and so service correlations have been essentially unachievable.

This fragmented approach to research has provided much information that has been useful at specific places and at specific times to solve local problems that had to be solved Now, however, highway materials engineers are facing a future in which aggregate supplies are becoming increasingly scarce The old approach of simply identifying a source as producing deleterious aggregate and then removing it from the approved list and finding a better one is no longer acceptable

For the future, highway materials engineers will have to know the service environment involved. They must have test methods that can identify an aggregate as capable of withstanding the environment in question when consideration is also given to the particular structural form involved. Based on test findings, the materials engineer should be led to an appropriate beneficiation process that will remove possible deleterious fractions when an adequate "as is" supply is not available. He might also be led to recommend the use of transported aggregate at an increased cost to achieve an improved performance level. A final alternative might be to tolerate poor performance at a relatively lower cost.

The possibility of unrecognized problems must be considered. Increasing demands on roadway pavements have produced new aggregate-related problems that require investigation. For example, the recent introduction of studded snow tires presents a problem of, as yet, unknown consequence This concerns both asphalt and portland cement concrete construction, but is probably more important with asphaltic concrete because, in this material, the brunt of the attack of the studs on the roadway must be borne by the aggregate The increased pressure for higher wheel loadings as well as increasing traffic volumes will most certainly accentuate problems of aggregate degradation in both base course and asphalt construction Pavement slipperiness is currently receiving considerable attention, along with all aspects of highway safety It appears that a great deal of pressure will be applied to restrict or eliminate the use of aggregates that contribute to that problem. However, there is not available, to date, a suitable test for aggregates, per se, to reveal the tendency of an aggregate to produce a slippery pavement. Other examples of "new" problems could be cited—suggesting the need for a flexible research attitude

A FRAMEWORK FOR RESEARCH

Approximately 730 million tons of aggregates are currently being used in highway construction each year. Therefore, as proven reserves are depleted the highway construction industry is being forced to turn to new sources Present acceptance test methods are simply not capable of providing a good picture of the suitability of new aggregate sources, and at the current rate of aggregate use the cut and try method can no longer be risked. Therefore, better acceptance test methods are needed Also, acceptance test methods are needed that will provide degrees of discrimination among aggregates with respect to such matters as durability, resistance to stripping, and resistance to polishing. Even further, the degree of discrimination will have to be related to environmental exposure and severity of service.

The ultimate objective alluded to here is a systematic approach permitting selective use of aggregates. A framework for knowledge relating to this objective might include the following elements.

1. Environmental conditions.
2. Aggregate description.
3 Condition of enclosure.
4. Response in service.
5. Failure criteria.
6. Exposure control.
7. Beneficiation.

These elements at least must be understood before a systematic selective use can be achieved.

ELEMENTS RELATING TO SELECTIVE USE OF AGGREGATES

Environmental Conditions

Much of the blame for the present inability to evaluate aggregate performance in a quantitative fashion can be laid to a past neglect for gaining a better understanding of the service environment (and resistance thereto) of highway structures. Until engineers know just what environmental forces an aggregate must withstand, it is improbable that they will be capable of developing discriminating tests. It is necessary to go beyond the immediate problems related to aggregates and lay a broad quantitative foundation. Only then can the highway engineer be given the kind of information he needs to make better use of aggregate for highway concrete.

Aggregate Description

Aggregates may be described on the basis of the assemblage of particles or on the basis of individual particles. Both are important and both contain areas of inadequate understanding. Adequate description is a cornerstone to intelligent testing and specification writing.

With regard to the assemblage of particles, the practice has been to ascribe a degree of homogeneity to aggregate that rarely exists. As a matter of fact, most sources of gravels and many ledge rock quarries produce extremely heterogeneous aggregates. Because this is so, data on specific gravity, absorption, frost susceptibility, etc., of the assemblage may not relate in a meaningful way to performance.

Concerning aggregate description, highway engineers should be more aware of the science of petrography. In the past they have not adequately used the methodology available from this highly relevant discipline.

Condition of Enclosure

Aggregates in highway pavements serve in a variety of conditions of enclosure. For example, concrete aggregate serves in a paste environment. The paste matrix can vary widely in composition. Furthermore it is affected by discontinuities, by dimensional differences, and by surface treatments and conditions. The performance of aggregates is affected by, and perhaps significantly related to, the nature and condition of the paste enclosure. The physical and chemical nature of paste, its structure and the type of discontinuities that exist are reasonably well documented. The relationship of these factors or characteristics to aggregate performance has not been well documented. For example, it is not known how, why, or when water moves preferentially from the aggregate to the paste phase, or vice versa.

A similar analogy can be given for aggregate in bituminous concrete where it is enclosed by asphalt cement. The relationship between asphalt content and aggregate gradation and the ability for water to affect mix durability is not well known.

Response in Service

How does aggregate respond as it exists in the working elements of highway pavements? Experience is generally limited to acknowledging perfect success or failure. The concept of, and quantification of, response over time in a changing environment is a relatively new one to the highway materials engineer.

The immediate concern here is to provide methods for making selective use of aggregates This generally implies the need for a continuum of experience. When mid-level response of an aggregate to a test method is seen, for example, it is then possible to select a process by which this aggregate can be improved—or by which the demand for a high performance level can be reduced.

Failure Criteria

What constitutes aggregate failure? When is cracking, deflection, etc., excessive in highway pavement, and when is it excessive in aggregates? Failure criteria have obvious importance to test development.

For each different service environment and each level of service failure criteria must be established. These criteria must consider such things as cracking, deflection, disintegration, abrasion, volume change, and aesthetic qualities.

Exposure Control

The research objective of this project envisions the selective use of aggregates This involves attempting to control response through various types of exposure control It is conceptually feasible to partially control exposure, but quantitative information of several kinds is needed before it becomes a practical matter

It is obvious, for example, that bridge decks are exposed more severely than are bridge piers. However, a scale is not available to measure differences. Attempts are now made to lessen the severity of the deck exposure by surface treatments—linseed oil being a common one It seems reasonable that in other situations alternate design approaches or a different construction method might serve to modify the exposure that the aggregate must withstand

Beneficiation

Another approach to exposure control involves modifying aggregate on the assumption that the exposure is known and unalterable. Modification (beneficiation) is performed so that no significant portion of the aggregate is likely to be stressed beyond its capability. The weak fractions are simply removed

Implementation of this approach requires that the quality of various fractions be compared with the environment by means of field performance records, by test methods, or some combination of the two, and that an economical beneficiation process be available to remove all inappropriate material

Conclusions

Before the highway engineer will be able to match specifically aggregates to uses, a well-constructed research program must be initiated and carried to completion. It must be broad enough to include a concern for coming to a better understanding of the service environment of the highway pavement It must be basic enough to include such things as a search for the mechanisms of de-icing salt deterioration of concrete It must be applied enough to include the development of performance record-keeping systems It must persist in time and expenditure until the needed information becomes available.

Of necessity, the research problem statements presented in this report are outlined as discrete projects It should be made clear to agencies or groups working in these problem areas, however, that relationships between the specific research problems and the general framework of knowledge also should be considered

Research Problem Statement Summaries

Tables 1 through 4 give the research problem statements formulated for this project. They are in order of priority within a given study area (i e , portland cement concrete, bituminous concrete, base courses, and general) Each table summarizes the time and cost requirements of each project Category A projects are presented first, followed by those in Category B

Complete research problem statements are presented in Appendix A

TABLE 1

GROUP I, PORTLAND CEMENT CONCRETE

PROBLEM NO	PRIORITY CATEGORY	TITLE	ESTIMATED TIME (MONTHS)	ESTIMATED COST ($)
I-1	A_1	The Role of Aggregates in D-Line Cracking	18	100,000
I-2	A_2	Influence of Aggregate Particle Characteristics and Gradations on Properties of Fresh Concrete and Performance of Hardened Concrete	27	118,000
I-3	A_1	Identification of Alkali Reactive Aggregates	24	133,000
I-4	A_2	Live Loadings on the Aggregate Phase of Concrete in Various Service Environments	24	133,000
I-5	A_2	Quantitative Criteria for Determining Critical Size of Concrete Aggregates	24	115,000
I-6	A_1	Criteria for Judging the Performance of Concrete When Pop-Outs Occur	12	54,000
I-1B	B	Improved Field Method for Continuously Measuring Moisture Content of Bulk Aggregate	12	73,000
I-2B	B	Effects of De-Icing Salt on Aggregate Performance in Portland Cement Concrete	24	100,000
I-3B	B	The Aggregate-Paste Interface in Portland Cement Concrete	27	91,000
I-4B	B	Variation of Alkali Content of Highway Structures With Environment and Time	24	91,000
I-5B	B	Fundamental Mechanisms of Moisture Movement in Concrete	24	119,000
I-6B	B	Failure Criteria for Concrete Aggregate With Regard to Cracking	24	100,000
I-7B	B	Standardizing Outdoor Exposure Tests for Concrete Durability Studies	12	39,000

TABLE 2

GROUP II, BITUMINOUS CONCRETE AND RELATED MATERIALS

PROBLEM NO	PRIORITY CATEGORY	TITLE	ESTIMATED TIME (MONTHS)	ESTIMATED COST ($)
II-1	A_1	Stripping of Asphalt Cement in Bituminous Mixtures and Identification of the Significant Aggregate Surface Properties that Influence Coating and Adhesion	39	232,000
II-2	A_1	Soundness of Aggregate Particles in Bituminous Mixtures	36	163,000
II-3	A_1	The Influence of Asphalt Absorption Rate, Nature and Amount by Aggregate Particles on Bituminous Mix Design and Performance	24	126,000
II-4	A_1	Degradation of Aggregate Leading to the Production of Deleterious Fines in Bituminous Mixtures	42	232,000
II-5	A_2	The Role of the Aggregate in Relation to the Mechanical Properties of the Bituminous Mixture	36	144,000
II-6	A_2	Effect of Heat on the Integrity and Characteristics of Aggregates	24	81,000
II-1B	B	The Effect of Aggregate Gradation on Bituminous Mix Design	30	144,000
II-2B	B	Effect of Fines on Hardening of Asphaltic Concrete	24	90,000
II-3B	B	The Phenomenological Aspects of Internal Friction as Related to Bituminous Mix Design	30	90,000
II-4B	B	Spreading Rates and Gradation of Aggregates for Bituminous Surface Treatments	21	72,000

TABLE 3

GROUP III, BASE COURSE AND SHOULDER MATERIALS

PROBLEM NO	PRIORITY CATEGORY	TITLE	ESTIMATED TIME (MONTHS)	ESTIMATED COST ($)
III-1	A_1	The Relationship of Aggregate and Base Course Properties to Base Course Performance Under Varying Traffic Loads	36	115,000
III-2	A_1	Determination of the Causes of Change in Gradation for Aggregates Used in Highway Base Course Construction	27	160,000
III-3	A_2	Development of Test Methods to Predict Density Retention of Base Courses	18	118,000
III-4	A_2	Investigation of the Significance of Volume Change on Performance of Aggregate Base Courses	18	64,000
III-5	A_2	Study of the Nature and Effect of Bacterial Action on Aggregate Degradation	12	36,000
III-1B	B	Investigation and Development of a Density Standard for the Control of Field Compaction in Base Course Construction	18	115,000
III-2B	B	Development of Base Course Aggregate Criteria for the Accommodation or Reduction of Water	36	169,000
III-3B	B	Study of Base Course Admixtures and Stabilization Processes and Development of Recommended Practices	18	91,000
III-4B	B	Evaluation of Purpose, Function, and Performance of Current Highway Base Courses	18	54,000

TABLE 4

GROUP IV, GENERAL

PROBLEM NO.	PRIORITY CATEGORY	TITLE	ESTIMATED TIME (MONTHS)	ESTIMATED COST ($)
IV-1	A_1	Relating Aggregate Properties to Skid Resistance of Pavements	48	223,000
IV-2	A_2	Determination of the Surface Characteristics of Aggregates Used in Highway Construction	18	62,500
IV-3	A_1	Study of Aggregate Sampling Procedures and the Value of Aggregate Specifications Established by Statistical Procedures	18	54,000
IV-4	A_1	Procedures for Optimizing Aggregate Use With Regard to Economics and Conservation of Resources	24	99,000
IV-5	A_1	Development of a Systematic Modular Approach to Aggregate Testing	15	45,000
IV-6	A_2	Criteria for Evaluating Aggregate Performance	30	90,000
IV-7	A_2	Development of Procedures to Adequately Describe Aggregate Sources	12	36,000
IV-8	A_1	Data-Keeping Procedures on Aggregate Performance	15	54,000
IV-9	A_1	Influence of Climate and Environment on the Performance of Aggregates in Highway Construction for Use in Development of a Weather Severity Index	36	241,000
IV-10	A_2	Development of Rapid and Reliable Methods for Determining Aggregate Gradation	12	45,000
IV-11	A_1	Relationship of Aggregate Type and Susceptibility to Damage From Studded Tires	27	115,000
IV-1B	B	Aggregate Gradation Specifications	21	90,000
IV-2B	B	Investigation of Aggregate Pre-Conditioning Methods for the Benefit of Field Performance	18	81,000
IV-3B	B	Deleterious Effects of Aggregate Stockpiling, Handling, and Shipping, and Methods for Improvement	18	91,000
IV-4B	B	Compilation of Current Design, Construction, and Maintenance Practices as They Relate to Aggregate Performance	24	99,000
IV-5B	B	Investigation of Waste Products as Potential Sources of Aggregates	12	36,000
IV-6B	B	Study and Evaluation of Synthetic Aggregate Use, Specifications, and Tests	24	136,000
IV-7B	B	Review of Aggregate Beneficiation Processes	24	127,000
IV-8B	B	Evaluation and Development of Radioactive Techniques for Evaluating Moisture, Density, and Strength of Pavement Components	24	122,000
IV-9B	B	Development of Methods of Improving Fine-Aggregate Particle Shape and Surface Texture	18	91,000

CHAPTER THREE

INTERPRETATION, APPRAISAL, AND APPLICATION

A summation of the projects described in Chapter Two would show that the total cost of all category A projects is $3,188,500, and that the category B projects add another $2,311,000, for a grand total of $5,499,500. As a basis for comparison it might be noted that this is little more than the average cost of a mile of Interstate Highway in Virginia An expenditure of this magnitude on aggregate research, if the projects described were successfully pursued, would certainly go a long way toward solving the aggregate problems and would undoubtedly result in an overwhelming net savings to the total highway program.

However, not only is the possibility remote that this amount of funding would become available in the next few years, but there is some doubt that the research facilities and talent are available to accomplish the entire program in the next several years. Therefore, selective project funding must be contemplated.

Even if only the first two priority projects in category A for each group were funded, the cost is estimated to be approximately $1,173,500. This too may prove to be an insurmountable figure.

Certain projects stand out as having great importance and this is reflected in the priority ratings For example, the priority one project of Group IV deals with highway safety through the implications of skid resistance. Despite the use of pavement design procedures that work most of the time, base failures are an ever-increasing problem as heavier traffic volumes appear. Yet, priority one project of Group III could give the key to the reasons for the failures and eventually result in extremely large savings in maintenance cost.

Many engineers thought the concrete D-line problem was solved years ago, but it still persists in many states. The solution to this problem would cure a long-time headache. Similar comments could be made on every project on down the priority scale

Even though the category B projects, in the opinion of the researchers, do not exactly fulfill the requirements of NCHRP Project 4-8, they are prominently presented because they were given great emphasis in the Workshop-Conference. Their accomplishment should also contribute a great deal to solving aggregate problems.

Both the priority rating system and the values applied in individual cases entailed a high degree of judgment on the part of the researchers and are, therefore, subject to question. However, it should be stressed that the opinions formed by the researchers were based to a large extent on the opinions expressed by experts in the field at the Workshop-Conference and in individual interviews.

Similarly, the estimates of time and cost and the suggested research programs reflect the opinions and judgment of the researchers and the influence of the various experts consulted. Therefore, these too are subject to debate and possible revision or modification at the time of actual funding.

As noted in Chapter Two, the failure to take a systematic, generalized approach to aggregate research has led to a substantially reduced payoff. Now a framework for the knowledge related to the use of mineral aggregates has been developed, gaps in knowledge have been identified and statements outlining needed research have been prepared. Program funding is the next matter for concern.

As noted previously, the immediate initiation of the entire program is highly unlikely. However, a "critical" level of funding is strongly suggested. This level would be such that the following might occur:

1. Top talent would be attracted to this field—in highway research labs, commercial labs, and in university research programs.
2. There would be cross-fertilization of projects undertaken by different groups but in essentially the same time frame.
3. A measurable initial impact would be generated so that the program would receive support for its fulfillment.

APPENDIX A

RESEARCH PROBLEM STATEMENTS

GROUP I, PORTLAND CEMENT CONCRETE

Problem No.: I-1 *Estimated Time:* 18 months

Priority Category: A_1 *Estimated Cost:* $100,000

Title: The Role of Aggregates in D-Line Cracking

Problem Statement:

D-line (deterioration line) cracking normally develops along the joint or edge of a concrete surface and progresses away from the free edge with further deterioration. At least three theories have been advanced to explain the cause of D-line cracking, none of which indicates exactly how aggregate quality relates to this type of deterioration. Because this is the case, research with the objective of relating aggregate quality and type to D-line cracking is warranted. This project would lead to a comprehensive theory of this phenomenon and an understanding of aggregate characteristics which influence D-line cracking. These characteristics could then be evaluated by existing or new test methods. This information is urgently needed by highway materials engineers because they now have no sure way of selecting aggregates to avoid this problem.

Objectives:

1. Determine how D-line cracking develops in pavement.
2. Relate aggregate quality to D-line cracking.
3. Select or develop tests that will discriminate aggregates causing this type of failure.

TABLE A-1

PRIORITY RATINGS, GROUP I, PORTLAND CEMENT CONCRETE

PROBLEM NO	PRIORITY CATEGORY	EASE OF SOLUTION	VALUE OF SOLUTION	EASE OF IMPLEMENTATION	GEOGRAPHICAL SIGNIFICANCE	SUM
I-1	A_1	2	5-15	4	3-6	27
I-2	A_2	4	3-9	4	5-10	27
I-3	A_1	2	4-12	5	3-6	25
I-4	A_2	2	3-9	2	5-10	23
I-5	A_2	2	3-9	4	4-8	23
I-6	A_1	3	2-6	4	3-6	19
I-1B	B	1	4-12	5	5-10	28
I-2B	B	3	4-12	3	4-8	26
I-3B	B	4	3-9	3	5-10	26
I-4B	B	4	4-12	4	3-6	26
I-5B	B	2	4-12	2	4-8	24
I-6B	B	2	3-9	3	5-10	24
I-7B	B	5	2-6	5	3-6	22

Program.

1 Literature search and review

2 Through field and laboratory study determine how D-line cracking develops in highway pavements.

3. Through laboratory study relate aggregate type and quality to D-line cracking.

4 Data analysis, synthesis, and reports

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	18
3	6	6
4	6	3
		30 m-m

Calendar months for completion: 18 months

Cost. 30 m-m @ $3,000/m-m = $ 90,000
Initial cost = $ 10,000
$100,000

References·

1. Cook, H K., "Experimental Exposure of Concrete to Natural Weathering in Marine Locations." *Proc ASTM,* Vol. 52, pp 1169-80 (1952).
2. Cordon, W. A., "Freezing and Thawing of Concrete —Mechanisms and Control." *Amer. Conc. Inst Monograph No 3* (1966)

Problem No I-2 *Estimated Time* 27 months

Priority Category A_2 *Estimated Cost.* $118,000

Title. Influence of Aggregate Particle Characteristics and Gradations on Properties of Fresh Concrete and Performance of Hardened Concrete

Problem Statement.

Aggregate properties directly influence such factors as the workability and bleeding of fresh concrete. The durability and elastic properties of hardened concrete are therefore secondarily affected Although much work has been done in this area it is still not possible to quantitatively associate shape, texture, and size (coarse and fine fractions) of individual particles or of the gradation with performance levels of fresh and hardened concrete.

There are specific instances of a need for such capability. Premature deterioration of concrete bridge decks, for example, has been related to the workability, bleeding and consolidation characteristics of concrete mixtures. Special placement procedures such as slip forming, pumping, and conveyor transport also make this problem area an important one.

If the relationships just noted could be established in such detail that economic evaluation of benefits becomes possible then a highway engineer might specify shape, texture, and special size requirements with the assumption that beneficiation processes could be developed to meet the more rigid specifications.

Objectives.

Quantitatively evaluate the influence of shape, texture, and size of aggregate particles and of the gradation of the aggregate mass on the following·

1. Bleeding and workability of fresh concrete.
2. The elastic properties of the hardened concrete.
3. Durability of the hardened concrete.

Program

1 Literature search and review to identify research which has promise of quantitative interpretation and to identify gaps

2. Supplementary laboratory studies to evaluate influence of shape, texture, and size of aggregate particles and

the gradation of an aggregate mass on bleeding and workability of fresh concrete.

3 Supplementary laboratory study to evaluate the influence of aggregate on elastic properties of concrete and on durability

4. Development of quantitative association of aggregate properties and performance that will permit economic evaluation of special selection, importation, and beneficiation alternatives.

5 Data analysis, synthesis, and reports

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	9
3	12	12
4	6	6
5	6	6
		36 m-m

Calendar months for completion. 27 months

Cost. 36 m-m @ \$3,000/m-m = \$108,000
Initial cost = \$ 10,000
\$118,000

References.

1. BLOEM, D. L., and GAYNOR, R. D., "Effects of Aggregate Properties on Strength of Concrete." *J Amer Conc Inst*, Vol. 60, pp 1429-54 (Oct. 1963).
2. HALLSTROM, P., "Effect of Grading of Aggregate on Strength of Concrete." *Building Science Abstracts,* Vol. 38, No. 4 (Apr 1965)
3 HUGHES, B D, "Mix Design for High-Quality Concrete Using Crushed Rock Aggregate." *J. British Granite and Whinstone Fed.,* Vol. 14, No. 1, pp 35-53 (1964).
4. MATHER, B., "Shape, Surface Texture, and Coatings." *Tests and Properties of Concrete and Aggregates,* ASTM, STP 169, p. 284 (1955)
5. PHILLEO, R. E., "The Strength of Concrete—A Statistical Review." *Lecture No. 5,* Stanton Walker Lecture Series (Nov. 1967).
6. POPOVICS, S, "Effect of Mineral Aggregate on Concrete Strength." *Better Roads,* Vol. 35, No. 9, pp. 31-38 (Sept. 1965).
7. RITCHIE, A. G., "Stability of Fresh Concrete Mixes." *Proc ASCE, J. of Construction Div*, CO1, p. 17 (Jan. 1966).
8. TIMMS, A. G, "Undesirable Qualities in Aggregate for Concrete." *Modern Conc.,* Vol 30, No. 7 (Nov. 1966).
9 WALKER, S, "Quality Requirements for Concrete Aggregates." *Eng. Experiment Station Bull. No. 68,* Univ. of Ky., Vol. 17, pp. 52-56 (June 1963).

Problem No I-3 *Estimated Time* 24 months

Priority Category A_1 *Estimated Cost* \$133,000

Title Identification of Alkali Reactive Aggregates

Problem Statement

The reaction between certain siliceous and carbonate aggregates and the alkali constituents of portland cement to produce deleterious effects is well recognized. However, present tests can identify potentially deleterious aggregates in only a relatively gross fashion. The prediction of performance under various environments is not possible. The highway materials engineer needs methods for obtaining quantitative evaluation of alkali reactive aggregates that will permit selective use or beneficiation Selective use will be possible only when the alkali content of concrete in service is known. Beneficiation will require that an aggregate attribute be recognizable to a test method so that it can activate a screening process All projects in this topical area should have a corollary objective of seeking a method to neutralize aggregate alkali reactivity.

Objectives.

1. Develop laboratory test methods that would quantitatively identify reactive aggregates.
2. Develop criteria for use of potentially reactive aggregates.
3. Develop procedure for beneficiation of reactive aggregates.

Program:

1 Literature search and review.

2 Laboratory study to develop quantitative test method(s) for identifying aggregate particles that would be reactive in concrete under various environments.

3. Laboratory study to develop procedure for neutralizing deleterious effects of aggregates.

4. Test and evaluate beneficiation procedures based on test attributes.

5. Data analysis, synthesis, and reports.

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	6	6
5	3	3
		36 m-m

Calendar months for completion: 24 months

Cost: 36 m-m @ \$3,000/m-m = \$108,000
Initial cost = \$ 25,000
\$133,000

References

1. American Society for Testing and Materials, *Standards.* Part 10, "Concrete and Mineral Aggregates," Test Methods, C-227, C-289, C-295, and C-342.
2. Hansen, W. C., "Chemical Reactions." *Tests and Properties of Concrete,* ASTM, STP 169-A, p. 487 (1966).
3. "Chemical Reactions of Aggregates in Concrete." *HRB Spec. Rep. 31* (1958) pp. 1-10.
4. Mielenz, R. C., "Petrographic Examination." *Tests and Properties of Concrete,* ASTM, STP 169-A, p. 381 (1966).

Problem No.: I-4 *Estimated Time:* 24 months

Priority Category: A_2 *Estimated Cost:* $133,000

Title: Live Loadings on the Aggregate Phase of Concrete in Various Service Environments

Problem Statement:

Details concerning stress distribution on the aggregate phase in highway structures are lacking. There is a need to determine the limits and frequencies of loadings on aggregates in various highway structures. Consideration should be given to various strength categories of concretes. Closely related problems in this area are: What properties or characteristics of aggregates are significant in predicting the strength performance of concrete? How do these aggregate properties (texture and shape for example) influence distribution of stresses within the concrete mass? The answers to these questions could provide the highway materials engineer with methods to quantitatively evaluate the aggregate to be selected for a given level of performance.

Objectives

1. Considering various strengths of concrete and various structural applications, establish limits and frequencies of loadings on aggregates in various highway service environments.

2 Determine significance of aggregate properties in predicting strength performance of concrete.

Program:

1. Literature search and review.
2. Literature and laboratory studies to determine those aggregate properties significant to strength performance.
3. Laboratory and field testing to establish limits and frequencies of loadings on aggregates in various service environments.
4. Determine how aggregate particle characteristics (for example, texture and shape) influence distribution of stresses within concrete.
5. Data analysis, synthesis, and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	6
3	12	12
4	12	12
5	3	3
		36 m-m

Calendar months for completion: 24 months

Cost: 36 m-m @ $3,000/m-m = $108,000
Initial cost = $ 25,000
$133,000

References:

1. Bloem, D., and Gaynor, R., "Effects of Aggregate Properties on Strength of Concrete." *J. Amer. Conc. Inst*, Vol. 60, pp. 1429-54 (Oct. 1963).
2. Dantu, P., "Analysis of Stress Distribution in Heterogeneous Materials." Supplement to *Annales de l'Institute Technique de Batiment et des Travaux Publics* (Jan. 1958).
3. Gordan, W., and Gillespie, H., "Variables in Concrete Aggregates and Portland Cement Paste Influencing Concrete Strength." *J. Amer. Conc. Inst.,* Vol. 60, pp. 1029-50 (Aug 1963).
4. Hsu, T. C. H., "Mathematical Analysis of Shrinkage Stresses in a Model of Hardened Concrete." *J. Amer. Conc. Inst.,* Vol. 60, No. 3, pp. 371-90 (Mar. 1963).
5. Keeton, J. R., "Strain Distribution in Compressively Loaded Concrete Specimens." *Proc. ASTM,* Vol. 61, pp 1197-1220 (1961).
6. Popovics, S, "Effect of Mineral Aggregate on Concrete Strength." *Better Roads,* Vol. 35, No. 9, pp. 31-38 (Sept. 1965).
7. Stephen, R. M., and Pertz, D., "Application of Birefringent Coating to the Study of Strains Around Circular Inclusions in Mortar Prisms." *Experimental Mechanics,* Vol. 3, No. 4, pp. 91-97 (Apr. 1963).

Problem No.: I-5 *Estimated Time:* 24 months

Priority Category: A_2 *Estimated Cost:* $115,000

Title: Quantitative Criteria for Determining Critical Size of Concrete Aggregates

Problem Statement:

A paper by Verbeck and Landgren published in 1960 concluded: "The influence of aggregates on the durability of concrete depends upon the physical characteristics of the aggregate and certain properties of the mortar component of the concrete in a complex but understandable manner."

In this paper they developed the "critical size" concept for aggregates as a principal means for judging frost resistance. A further conclusion was that: "Through proper design, based on the principles discussed, much can be done to improve significantly the actual performance of field concrete made with many aggregates rejected by commonly used tests."

The exciting promise of this paper has been largely unrealized because quantitative bases for using the concepts and even for the concept itself have not been developed. Perhaps the complexities introduced by such factors as widely varying paste compositions, unpredictable discontinuities, and changing surface characteristics have discouraged further experimentation.

Much needs to be learned concerning the internal pore characteristics of aggregate, such as the size, quantity, and continuity of pores as they affect moisture movement and freeze-thaw resistance of concrete. Definition of the significant parameters of the pore system and development of relationships between the pore characteristics and performance is also needed. Permeability and porosity test procedures should be developed and evaluated for use in specifying limits on the properties of concrete aggregate.

Objectives.

1. To study and develop test methods for internal pore characteristics, permeability, and porosity as they affect moisture movement of concrete aggregate.

2. To develop quantitative criteria for determining critical size of aggregate for portland cement concrete that can be used as the basis for selective use of various quality aggregates.

Program·

1. Literature search and theoretical review of critical size concept.

2. Laboratory study to determine critical size versus performance relationships for basic aggregate types, including study of internal pore characteristics, permeability and porosity as related to critical size.

3. Through laboratory work, establish criteria for determining critical size of aggregate.

4. Data analysis, synthesis, and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	18
3	6	6
4	9	3
		30 m-m

Calendar months for completion: 24 months

Cost: 30 m-m @ $3,000/m-m = $ 90,000
Initial cost = $ 25,000
$115,000

References:

1. CORDON, W. A., "Freezing and Thawing of Concrete —Mechanisms and Control." *Amer. Conc. Inst. Monograph No. 3* (1966).
2. LARSON, T, CADY, P., FRANZEN, M., and REED, J., "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." *HRB Spec. Rep. 80* (1964) pp. 1-81.
3. LEWIS, D. W., DOLCH, L. W., and WOODS, K. B., "Porosity Determinations and the Significance of Pore Characteristics of Aggregates." *Proc. ASTM*, Vol. 53, p. 949 (1953).
4. NAAR, J., and WYGAL, R., "Structure and Properties of Unconsolidated Aggregates." *Canadian J. of Physics*, Vol. 40, No. 7.
5. DUNN, J. R., and HUDEC, P. P., "The Influence of Clay on Water and Ice in Rock Pores." *Physical Research Report RR 65-5*, N.Y. State Dept. of Public Works, Albany, 149 pp. (1965).
6. POWERS, T. C., "Basic Considerations Pertaining to Freezing and Thawing Tests." *Proc. ASTM*, Vol. 55, p. 1132 (1955).
7. VERBECK, G., and LANDGREN, R., "Influence of Physical Characteristics of Aggregates on Frost Resistance of Concrete." *Proc. ASTM*, Vol. 60, pp. 1063-79 (1960).

Problem No: I-6 *Estimated Time:* 12 months

Priority Category: A_1 *Estimated Cost.* $54,000

Title: Criteria for Judging the Performance of Concrete When Pop-Outs Occur

Problem Statement:

Pop-outs are essentially superficial failures of concrete caused by near-surface pressure development. Expanding aggregate particles are often the source of the pressure. A diminished aesthetic quality is the first consequence of this mark of failure. If it is progressive, however, the total performance of the concrete structure may be impaired.

Research has provided a reasonably good understanding of why aggregate pop-outs occur and what can be done about them through beneficiation or exposure control. However, criteria are not available by which to choose between costly beneficiation and permitting the pop-outs to occur. Specific problems to be answered are:

1. What is the aesthetic value of highway concrete? Can it be quantified and, if so, by whom?

2. Can pop-out occurrence be quantitatively related to aesthetic value?

3. How many pop-outs can be tolerated from the several performance viewpoints? How does this vary with different structural applications of concrete?

Objectives.

1. Develop a unifying view of pop-out causes and controls based largely on existing literature
2 Suggest an evaluation scheme for the effects of pop-outs on concrete performance in various highway applications

Program

1. Literature search.
2. Investigate the basic mechanisms of pop-outs and pop-out control
3. Literature, laboratory and field study to determine effect of pop-outs in concrete performance
4. Data analysis, synthesis, and report.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	6
3	6	6
4	3	3
		18 m-m

Calendar months for completion. 12 months

Cost. 18 m-m @ $3,000/m-m = $54,000.

References.

1. BACHE, H. H, and ISEN, J. C., "Modal Determination of Concrete Resistance to Pop-Out Formation." *J. Amer. Conc. Inst., Proc.*, Vol. 65, No. 6, pp. 445-50 (June 1968).
2. IOWA STATE ENGINEERING RESEARCH, *Concrete Pop-Outs, a Concrete Problem* (Winter 1968).

Problem No. I-1B *Estimated Time* 12 months

Priority Category: B *Estimated Cost* $73,000

Title: Improved Field Method for Continuously Measuring Moisture Content of Bulk Aggregate

Problem Statement

Excess water in aggregate adds to the water/cement ratio of concrete paste. If the moisture content of the aggregate is large enough it will reduce strength and other performance characteristics of concrete. If aggregate moisture changes by only minor amounts the mix proportions should be adjusted so that the w/c ratio and workability characteristics are maintained.

There are laboratory and batch methods that can evaluate moisture content of the aggregate. However, there is no method available which can continuously and accurately monitor the moisture content of aggregate as it exists in stockpiles and bins. A field method is needed so that the highway engineer can control the amount of water being used in the mixture through the presence of moisture in the aggregate. Aggregate performance depends in part on the quality of the paste phase and so selective aggregate use demands tighter quality control at all levels.

Objectives:

1. Develop a field method by which a highway engineer can monitor the moisture content of bulk aggregate.

Program

1. Literature search and review.
2 Develop a field method for continuously and accurately measuring moisture content of an aggregate mass
3. Test and evaluate method
4 Data analysis, synthesis, and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	9	9
3	6	6
4	6	3
		21 m-m

Calendar months for completion: 12 months

Cost. 21 m-m @ $3,000/m-m = $63,000
Initial cost = $10,000
$73,000

References

1 ABDUN-NUR, E. A., "Techniques, Procedures, and Practices of Sampling of Concrete and Concrete-Making Materials." *Tests and Properties of Concrete,* ASTM, STP 169-A, p. 7 (1966).
2 BRINK, R H., and TIMMS, A. G, "Weight, Density, Absorption, and Surface Moisture." *Tests and Properties of Concrete,* ASTM, STP 169-A, p. 432 (1966).
3. HUGHES, B., and BAHRAMIAN, B., "An Accurate Laboratory Test for Determining the Absorption of Aggregates." *Materials Research and Standards,* Vol. 7, No. 1, pp. 18-23 (Jan. 1967).

Problem No I-2B *Estimated Time.* 24 months

Priority Category: B *Estimated Cost* $100,000

Title. Effects of De-Icing Salts on Aggregate Performance in Portland Cement Concrete

Problem Statement:

The acceleration of concrete deterioration in the presence of de-icing salts is a poorly understood phenomenon. The increasing reliance on de-icing salts in winter maintenance programs makes it urgent that this situation be changed.

The problem must be approached from a broad base if the role of aggregate is to be isolated. The various theories must be examined through the literature and by experiments with the purpose of identifying the principal mechanisms in this form of concrete deterioration. After this has been accomplished the more specific problem of the role of aggregate can be studied.

Because the application of de-icing salts changes the chemical environment of concrete (and aggregate) in service, the forms of aggregate deterioration that have been clearly identified as chemical in nature would deserve early attention. For example, how do de-icing salts relate to the alkali aggregate reaction (consider levels, rates, and gradients with regard to de-icing salt application).

It seems probable that de-icing salts help to create a hostile environment for aggregates. This proposition needs to be verified and quantified so that test methods, beneficiation processes, and specifications can be geared to avoidance of the form of distress.

Objectives.

1. Determine the nature of the deterioration mechanism in concrete induced by de-icing salts.
2. Determine the effect of applied chemicals (i.e., de-icing salts) on aggregate performance.
3. Develop recommendations concerning use of typical aggregate types with various levels and rates of de-icing salt application.

Program:

1. Literature search and review.
2. Literature and laboratory study to determine the nature of the deterioration mechanism in concrete.
3. Laboratory effort to determine effect of de-icing salts on aggregate performance.
4. Field studies to establish effect of rates, levels, and gradients of application of de-icing salts.
5. Data analysis, synthesis, and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	9	9
4	12	3
5	3	3
		30 m-m

Calendar months for completion: 24 months

Cost: 30 m-m @ $3,000/m-m = $ 90,000
Initial cost = $ 10,000
$100,000

References.

1. Craik, D. W., and Yuill, G. K, *De-Icing Chemicals Corrosion Investigation.* Univ. of Manitoba, Mech. Eng. Dept. (Sept. 1965).
2. "Effects of De-Icing Chemicals on Structures." *HRB Bull. 323* (1962) pp. 1-96.
3. Kennedy, T. W., "Mechanisms of Concrete Scaling." Ph.D thesis, Univ. of Ill (1965).
4. Malisch, W. R., et al., "Physical Factors Influencing Resistance of Concrete to Deicing Agents" *NCHRP Report 27* (1966) pp. 1-41.
5. Ost, B, and Monfore, G. E., "Penetration of Chloride into Concrete." *Research Dept. Bull. 192,* Portland Cement Assn. (1966).
6. Verbeck, G., and Klieger, P., "Studies of 'Salt' Scaling of Concrete." *HRB Bull. 150* (1957) pp. 1-13.

Problem No: I-3B *Estimated Time:* 27 months

Priority Category B *Estimated Cost:* $91,000

Title: The Aggregate-Paste Interface in Portland Cement Concrete

Problem Statement.

Interfaces are critical to the performance of a heterogeneous multi-phase material such as concrete. A wide range of interface problems exists, but bond strength variation is perhaps the one most widely known, as well as the most critical.

Bond strength varies with aggregate type, paste characteristics, environment, and time. Some aggregate paste combinations develop highly superior bonding that contributes significantly to structural strength. Environment probably plays a part in improving or breaking down bond strength.

There is not yet a systematic presentation of data by which bond strength of the paste aggregate interface can be optimized. Many of the variables have been treated in the literature but a comprehensive and quantitative position has not been developed. Among the factors to be included are the following:

1. Bond changes with time and environment
2. Synthetic improvement of bond
3. Basics of paste-aggregate bond (relating bond to fundamental characteristics of the system).

Objectives.

1. Develop a conceptual framework for the problem of paste-aggregate bond optimization.
2. Develop practical methods for optimizing bond under situations when environment, service life, aggregate type, etc, offer significant alternatives.

Program:

1. Literature search and review of extensive but fragmented data on bond.
2. Development of conceptual framework for the aggregate-paste interface bond situation.
3. Laboratory study to determine how bonding varies

with significant aggregate-paste variables with time and with service environment.

4. Data analysis, synthesis, and reports

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	3	3
3	12	18
4	12	3
		27 m-m

Calendar months for completion: 27 months

Cost· 27 m-m @ $3,000/m-m = $81,000
Initial cost = $10,000
$91,000

References:

1. ALEXANDER, K., "Strength of the Cement-Aggregate Bond." *J. Amer. Conc. Inst.*, Vol. 56, No 5, pp. 377-90 (Nov 1959).
2. ALEXANDER, K., and TAPLIN, J., "Analysis of the Strength and Fracture of Concrete Based on an Unusual Insensitivity of Cement-Aggregate Bond to Curing Temperature." *Australian J. of Applied Science*, Melbourne, Vol. 15, No. 3, pp. 160-70 (Sept. 1964).
3. SCHOLER, C. F., "An Investigation of the Bond Between Portland Cement Mortar and Coarse Aggregate." Ph.D. thesis, Purdue Univ. (Jan. 1965).
4. SCHOLER, C. F., "The Role of Mortar-Aggregate Bond in the Strength of Concrete." *Hwy. Res Record No. 210* (1967) pp. 108-17.
5. TAYLOR, M., and BROMS, B, "Shear Bond Strength Between Coarse Aggregate and Cement Paste or Mortar." *J. Amer. Conc Inst.*, Vol. 61, pp. 939-55 (Aug. 1964)

Problem No: I-4B *Estimated Time.* 24 months

Priority Category: B *Estimated Cost* $91,000

Title Variation of Alkali Content of Highway Structures with Environment and Time

Problem Statement:

A principal concern in regard to the chemical environment of aggregate in service is alkali content of the concrete. This environment has a well-known deleterious effect on certain aggregates. However, more information is needed on the variation of alkali content of concrete with environment and time in various types of highway structures.

Objectives:

Determine the effect of changes in environment with time on alkali content of in-service concrete, considering various types of highway structures.

Program·

1. Literature search and study.
2. Development of field techniques for detecting alkaline environments in concrete.
3. Laboratory and field testing to determine effect of environment and time on alkali content of concrete in service.
4. Data analysis, synthesis, and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	3	3
3	18	18
4	6	3
		27 m-m

Calendar months for completion: 24 months

Cost. 27 m-m @ $3,000/m-m = $81,000
Initial cost = $10,000
$91,000

References.

1. HADLEY, D., "Alkali Reactivity of Carbonate Rocks." *Hwy. Res. Record No. 45* (1964) pp. 1-19.
2. HADLEY, D., "Alkali Reactivity of Carbonate Rocks—Expansion and Dedolomitization." *Proc. HRB*, Vol. 40 (1961) pp. 462-74.
3. HANSEN, W. C., "Chemical Reactions." *Tests and Properties of Concrete and Concrete-Making Materials*, ASTM, STP No. 169-A (1966).
4. "Chemical Reactions of Aggregates in Concrete." *HRB Spec. Rep. 31* (1958) pp. 1-10.
5. LEMISH, J., HARWOOD, R. J., HILTROP, C. L., and WERNER, M. A., "Compositional Variations Associated with Carbonate Aggregate Reactions." *Hwy. Res Record No 3* (1963) pp. 1-8.
6. MATHER, K., BUCK, A. D., and LUKE, W. I., "Alkali-Silica and Alkali-Carbonate Reactivity of Some Rocks from South Dakota, Kansas, and Missouri." *Hwy. Res. Record No. 45* (1964) pp. 72-109.
7. MIELENZ, R. S., "Reactions of Aggregates Involving Solubility, Oxidation, Sulfates and Sulfides." *Hwy. Res. Record No. 43* (1963) pp. 1-7.
8. SHERWOOD, W. C., and NEWLON, H. H., "Studies on the Mechanism of Alkali-Carbonate Reaction—Part I. Chemical Reactions." *Hwy. Res. Record No. 45* (1964) pp. 72-109.

Problem No.: I-5B *Estimated Time·* 24 months

Priority Category: B *Estimated Cost.* $119,000

Title: Fundamental Mechanisms of Moisture Movement in Concrete

Problem Statement:

For moisture content data to be meaningful, there must be a better understanding of the fundamental mechanisms by which water moves in concrete and in aggregates. It is currently not possible to describe moisture movements, or moisture changes with changing ambient conditions. Factors that appear to be critical include the basic nature of the paste, aggregate properties, and temperature, hydraulic, and solution gradients. The significance of all of these on the rate and degree of moisture content changes of aggregate particles in concrete in service needs to be studied intensively.

Objectives:

1. Relate moisture contents, moisture movements, or moisture changes in concrete, and in the aggregate phase, to changes in ambient conditions.
2. Broaden the knowledge of fundamental mechanisms by which water moves through concrete and the aggregate particles with specific attention toward:
   a. Properties of matrix.
   b. Properties of aggregate.
   c. Temperature gradients.
   d. Hydraulic gradients.
3. Dissolved materials.

Program:

1. Literature search and study, emphasizing related disciplines, i e , petroleum engineering and agriculture.
2. Laboratory study of the mechanisms of water movement which may be peculiar to particles and concrete.
3. Laboratory and field study aimed at relating moisture contents and gradients to ambient conditions.
4. Analysis, synthesis, and report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	16
3	12	16
4	6	3
		38 m-m

Calendar months for completion: 24 months

Cost: 38 m-m @ \$3,000/m-m = \$114,000
Initial cost = \$ 5,000
\$119,000

References:

1. CADY, P. D., "Mechanisms of Frost Destruction in Concrete." Ph.D. thesis, Penn. State Univ. (1967).
2. DUNN, J. R., and HUDEC, P. P., "Water, Clay, and Rock Soundness." *The Ohio Journal of Science,* Vol. 66, pp. 153-68 (1966).
3. HUGHES, B., and BAHRAMIAN, B., "An Accurate Laboratory Test for Determining the Absorption of Aggregates." *Materials Research and Standards,* Vol. 7, No. 1, pp. 18-23 (Jan. 1967).
4. PICKETT, G., "Flow of Moisture in Hardened Portland Cement During Freezing." *Proc. HRB,* Vol. 32 (1953) pp. 276-84.
5. REILLY, R. J., "The Effect of Moisture Content and Distribution on the Durability of Concrete Containing Various Coarse Aggregates." M.S. thesis, Univ. of Md. (1962).
6. SIKTBERG, C. Y., "Effective System for Control of Moisture in Concrete Aggregates." *Modern Concrete,* Vol. 30, No. 2, pp. 52-54 (June 1966).
7. SNOWDEN, L., and EDWARDS, A., "The Moisture Movement of Natural Aggregate and its Effect on Concrete." *Magazine of Concrete Research,* Vol. 14, No. 41 (July 1962).
8. SWEET, H. S., and WOODS, K. B., "A Study of Chert as a Deleterious Constituent in Aggregates." *Eng. Bull. of Purdue Univ.,* Res. Series 86, Vol. 26, p. 5 (1942).
9. "The Properties of Chert Aggregate in Relation to their Deleterious Effect in Concrete." *Hwy. Res. Abstract,* Vol. 36, No. 7, p. 8 (July 1966).
10. TREMPER, B., and SPELLMAN, D. L., "Tests for Freeze-Thaw Durability of Concrete Aggregates." *HRB Bull. 305* (1961) pp. 28-50.
11. TROXELL, G. E., and DAVIS, H. E., *Composition and Properties of Concrete.* McGraw-Hill, 434 pp. (1956).

Problem No.: I-6B *Estimated Time:* 24 months

Priority Category. B *Estimated Cost* \$100,000

Title: Failure Criteria for Concrete Aggregate With Regard to Cracking

Problem Statement:

Cracking is a manifestation of failure in concrete. The role aggregate plays in various types of cracking has not been described. Does a pre-cracked particle become the focus of a concrete crack, for example? How does this change with different aggregates and different service environments?

Concern has been expressed over the prospect that certain quarrying and handling practices may crack aggregate particles in a detrimental fashion. Little quantitative information seems to be available in this speculation.

The problem then is that it is not known if aggregate cracks are significant in concrete cracking, by drying shrinkage for example, and neither is it known how quarrying and handling practices contribute to particle cracking.

Objectives:

1. Establish relationships between aggregate cracks and concrete cracking by various mechanisms.
2. Establish relationships between quarrying and han-

dling practices and aggregate particle cracking considering basic aggregate types.

3 Suggest failure criteria for particle cracking that could serve as a basis for a meaningful acceptance procedure.

Program.

1 Literature search and study. Emphasize geologic, mining, and quarrying literature.

2. Laboratory and plant study to evaluate cracking tendencies of aggregate particles with various quarrying, crushing, and handling practices

3. Laboratory study to evaluate relationship of concrete cracking to aggregate cracking.

4 Establish failure criteria for aggregate cracking in concrete.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	6	3
		30 m-m

Calendar months for completion: 24 months

Cost: 30 m-m @ \$3,000/m-m = \$ 90,000
Initial cost = \$ 10,000
\$100,000

References

1 Blakey, F. A , "Some Considerations on the Cracking or Fracture of Concrete." *Civil Eng.*, London, 52 (615), 1000-3 (1957).

2. Hansen, T., and Nielsen, K., "Influence of Aggregate Properties on Concrete Shrinkage." *J. Amer Conc. Inst.*, Vol. 62, pp. 783-93 (July 1965)

3. Jones, R., "The Development of Microcracks in Concrete." Road Research Lab. (Dec. 1960).

4. Linger, D. A., and Gillespie, H. A., "A Study of the Mechanism of Concrete Fatigue and Fracture." *Hwy. Res. News, No 22*, p. 40 (Feb. 1966).

5. Roper, H., "Shrinking Aggregates in Concrete." *Special Tech Report No. 502*, National Building Research Inst., Pretoria, pp. 1-136 (Dec. 1966).

6 Tremper, B., "Discussion of Drying Shrinkage of Concrete." *Hwy Res. News No. 23*, p. 45 (May 1966).

Problem No. I-7B   *Estimated Time* 12 months

Priority Category: B   *Estimated Cost* \$39,000

Title: Standardizing Outdoor Exposure Tests for Concrete Durability Studies

Problem Statement.

Outdoor exposure tests are used to study concrete response to a natural environment on a model basis. They provide a necessary step in the spectrum of test methods—all of which trade in cost versus realism.

It would be useful if there were elements of standardization in outdoor exposure tests which would facilitate transfer of findings to a greater extent than is now possible. An equally useful and necessary result would be a systematic review of outdoor concrete exposure testing, rationality, application, and the trade-off variables, realism and cost.

Objectives:

1. Make a systematic study of outdoor tests for concrete durability.

2. Develop a standard outdoor exposure method for concrete deterioration studies.

Program:

1. Literature search and review.

2. Survey and compile details on the present test procedures used for concrete outdoor exposure testing

3. Critically evaluate outdoor testing as a method for concrete and aggregate performance studies.

4. Develop a standard test method, synthesis, and report

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	3
3	6	6
4	6	1
		13 m-m

Calendar months for completion: 12 months

Cost: 13 m-m @ \$3,000/m-m = \$39,000.

References:

1. Grieb, W. E., Werner, G., and Woolf, D. O., "Resistance of Concrete Surfaces to Scaling by De-Icing Agents." *Pub. Roads*, Vol. 32, No. 3 (Aug. 1962).

2. Missouri State Highway Department, *Laboratory Freeze-Thaw Tests vs. Outdoor Exposure Tests* (July 1966).

3. Oleson, C C., and Verbeck, G., "Long-Time Study of Cement Performance in Concrete." *Research Dept. Bull. 217*, Portland Cement Assn. (Dec. 1967)

4. Tatum, P. J., and Landgren, R., "Outdoor Concrete Exposure Test Plot at Skokie." *Research Dept. Bull. 202*, Portland Cement Assn. (May 1966).

GROUP II, BITUMINOUS CONCRETE AND RELATED MATERIALS

Problem No II-1 *Estimated Time:* 39 months

Priority Category. A_1 *Estimated Cost.* $232,000

Title: Stripping of Asphalt Cement in Bituminous Mixtures and Identification of the Significant Aggregate Surface Properties that Influence Coating and Adhesion

Problem Statement.

The stripping of asphalt cement from aggregate particles is a severe problem in many areas. Neither the mechanism of stripping nor the aggregate surface properties that influence it are clearly understood at this time. Identification of the aggregate properties and environmental conditions that affect the bond between aggregate and asphalt cement is needed to develop techniques for rating aggregates according to their coatability, bondability, and stripping resistance, and to develop means of improving these properties when necessary. These techniques should permit the highway engineer to optimize his choice of aggregates where stripping might be a problem, or to specify appropriate corrective measures or beneficiation processes.

Objectives:

1. Identify the aggregate surface characteristics that influence stripping, coating, and adhesion of bituminous mixtures
2. Develop test methods that would indicate the degree of adhesion of bituminous mixtures.
3. Develop techniques for improving the coating and adhesion of bituminous material with aggregates.
4. Investigate the environmental factors that affect stripping and the appropriate corrective measures to mitigate these conditions.

Program

1. Literature search and review.
2. Through laboratory effort identify aggregate surface characteristics that influence coating and adhesion of bituminous mixtures and develop classification system.
3. Develop laboratory test method that would measure amount of adhesion of bituminous mixture.
4. Through laboratory effort develop technique for improving the coating and adhesion of bituminous materials with aggregate.
5. Investigate the environmental factors that affect stripping and develop corrective measures.
6. Verification of technique on wider sampling.
7. Data analysis and report.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	12	12
5	12	12
6	12	12
7	3	6
		69 m-m

Calendar months for completion: 39 months

Cost: 69 m-m @ $3,000/m-m = $207,000
Initial cost = $ 25,000
$232,000

References:

1. MAJIDZADEH, K., and BEOVOLD, F., "Effect of Water on Bitumen-Aggregate Mixture." *Research Report*, Fla. Univ. Dept. of Civil Eng. (Sept. 1966).
2. "Symposium on Effect of Water on Bituminous Pav-

TABLE A-2

PRIORITY RATINGS, GROUP II, BITUMINOUS CONCRETE AND RELATED MATERIALS

PROBLEM NO.	PRIORITY CATEGORY	EASE OF SOLUTION	VALUE OF SOLUTION	EASE OF IMPLEMENTATION	GEOGRAPHICAL SIGNIFICANCE	SUM
II-1	A_1	3.8	4-12	3 8	3-6	25.6
II-2	A_1	2.5	4-12	2	4-8	24.5
II-3	A_1	4	2.5-7 5	3.5	4.5-9	24
II-4	A_1	2	4-12	2.5	3-6	22.5
II-5	A_2	4	2-6	3	4-8	21
II-6	A_2	4	2-6	3	4-8	21
II-1B	B	4	2.5-7.5	4	5-10	25.5
II-2B	B	4	3-9	3	4-8	24
II-3B	B	5	2-6	3	5-10	24
II-4B	B	3.5	2-6	4	3-6	19.5

ing Mixtures." *ASTM Spec. Tech. Pub. No. 240* (Dec. 1958).
3. "Asphalt Durability and its Relation to Pavement Performance—Adhesion." Unpublished draft copies of agency reports from NCHRP Project 9-2.

Problem No II-2 *Estimated Time* 36 months

Priority Category: A_1 *Estimated Cost.* $163,000

Title: Soundness of Aggregate Particles in Bituminous Mixtures

Problem Statement.

It has been assumed in the past that the aggregate in bituminous concrete mixtures is protected from weathering by the supposed waterproofing characteristics of the asphalt cement. However, increasing evidence from the field shows that the aggregate, especially in the binder course, may break down due to adverse environmental conditions in combination with some deleterious characteristic of the aggregate Traffic loadings may also play a role. The highway engineer needs some measurement or system of measurement for establishing the soundness of mineral aggregates for bituminous paving mixtures in order that, for given environmental conditions and traffic loadings, he may make an intelligent choice from the available aggregate sources.

Objectives.

1. Develop a test method that would simulate actual field conditions and would give a reliable indication of the soundness of aggregate particles in bituminous mixtures.
2. Relate the soundness of the aggregate in the bituminous mixture to the soundness of the unconfined aggregate.

Program.

1. Literature search and review.
2. Develop test method(s) for soundness of unconfined aggregate and aggregate in bituminous mixtures.
3. Relate soundness of aggregate in mixtures to soundness of aggregate by itself.
4. Establish acceptable limits for aggregate soundness based on both field and laboratory testing.
5. Analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	4	4
2	18	18
3	12	12
4	6	6
5	3	6
		46 m-m

Calendar months for completion: 36 months

Cost. 46 m-m @ $3,000/m-m = $138,000
Initial cost = $ 25,000
$163,000

References.

1. GRAY, J. E., "Specifications for Mineral Aggregates." *Crushed Stone J*, Vol. 35, No. 2, pp. 3-10 (June 1961).
2. POPOVICS, S., "Mineral Aggregates in Highway Engineering." *Alabama Hwy. Res. Report No. 19* (Sept. 1965).

Problem No · II-3 *Estimated Time*· 24 months

Priority Category· A_1 *Estimated Cost* $126,000

Title. The Influence of Asphalt Absorption Rate, Nature and Amount by Aggregate Particles on Bituminous Mix Design and Performance

Problem Statement:

The water absorption characteristics of aggregates and the effect of absorption has been studied intensively. However, the nature and extent that aggregates absorb the asphalt in a bituminous mixture has not been thoroughly investigated. Further research is needed to determine more accurately the influence that asphalt absorption by the aggregate has on the mix design and subsequent performance. This investigation should establish asphaltic absorption tolerance levels as well as define types of aggregates that might have a high absorption rate. The various aspects of absorption such as rate, total, and selective absorption should be studied in this project. The information generated by this research should permit the highway engineer to judge the suitability of aggregates with respect to their asphalt absorption characteristics and the possible effect of absorption on pavement durability.

Objectives:

1. Determine the influence that asphalt absorption by aggregate particles has on bituminous mix design and performance.
2. Establish tolerance levels of asphalt absorption rate and amount.

Program.

1. Literature search and review.
2. Through laboratory effort evaluate the influence of asphalt absorption by aggregate on the mix design.
3. Identify aggregate types that have high asphalt absorption rates.
4. Establish absorption rates and amounts that would be detrimental to performance of mix.
5. Data analysis and reports.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	6	12
5	3	3
		42 m-m

Calendar months for completion: 24 months

Cost 42 m-m @ $3,000/m-m = $126,000.

References

1 "Density, Absorption and Specific Gravity Tests of Aggregates, Bituminous Materials, Bituminous Mixtures and Surfaces." *HRB Bibl. 25* (1960) pp. 1-12.

Problem No II-4 *Estimated Time.* 42 months

Priority Category· A_1 *Estimated Cost.* $232,000

Title: Degradation of Aggregate Leading to the Production of Deleterious Fines in Bituminous Mixtures

Problem Statement:

Physical and chemical degradation occur to a greater or lesser degree in all aggregates, and they occur during all phases of aggregate storage, handling, mixing, placing, compacting, and service. The primary detriment of degradation is that it results in the production of fines that unavoidably change the characteristics of the aggregate and the bituminous concrete mixture of which it is a part. The degradative processes of primary interest here are those that occur in compacted bituminous concrete under field conditions. Basically they are of two types: (1) physical degradation caused by traffic loadings, and (2) chemical degradation resulting from interactions between the aggregate in the pavement and its environment. Needed in this respect are basic studies of the mechanisms of degradation, both physical and chemical, and development of a system of measurement for evaluating extent and rate of degradation. The highway engineer should be able to use the system of measurement to optimize his choice of materials from competitive sources and to screen out those aggregates that fail to meet the minimum acceptability criteria established in the basic research phases.

Objectives:

1. Identify the basic mechanisms of aggregate degradation in bituminous concrete pavements.
2. Determine the effects of degradation on pavement serviceability.
3. Develop a system of measurement for evaluating the extent and rate of degradation.

Program:

1. Literature search and review.
2. By laboratory and field testing, identify the mechanisms of chemical and physical degradation that occur in aggregates.
3. Develop a system of laboratory test methods for measuring degradation and production of deleterious fines.
4. By laboratory and field testing, determine those aggregates which degrade and aggregate properties which influence degradation.
5. By laboratory and field study, evaluate the effects of degradation on pavement serviceability.
6. Data analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	12	18
5	12	18
6	3	6
		69 m-m

Calendar months for completion: 42 months

Cost: 69 m-m @ $3,000/m-m = $207,000
Initial cost = $ 25,000
$232,000

References:

1. BUCKLAND, A. H., *Degradation of Roading Aggregate.* Report to New Zealand Road Federation (1966).
2. HARRA, G. W., "Degradation of Aggregates." *Pacific Builder and Eng.*, Vol. 68, No. 9, p. 86 (Sept. 1962).
3. MARSHALL, T. R., "The Washington Degradation Test, A Status Report." *Wash. State Hwy. Comm. Report No. 103* (Dec. 1967).
4. MOAVENZADEH, F., and GOETZ, W., "Aggregate Degradation in Bituminous Mixture" *Hwy. Res. Record No. 24* (1963) pp. 106-37.

Problem No.: II-5 *Estimated Time:* 36 months

Priority Category: A_2 *Estimated Cost:* $144,000

Title: The Role of the Aggregate in Relation to the Mechanical Properties of the Bituminous Mixture

Problem Statement:

Aggregate, being the major ingredient of bituminous concrete, imparts its qualities to the mechanical properties of the mixture. The nature and extent of this influence on the mixture, however, are not fully understood. Further research is warranted to determine the role of the aggregate in relation to the mechanical properties of the mixture such as fatigue behavior, resiliency, shear stability, and stiffness modulus Included in this project would be development of test methods, and methods to improve the aggregate and/or the mixture that would enhance these mechanical properties. The test methods and procedures should permit the highway engineer to optimize his choice of materials and beneficiation processes with respect to the mechanical properties required of the pavement.

Objectives.

1. To determine the effects of aggregate characteristics on the mechanical properties of bituminous concrete.
2. To develop means of altering aggregates to improve the properties of bituminous concrete.

Program:

1. Literature search and review.
2. Develop laboratory test methods that will indicate the influence of the aggregate on various mechanical properties of the mixture
3 Carry out experiments to determine how aggregate characteristics influence mechanical properties of the mixture
4. Develop methods to improve the aggregate and/or the mixture in relation to its mechanical properties.
5. Data analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	18
4	12	12
5	3	3
		48 m-m

Calendar months for completion: 36 months

Cost: 48 m-m @ $3,000/m-m = $144,000.

References

1. FINN, F. N., "Factors Involved in the Design of Asphaltic Pavement Surfaces." *NCHRP Report 39* (1967) pp. 1-112.

Problem No. II-6 *Estimated Time.* 24 months

Priority Category. A_2 *Estimated Cost.* $81,000

Title: Effect of Heat on the Integrity and Characteristics of Aggregates

Problem Statement:

In the production of hot-mix bituminous concrete, heating can affect the integrity and characteristics of certain aggregates. In addition to changing the moisture content of the aggregates, other characteristics such as its surface chemistry may be modified. The most critical aspect of this area is the rate of heating of the aggregate. Further research is required to provide more information on effects of heating on aggregates.

Objectives:

1. Determine what characteristics of aggregates are changed by heating.
2. Evaluate the influence of rate of heating on changes in aggregate characteristics and establish tolerable heating rates.

Program:

1. Literature search and review.
2 Through field testing determine which aggregate characteristics are modified by heating.
3. Through field testing determine how rate of heating affects the aggregate and establish acceptable limits of heating rates.
4. Data analysis and reports.

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	6	6
4	3	6
		27 m-m

Calendar months for completion. 24 months

Cost. 27 m-m @ $3,000/m-m = $81,000.

References.

1. PARR, W. K., "The Drying and Heating of Aggregates· Basic Theory and Practical Application." *Canadian Tech. Asphalt Assn. Proc.* (Nov. 1960).
2 PARR, W. K., and KALE, L., "Observations on Drying and Heating of Aggregate." *Proc. Assn. of Asphalt Paving Technologists,* Vol. 34, pp. 149-89 (1965).
3 SMEINS, V G., "Investigation of the Effect of Changes in Aggregate Characteristics on the Dryer Discharge." *Ohio State Univ. Trans. Eng. Center Report No. CE 15-5* (Nov. 1960).

Problem No II-1B *Estimated Time* 30 months

Priority Category: B *Estimated Cost:* $144,000

Title: The Effect of Aggregate Gradation on Bituminous Mix Design

Problem Statement·

Aggregate gradation plays an important role in the design of bituminous mixtures. In actual practice, gradation of the aggregate is judged by its conformity to arbitrarily defined limits with permissible variations tolerated. Considerable feeling exists among highway engineers that the current gradation specifications are overly stringent and arbitrary The need for a rational approach relating aggregate gradation requirements to needs is in evidence.

Objectives:

1. Determine the effect of aggregate gradation on mix design and surface characteristics.
2. Establish tolerable limits of aggregate gradation or develop alternate particle size distribution criteria.

Program

1. Literature search and review.
2. Through laboratory testing determine the effect of aggregate gradations on mix design.
3. Through field testing, determine the effect of aggregate gradations on pavement surface characteristics.
4. Develop comprehensive specifications and guidelines for aggregate particle size distribution for bituminous concrete mixtures.
5. Data analysis and reports.

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	18
4	12	12
5	3	3
		48 m-m

Calendar months for completion: 30 months

Cost· 48 m-m @ $3,000/m-m = $144,000.

References

1. Goode, J. F., and Lufsey, L. A., "A New Graphical Chart for Evaluating Aggregate Gradations." *Proc. Assn. of Asphalt Paving Technologists,* Vol. 31 (1962).
2. Hudson, S. B, and Davis, R. L., "Relationship of Aggregate Voidage to Gradation." *Proc. Assn of Asphalt Paving Technologists,* Vol. 34, pp. 574-93 (1965).

Problem No II-2B *Estimated Time* 24 months

Priority Category: B *Estimated Cost:* $90,000

Title Effect of Fines on Hardening of Asphaltic Concrete

Problem Statement:

The role played by the fines (minus #200 sieve material) on the durability of asphaltic concrete is not clearly defined. It has been suggested that the use of increased fines could promote durability by permitting higher percentage asphalt cement contents in asphaltic concrete. Therefore, at a given asphalt cement hardening rate the deterioration rate should be lower for the one having the higher AC content, assuming approximately equal exposed surface areas of AC Research is needed to establish optima between durability and stability, percentage AC, and percentage passing #200 sieve.

Objectives.

1. Determine the effect of fines (minus #200 sieve material) on the hardening of asphaltic concrete and durability of the mixture.

Program.

1. Literature search and review.
2. Laboratory study to determine the effect of fines on asphalt hardening.
3. Laboratory and field study to determine if increased fines can improve durability of asphaltic concrete pavements.
4. Data analysis, synthesis, and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	6	3
		30 m-m

Calendar months for completion: 24 months

Cost: 30 m-m @ $3,000/m-m = $90,000.

References.

1 Goode, J. F., and Lufsey, L. A., "Voids Permeability, Film Thickness vs. Asphalt Hardening." *Proc. Assn. of Asphalt Paving Technologists,* Vol. 34, pp. 430-63 (1965).
2. Hein, T. C., and Schmidt, R. J., "Air Permeability of Asphaltic Concrete." *ASTM Spec. Tech. Pub. No. 309,* pp. 49-62 (June 1961).
3. Heukelom, W., "The Role of Filler in Bituminous Mixes." *Proc. Assn. of Asphalt Paving Technologists,* Vol. 34, pp. 396-426 (1965).
4. "Symposium on Mineral Fillers for Bituminous Mixtures." *HRB Bull. 329* (1962) pp. 1-89.
5. Tunnicliff, D. G., "A Review of Mineral Filler." *Proc. Assn. of Asphalt Paving Technologists,* Vol. 31, pp. 118-50 (1962).

Problem No.: II-3B *Estimated Time:* 30 months

Priority Category: B *Estimated Cost:* $90,000

Title: The Phenomenological Aspects of Internal Friction as Related to Bituminous Mix Design

Problem Statement

The stability of bituminous concrete depends to a very great extent on the degree of interlock of aggregate particles and the internal friction of the bituminous concrete mixture. Unfortunately, these characteristics, which are related to the aggregate properties of particle shape and surface texture, have not been extensively evaluated. With the constantly increasing traffic loadings imposed on today's pavements, the need for basic research on the mechanisms of strength and stability of asphaltic concrete is clearly indicated

Objectives:

1. Investigate the phenomenological aspects of internal friction as related to bituminous concrete mix design and performance.
2. Determine the effects of aggregate qualities such as shape and surface texture in relation to internal friction of the mix.

Program.

1. Literature search and review.
2. Through laboratory testing, determine the effects of aggregate characteristics (such as shape and surface texture) on internal friction of the bituminous mixture.
3. Develop methods (mix design, aggregate beneficiation) that would improve internal friction of mix.
4. Data analysis and report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	3	3
		30 m-m

Calendar months for completion: 30 months

Cost: 30 m-m @ $3,000/m-m = $90,000.

References:

1. Li, M. C., and Kett, J., "Influence of Coarse Aggregate Shape on Strength of Asphalt Concrete Mixtures." *Hwy. Res. Record No. 178,* pp. 93-106 (1967).
2. Puzinauskas, V. P., "Influence of Mineral Aggregate Structure on Properties of Asphalt Paving Mixtures." *Tenn. Univ. Eng. Experiment Station Bull. 30,* pp. 99-124 (Jan. 1965).
3. Vallerga, B. A , Seed, H. B., Monismith, C. L., and Cooper, R. S., "Effect of Shape, Size and Surface Roughness of Aggregate Particles on the Strength of Granular Materials." *ASTM Spec. Tech Pub. No 212* (1957).

Problem No II-4B *Estimated Time:* 21 months

Priority Category. B *Estimated Cost:* $72,000

Title: Spreading Rates and Gradation of Aggregates for Bituminous Surface Treatments

Problem Statement

The quality and performance of surface treatments are determined by the gradation of the coverstone and the spreading rates of the aggregate and the bituminous material Aggregate gradation is especially critical for coverstone. There seems to be an optimum gradation range as yet undefined. The spreading rate which is dependent on surface texture and particle size is likewise critical. An excess or deficiency of aggregate will result in bleeding and slippery pavements or unstable pavement surfaces. Therefore, research is needed to determine optimum aggregate spreading rate and aggregate gradation for coverstone in surface treatments.

Objectives

1. Establish an optimum particle size and gradation band for surface treatment aggregates.
2. Establish optimum aggregate spreading rates for surface treatments.

Program:

1. Literature search and review.
2. Through laboratory and field studies determine an optimum particle size.
3. Through field studies determine an optimum spreading rate of aggregate for coverstone.
4. Data analysis, synthesis, and reports.

Time·

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	6	6
4	6	3
		24 m-m

Calendar months for completion: 21 months

Cost: 24 m-m @ $3,000/m-m = $72,000.

References:

1. Finn, F. N., "Factors Involved in the Design of Asphaltic Pavement Surfaces." *NCHRP Report 39* (1967) pp. 1-112.
2 Gallaway, B., and Harper, W., "Laboratory and Field Evolution of Light-weight Aggregates as Coverstone for Seal Coats and Surface Treatment." *Hwy. Res. Record No. 150* (1966) pp. 25-75.
3. McLeod, N. W., "Basic Principles for the Design and Construction of Seal Coats and Surface Treat-

ments with Cutback Asphalts and Asphalt Cements." *Proc. Assn. of Asphalt Paving Technologists,* Vol 29, Suppl.

4 SCHIVEYER, H. E., and GARTNER, W., "A Study of Tenacity of Aggregates in Surface Treatments." *Hwy. Res. Record No. 104* (1965) pp. 18-36.

GROUP III, BASE COURSE AND SHOULDER MATERIALS

Problem No: III-1 *Estimated Time.* 36 months

Priority Category: A_1 *Estimated Cost.* $115,000

Title: The Relationship of Aggregate and Base Course Properties to Base Course Performance Under Varying Traffic Loads

Problem Statement:

Recent trends by many states toward higher maximum allowable gross truckloads combined with increasing ADT volumes have resulted in deterioration of highway pavement and base courses. Information is needed on the relationship of degree and frequency of loading to aggregate properties which affect base course strength, stability, stiffness, resilience, and brittleness.

Properties of aggregate, such as surface texture and shape, in various service environments are significant in influencing stress distribution or concentration at aggregate interfaces. Development of a relationship between base course aggregate properties and level of service should be investigated for the purpose of identifying those properties which are most critical for good performance under heavy loads; for example, what properties cause some coarse aggregate to retain desirable "texture" under traffic. Data of this type may assist in the efficient and economical selection of aggregate for a particular use, such as using a lower quality aggregate where the service environment is not severe.

One commonly encountered problem throughout the United States is a lack of knowledge of relative strength of aggregates and an accurate means of measurement. For the over-all base course "system" or mixture, triaxial test procedures are frequently used. However, test procedures are needed which can be applied to the aggregate particles per se in an effort to obtain a relative measure of strength. For example, a triaxial test for strength of base course mixtures may not yield information on future strength or degradation to be expected in individual particles of various aggregate types. Required strength is somewhat dependent on location of the aggregate within the base course, and as such it may be found that meaningful studies should be carried out on entire base course mixtures rather than on individual particles.

In addition to strength, stability of aggregate base course mixtures is generally a necessity for proper pavement performance. In sections of the Indiana Test Road, for example, longitudinal cracking of the concrete pavement, due to lack of stability in the subbase, was observed after a number of years. Although stability is thought to be dependent on material type, further research is warranted to define this relationship. Also, information on the relation between density and stability is needed. Because present trends toward wider pavements have resulted in reduced base course drainage, the effect of moisture on stability must be further studied.

An evaluation and development program on laboratory testing procedures for stability should be undertaken before extensive base course stability studies are conducted. One difficulty with present test methods such as CBR, Stabilometer, or Triaxial is that the loading is static or gradually applied and does not accurately reflect the mix properties under dynamic, repetitive traffic loading.

Stiffness may be defined as the quality or ability of a material to resist deflection, i.e., to be "inelastic." However, stiffness needs to be further defined (or a new term introduced) to include the ability of a material to damp out deflections and to provide greater load-carrying capacity, much like the requirements of a base course in highway pavements.

Strength and elasticity of individual aggregate particles are desirable in base courses because degradation is reduced and stability is maintained. The question to be answered is, "What degree of elasticity or stiffness is desirable and

TABLE A-3

PRIORITY RATINGS, GROUP III, BASE COURSE AND SHOULDER MATERIALS

PROBLEM NO.	PRIORITY CATEGORY	EASE OF SOLUTION	VALUE OF SOLUTION	EASE OF IMPLEMENTATION	GEOGRAPHICAL SIGNIFICANCE	SUM
III-1	A_1	3	4-12	3	5-10	28
III-2	A_1	2 5	4.5-13.5	3	4-8	27
III-3	A_2	4	4-12	3	4-8	27
III-4	A_2	4	1.5-4.5	2	4-8	18.5
III-5	A_3	3	2-6	3	2-4	16
III-1B	B	2	4-12	2	5-10	26
III-2B	B	2	4.5-13.5	2.5	4-8	26
III-3B	B	4	3.5-10.5	3	4-8	25 5
III-4B	B	3	3 5-10.5	2 5	4-8	24

what significance does it have in the base course?" For example, the total deflection of the pavement surface will depend in part on the stiffness of the various underlying layers.

Research is needed to better determine the relationship between stiffness and load or stress distribution in base courses. Test methods that adequately measure stiffness are also needed and are essential for meaningful research results. Circular track-type test facilities may be useful for studies on such base course properties as strength, stability, and stiffness, but information on the actual in-situ pavement loadings, stresses, and strains must be available before these quantities can be duplicated in a test track. If available, a controlled climatic environmental test track would be useful.

The ability of a base course to deflect and rebound when a load is applied and removed is important, especially for flexible pavements, and is, in fact, more important in base courses than in underlying subgrade soils. Many factors affect resilience—material type is generally the most important Information is needed on the aggregate properties that influence resilience and the effect that resilience of the aggregate particle itself has on total base course resilience Test methods are needed for base course systems that are widely applicable and will yield resilience values that can be related and applied to different environmental conditions

Also included among base course aggregate characteristics is the property of brittleness Closely related with flexibility and resilience, brittleness should be studied and defined to reflect its significance in the total base course mixture and its effect on performance. The desire is to have little or no base course brittleness while maintaining adequate stability. Development of test methods for measurement of brittleness in both aggregate particles and base courses is needed.

Note: A current test method for evaluation is the resiliometer (in use by California and Washington). Examination of so-called "systems approach" to pavement design—i e , Modulus of Elasticity (E) is known—may be included in this study.

Objectives.

1. To conduct investigation of the critical aggregate properties which influence base course strength and stability and determine the extent of this influence.
2. To investigate the nature, effect, and significance of brittleness, stiffness, and resilience in:
   a. Aggregate particles per se.
   b. Highway base course mixtures.
3. To determine the tolerable limits and frequency of loading on base courses with given aggregate properties.
4. To evaluate present laboratory and field test methods for measuring aggregate and base course strength, stability, stiffness, brittleness, and resilience, and develop new test methods, if needed, that will indicate values to be expected under dynamic, repetitive traffic loading.
5. To identify those aggregate types that exhibit a detrimental degree of brittleness, stiffness, and resilience, and develop recommended design and construction practices for the accommodation of such aggregates.
6. To develop recommendations on aggregate use for given levels of pavement loading and performance, including recommendations as to the strength and stability values necessary for given aggregate types and given levels of service.

Program:

1 Literature search and review.
2. By laboratory testing and field investigations, evaluate present test methods for base course strength, stability, resilience, stiffness, and brittleness and develop new methods of test and measurement as needed
3. By the use of laboratory and/or field test procedures determine the critical or significant aggregate properties which affect the base course quantities mentioned in item 2.
4. Evaluate the influence of the aforementioned qualities on base course performance and develop workable relationships between test values and limits required for good base course performance under varying types of construction and traffic loads
5. Develop recommendations, where applicable, for the use of aggregate types for given levels of service loading and performance.
6. Data analysis and report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	9
3	12	12
4	3	3
5	3	1½
6	3	1½
		30 m-m

Calendar months for completion: 36 months

Cost: 30 m-m @ $3,000/m-m = $ 90,000
Initial cost = $ 25,000
$115,000

References

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Problem No.: III-2 *Estimated Time.* 27 months

Priority Category: A_1 *Estimated Cost.* $160,000

Title: Determination of the Causes of Change in Gradation for Aggregates Used in Highway Base Course Construction

Problem Statement

An important area of concern is change in base course aggregate gradation caused by physical and chemical action during storage, shipment, or construction, and while in service. Information is needed on the causes of the gradation changes and the means to control them, as well as information on the quantity and characteristics of the fines produced.

Base course degradation may be caused, for example, by one or a combination of the following factors· (1) mechanical breakdown during compaction and under traffic loading, (2) chemical action as a result of ground water infiltration, (3) unusual materials, such as bentonite, in the aggregate, (4) movement of the subgrade into the base (contamination), and (5) conditions of freezing and thawing Climatic environment must be considered when studying the degradation problem because it plays a large role in determining the severity of the factors causing gradation changes.

Adequate procedures need to be developed for testing aggregates for susceptibility to both physical and chemical degradation Some of the test methods currently in use have poor correlation with actual field degradation and performance (Los Angeles abrasion, for example). Knowledge of the expected changes in aggregate gradation must be available before proper control specifications can be written for a given base course aggregate.

Information is needed concerning the amount and characteristics of fines produced during the construction and service life of highway base courses and their effect on base course density, stability, permeability (drainage), and frost action. It is known that certain aggregates produce fines that cause loss of drainage and stability of a base as well as making it more frost susceptible. Little is known concerning the relationship between the quantity and nature of the fines and their effect on these properties. For example, larger quantities of certain fines may produce less deleterious effect than smaller amounts of other fines.

Because of a wide variation in climatic environments and levels of service to which pavements are subjected throughout the United States, much remains to be learned concerning the combinations of aggregate properties that allow deterioration and breakup of highway base courses due to frost heave or freeze-thaw conditions. It is known that the greatest base course damage from frost heave occurs with heavy pavement loads during periods of thaw following extended periods of high moisture and below-freezing temperatures Information is needed on the aggregate properties or base course design criteria which allow frost heave to occur. For example, degradation of base course aggregate produces fines (previously mentioned) that reduce or restrict drainage of water. During freezing temperatures this undrained water is available for formation of ice lenses within the base and, when thawing occurs, pavement breakup may follow.

Laboratory testing of the effect of fines on frost may include varying the percentage of fines passing the #200 sieve. Other variables that should be examined to determine their effect on frost action in base courses include·

1. Penetration rate of frost line.
2 Relative compaction or dry density.
3. Surface tension and quantity of fines versus capillary rise of water and freezing rate.
4. Cyclic freeze-thaw conditions.

Included in the study of water rise in base courses should be the relationship between the pore size and distribution (largely determined by quantity and characteristics of fines), surface tension, and direction of saturation. Consideration should also be given to vapor rise and recondensation theories.

Field observations of frost action should be combined with laboratory investigations and may include examination of core samples and measurement of base course temperatures, surface heave, and frost line location. Development of test methods to predict frost potential of various aggregate types is needed, especially when a decision must be made to import aggregate or beneficiate available aggregate.

With knowledge of the causes of change in gradation in base course aggregates and the quantity and characteristics of the fines produced (as well as the effect of these fines on base course stability, frost action, etc.) steps may be taken by the highway engineer to reduce degradation and the effects of frost heave and improve over-all highway performance.

Objectives.

1. Identify the mechanical and chemical causes of degradation and their deleterious effects, including the relationship between degradation, climatic environment, and performance.

2. Conduct a pilot study (concentrating on techniques) that will provide test methods and procedures for determining:

   a. Extent of gradation change to be expected.
   b. The quantity and characteristics of fines passing the #200 sieve.
   c. The effect of fines passing the #200 sieve on density, stability, drainage, and frost susceptibility of highway base courses.
   d. Acceptance limits on the amount of fines.
   e. Frost susceptibility of aggregates.

It is anticipated that several aggregates of different types (representing major rock groups, both good and poor materials) will be used in this pilot study so that, based on the results of the project, other aggregates can be studied in a simple manner on a regional or state basis. The fundamental physical and chemical properties of aggregate-produced fines is expected to be an integral part of the project.

3. Identify those aggregate types that are most susceptible to changes in gradation and production of fines.

4. Identify the effect and significance of aggregate and base course properties on capillary moisture rise.

5. Develop recommendations for aggregate use in base course construction in areas where frost susceptibility may be a critical design factor. Involved in the study will be investigation of:

   a. Physical and climatic environmental factors most conducive to frost action and damage.
   b. Aggregate properties that intensify the formation of ice lenses and the frost heave problem.
   c. Base course design criteria that may affect frost heave, such as gradation, permeability, and density.

Program:

1. Literature search and review.
2. Laboratory and field investigation of the causes of gradation changes during storage, shipment, construction, and service.
3. Develop techniques and test methods for examination and classification of the quantity and characteristics of fines passing the #200 mesh sieve.
4. Determine the effects of fines on base course qualities (including drainage and stability) and over-all performance.
5. Laboratory and field study on the aggregate and base course properties that affect frost potential and damage by freeze-thaw action, including the climatic environments involved.
6. Develop methods for the identification of the susceptibility of aggregate types to gradation changes and damage by freeze-thaw conditions
7. Develop acceptance limits for the amount of fines for a given service and climatic environment.
8. Analyze present base course design criteria and develop recommendations regarding the use of aggregates in base course construction for the purpose of reducing degradation and frost damage.
9. Data analysis, synthesis, and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	15
3	6	6
4	9	9
5	6	6
6	3	3
7	3	1
8	3	1
9	3	1
		45 m-m

Calendar months for completion: 27 months

Cost. 45 m-m @ \$3,000/m-m = \$135,000
Initial cost = \$ 25,000
\$160,000

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30. West, T. R., Johnson, R. B., Smith, N. M., and Aughenbaugh, N. B., "Tests for Evaluating Degradation of Base Course Aggregates." *NCHRP Report 98* (1970).

Problem No.: III-3 *Estimated Time:* 18 months

Priority Category· A_2 *Estimated Cost:* $118,000

Title: Development of Test Methods to Predict Density Retention of Base Courses

Problem Statement:

Closely associated with the problem of attaining adequate density and stability in highway base courses during construction is the problem of retaining the density during the service life of the pavement. During construction, various procedures are used in an attempt to retain the degree of compaction desired. Ideally, the full structural load should be applied immediately. However, if the base must remain exposed during the winter months, recompaction might generally be specified for spring.

Laboratory and field test methods are needed to predict long-term density retention of base courses while in service. In other words, one must be able to anticipate the degree of density retention during and after addition of pavement. Methods should be developed that will be applicable to laboratory testing of compacted specimens and useful also for field testing of base course mixtures in place.

Objectives

1. Study aggregate properties relevant to base course density retention and mechanism by which density during service may vary from that obtained during construction
2 Develop laboratory and/or field test methods for the prediction of base course density retention

Program

1. Literature search and review.
2. Investigate the base course characteristics which affect density retention
3 Laboratory and field study of relative effectiveness of various methods of density retention for base courses.
4. Develop new laboratory and field test procedures useful for the prediction of density retention.
5 Data analysis and report

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	6
3	9	18
4	6	6
5	3	3
		36 m-m

Calendar months for completion· 18 months

Cost: 36 m-m @ \$3,000/m-m = \$108,000
Initial cost = \$ 10,000
\$118,000

References.

1. DUNLOP, W., "Deformation Characteristics of Granular Materials Subjected to Rapid Repetitive Loading." Extracted from *U S Gov't R and D Reports*, Vol. 67, No. 7, p. 78 (Apr 10, 1967).

Problem No III-4 *Estimated Time* 18 months

Priority Category. A_2 *Estimated Cost:* \$64,000

Title. Investigation of the Significance of Volume Change on Performance of Aggregate Base Courses

Problem Statement:

Little is known concerning the effect of aggregate volume change, i.e., shrink and swell, on the performance of unbound aggregate base courses.

Information is needed on the cause and effect of aggregate volume change and the type of aggregate most critically affected.

Data on the relationship between freeze-thaw and/or wetting and drying conditions and resulting volume change in unbound aggregate is also needed. In addition to information on volume change of the aggregate particle per se, data are needed on volume change of the base course mixture as might be caused, for example, by montmorillonite clay fractions.

Objectives

1 To investigate the factors causing, and mechanism of, volume change in aggregate particles and in unbound base course mixtures.
2 To determine the significance of aggregate volume change on base course performance.
3 To identify those aggregate types most susceptible to shrink and swell.
4 To develop recommendations regarding use of aggregate types susceptible to volume change in highway base course construction.

Program:

1 Literature search and review.
2. By laboratory investigation, determine the mechanisms and extent of volume change in aggregates.
3. By laboratory and field study, examine the significance of aggregate volume change on base course performance.
4. Develop recommendations on the use of aggregate types susceptible to volume change in base course construction.
5 Data analysis, synthesis, and reports

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	6
3	6	6
4	3	1½
5	3	1½
		18 m-m

Calendar months for completion: 18 months

Cost: 18 m-m @ \$3,000/m-m = \$54,000
Initial cost = \$10,000
\$64,000

Problem No.. III-5 *Estimated Time* 12 months

Priority Category. A_2 *Estimated Cost* \$36,000

Title: Study of the Nature and Effect of Bacterial Action on Aggregate Degradation

Problem Statement

Investigation is needed of the nature and extent of bacterial action on base course aggregate degradation.

Previous research has indicated that long-term degradation may be caused by the action of bacteria on aggregate particles Data are needed on the type of aggregate most commonly affected and the significance of this action in terms of highway base course performance. Information on the materials produced as a result of this action is also desired. In addition, development and recommendation of procedures to reduce bacterial action on aggregates may be included in this study.

Objectives

1 Determine the physical or chemical mechanism and extent of aggregate degradation by bacterial action.

2. Identify the aggregates most susceptible to bacterial action and the properties of the materials produced.

3. Determine the significance of bacterial action of aggregates on base course performance.

4. Develop recommendations for use of susceptible aggregate in highway base course construction

Program

1. Literature search and review.

2. By laboratory and/or field study, examine the mechanism and extent of aggregate degradation by bacterial action.

3. Identify the relationship between effects of bacterial action and aggregate performance in base courses.

4. Develop recommendations on the use of aggregate types under conditions where bacterial action may be likely.

5. Data analysis and reports.

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	3
3	3	3
4	3	1½
5	3	1½
		12 m-m

Calendar months for completion: 12 months

Cost. 12 m-m @ $3,000/m-m = $36,000.

References:

1. CRUMPTON, C. F., and BADGLEY, W. A., "Underclay Development Beneath Asphalt Roads in Kansas." *Hwy Res. Record No. 215* (1968) pp. 24-34.

Problem No.. III-1B *Estimated Time:* 18 months

Priority Category B *Estimated Cost.* $115,000

Title: Investigation and Development of a Density Standard for the Control of Field Compaction in Base Course Construction

Problem Statement:

Information is needed on the applicability of present methods for determining degree of compaction of base courses under construction. Especially with granular base materials the so-called degree of compaction (such as 95% Modified AASHO) may not be directly related to the properties (or performance) of base courses in the field.

Development of standards that will allow different degrees of compaction based on material type is needed. Even though 95% Standard AASHO may be adequate for many subgrade soils, it is not known whether the same standard is adequate for granular bases. Also, it is not known if the current standard laboratory procedure for compacting samples is sufficient for different granular materials. Further, different standards may be required for different types of granular materials (angular, rounded, etc.).

Realistic standards are necessary that may be easily interpreted or understood by those working from the specifications in the field Information is also needed on the field performance to be expected with a given compaction standard, i.e., what kinds of performance can be expected with a certain density? Although laboratory tests of molded specimens (CBR, triaxial) may serve as some control for field compaction, they are not realistic indicators of field performance. Also, information is needed on the degree of density uniformity obtainable under various circumstances

Objectives.

1 Evaluate present standards and tests used to control field compaction in order to determine their applicability to current needs.

2. Revise current standards and develop new standards, if necessary, for compaction control so that specifications (method or end-result) are responsive to changes in material type.

3. Investigate and define the interrelationship between density, permeability, stability, porosity, gradation, moisture content, and method of compaction.

4. Determine the degree of compaction required for the desired field performance and the significance of the preceding factors on this performance

Program:

1. Literature search and review.

2. By laboratory and field testing, identify the degree of compaction necessary for the desired base course field performance for a few of the basic aggregate types.

3. By laboratory and field testing, study the present density standards to determine their applicability to current needs

4. Develop density standards that will guide field compaction and will be relevant to various base course aggregate types.

5. Data analysis and reports.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	12
3	6	6
4	3	6
5	3	3
		30 m-m

Calendar months for completion: 18 months

Cost: 30 m-m @ $3,000/m-m = $90,000
Initial cost = $25,000
$115,000

References:

1. AUGHENBAUGH, N. B., JOHNSON, R. B., and YODER, E. J., "Factors Influencing the Breakdown of Carbonate Aggregate During Field Compaction." *Soc. of Mining Eng.—Transactions* (1962).
2. VIRGINIA HIGHWAY RESEARCH COUNCIL, "Compaction Control of Granular Base Course Materials by Use of Nuclear Devices and a Control Strip Technique."
3. HUMPHRES, H. W., "A Method for Controlling Compaction of Granular Materials." *HRB Bull. 159* (1957) pp 41-57.
4 JAMES, H. D., and LAREW, H. G., "Compaction of Coarse-Grained Granular Materials." *Proc. HRB*, Vol 40 (1961) pp. 676-80.
5. JOHNSON, A. W., and SALLBERG, J. R., "Factors Influencing Compaction Test Results." *HRB Bull. 319* (1962) pp 1-148.

Problem No.. III-2B *Estimated Time.* 36 months

Priority Category. B *Estimated Cost:* $169,000

Title: Development of Base Course Aggregate Criteria for the Accommodation or Reduction of Water

Problem Statement.

Environment (including climatic factors of temperature and moisture and physical factors of rate and magnitude of loading) plays an important role in the performance of aggregate within highway pavements. The performance of base course aggregate, in particular, will depend partly on these environmental factors that will vary throughout the entire base course and shoulder.

Moisture control during construction and while in service has been a constantly reappearing source of difficulty with highway base courses Present knowledge indicates that in spite of efforts to provide free-draining base materials, water is always present in varying amounts (though not necessarily to saturation) at different locations within the base.

Information is needed on the type (gravity, capillary, hygroscopic) and quantity of moisture present and the mechanisms by which this water is transported. Also, investigation is needed to determine (1) the effect of changing ambient environmental conditions on base course moisture, (2) how much water can be tolerated, (3) the effect of gradation, density, permeability, void content, and pore size and distribution on moisture movement, (4) the relationship between so-called open-graded and dense-graded bases, and (5) the feasibility of trench and through-the-shoulder base course construction in terms of drainage. It should be determined whether emphasis should be applied to design concepts which allow for a saturated condition rather than designs which attempt to restrict or reduce the moisture. Strength must be maintained, however, even when the base course is saturated Establishment of guidelines for underdrain and filter material is also needed.

Information is needed on the variation in performance of aggregates in different vertical or horizontal locations. For example, are aggregates located in the upper portion of the base course subject to greater action by water than those aggregates near the subbase? What aggregate properties are most desired at different positions? These positions may be defined as:

1. Upper portion of base next to asphaltic binder or base course.
2. Lower base course near subbase or subgrade.
3. Edge of base course near shoulder.
4. Center of base equidistant from shoulders.

Data are needed on the design requirements for shoulders so that adequate provision is made for strength and drainage. The traffic loading is essentially static (vehicles braking, stopped, and accelerating) and demands shoulders of high load-carrying capacity. The repetitive loading common to the main pavement, however, is seldom encountered on shoulders. Study is needed on the effects which full strength shoulder design will have on pavement drainage For example, will a paved shoulder (versus gravel treatment) reduce moisture movement?

The feasibility of theories such as that in which a wicking condition is established between the base and free atmosphere should be studied. Further research is needed on the role of the shoulder in achieving moisture movement and on the type of shoulder treatment (i.e., grass, shrubs, etc) that will be most conducive to this type of drainage action.

Objectives:

1. Identify the type, quantity, and location of water within highway base courses, including the amount available for drainage through the shoulder.

2. Identify the factors or basic mechanisms that contribute to the formation of movement of water within base courses.

3. Study the effect of variation of base course properties (gradation, permeability, etc.) on water content and movement.

4. Determine the tolerable quantity of water in a base course.

5. Develop design criteria and construction specifica-

tions that will result in improved control of moisture with a resulting increase in base course performance.

6. Determine the relationship of structural requirements and function of the shoulder to the through-pavement structure.

7. Determine the effect of temperature and water gradients on aggregate properties.

8. Determine the effect of changing locations within the base on aggregate properties and performance.

Note: Study may be included on the "drainability" of a base and the establishment of a "drainage factor" test. Correlate with work on moisture control, gradation, and weather severity index.

Program:

1. Literature search and review.

2. By laboratory and field testing, examine and identify the type, quantity, location, and mechanisms for movement of water in highway base courses and shoulders, including development of necessary instrumentation for its measurement.

3. Install instrumentation in highway test sections and, by field testing under various environmental conditions, study the variation of water content with gradation, permeability and void content.

4. Through field study, examine the changes in physical, chemical, and climatic environment that occur at different locations within the base.

5. Develop laboratory model to simulate field conditions and determine the tolerable limits of water within a base course to retain the required strength for the desired performance.

6. Determine the drainage potential of shoulders when designed for full traffic loading.

7. Through experimentation and data correlation, develop base course and shoulder design and construction criteria for the accommodation or reduction of water.

8. Data analysis and reports.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	9	9
3	12	18
4	3	3
5	6	6
6	3	3
7	3	3
8	3	3
		48 m-m

Calendar months for completion: 36 months

Cost: 48 m-m @ \$3,000/m-m = \$144,000
Initial cost = \$ 25,000
\$169,000

References.

1. "A Symposium on Highway Shoulders." *HRB Bull. 151* (1957) pp. 1-27.
2. BARBER, E. S., and SAWYER, C. L., "Highway Subdrainage" *Proc. HRB*, Vol. 31 (1952) pp. 643-66.
3. CHAMBERLAIN, W. P., and YODER, E. J., "The Effects of Base Course Gradation on the Results of Laboratory Pumping Tests." *HRB Bull. 202* (1958) pp. 59-79.
4. HAAS, W. M., "Drainage Index in Correlation of Agricultural Soils with Frost Action and Pavement Performance." *HRB Bull. 111* (1955) pp. 85-98.
5. HAAS, W. M., "A Study of the Mechanism Whereby the Strength of Bases and Subbases is Affected by Frost and Moisture." Unpublished final report, NCHRP Project 4-5 (Aug. 1965).
6. SMITH, T. W., CEDERGREN, H. R., and REYNER, C. A, "Permeable Materials for Highway Drainage." *Hwy. Res. Record No. 68* (1965) pp. 1-16.

Problem No.: III-3B *Estimated Time.* 18 months

Priority Category: B *Estimated Cost:* \$91,000

Title: Study of Base Course Admixtures and Stabilization Processes and Development of Recommended Practices

Problem Statement.

When problems began to appear in highways with non-treated unbound base courses, the practice of adding certain admixtures to the mix in an effort to improve performance of the base course became frequent. However, problems are currently encountered with treated base courses also, and information is needed on the causes of these difficulties.

Materials such as lime, calcium chloride, portland cement, and bitumen are frequent admixtures or stabilizing agents that result in the "cementing" of subbase or base course aggregate particles. The question to be answered is, "What effects do these materials have on aggregate particles and on the total base course mixture?"

For example, does calcium chloride ($CaCl_2$) when used as a stabilizing agent for subbases cause deterioration of aggregate?

Objectives:

1. To investigate the physical and chemical effects of common admixtures on aggregate properties.

2. To investigate the significance of these effects on base course characteristics and performance.

3. To study the effectiveness of application methods or processes for various stabilizing agents.

4. To develop recommendations regarding material and method of application for various admixtures for different base course aggregate types.

Program:

1. Literature search and review.
2. Investigation of effects on base and subbase aggregate from admixtures or stabilizing agents
3. Investigation of the significance of admixtures on base course performance.
4. Study of the various admixture application processes, rates, etc
5. Development of recommendations concerning the use and application of admixtures for base course stabilization.
6. Data analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	9
3	6	9
4	6	6
5	3	1½
6	3	1½
		27 m-m

Calendar months for completion: 18 months

Cost: 27 m-m @ \$3,000/m-m = \$81,000
Initial cost = \$10,000
\$91,000

References

1. AHLBERG, H. L, and BARENBERG, E. J., "Pozzolanic Pavements." *Bull. 473,* Eng. Experiment Station, Univ. of Ill. (1965).
2. AHLBERG, H. L., and MCVINNIE, W. W., "Fatigue Behavior of a Lime-Fly Ash-Aggregate Mixture" *HRB Bull. 335* (1962) pp. 1-10.
3. BARENBERG, E. J., "Behavior of Pozzolanic Pavements Under Load" *Hwy. Res. Record No. 112* (1966) pp. 1-24.
4. BARENBERG, E. J., "Development of Appropriate Methods for Evaluating the Effectiveness of Stabilizing Agents." Unpublished final report, NCHRP Project 4-1 (1967).
5. BENKELMAN, A. C, KINGHAM, R. I., and SCHMITT, H. M., "Performance of Treated and Untreated Aggregate Bases." *HRB Spec. Rep. 73* (1962) pp. 242-55.
6. COLLETT, F., WARNICK, C., HOFFMAN, D., "Prevention of Degradation of Basalt Aggregates Used in Base Construction." *HRB Bull. 344* (1962) pp. 1-7.
7. JOHNSON, C. W., "Comparative Studies of Combinations of Treated and Untreated Bases and Subbases for Flexible Pavements." *HRB Bull. 289* (1961) pp. 44-61.
8. JOHNSON, C. W., "Comparative Studies of Various Combinations of Treated and Untreated Bases and Subbases for Flexible Pavement." New Mexico State Hwy. Comm (1965).
9. MACLEAN, D. J., and LEWIS, W. A., "British Practice in the Design and Specification of Cement-Stabilized Bases and Subbases for Roads" *Hwy. Res. Record No. 36* (1963) pp. 56-76.
10. MILLER, R. H., and COUTURIER, R. R., "An Evaluation of Gravels for Use in Lime-Fly Ash-Aggregate Composition." *HRB Bull. 304* (1961) pp. 139-47.
11. NICHOLS, F. P., JR., "Effects of Compaction and Subgrade Stabilization on Deflections and Performance of Virginia Pavements." *Proc. Internat Conf. on Structural Design of Asphalt Pavements,* Univ of Mich., pp 581-91 (1962).
12. SIBLEY, E. A, "Degradation of Cement Treated Aggregates" *Bull. 244,* Wash. State Inst. of Tech. (1958).
13. VAUGHAN, F. W., and REDUS, J. F., "A Cement-Treated Base for Rigid Pavement." *HRB Bull 353* (1962) pp. 1-7.

Problem No.: III-4B *Estimated Time* 18 months

Priority Category: B *Estimated Cost:* \$54,000

Title. Evaluation of Purpose, Function, and Performance of Current Highway Base Courses

Problem Statement:

Various research efforts and investigations have found indications that highway base courses are not performing in accordance with design criteria. For example, design specifications have been established to provide drainage with the base course. The main function of a base course beneath a rigid pavement, for instance, is thought to be drainage. However, data indicate that this drainage is not necessarily obtained but pavement performance, in some cases, continues to be adequate. This may indicate that present theories regarding the purpose of a base course may not be valid.

Information is needed to define the purpose or function of a base course in terms of drainage, stability, density, stiffness, etc In other words, "What do we want the base course to do?" This must be known to determine the desirable and necessary aggregate properties.

Objectives:

1. To investigate and redefine the purpose of a base course beneath a highway pavement structure in relation to present knowledge and needs regarding its function and performance. Included should be a study of the true worth of different base systems, such as a comparison between the use of cement-stabilized materials and high-quality crushed stone.

It is suggested that study of base systems be grouped according to base courses for (1) rigid pavements or (2) flexible pavements.

Program.

1. Literature search review.
2. By questionnaire, conference, or field visitation gather data on present base course construction practices by individual states and obtain relative evaluations of the performance of these base systems.
3. Correlate current base course design criteria with performance in order to develop the relative significance of different base systems.
4. Define the purpose, function, and desirable characteristics of highway base courses in view of evaluations conducted.
5. Data analysis, synthesis, and reports.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	3
3	9	9
4	3	1½
5	3	1½
		18 m-m

Calendar months for completion: 18 months

Cost. 18 m-m @ $3,000/m-m = $54,000.

References.

1. FAROUKI, O. T., and WINTERKORN, H. F., "Mechanical Properties of Granular Systems." *Hwy. Res. Record No. 52* (1964) pp. 10-41.
2. "Performance of Granular Subbases Under Concrete Pavement." *HRB Bull. 202* (1958) pp. 1-81.

GROUP IV, GENERAL

Problem No.: IV-1 *Estimated Time:* 48 months

Priority Category. A_1 *Estimated Cost:* $223,000

Title: Relating Aggregate Properties to Skid Resistance of Pavements

Problem Statement:

One of the most critical problems facing highway engineers today is the polishing of aggregates by traffic and subsequent loss of pavement skid resistance for both portland cement and asphaltic concretes. The polishing susceptibility of the aggregate appears to be a major variable affecting the coefficients of friction of pavements. Although much research has been accomplished in this area, it is still not possible to specify basic properties of aggregate that cause it to retain or lose desirable skid-resistant properties. Additional factors that should be investigated are: (1) aggregate properties of texture and shape, (2) rate of aggregate wear, (3) permeable voids, (4) size of aggregate (top size), and (5) speed of traffic. Much basic information concerning aggregate properties is available through the descriptive and classification systems of geologists, pe-

TABLE A-4

PRIORITY RATINGS, GROUP IV, GENERAL

PROBLEM NO	PRIORITY CATEGORY	EASE OF SOLUTION	VALUE OF SOLUTION	EASE OF IMPLEMENTATION	GEOGRAPHICAL SIGNIFICANCE	SUM
IV-1	A_1	3 9	5-15	3	5-10	31.9
IV-2	A_2	3	3 5-10.5	3	5-10	26.5
IV-3	A_1	3	3.5-10.5	3	5-10	26.5
IV-4	A_1	2 5	4.5-13.5	2	4-8	26
IV-5	A_1	2	4 5-13 5	1	4 5-9	25 5
IV-6	A_2	3	4-12	2	4-8	25
IV-7	A_2	3.5	3-9	2.5	5-10	25
IV-8	A_1	4	3-9	3	4.5-9	25
IV-9	A_1	1.5	4-12	2	4.5-9	24 5
IV-10	A_2	2	2-6	3	4-8	19
IV-11	A_1	3	2-6	3	3-6	18
IV-1B	B	3	4-12	3.5	4.5-9	27 5
IV-2B	B	2 5	4-12	2 5	5-10	27
IV-3B	B	2	4-12	3	5-10	27
IV-4B	B	4	3-9	2	4.5-9	24
IV-5B	B	3	3 5-10.5	3	3-6	22 5
IV-6B	B	4	3-9	3	3-6	22
IV-7B	B	3	3-9	2	3-6	20
IV-8B	B			Not rated		
IV-9B	B			Not rated		

trographers, and mineralogists. Further study and application of this information is needed.

One of the major products of this research should be development of a laboratory test or series of tests for determining the polishing or skid susceptibility of mineral aggregates, followed by correlation with field performance. This should afford the highway engineer the means to optimize his choice from among competitive sources, as well as provide a screening mechanism for minimum acceptability.

A next step is to develop beneficiation and blending procedures that will provide an economical means of upgrading otherwise unacceptable sources. Blending provides a rather straightforward possible solution, but tests and guidelines for blending aggregates at several levels of skid resistance are needed before an acceptable product is obtained

Beneficiation of unacceptable aggregates to improve frictional performance has not been explored in any detail, but the potential for this justifies additional research effort. Ideas to be explored might include removal of deleterious fractions and physical or chemical treatment of the entire aggregate before it is used.

This research may also include the effects of maintenance practices and use of pavement surface treatments on skid-resistant properties.

Objectives:

1. Define and quantify basic properties of aggregate significant to its ability to retain or lose desirable skid-resistant properties.
2. Develop laboratory test methods for simulating aggregate polishing.
3. Determine the aggregate types susceptible to polishing
4. Develop procedures for selecting, blending, or beneficiating aggregates so as to obtain optimum skid-resistant performance.
5. Develop methods or recommendations for the use of aggregates with various rates of polishing in pavements.

Program.

1. Literature search and review, including geologic literature.
2. Laboratory study to determine basic properties of aggregates that influence polishing and skid resistance.
3. Develop mineralogic and geologic bases for identification of aggregates susceptible to polishing.
4. Develop means for measuring aggregate microtexture and its influence on skid resistance.
5. Develop limits of acceptable rate and extent of polishing.
6. Determine rate of polishing versus aggregate type and loads
7. Through laboratory and field testing develop criteria and methods for blending and beneficiating aggregate and economic guidelines for their use.
8. Data analysis, synthesis, and report.

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	18
3	12	12
4	6	6
5	6	6
6	6	6
7	12	12
8	6	3
		66 m-m

Calendar months for completion: 48 months

Cost: 66 m-m @ \$3,000/m-m = \$198,000
Initial cost = \$ 25,000
\$223,000

References:

1. CSATHY, T. I., ET AL., "State of the Art of Skid Resistance Research." *HRB Spec. Rep. 95* (1968) pp. 34-48.
2. GRAY, J. E., and RENNINGEY, F. A., "Limestones with Excellent Non-Skid Properties." *Crushed Stone J.*, Vol. 35, No. 4 (1960).
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4. MEYER, W. E., "Friction and Slipperiness." *Hwy. Res. Record No. 214* (1968) pp. 13-17.
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6. ORCHARD, D. F., "Testing of Aggregate." *Quarry Managers J.*, Vol. 48, No. 1 (Jan. 1964).
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8. STIFFLER, K., "Mineral Wear in Relation to Pavement Slipperiness." *Report No. 15*, Penn. State Univ. Joint Road Friction Program, pp. 1-89 (Nov. 1967).
9. STULZENBERGER, W. J., and HAVENS, J. H., "A Study of the Polishing Characteristics of Limestone and Sandstone Aggregates in Regard to Pavement Slipperiness." *HRB Bull. 186* (1958) pp. 58-81.
10. WHITEHURST, E., and MOORE, A., "An Evaluation of Several Expanded Aggregates for Use in Skid-Resistant Pavement Surfaces." *J. of Materials*, Vol 1, No. 9, pp. 609-24 (1966).

Problem No. IV-2 *Estimated Time* 18 months

Priority Category: A_2 *Estimated Cost:* \$62,500

Title: Determination of the Surface Characteristics of Aggregates Used in Highway Construction

Problem Statement:

Information is needed concerning the basic surface characteristics of aggregates. Little is known about identification, measurement, or classification of aggregate properties such as surface texture, charge, chemistry, affinity for liquids, or polishing characteristics.

Many highway problems occur in which a basic or fundamental aggregate property such as surface characteristics must be examined before more specific research can be undertaken toward finding a solution. An exact method for measurement of surface texture, for example, must be developed before the relationship of surface texture to stability may be determined.

A system of classifying aggregate surface characteristics is needed to provide a means of relating these properties to field performance of portland cement, bituminous concrete, and base courses.

Objectives:

To conduct a pilot study that will provide test methods and procedures to:

1. Measure aggregate surface characteristics of:
   a. Texture.
   b. Affinity for liquids
   c. Charge.
   d. Chemistry.
   e. Polishing.
2. Determine the effect of these factors on aggregate performance.
3. Apply to each of these surface properties a numerical scale of values that will allow classification of aggregates by surface characteristics
4. Determine the acceptable limits of variation for these properties.

It is anticipated that several aggregates of different types will be used in this pilot study so that, based on the results of the project, other aggregates can be studied in a similar manner on a regional or state basis.

Program:

1. Literature search and review.
2. By laboratory study, develop test procedures to measure aggregate surface characteristics.
3. Develop a relative scale of values for each surface characteristic.
4. Through laboratory and field study, determine the effect and relative significance of the surface properties on aggregate performance in various types of construction and service environment.
5. Develop guidelines for the establishment of acceptance limits for aggregate surface properties based on performance.
6. Data analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	6
3	3	1
4	9	6
5	1	½
6	2	1
		17½ m-m

Calendar months for completion. 18 months

Cost. 17½ m-m @ \$3,000/m-m = \$52,500
Initial cost = \$10,000
\$62,500

References.

1. BAHRAMIAN, B., and HUGHES, B., "Laboratory Test for Determining Angularity of Aggregate." *Mag. of Conc. Res.*, Vol. 18, No. 56, pp. 147-52 (Sept. 1966).
2. HUANG, E., "Improved Particle Index Test for Evaluation of Geometric Characteristics of Aggregates." Extracted from *Hwy. Res. Abstracts*, Vol. 36, No. 7, p. 9 (July 1966).
3. ORCHARD, D. F., "Testing of Aggregate." *Quarry Managers J.*, Vol. 48, No. 1 (Jan. 1964).
4. POWERS, T. C., "Topics in Concrete Technology—Geometric Properties of Particles and Aggregates." *Portland Cement Assn. R and D Lab. J.*, Vol. 6, No. 1, pp. 2-15 (Jan. 1964).
5. VALLERGA, B. A., ET AL., "Effect of Shape, Size and Surface Roughness of Aggregate Particles on the Strength of Granular Materials." *ASTM Spec. Tech. Pub. No. 212*, pp. 63-76 (1957)

Problem No.: IV-3 *Estimated Time.* 18 months

Priority Category: A_1 *Estimated Cost.* \$54,000

Title: Study of Aggregate Sampling Procedures and the Value of Aggregate Specifications Established by Statistical Procedures

Problem Statement:

As aggregate sources become depleted and it becomes increasingly important to effectively use the present sources, knowledge of the properties of the aggregate becomes significant. Complete, accurate, and reliable sampling procedures are essential to adequately determine, by test, the mineral content and physical and chemical properties likely to be encountered within a particular aggregate source. The sample should be representative of the parent material in order for the test data to be meaningful. The point at which the sample is secured, the size of the sample, and the frequency of sampling are a few of the critical factors and could, conceivably, be subject to wide variation at the discretion of the sampler.

Survey and evaluation of current aggregate sampling and control procedures could begin with the compiling of state highway sampling practices in an effort to determine geographical and geologic similarities or trends Applicability of procedures outlined in ASTM D 75 should also be considered. Evaluation of sampling procedures should include a study of the variation caused by changes such as the manner of sampling and the locations within the production line where samples are taken Where needed, development of new procedures and equipment that will result in improved sampling accuracy or control should be considered.

Sampling of bulk materials, such as aggregate for highway construction, will continue to be of importance until statistical specifications become a reality. A current need exists for development of sound statistical sampling procedures on which to base aggregate acceptance specifications.

For example, only one gradation analysis can be obtained from an aggregate stockpile when taken as a whole However, sample to sample variation of tests from this stockpile may reflect segregation when, in fact, production has met gradation specifications. Every portion of the stockpile would need to be available to produce a true random sampling procedure. Thus, development of a statistically reliable sampling plan is needed to guide and protect both the consumer and producer when specifications are to be met. Further study may also be useful to determine the value of specifications established by statistical procedures versus non-statistical, conventional methods. For example, does a significant difference occur to make one procedure more applicable for highway materials than another? In addition, definition is needed of the respective role of the geologist and petrographer in the sampling process.

Objectives:

1. Compilation and evaluation of current state aggregate sampling procedures and techniques to determine the degree of accuracy or representation with the actual parent material.
2. Development of new sampling procedures and equipment as needed.
3. Development of statistical aggregate acceptance sampling procedures and specifications.
4. Evaluation of the value of aggregate acceptance specifications established by statistical procedures.
5 Development of statistical sampling procedures and techniques.
6. Data analysis and report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	3
3	9	6
4	3	3
5	2	2
6	2	1
		18 m-m

Calendar months for completion: 18 months

Cost. 18 m-m @ $3,000/m-m = $54,000.

References:

1. AMERICAN SOCIETY FOR TESTING AND MATERIALS, "Sampling Stone, Slag, Gravel, Sand, and Stone Block for Use as Highway Materials." *ASTM D 75.*
2. BAKER, R. F, "A Study to Determine the Normal Variation in Aggregate Gradation Produced by Asphalt Plants." *Report No. 201-1,* Part 1, Eng. Experiment Station, Ohio State Univ., pp. 1-41 (Aug. 1962).
3. BEATON, J L., "Statistical Quality Control in Highway Construction." *Proc. ASCE, J. of Construction Div.* (Jan. 1968).
4. BERTHOLF, W. M , "The Effect of Increment Weight on Sampling Accuracy." *ASTM Spec. Tech. Pub. No. 242,* pp. 27-32, discussion pp. 32-43 (1958).
5. BICKING, C A., "The Sampling of Bulk Materials." *Materials Research and Standards,* Vol. 7, No. 3, pp. 95-116 (Mar. 1967)
6. CORDON, W. A., "Size and Number of Samples and Statistical Considerations in Sampling." *Significance of Tests and Properties of Concrete and Concrete Aggregates,* ASTM, STP 169, p. 14 (1956).
7. GRAY, J. E., "Specifications for Mineral Aggregates" *Crushed Stone J.,* Vol. 36, No. 2, pp. 3-10 (June 1961).
8. ISHIKAWA, K , "Some Experimental Methods for Bulk Material Sampling." *Report on Seminar on Sampling of Bulk Materials,* National Science Foundation, Japan Soc. for Promotion of Science, pp. 187-223 (Nov. 1965).
9. MILLER-WARDEN ASSOCIATES, "Effects of Different Methods of Stockpiling Aggregates—Interim Report." *NCHRP Report 5* (1964) pp. 1-48.
10 MILLER-WARDEN ASSOCIATES, "Evaluation of Construction Control Procedures—Interim Report." *NCHRP Report 34* (1967) pp. 1-117.
11. NEAMAN, D., and LAGUROS, J , "Statistical Quality Control in Portland Cement Concrete Pavements." Not published, 24 pp. (Jan. 1967).
12 PROUDLEY, C. E., "Sampling of Mineral Aggregates." *ASTM Spec. Tech. Pub. No. 83,* pp. 74-87 (1948).
13. SHAH, S. C , "Quality Control Analysis, Part III: Concrete and Concrete Aggregates." Extracted from *U.S. Gov't R and D Reports,* Vol. 67, No. 5, p. 97 (Mar. 10, 1967).
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15. STEPHENS, J. E., "Acceptance Sampling of Aggregate." Presented at NCSA Meeting, Chicago (Feb. 8, 1966).
16 VISMAN, J., "Sampling to a Pre-Assigned Accuracy." *Report No F R L 212* of the Fuels Div.,

Canada Dept. of Mines and Technical Surveys, pp. 1-11 (Aug. 1955).

Problem No. IV-4 *Estimated Time* 24 months

Priority Category: A_1 *Estimated Cost* $99,000

Title: Procedures for Optimizing Aggregate Use With Regard to Economics and Conservation of Resources

Problem Statement:

The supply of natural aggregate suitable for all facets of highway construction is diminishing This is due in part to the present rigid specifications which require aggregates for all uses and environments to be of the same high quality. This results in wastage of aggregates that might be suitable for some applications, and in high production and haul costs. The condition requires the development of a generalized framework in which aggregate use might be optimized with regard to basic economics and conservation of resources. Efficient use of aggregate for a given level of performance must be established.

Objectives.

1. Develop a generalized framework in which aggregate use might be optimized with regard to economics and conservation of resources.

Program:

1. An exhaustive literature search and review on aggregate use for highways with reference toward economics and conservation of resources.
2. Develop generalized framework for efficient and economic aggregate use.
3. Data analysis, synthesis, and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	6	6
2	12	24
3	6	3
		33 m-m

Calendar months for completion: 24 months

Cost. 33 m-m @ $3,000/m-m = $99,000.

Problem No.: IV-5 *Estimated Time:* 15 months

Priority Category: A_1 *Estimated Cost:* $45,000

Title: Development of a Systematic Modular Approach to Aggregate Testing

Problem Statement:

There are common aspects to the problem of specifying aggregate use in portland cement and asphaltic concretes and for base courses. However, test methods have developed in each of the three areas with a good deal of independence and with the philosophy that simple "go-no go" test results were adequate.

If highway materials engineers are to make selective use of aggregates, they must have new concepts for acceptance testing. The common aspects of testing for various aggregate uses must be recognized so as to minimize the number of tests. A general battery of tests must be available so that a test sequence can be selected to meet a specific situation—relating aggregate properties to class of use, environment, and level of performance.

Work to date on these concepts has not been encouraging. Subcommittee III-e of ASTM Committee C-9 has been unable to develop an acceptable type of Modular Specification (C33) for concrete aggregate. However, a broad study of this whole matter is in order to determine new approaches.

As a prerequisite to development of acceptance testing procedures, information on the current state aggregate acceptance specifications may be useful. This study may include information on the variance encountered in specifications for a particular aggregate or test method. Research of this type may be helpful in determining the applicability or relevance of certain specifications to the aggregate property under test, i.e., "Do the specifications result in the best materials being used where practical and economical?" The diminishing supplies of aggregate, together with demands for higher levels of performance, lend urgency to the problem of acceptance specifications and testing.

Objectives.

1. Compile current state aggregate acceptance specifications.
2. Develop improved concepts for aggregate testing.

Program·

1. Literature search and review to find common and related aspects of highway aggregate tests and specifications.
2. Develop systematic modular aggregate testing concepts.
3. Develop framework for improved, integrated, modular aggregate testing methods identifying major gaps in current knowledge.
4. Data analysis and reports.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	6
3	3	3
4	3	3
		15 m-m

Calendar months for completion: 15 months

Cost. 15 m-m @ $3,000/m-m = $45,000.

References.

1. Bloem, D., "Aggregate Economy Through Universal Standardization." *Pit & Quarry*, Vol. 57 (Aug. 1964).
2. Chamberlin, W., and Eucker, A., "Evaluation of Concrete Containing Coarse Aggregate from Manlius, Lockport and Onondaga Formations in Western and Central New York." Extracted from *U.S. Gov't R and D Reports*, Vol. 41, No. 19, p. 119 (Oct. 10, 1966).
3. Gray, J. E., "Specifications for Mineral Aggregates." *Crushed Stone Journal*, Vol. 36, No. 2, pp. 3-10 (June 1961).
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5. Larson, T. D., and Cady, P. C., "Identification of Frost-Susceptible Particles in Concrete Aggregates." *NCHRP Report 65* (1969) pp 1-62.
6. Larson, T. D., Cady, P. C., and Walker, R D., "New Tests for Aggregate Frost Susceptibility." Paper presented at 1968 AASHO Meeting (Dec. 1968).
7. Orchard, D. F, "Testing of Aggregate." *Quarry Managers J.*, Vol. 48, No. 1 (Jan. 1964).
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11. Warden, W. B, and Sandvig, L. D, "Tolerances and Variations of Highway Materials from Specification Limits." *ASTM Spec. Tech. Pub. No. 362*, pp. 31-38, discussion pp 39-43 (1963).

Problem No. IV-6 *Estimated Time:* 30 months

Priority Category: A_2 *Estimated Cost:* $90,000

Title: Criteria for Evaluating Aggregate Performance

Problem Statement:

How does the highway materials engineer determine levels of performance of aggregate in base course, portland cement concrete, and asphaltic concrete? In the past only two levels have been in common use—perfection and failure. So long as an economical supply of aggregates exists that can give perfect results, it should certainly be used. However, this option no longer exists in many parts of the United States.

Selective use of aggregates having different performance potential requires that service environments be categorized and that acceptance tests which provide information between "go" and "no go" be developed. Such tests can develop rationally only if performance criteria can be established.

Performance of aggregate has some external manifestations but these may not be adequate either with regard to timing or sensitivity. Performance levels must certainly be set with full regard to total service environment and aggregate type. Terminology is a common stumbling block to such projects.

Objectives:

1. Develop criteria for defining level of aggregate performance for highway use.

Program:

1. Literature search and review.
2. Through literature and field study, examine the deterioration and failure characteristics of aggregate specific to structure and environment.
3. Develop criteria and terminology for defining level of aggregate performance.
4. Data analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	6	3
		30 m-m

Calendar months for completion: 30 months

Cost 30 m-m @ $3,000/m-m = $90,000.

References:

1. Axon, E. O., Gotham, D. E., and Couch, R W., "Effects of De-Icing Chemicals on Structures: Investigative Techniques Used or Contemplated." *HRB Bull 323* (1962) pp. 3-11.
2. Finn, F. N., et al., "Systems Approach to Pavement Design: System Formulation, Performance Definition, and Material Characterization." Unpublished report, NCHRP Project 1-10 (Mar. 1968).
3. Larson, T. D., Malloy, J. J., and Price, J. T., "Manual of Procedures for Bridge Deterioration Studies." *Materials Research Report No. 5*, Penn. State Univ., Dept. of Civil Eng. (July 1967).

Problem No.: IV-7 *Estimated Time.* 12 months

Priority Category: A_2 *Estimated Cost.* $36,000

Title: Development of Procedures to Adequately Describe Aggregate Sources

Problem Statement

Difficulties are frequently encountered in attempting to describe an aggregate source in terms relevant to its expected use and performance as a highway construction material. Procedures are needed that will furnish a quantitative description (adequate for highway engineering purposes) of the aggregate source regardless of its location. For example, can the quantity of chert, clay, or other deleterious constituent likely to be found in a given source be determined and, if not, what is the best procedure for this? Adequate aggregate description is important because it forms the basis for specifications and testing. Study is also needed on whether ranges of variability within aggregate sources can be used in a meaningful way.

Another important aspect of this project would be to evaluate and determine the respective roles of the petrographer, geologist, and engineer in the preceding process. When performing mineralogical composition and aggregate property studies, for example, how much information is available by petrographic analysis? Methods are needed to effectively use this petrographic data in describing aggregate sources and in predicting performance of the aggregate as a highway material.

Objectives:

1. Evaluate and test applicability of present methods of aggregate source description and development of new methods or procedures, as needed, which are adequate for highway engineering purposes. Define the role of the petrographer and geologist in this process.

Program:

1. Literature search and review.
2. Compile and evaluate present methods for aggregate source description.
3. Develop new test procedures, techniques, and methods of application for description of aggregate sources.
4. Develop recommendations concerning the use of petrographic data in the description process.
5. Data analysis and reports.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	1½
2	3	2
3	6	6
4	3	1½
5	3	1
		12 m-m

Calendar months for completion: 12 months

Cost: 12 m-m @ \$3,000/m-m = \$36,000.

References:

1 "Aggregate Characteristics and Examination." *Hwy. Res Record No. 120* (1966) pp. 1-40.
2. BAYNE, R. L., and BROWNRIDGE, F. C., "Petrographic Analysis for Determining Quality of Coarse Aggregates." *Proc. Canadian Good Roads Assn.*, 36th Conv. (1955).
3. DOLAR-MANTUANI, L., "Petrographic Examination of Natural Concrete Aggregates." *Hwy. Res. Record No. 120* (1966) pp. 7-17.
4. LEWIS, D. W., and VENTERS, E., "Deleterious Constituents of Indiana Gravels." *HRB Bull. 94* (1954) pp. 1-10.
5 LYON, A. C., "Maine Test for Deleterious Material in Aggregates" Extracted from *U.S. Gov't R and D Reports*, Vol. 41, No. 24, p. 98 (Dec. 25, 1966).
6. RHOADES, R., and MIELENZ, R. C., "Petrography of Concrete Aggregate." *Proc. Amer. Conc. Inst.*, 42: 581 (1946).
7. RHOADES, R, and MIELENZ, R. C., "Petrographic and Mineralogic Characteristics of Aggregates." *Symposium on Mineral Aggregates*, ASTM, pp. 1-20 (1948).
8. VOLIN, M E., and MICHAEL, E., "Developing a Method of Determining Deleterious Properties of Chert Aggregates in Concrete." Mich. Tech. Univ.

Problem No.: IV-8 *Estimated Time:* 15 months

Priority Category· A_1 *Estimated Cost*· \$54,000

Title. Data-Keeping Procedures on Aggregate Performance

Problem Statement:

Apart from elaborate field and laboratory testing, aggregate performance for highway use can be determined through in-service performance records. Much critically needed information concerning aggregate use in portland cement and bituminous concretes and for base course construction can be gleaned from previous experience. It is imperative that adequate data compilation procedures are used so that the maximum useful information can be obtained. Present record-keeping procedures vary among the states, and there are no generally accepted standard procedures.

It would be beneficial, therefore, to develop a systematic data-keeping procedure for aggregate performance. This would necessitate a survey of the types of records that have been kept in the past and the development of a procedure least disruptive to existing records and amenable to automatic data processing. The relationships between design, construction, and maintenance should be considered in developing this procedure.

Objectives:

1. Develop a systematic data-keeping procedure for aggregate performance in portland cement, concrete, asphaltic concrete, and base courses for use by highway departments.

Program

1. Survey state agencies for present data-keeping procedures. Determine constraints to system development
2. Develop systematic data-keeping procedure.
3. Field test the system
4. Reports

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	6
2	6	6
3	3	3
4	3	3
		18 m-m

Calendar months for completion: 15 months

Cost: 18 m-m @ \$3,000/m-m = \$54,000.

References:

1 *Index Maps of Portland Cement Pavements and Coarse Aggregates.* Prepared by the Materials Dept., Iowa State Hwy. Comm.
2. SMITH, P., "Computer Evaluation of Concrete Quality." *Report RR 125,* Ontario Hwy. Dept. (Jan 1967).
3. U S. ARMY CORPS OF ENGINEERS, *Technical Memo. 6-370.* Corps of Engineers District Offices

Problem No.. IV-9 *Estimated Time* 36 months

Priority Category. A_1 *Estimated Cost* \$241,000

Title: Influence of Climate and Environment on the Performance of Aggregates in Highway Construction for Use in Development of a Weather Severity Index

Problem Statement.

Environment in combination with aggregate properties probably constitutes the greatest single factor affecting the durability of highway pavement. Therefore, when one looks at aggregates with a view toward their durability in service it is necessary to know something of the environment to which they will be subjected. Knowledge is needed of the environmental factors that are most critical and should be recognized. Attempts have been made to classify environmental conditions by means of a weather severity index based on Weather Bureau meteorological data. Such an approach is useful for providing general or regional guidelines However, highly significant variations can occur within the regions and, therefore, such indices provide little help in selecting aggregate for specific uses. Research is needed on ways of classifying microclimates and evaluating the effects of various microclimatic conditions on pavement performance. Several general classification systems have been proposed, such as cool and moist, warm and dry, etc , or by soil grouping, which would indicate climate by degree of weathering. Another possibility is to correlate weather severity with elevation (as done in Arizona, for example).

Prerequisite to environmental classification, methods and equipment must be developed to measure temperature and, especially, moisture conditions within and below pavements Temperature and moisture variations would greatly influence, for example, the extent of frost heave in base courses Adequate means (i e., resistance thermometers, thermocouples, and thermistors) are generally available to measure temperature gradients, minimums and maximums, and deviations for all depths within the pavement structure.

The moisture content of aggregates, and concrete in particular, is a critical determinant of service life However, very little is known about factors affecting it. A principal reason is that current techniques for measuring moisture content of concrete in service (i.e , relative humidity gauges and weight loss tests) are generally inadequate Therefore, data collection on the scale necessary to provide some promise of real identification, quantification, and categorization of this aspect of concrete environment has been impossible. A field-test method is therefore required to measure adequately the moisture content of hardened concrete Note: Temperature and moisture measurement instrumentation should be applicable to all types of materials, including soils, aggregates, portland cement concrete, and bituminous mixtures.

With suitable field measurement devices, application may follow to determine the temperature and moisture variations for different climatic environments and for different types of materials and highway construction.

Following classification of climatic factors or microclimates, investigation of the effects of various climates on pavement performance is needed. The desire would be to develop a more detailed and specific national weather severity index system which may be helpful to: (1) indicate the quality or severity of local weather conditions as applied to aggregate performance, (2) indicate the applicability of a given aggregate type for a particular location, (3) anticipate pavement performance and aggregate sampling and storage problems. Note: This project may be approached on a state or regional basis for efficient coordination with meteorological data and records Joint effort may be required by the physicist (to instrument in situ conditions), the meteorologist, and the highway materials engineer.

Objectives:

1. Investigate and determine the critical climatic environmental factors affecting aggregate performance in highways.
2. Develop equipment and methods for measuring and characterizing microclimatic data, including the moisture content of concrete in service, at a level of detail such that differences between materials and gradients within a single phase can be determined.
3. Develop framework for defining aggregate performance in laboratory tests in terms of microclimatic characteristics in the field.
4 Develop a classification system for climatic factors

applicable for all weather conditions throughout the United States and, within such a system, apply severity ratings to typical climatic environments based on aggregate performance.

5. Develop a rational weather severity index system, perhaps supplemented by a map or other means.

Program:

1. Literature search and review in the areas of microclimatology, temperature and moisture data in pavements, techniques for measuring temperature and moisture in and beneath pavements (including a patent search), and the properties of portland cement and asphaltic concrete and base courses which affect their response to environment.
2. Develop suitable equipment and techniques to characterize microclimatic conditions.
3. Develop laboratory tests and criteria by which aggregate can be evalauted in terms of microclimatological data from the field.
4. Develop a weather severity index or classification system by which climatic environments can be evaluated in terms of aggregate performance.
5. Summarize and report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	24
3	24	36
4	6	6
5	3	3
		72 m-m

Calendar months for completion: 36 months

Cost. 72 m-m @ \$3,000/m-m = \$216,000
Initial cost = \$ 25,000
\$241,000

References

1 AMERICAN CONCRETE INSTITUTE, "Recommended Practice for Selection Proportions for Concrete (AC1 613-54)." *J. Amer. Conc. Inst.* (Sept. 1954).
2. AMERICAN SOCIETY FOR TESTING AND MATERIALS, "Standard Specifications for Building Brick." *ASTM C 62*
3. BARBER, E. S., "Calculation of Maximum Pavement Temperatures from Weather Reports." *HRB Bull. 168* (1957) pp. 1-8.
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5. GEIGER, R., *The Climate Near the Ground* Harvard Univ. Press (1950) pp. 1-482.
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7. LOBDELL, H. L., TURNER, K. A., and JUMIKIS, A R, "Study of Subsurface Temperature in Six Soils During the Winter of 1953-4." *HRB Bull. 168* (1957) pp. 123-42.
8 MELVILLE, P. L., "Weathering Study of Some Aggregates." *Proc. HRB,* Vol. 28 (1948) pp 238-248.
9. MENZEL, C., "A Method for Determining the Moisture Condition of Hardened Concrete in Terms of Relative Humidity." *Bull. D4,* Portland Cement Assn. R and D Labs. (1955).
10. MONFORE, G. E., "A Small Probe-Type Gage for Measuring Relative Humidity." *J. Portland Cement Assn*, Vol. 5, No. 2, pp 41-47 (*Research Dept. Bull. 160*) (1963).
11. MONFORE, G. E., "Application of a Small Probe-Type Relative Humidity Gage to Research on Fire Resistance of Concrete." *J. Portland Cement Assn.,* Vol. 7, No. 3, pp. 2-12 (*Research Dept. Bull. 186*) (1965).
12. NIELSEN, K, "Measurements of Water Vapour Pressure in Hardened Concrete." *Bull No. 35,* Swedish Cement and Conc. Res. Inst., Stockholm (1967).
13. SHAW, M., and ARBLE, W. C., "Bibliography on Methods for Determining Soil Moisture." *Eng. Research Bull. B-78,* Penn. State Univ. (June 1959).
14. SNOWDEN, L., and EDWARDS, A., "The Moisture Movement of Natural Aggregate and Its Effect on Concrete." *Mag. of Concrete Research,* Vol. 14, No. 41, pp. 109-16 (July 1962).
15. TREMPER, B., and SPELLMAN, D. L., "Tests for Freeze-Thaw Durability of Concrete Aggregates." *HRB Bull 305* (1961) pp. 28-47.
16 TROTT, J. J, "An Apparatus for Recording the Duration of Various Temperatures in Roads." *Roads and Road Const.* (Nov. 1963).

Problem No.: IV-10 *Estimated Time:* 12 months

Priority Category: A_2 *Estimated Cost* \$45,000

Title: Development of Rapid and Reliable Methods for Determining Aggregate Gradation

Problem Statement.

If highway engineers are to use aggregates that are "borderline" in terms of quality for selected applications, they must have rapid and reliable test methods to monitor such use

Gradation is perhaps the most commonly specified aggregate requirement. The process of monitoring gradation is currently time-consuming and unreliable in the sense that adequate sampling is very difficult.

There is a need, then, for research on the entire process of sampling aggregate and monitoring gradation with emphasis on situations where the aggregate is known to be near the lower specification limit The emphasis must clearly be on speed and accuracy.

Objectives:

1. Develop rapid and reliable sampling and gradation testing methods suitable for control of borderline (with respect to gradation) aggregates.

Program:

1. Review sampling and gradation practices from highway departments and other organizations.
2. Develop sampling and gradation methods, possibly as a combined procedure.
3. Field check to develop statistical information concerning reliability under typical job situations.
4. Data analysis and report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	6
3	6	3
4	3	3
		15 m-m

Calendar months for completion: 12 months

Cost: 15 m-m @ \$3,000/m-m = \$45,000.

References:

1. MILLER-WARDEN ASSOCIATES, "Development of Guidelines for Practical and Realistic Construction Specifications." *NCHRP Report 17* (1964) pp. 1-109.
2. MILLER-WARDEN ASSOCIATES, "Effects of Different Methods of Stockpiling and Handling Aggregates." *NCHRP Report 46* (1965) pp. 1-102.
3. STEPHENS, J. E., "Reduction of Apparent Aggregate Variation Through Improved Sampling." *Report No. JHR 66-1*, Civil Eng. Dept., Univ. of Conn (May 1966).

Problem No.: IV-11 *Estimated Time* 27 months

Priority Category: A_1 *Estimated Cost:* \$115,000

Title. Relationship of Aggregate Type and Susceptibility to Damage From Studded Tires

Problem Statement:

As an increasing number of states allow use of the studded tire for winter driving, highway engineers are observing increased pavement damage. This damage has been directly attributed to the tire stud which can penetrate into the pavement. Research has been initiated to study the type of damage caused by studded tires However, a need remains to determine what role the aggregate plays in the amount of damage incurred and which aggregate types best resist the effects of studded tires under various service and weather environments. For example, as motorists seek improved traction on snow and ice, the long-term result may be aggregate polishing and reduced skid-resistance as well as pavement deterioration. Research could lead to a specification that would limit the use of aggregates that abrade easily under the action of studded tires, particularly in climatic areas where heavy use of studded tires may be anticipated. Such information could be useful for predicting performance of existing highway pavements and future maintenance requirements. Note: Use of circular test-tracks may be considered.

Objectives:

1. Determine which aggregate properties relate to resistance to wear or breakdown by studded tires.
2. Determine which aggregate types are most resistant to damage by studded tires.

Program:

1. Literature search and review.
2. Laboratory study to determine what aggregate characteristics are influential in resisting damage.
3. Field study on wide sampling of aggregates.
4. Data analysis, synthesis, and reports.

Time

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	12
3	12	12
4	3	3
		30 m-m

Calendar months for completion: 27 months

Cost. 30 m-m @ \$3,000/m-m = \$90,000
Initial cost = \$25,000
\$115,000

References:

1. "Studded Tires." *Hwy. Res. Record No. 171* (1967) pp. 1-51.
2. ROSENTHAL, P., ET AL., "Evaluation of Studded Tires." *NCHRP Report 61* (1969) pp. 1-66.

Problem No.: IV-1B *Estimated Time:* 21 months

Priority Category: B *Estimated Cost:* \$90,000

Title: Aggregate Gradation Specifications

Problem Statement:

Many highway materials engineers have expressed doubts on the value of rigid specifications for aggregate gradation. Adherence to these rigid specifications raises considerably the cost of highway construction. Weighed against this increased cost is the hope of better performance which can not be adequately quantified. Therefore, the question of how much performance is being purchased or what is the benefit-cost ratio remains unanswered. In addition, many engineers believe that uniformity within any gradation is more important than the gradation itself. It may be more economical to adapt construction practices to gradations that can be achieved with greater uniformity than to demand gradations that cannot be met with consistency.

Objectives:

1. Determine the value (benefit-cost ratio) of rigid aggregate gradation specifications.
2. Determine the economics of adapting construction practice to a gradation that can be achieved with great uniformity.

Program:

1. Literature search and review.
2. Economic analysis of rigid aggregate gradation specifications and aggregate performance through a benefit-cost study.
3. Study to determine if greater economics can result by emphasizing uniformity within aggregate gradation.
4. Data analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	8	12
3	8	12
4	6	3
		30 m-m

Calendar months for completion: 21 months

Cost: 30 m-m @ $3,000/m-m = $90,000.

References:

1. BLOEM, D., "Aggregate Economy Through Universal Standardization." *Pit & Quarry*, Vol. 57, p. 119 (Aug. 1964).
2. GRAY, J. E., "Specifications for Mineral Aggregates." *Crushed Stone J.*, Vol. 36, No. 2, pp. 3-10 (June 1961).

Problem No. IV-2B — *Estimated Time:* 18 months

Priority Category: B — *Estimated Cost:* $81,000

Title: Investigation of Aggregate Pre-Conditioning Methods for the Benefit of Field Performance

Problem Statement:

Investigation is needed into aggregate pre-conditioning methods which may result in improved field performance of highway materials. For example, long-term benefits of concrete in service may result from moisture-conditioning the aggregate to a uniform degree of dryness before mixing. The objective is to control the rate or degree of aggregate response to various external conditions by means of aggregate beneficiation. In the preceding example, the desire is to reduce the deleterious effects of water in concrete aggregate. However, the question remains: How much of what moisture should be removed? Comparison between concrete performance following such pre-conditioning procedures and performance obtained after free water has been allowed to drain from the aggregate in a stockpile help to indicate the value of moisture conditioning.

Pre-conditioning methods may also be developed to (1) improve concrete soundness or freeze-thaw durability, (2) decrease chemical reactivity, or (3) improve volumetric stability or resistance to drying and shrinkage. For example, chemical pre-conditioning procedures that result in reduced alkali-aggregate reaction or reactions due to de-icing salts may be effective in improving concrete performance. Similar procedures may also be applicable to bituminous concrete and base courses.

Objectives:

1. Investigate deleterious aggregate properties that may be improved by pre-conditioning procedures.
2. Examine and develop laboratory and/or field pre-conditioning methods and evaluate their effectiveness.
3. Develop recommendations on the use of pre-conditioning processes for various types of aggregate and construction.

Program:

1. Literature search and review.
2. Investigate aggregate properties that may be improved by pre-conditioning procedures.
3. Examine, evaluate, and develop pre-conditioning methods.
4. Develop recommendations for laboratory and/or field pre-conditioning methods.
5. Data analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	6
3	12	12
4	3	3
5	3	3
		27 m-m

Calendar months for completion: 18 months

Cost: 27 m-m @ $3,000/m-m = $81,000.

Problem No.: IV-3B — *Estimated Time:* 18 months

Priority Category: B — *Estimated Cost:* $91,000

Title Deleterious Effects of Aggregate Stockpiling, Handling, and Shipping, and Methods for Improvement

Problem Statement

Stockpiling, handling, and transporting of aggregate can have pronounced deleterious effect on the properties of the material. Changes in the gradation, amount, and characteristics of the fine content, surface texture, and shape are a few of the possible results of mechanical and/or chemical action on the aggregate particles. The significance of such deterioration ranges from inconsequential to extremely serious in those cases where the aggregate goes "out of specification" and the performance of the material, whether in portland cement concrete, asphaltic concrete, or base courses, is adversely affected. Further study is needed to determine, in particular, the increase of minus #200 mesh fines through stockpiling

The nature of aggregate, the length and type of exposure, and the amount and kind of handling and shipping are all important variables. These must be related in a systematic fashion so that guidelines for material selection, handling, and storage practices will result Proper storage of aggregate becomes especially important when future testing may be necessary to determine the original properties of the material.

Information is limited on procedures by which these adversely affected aggregates may be improved for use in highway construction For example, studies on the value of washing aggregate would be useful to determine whether washing of some aggregate types might be more detrimental than beneficial, and whether the operation is economical at all. Note: Coordinate with studies on changes in gradation and beneficiation processes.

Objectives:

1. Determine the particular consequences of handling and stockpiling deterioration of aggregates, particularly the generation of fines.

2. Relate aggregate class, exposure, and handling in a general quantitative framework.

3. Propose guidelines by which highway materials engineers can use information from item 2.

Program:

1. Literature search and review, determining causes of this type of deterioration and effects on performance.

2. Laboratory and field study of factors which cause deterioration of coarse aggregate in stockpiles and their rates.

3 Case and laboratory study to determine the extent to which generated minus #200 mesh material diminishes portland cement, bituminous concrete, or base course properties.

4 Determine the value of beneficiation by washing, for example, in view of deleterious effects of minus #200 mesh material.

5. Data analysis, synthesis, and report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	9
3	12	9
4	6	3
5	6	3
		27 m-m

Calendar months for completion. 18 months

Cost: 27 m-m @ \$3,000/m-m = \$81,000
Initial cost = \$10,000
\$91,000

References:

1. ACI Committee No. 621, "Selection and Use of Aggregates for Concrete." *J. Amer Conc. Inst.*, Vol 58, No. 5, pp. 513-41 (Nov. 1961).
2. Buth, E., Ivey, D L, and Hirsch, T. J., "Dirty Aggregate, What Difference Does It Make." *Hwy. Res. Record No. 226* (1968) pp. 26-34.
3. Harra, G. W., "Degradation of Aggregate." *Pacific Builder and Eng*, Vol. 68, No. 9 (Sept. 1962).
4. Miller-Warden Associates, "Effects of Different Methods of Stockpiling Aggregates—Interim Report" *NCHRP Report 5* (1964) pp 1-48.
5 Miller-Warden Associates, "Effects of Different Methods of Stockpiling and Handling of Aggregates." *NCHRP Report 46* (1967) pp. 1-102.
6. Reagel, F. V., "How Good is Good Enough." *Crushed Stone J.*, Vol. 35, No. 1 (Mar. 1960).

Problem No. IV-4B — *Estimated Time:* 24 months

Priority Category. B — *Estimated Cost* \$99,000

Title. Compilation of Current Design, Construction, and Maintenance Practices as They Relate to Aggregate Performance

Problem Statement.

Before aggregate response to service conditions can be controlled, there must be a better definition of critical relationships, including the relationships between design, construction and maintenance practices and aggregate performance

Currently there are isolated cases in which the relationship between design and performance has been described This information needs to be collected and analyzed. Some specific design features that might be examined include:

1. The sloping and drainage of surfaces.
2 The sealing of surfaces (top, bottom, joints).
3. Precasting practices (for example, curing and storage of slabs and beams)
4. Drainage of various subgrade designs
5. Shoulder design.
6 Joint design and control.

Construction practices vary considerably among the states for asphaltic pavements, portland cement concrete pavements and structures, base courses and shoulders. There is a need for a survey and compilation of these construction practices with respect to aggregate performance. A survey should permit a critical review of these practices and the development of a "state of the art" of construction practices related to aggregate performance. Some specific items for attention in this area might include:

1. Compaction.
2. Finishing.
3. Curing.
4. Consolidation.
5. Construction tolerance (quality control).
6. Aggregate degradation during construction.

Maintenance practices are considered to be significant in the performance of aggregates for given environment and service conditions. This, however, is an elusive relationship and one difficult to isolate. There is a need to develop case histories where the following items, among others, might be considered.

1 Possible treatments for D-line cracking.
2 Expansion control.
3. Crack sealing and filling (consider both durability and structural integrity).
4. Surface sealing and resealing.
5. Undersealing.
6. Drying treatments and treatments to maintain moisture content at a low level.
7. Treatments for restoring skid resistance.
8. Patching practices.
9. Snow and ice removal.
10. Maintenance on drainage systems.

A systematic and somewhat standardized record-keeping system that could be adopted by the state highway departments is needed to facilitate the gathering of good data and the subsequent development of quantitative relationships between design, construction and maintenance practices and aggregate performance.

Objectives

1 Survey and compilation of highway design, construction, and maintenance practices as they relate to aggregate performance.
2. Critical review and analysis of these practices and development of a state of the art as related to aggregate performance.
3. Development of recommendations concerning record-keeping procedures.

Program.

1. Through literature review and field surveys, compile design, construction, and maintenance practices and relationships to aggregate performance.
2. Review and analyze existing design, construction, and maintenance practices and develop a state of the art for each as related to aggregate performance in highways.
3. Develop recommendations on record-keeping methods.
4. Data analysis, synthesis, and report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	18	18
2	9	9
3	3	3
4	6	3
		33 m-m

Calendar months for completion: 24 months

Cost 33 m-m @ \$3,000/m-m = \$99,000.

References:

1. DOLCH, W. L., "Protective Coatings for Concrete." *Tech. Report No. 2-29,* U.S. Army Corps of Engineers (Sept. 1963).
2. HUDSON, S. B., and WALLER, H. F., "Evaluation of Construction Control Procedures—Aggregate Gradation Variations and Effects." *NCHRP Report 69* (1967) pp. 1-58.
3. KLIEGER, P., "Curing Requirements for Scale Resistant Concrete." *HRB Bull. 150* (1957) pp. 18-31.
4. LARSON, T. D, ET AL., "Identification of Concrete Aggregates Exhibiting Frost Susceptibility—Interim Report." *NCHRP Report 15* (1965) pp. 1-66.
5. LARSON, T. D., ET AL., "Durability of Bridge Deck Concrete." *Materials Res. Report No. 4,* Vol. 1, Penn. State Univ., Civil Eng. Dept. (July 1967).
6. MICHIGAN STATE HIGHWAY DEPARTMENT, "Durability of Concrete Bridge Decks." *Report No. 2* (1965).
7. MIESENHELDER, P. D., "Effect of Design and Details on Concrete Deterioration." *J. Amer. Conc. Inst.,* Vol. 31, No. 7 (Jan. 1960).
8. State Highway Specifications and Related Manuals on Design, Construction, and Maintenance Practices.
9. VASWANI, N. K., and KRISHNA, J., "Pavement Performance as a Basis for Design." *Proc ASCE, J. of Highway Div.* (Nov. 1967).

Problem No. IV-5B *Estimated Time·* 12 months

Priority Category· B *Estimated Cost:* \$36,000

Title. Investigation of Waste Products as Potential Sources of Aggregates

Problem Statement:

The sheer bulk of material that goes into highways makes the notion of using "waste" products in highway construction an attractive one. There is a considerable precedence for using certain kinds of waste products in the past. For example, fly ash has been used directly in concrete and sintered into aggregate; slag has been used as aggregate extensively; certain kinds of coal have been used as filler for bituminous concrete.

Rigid specifications have discouraged experimentation with "waste" products in highway construction. Also, there has not been a broadly based research effort on this problem. As conventional aggregate sources are depleted and as the problems of waste disposal mount, the economics of using "waste" materials is constantly changing. A comprehensive study followed by periodic updating is in order for this problem area.

Objectives:

1. Develop successful case history and potential use files. Identify factors hindering use in each case.
2. Develop a coordinated research and promotion program to encourage appropriate waste use.

Program·

1. Literature and field search and review to discover successful cases and potential cases of waste product use in highway construction.
2. Study specification requirements for those waste products that could be used as aggregate, and economics of bringing products to specification level.
3. Develop detailed research needs file; report.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	6	6
3	3	3
		12 m-m

Calendar months for completion: 12 months

Cost: 12 m-m @ \$3,000/m-m = \$36,000.

References:

1. FONDRIEST, F. F., and SNYDER, M., "Synthetic Aggregates for Highway Construction." *NCHRP Report 8* (1964) pp 1-13.
2. GOLDMAN, H. B., "Aggregates from Fossils." *Rock Products,* Vol. 65, No. 11, pp. 65-68 (Nov. 1962).
3. GUTT, W., KINNIBURGH, W., and NEWMAN, A., "Blast Furnace Slag as Aggregate for Concrete." *Mag of Concrete Research,* Vol. 19, No. 59, pp. 71-82 (June 1967).
4. HOWARD, G. G., "A Laboratory Investigation of the Properties of Coal-Bituminous Paving Mixture." *Eng. Experiment Station Bull. No. 71,* Univ. of Ky., Vol. 18, pp. 1-46 (Mar. 1963).
5. MINNICK, J., "New Fly Ash and Boiler Slag Uses." *Tappi,* Vol. 32, No 1 (Jan. 1949).

Problem No. IV-6B *Estimated Time.* 24 months

Priority Category B *Estimated Cost.* \$136,000

Title: Study and Evaluation of Synthetic Aggregate Use, Specifications, and Tests

Problem Statement:

An immediate need relating to use of synthetic aggregates in highway construction is for a literature search to determine the present status of research in this field and to locate sources of available information. Evaluation of the research and experimentation which has been conducted by state and Federal highway agencies, universities, commercial organizations, and others on the use of synthetic materials will help to guide future research into those areas that show promise as highway materials.

Synthetic aggregates may include commercially produced materials such as blast furnace slag, fly ash, other "waste products," and pozzolanically active aggregates such as cinders, brick fragments, and expanded shale. Study should extend beyond these materials to include manufactured products such as plastics and resins that may be adapted for highway use.

Investigation and evaluation of existing specifications and tests for synthetic aggregates are needed. Development of new tests and procedures for identification and classification of these materials should also be considered, including, for example, development of criteria for the evaluation of synthetic aggregate performance in highways. Consideration should be given to the matter of information on natural aggregate which may be transferred for use with synthetic aggregate.

In addition, study is needed on the soundness and durability problem with synthetic aggregate, including development of soundness criteria and methods of retaining or controlling soundness.

Objectives:

1. Compile information from all available sources on synthetic aggregate use and research in progress.
2. Investigate present test procedures and develop new tests, as required, applicable to synthetic aggregate.
3. Evaluate use of synthetic aggregate for highway construction and develop recommendations concerning the use and specifications, including properties and qualities desired.

Program.

1. Literature search and evaluation, especially to determine the most profitable areas for further study.
2. Laboratory and field study and investigation of test procedures.
3. Develop recommendations for testing and use of synthetic aggregate in highway construction.
4. Data analysis and reports.

Time:

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	24
3	12	12
4	6	3
		42 m-m

Calendar months for completion: 24 months

Cost: 42 m-m @ \$3,000/m-m = \$126,000
Initial cost = \$ 10,000
\$136,000

References:

1. FONDRIEST, F. F., and SNYDER, M., "Synthetic Aggregates for Highway Construction." *NCHRP Report 8* (1964) pp. 1-13.
2. GALLAWAY, B., and HARPER, W., "Interim Report on the Laboratory Considerations for Use of Synthetic Aggregates for Hot-Mix Asphalt Pavement," Extracted from *U.S. Gov't R and D Reports,* p. 125 (Sept. 10, 1967).
3. GOLDMAN, H. B., "Aggregates from Fossils." *Rock Products,* Vol. 65, No. 11, pp. 65-68 (Nov. 1962).
4. GUTT, W, KINNIBURGH, W., and NEWMAN, A., "Blast Furnace Slag as Aggregate for Concrete." *Mag. of Concrete Research,* Vol. 19, No. 59, pp. 71-82 (June 1967).
5. HOLLAN, G., and MARKS, B., "A Correlation of Published Data on Lime-Pozzolan-Aggregate Mixtures for Highway Base Course Construction." *Circular No. 72,* Univ. of Ill. Exp. Station, pp. 1-55 (1962).

Problem No.. IV-7B *Estimated Time:* 24 months

Priority Category. B *Estimated Cost.* \$127,000

Title: Review of Aggregate Beneficiation Processes

Problem Statement:

The availability of quality aggregate for highway construction is limited. The rapid depletion of proven aggregate sources and the cost of increasingly longer haul distances make it difficult to obtain or uneconomical to purchase the quality aggregate desired, thus creating ever greater pressures for use of marginal aggregate sources that were previously rejected.

Marginal aggregates are those that contain some constituent or constituents that may be detrimental to the performance of portland cement or asphaltic concrete, or base courses made from them. Therefore, it is becoming increasingly more attractive, economically, to apply some means of beneficiation to marginal aggregates, thereby rendering them attractive for highway use. This is particularly true of gravels.

Many beneficiation processes are presently in use or in the experimental stage; some are too expensive, such as heavy media separation, and others have limited application, such as elastic fractionation, which is successful only for rounded aggregates. A review of beneficiation processes is needed to define the effectiveness and economy of removing various deleterious materials such as:

1. Mica from fine aggregate
2. Highly porous, unsound particles subject to freeze-thaw damage.
3. Soluble substances; for example, gypsum.
4. Particle coatings.
5. Unsound, chemically reactive materials.

Study is also needed on so-called beneficiation processes such as heat treatment (to produce a lightweight aggregate from burnt clays) and blending of "good" and "bad" aggregate. Additional research may be included on methods of beneficiating aggregates to reduce degradation. An investigation should be undertaken to determine the feasibility of developing new beneficiation techniques. Economical and efficient beneficiation processes may ultimately allow use of aggregates presently classified as marginal or poor quality and give greater flexibility in the choice of highway aggregate materials.

Objectives:

1. Review of aggregate beneficiation techniques with economic considerations.
2 Identify areas that can benefit most by immediate research and development.
3. Investigate the development of new aggregate beneficiation techniques.

Program·

1. Literature search and review.
2. Field study to evaluate the significance and economics of present beneficiation techniques.
3. Develop criteria for using certain techniques for a given use of aggregate.
4. Laboratory and field study investigating the development of new aggregate beneficiation techniques and establishing guidelines for future research.
5. Data analysis, synthesis, and report.

Time.

PROGRAM ITEM	TIME	MAN-MONTHS
1	3	3
2	12	18
3	3	3
4	12	12
5	6	3
		39 m-m

Calendar months for completion: 24 months

Cost 39 m-m @ $3,000/m-m = $117,000
Initial cost = $ 10,000
$127,000

References.

1 GOLSON, C. E, and NEWTON, D. E., "Aggregate Processing Tips, Part 3: Beneficiation Pays Off." *Rock Products*, Vol. 64, No. 11, pp. 104-18 (Nov 1961).
2 GOLSON, C, and NEWTON, D, "Aggregate Processing Tips." *J Amer Conc. Inst.*, Vol 59, No. 5, p 735 (May 1962).
3. GOODWIN, W. A, "The Application of Geology in the Beneficiation of Aggregates." *Eng Experiment Station Bull. No. 76*, Vol. 20, Univ. of Ky., pp. 3-5 (Sept. 1965).
4. INGHOM, K. W, "The Beneficiation of Aggregates by Jigging." *Report No. RB 107*, Dept. of Highways, Ontario, D H.O. (Nov. 1965).
5. JENKINSON, D. W, "Beneficiation of Aggregate by Heavy Media Separation." *Mining Eng.*, Vol. 12, No. 7 (July 1960).
6. MISSOURI STATE HIGHWAY DEPARTMENT, "Beneficiating a Shale Contaminated Limestone by Heavy Media Separation." Extracted from *U.S. Gov't R and D Reports*, Vol. 41, No. 19, p. 119 (Oct. 10, 1966).
7. MONTANA STATE HIGHWAY DEPARTMENT, "Report on Beneficiation of Aggregates for Upgrading of Substandard Native Materials in Eastern Montana, 1966."
8. PRICE, W., "Ten Years of Progress in Gravel Beneficiation, 1948-1958." *National Sand and Gravel Circ. No. 71*, pp. 3-19 (Mar. 1958).
9. RAMSAY, D. M, "Factors Influencing Aggregate Impact Value in Rock Aggregate." *J. Quarry Managers*, Vol. 49, No. 4 (Apr. 1965).

Problem No. IV-8B *Estimated Time.* 24 months

Priority Category B *Estimated Cost.* $122,000

Title: Evaluation and Development of Radioactive Techniques for Evaluating Moisture, Density, and Strength of Pavement Components

Problem Statement. By title only.

Time: Calendar months for completion: 24 months

Cost. 24 m-m @ $3,000/m-m = $ 72,000
Initial cost = $ 50,000
$122,000

References.

1 VIRGINIA HIGHWAY RESEARCH COUNCIL, "Correlation and Conference of Portable Nuclear Density and Moisture Systems" (1965).
2 HUGHES, C S., "Investigation of Nuclear Device for Determining the Density of Bituminous Concrete." *Proc. Assn. of Asphalt Paving Technologists*, Vol. 31, p. 400 (1962).

Problem No.. IV-9B *Estimated Time:* 18 months

Priority Category. B *Estimated Cost·* $91,000

Title: Development of Methods of Improving Fine-Aggregate Particle Shape and Surface Texture

Problem Statement: By title only.

Time. Calendar months for completion: 18 months

Cost· 27 m-m @ $3,000/m-m = $81,000
Initial cost = $10,000
$91,000

APPENDIX B

WORKSHOP-CONFERENCE SUMMARY

In an effort to develop information that would permit the formulation of a comprehensive series of statements of research problems relating to the performance of aggregate in highway construction, a Workshop-Conference was held at the F. Donaldson Brown Continuing Education Center at Virginia Polytechnic Institute in Blacksburg, Virginia, on Monday and Tuesday, March 18 and 19, 1968.

Because the unpublished knowledge concerning aggregates and problems of their use is extensive, it was believed that the experience of authorities in specific areas should be used. Through the conference, it was possible to get an interaction between the individuals who are knowledgeable in these areas that produced results that were extremely valuable in writing the problem statements presented in this report. The conference program included sessions on problem listing for (1) portland cement concrete, (2) bituminous concrete and related materials, (3) base course and shoulders, development of priorities; priorities, case of solution categories; and time and cost analysis.

PARTICIPANTS

There were approximately 60 participants from all parts of the United States, including Alaska and Florida. They participated in the sessions as follows.

Portland Cement Concrete Session

The consultants participating were as follows:

Katherine Mather, U.S. Army, Corps of Engineers
Russell H. Brink, BPR
W. L Dolch, Purdue Univ.
Donald L Spellman, California Div. of Highways
E. A. Jumper, Consolidated Rock Products Co.
Howard Newlon, Jr., Virginia Council of Highway Research & Investigation
E O. Axon, Missouri State Highway Commission
William Cordon, Utah State Univ.
W. M. Stingley, State Highway Commission of Kansas
William P. Chamberlin, New York Dept. of Public Works
Richard C Mielenz, The Master Builder Co.

Dr. Thomas D. Larson presided over the session, assisted by Mr. Harry J. Pence.

Bituminous Concrete Session

The consultants participating were as follows:

Jack H. Dillard, Virginia Dept. of Highways
Bernard F. Kallas, The Asphalt Institute
W. H Gotolski, Pennsylvania State Univ.
William H. Goetz, Purdue Univ
R D. Shumway, Alaska Dept. of Highways
Stewart R. Spelman, BPR
Frank M. Williams, Ohio Dept. of Highways
Joseph E. Gray, Consulting Engineer
W. K. Parr, Chicago Testing Laboratory, Inc.
William A. Goodwin, Univ. of Tennessee
Bob M. Galloway, Texas A&M Univ.
R. V. Le Clerc, Washington State Dept. of Highways

Dr. Philip D. Cady presided over the session, assisted by Mr. H W. McGee.

Base Course Session

The consultants participating were as follows:

D. W. Lewis, National Slag Assn.
Chester McDowell, Texas Highway Dept.
Olof L. Stokstad, Michigan Dept. of State Highways (retired)
Richard D. Gaynor, National Sand and Gravel Assn.
F. N. Hveem, California Div. of Highways (retired)
Robert S. Barneyback, Kaiser Industries Corp.
Karl H. Dunn, State Highway Commission of Wisconsin
H. G. Larew, Univ. of Virginia
John Lemish, Iowa State Univ.
J. P. Bassett, Virginia Dept. of Highways
Leo Sandvig, Pennsylvania Dept. of Highways
John C. Cook, Washington State Univ.
James H. Havens, Kentucky Dept. of Highways

Dr. Richard D Walker presided over the session, assisted by Mr. John Harman.

Other Participants

Other persons participating were either members of the Highway Research Board Staff, members of the NCHRP Panel D70, Section 4, or invited guests. These were as follows:

L. F. Erickson, Idaho Dept. of Highways
LeRoy T. Oehler, Michigan Dept. of State Highways
F. E. Legg, Jr., Univ. of Michigan
Preston C Smith, BPR
E A. Whitehurst, Tennessee Highway Research Program
Harry A. Smith, HRB (NCHRP)
Adrian Pauw, Univ. of Missouri
Bryant Mather, U.S. Army Corps of Engineers
F P. Nichols, Jr., National Crushed Stone Assn.
W. G. Gunderman, HRB
R. E. Bollen, HRB
P. L. Melville, U.S. Army Corps of Engineers

Also, Mr. Fred R. Allen assisted in general arrangements during the conference.

RESULTS

The results of the conference are contained in this report. The information obtained from the unrehearsed discussions that took place in the three simultaneous sessions provided the main source of information on which the research problem statements were based. The summarized results of the conference, as sent to the participants soon after the conference conclusion, appear in the following section of this appendix.

WORKSHOP-CONFERENCE SUMMARY REPORT

Portland Cement Concrete—Aggregate Research Needs

The performance of concrete aggregate is intimately related to the total performance of highway concrete. It is improbable, therefore, that a direct and simple approach can be made to the stated research objective—namely, to develop procedures by which a highway materials engineer can evaluate properties of concrete aggregates quantitatively for a given use, environment, and level of performance. A highway engineer can evaluate concrete aggregates if he has test and performance guidelines available to him. Better tests and guidelines are likely to become available only as broad understanding of concrete, of aggregate in concrete, and the total service environment improves.

Research needs, then, range from collecting basic environmental data through basic studies of moisture transfer processes. The panel that was convened to develop problem statements over this broad range felt that this could be done best in an organized fashion, and so worked to develop the following framework.

Research Needs Framework

The following outline is the framework in which problem statements were written. Brief background information is provided for each of the major items. Problem statements developed at the VPI Workshop-Conference are related to this outline.

I. Identification, Quantification, and Categorization of Elements of the Environment of Concrete in Service.

Background.—Much of the blame for the present inability to evaluate aggregate properties quantitatively can be laid to the past neglect of gaining a better understanding of concrete service environment. Until one knows what an aggregate must withstand, it is improbable that it will be possible to intelligently evaluate properties of aggregate for various uses, environments, and levels of service.

A. Natural (Micro-Macro):
  1. Moisture. (1) levels; (2) gradients.
  2. Temperature: (1) levels; (2) gradients
  3. Chemical.

B. Applied (Micro-Macro):
  1. Chemical.
  2. Loads (type, rates).
  3. Abrasion.

II. Aggregate Description.

Background.—Aggregates may be described in the assemblage of particles or on the basis of individual particles. Both are important and both contain areas of inadequate understanding. Adequate description must be the basis for specification and testing.

A. Assemblage of Particles:
  1. Gradings.
  2. Coatings.
  3. Composition.
  4. Moisture content.

B. Properties of Particles.
  1. Physical.
  2. Chemical.

III. Condition of Enclosure in Service Environment (Micro-Macro).

Background.—Aggregates serve in a paste environment The paste matrix can vary widely in composition. Furthermore, it is affected by discontinuities, by dimensional differences, and by surface treatments and conditions. The performance of aggregate is affected by, and perhaps can be predicted by, the nature and condition of the enclosure.

A. Property of Matrix:
  1. Physical—chemical.
  2. Uniformity.

B. Discontinuity:
  1. Cracks.
  2. Air voids.

C. Dimensions (cover).

D. Surface:
  1. Cracked.
  2. Formed.
  3. Wear.

IV. Response of Aggregate in Concrete in Service Over Time and Environment (Micro-Macro).

Background.—How does aggregate respond as it serves in concrete? Experience is generally limited to acknowledging perfect response or failure response, but the concept of and quantification of response over time and environment is a relatively new one to concrete technologists

A. Mechanical:
  1. Volume change.
  2. Fracture.
  3. Abrasion (polishing)

B. Chemical:
  1. Deterioration.
  2. Volume change.
  3. Bond.
  4 Void change.

V. Failure Criteria.

Background.—What characterizes aggregate failure? When is cracking, deflection, etc., excessive in concrete, and when is it excessive in aggregate? Failure criteria have obvious import to test development.

A. Cracking.
B. Deflection.
C. Disintegration.
D. Abrasion (wear).
E. Volume change.
F. Aesthetics.

VI. Control of Response (Degree-Rate).

Background.—The research objective (NCHRP Project Statement) envisions the selective use of aggregates for various environments and levels of performance. It is possible to control response through design, material selection, etc., but much more quantitative information is needed before this can be done to any significant degree. The problem runs full circle at this point. The environment must be understood, ways of treating elements of the environment must be available, and, finally, the aggregates on hand must be grouped so that they can be used selectively.

A. Design (structural).
B. Material sampling, selection, beneficiation, and control.
C. Proportioning.
D. Construction and records.
E. Maintenance and records.

Problem Statements—Outline Reference I—Identification, Quantification, and Categorization of Elements of the Environment of Concrete in Service

A series of closely related and interrelated problems can be posed relating to the identification, quantification, and categorization of elements of the environment of concrete in service. The following appear to be of particular urgency:

1. Data on the moisture content of concrete in service is inadequate. Questions that have been raised include:
   a. How does moisture content in concrete vary with ambient environmental conditions?
   b. Is climate the critical element in determining moisture content?
   c. Is structure a critical factor, or what is the relation between climate and structure and moisture content (here "structure" is used in the broadest sense to connote total physical differences between concretes used for highway purposes, climate is used to connote aspects of the natural environment of highway concrete)?
2. Before moisture content data can be made fully meaningful there must be a better understanding of the fundamental mechanisms by which water moves in concrete.
3. The lack of information concerning items 1 and 2 is probably the result of having inadequate methods for measuring moisture content of concrete in service. Data collection on the scale necessary to provide real identification, quantification, and categorization of this aspect of concrete environment is impossible with current techniques
4. Paralleling the lack of understanding about moisture in concrete is the lack of understanding of moisture in aggregates. It is not possible to define moisture contents, moisture movements, or moisture changes with changing ambient conditions.
5. To effect a more complete understanding of the problems of moisture content and aggregates, the following must be given additional study:
   a. Properties of the matrix.
   b. Properties of the aggregate particle.
   c. The size of the particle.
   d. Temperature gradients.
   e. Hydraulic gradient.
   f. Dissolved materials.

The significance of all of these on the rate and degree of moisture content changes of aggregate particles in concrete in service needs to be studied intensively.

Much of what has been said concerning a lack of understanding of moisture in concrete aggregates in service could be said for temperature as well. The general problem can be stated as follows:

6. What temperature minimums, gradients, and durations occur in various elements of highway concrete in service? Can these be quantified and categorized in a meaningful way?

With regard to chemical environment of concrete in service, a principal concern is the various alkali environments The following question can be raised in this regard:

7 How does the alkali content in various types of highway structures and in various positions within the several highway structures vary with the environment over time?

The service environment of concrete may be modified by applied forces. Chemical change in the environment is caused by application of de-icing salts. A question that can be raised in this regard is as follows:

8. What is the effect of applied chemicals on aggregate performance? For example, how do de-icing salts relate to the alkali aggregate reaction (consider levels, rates, and gradients with regard to de-icing salt application)?

Details concerning live loading on concrete, and therefore on aggregates, in highways are somewhat vague. Problems in this area can be phrased as follows:

9. What are the limits and frequencies of loadings on aggregates in various highway service environments? Consider various types of structures and various strength categories of concretes.

Related questions might include:

10. How does aggregate particle texture and shape influence distribution of stresses within the concrete mass? Is there an optimum shape for major use categories?

11. What properties of aggregates are significant in predicting the peak performance of concrete?

Critical problems of performance of highway pavements are related to the abrasion characteristics of aggregate. Several problem statements in this area are as follows:

12. There is a need for better definition of, and means for measuring, micro texture as it contributes to skid resistance. Both coarse and fine aggregate should be considered in this regard.

13. What basic properties of coarse aggregate cause it to retain or lose desirable skid-resistant textural properties under traffic?

14 On the basis of a theoretically sound understanding of the aggregate-polishing problem there should be developed a laboratory method for simulating this polishing.

A related problem with implications for the more immediate type of solutions is stated as:

15. How does one select, blend, or beneficiate aggregates so as to obtain optimum skid-resistant performance when they are used in pavements?

Problem Statements—Outline Reference II—Aggregate Description

A basic problem concerning the use of aggregates is the matter of describing sources adequately. A problem statement in this area is as follows:

1. Can an adequate (for highway engineering purposes) quantitative description of aggregate sources be made?

Subsidiary questions are:

2. What should be the role of the petrographer, the geologist, and the engineer in this process?

3. Can ranges of variability within aggregate sources be used in a meaningful way?

A less important problem but one of long standing relates to aggregate gradation. Two problems that might be stated are as follows:

4. Is uniformity within any specified gradation more important than changes in gradation itself, or, in other words, can economies result from adapting construction practice to a gradation that can be achieved with great uniformity as opposed to demanding gradations that cannot be met with consistency?

5. There is a need to develop new methods for rapid and reliable indication of aggregate gradation.

Another practical problem in the area of aggregate use relates to moisture content. The problem can be stated as follows:

6 At present, the moisture content of aggregate and its contribution to the water/cement ratio of the paste cannot be adequately evaluated. Can this situation be corrected; if so, how?

Aggregate acceptance for highway use is based largely on highly empirical tests that have been widely adopted. In spite of numerous statements which tend to discredit the validity of these test methods, they continue to be used. A problem statement in this area might be phrased as follows:

7. A comprehensive review should be made of such tests as Los Angeles abrasion, sodium sulfate soundness, scratch hardness, etc., with a view to answering the following questions:

a. What, that these tests purport to tell, must be known to use aggregates in highway concrete?
b Are better tests available, or can better tests be developed on the basis of fundamental understanding of aggregate properties?
c When and how should these empirical tests be phased out?

With regard to single aggregate particles, several questions can be raised.

8. What is the influence of shape, texture, and size (coarse and fine aggregate) of individual particles and of the gradation of the aggregate mass on the following:

a. Bleeding and workability of fresh concrete (special consideration might be given to the durability problems of bridge decks in this regard).
b. On the elastic properties of the hardened concrete.
c. On durability of the hardened concrete.

9. Are micro-cracks that may be produced in varying degrees by different production practices detrimental to aggregate performance?

A subsidiary question would be, how do these micro-cracks relate to varying quarrying practices?

Problem Statements—Outline Reference III—Condition of Enclosure in Service Environment

The concept of critical aggregate size was advanced several years ago, but has not been fully used. A problem in this regard is as follows:

1. Can quantitative criteria for determining critical size of specific aggregates be developed, considering such things as property of the matrix, discontinuities, dimensions, and surface characteristics?

Problem Statements—Outline Reference IV—Response of Aggregate in Concrete in Service Over Time and Environment

Many aspects of response of aggregate in service need elucidation. Of particular import, perhaps, is the effect that changes in aggregate properties may have on total moisture changes. A problem might be phrased as follows:

1. What alterations in aggregate particles in concrete occur that affect moisture migration, moisture gradation, and moisture levels in subsequent service?

The paste-aggregate interface is not well understood, particularly as it changes over time and environment. The problem might be stated as follows:

2 How does the paste-aggregate bond vary with the compositional aspects of the concrete mixture, and how does it change with time, considering the chemical and mechanical aspects of the service environment?

Because synthetic aggregates are coming into more common use for highway concrete, there is a need to consider their performance response. A problem could be stated as follows:

3. What criteria should be used in and are available for evaluating performance of synthetic aggregates in highway concrete (careful consideration should be given to the matter of what information from natural aggregate is transferable)?

Problem Statements—Outline Reference V—Failure Criteria

If meaningful failure criteria for aggregate exist, then there is an improved possibility for devising meaningful tests and specifications. Several problems exist within this area. They have in part been treated in previous sections; for example, the matter of abrasion was treated as a problem under particle description. General questions, however, can be raised in this area as follows.

1. How should failure criteria differ for different aggregates in different service environments? Consider cracking, deflection, disintegration, abrasion, volume change, and aesthetics.

A more specific problem might be:

2. What are the failure criteria for aggregate with regard to cracking as this affects concrete cracking tendencies (both internal and external) due to drying shrinkage?

With regard to aesthetics, the following questions could be asked:

3. What is the aesthetic value of highway concrete? Can it be quantified? By whom?

The subsidiary and germane question is:

4. What effect does poor aggregate performance have on aesthetics? For example, aggregate pop-outs.

Problem Statements—Outline Reference VI—Control of Response

Before aggregate response to service conditions can be controlled, the relationships need better definition. Problem statements in this area include the following:

1. There should be a survey and compilation of concrete design practices as they relate to aggregate performance Specific items for attention might include:
   a. The sloping and drainage of surfaces.
   b. The sealing of surfaces (top, bottom, and joints).
   c. Precasting practices (for example, curing and storage of slabs and beams).
   d. The drainage of various subgrade designs.
   e. Shoulder design.
   f Joint design and control.
2. There is a need for a survey and compilation of concrete construction practices with respect to aggregate performance. Specific items for attention include:
   a. Finishing.
   b. Curing.
   c. Consolidation.
   d. Construction tolerance (quality control).
   e. Mixer degradation.
3. There is a need for a survey and compilation of concrete maintenance practices that affect aggregate performance. Items for attention include:
   a. Possible treatment for D-line cracking.
   b. Expansion control.
   c. Crack sealing and filling (consider both durability and structural integrity).
   d. Surface sealing and resurfacing.
   e. Undersealing.
   f. Drying treatments and treatments to maintain moisture content at a low level.
   g. Treatments for restoring skid resistance.
   h. Patching practices.
   i. Snow and ice removal.
   j. Maintenance practices on drainage systems.
4. There is a need to survey and evaluate aggregate sampling and control procedures used by the various highway departments.
5. Related to all of the foregoing, there is a need to develop systematic data-keeping procedures on concrete and aggregate performance. Related questions are:
   a. What kinds of records have been kept in the past?
   b. What system would be least disruptive to existing records and most amenable to mechanized data processing?

As a final problem in the general area of control of aggregate response, the following statement is suggested:

6. There is a need to develop a generalized framework in which aggregate use might be optimized with regard to basic economics and conservation of resources.

Some more specific problem areas with regard to controlling responses of aggregate are as follows:

7. Can aggregate be pre-conditioned in some fashion so that long-term benefits with respect to the field performance of concretes result?

8. Can synthetic aggregates be beneficiated with respect to soundness, and can criteria be developed for synthetic aggregate production process evaluation? Specific areas of concern include the free lime content, MgO sulfides and sulfates content.

9. How can deleterious constituents be removed more effectively and economically? Some specific constituents to be considered include:
   a. Mica removal from fine aggregate.
   b. Highly porous unsound particles (with respect to freeze-thaw).
   c. Soluble substances; for example, gypsum.
   d. Particle coatings.
   e. Unsound (reactive) particles.

10. What are the criteria for use of potentially reactive (alkali, silica, and alkali-carbonate) aggregates?

11. How can fine aggregate particle shape and surface texture be improved?

12. How can the deleterious effects of aggregate stockpiling, handling, and mixing be reduced by beneficiation?

A final problem that perhaps crosses all of the topics in the foregoing outline concerns the use of waste products in concrete. A problem might be stated as follows:

1. The potential use of waste products for use in concrete aggregates should be given careful investigation (investigation should extend beyond the use of fly ash, slag, and other waste products that are in common use at the present time).

Bituminous Concrete and Related Materials—Aggregate Research Needs

Problems encountered with aggregates in bituminous concrete can be broken down into two broad categories:

1. Those associated with the ability of the aggregate to withstand construction operations, physical, chemical, and weathering conditions, and traffic loadings.
2. Those associated with the effect of the aggregate characteristics on the durability, stability, resiliency, cohesion, weathering, and surface condition of the bituminous concrete.

There are also, in several instances, problems involving both of these categories. These cases result when aggregate breakdown in category 1 produces a change in aggregate characteristics that is reflected in category 2.

Procedure

To delineate the problem areas in their simplest form, the Workshop-Conference group first tried to identify the basic properties or phenomenological aspects of aggregate integrity, aggregate characteristics, aggregate mixtures, and bituminous concrete mixtures. The results are given in Table B-1.

The second step involved the establishment of tentative priorities for each of the items in Table B-1, based on the following criteria:

1. In need of immediate research to solve urgent problems that have reasonable possibility of being solved.

TABLE B-1

BASIC PROPERTIES AND PHENOMENOLOGICAL ASPECTS OF AGGREGATES RELATIVE TO USE IN BITUMINOUS CONCRETE

INTEGRITY	CHARACTERISTICS	AGGREGATE MIXTURE	BITUMINOUS CONCRETE
Soundess	Shape	Gradation	Modulus (stiffness)
Abrasion resistance	Texture	Internal friction	Permeable voids
Crushing strength	Absorption	Deleterious	Resilience
Resistance to heat	Elastic properties	1. Fines	Cohesion
Polishing	Surface chemistry	2. Coatings	Adhesion
Chemical degradation	Volume change	3 Cleanliness	Selective absorption
		Voids—VMA	Shear stability
		Dryness	Effect of water
			Volume change

2. Requires research for problems of long-standing importance.

3. Research not aimed at immediate problem, but intended as basis for more rational specifications.

Obviously, a great deal of interdependence exists among the items given on Table B-1. For example, adhesion is related to texture and surface chemistry, and internal friction is a function of particle shape and texture. The third step, then, was to formulate research needs statements that incorporated the related items in Table B-1 in the framework of problems experienced in the field. Priorities for each of the research needs statements were established at the same time.

The output of the Bituminous Concrete Session of the Workshop-Conference is presented as the following listing of the research needs statements.

Research Needs

1. Soundness Test: Indication of durablity under weathering. General agreement existed among the panel members that the present soundness tests are inadequate.
Problem Statement: "There is need for a system of measurement for determining the soundness of aggregate particles in bituminous mixtures."
Notes: "System of measurement" implies one or more tests that would indicate the aggregate soundness both in the mix and by itself. The soundness of the aggregate in the mix should be related to the soundness of the unconfined aggregate.
Priority: A.

2. Polishing: Skid resistance or influence of aggregate on skid resistance. The panel agreed that the most critical problem facing the highway departments is the skid resistance of the pavement. It was also agreed that research should begin immediately on the influence of aggregate on skid resistance.
Problem Statement: "There is a need to determine the effect of aggregate properties on skid resistance."
Notes: Factors that should be investigated under this project are: (1) aggregate properties of texture, shape and polishing; (2) rate of aggregate wear; (3) permeable voids; (4) size of aggregate (top size); and (5) speed of traffic. Also, research on upgrading materials for skid resistance.
Priority: A.

3. Chemical Degradation: Although there was general agreement that chemical degradation and soundness are interrelated, it was believed that there should be separate research on chemical degradation of aggregate. It was pointed out that this is a regional problem, but one that is of considerable concern where it appears.
Problem Statement: "There is a need for research on the chemical and physical changes in aggregate leading to the production of deleterious fines, including the development of a system of measurement."
Priority: A.

4. Surface Chemistry: Three problem statements were proposed during the discussion of surface chemistry; they are as follows:

I. "Identification of the significant aggregate surface characteristics that influence coating and adhesion with different bituminous mixes." This would include two phases: (1) degree of adhesion; and (2) how to improve on it.

II. "Need to evaluate the presently known techniques of measuring adhesion of bituminous material with aggregate."

III. "Techniques for improving the coating and adhesion of bituminous material with aggregates." This problem is implied under Statement I.

It was finally agreed that research for aggregate purposes should be confined to Statement I.
Priority. Changed from A to B because, although it was agreed that this is an important problem, the amount of research needed will require such a long time that it should be placed in B category.

5. Abrasion Resistance (mechanical abrasion or aggregate wear): Effect of abrasion loss on the performance of bituminous mix is not known. A better test method than the Los Angeles abrasion or Deval is needed.
Problem Statement: "Influence of aggregate wear and resistance to fracture on mix design and pavement performance."
Priority: B.

6. Absorption: Discussion of absorption by aggregate particle led to the following problem statement:
Problem Statement: "The influence of bituminous absorption rate, nature, and amount on mix design and performance."
Priority: B.

7. Gradation: There was considerable discussion on aggregate gradation. Some of the participants believed it was more of a mix design problem that did not warrant further research. However, others believed that the real influence of gradation on the mix is not really understood. (All agreed that uniformity was an important aspect in gradation.)

A general statement finally evolved: "The effect of aggregate gradation on mix design and pavement surface characteristics "
Priority: B.

8. Internal Friction: Internal friction involved other aggregate quality variables such as shape, texture and density.
Problem Statement: "The phenomenological aspects of internal friction as related to mix design and performance, including particle shape and texture of the aggregate."
Priority: B.

9. Deleterious: There was general agreement that more research is required in identifying deleterious materials and to what extent they can be tolerated.
Problem Statement: "Identify and determine the effect of deleterious secondary (extraneous) materials on pavement mixtures."
Priority: B.

10. Resistance to Heat: The rate of heating seems to be most critical; heat affects the integrity and characteristics of aggregates, such as its surface chemistry.
Problem Statement: "Effect of heat on integrity and characteristics of aggregates."
Priority. C.

11. Dryness: Panel agreed that the dryness aspect has not been fully explored. There appeared to be two problem areas that came out of the discussion.

I. "The significant aggregate surface characteristics and aggregate moisture that influence coating and adhesion with bituminous mix."

II. "Moisture movement in aggregates during drying process as influenced by heat transfer, pore size, etc."

Problem II has had previous research that might not warrant additional work.
Priority: C.

12. Fatigue: Panel agreed that the fatigue behavior of bituminous concrete needs more research.
Problem Statement: "Role of aggregate in relation to the fatigue behavior of the bituminous mix."
Priority: C.

13. Panel agreed that for all other qualities of bituminous mixture (see Table B-1) the same statement as in (12) should be used, except for insertion of quality aspect in place of fatigue behavior, e.g., "Role of aggregate in relation to the resiliency of the bituminous mix."
Priority: C, in all cases

Other Problem Areas

Beneficiation.—Consensus of the panel was that beneficiation should be a later phase of all previous research statements, where applicable.

Construction Procedures.—No definite problem statements were made, but again it was agreed that this could also be a research phase of previous statements.

No priorities were mentioned for beneficiation for construction procedures.

**Base Course and Shoulder Materials—
Aggregate Research Needs**

Objective

The objective of the project as stated in the NCHRP Project Statement is as follows:

> . . . to formulate a comprehensive series of statements of research problems and recommended studies (including estimates of time, cost, and priority) which have as their objective the development of procedures by the use of which a highway materials engineer may evaluate quantitatively the relevant properties of aggregates to be selected for a given class of use, in a given environment of service, for a given level of performance.

General Properties

The critical area of concern is to define the problems with aggregates in terms of a given class of use, i.e., portland cement concrete, bituminous concrete, or base courses. Present discussion includes base courses and shoulder materials. However, in the final specifications some degree of uniformity between all groups should be retained. Also, the service environment (i.e., weather, traffic, and the position of the aggregate in the pavement) must be defined. The level of performance must be examined to determine what service life is desirable and how much deterioration can be tolerated during this period.

Many highway designers want numbers or coefficients that can be applied to the aggregates for design purposes and for determining the expected performance. However, a problem occurs when data (from test road projects, for instance) are applied in the other climatic regions, under different loading situations, or to dissimilar materials. Coefficients from these test roads have not been found to correlate well with performance in other areas. Some designers, because of a lack of better information or tests have applied these test road coefficients to their own particular problem with unsatisfactory results. An apparent need is to develop further tests that will yield aggregate property values that can be applied to various environment and use categories. Some individuals think it best to define the environment and then select the tests that will yield the data needed. For a given area the aggregate properties to be measured and the means for measuring these properties could then be determined.

The following is a list of the aggregate properties that need to be measured·

1. Gradation.
2. Surface characteristics (1) affinity for liquids; (2) surface texture.
3. Hardness and wear.
4. Porosity, freeze-thaw resistance.
5. Physical composition.
6. Mineralogical (chemical) composition.
7. Geologic composition.
8 Particle shape.

The effect of the aggregate on the pavement cannot be determined until the effects of the properties on the aggregate are known. Once these properties are defined, then (1) determine how to measure them, (2) decide on a scale of values or numbers, and (3) determine how to apply the values to a given environment.

Although it is possible to define the levels of service, it may be difficult to develop representative groups of environment for the entire United States, especially in view of the micro-climates that exist in small areas alone. Also, it must be kept in mind that the location of the aggregate within the pavement will determine to some extent its environmental classification.

Specific Problems

The following problems were discussed (not necessarily in order of significance).

Base Failures—Excess Fines—One of the primary causes of base failure is an excess of fines or undesirable fines of a plastic nature. These fines are produced by degradation, freezing and thawing, or wetting and drying, and overlap into all climatic regions.

Changes in Gradation.

1. During shipping and handling.
2. During construction.

One definite problem that stands out is that of degradation of aggregates. No single test method has been found that will group the materials in relationship to their expected degradation, frost susceptibility, or strength. Degradation is most serious in an upper base course in the northern climates, but is also a problem in southern climates.

A few of the causes of change in gradation are as follows:

1 Mechanical breakdown (1) construction–compaction; (2) under traffic.
2. Freezing and thawing.
3. Chemical action—effect of ground water.
4. Movement of subgrade into base.
5. Unusual materials in aggregate.

As climatic environments become less severe some of the foregoing factors will be altered and it will be possible to have less rigid specifications on the aggregates.

For the measurement of degradation of aggregates, the standard Los Angeles abrasion test does not correlate well with breakdown during rolling or performance and is believed to be an unsatisfactory test method. Several states and the Corps of Engineers use the wet ball-mill test to anticipate the degree of degradation and wear. A strength test on the aggregate will not indicate the amount of degradation to be expected. An investigation into the different methods of degradation testing and prediction should be undertaken to determine the effect that degradation may have on the strength of the ultimate mixture.

Breakdown also occurs where stresses are low and may be caused by chemical action of the ground water. Tests need to be developed to determine the chemical action of water on aggregates.

The following tests are suggested as possibilities to indicate the degree of degradation: (1) Los Angeles abrasion (wet, dry); (2) wet ball-mill; (3) kneading compactor; (4) freeze-thaw; (5) repetitive load tests; (6) track-type tests; (7) repetitive triaxial; (8) chemical addition; (9) wetting and drying; and (10) pulverization.

Two problems that need to be studied are (1) the relationship between the aggregate type and the optimum gradation, and (2) the effect of gradation on mix properties. The problem of how to obtain a "sample" of aggregate from a highway for test purposes is often encountered. The most representative sample may be obtained if highway departments were to stockpile some of each aggregate along with the gradation data at various stages.

Amount and Characteristics of Fines.—Information on the amount and characteristics of fine particles is necessary to properly control the mix and to determine data such as stability, density, and permeability Different aggregates will produce differing amounts and types of fines An area for study would be to determine what materials are produced by some known aggregate sources, what effect they have on performance, and what quantity of these fines are acceptable. Also, it must be determined if conventional testing will detect the differences in the fines. The act of testing itself has, in some cases, altered the character of the fine material under test.

Especially troublesome are the silt fines which may occur by degradation or may be added during construction in an effort to obtain stability. Research is needed to determine the effectiveness of using chemicals, lime, portland cement, or bituminous materials to nullify the effect of these additional fines. In the area of frost heave, the silt particles cause the most trouble. The stabilometer test is difficult to run on the very sensitive silt particles that are not easily compacted Montmorillonite clay factions also cause problems because of their expansion and shrinkage characteristics.

Various means are available to evaluate the amount and characteristics of the fines produced. Among these are: (1) sand equivalent test; (2) sieve analysis; (3) hydrometer, (4) Atterberg limits, (5) mineral content, X-ray, DTA; (6) base exchange, surface chemistry, and tension; (7) effect of soluble salts, and (8) presence of organic colloids.

A problem area will be to determine the effect of sample preparation and storage on plasticity index, gradation, and fine characteristics.

The possibility that excess fines are a result of subgrade material working up into the base, or vice versa, should be examined. It may be possible to put a sand subbase filter over a clay subgrade to prevent pumping of the subgrade into the base. This procedure has been used successfully in several states. Problems vary, depending on (1) the type of subgrade material and its capacity for drainage, and (2) the compaction, confinement, and drainage of the sand layer, which will, in turn, determine the stability of the subbase.

Moisture Control

1. During construction.
2 Permanently.

The control of moisture is a frequent problem. Test borings have shown that the base course is almost always wet, but not necessarily saturated. It is necessary to know the moisture content that is likely to produce problems, even though this may not be saturation. Designs should be based on stability when saturated, especially for 60- to 80-ft pavements where drainage is difficult to obtain, even with "open-graded" bases.

The problem of "open-graded" versus "dense-graded" bases is related to the type of subgrade and pavement to be used. Questions to be answered are: (1) what is the permeability of these bases? (2) what is the actual gradation, void content, pore size, and distribution? (3) what types of water movement exist?

Moisture content is affected by permeability and density and affects compaction and retention of density. Distinction must be made between gravity, capillary, and hygroscopic moisture. When bituminous surfaces are added on old gravel-surfaced roads the water is confined and the resulting performance is lower than before. Also, for "sandwich" construction (i.e, an asphalt-surfaced road resurfaced with a layer of gravel and a new surface coat) the aggregate must be good to withstand the severe moisture conditions. The possibility of using asphalt or plastic membranes to control moisture has been tried with mixed success The type of base construction (i.e., trench vs full width) should be studied in relation to the open- versus dense-graded base problem. New design concepts are needed that will consider the relative merits and feasibility of unbound, open-graded base courses versus dense, impermeable bases in relationship to the total pavement design.

Control of Compaction—Retention of Density.—Compaction specifications are needed that will allow different degrees of compaction, depending on the type of material. Texas, for example, has had success with a "compaction ratio" which changes the compaction requirements by material type. California has conducted research on compaction and has found that the density is not directly related to the compactive effort, but that moisture control and methods of compaction are also important. It is common practice to mold total mixture specimens and test them by CBR or triaxial methods, but these test results are useful principally as a control for field compaction and are not realistic indications of performance

The compaction procedures usually follow (1) "method specifications," where the equipment and method are prescribed, or (2) "end-result specifications," where the final density is specified. Both of these procedures are presently in use. Once the density has been obtained it can be retained by specifying recompaction later or, preferably, by applying the full structural load immediately.

In the area of compaction, realistic standards are needed to guide the compaction of dissimilar materials. One area for study is the relationship between compaction, stability, gradation, and the resulting densities needed for proper performance. Confusion has resulted from interchanging of the terms permeability, porosity, compaction, and density, because these terms are not synonymous.

There is a need for better field density procedures for base course aggregates. Also, better laboratory standards should be developed. For stability tests, the following methods of specimen preparation may be appropriate: (1) kneading compactor; (2) standard or modified AASHO; (3) static compaction; (4) gyratory methods, (5) vibratory methods; and (6) sledge hammer.

Stability and Strength.—One difficulty with present test procedures is that the loading is static or applied gradually (example, CBR test) and does not accurately reflect the properties under dynamic, repetitive traffic loading.

The following tests may be useful in obtaining information on the total mixture:

1. Stability: (1) stabilometer—friction; (2) cohesiometer—tension, (3) CBR; (4) triaxial; and (5) freeze-thaw.
2. Permeability.
3. Density—compaction.
4. Change in gradation.
5. Stiffness: (1) repetitive loading; and (2) single loading.
6. Resilience.

Resilience is an important property of the total mix, especially for flexible pavements, and warrants further study. Also, the effect of stabilization and changes in modulus of elasticity (systems approach) on resilience need investigation.

Adapting Design to Available Materials.

Frost Heave.

Relation of Tests to Design and Performance.—Test methods do not exist which show the relative importance of the aggregate properties to pavement performance. These properties, of course, vary by region, but generally the laboratory test values would be obtained and applied as necessary to a given set of conditions. The problem is to find those tests that have the greatest validity to design and performance in actual service.

Analysis of Existing Specifications.

Other.—A literature search is needed in the area of aggregate beneficiation. Some of the processes presently in use or in experimental stages are as follows: (1) heavy media; (2) elastic fractionation; (3) crushing and screening; (4) electrochemical induration; (5) heat treatment; and (6) air jet and electrical conductivity.

Further investigation into the stabilization of clay-gravel materials should be conducted. By blending, or "granular stabilization" it is possible to get a satisfactory mixture from otherwise undesirable aggregates.

Petrographic studies or analyses may be very helpful, but care must be taken not to rely solely on these subjective data. A petrographer or geologist is needed to separate the aggregate into fractions which can be tested to determine the effect of different minerals on the total mixture. Therefore, two testing procedures are required: (1) tests on the mineralogical fractions, and (2) tests on the total mixture. A balanced research program is needed in this area where petrographic data can be useful in studying unique or unusual problems.

Summary

The following properties and needed tests were developed as being first priority areas for study:

1st Order Properties:

1. Stability.
2. Plasticity of fines.
3. Potential degradation.
4. Resilience.
5. Gradation.
6. Frost susceptibility.
7. Permeability.
8. Density retention.
9. Volume change (shrink and swell).
10. Brittleness.

1st Order Tests Needed:

1. New density tests.
2. Modulus tests.
3. Characterization of percent passing #200 sieve.
4. Potential degradation.
5. Resilience.
6. Frost potential: (1) heave; (2) thaw damage.

Opinions on first-priority problems are as follows:

Highway Departments:

1. Control field compaction.
2. Rational density.
3. Control of moisture.
4. Control of fines passing #200 sieve.
5. Compaction and the fines.
6. Density standards and fines on frost.
7. Degradation.
8. How to use base material which is now rejected.
9. Definition of intent of base course.

Industry:

1. Better evaluation of well-controlled quality materials.
2. Better evaluation of true worth of different base systems.
3. Gradation control.

APPENDIX C

WORKSHOP-CONFERENCE FOLLOW-UP VISITS

When planning the Workshop-Conference, it was realized that it would not be possible to have an efficient-size group and still cover all areas of the United States or have the ideas of all persons who should be heard from. Thus, follow-up visits were planned so that other geographical areas could be visited and other aggregate experts could be interviewed.

The results of the visits were analyzed and proved to be an invaluable input to the formulation of the research problem statements. Summaries of all of the interviews made on the follow-up visits are presented in this appendix.

INTERVIEW SUMMARIES

Person Visited: Professor K. B. Woods

Organization: Purdue University

Place: Lafayette, Indiana

Date: July 5, 1968

Introductory Comments:

Professor Woods has for years been one of the most outstanding authorities on aggregate problems. In general, discussion followed the VPI Conference summary.

Discussion of Specific Problems:

1. Separate the physical and chemical aspects of aggregate problems.

2. Study the effect of landform environment on pavement performance. This would be a type of modular concept, but with emphasis placed on the landform.

3. Use well-draining bases. Even though head is too low to provide drainage it will act as a wick with the aid of vegetation on the berm and water will be pulled out.

4. In studying skid resistance, study should be made in correlating geologic strata with skid-resistance properties.

5. Concerning stripping, physical or chemical methods are required to remove film around aggregate (see the Nebraska discussion which follows).

6. Abrasion test has value when it is used to show up abrasion loss abnormalities for a given rock type.

Person Visited.	Mr. O. L. Lund, Asst. Engineer of Materials and Tests
Organization:	Nebraska Highway Department
Place:	Lincoln, Nebraska
Date:	July 3, 1968

Introductory Comments:

Discussion with Mr. Lund included the VPI Conference report as well as the availability of aggregates and aggregate problems in Nebraska generally.

Discussion of Specific Problems:

Because of a general lack of high-quality aggregates in Nebraska, portland cement concrete is used for virtually all high-traffic roads. Low-cost bituminous construction is used for roads of lesser importance.

Alkali silica reaction is purported to be Nebraska's biggest problem. However, they have found that even with Type II cement, D-line cracking still results. Blending eastern limestone with Platte River gravels seems to give adequate results. This requires the shipping of the limestone from as far away as 400 miles.

In bituminous construction, stability is the problem. Because only rounded aggregates are used, close gradation control is attempted. Stripping is a problem with the territory gravels in the west but not with the Platte River gravels. Farther east, sand-asphalt mixes become more common. They have begun to use anti-stripping agents but do not have sufficient experience to evaluate them.

To evaluate stripping, Nebraska uses an immersion-compression test. However, the *main* difficulty is in the *variability* in the sample. The stripping in this case is caused by a coating on the aggregate which could be removed if scrubbing techniques were used, but this is considered too expensive. The coatings on the aggregates are highly variable. A test pit sample can test out all right, but stripping might still occur on the job. Nebraska would like to know how to inexpensively sample their material with success. Washing of the gravels is used only for seal coats.

Rutting of base course or lack of stability due to rounded aggregates seems to be the biggest base problem. Cement-stabilized bases always cause cracking in the surface. Some success is obtained by using lime-stabilized bases in areas where there is a clay binder for granular material. Nebraska wants techniques that would enable them to be less restrictive on gradation specifications of base courses.

Person Visited:	Mr. M. A. VerBrugge, State Materials Engineer
Organization.	Wyoming Highway Department
Place:	Cheyenne, Wyoming
Date:	July 1, 1968

Introductory Comments:

With Mr. VerBrugge and several of his staff discussion centered primarily on the VPI Conference report.

Discussion of Specific Problems:

The most important problem in Wyoming seems to be pavement stripping. They have no tests to evaluate aggregates for potential stripping. Currently, aggregates are accepted or rejected on the basis of an immersion and compression test along with the standard Los Angeles abrasion and sodium sulfate soundness tests. Wyoming makes extensive use of non-stripping agents with considerable success.

Aggregate absorption of asphalt is another problem. Present hot-mix procedures do not permit sufficient time for absorption of asphalt, resulting in under-asphalted mixes. They find that aggregate (basalt-type materials) left with water in it absorbs less asphalt. They use this technique in road mixes.

They question the need for as rigid gradation specifications as they use because they know lower-grade aggregates can be successfully used. They would like to know just how important gradation is.

In concrete construction, alkali reactivity is a problem that is somewhat alleviated with low-alkali cements. Wyoming has less than 100 miles of concrete pavement.

Wyoming would also like to know more about the importance of base course gradation. They generally use what they can get, and when it is sand they often get cracks in the bituminous surface.

"What effect do freezing and thawing have on bases and base course resiliency?" were other problems mentioned.

Persons Visited:	Messrs. Francis Hveem, Donald Spelman, and Travis Smith
Organization:	California Highway Department
Place:	Sacramento, California
Date:	June 27, 1968

Introductory Comments:

The day was spent mostly with Mr. Hveem on a tour of the Materials Testing Laboratory, accompanied by Mr. Spelman, in charge of the Concrete Division. There was a brief general discussion with Mr. Smith, Chief Materials Engineer.

Discussion of Specific Problems:

Too much research is directed to symptoms without proper attention to the basic properties of the materials in question In general, such areas as colloidal or surface chemistry of aggregates and the effect of water on aggregate systems must receive more attention.

In the design of better bituminous mixtures, more attention should be given to surface area concepts.

More study on the effects of slow-moving heavy loads is necessary.

In base course studies, attention should be given to vapor rise and recondensation theories.

Person Visited:	Dr. Donald Lambe, Head, Dept. of Civil Engineering
Organization:	University of Wyoming
Place:	Laramie, Wyoming
Date	July 1, 1968

Introductory Comments·

Dr. Lambe had reviewed the VPI Conference summary with several of his staff. Discussion involved the report and aggregate problems generally.

Discussion of Specific Problems:

Discussion centered on bituminous paving, by far the most prevalent in Wyoming Stability of bituminous pavements under high temperatures was discussed. The University has some excellent information with temperature data from bituminous pavements throughout the state. They have done work in investigating the use of high-penetration asphalt cements in their mixer. Also, they are in a position to evaluate pavement aggregate performance on the basis of information already surveyed.

Specifically, the two most important problems are:

1. Interaction of aggregate with surrounding material.
2. Effect of fines on hardening of asphalt

Person Visited:	Mr. Eli Axon, Research Engineer
Organization:	Missouri Highway Department
Place:	Jefferson City, Missouri
Date:	June 10, 1968

Introductory Comments:

The visit to Missouri was prompted largely by their experience of D-line cracking in relatively new concrete pavements and by their long-time concern for performance of aggregates in concrete pavements. The visit involved a rather complete tour of their facilities, including the outdoor site where long-time performance studies of concrete are under way. Mr. Axon participated in the VPI Conference, so the problem statements that had been prepared there were reviewed.

Discussion of Specific Problems:

The development of D-line cracking in concrete pavements is perhaps the most serious aggregate problem that Missouri faces today. They have not positively identified the mechanism, but experience implicates aggregate along with high moisture content of pavement slabs. It has been suggested that research should be undertaken using the slow-cooling dilation method in an attempt to identify aggregates that contribute to D-line cracking.

Mr. Axon believes that concrete pavements are deteriorating because they achieve and maintain moisture conditions at or near the saturation point. He described the process of using polyethylene sheets under new pavements adopted by Missouri in an effort to reduce moisture levels. He agrees that Missouri would be interested in installing a series of moisture-measuring discs and it was agreed that the details of the system that is in use at Penn State would be sent to him.

Person Visited:	Mr. F. C. Fredrickson, Materials Engineer
Organization:	Department of Highways, State of Minnesota
Place:	San Francisco, California (during ASTM meeting)
Date.	June 25, 1968

Discussion of Specific Problems:

1. Mr. Fredrickson commented on some of the general environmental problems that Minnesota experiences. They have, of course, very deep frost penetration, and so frost break-up poses a major problem. Also, their temperature range is such that all of their paving materials undergo severe thermal stress and strain. The temperature range is from in excess of 100°F to —45°F.

2. Minnesota uses the magnesium sulfate test for determining the soundness of aggregate. They believe that a better test for soundness is urgently needed, but as an interim measure they are searching for a relation between sulfate soundness and performance and, more immediately, between magnesium and sodium sulfate soundness.

3. They have experienced more pop-outs and surface defects in their concrete than deep-seated failures. They believe that some evaluation of the effect of pop-outs on concrete highway structures and general performance is needed. They are concerned with the development of economic methods for removal of deleterious particles from the gravel deposits which are abundant in Minnesota.

4. In the bituminous concrete area, stripping is a major concern. They believe that research on the characteristics of the aggregate particle as a whole or on the surface properties that are related to stripping would be particularly helpful to them. (They use a cold-water abrasion test as a means of evaluating the stripping potential. After being coated with asphalt cement, aggregates are mixed with ice water and tumbled in an abrasion machine and the amount of stripping is then evaluated.)

5. They have experienced a certain amount of cracking in their bituminous pavements, and are uncertain as to the cause. They believe that it might be related to aggregate They believe this matter needs further study.

6. They have a program for studying degradation of base

aggregate under way. This consists of using aggregates of various Los Angeles abrasion numbers and determining the degradation in actual field test sections. The principal base degradation problems appear to be with crushed carbonate rock.

Mr. Fredrickson said that perhaps the most pressing need in the aggregate area is for a new test for soundness. He believes that they cannot abandon the sulfate soundness tests until something better has been offered and, in the meantime, a great deal of reliance is being placed on a test that is under constant criticism.

Person Visited.	John C. Cook, Research Engineer
Organization:	Washington State University
Place:	Pullman, Washington
Date·	July 2, 1968

Introductory Comments:

Mr. Cook attended the VPI Conference but it was decided that a visit should be made to Washington State University to study in some detail the test facility that exists there, because this might be significant in pricing some of the research projects. There was an opportunity to visit the research facility on two occasions, see its operation, and assess its worth for various types of research on aggregate related problems.

Test Track Capability:

The test track can apply variable wheel loads over the range commonly accepted by highway departments. Speeds are over the range of those commonly experienced. If one assumes a 35 mph speed for 20 hours per day, then approximately 200,000 loads per month could be achieved. The facility has been in operation for approximately two years and the staff believes that they are indeed achieving success in simulating pavement performance at a much lower cost and in a shorter period of time than can be achieved by any other means.

Costs:

Mr. Cook indicated that the cost of test or research work involving the circular track is approximately $6,000 per month. This includes the constructing of two test pavements per year (at approximately $12,000 each), the cost of power, and the necessary operating personnel. This figure does not include analysis of data or the preparation of reports. Mr. Cook had looked into the matter of shipping materials from outside the state of Washington and found that for a maximum of $5,000 enough material to construct test sections could be shipped from any point in the United States.

Potential Application·

The work to date on this facility has been entirely in the area of thickness design of bituminous concretes. However, it would appear to have potential for polishing or friction studies because it would seem that a friction testing device could be used on the large radius road surface. It would also appear that base degradation studies could effectively be accomplished The Washington facility is not enclosed but it would be feasible to climatize the entire facility so that the utilization factor would be improved and a wider range of variables could be studied.

Mr. Cook and his colleagues have currently undertaken a study of audio emissions of internal friction in asphaltic pavements. The study is in a very preliminary stage but it appears that prior to failure there is a distinctive pattern in the audio emissions.

Discussion of Specific Problems.

In commenting on the VPI Conference, Mr. Cook believed that much of the discussion was too restricted to old specifications and material test methods. He believed that new technology and new ideas must prevail if progress is to be made in the future. Some of the problem areas that he highlighted and on which he believed fresh thinking was particularly needed were:

1. Gradation for each of the problem areas—base course, portland cement, and asphaltic concretes. How important is gradation to performance? Gradation is perhaps the commonest of the enforced requirements on aggregates and he feels that the highway engineer knows too little of what he is buying when he pays for a precise gradation.

2. Density requirements of base courses and asphaltic concretes are not adequately known. Mr. Cook believes that nuclear density equipment has not been used to the extent that it might be and, therefore, proper progress has not been made in finding out what density uniformity can be achieved under various circumstances. What kinds of performance can be expected when a certain density is achieved? This question needs study.

Person Visited:	Dr. Robert P. Lottman, Associate Professor of Civil Engineering
Organization:	The University of Idaho, Civil Engineering Department
Place:	Moscow, Idaho
Date:	July 3, 1968

Introductory Comments:

In response to an earlier inquiry, Dr. Lottman had commented by letter on a research project dealing with stripping in asphaltic mixtures. This topic occupied much of the discussion.

Discussion of Specific Problems:

Dr. Lottman gave a brief history of their stripping problem. It appears that this became evident when significant parts of the Interstate System were built and put in service. This was the first major experience with hot-mixed asphaltic concrete in Idaho. Most of the previous work had been surface treatments and road mixes of one kind or another.

In a very short time this hot-mixed asphaltic concrete showed severe raveling, which appeared to be due to stripping away of the asphaltic coating on the aggregate. Dr. Lottman believes that this stripping problem has been looked at only superficially in the past and that only superficial test methods exist. Therefore, they are concentrating on trying to find basic data that will help them understand the phenomena that are involved. Questions on which they are working include:

1. What size groups of aggregate are actually coated with asphalt during mixing?
2. What size groups of aggregate are mixed into the asphalt as a total mastic?
3. What measures of these phenomena exist?

Their work is still in a relatively early stage. They see this problem as a major one and suspect that other states might be experiencing the same failure, although it may be less well-identified than in Idaho.

Dr. Lottman had prepared a list of problems after he had had an opportunity to review the VPI Conference list. These include the following:

1. There is a need to develop procedural testing and data analysis for aggregate. A systematic approach with rational tests would provide a rational decision-making process with regard to use.
2. There needs to be an identification of aggregates that should be modified, or used with binders different from ordinary asphalt, in order to make a satisfactory pavement (in other words, if an aggregate must be used as is, then perhaps the binder can be specified to provide a satisfactory pavement).
3. Define poor-quality aggregates. For example, how much loss of performance does poor aggregate produce in terms of the highway system?

Person Visited.	James G. Latham, Senior Materials Field Engineer
Organization.	Arizona Highway Department
Place:	Phoenix, Arizona
Date:	June 17, 1968

Introductory Comments:

Correspondence with Mr. G. J. Allen, Engineer of Materials for the Arizona Highway Department, indicated that in the past Arizona has depended almost entirely on natural aggregate sources, but that they are now starting to use quarry deposits. With these quarried materials they are finding that coatings are now causing some problems. Mr. Allen suggested that both ASTM and AASHO specifications are not specific enough in this regard and that research is needed. A meeting was held with Mr. Latham, Senior Materials Field Engineer, and Mr. Boyd Smith, Materials Field Engineer, in their office in Phoenix.

Discussion of Specific Problems:

Mr. Latham outlined several problems of a general nature. The northern part of Arizona is relatively poor in sand and other natural aggregate deposits, and in the past a good deal of volcanic cinder material has been used. The cinder aggregate poses a problem for high-quality asphaltic concrete construction in that it continues to consolidate over a long period of time.

In the production of crushed rock, specifically the Flagstaff rhyolitic sources, coatings are causing a problem.

At present a lime slurry is being used in asphaltic concretes to reduce the related stripping problem. Arizona has had stripping problems with seal coats and is investigating this with assistance from The Asphalt Institute and other western states.

The immersed compression test for stripping is used in Arizona. A Hveem Stabilometer measures a percentage of load loss after a period of soaking.

They have used volcanic cinder in portland cement concrete in the Flagstaff area and, although construction is relatively new, it appears that it will perform satisfactorily.

Arizona has very little experience with problems of skid resistance. This has simply not come up as a major item as yet.

Dense graded bases seem to be the type most widely used in Arizona. They modify their specification by changing the allowed percentage passing the #200 mesh sieve with elevation. They believe that elevation is a simple and adequate indicator of weather severity in Arizona.

Arizona maintains a statewide awareness of aggregate deposits because highway projects are let with the aggregate source specified. The contractor is required to negotiate for a change in the recommended source. This means that the burden of recommending the right aggregate for the right job, so as to get a technically sound and economically feasible project, falls on the Highway Department.

Person Visited:	Mr. Peter Smith
Organization:	Department of Highways, Ontario
Place:	San Francisco, California (during ASTM meeting)
Date:	June 25, 1968

Discussion of Specific Problems:

With regard to aggregates in portland cement concrete, Mr. Smith cited the following as primary problem areas:

1. Lack of effective means of rating marginal aggregates.
2. Alkali-carbonate reactivity.
3. Means of determining moisture conditions within concrete (Monfore gauge impractical; Tremper's moisture discs freeze).
4. Skid resistance (or lack of) a problem with concrete pavement made with certain limestones.
5. Basic research on aggregate-paste bond needed. (With regard to this item, DHO found cases of old bridge piers where slow alkali-carbonate reaction produced reaction rims half way to the centers of the aggregate particles. However, the concrete was very sound and strong because of the stronger bond created by the reaction rim and the increased homogeneity of the mass.)

Mr. Smith described some of the work being carried out by DHO relative to problem areas in the portland cement concrete field. For example, they have devised a computerized setup in which concrete mixture, materials, placement, environment, and behavior data are cataloged for future use. The major difficulty encountered with this is putting numbers on exposure and behavior conditions. DHO is planning to do some work with the Powers freeze-thaw test method. The major problem here is getting field exposure data to incorporate into the laboratory test, especially moisture condition. DHO is also working on the alkali-carbonate reaction. This is a very slow reaction and, hence, may not be as critical as many believe because it may not necessitate concrete repair or replacement for 30 or 40 years.

With regard to the portland cement concrete session of the VPI Conference summary report (reproduced in Appendix B of this report), Mr. Smith had these comments to offer:

1. Prob. Statements—Outline Ref. I, item 8: NaCl does affect performance, $CaCl_2$ does not (ref. DHO papers, Axon paper).
2. Prob. Statements—Outline Ref. I, item 9: not clear; difficult to evaluate.
3. Prob. Statements—Outline Ref. I, item 14: see work of Barbara Saby—British Road Research Laboratory.
4. Prob. Statements—Outline Ref. II, item 4: uniformity believed most important.
5. Prob. Statements—Outline Ref. VI, item 1b: Sealing of surfaces can be dangerous in that it does not allow trapped moisture to escape. For that reason DHO does not permit steel stay-in-place forms to be used on bridge decks.
6. Prob. Statements—Outline Ref. VI, item 10: DHO uses 0.02 percent max. expansion at 84 days as criterion.

With regard to the asphaltic concrete area, Mr. Smith cited the following problem areas:

1. Stripping is the major problem.
2. The basic mechanism of asphalt-aggregate bond needs research. Work on the stripping problem is currently under way at DHO. Experiments are being carried out using 1-in. sand/asphalt seal over base before applying asphaltic concrete binder course on the theory that stripping is caused by moisture coming up through the base course. However, it is believed that there is an equal chance that the moisture is condensed from the atmosphere. Mr. Smith had no other comments on the asphalt section of the VPI Conference summary.

Regarding base courses and shoulders, Mr. Smith believes that degradation is the only problem that DHO has encountered. There is little research work being done by DHO in this area. Mr. Smith had no comments on the VPI session report regarding this area.

By way of general comments, Mr. Smith suggested a visit to DHO in Toronto to obtain additional information. Also, while in Toronto, he suggested that a visit with Mr. T. G. Clendenning at Ontario Hydro would probably be very beneficial.

Person Visited.	Mr. Peter Smith
Organization:	Department of Highways, Ontario
Place:	Toronto, Ontario
Date:	August 7, 1968

Introductory Comments:

Mr. Smith arranged a meeting with nine DHO people (including Mr. Smith). The roundtable discussions lasted about three hours. Later, individual discussions were held with Mr. Bob Schoenfeld on the subject of skid resistance, and with Mr. Harold Fromm on stripping. A brief tour was made of the DHO laboratories.

Discussion of Specific Problems:

Base Courses and Shoulders.—A considerable amount of discussion centered around the feasibility of (and the need for) free-draining base courses. Even in dry weather, free water levels have been found in supposedly free-draining bases. The major question seems to be: With four-, six-, or more-lane roadways is it possible to have free-draining conditions in the base courses? Other important questions are: To what extent do base courses degrade in service to produce deleterious fines? Can a build-up of fines occur by inflow of water? Does the calcium chloride used for stabilization contribute to degradation? It was also believed that research is needed in the area of compaction, especially as related to equilibrium compaction and the effects of rebound or relaxation. With regard to test methods, the value of the Los Angeles abrasion test was questioned. Regarding beneficiation techniques, it was believed that this is definitely an area of needed research.

Portland Cement Concrete.—It was reported that DHO has had good results in evaluating aggregates with respect to durability by using the sulfate soundness test (magnesium) in conjunction with a simplified petrographic technique. The petrographic technique is devised to yield a "petrographic number" (or "PN") which takes into account both the type and the amount of the individual constituent minerals present. The most pressing research needs, as viewed by the DHO group, are:

1. Criteria for defining level of performance.
2. Correlations between lab tests and field performance.
3. Moisture content and distribution in hardened concrete pavements (how to measure it).
4. A better laboratory freeze-thaw method related to field exposure environmental indices.
5. Effect of minus #200 material in coarse aggregate on concrete properties.
6. Means of improving aggregate-paste bond.

Asphaltic Concrete.—The areas of needed research in the asphaltic concrete field include:

1 Aggregate durability in both the binder and wearing courses. In support of this it was mentioned that deterioration of clayey limestones had been found in binder courses.
2. Antiskid properties of pavement and aggregate polishing as related to aggregate type.
3. Aggregate type versus damage from studded tires.

4. The nature of the fundamental mechanisms of stripping including the effects of moisture migration and aggregate characteristics.

Bob Schoenfeld described his work using photographic stereopairs for evaluation of skid resistance of asphaltic concrete surfaces. Several variables are being investigated, including aggregate particle size, aggregate protrusion, particle shape, degree of polishing, and percentage of surface area covered with aggregate. These will be evaluated against skid trailer readings using factor analysis and multiple regression.

Harold Fromm's experiments on the stripping mechanism, to date, indicate that stripping is due, at least in part, to emulsification of asphaltic concrete in water. This is the tentative conclusion from his continuing research. He believes that more research is needed on the basic mechanisms of stripping, especially as regards the aggregate/asphalt interfacial reactions, and on the nature of adhesion.

Person Visited.	Mr T. G. Clendenning
Organization:	The Hydro Electric Power Commission of Ontario
Place:	Toronto, Ontario
Date.	August 8, 1968

Discussion of Specific Problems:

The discussion with Mr. Clendenning centered primarily around problems related to aggregates in portland cement concrete. Ontario Hydro uses the sodium sulfate soundness test and has found that it agrees well with petrographic evaluations That is, the petrographer can usually predict quite accurately how an aggregate will perform in the sulfate soundness test. However, correlation between sulfate soundness and laboratory freeze-thaw tests or field performance is usually not good. Regarding the Los Angeles abrasion test, Ontario Hydro uses this only where abrasion is a problem (e.g., spillways) and not as a soundness test. Ontario Hydro has developed a technique for detecting deleterious seams or minor constituents (e.g., clay shales) in carbonate rocks. It involves immersion in copper nitrate solution. The method also provides means for rapid differentiation of limestones and dolomites.

The areas needing research, based on Ontario Hydro's experience, include.

1. The need for assessment criteria in laboratory freeze-thaw tests.

2. What percentage of inferior material can be tolerated?

3. Development of an individual aggregate particle durability test (to lend credence to petrographers' evaluations).

4. The need for a standard outdoor exposure test method.

5. Reducing the length of the "Powers" test method.

6. Cataloging of deleterious aggregates.

7. Nature of the mechanisms of deterioration induced by calcium chloride.

8. Investigation of grading specifications (believed to be overly arbitrary and stringent).

9. Development of a "standard specimen" for the rapid freeze-thaw tests (ASTM C290 and C291) so that interlaboratory comparison will be valid.

10. Evaluation of existing specifications and tests and development of new ones for synthetic aggregates (based on difficulties encountered by Ontario Hydro in the use of existing specifications and tests for heavy aggregates).

Person Visited:	Dr. Norman W. McLeod
Organization·	Imperial Oil Limited
Place.	Toronto, Ontario
Date:	August 6, 1968

Discussion of Specific Problems:

1. The principal problem related to aggregates for asphalt concrete in Canada is that the VMA (voids in mineral aggregates) is usually much too low. Frequently, the grading bands specified are so narrow that it is not possible to blend coarse and fine aggregates in any proportion to satisfy grading requirements that will at the same time also meet the minimum VMA specified. Because of the low VMA values that usually result, if sufficient asphalt cement is incorporated to provide a reasonably durable pavement, the air voids values are so low that the pavement flushes or bleeds. On the other hand, if the asphalt paving mixture is designed to have sufficient air voids to avoid flushing or bleeding, its asphalt content is too low and its service life is seriously curtailed. In extreme cases, the asphalt content is so low that the pavement ravels, and otherwise shows serious deterioration in its very early life.

Grading limits for asphalt concrete should be wide enough to ensure that the minimum VMA requirements can be satisfied. The densest grading for any nominal maximum particle size is given by the corresponding Weymouth or Fuller grading curve. The Weymouth or Fuller grading curve therefore gives the minimum VMA. Only occasionally, when both coarse and fine aggregates consist of 100 percent crushed material, is it possible for a Weymouth or Fuller grading to satisfy the minimum VMA requirements. It is to be emphasized that this happens only infrequently under these conditions. Consequently, with most aggregates, the coarse and fine aggregate fractions must be blended in proportions to give a grading curve that is made to deliberately deviate away from the Weymouth or Fuller grading curve, in order to meet minimum VMA requirements.

Because mineral dust (the portion of a total aggregate passing the #200 sieve) is a void-filling material, care must be taken when blending coarse and fine aggregates to see that the percentage passing the #200 sieve does not exceed the percentage associated with the corresponding Weymouth or Fuller grading curve.

2. With respect to good, acceptable, and poor grading, on the basis of the usual semi-logarithmic grading chart (1) good grading is indicated when the grading curve is

generally concave upward, (2) acceptable grading is indicated by a grading curve that does not exceed a straight line drawn from the percentage passing the #200 sieve to 100 percent passing the nominal maximum particle size, and (3) poor grading is indicated by any grading curve that is concave downward. A concave downward shape shows that there are too many particles of several fine sizes to fill the void spaces available for them. Therefore, they force the entire aggregate structure apart, and destroy coarse aggregate interlock. This, in turn, provides paving mixtures that are very low in stability, that tend to be unworkable, and that are difficult to compact to specified density.

References to research done in this area:

a. J. A. A. Lefebvre, *Proc. Association of Asphalt Paving Technologists*, Vol. 26, p. 321.

b. N. W. McLeod, *ASTM STP 252* (1959).

3. Research is needed to establish the width of grading band associated with each nominal maximum size of coarse aggregate that will enable the minimum VMA associated with each nominal maximum size of coarse aggregate to be met.

4. The number two problem in Canada is absorption of a portion of the asphalt cement by the aggregate. This is not always taken into account by engineers when designing or analyzing paving mixtures, and can lead to large errors in the reported values for air voids.

5. There is a serious need for the development of methods of test that will enable the specific gravities of fine and coarse aggregates, and of asphalt paving mixtures, to be measured accurately to the third decimal place. Present ASTM methods permit a reproducibility of 0.02—that is, two units in the second decimal place Two specific gravity determinations are required to establish the air voids content of a compacted asphalt paving mixture. Consequently, a range of error of 0.04 in the second decimal place (0.02 for each of two specific gravity determinations) in specific gravity determinations is considered to be acceptable. However, each error of 0.01 (one unit in the second decimal place) in a specific gravity value makes a corresponding error of 0.4 percent in the air voids determination for a compacted paving mixture. Consequently, the permissible range of 0.04 in two specific gravity determinations makes a permissible error of 1.6 percent in air voids possible. Therefore, the normal 2 percent range in air voids normally permitted by specifications (for example, from 3 to 5 percent) is largely meaningless, because most of this permissible range is required to accommodate the permissible range of error, 1.6 percent, when determining the air voids value.

If specific gravity values were accurate to 0 002—that is, to two units in the third decimal place—the error in air voids determinations would be reduced to 0.16 percent, which would be quite acceptable.

6. Research is required to indicate the correct formula to use to obtain the grading curve giving maximum density or lowest VMA. The general formula for this curve is

$$P = 100\left(\frac{d}{D}\right)^n$$

in which

P = percentage passing any sieve smaller than D;
D = nominal maximum particle size;
d = any particle size smaller than D; and
n = an exponent.

The Bureau of Public Roads favors $n = 0.45$. However, the investigations of Professor Huang (Michigan Tech.), who has done much research on aggregates, indicates that $n = 0.5$. In this connection, it should be recognized that Fuller and Weymouth also reported maximum density when $n = 0.5$.

7. Stripping of asphalt cement from the aggregate in asphalt paving mixtures in service has been an occasional very serious problem in British Columbia, and it has also occurred in Ontario. Research is required to identify those aggregates that are likely to be subject to stripping. British Columbia experience indicates that stripping is probably a problem that is specific to each combination of aggregate and asphalt cement. For example, in every situation encountered so far, British Columbia has been able to select an asphalt cement that appears to successfully resist stripping from an aggregate for which serious stripping occurs when it is combined with asphalt cements from other sources.

8. With respect to aggregate degradation, Mr. McLeod had no personal acquaintance with this problem. However, an engineer from New Zealand traveled to North America and Europe recently, collecting information on this problem. A copy of the report he prepared on his return to New Zealand could probably be obtained from

Mr. Fred Langbein, Chief Highways Engineer
Roading Division, Ministry of Works
P. O. Box 12-041, Wellington, New Zealand.

NCHRP Report 34 also contains information on this problem.

9. In North America, the nearest approach to one-size cover aggregates for surface treatments and seal coats is the "Simplified Practice Gradings" (AASHO M 43). However, relative to the one-size aggregates specified and used so successfully for surface treatments in Australia and New Zealand, these "Simplified Practice Gradings" provide graded cover aggregates. This is one of the principal reasons for the generally inferior performance of seal coats and surface treatments in North America.

General Comments:

1. Most of the aggregate used in Canada for hot-mix asphalt pavement construction consists of crushed gravel or crushed stone as coarse aggregate, and natural sand as fine aggregate. Sands produced entirely by a crushing operation give paving mixtures that are too harsh.

2. In Ontario, traprock is specified as the coarse aggregate for all highways carrying more than 5,000 vpd. This aggregate is quite expensive. However, it is so hard and tough that it does not crack within itself in service, whereas when crushed limestone or crushed gravel are used as coarse aggregate, practically every coarse aggregate particle has one or more cracks after several years of service.

Person Visited. Mr. G. Bryce Bennett

Organization. International Engineering Co. (formerly with Idaho Dept. of Highways)

Place: San Francisco, California

Date: June 25, 1968

Discussion of Specific Problems.

A major problem with aggregate degradation exists in the northwest (Idaho, Oregon, Washington). The degradation, consisting of increase in minus #200 and marked increase in plastic index, has been identified primarily with basalt rock crushed from quarries. Degradation of the material has been noted in materials used for base and in stockpile storage. In some cases crushed basalt, originally having 3 percent to 4 percent passing #200, is reported having up to 20 percent passing #200 after several months in a stockpile. Detailed reports and research toward identifying and treating problem materials of this type are available from L.F. Erickson, Materials and Research Engineer, Idaho Department of Highways, and Carl E. Minor, Assistant Director, Washington Department of Highways.

Mr. Bennett's experience while with the Idaho Department of Highways indicated that neither the abrasion tests (Los Angeles and Deval) nor the sulfate soundness tests (sodium and magnesium) are reliable test methods, and research should be conducted toward developing better test methods.

Mr. Bennett indicated that the major problems in the west (in addition to degradation previously described) are alkali-aggregate reactivity and freeze-thaw susceptibility. He stated further that often these two appear to be related and are sometimes inseparable. He observed that gravels are used more extensively for concrete aggregate in the west than ledge rock, which may be the basis for some of the problems encountered.

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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
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