NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT **135**

PROMISING REPLACEMENTS FOR CONVENTIONAL AGGREGATES FOR HIGHWAY USE

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

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION
OF STATE HIGHWAY OFFICIALS IN COOPERATION
WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:

- BITUMINOUS MATERIALS AND MIXES
- CFMENT AND CONCRETE
- CONSTRUCTION
- MINERAL AGGREGATES

HIGHWAY RESEARCH BOARD
DIVISION OF ENGINEERING NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES – NATIONAL ACADEMY OF ENGINEERING 1972

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 Federal Highway Administration, 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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The study reported herein was undertaken under the aegis of the National Academy of Sciences—National Research Council. The National Cooperative Highway Research Program, under which this study was made, is conducted by the Highway Research Board with the express approval of the Governing Board of the NRC. Such approval indicated that the Board considered that the problems studied in this program are of national significance; that solution of the problems requires scientific or technical competence, and that the resources of NRC are particularly suitable to the conduct of these studies. The institutional responsibilities of the NRC are discharged in the following manner: each specific problem, before it is accepted for study in the Program, is approved as appropriate for the NRC by the Program advisory committee and the Chairman of the Division of Engineering of the National Research Council.

The specific work to be performed in each problem area is defined by an advisory panel that then selects a research agency to do the work, monitors the work, and reviews the final reports. Members of the advisory panels are appointed by the Chairman of the Division of Engineering of the National Research Council. They are selected for their individual scholarly competence and judgment, with due consideration for the balance and breadth of disciplines.

Responsibility for the definition of this research project and for the publication of this report rests with the advisory panel. However, the opinions and conclusion expressed or implied are those of the research agency that performed the research, and are not necessarily those of the Highway Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway Officials, nor the individual states participating in the Program.

Although reports in this category are not submitted for approval to the Academy membership nor to the Council, each report is reviewed and processed according to procedures established and monitored by the Academy's Report Review Committee. Such reviews are intended to determine, *inter alia*, whether the major questions and relevant points of view have been addressed, and whether the reported findings, conclusions and recommendations arose from the available data and information. Distribution of the report is permitted only after satisfactory completion of this review process.

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FOREWORD

By Staff

Highway Research Board

This report reviews the current status of availability of acceptable aggregates for highway construction, and notes areas where shortages now exist or can be expected to occur in the forseeable future. Various possible ways for alleviating shortages, including techniques for benefiting existing low-quality natural aggregates, and processes for manufacturing synthetic aggregates from various source materials, including waste materials, are suggested. The research effort was confined to a workshop-conference and a supplemental literature study that provided a good overview of the aggregate situation, both present and future. The technologies for beneficiating existing aggregates and for manufacturing synthetic aggregates remain to be developed by others. Fourteen principal areas for research were identified in the study. The contents of this report will be of particular interest to highway materials engineers and highway research and development engineers, aggregate producers, and others who are interested in the development of natural resources or who are involved in waste management and are seeking economical means for the disposal of waste products.

Highway construction and maintenance in the United States is consuming sand, gravel, and crushed-stone supplies at a steadily increasing rate that is nearing and will soon surpass one billion tons annually. Although the nation's over-all supply of aggregate is sufficient to meet any forseeable demand, and plant capacity is presently adequate, the unequal distribution of sources has created local and regional shortages that are considered critical. As the use rates increase, and supplies become depleted or unavailable because of zoning restrictions, appreciating land values, and other similar reasons, the areas of shortage will broaden and the shortages will become more intense. The work described in this report was undertaken for the principal purpose of providing a systematic exploration of the processes, primarily of a technological nature, that could now, or could through future development, produce additional and perhaps improved aggregates where conventional aggregate production is insufficient.

The workshop-conference, about which the project centered, was attended by experts from a wide variety of disciplines, not all of which are usually considered to interface with the highway field, but which in this instance clearly did so. As would be expected in an amalgam of this sort, a great variety of ideas were expressed. Some obviously should be pursued with vigor; some need not be pursued. A few may appear to the highway engineer to be too exotic for real consideration. But occasionally one finds that what is exotic today becomes mundane tomorrow.

The 14 research project statements that are presented deserve the attention of all highway engineers faced with aggregate shortages and wishing to become involved in research directed at improving the supply situation. Entrepreneurs wishing to develop new enterprises in the highway aggregate supply field will find more than one of the research project statements to be challenging, because developmental activities are suggested as well as pure research. The suggestions for research that may lead to the incorporation of waste materials as aggregates in highway facilities are also attractive.

CONTENTS

ACKNOWLEDGMENTS

The study reported herein was performed under NCHRP Project 4-10 in the Department of Civil Engineering for the Engineering Experiment Station of the University of Illinois. The project was under the general administrative supervision of D. C. Drucker, Dean of the College of Engineering; Ross J. Martin, Director of the Engineering Experiment Station; and N. M. Newmark, Head of the Department of Civil Engineering.

Charles R. Marek, Assistant Professor of Civil Engineering, was principal investigator. E. J. Barenberg, Associate Professor of Civil Engineering, and M. R. Thompson, C. E. Kesler, and M. Herrin, Professors of Civil Engineering, assisted in the study.

Grateful acknowledgment is made to the project's Board of Consultants who assisted in planning the seminar and evaluating the results. The members of the Board were: B. M. Gallaway, Professor of Civil Engineering, Texas A & M University; Hendrik Heystek, Ceramist, Interpace Corporation; T. R. Jones, Jr., Technical Director, Vulcan Materials Company; Bryant Mather, Chief, Concrete Division, Waterways Experiment Station, U. S. Army Corps of Engineers; G. J. Verbeck, Director of Materials Research, Portland Cement Association; and G. H. Williams, Jr., Plastics Consultant and Member of the Technical Staff, Bell Telephone Laboratories. Dr. Heystek found it necessary to resign from the Board prior to the seminar.

The gratitude of the project staff is extended to the participants who gave generously of their time and ideas during the workshop-conference held at the University of Illinois Conference Center, Allerton Park, near Monticello, Ill., in April 1970.

Finally, the project staff would like to acknowledge the contributions to the project report from G. H. Williams, Jr., G. C. Robinson, and R. Valore, Jr., who served as outside consultants and assisted in the preparation of detailed research project statements.

PROMISING REPLACEMENTS FOR CONVENTIONAL AGGREGATES FOR HIGHWAY USE

SUMMARY

In many areas of the United States the supply of conventional aggregates suitable for highway construction is becoming, or has already become, depleted. This situation is compounded because many existing sources are now or will shortly become unavailable because of economic reasons, through zoning restrictions, pollution control, and appreciating land values. In localized areas, supplemental aggregates, either manufactured from specific raw materials or resulting from the beneficiation or direct use of a waste product, may offer relief and possibly the solution to the problem of a diminishing supply.

The purpose of this project was to explore the potential for:

1. Production of synthetic aggregates.
2. Beneficiation of unsuitable materials.
3. Use of manufactured and waste materials as supplements and replacements for conventional aggregates in highway construction.

To establish this potential, a two-day seminar was conducted involving approximately 50 authorities in various disciplines, including engineering, chemistry, ceramics, geology, and related sciences. The participants were selected by a five-man Project Board of Consultants in cooperation with the project staff. The consultant board members also participated in the seminar and in the review of the project report.

Relevant ideas pertaining to supplemental aggregates were introduced at the seminar and developed as much as possible. The information forthcoming in the proceedings of the seminar, combined with information obtained from a limited literature search and from the personal knowledge of the project staff, was the basis for the project report.

The findings and conclusions drawn from the research effort are numerous. Briefly, it can be said:

1. The United States as a whole has an abundant supply of conventional aggregates suitable for highway construction.
2. There are localized areas within the United States that are seriously deficient in conventional aggregates.
3. Raw materials for use in the manufacture of synthetic aggregates are abundant throughout the country.
4. Various beneficiation processes are available to upgrade unsuitable aggregates and waste materials to usable quality.

5. The technical capability exists or can be developed to provide all of the aggregates of suitable quality needed in the future.

An essential end product of the study was the formulation of detailed project statements for research efforts that should provide information needed for rapid relief of the problem of diminishing aggregate supplies in areas now afflicted. Fourteen statements were prepared by consultants and the project staff. Three of these are directed to general research needs, as follows:

1. Characterization of acceptable aggregates.
2. Application of plastics to improve aggregates.
3. Identification and cataloging of raw materials for use in the manufacture of synthetic aggregates.

Before projects directly concerned with the development of promising replacements can be pursued intelligently, these three projects should be initiated to provide necessary background information.

The remaining 11 statements are concerned with specific research efforts on promising replacements and beneficiation techniques. The suggested projects should yield significant, definitive, practical results for the attainment of supplemental aggregates for highway use.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

In 1969, the total number of motor vehicles in the United States was close to 100 million, and this no doubt will continue to rise. More than 79 percent of the families in the United States own automobiles, traveling 960 billion vehicle-miles per year. Furthermore, it has been forecast that by 1985 there will be 144 million motor vehicles in the United States and that travel will exceed 1.5 trillion vehicle-miles per year (*8*).* Therefore, highway engineers not only must continue with the design and construction of highway facilities, but also must do so at an accelerated pace.

Aggregates comprise much of the material required for highway construction and maintenance. Base courses and subbases contain 95 to 100 percent aggregate. Bituminous base, binder, and surface courses may contain more than 90 percent aggregate. Portland cement concrete averages about 75 percent aggregate.

Rapid growth in both the highway construction and structural building areas has increased the demand for high-quality aggregate materials. Fondriest and Snyder reported in 1964 (*21*) that the annual aggregate requirements for new highway construction were about 580 million tons. Maintenance of existing facilities requires an additional 170 million tons annually. This total consumption is expected to increase steadily at a rate of 4 to 7 percent per year.

Crushed stone, gravel, slag, and sand are the conventional aggregates of highway construction. They have been used as construction materials from earliest times because of availability, a usually small effort required to obtain them, and a generally good record of satisfactory performance. This situation is now changing. Although the United States as a whole possesses an abundant supply of conventional aggregates suitable for highway construction, areas exist in which conventional aggregates are not economically available or are becoming depleted. The problem is being compounded because many sources are becoming unavailable through zoning restrictions, appreciating land values, and air, water, and noise pollution control.

Highway materials engineers can approach the problem of a diminishing aggregate supply in one or more ways, including:

1. Construction of roads with materials other than conventional aggregates, with concomitant alteration of existing construction practices as may be required.
2. Better utilization of existing and available conventional aggregates through selective use or beneficiation.
3. Improved methods of handling and distributing available aggregates to reduce the cost of transporting them from areas that have an abundance of such materials to localized areas that have exhausted the available supply.
4. Manufacture of synthetic aggregates as supplements or replacements for conventional aggregates.

* References are to entries in the "Selected Bibliography" (Appendix H).

Each approach has merit and all are discussed in the following. Some, however, are not within the scope of this study.

Materials Requiring Alteration of Existing Construction Practices

It is conceivable that at some time in the future the technology of highway construction in the United States will advance to where highways will be built on an assembly line using plastics and other synthetic materials. This type of construction will require major changes in existing design and construction practices. Obviously, implementation will require considerable time, even after feasibility and practicability have been established. Therefore, such an approach to the problem of a diminishing aggregate supply would not provide early relief for the localized areas now experiencing a problem. Nevertheless, research in this direction could be worthwhile.

Better Utilization of Existing Supply

Better utilization of existing aggregate supplies is a reasonable and sound approach to the problem of diminishing aggregate supplies and should be adopted whenever possible. This approach includes:

1. Adjustment of specifications to permit use of aggregates not meeting current requirements in locations where their performance would be adequate.
2. Use of additives and blending to improve the performance of marginal aggregates.
3. Beneficiation of low-quality material by removal of deleterious fractions by washing and heavy-media separation, or by impregnation, coating, etc.

Substantial quantities of natural aggregates distributed throughout the country have been discarded or rejected for the use in past construction activities. These must be reexamined. Procedures can be taken to utilize many of these existing natural aggregates. Research is presently being conducted in this area and should be continued.

Improved Methods of Handling and Transporting

Better and more economical methods of aggregate production, handling, and transportation offer definite potential for alleviating localized problems of shortages of conventional aggregates, both now and in the future. Such methods need to be explored.

Manufacture of Synthetic Aggregates

The manufacture of synthetic aggregates to supplement or replace conventional aggregates has great potential. Present technology has advanced to where a variety of synthetic aggregates can be manufactured. Raw materials are abundant in nature and as waste products from industry. Economics can be expected to be sometimes a restricting factor in the use of synthetic in place of conventional aggregates.

OBJECTIVES

The general objective of this project was to study the utilization of modern technology as it applies to production and upgrading of materials for use as aggregates in portland cement concrete, bituminous mixtures, and base courses. The specific tasks were to:

1. Plan and conduct a seminar including representatives of a variety of disciplines, with emphasis on disciplines outside of the highway area, with the objective of exploring the possibilities that are available for the production of new aggregate materials. This was intended to include the upgrading of unsuitable aggregates and utilization of waste products and other readily available materials, using new production techniques.
2. Evaluate the ideas evolving from the seminar and select the promising replacements for the conventional aggregates for use in highway construction and maintenance.
3. Formulate an experimental program to investigate the feasibility of production, to evaluate the performance, and to determine the practicality of the selected replacement materials.

SCOPE

The following guidelines were established to provide direction for the research effort:

1. The current economic feasibility of a new aggregate material or a new or modified production process must not influence the seminar discussions.
2. New aggregate materials should be manufactured in a form that will permit handling, transporting, and using in a manner similar to conventional aggregates.
3. The new aggregate materials need not necessarily possess the properties of conventional aggregates.
4. The new aggregates need not meet existing specifications if the desired performance of the system in which they are incorporated can be obtained.

Although the scope of the project was thus defined, the discussions nevertheless entered fringe areas at times and the results are given in the appendices.

RESEARCH APPROACH

To meet the objectives of the project, a two-day seminar was conducted according to the format of Appendix A to obtain from experts in a variety of disciplines new ideas concerning beneficiation of existing aggregates and production of supplementary materials for use in lieu of conventional aggregates. Participants, drawn from several industries, trade organizations, government agencies, and universities, represented the disciplines of engineering, chemistry, ceramics, geology, and related sciences. A list of the participants is given in Appendix A.

Relevant information from the proceedings of the seminar is given in the prepared papers (Appendix B). Additional information from a limited search of related literature and from personal knowledge of the researchers is presented in Appendices C, D, E, and F. This information provides the major data input for the study.

Pertinent findings and conclusions from the research effort are presented in Chapter Two. These resulted from evaluation and interpretation of the input data by the researchers.

Chapter Three describes recommended research efforts. These essential end products of the study were developed from a detailed evaluation of the seminar input data and supplemental information. Implementation of the recommendations should yield significant and practical progress toward providing replacements for conventional aggregates where needed.

CHAPTER TWO

FINDINGS AND CONCLUSIONS

The pertinent findings and conclusions of the investigation have been divided into three categories. Category One contains findings and conclusions of a general nature regarding the relationship between need and supply of aggregates for highway construction now and in the future, and with regard to means for alleviating a shortage. Category Two contains findings and conclusions of a specific nature with regard to possible corrective actions relating directly to the materials, processes, and procedures of aggregate production. This category contains ideas relating to the manufacture of new supplemental aggregates and to the beneficiation of existing poor-quality materials currently rejected by specifications. Category Three contains findings and conclusions of a specific nature pertaining to possible corrective actions that mostly do not bear a primary relationship to the materials, processes, and procedures of aggregate production. They include ideas or suggestions for pavement design changes, specification changes, and economic changes relative to existing conventional aggregate production practices or material deposits. Data to support the findings are given in the appendices.

CATEGORY ONE—GENERAL FINDINGS AND CONCLUSIONS

1. The continually increasing use of conventional aggregates, especially following World War II, has seriously depleted supplies in many sections of the United States.

2. In the United States as a whole, conventional aggregate production capacity currently exceeds aggregate consumption and there is a supply of conventional aggregate adequate for all purposes (Appendix C).

3. Local areas exist within each American Association of State Highway Officials (AASHO) Region where shortages of conventional aggregate are being experienced (Fig. C-6).

4. If the average annual increase in total aggregate production remains the same as it has for the past decade, and if the use of conventional aggregate for highway construction remains at 40 percent of the total production, at least one of the four AASHO Regions of the United States will have a critical shortage by the year 1975 (Table C-6).

5. There is a definite need for developing economical methods of upgrading existing poor-quality conventional aggregates or for producing new supplemental materials, or both.

6. The technical capability exists or can be developed for the manufacture of new supplemental aggregate materials and the upgrading of poor-quality aggregates.

7. Scientists outside of the highway area, with backgrounds in ceramics, plastics, chemistry, metallurgy, and mineralogy, can, and are willing to, assist highway engineers in solving the problem of a diminishing aggregate supply.

8. To meet the expected future aggregate demands for highway uses, the following can be done to assure a satisfactory supply:

(a) Increase conventional aggregate production in areas where supplies are favorable.
(b) Import conventional aggregate into areas experiencing shortages from areas of high aggregate production capacity.
(c) Manufacture supplemental aggregates using local raw materials or waste products.
(d) Beneficiate existing low-quality natural aggregates.

9. Desired aggregate properties need to be characterized for specific uses to provide a basis for producing replacement materials.

10. Standard specifications for aggregate quality should be reviewed and, when appropriate, modified to permit use of conventional aggregates not now acceptable for specific applications. Such aggregates may be used effectively in specific locations. Selective use of existing high-quality conventional aggregates is to be emphasized.

11. As the areas experiencing shortages of conventional aggregate enlarge, the cost of importation will increase as the haul distances increase.

12. Production of supplemental aggregates can be eco-

nomically feasible only with continuity of supply and demand.

13. Quality levels that supplemental aggregates must possess will vary locally.

14. Any substantial change in the market price for conventional aggregates may be expected to lead to the opening of new sources heretofore considered to be uneconomical.

15. Currently undeterminable future developments in vehicular and pavement design could reduce the demand for aggregates.

16. Solutions to solid waste disposal problems could result in economical supplemental aggregate production. One possibility would involve the application of heat from the incineration process to supplemental aggregate kilns or sintering grates where combustible waste residue could be used as one component of the supplemental aggregate.

17. No single universal solution to the problem can be expected; different solutions will be utilized in different areas.

18. The United States is not alone in facing the problem of a diminishing aggregate supply. Other countries, including Great Britain, are experiencing a similar problem.

19. The general decrease in the required levels of aggregate quality with increased depth below the wearing surface needs to be recognized in aggregate use.

20. In the past, the cost factor has been the principal motive for using nonconventional aggregates.

21. Present synthetic aggregate production totals approximately 12 million cubic yards annually in the United States, but makes up only a very small part (1.2 percent) of the total aggregate market. Almost all of the synthetic material produced is lightweight aggregate. The market for synthetic aggregate now exceeds the supply, and the shortage can be expected to become much more critical in the future.

CATEGORY TWO—SPECIFIC FINDINGS DIRECTLY RESPONSIVE TO THE PROBLEM

1. Raw materials for producing supplemental aggregate include clays, shales, marls, industrial wastes, and mine tailings. One or more of these raw materials is available in regions that are experiencing a shortage of conventional aggregates.

2. Supplemental aggregates can be produced for a given purpose that are better than any available natural aggregate. Pore structure, chemical composition, particle shape, as well as other properties of aggregate appear to be subject to production control.

3. Speciality aggregates offering specific qualities such as high skid resistance and high wear resistance are currently being produced.

4. Means for providing supplemental aggregates include:
   - (a) Heat treatment of raw minerals.
   - (b) Chemical or thermochemical processing of raw minerals or solid wastes from conventional aggregate production.
   - (c) Pelletizing of fine minerals and beneficiation to suitable quality.
   - (d) Utilization of solid wastes.
   - (e) Beneficiation of low-quality aggregate.
   - (f) Utilization of marine deposits.

5. From an economic and continuous-supply basis, low-cost natural materials that can be combined in a precision-formulated raw mix and processed to an aggregate by heat treatment appear to be the most promising raw materials for supplemental aggregate. In some cases, *in situ* earth materials can be transformed into suitable aggregate by heat generated by underground nuclear blasts.

6. It is feasible to produce aggregates from available fine materials by agglomeration followed by one or more supplementary processes of beneficiation such as:
   - (a) Coating.
   - (b) Impregnation with plastics or other materials.
   - (c) Blending.
   - (d) Mechanical processing.

7. Chopped rubber tires, crushed battery cases, structural building rubble, mine tailings, ceramic waste, scrap plastic, and other materials of a similar nature have potential for use in local areas as supplemental aggregates for highway construction. Many of these materials have the chemical and physical characteristics required of conventional aggregates and need only to be recovered, separated from deleterious substances, and crushed and sized.

8. The conversion of waste materials into aggregate for highway construction is a problem that involves technology, economics, and social concern (*84*). Increasing social concern regarding the environment will ultimately make the utilization of some waste materials of economic importance.

9. Steel cans and scrap automobiles can be compressed and shredded for use in portland cement concrete. Such materials might reduce the required amount of conventional aggregate and strengthen the concrete, but might also lead to durability problems.

10. Certain organic materials, although capable of providing some of the desirable qualities of supplemental aggregates for pavement construction, may be seriously deficient in others. Some undoubtedly would degrade by bacterial action, develop a bad odor, and produce pressure build-up that would result in poor performance.

11. Lightweight supplemental aggregates can be transported at less cost.

12. A supplemental aggregate for use in portland cement concrete should have an appropriate modulus of elasticity, acceptable thermal expansion characteristics, and a low drying shrinkage potential.

13. Supplemental aggregates should have adequate mechanical and chemical bonding with the matrix and should have no deleterious chemical reaction with the matrix.

14. Supplemental aggregates, especially when intended for use in the surface layer of pavements, should have a high abrasion resistance. An aggregate that would wear differentially within itself or between itself and the matrix might provide this property.

15. The development of a supplemental aggregate that has a phase change or some great energy release when covered with ice or snow would be desirable. Such an aggregate would reduce winter maintenance efforts on pavements in severe climates.

16. An aggregate with built-in skid resistance might be

produced by processing materials that have an affinity for other materials possessing different fusion points. For example, a clay could be heated in a kiln and then mixed with a material having a higher melting point and possibly greater hardness. Small quantities of the hard material might form a skin on the fused clay mass and result in a coated aggregate of high skid resistance.

17. The surface characteristics of an aggregate could be altered by pretreatment to promote binder adhesion and possibly a rehealing capability in flexible pavement systems to produce the most desirable properties.

18. An aggregate possessing a reheal capability can be produced wherein the capability is stored in the aggregate and released over a period of time, while permitting the aggregate to retain its outward surface characteristics.

19. Cement clinker can be used to produce an artificial aggregate. The aggregate will react with portland cement paste to produce an excellent aggregate-matrix bond. A "gradual interface" bond will be produced, alleviating stress concentration problems that otherwise might exist.

20. Flax fiber and asbestos fiber have application in bituminous pavements as partial replacements for conventional aggregates and as reinforcing materials.

21. A low-modulus supplemental aggregate could be produced by the use of plastics in combination with finely divided minerals. Such an aggregate should not be used in long-term exposures to light and heat because of potential degradation under this condition.

22. Some of the silicones and other materials, including linseed oil, may offer potential for aggregate coatings.

23. "Instant aggregate" that pops up to size in the presence of moisture might be produced. Some type of "foaming" concept might be feasible.

24. Coatings can be produced on low-quality aggregates by physical, thermal, chemical, or combined processes. Such coatings have the potential of preventing intrusions of harmful substances, and of increasing strength, wear resistance, skid resistance, durability, and bond between the aggregate and the matrix.

25. Porous aggregates of low quality may be beneficiated by impregnation with plastics and then polymerization through catalytic or thermal action.

CATEGORY THREE—SPECIFIC FINDINGS INDIRECTLY RESPONSIVE TO THE PROBLEM

1. Changes in the transportation cost structure to make longer hauls of conventional aggregates from existing sources more economical offers one means of overcoming shortages in certain critical areas.

2. Changes in design practice could sometimes bring about a better utilization of the properties of existing materials. New concepts regarding cross section, construction methods, and other pertinent features might be involved.

3. Consideration should be given to developing methods of testing for those properties that relate directly to performance. Current practices are based on such empirical test methods as the Los Angeles abrasion (ASTM C-535) and the sodium sulfate soundness (ASTM C-88), which almost certainly are not applicable to many materials. The probable rejection of some usable materials on the basis of these tests, and the acceptance of others that should not have been used, must be recognized.

4. Deep mines or quarries for conventional aggregates under or adjacent to metropolitan areas might be considered to extend the existing supply. A changing economic picture might make this approach more attractive.

5. Desirable properties of supplementary aggregates for bituminous mixtures, for portland cement concrete, and for base or subbase courses are not all the same. This should be considered carefully in developing an artificial aggregate or in selecting a replacement for a mineral aggregate.

6. The use of special binder additives in the pavement wearing course to improve the adhesion between tires and pavement or other properties may be a feasible method for obtaining acceptable skid resistance, while permitting the use of aggregates not meeting present requirements.

7. Steps can be taken to better utilize existing natural aggregates and to reduce substantially the quantities of natural aggregate waste material being produced.

8. Increased use of performance-type specifications might do more to extend the supply of conventional aggregates than any other single item.

CHAPTER THREE

SUGGESTED RESEARCH

Many research projects for extending and increasing the supply of aggregate for highway use are suggested throughout this report. Only those that appear to the researchers to have the greatest potential for yielding significant results of practical value are described and outlined in some detail in this chapter. The suggested programs are designed to serve three purposes: to characterize acceptable aggregates, to evaluate materials related to the development or improvement of aggregates, and to develop replacement aggregates. The researchers found the selection of projects for inclusion in this chapter to be extremely difficult, and are aware that universal agreement on the selections can never be achieved.

GENERAL RESEARCH NEEDED

Before projects concerned directly with the development of acceptable aggregate replacements can be undertaken with an optimum expectation of success, certain background information must be developed. The single most important task is the definition of the minimum aggregate qualities related to specific uses, and to the climatic environments under which they will be used. Minimum standards are necessary guidelines for those who would manufacture new aggregates.

Plastics might be used in many ways to increase the aggregate supply. However, because so many are available, plastics themselves must be evaluated before projects related to their use with aggregates are undertaken.

Currently no inventory of the possible raw materials from which to make synthetic aggregates exists. This inventory is a necessity for intelligent consideration of the utilization of these materials for new aggregates.

1. Characterization of Acceptable Aggregates

Estimated Time: 5 years
Estimated Cost: $500,000

Problem

Information on the correlation between aggregate properties and the performance of aggregates in highways, and on appropriate test methods predictive of performance, need to be developed. The lack of this information presents a major obstacle to better utilization of currently available aggregates and to the development of new supplies of aggregates for highway construction.

Objectives

1. Determine the correlation between quantitatively different levels in aggregate properties and aggregate performance in highway construction.
2. Develop suitable test methods for predicting field performance through review and evaluation of existing tests, where appropriate, and develop new test procedures where existing methods are inadequate or nonexistent.
3. Develop aggregate specifications based on fundamental properties. These specifications would include relation to performance criteria in order that aggregate selection can be suited to the requirements of a particular job and location.

Program

1. Review of existing test methods of a steering committee composed of (a) engineers knowledgeable in highway construction, performance, and testing; (b) scientists knowledgeable in characterization of raw materials and products; and (c) geologists and plastics experts. This committee first should determine the aggregate properties and the existing test methods that correlate with performance, then recommend the aggregate properties that require further investigation and the test procedures that should be developed. The committee should meet bi-monthly, after formulation of the initial plan, to review the project performance and to determine the direction of the research.
2. Investigate in the laboratory the characterization of aggregates in accordance with the plan previously developed. It is anticipated that the characterization would evaluate the variety of aggregates that have known differences in field performance. The properties evaluated may include: Strength, pore quantity, toughness, particle size distribution, pore size distribution, particle shape, abrasion resistance and hardness, wettability by different classes of cementitious agents, adhesion strength to different types of cementitious agents, drainage characteristics and water retentivity, thermal expansion, moisture expansion, surface characteristics, soundness of a composite under repeated temperature and moisture cycling (weatherability), composition, soluble salts.
3. Prepare proposed specifications for aggregate properties based on the knowledge gained from the research outlined previously. The specifications should recognize different levels of performance to assist in the characterization of aggregates for particular job localities and requirements.

Note: This project is relevant to the other projects suggested in this section. Because of its size and urgency, it might be divided into several projects to be undertaken by more than one research organization. One of the main functions of the steering committee would be to maintain coordination and continuity.

2. Application of Plastics to Improve Aggregates

Estimated Time: 4 years
Estimated Cost: $300,000

The word "plastics" encompasses a great many chemical types, including those referred to as resins and polymers. Two broad classes exist: *thermoset* plastics and *thermoplastic* plastics. Thermoset plastics become permanently set or rigid when subjected to heat treatment or curing; thermoplastic plastics do not.

Thermoset Plastics.—The following are all members of the thermoset plastic family: Phenol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, polyesters, epoxys, styrene-polyesters, allyl. Thermoset plastics, when chemically reacted with the addition of heat and pressure, become materials that are practically infusable and insoluble to most organic solvents. Prior to heat and pressure treatment, they are soluble in a variety of solvents. Aggregates could be impregnated or coated with these plastics and heat treated to bring the plastics to their insoluble state.

Thermoset materials have their greatest potential for use with porous aggregate. They also could be used with finely divided minerals to heat-form a shaped aggregate that later would be heat treated. Thermoset plastic scrap from molding plants could be used as filler material. Cost is likely to be a major deterrent in the use of these materials.

Thermoplastic Plastics.—The following are thermoplastic plastics: Styrene, cellulosics, polyolefins, polyvinyl chloride, polycarbonates, acetal, polyamides, methacrylate, styrene-butadiene, styrene-acrylonitrile, acrylonitrile-butadiene-styrene. Thermoplastic plastics are manufactured commercially in large quantities and are readily available. They can be processed and reprocessed by the addition of heat and pressure, and dissolved in a variety of organic solvents for use as coatings. Liquid monomers of some of the listed plastics are available.

The use of thermoplastics has considerably greater potential than the use of thermoset materials because the availability of such materials has continuously increased the demand for their commercial applications. Large quantities of scrap plastics are available at costs considerably below those of the virgin materials. Scrap thermoplastics may be used as filler materials, either cold- or heat-processed, and as solvent solutions for coating aggregates.

Scrap thermoplastics may be obtained from plastic processing plants from sprue and runner systems, and from molding in compression, transfer, and injection machines. The scrap is normally either sold for reprocessing, or incinerated. Large volumes are available, especially on the East Coast and in the Midwest.

The use of virgin thermoplastics may be justified where high-grade synthetic aggregates are needed. However, scrap plastics could be used economically to produce synthetic aggregates with physical, mechanical, and chemical properties not much different from those obtained with virgin plastics. The strength properties of both virgin and scrap plastics of both the thermoset and thermoplastic types could be improved with fiber glass reinforcement.

The Portland Cement Association is now investigating the use of ground polyolefin scrap in place of sand in concrete. Improvements in the mechanical properties of the concrete are anticipated.

Objectives

1. Search the plastics literature and industry for plastics that are economically suitable and might be applicable for use in synthetic aggregates. Determine the quantities needed and available of acceptable virgin and scrap materials.
2. Investigate and evaluate test procedures that can be used to evaluate adequately synthetic aggregates containing plastics.
3. Evaluate the applicability of plastics for use in the beneficiation of or in the production of an aggregate.

Program

1. Review and evaluate literature pertaining to research previously performed and programs currently in progress or proposed.
2. Determine the compatibility of inorganic aggregates and organic plastic compounds as affected by heat aging in the presence of water and light.
3. Determine if volume changes in the plastics due to temperature and moisture changes are compatible with changes in binders for the intended uses of the aggregates.
4. Determine the desirable amount of plastic material to be used in synthetic aggregates.
5. Investigate the compression and flexural strengths of synthetic aggregates containing plastics when subjected to thermal cycling in the presence of water.
6. Develop test procedures for laboratory and field studies for the determination of requirements for specifications.
7. Determine the correlation of test data obtained with and without synthetic aggregates containing plastics and perform data analyses.
8. Field test those materials which the previous analyses have determined to be most promising for highway use.

Reference (*92*).

3. Identification and Cataloging of Raw Materials for Potential Use in the Manufacture of Synthetic Aggregates

Estimated Time: 2 years
Estimated Cost: $400,000

Problem

Declining resources of natural aggregates suitable for highway construction, from the viewpoint of quality and location, prompt immediate exploration of raw materials potentially convertible to suitable aggregates by presently known processes. Many potential raw materials are available throughout the United States. These include, but are not limited to, the following:

1. Waste materials:
   (a) Accumulated wastes (ponded slurries, tailings, slag dumps, etc.)
   (b) Currently produced wastes (fly ash, boiler slag, slag from processing of iron and steel, copper, nickel and phosphate, chrysotile tailings, phosphogypsum, waste lime, alumina red and brown muds, incinerator residue, lignite ash, collected mineral dusts, etc.)
2. Naturally occurring shales, clays, and slates:
   (a) Materials suitable for production of synthetic aggregates.
   (b) Materials suitable for production of brick, but not for synthetic aggregates.
   (c) Materials unsuitable for brick or aggregate production, but suitable for upgrading by use of additives.

Objectives

1. Determine inorganic materials suitable for production of synthetic aggregates.
2. Determine the potential of such materials for use in the manufacture of synthetic aggregates.

Program

1. Catalog naturally occurring and waste materials having potential use for the production of aggregates by thermal, hydrothermal, or air-hardening processes.
2. Compile the following information on potentially useful materials:
   (a) Location-distance from likely points of use.
   (b) Quantity (accumulated and annual production).
   (c) Chemical and mineralogical composition (average and range).

(d) Physical state (particle size, ponded or dry, uniformity).
(e) Beneficiation feasibility and requirements to produce a uniform and continuous supply.
(f) Estimated processing requirements—thermal, hydrothermal, air-hardening (rotary kiln, sintering strand, autoclave)—and the economics involved.

3. Make a preliminary judgment of the potential of the materials that have been cataloged for use in the manufacture of aggregates. For promising materials, indicate the information needed to convert each material to an aggregate.

References (*1, 2, 3, 19, 65, 81, 84, 101, 102, 103*).

RESEARCH NEEDED ON PROMISING REPLACEMENTS OR BENEFICIATION TECHNIQUES

Conventional aggregates can be supplemented by upgrading low-quality aggregates or by creating aggregates from new sources. The following projects are those believed most likely to yield significant definitive practical resutls. In some cases, feasibility studies are needed before the projects can be initiated.

4. Use of Calcareous and Argillaceous Materials to Manufacture Synthetic Aggregates by High-Temperature Transformation

Estimated Time: 5 years
Estimated Cost: $500,000

Problem

Calcareous and argillaceous materials occur in large quantities in virtually all geographical regions of the United States. These materials may be transformed into high-quality aggregates by processing at temperatures in excess of 1,900 F in rotary kilns, sintering strands, shaft kilns, or Lepol kilns. Although the technology exists to make such aggregates, no significant production of aggregates from these materials utilizing the high-temperature process has occurred.

Objectives

1. Determine existing and potential procedures for manufacturing acceptable synthetic aggregates from abundantly occurring calcareous and argillaceous materials using high-temperature transformation techniques.

Program

1. Explore existing and potential procedures for making aggregates from calcareous and argillaceous materials by high-temperature conversion.
2. Select and refine the most promising procedures for synthetic aggregate production by high-temperature conversion.

5. Use of Abundant Earth Materials and Moderate Heats for Production of Synthetic Aggregates

Estimated Time: 4 years
Estimated Cost: $250,000

Problem

Clays, shales, and similar materials exist in nearly all areas of the United States, including those areas having conventional aggregate shortages. These materials are not suitable for use as aggregates in their natural forms, but may be transformed into suitable aggregates by proper processing. The potential exists of processing these materials into suitable aggregates at temperatures of 1,200 F or less, rather than the high temperatures of 2,100 F required for the manufacture of lightweight aggregates.

Objectives

1. Develop new manufacturing methods or modifications of existing methods for the production of aggregates from argillaceous materials without requiring excessive temperatures for transformation.

Program

1. Investigate thermal processing methods of agglomerating argillaceous materials. These methods would be distinct from the existing process of manufacturing lightweight aggregate from clay, in that lower temperatures would be employed. There would be no attempt to vesiculate the clay or shale. The temperatures to be employed would be just sufficient to produce an agglomerate that would have resistance to attack by water and have the required strength. It is anticipated that a temperature elevation to 1,200 F would be employed, as distinct from the temperature of approximately 2,100 F presently used in lightweight aggregate manufacture. Use of the lower temperature would result in lower fuel consumption, greater production through a given size furnace or kiln, and equipment that is simpler to operate. However, a lower-quality aggregate would be produced.
2. Design equipment for accomplishing the thermal processing developed. Consideration should be given to equipment that would be portable and accomplish the raw material pick-up, thermal processing, and positioning of the aggregate on the highway right-of-way in one pass. Such equipment might also provide for the addition and mixing of a cementitious substance in paving applications.

6. Protective Ceramic Coatings for Aggregates

Estimated Time: 5 years
Estimated Cost: $400,000

Problem

Some unsatisfactory natural or synthetic aggregates may be upgraded by a ceramic coating that would reduce or prevent penetration of the aggregates by undesirable elements, reduce or prevent undesirable reactions with the matrix, and possibly increase the bond between the aggregates and the matrix. The degree and type of beneficiation needed will depend on the aggregate and its intended use.

Objectives

1. Develop ceramic coatings, and means of application, that would improve unsatisfactory aggregates so that they may be used for various purposes in highway construction.

Program

1. Review the various means and types of ceramic coatings that can be produced. Vapor deposition, ion exchange, flame spraying, as well as the more conventional ceramic techniques, should be considered.
2. Investigate the most promising coatings and determine whether or not they would be both economical and practical for production.
3. Evaluate promising feasible coatings and demonstrate their benefits by laboratory tests and field use.

7. Protective Plastic Coatings for Aggregates

Estimated Time: 4 years
Estimated Cost: $300,000

Problem

Some unsatisfactory natural and synthetic aggregates may be upgraded by plastic coatings. Such coatings may prevent attack of the aggregate by corrosive elements, prevent undesirable reactions with the matrix, and, possibly, enhance bond with the matrix. The amount of beneficiation and the quality or type of coating must be determined for the particular aggregate as influenced by its intended use.

Objectives

1. Develop plastic coatings that will beneficiate unsatisfactory aggregates for various uses in highway construction.

Program

1. Review various types of plastics and means of coating aggregates. Among other materials, latex water emulsions should be considered. They have been shown to improve tensile bond strength between mortars and brick and it is anticipated that they would result in improved adhesion between aggregate and portland cement paste.
2. Evaluate those plastics showing the most promise for their practical value and cost of production.
3. Demonstrate the benefit of the coatings by laboratory tests and field use.

8. Impregnation of Aggregates with Plastics

Estimated Time: 4 years
Estimated Cost: $200,000

Problem

Some low-quality, porous, natural or synthetic aggregates may be upgraded by impregnation in much the same manner as concrete has been impregnated with plastics. Impregnation of the aggregate may increase its strength, prevent attack by corrosive elements, prevent undesirable reactions with the matrix and, possibly, enhance bond to the matrix. The type of plastic and the amount of impregnation required will depend on the particular aggregate and its intended use.

Objectives

1. Improve low-quality natural or synthetic aggregates by impregnation with plastics so that they can be used for base courses or in bituminous and portland cement concretes.

Program

1. Review the various types of plastics, means of impregnation, and polymerization that could be used.
2. Determine the practicality of the most suitable plastics and techniques.
3. Demonstrate the benefit of the method(s) by laboratory tests and field use.

9. Impregnation of Aggregates with Cements

Estimated Time: 4 years
Estimated Cost: $200,000

Problem

Some low-quality porous natural or synthetic aggregates may be upgraded by impregnation with bituminous or portland cements or similar materials. Impregnation of these aggregates may increase their strength, prevent attack by corrosive elements, prevent undesirable reactions with the matrix, and, perhaps, enhance bond to the matrix.

Objectives

1. Improve low-quality naturally existing or manufactured aggregates by impregnation with cements so that they may be used for base courses or in bituminous and portland cement concretes.

Program

1. Evaluate the improvement that can be made in aggregates by impregnation with bituminous cement, portland cements, and, perhaps, inorganic precipitation cements.
2. Demonstrate the improvements achieved by laboratory and field use.

10. Agglomeration of Particulate Solids in the Manufacture of Synthetic Aggregates from Inorganic Wastes and Naturally Occurring Materials

Estimated Time: 3 years
Estimated Cost: $400,000

Problem

Most of the solid natural and waste materials that have potential use in synthetic aggregate production are composed of particles too fine to be considered for direct use as aggregate. Such finely divided materials as screenings, fly ash, granulated slag, phosphate slime, or taconite tailing slurries must be agglomerated or agglutinated in the form of balls or pellets of aggregate size prior to use in highway construction.

Objectives

1. Determine the best means for agglomeration of fine particulate solids, obtained from inorganic wastes or from the production of conventional aggregates, to yield an abundant supply of synthetic aggregate for highway use.

Program

1. Conduct a literature study of agglomeration methods to determine the types of equipment best suited to particular varieties of solid fines.
2. Evaluate, in the laboratory, pan, drum, and cone pelletizers, rolls, extruders, and presses in terms of water requirements, green strength, and density of the agglomerates. Evaluate the qualities of fired or cured pellets in laboratory furnaces, pot grates, and autoclaves. Comparisons of properties should be made between experimental pellets and commercial aggregates of established high performance.
3. Determine the density, strength, hardness, porosity, saturation coefficient, free lime content, glass content, and mineralogical and chemical composition of the agglomerates.
4. Prepare small batches of concrete with the experimental aggregates and evaluate the strength, frost dilation, drying shrinkage, and other properties.
5. Evaluate the various agglomeration procedures and establish those most suitable for use in producing synthetic aggregates.

References (*1, 2, 3, 19, 65, 81, 84, 101, 102, 103*).

11. Hydrothermal Hardening of Pelletized Calcium Silicate-Bound Synthetic Aggregates for Highway Use

Estimated Time: 3 years
Estimated Cost: $450,000

Problem

Many finely divided natural and waste materials have pozzolanic properties; these and certain noncementitious, nonpozzolanic materials become cementitious or pozzolanic when mixed with lime, portland cement, or other lime-bearing fines and subjected to curing in steam at high temperatures. Silica flour, pumicite, calcined clays and shales, volcanic ash, fly ash, granulated slag, and other materials containing appreciable percentages of silica, or silica and alumina, form stable calcium silicates at temperatures of 300 F or higher when a source of lime is also present. Many of these materials are highly reactive at temperatures of 150 to 200 F, but calcium silicate formation is greatly accelerated under autoclave curing conditions. Even relatively inert materials such as air-cooled crystalline slag may become suitably reactive at temperatures near 400 F. Many mixtures may be hardened in a matter of 30 min or less at 400 to 425 F, to form strong, highly stable calcium silicates.

Hydrothermally synthesized aggregates may be economically viable if mixtures containing as little as 5 percent of portland cement or lime are formed into highly compacted water-bound pellets. Heat-up and blow-down may be more rapid than in commercial autoclave curing of calcium silicate products because of the small size of the pellets. A single large commercial-size autoclave (11 by 150 ft) may process, in six cycles, up to 1,500 cu yd of pellets per day.

Leanness of the pellet mixture and autoclave curing should provide low drying shrinkage. Strength and hardness of hydrothermally cured aggregate should be a function of density rather than of duration of cure, within wide limits.

Objectives

1. Summarize the literature on hydrothermal synthesis of calcium silicates based on mixtures of lime, portland cement, or other lime-bearing materials and various finely divided, nonmetallics of natural and waste origins.
2. Investigate the calcium silicate-forming potential of mixtures of materials formed into small specimens under high compactive forces.
3. Determine the suitability of selected mixtures of materials for hydrothermally hardened aggregates for further study on a pilot-scale basis.

Program

1. Study the literature related to hydrothermal synthesis of calcium silicates.
2. Develop laboratory techniques for investigating the calcium silicate-forming potential of various mixtures.
3. Investigate and evaluate selected materials for use as aggregates.
4. Develop recommendations for further study, including decisions on scaling up to pilot-plant study.

References (*64, 65, 77, 78, 79, 80, 103*).

12. Use of Salvaged Structural Rubble for Aggregates

Estimated Time: 4 years
Estimated Cost: $300,000

Problem

In many instances, rubble from demolition of structures and pavements could be converted to supplemental aggregates at the site, if suitable equipment and processes were available. Characteristics of suitable equipment need to be determined. Currently available equipment needs to be evaluated to determine its adequacy. Techniques for evaluating, handling, and using the rubble should be developed. The entire system of using rubble for aggregates needs to be studied and recommendations need to be made for its economical use.

Objectives

1. Develop and demonstrate practical methods of converting rubble obtained from demolition of structures and pavements to useful aggregates.

Program

1. Review what has been accomplished in the reuse of rubble for various aggregate uses.
2. Develop or modify methods of converting rubble to aggregate for various uses.
3. Evaluate those procedures and equipment best suited for recycling rubble.

13. Development of Aggregates with Special Properties

Estimated Time: 3 years
Estimated Cost: $200,000

Problem

The manufacture of aggregates from clays, shales, or waste mineral products offers the possibility of better control over relevant characteristics than can be exercised in conventional aggregate production. For example, it may be possible to produce a wide range of pore structures in a synthetic material, whereas conventional aggregates are limited to the pore structure available in the natural rock. Similarly, one can provide a variety of controlled particle shapes or a variety of colors in the synethetic aggregate. This flexibility suggests the possibility of producing aggregates with better skid resistance, toughness, visibility of highway pavements, and other improvements.

Objectives

1. Develop paving aggregates that possess special properties to provide characteristics in a pavement system at a level as good as or better than that which can be achieved by use of current conventional aggregates.

Program

1. Formulate an aggregate mixture composed of particles of different wearing rates to provide a surface that will not polish during its life. Such a mixture would continue to supply irregularities to maintain a high surface coefficient of friction.
2. Determine the influence of controlled-size pores on skid resistance of aggregates having different wearing characteristics.
3. Produce synthetic aggregates with a variety of shapes and evaluate the use of special shaped particles to increase strength toughness and dimensional stability in paving compositions.
4. Manufacture aggregates of different colors and reflectivities and with a variety of optical properties. Evaluate the visibility of paving produced from these aggregates for both wet and dry conditions under daylight and headlight illumination, and with and without fog.

14. Synthesis of Dense, Crystalline, Rocklike Materials Through Fusion of Selected Compositions and Subsequent Treatment to Control Crystallinity and Microstructures

Estimated Time: 4 years
Estimated Cost: $400,000

Problem

Many of the aggregates presently in use originate from rocks of varying compositions formed by nature. Although these materials usually have been adequate, they do not possess the optimum properties for aggregates. They are subject to a variety of flaws and inconsistencies attendant with formations arising from natural occurrences. Further, as the supply of natural-occurring rocks suitable for aggregates dwindles, the use of synthetic aggregates will be necessary. In developing synthetic aggregates, every effort should be made to obtain optimum properties consistent with economic production.

Assuming that the optimum properties for aggregates can be known, the problem remains of establishing those compositions from which these properties can be developed. Another problem arises in determining the processing methods to be used in making the aggregates from selected compositions.

The source materials for synthesizing aggregates may be metallurgical slags, shales, wastes, fly ash, clays, or other inorganic substances that are present in abundance. However, only those with sufficient uniformity to yield specific compositions can be used. The proper compositions and the treatment processes for producing good aggregates must be determined. Fusing the constituents and then crystallizing them into a dense product with desired qualities offers a promising approach. The development of applicable processes will require a systematic research effort that draws heavily on existing knowledge of related techniques.

Objectives

1. Determine from the literature the state of the art for synthesizing dense, crystalline, rocklike materials.
2. Determine those compositions which, when properly fused and crystallized, will yield an aggregate with specified optimum properties. The compositions will contain compounds such as silicates, oxides, and/or nucleating agents combined in specific proportions to produce the desired end products.
3. Determine those source materials, such as slags, natural deposits, or possibly waste, which will yield the specific compositions referred to above.
4. Develop processes whereby selected compositions can be fused and, through controlled crystallization, made into an aggregate with specified properties.
5. From experimental observations, determine the behavior of the synthesized materials as aggregates in the highway construction field.
6. Gain information on which to base recommendations for a pilot-plant investigation.

Program

1. Thoroughly investigate European developments in rock synthesis. Determine compositions that have been used, the process technology, and the extent to which resulting materials have found application.
2. Make an extensive review of the literature on crystallization processes such as those used in making glass-ceramics.

3. Establish, insofar as possible, the desired aggregate properties for specific uses.
4. Make laboratory formulations to yield specific compositions and controlled mineralogical phases.
5. Fuse laboratory formulations and crystallize them under controlled conditions so as to develop structures that possess properties as close as possible to the desired properties for aggregates for specific uses.
6. Determine what the size, shape, texture, and other factors should be to favor making the material into a good aggregate.
7. Investigate making aggregates of different colors.
8. Evaluate the aggregate by using it in combination with various binders and making appropriate tests on the combinations.
9. From the laboratory experience, make preliminary plans and suggest designs that will lead to the development of a pilot-plant operation for aggregate synthesis.

Supplemental Research Project Statements

Attention is directed to *NCHRP Report 100* (*104*) titled "Research Needs Relating to Performance of Aggregates in Highway Construction." This report contains several research project statements related to synthetic aggregates or beneficiation of unsatisfactory aggregates. These statements were developed in a study of the total research needs related to aggregates and their use in the highway construction field. Specific statements directly applicable to the current project include:

Problem No. IV-5B, "Investigation of Waste Products as Potential Sources of Aggregates."

Problem No. IV-6B, "Study and Evaluation of Synthetic Aggregate Use, Specifications, and Tests."

Problem No. IV-7B, "Review of Aggregate Beneficiation Processes."

RESEARCH NEEDED ON OTHER MEANS OF ALLEVIATING THE AGGREGATE SHORTAGE

Aggregate shortages may be relieved by means other than beneficiation of low-quality aggregates or the manufacture of supplementary aggregates. Some research related to selective use of aggregates may yield beneficial results for many portions of the country.

Many specifications for aggregates are written to be applied nationwide and under a wide range of conditions, and are not always ideally suited for a particular area or a particular use. Unfortunately, specifications prepared by local agencies are often virtual copies of national specifications and do not properly reflect local conditions, even when the use of readily available and less costly local aggregates not meeting generalized specifications would be satisfactory.

An in-depth review is needed of aggregate specifications and experience in several widely different sections of the country to determine what steps might be taken to develop less restrictive, but satisfactory, local specifications.

SUMMARY

Only a few research projects have been suggested, but these few should yield practical solutions to the shortage of conventional aggregates. The projects concerned with coating and impregnating low-quality conventional aggregates and the use of calcareous and argillaceous materials to manufacture supplementary aggregates should be pursued vigorously. In pursuing the research suggested, some of the projects may be divided or portions of some may be combined. The project suggestions contained in this report may serve only as general guides.

A comprehensive program for developing supplemental aggregates can be effective only if the available raw materials are well known and understood and the needed properties of aggregates for various uses in different environments are known. Consequently, three projects have been suggested to develop this information.

The total research program suggested herein is broad, complex, and expensive, but with potential for yielding a high rate of payoff. If it is undertaken in its entirety, or only in part, its breadth and complexity are of such magnitudes that, in the interest of conserving resources, funds, time, materials, and services, a commission is suggested to guide the undertaking. The commission should consist of recognized experts in aggregate production, highway pavement design, aggregate use, maintenance of highways and structures, geology, ceramics, plastics, chemistry, and economics, and be responsible for selection and monitoring of the research to be done, allocation of the available funds, and dissemination of the results.

APPENDIX A

SEMINAR PROGRAM AND PARTICIPANTS

ORGANIZATION OF THE SEMINAR

The seminar concerned with "Promising Replacements for Conventional Aggregates for Highway Use" was held April 27-29, 1970, at the Allerton Park Conference Center of the University of Illinois. The seminar program and the participants and their affiliations are given later in this appendix.

Four prepared papers (Appendix B) were presented in the first two sessions. These covered the scope of the conference and provided stimulus for the creative workshops and discussions to follow. They provided a common base from which to work.

Dean Fred Benson, the keynote speaker, outlined the existing aggregate situation. His talk indicated the geographical locations that now have or that expect conventional aggregate shortages and the problems that arise from such shortages. Cedric Willson discussed present and future capabilities for the production of aggregates that would replace existing conventional aggregates or beneficiate existing substandard aggregates. Truman R. Jones, Jr., spoke on "Benefaction * of Existing Aggregates," and Howard H. Newlon, Jr., discussed "Replacements to Conventional Aggregates."

During Sessions III and IV the participants worked in small groups, concentrating on a limited portion of the total problem. The information generated by the discipline-oriented groups in Session III was used as background for Session IV, in which each group concentrated on a major use of aggregates.

Session V of the seminar was a summarization of the ideas advanced at earlier sessions and an in-depth discussion of the promising suggestions.

SEMINAR PROGRAM

Monday, April 27, 1970—7:30 PM

SESSION I INTRODUCTION

C. R. Marek, Chairman

(a) Purpose, Scope and Organization of Conference
Harry A. Smith and Charles R. Marek

(b) "Technical Background for the Existing Aggregate Situation"
Fred Benson

(c) "Technical Capabilities—Current and Future"
Cedric Willson

* Now referred to as "beneficiation."

Tuesday, April 28, 1970—8:30 AM

SESSION II BENEFICIATION AND REPLACEMENT

Clyde E. Kesler, Chairman

(a) "Benefaction * of Existing Aggregates"
Truman R. Jones, Jr.

(b) "Replacements to Conventional Aggregates"
Howard H. Newlon, Jr.

2:00 PM

SESSION III POSSIBILITIES WITHIN SCIENTIFIC DISCIPLINES

(a) Chemistry
Group Leader, Marshall R. Thompson

(b) Ceramics
Group Leader, Charles R. Marek

(c) Geology
Group Leader, Ernest J. Barenberg

7:30 PM

SESSION IV APPLICATIONS, NEEDS, AND RESEARCH

Group 1—Portland Cement Concrete
Leader—George Verbeck

Group 2—Bituminous Construction
Leader—Bob Gallaway

Group 3—Base and Subbase
Leader—Truman R. Jones, Jr.

Wednesday, April 29, 1970—8:30 AM

SESSION V EVALUATION AND SUMMARY

Bryant Mather, Chairman

(a) Reports from Group Leaders
(b) Evaluation
(c) Research Needs

Roster of Participants

ARONI, S., Professor of Building Technology, UCLA

BARENBERG, E. J., Associate Professor of Civil Engineering, University of Illinois

BARTON, W., Supervisory Physical Scientist, U.S. Bureau of Mines

BENSON, F., Dean of Engineering, Texas A & M University

BEST, C. H., Associate Dean of Engineering, Kansas State University

BOLLEN, R. E., Engineer of Materials and Construction, Highway Research Board
BRADBURY, W. C., Research and Development, Vulcan Materials Co., Wichita, Kans.
BROWN, R., PCA Research and Development Laboratories, Skokie, Ill.
COCKRELL, C. F., Assistant Professor, Supervising Research Chemist, School of Mines, West Virginia University, Morgantown
CORNELIUS, D., Structural Properties Section, British Road Research Laboratory, England
DEMPSEY, B. J., Assistant Professor of Civil Engineering University of Illinois
EITEL, W., University of Toledo, Ohio
ERSKINE, F. G., Expanded Shale, Clay, and Slate Institute, Washington, D.C.
FABER, J., National Ash Association, Washington, D.C.
FRIEDBERG, A. L., Head, Department of Ceramic Engineering, University of Illinois
GALLAWAY, B. M., Professor of Civil Engineering, Texas A & M University
GAST, L., Chemist, Northern Regional Laboratory, U.S. Department of Agriculture, Peoria, Ill.
HALSTEAD, W. J., Chief, Materials Division, Federal Highway Administration
HARTRONFT, B. C., Research and Development Engineer, Oklahoma Department of Highways
HARVEY, R., Associate Geologist, Illinois State Geological Survey
HERRIN, M., Professor of Civil Engineering, University of Illinois
HILSDORF, H. K., Professor of Civil Engineering, University of Illinois
HOLE, W. E., President, American Aggregate Corp.; Vice-President, National Sand and Gravel Association
JONES, T. R., JR., Technical Director, Construction Materials, Vulcan Materials Co., Birmingham, Ala.
KESLER, C. E., Professor of Civil Engineering, University of Illinois
KLIEGER, P., PCA Research and Development Laboratories, Skokie, Ill.
KORNHAUSER, B. A., Staff Metallurgist, Materials Advisory Board, National Academy of Sciences
LANKARD, D. R., Research Ceramist, Battelle Memorial Institute, Ohio
LARSON, T. D., Professor of Civil Engineering, Penn State University
LEDBETTER, W. B., Associate Processor of Civil Engineering, Texas A & M University
LEGG, F. E., Associate Professor, University of Michigan
LEWIS, D. W., Chief Engineer, National Slag Association, Alexandria, Va.
LOTZ, E. A., Chief, Materials Laboratory, U.S. Army Construction Engineering Research Laboratories, Champaign, Ill.
MALISCH, W., Assistant Professor of Civil Engineering, University of Missouri at Rolla
MAREK, C. R., Assistant Professor of Civil Engineering, University of Illinois
MATHER, B., Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss.
MAVES, P., Engineer, Concrete Materials, Martin-Marietta Corp., Indianapolis, Ind.
MELVILLE, P. L., Engineering Division, U.S. Army, Military Construction, Washington, D.C.
MIELENZ, R. C., Petrographer, Master Builders, Cleveland, Ohio
MILLER, J. (Lt.), Ceramic Engineer, U.S. Army Construction Engineering Research Laboratories, Champaign, Ill.
MORRIS, C. E., National Flaxseed Processors Association, Chicago
NEWLON, H. H., JR., Highway Research Engineer, Virginia Department of Highways
NICHOLS, F. P., JR., Engineering Director, National Crushed Stone Association, Washington, D.C.
OUTWATER, J. O., Professor of Mechanical Engineering, University of Vermont
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APPENDIX B

PREPARED PAPERS

During each of the first two sessions, two speakers gave previously prepared talks. These papers set the theme for the discussions and workshops that followed. They provided important background for those whose major interests were outside the highway field.

Technical Background for the Existing Aggregate Situation

Fred J. Benson, Dean of Engineering, Texas A & M University

Mr. Willson and I have been given the assignment of presenting the technical background for the existing aggregate situation. Earlier discussion of our joint presentation resulted in agreement that he would stress the technical aspects and that I would confine myself to the background and, hopefully, the foreground. This works out to your advantage, because I cannot claim technical competence in the area of aggregate benefaction * and manufactured aggregates.

Aggregate benefaction is defined as the "improvement of otherwise unsatisfactory naturally occurring aggregates by either mechanical or chemical means."

Manufactured aggregates, which are now being termed "synthetic aggregates" by several agencies, are defined as "those produced by processing nonaggregate materials." The raw material may be naturally occurring, man-made, or waste materials.

Prior to World War II, little attention was directed to the matter of aggregate supply except in a few isolated areas. The existing supplies of naturally occurring materials were considered adequate for the foreseeable future. There was some interest in manufactured aggregates with important specific properties, particularly aggregates with light weight for use in portland cement concrete to reduce the dead weight of structures.

The extensive use of aggregates during and immediately following World War II seriously depleted this natural resource in some sections of the United States and thus changed people's ideas with regard to the available aggregate supply. A substantial interest developed in manufactured aggregates at this time and at the same time considerable attention was directed to the use of natural aggregates not previously considered to be satisfactory. Over the intervening years the shortages have become even more serious. There are geographical areas today in which the natural aggregate shortage is approaching a critical stage; for these areas the manufactured aggregates offer a solution.

What is the aggregate situation in the United States today? This topic is discussed from three points of view—the situation with respect to naturally occurring aggregates, the situation with regard to materials for the production of manufactured aggregates, and the major deficiencies in aggregates in use today. Aggregate production in the United States can be conveniently separated as follows:

AGGREGATE TYPE	PRODUCTION (MIL TON/YR)	YEARLY INCREASE (%)
Sand and gravel	1,000	3.7
Crushed stone	855	3.4
Manufactured	23	5.0

Thus, it is seen that manufactured aggregates fill only a very small part of the total aggregate market today. The market for manufactured aggregates exceeds the supply and this shortage will become much more critical in the years ahead. The impact of the shortage is becoming increasingly apparent with the introduction of lightweight aggregate into highway construction.

The greatest shortages of naturally occurring aggregates exist in the Mid-Continent region and the Southeastern coastal sections of the United States. The severest shortages are found in the areas along the Gulf Coast. The 25-year period since World War II has been one of continually increasing use of aggregates for all types of construction activities. Aggregate supplies in critical areas have shown no improvement and the future appears even darker. Areas with modestly good natural aggregate supplies 10 to 15 years ago are now beginning to experience shortages. To some extent the shortages have been offset by better exploration methods and greater emphasis on surveys for new natural aggregate sources. It is my prediction that the demand for aggregates will increase in all areas of the United States during the next two decades. Under this stress, more and more geographic areas of the nation will fall into the category of natural-aggregate-deficient areas.

The money spent for aggregates represents a large proportion of the expenditures for construction, whether for buildings, pavements, dams, structures, or public works. Aggregate costs represent 20 to 30 percent of total costs for these types of construction (*45*).

Many available natural aggregate sources contain aggregates with serious deficiencies for some types of use. For example, many limestone aggregates used in asphaltic concrete or portland cement concrete paving mixtures are found to polish rapidly in service, resulting in slick surfaces. Other aggregates contain constituents that react adversely with the binder, particularly portland cement. Alkali-silica reactions and alkali-carbonate reactions in

* Now referred to as "beneficiation."

portland cement concrete have been identified and studied (*37*). Poor gradation is a common problem of natural aggregates. It is in the area of alleviating or eliminating these deficiencies that benefaction can be helpful.

Manufactured aggregates depend on an adequate and satisfactory source of raw materials for use in the production process. The U.S. Bureau of Mines recognizes the scarcity of aggregates as a resource problem and has begun a series of regional studies on the availability of source materials for manufactured aggregates (*41*). However, no really extensive study seems to have been made on a national scale of the availability of source materials for manufactured aggregates. There is little reason to believe, however, that such materials cannot be found in virtually all areas of the country. With the current interest in manufactured aggregates, as evidenced by this seminar and the recent symposium on synthetic aggregates held at the 49th Annual Meeting of the Highway Research Board (January 12-16, 1970), there is good reason to believe that new processes using materials not now under consideration will be developed in the next ten years.

Benefaction methods can be classified generally as mechanical and/or chemical. Mechanical methods have been in use for many years. Included are such time-honored operations as crushing, gradation control by screening, washing to remove deleterious fines, and blending. As natural aggregate supplies and quality have decreased in recent years, the aggregate suppliers have begun to consider more sophisticated methods of handling granular materials. Methods commonly used in the ore processing industry are finding their way into natural aggregate production.

Chemical processes for benefaction of aggregates have not been widely used. Probably the oldest chemical treatment is the use of small quantities of lime to improve the adhesion characteristics of aggregates for bituminous mixtures; i.e., to improve their affinity for asphaltic materials. Much research has been devoted to studies of chemicals for use in soil stabilization. Some of the results of these studies may be applicable to processes for benefaction of natural aggregates. Probably, more attention should be devoted to the potential of chemical treatments for improving the characteristics of natural aggregates. The greatest promise probably lies in the use of surface-active agents. Those interested in this subject should carefully review the work of Winterkorn (*108*), carried on in the 1930's and 1940's. Extensive research in the field of agronomy and agricultural soil science has proved conclusively that surfactants offer effective means of altering the surface properties of soil-aggregate systems. Used in trace amounts, such chemicals cause drastic changes in the physical properties of selected soils.

Manufactured aggregates are relative newcomers. At Purdue University, in 1936-37, I had an opportunity to observe some of the research conducted on the burned shale aggregate (Haydite) originally developed during World War I. This lightweight aggregate was developed to reduce the dead weight of structural concrete and produced a reduction of about 50 pcf in comparison with concrete made from natural aggregates. Haydite concrete strengths were quite high. The Haydite patents have expired since that time, but the process continues in use and will be discussed by Mr. Willson.

Recent developments other than the burned clay and shale aggregates include a wide range of products. Sinopal is a white synthetic aggregate developed in Denmark and produced by melting sand and lime fluxes in a kiln, then reheating to cause crystallization. The resulting material is a form of devitrified glass, and has high strength and a snow-white color. It has been successfully used in Europe for nearly ten years and is reputed to give a roadway surface improved skid resistance and high night visibility. Sinopal's hardness makes it resistant to polishing and its low affinity for oil minimizes discoloration of the roadway surface. It produces a good quality asphaltic concrete. The British Road Research Laboratory (*46*) has experimented with calcined bauxite as a roadway surface aggregate using epoxy resin as a binder. The calcined bauxite was found to have very high resistance to polishing under traffic and in the road trials showed better skid resistance characteristics than the best natural aggregates.

Currently, the electric power industry, in burning coal and lignite, is annually producing 22 million tons of fly ash and an added 11 million tons of bottom ash and boiler slag. This is expected to increase to 29 million tons of fly ash and 13.5 million tons of other ash by 1975. Less than 15 percent of this material is utilized at the present time. One potential use of this material is in the production of lightweight aggregates by a sintering process. Research conducted in Yugoslavia (*13*) on lignite fly ash has demonstrated the feasibility of commercial production of sintered fly-ash aggregates with unit weights in the range of 23 to 48 pcf. Three commercial plants now operate in the United States and others are in the planning stage. Pellets are formed from stiff mixtures of ash and water by extrusion or on pelleting discs. The green pellets are burned on a sintering grate. Portland cement concrete of good quality is being produced from these aggregates with compressive strengths at 28 days of 2,000 to 5,000 psi and unit weights of 70 to 100 pcf.

Undoubtedly there are other waste materials that can be used in the production of manufactured aggregates. The tremendous quality of solid waste generated in our economy today contains many potential raw materials. Blast furnace slag is an old and very reliable aggregate that has been used successfully for many years (*69*). Slag from other metal extraction processes may be useful. Waste glass and plastic represent other potential sources.

Probably the most exciting development in the aggregate field is the possibility of producing manufactured aggregates with specific characteristics for particular uses. The original manufactured aggregates were developed almost entirely for lightness in weight. It now is evident that many desirable characteristics can be designed into these aggregates.

Surface characteristics are an important characteristic of aggregates to be used in pavement surfaces for both rigid and flexible pavements. Gallaway and Epps (*23*) cover several possibilities for the production of aggregates that will provide long-term skid-resistance characteristics in pavement surfaces. Much work remains to be done, but the potential for designing aggregates with the desired surface characteristics has been established.

A second promising prospect in the paving field is the possibility of developing a manufactured aggregate to yield a high-strength portland cement concrete with substantially reduced stiffness. Concrete pavements as built today are not compatible in stiffness with most of the subgrades over which they are placed. As a consequence, pavement deflections that substantially mobilize subgrade support exceed the deflection capabilities of the concrete. A low-modulus concrete would permit larger pavement deflections and more effectively mobilize subgrade support at lower concrete stresses.

A third area of great potential is that of developing aggregates and aggregate-binder systems having very low volume changes. Many of the difficulties that occur in structures and pavements are primarily due to volume changes or are associated with volume changes. There is a need to develop aggregate-binder combinations that will have little or no initial shrinkage and minimum change in volume with changes in moisture content and temperature. This matter has not been given much serious study. Much information is available concerning the magnitude of volume changes that occur in normal pavements and structures but the real issue is whether or not these changes can be eliminated or substantially minimized.

There are other areas of high potential for the production of aggregates with specific capabilities; some of you will probably think of others not mentioned here. Color is an item of importance for many uses; thus, the design of aggregates having permanent color is of interest. For some uses, such as nuclear shielding, heavy aggregates producing concrete of high unit weight are needed.

Today's aggregate shortages, which will become more severe in the years ahead, call for a new attack on the aggregate problem. Scattered over the country are substantial quantities of materials that were discarded for use in prior construction activities. Steps can be taken to better utilize the existing natural aggregates, thus reducing this waste material. Furthermore, these waste stockpiles are a potential source of material for future construction aggregates.

As the profession searches for new methods for solving the aggregate shortage problems, particular attention should be devoted to assessing the possibilities of utilizing the technical capabilities of other industries. The mining industry, the metal processing industry, the ceramics industry, the chemical industry, and the coal-using industries all have technologies to offer that relate to aggregate production. Benefaction and manufactured aggregate production can probably be enhanced by utilizing mechanical, chemical, and heat processes from these industries. A large percentage of aggregate is used with binders of various types, with portland cement and bituminous materials being most widely used. There is also a need to develop aggregate binders that will permit the use of aggregates not now considered suitable. Certainly the binder portion of the mixture, particularly as it is related to the aggregate, should be continually assessed for improvement.

In summary, the points emphasized here are the following:

1. Aggregate shortages are becoming increasingly more significant in the United States, particularly in the Mid-Continent region and in some of the Southeastern states. The shortage is most serious along the Gulf Coast.
2. Better utilization of existing natural aggregates, benefaction of lower-grade materials, and manufactured aggregates offer solutions to the aggregate shortage problem.
3. The modern technology of the mining, metal producing, chemical, and coal-using industries can probably be adapted to the processes of aggregate production with beneficial results.
4. A particularly important aspect of the development of manufactured aggregates is the possibility of designing aggregates to produce specific properties in resultant aggregate-binder mixtures.

References (*13, 23, 37, 41, 45, 46, 68, 108*).

Technical Capabilities—Current and Future

Cedric Willson, Vice-President, Research and Development, Texas Industries, Arlington, Tex.

The sponsors of this seminar have asked me to follow Dean Benson's talk with a short discussion on the technical capabilities, now and in the future, for the production of aggregates that would replace existing conventional aggregates or for the benefaction of existing substandard aggregates. This obviously requires a theoretical approach, whereas my 40-year background in the cement and concrete business has been essentially practical. So my remarks on the subject must of necessity be practical theorizing, aided by a most helpful discussion earlier with Dean Benson.

This discussion of aggregates includes the broad field of concretes that may be useful in highway construction; i.e., binders of portland cement paste, bituminous materials, possibly organic resins, and, perhaps, some presently unknown binder. The engineering properties of each type of concrete produced by these binders are, or will be, quite different, but each must have a useful place in highway construction. Regardless of the binder used, all practical concretes have one common characteristic; namely, a strong, inert, and reasonably uniform mineral aggregate is required to enable the binder to glue this coalition of particles together into a solid mass. This mass not only must have the desired engineering properties, but also will maintain them permanently. Also, for certain types of concrete, it is desirable for the aggregates to have special properties to develop the required performance.

Aggregates for highway construction may be classified as natural and processed. Other broad classifications are normal weight and lightweight. ASTM Method C33 covers natural normal-weight aggregates that generally are in the range of 95 to 115 pcf dry and rodded. The exception is air-cooled blast furnace slag, a processed aggregate required by C33 to have a minimum weight of 70 pcf. Available lightweight aggregates that have the properties required for highway construction range in weight from about 40 to 55 pcf for the coarse and up to 70 pcf for the fine. They may be natural, such as volcanic scoria or pumice, although probably 95 percent or more are in the processed category. In fact, all processed aggregates now available, with the exception of air-cooled slag, are lighter in weight than the so-called normal-weight materials. However, in this discussion, consideration of processed aggregates is not confined to those that are lighter in weight. For highway construction, aggregate properties, performance, and economics are more important considerations. In any type of concrete made with binders, whether known or presently unknown, the binder and aggregates work together, so it is difficult to discuss one without some mention of the other. Therefore, binders are necessarily brought into the discussion to some degree.

The possible benefaction of available normal-weight aggregates is discussed later by Truman Jones. However, brief attention is called to the possible production of high-quality, normal-weight aggregates that are now thought of as being unavailable. I know several populated areas where there are known deposits of high-grade aggregate rock 400 or 500 ft or more below the surface, and I am sure there are many more. As the supply of high-grade natural aggregates comes closer to depletion in these regions, consideration might be given to the mining of deep deposits of aggregate rock to provide underground storage for additional water supply reserves. I believe all would agree that not nearly enough water is being stored for domestic and industrial use in many metropolitan centers. With modern, highly efficient mechanical methods, it might be possible to obtain this aggregate and create an underground reservoir for storage of a substantial amount of water now lost by runoff. With the present economic situation, this may not be practical; but, in the years ahead, additional requirements for both aggregate and water storage could make this a feasible source of aggregate supply.

Except for air-cooled slag, present production of processed aggregate is virtually 100 percent lightweight and totals approximately 12 million cubic yards annually in the United States. This includes expanded clays, shales, and slates, with a lesser amount of expanded slag and sintered fly ash. The dominant and oldest aggregates in this group are clays, shales, and slates expanded by the rotary kiln process developed and patented by Hayde and first used commercially in 1918. The material was named Haydite, and was developed primarily for producing lightweight concrete block in competition with coal-cinder aggregate. During the late 1920's, several high-rise buildings were constructed with Haydite concrete frames, but its structural use was limited. Hayde's patents expired early in 1946 and the small production of 500,000 or 600,000 cu yd annually multiplied rapidly. There are now about 50 plants in the United States that produced approximately 8 million cubic yards in 1969, of which close to 3 million cubic yards were used for structural concrete. This type of aggregate has been used for bridge decks on several hundred jobs, both large and small, throughout the United States, dating back to the early 1930's. These decks, with a few exceptions, have an excellent performance record, and, in many cases, substantially reduced costs. There is a new and rapidly increasing use for this type of aggregate in bituminous flexible pavements.

There are now twelve plants producing a similar aggregate by sintering clays and shales that may or may not have a natural bloat. Approximately 10 percent by weight of a pulverized solid fuel, such as coke, is added to the raw material. This process had its beginning about 1950. Several plants are now producing lightweight aggregate of structural grade by sintering fly ash. A large plant is about ready to start production near Toronto, Canada. Development of this type of aggregate is in its infancy and much more work will be done during the next few years. Expanded slag has been used primarily for concrete masonry production, but has been used only to a limited degree for structural concrete. The production of this group totaled about 5 million tons in 1969.

There is a large and wide-open field for research and development in the area of processed aggregates, both lightweight and normal weight. The occurrence of clays, shales, and slates is widespread and there is virtually no geographical region in the United States where one or more of these raw materials does not occur in an almost inexhaustible volume. Many such materials do not expand, but the sintering process does not require a natural-bloating raw material, the combustion gases from the solid fuel being sufficient to bloat it. Bunker C crude oil, and possibly other low-cost chemicals, added to the clays and shales may improve and/or control bloating. These types of processed aggregates have now proven their ability to produce satisfactory portland cement or bituminous concrete for virtually every type of highway construction. The abundant supply and low cost of raw material could relieve the shortage of aggregate in practically every part of the nation. However, further research and development work is necessary to overcome certain problems related to their use. Some of the most important problems are:

1. Lack of uniform aggregate properties from one raw material deposit to another.
2. Better control of unit weight.
3. Control of absorption to a lower and narrower band.
4. Greater uniformity in compressive and flexural strengths, resistance to shear, and elastic modulus.

Research in rotary kiln and/or sintering machine techniques can and must bring these properties within bands of property variations that are no greater and possibly less than natural high-quality normal-weight aggregates. At the same time, such a program can result in a reduction of production costs. If the successful result of this work should increase the weight of these processed aggregates above that of the present lightweight category, it will not be a serious disadvantage for most highway construction. If the light weight can be retained, so much the better, because highway construction costs will be reduced.

Contrary to what some may believe, the production of fly ash from coal-fired power plants is increasing rapidly. In 1967, the estimated fly ash production in the United States was about 28 million tons. The National Ash Association now predicts that in the six years from 1968 through 1973, production will increase approximately 40 percent to a total of 41 million tons. Except for the relatively small use as a pozzolana for replacing cement in portland cement concrete, this is waste material and disposing of it is becoming increasingly difficult and costly. In past years, much research has been done on producing a high-quality aggregate from this material and progress has been made. However, much more work is needed to convert this increasing supply of low-cost material to a high-quality aggregate suitable for highway construction.

The current production of slag from iron and steel operations is approximately 34 million cubic yards annually. As previously mentioned, a relatively small amount is further processed to expanded-slag lightweight aggregate. A large percentage, probably 95 percent or more, is available for normal-weight structural aggregate and is being used for both portland cement and asphaltic pavements, as well as base courses for both types of pavement. As the economy requires, more iron and steel and additional supply of air-cooled slag will become available.

A possible source of high-quality aggregate would be a combination of calcareous and argillaceous materials processed in rotary kilns, following the pattern of portland cement clinker production. There are many deposits of limestone and other calcareous materials that are not suitable for aggregates. They could be combined with clay or shale and processed to high-quality aggregates. They might have a somewhat higher unit weight than natural aggregates, but the difference would not be great enough to be a serious disadvantage for highway construction. Present portland cement kiln burning techniques would have to be modified in order to develop satisfactory particle shape and surface, but there is no question that this could be accomplished by a well-conceived research and development program.

Much research has been done or is now in progress to develop glass fibers that are suitable for reinforcing portland cement concrete. The principal problems in the use of glass for this purpose are the susceptibility to breakage of the fibers and chemical attack on the glass by the alkalies found in hydrated portland cement. Both problems are being investigated and some progress has been made in the production of glass that is alkali resistant. Although this does not involve aggregates directly, success in this field could provide a use for the millions of tons of throw-away glass containers that have become such a serious problem in refuse disposal. Work is already under way to convert these disposable glass containers to an aggregate suitable for bituminous concrete, because this binder is inert to glass with respect to chemical attack. The progress of this work will be followed with interest and a more comprehensive study should be initiated if warranted by the preliminary results.

Attention also is called to the millions of tons of organic waste that are creating a disposal problem that almost defies solution. Sludge from sewage treatment plants contains enough fuel value to dry itself, with some to spare. This material could possibly provide the fuel for all types of sintered aggregates. A large percentage of garbage is paper. This source of fuel is now wasted. Research may be able to find a way to convert waste paper into a usable fuel for one or more types of clay, shale, slate, or fly ash aggregate processing. Food garbage, which is almost 100 percent organic, could also possibly be converted into a form of fuel for certain aggregate processing operations.

Another development related to binders, and possibly aggregates as well, is the current research on impregnating hardened concrete with liquid resin monomers, which are then polymerized and hardened by radiation. A paper on this subject was presented at the 1969 ACI Annual Meeting in Chicago. Briefly, after the concrete was cured and dried, it was placed under vacuum to remove air from the pores and, while under vacuum, was saturated with the liquid resin. Radiation was then applied to cure the resin in the pore structure of the concrete. The compressive, tensile, and flexural strengths were increased by as much as from 200 to 400 percent when compared to non-impregnated concrete. The absorption was reduced by an even greater percentage. The work was the result of a joint research by the U.S. Bureau of Reclamation Laboratory in Denver and the Brookhaven National Laboratory in Long Island. It may be that further research will show that the resin monomer becomes the continuous phase, in which the portland cement concrete is merely a comparatively low-strength filler. If this should prove to be true, it may be that natural aggregates now considered substandard in quality would be satisfactory for producing this type of concrete. It also may be possible to modify this process by penetrating hardened concrete made with substandard aggregates to ½ in. or so with one of the low-cost monomers and improve the properties of such concretes to bring them up to a high performance level at a nominal cost. These preliminary developments should be followed with more comprehensive research and I feel sure that they will be.

Summary

1. Waste organic materials may be a possible source of fuel for future production of processed aggregates, but the outlook is not promising. The task of converting organic material to inorganic aggregates need not be undertaken in the foreseeable future.

2. In considering inorganic waste, metal offers little or no promise. It may be possible to convert disposable glass and plastic containers to useful bituminous concrete aggregates. This is now being studied and, if the preliminary work shows promise, additional research and development should be encouraged.

3. Under future economic conditions, mining of deep rock deposits for aggregate may provide a future source in certain areas where surface deposits are near or at total depletion.

4. Resin impregnation of the pore structure of hardened portland cement concretes, followed by curing, may improve the properties of substandard aggregate concrete so that it will be acceptable for highway construction. This process applied to high-quality concrete may conserve existing aggregate supplies by reducing the size of structural concrete members. The economic situation will control the

use of this process and further intensive work is certainly warranted.

5. The best possibility for creating new supplies seems to be extensive research to develop improved processing techniques for converting low-cost abundant shales, clays, slates, slates, and fly ash to high-quality aggregates. There is a substantial 50-year-old commercial industry already in this field. A large reservoir of knowledge and experience from these people is available and should be used to avoid duplication and conserve time and money. Aggregates of this general type have been successfully used for more than 40 years in highway construction and they have a proven acceptable performance. With this head start, this research and development program should be aimed toward refinement—the bringing of aggregate properties into greater uniformity and a reduction in production costs.

6. An increase in the production of iron and steel may provide an additional supply of air-cooled slag for highway construction aggregate.

7. When and if economic conditions justify, a more complex and sophisticated processed aggregate may be feasible. A combination of calcareous material unsuitable for aggregate could be combined with low-cost clays or shales and processed in rotary kilns to a hard clinker following the basic pattern of portland cement production. An extensive research and development program would be required to develop a satisfactory particle shape and surface.

8. In areas where supplies of low-cost flexible pavement base material are being depleted, consideration should be given to processing clays and shales in rotary kilns. Expansion or bloating is not necessary to produce an excellent flexible pavement base material. Cost of production is low, because the kiln will handle a greater load with a substantial reduction in fuel requirements per cubic yard.

References (*66, 72*).

Benefaction * of Existing Aggregates

Truman R. Jones, Jr., Technical Director,
Vulcan Materials Co., Birmingham, Ala.

The purpose of this paper is to stimulate thinking, broaden viewpoints, and, perhaps, define what the particular problem of replacements for conventional aggregates for highway use really is. Even though the general title for this project limits the subject matter to replacements for conventional aggregates, the objectives in the project statement specifically include the upgrading of unsuitable aggregates, the utilization of waste products, and the use of new production techniques. Reference is made to known methods that could be used for benefaction of existing conventional aggregates, including coatings, stabilization, polymerization, and others.

To better understand the terminology used, the following are selected terms with definitions from the dictionary:

1. *Benefaction,** the act of benefiting; a benefit conferred; a charitable donation.

2. *Benefit* (v.t. form), to be beneficial to; to do good to; to advance; improve; to profit; . . . .

3. *Aggregate,* (a) a mass or body of units or parts somewhat loosely associated with one another, (b) an aggregate rock. Any of several hard, inert materials used for mixing with a cementing material to form concrete, mortar, or plaster. A clustered mass of individual soil particles, varied in shape, ranging in size from a microscopic granule to a small crumb and considered the basic structural unit of soil.

In discussions among materials engineers, and researchers, when the point is made that poor performance has been encountered in the use of a particular aggregate, each generally visualizes a problem of a specific nature in accordance with his own experiences. This problem may be a symptom of the real cause and effect, and years may be spent treating this symptom without ever beginning to approach the treatment of the real "disease." To keep the viewpoint broad, the lines of products that might fall under the general category of aggregates for highway use must not be the only consideration.

Products

In 1969, the technical committee of the National Crushed Stone Association, while endeavoring to define a program of research and development for the Association to undertake, made a survey of all the producers to determine which products were being manufactured and which products constituted a major source of income. The following list includes more products than would be used simply for highway construction, but it is only a partial list of all products being manufactured by current producers:

1. Concrete coarse aggregate, in some 215 dissimilar gradations, in the United States as a whole.
2. Manufactured fine aggregate (stone sand).
3. Macadam aggregates.
4. Plant-mix asphaltic aggregates.
5. Surface treatment aggregate.
6. Dense-graded stone base.
7. Crushed-stone subbase.
8. Riprap.
9. Railroad and other ballast.
10. Filter media for stone filters.
11. Filter media for sewage treatment plants.
12. Terrazzo aggregate.
13. Mineral fillers for asphalt.
14. Mineral fillers for an infinite number of other products, such as paint.
15. Mine dust.
16. Agricultural limestone.
17. Architectural aggregate.
18. Roofing granules.
19. Base material for athletic fields, such as the underlying material for synthetic football turf.
20. Wall stone or building stone, such as rubble masonry.

* Now referred to as "beneficiation."

21. Concrete manufactured products, such as block, precast stone.
22. Flux stone.
23. Chemical stone.

Problems

Examination of this list should help to identify a number of problems, specific in nature, for which solutions can readily be determined; but there are also a number of problems, general in nature, that have existed for long periods of time and are more difficult to solve.

Many of the problems in practice are imaginary in nature and are simply imposed by specifications. In many instances the specification is in use simply because it has resulted in good performance. But, because specifications generally are empirical in nature, they frequently are misapplied and result in problems. Some of the imaginary problems are simply imposed by common practice. It should be obvious that certain practices adopted in the 1920's and 1930's are not adequate for this day and age. In this problem, as well as the specification problem, the advantage of a new product might be that users will get good results simply because they follow the newly recommended practice. Some imaginary problems are simply imposed by ignorance. These problems continue to generate because many authorities know no other way, although any method to alleviate the problem should be welcomed. Any problem that results in poor performance is, of course, a real problem regardless of why it occurred. To mention a few of the problems that are encountered in present day practice, the following have been selectively picked from the foregoing list of products.

Concrete Aggregates.—In cold climates, pop-outs are frequently experienced due to a porous type of chert or other porous types of aggregate. This usually can be corrected by heavy media separation to remove the deleterious particles. Equipment is now available for performing this task. In plants having a high demand for aggregate of this type, the cost might run from $0.25 to $0.50 per ton. This practice is not followed in the Chicago area, for example, even though there is a great amount of conversation concerning poor aggregates; it seems to be simply a matter of the user not wanting a good aggregate enough to pay the difference in cost.

Concrete aggregates also perform poorly due to chemical reactions, such as silica-alkali and carbonate-alkali reactions. This has been successfully controlled in a number of cases by the proper use of additives in the concrete mix or by using a low-alkali cement. Poor performance has been experienced in a number of cases, because the problems were not identified before the structures were built.

Poor performance due to volume instability may result from the presence of clay in the aggregate or from a poor mix design. The solution to this problem frequently involves cleaning up the aggregate with pure, clean water, or improving the mix design.

Durability problems, such as D-cracking, have been experienced in concrete pavements in the Midwest. A considerable amount of research is under way to find a solution to this problem. One of the solutions might simply be to change the geometric design of the base and surfacing materials so that water is drained out from under the pavement. It has been found in some areas that full-width construction, carrying a base material under the shoulders so that the cross section will drain, reduced the long-time maintenance costs, improved the life of the road, and actually made a safer highway to drive on.

Asphaltic Concrete.—Stripping of asphaltic mixes is a problem frequently blamed on the aggregate. Aggregates are generally hydrophilic or hydrophobic in nature, with the former, having a greater affinity for water than for asphalt, frequently performing poorly in asphaltic mixes. Water intrudes at the interface of the asphalt and aggregate, causing raveling, after the materials have been placed in service. This problem can generally be corrected by using additives in the asphalt or by treating the aggregate with some material, such as a limewash, to change the ion exchange potential.

Base Materials.—Poor performance has been observed from base materials in a number of cases. In some of these cases, the poor performance could have been corrected by using good practices that are now known.

The AASHO Road Test resulted in very poor performance by the dense-graded base. Examination of the materials showed that they were constructed with a frost-susceptible gradation and that they were poorly compacted, in the light of present practices. In this particular installation, after being exposed to sufficient traffic to further compact the base many of these sections were resurfaced and performed satisfactorily for the rest of the test. It is shocking to engineers and scientists not engaged in the design of highways to be informed that in most states compaction practices are the same as they were in 1933: compare the current truck sizes, traffic volumes, etc., with those we had in 1933.

Filter Media for Sewage Treatment Plants.—The gradation specification for filter media is very tight. Generally, relatively large pieces are specified, with the idea that this filter should drain readily and should provide adequate surface area for the growth of algae. The small pieces that occur have a tendency to clog the drains and this, of course, is bad for the filter. One substitute might be a manufactured product of a ceramic nature that could be made from any number of clays. Another correction for this problem might simply be to develop a better underlying medium so that the smaller pieces would have less tendency to clog the drains.

Testing

Test methods are intended to ensure good performance, but they also tend to continue the present problems. In general, the test methods applied to all the products listed previously do not, in truth, relate to the performance of the material in service. Very little work is now being done in the general area of test methods that would attempt to relate some fundamental property of the various materials to the performance of the material in the finished product.

Examination of two or three of the test methods now being used on concrete aggregates shows the seriousness of this problem. The sulfate soundness test is applied to all aggregates, regardless of their mineralogical character, and specification limits are the same for most of the aggregates; but the method of test is such that the coefficient of variation may be as high as 200 percent. The Los Angeles abrasion test is applied to most aggregates for concrete, and the allowable abrasion loss might be on the order of 40 percent in a particular state. This would be the same regardless of the aggregate being used. Some granites with an L.A. loss of 50 to 55 percent make very good concrete for many uses, but limestones with a loss this high would be unlikely to perform well.

Solving the Problem

The end use must be considered in every case and a determination of the required properties for an aggregate to do the job must be made before the problem of benefaction, or substitution, for conventional aggregates can be solved. The product for which a replacement is being sought must be defined.

The general area of benefaction, or learning how to use natural aggregates to their best advantage, offers a fertile field for the exercise of ingenious minds.

Areas of Needed Research

The areas of needed research demonstrated previously are as follows:

1. Research on the fundamental properties of aggregates:
   - (a) Determine the effect or function of physical, mechanical, and chemical properties upon performance:
     - (1) Properties controlled by nature.
     - (2) Properties controlled by processing, handling, and installation.
   - (b) Determine the factors affecting these properties and evaluate the effect of the factors on performance.
2. Operations, processing, and handling (impossible to stockpile without segregation, degrading, etc.)
3. Construction methods (obtaining density with base on soft subgrades, placing concrete, etc.)
4. Methods of test to determine suitability of a material for performing a particular function (L.A. abrasion, soft particles, sulfate soundness, do not relate to performance).
5. Recommended practices for structural design, geometric design, quality control, etc.

Conclusion

The challenge is to try to recognize what the real problems are in relation to aggregates and then to apply present technology and future research to possible solutions of these problems. Modern technology certainly should be able to make some improvement on present practices in all of these areas.

Replacement of Alternate Materials for Existing Aggregates

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The existing and potential shortages of quality aggregates, particularly in urban areas, have been the subject of considerable discussion in both technical and popular publications. The purpose of this outline is to serve as a starting point from which it is hoped that a more detailed consideration of specific possibilities for replacement materials and/or methods when and where such replacement becomes necessary will develop out of the expertise of the conferrees. Perhaps a more suitable term would be "supplementary" rather than "replacement," because it is obvious that conventional aggregates will be used in large quantities for many years. This is true not only because of their utility, but also because of economic factors.

For the purpose of this discussion, a "conventional aggregate" is defined as sand, gravel, or crushed stone used from commercial sources or produced on-site. This normally means that the only processing involved is that necessary to the sizing and cleaning of the naturally occurring material.

There appear to be at least three different motives for considering supplements for conventional aggregates. These are:

1. To obtain an improved property of the pavement or structural element. Such improvement would normally be bought at an increased cost. Examples are lightweight aggregate to reduce the dead load of concrete and various materials to increase the skid resistance of wearing surfaces.
2. To utilize a locally abundant material that will provide an acceptable alternative although the required level of some properties might be less than required from commercially produced aggregates. Such replacements are usually obtained at reduced cost. Examples are reef shells available in the southeastern United States and waste output from specific localized industries or natural deposits.
3. To create an output for an otherwise unusable waste that might, in fact, be a pollutant or create a disposal problem. Properties might or might not be equal to those of commercially available materials and processing costs would be expected to be significant, because new or improved technology would be required. An established example would be fly ash. A speculative example would be the processing of various solid wastes (bottles, rubber, old car bodies, garbage, etc.) into usable aggregates.

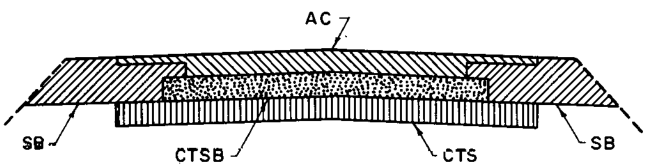
Exercise of the various options usually is dictated by economic considerations. Conventional aggregates sell for $1.00 to $2.00 per ton (in Virginia, at least), but transportation costs are approaching $0.05 per ton-mile. The second and third motives thus take on increased importance when commercial sources are preempted by zoning, pollution, etc., necessitating long-distance transportation.

Because of the varied backgrounds brought to this discussion by the participants, definitions of highway terminology and conditions may be of some value as a basis for the expected discussion of specific solutions. Concern with brevity breeds oversimplification, but for the purpose of this outline the end product is considered to be either a structure or a pavement.

The pavement can be divided into three components—wearing surface, base, and in-place soil. This discussion considers only the wearing surface, which would normally be of asphaltic or portland cement concrete, and that portion of the base that would conventionally be built with transported rather than on-site materials.

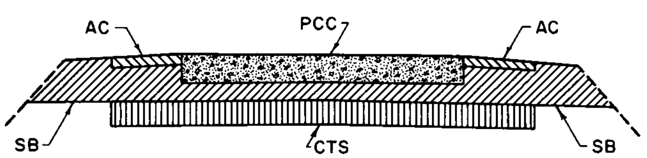
In structures, a similar classification can be made, philosophically at least, in that there exists a foundation, a substructure support, a slab, a wearing surface, etc. In structures, the primary construction material involving aggregates would be concrete.

In general, the required quality of the material (i.e., the restrictions placed on various characteristics) decreases as the depth below the wearing surface increases. Although the lower portions of structures or pavements are more massive, no parity exists between volume and cost. In general, the more expensive materials are placed near the top in heavy-duty roads, but these are not necessarily the materials used in greatest volumes. Greater volumes are required for the lower layers, but the portion of the expenditure required in the base layers is fairly small. Shortages of aggregates would, however, be felt most greatly in locations requiring such high volumes of material.



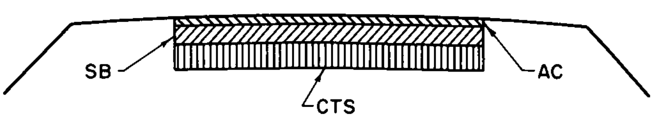
	Cost, %	Volume, %
AC	44	27
CTSB	18	19
SB	20	28
CTS	18	26

Figure B-1. Typical Virginia Interstate section, asphaltic concrete.



	Cost, %	Volume, %
PCC	56	26
AC	6	5
SB	22	39
CTS	15	30

Figure B-2. Typical Virginia Interstate section, portland cement concrete.



	Cost, %	Volume, %
AC	23	8
SB	50	42
CTS	27	50

Figure B-3. Typical Virginia secondary or farm-to-market section.

Two typical designs for an Interstate project in Virginia are shown in Figures B-1 and B-2. Both start from a stabilized in-place soil and, based on Virginia experience, are initially comparable. It will be seen that the distribution of volumes among the various levels is of the same order, but the major cost in both types is in the surfacing materials. This is primarily related to the need for higher quality near the surface, which in turn affects materials and processing costs. The significant point is that increasing the unit cost of the large-volume, lower-quality material significantly affects the economics of pavement design, particularly if the reduced quality requires larger volumes.

The cost distribution is quite different for low-traffic (farm-to-market) roads, as shown in Figure B-3. For this type of roadway, the base layers represent both a significant volume and a substantial fraction of the total pavement cost.

In addition to economic considerations relating to construction, the highway engineer is particularly sensitive to performance with minimal maintenance expenditure. The reasons for this are quite obvious when one considers typical highway budgets. For example, expenditures in Virginia for the last year of record are given in Table B-1.

In addition to the limited funds available for maintenance, maintenance activities in urban areas, where replacement aggregates would find greatest use, create many other problems at daily volumes of 50,000 or more vehicles per day.. This situation emphasizes the need to ensure long-time stability (durability), as well as more immediately evident characteristics such as strength and placeability. The adage, "Out of sight, out of mind," does not apply to highway materials.

The development of supplementary aggregate materials must also recognize the need for a continuity of supply. The highway industry has, in the past, experienced many instances of projected economies by utilization of a waste product, which after the development stage either became depleted or was patented at a premium cost. The continuity of supply is particularly important for the development of long-term performance criteria and user confidence.

The most comprehensive summary of potential replacement or supplementary aggregate materials is that by Fondriest and Snyder (*21*). Table B-2 is a summary listing from that publication.

Obviously, some of the materials listed in Table B-2 have proven performance over a wide area and some are restricted geographically, whereas at this point others are speculative. Rather than reiterating here the backgrounds leading to the possibilities listed in Table B-2, several limited examples illustrative of the three motives listed earlier are described. These examples are taken primarily from experiences in Virginia, with the expectation that many others will be presented by other participants.

Motive 1—Improved Characteristics

It does not seem appropriate to consider lightweight aggregates in the same vein as other supplementary sources, in view of the fact that most of the major lightweight aggregates have a proven service history.

Lightweight aggregate characteristics have been widely studied in relation to their building applications (*51*). The widest geographical application in highways seems to have been in bridge decks (*20*). Particular emphasis has been placed on wider applications for flexible pavements in Texas, where the motive appears to be reduction of shipping costs to aggregate-poor areas (*22, 49*).

Another example of improved characteristics would be importation of polish-resistant aggregates to improve the skid resistance of surfaces where the local materials are susceptible to polishing (*38*).

Motive 2—Utilization of Local Materials

In the past, use of local materials in the interest of economy has been perhaps the most common motive for utilization of materials to supplement conventional aggregates in the highway industry. Although not applicable to this discussion, in base construction extensive use often is made of pit-run sands and gravels requiring minimal processing in lieu of higher-quality materials requiring transportation.

Numerous examples of specialized situations could be cited, but because these are greatly dependent on local circumstances, several experiences from Virginia are used as typical examples.

1. *Oyster Shells.*—Considerable emphasis has been placed on the use of dead reef oyster shells in areas of the Southeast where they are locally abundant. Much of this work has been coordinated through the Shell Aggregate Research Committee (*88*). In Virginia, these materials have been used with soil in base construction (*6*) (Fig. B-4), as well as in bituminous concrete base and

TABLE B-1

VIRGINIA CONSTRUCTION ECONOMICS

ITEM	COST ($1,000/MILE) INTERSTATE	PRIMARY	SECONDARY
Construction	1100	531	200
Maintenance	7	2.5	<1

TABLE B-2

POSSIBLE USES OF SYNTHETIC AGGREGATES IN HIGHWAY CONSTRUCTION *

ITEM	SUB-BASE	BASE	PAVEMENT RIGID	PAVEMENT FLEXIBLE	REINFORCED CONCRETE	PRESTRESSED CONCRETE
Heat-treated materials:						
Clay	×	×	×	×	×	×
Shale	×	×	×	×	×	×
Slate	×	×	×	×	×	×
Phosphate slimes	×	×		×	×	
Coal mine tailings	×	×		×	×	
Fly ash	×	×		×	×	
Electric steel furnace dust	×	×		×	×	
Smoke abatement dust	×	×		×	×	
Sand	×	×			×	
Soils	×	×				
Clay-coated particles	×	×		×	×	×
Processed waste materials:						
Glass	×	×		×		
Waste ceramic ware	×	×		×		
Cast-iron enameling	×	×		×		
Brick	×	×	×	×	×	×
Clay pipe and tile	×	×	×	×	×	×
Ash clinker	×	×			×	
Garbage clinker	×	×			×	
Open hearth slag	×	×		×		
Demolition materials	×	×		×	×	×
Abandoned road materials	×	×	×	×	×	×
Scrap iron or steel	×	×	×	×	×	×
Manufactured aggregates:						
Sand-lime compositions:	×	×			×	
Fly ash-lime compositions	×	×			×	

* From *NCHRP Report 8* (*21*).

Figure B-4. Dead reef oyster shells in a base.

surfacing (Fig. B-5). Unfortunately, when specifications for their use were developed, the dredging of these shells was prohibited by the State Oyster Commissions of Maryland and Virginia.

In the areas of Virginia where aggregates are scarce, sand-shell mixtures, preferably pugmilled or mixed-in-place, can be used at substantial savings (about $1 per ton) when compared with conventional base construction. Virginia's experience with sand-shell was very favorable; sand-shell mixtures were successfully used to replace Grading I subbase material, inch for inch.

Shell-sand mixtures were treated as a material different from aggregate; therefore, the two were not compared as if shell was an aggregate.

Some requirements when using shells are:

(a) Crushable old shell.

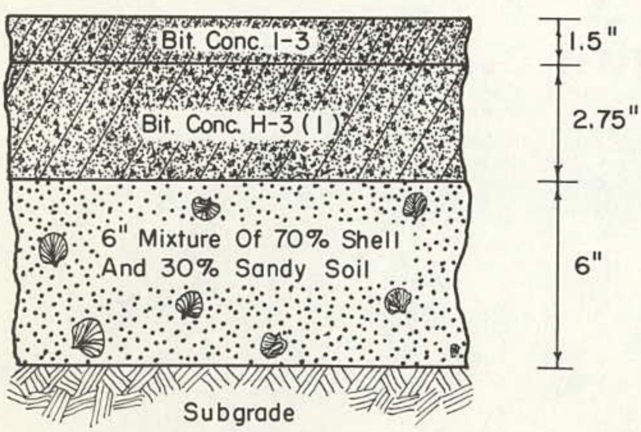


Figure B-5. Design features of roadway using oyster shells in a base.

(b) Sufficient crushing so that the shell doesn't break up later under traffic, leaving voids.

(c) Uniformity of mixture.

(d) Clean shell.

Another advantage in Virginia is that the use of shells permits utilization of otherwise unsatisfactory local sandy soils in the mixture (70 percent shell, 30 percent soil). Virginia experience confirms the results of 30 years of experience along the Gulf Coast in states such as Alabama, Mississippi, Florida, and Louisiana, where shells are still available.

Dead reef oyster shells were also investigated as a possible source of coarse aggregate for black base (Fig. B-6) due to the unavailability of coarse aggregate for this mix on the eastern shore of Virginia. The shells were available at the time and would have possibly lowered the cost of black base because coarse aggregate is presently shipped as far as 75 to 100 miles.

One test section of black base (approximately 60 percent shell, 40 percent sand) with a 1-in. maximum size aggregate was placed in 1966 and appears to be performing satisfactorily. Also, other states, such as Louisiana and Alabama, have used shells similarly with success.

One test section was also placed as a surface mix, but developed a low skid coefficient. The use of shells in a surface mix appears to be questionable with regard to maintaining a safe skid-resistant surface.

2. *Slate Wastes.*—In one area of Virginia a large slate quarry produces dimension stone for roofing and various architectural purposes. Production of this material also provides a considerable quantity of crushed tailings (Fig. B-7), which have been wasted.

Although this material has very poor particle shape, and its use would be discouraged in the presence of better aggregates, the nearest commercial rock quarry is about

25 miles away. Therefore, transportation costs would almost double the cost of stone if the slate tailings were not utilized.

The amount of construction in the area, and the geology, apparently did not justify production of conventional crushed stone. Research (*60*) showed that the important properties (resistance to freezing and thawing, strength, chemical stability, etc.) were entirely satisfactory and that acceptable concrete could be made economically with suitable attention to the mixture proportioning and controls.

The material is now used for roadcover stone and is sold commercially in the area of the quarry. Although the primary concern was with the particle shape, which was approximately that of various-sized coins, the particle shape of the aggregates from the nearest commercial rock quarry wasn't too good either.

The foregoing examples are typical of many others that could be developed from other areas. The experience with shells in Virginia does, however, illustrate the frustration caused by lack of continuity of supply.

Motive 3—Use of Wastes

Experience in the use of wastes as aggregate is limited, but this area is receiving considerable attention in the popular press. A recent issue of *Business Week Magazine* (*71*) carried an advertisement announcing a roadbed to be constructed with residue from high-temperature incineration of waste. Inquiries concerning the advertisement indicate that this construction has not yet been accomplished. Use of crushed glass in subbase, and rubber and plastic waste in asphaltic mixtures, was described in a recent issue of *Engineering News-Record* (*105*).

Such utilization of by-products is not new, as witnessed by the extensive use of fly ash, particularly in concrete, which is being summarized by Highway Research Board Committee MC-B5 (*39*).

A session of the 1970 Annual Meeting of the Highway Research Board focused attention on fired-clay aggregates for use in flexible bases (*67*), lightweight concrete aggregate from sintered fly ash (*63*), domestic waste glass in bituminous mixtures (*56*), cinders for road surfacing aggregates (*36*), and slag as aggregate (*25*).

Recent research on concrete reinforced with chopped fibers of various materials suggests the use of metal from shredded automobile bodies, but no examples of this use are known.

Summary

In summary, there appears to be a variety of materials that could be used, if necessary, to supplement conventional aggregates, and undoubtedly technology exists or can be developed for the production of others.

The summarizing paragraphs of *NCHRP Report 8*, "Synthetic Aggregates for Highway Construction" (*21*), still seem appropriate:

> Synthetic aggregates represent an alternative to importing natural aggregates from other localities. The primary determinant of the utility of synthetic aggregates is an economic one: the relative cost of importing suitable natural aggregates versus the cost of producing a synthetic aggregate locally. As nearby natural aggregates are depleted, the cost picture becomes more favorable where there are local sources of suitable by-product or waste materials that require only mechanical processing or where there is a local source of suitable raw materials and energy for the manufacture of a low-cost synthetic aggregate.
>
> When the aggregate shortage becomes more widespread and with importing natural aggregates, an extremely costly solution in most localities, the manufacture of synthetic aggregates will become more feasible. In the long run, the most useful development is likely to be either utilization of job-site materials for making synthetic aggregates in versatile and portable processing equipment or the establishment of a widespread synthetic aggregate industry that processes available materials such as clays and shales.

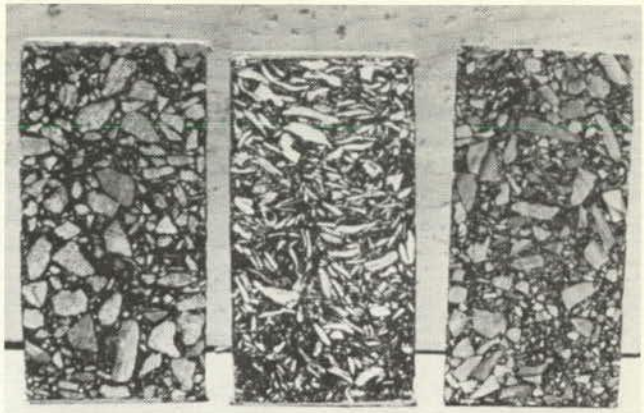


Figure B-6. Dead reef oyster shells in bituminous concrete.

Figure B-7. Slate aggregate.

The entire cost of using domestic waste materials to solve pollution problems could not be borne by the highway budget. Therefore, the disposing agencies involved would necessarily have to bear some share of that cost.

If it is assumed that economics allow or demand the use of supplemental aggregate sources for any of the three motives listed, the following would have considerable bearing on acceptance throughout the highway industry:

1. Long-range stability to minimize maintenance.
2. Continuity of supply.

Undoubtedly, changing economic patterns may make mining of conventional aggregates a more attractive alternative in urban areas. Obviously, the search should continue for design sections that require smaller volumes of the more critical materials.

References (*6, 20, 21, 22, 25, 36, 38, 39, 49, 51, 56, 60, 63, 67, 71, 88, 105*).

APPENDIX C

CAPABILITIES TO MEET FUTURE AGGREGATE REQUIREMENTS

The need for supplementary aggregates varies in the regions of the United States from almost none to almost total reliance on manufactured aggregates. Before exploring the country's capability to meet this need, the current aggregate situation is reviewed.

NATURAL AGGREGATE PRODUCTION AND SOURCES

The total conventional sand and gravel production data by state for the years 1964-67 are given in Table C-1 (*99*). Similar data for stone production are given in Table C-2. A ranking has been included in these tables to indicate relative production by state.

These data show that sand and gravel production by state varies from 2 million tons to 115 million tons per year and that stone production varies from ¼ million tons to 50 million tons per year. Totals of about 900 million tons of sand and gravel aggregates and about 800 million tons of crushed stone aggregates are produced in the United States each year.

Differences in production quantities by state are due to:

1. Supply equaling demand, and thus no need to increase production.
2. A shortage of conventional aggregate deposits.

In areas where supply equals demand, the problem is to interest aggregate producers in the mineral resource in the future. In areas where a lack of material exists, users must resort to the transport of aggregate from some distant source, beneficiation of local material, or manufacture of supplemental aggregates utilizing local material or waste materials.

Aggregate production data for each American Association of State Highway Officials (AASHO) Region (Fig. C-1) are given in Table C-3.

Witczak (*110*) has prepared several maps (Figs. C-2 to C-5) showing the location of potential conventional aggregate sources in the United States. Figure C-2 shows the distribution of potential crushed carbonate stone areas; Figure C-3, the potential crushed granitic/metamorphic complex stone areas; Figure D-4, the potential crushed igneous stone areas; and Figure C-5, the potential sand and gravel areas. Witczak also prepared a map (Fig. C-6) depicting areas in the United States that are lacking in "quality" aggregates.

PROJECTED AGGREGATE REQUIREMENTS

A previous study (*5*) provides information to estimate the yearly tonnage of aggregates needed in each of the AASHO Regions through 1985. Table C-4 (*5*) gives past and predicted total production, as well as the portion needed for construction and maintenance of highways. Table C-5 gives the estimated needs for each AASHO Region for 1975 and 1985. A doubling of the aggregate requirements for 1985 over the amount used now is predicted.

PROJECTED AGGREGATE SUPPLY

The regional aggregate production data given in Table C-3 for 1966 were projected to 1975 and 1985 by assuming a constant annual aggregate production increase of 5 percent, which is slightly in excess of the average annual increase of 4.3 percent that occurred during the decade from 1956 to 1966 (*5*). The projected total aggregate production data were reduced to projected aggregate supply for highway consumption (Table C-6) by using a factor of 39.4 percent from Table C-4. The average percentage of total aggregate production used for highway consumption has been suggested as being between 30 and 50 percent (*5*). Some states, however, may use 75 percent or more of a specific conventional aggregate for highway consumption, whereas other states use as little as 10 percent (*99*).

AGGREGATE REQUIREMENTS VERSUS SUPPLY

Table C-6 gives the difference between the estimated aggregate supply and estimated needs for 1975 and 1985.

The aggregate demands for highways in Region 1 will not be met in the future unless:

TABLE C-1

TOTAL CONVENTIONAL SAND AND GRAVEL PRODUCTION, BY STATE *

STATE	PRODUCTION (MIL. TONS) 1964	1965	1966	1967	RANK
Alabama	5.84	6.42	7.08	7.23	40
Arizona	18.12	14.92	18.73	16.58	18
Arkansas	11.79	12.81	16.06	14.24	20
California	112.99	118.31	120.69	116.12	1
Colorado	20.74	20.81	22.24	21.81	11
Connecticut	10.09	9.94	9.56	8.32	36
Delaware	1.28	1.54	1.61	1.97	48
Florida	7.42	7.30	7.40	6.91	41
Georgia	3.59	3.67	3.91	3.79	45
Idaho	9.58	12.15	7.54	11.25	28
Illinois	34.88	36.23	38.24	38.80	7
Indiana	24.42	24.87	24.99	26.26	10
Iowa	13.89	18.20	19.64	17.73	16
Kansas	12.96	12.54	11.63	12.07	25
Kentucky	6.56	6.74	8.06	7.98	38
Louisiana	13.59	14.30	18.22	20.31	12
Maine	13.55	17.29	15.36	11.63	27
Maryland	15.04	16.20	15.11	12.87	23
Massachusetts	21.34	22.14	17.32	17.88	15
Michigan	51.92	53.17	55.12	52.31	2
Minnesota	35.82	37.55	39.33	41.21	6
Mississippi	7.83	8.45	12.67	14.04	21
Missouri	11.48	12.07	10.70	9.72	32
Montana	16.02	12.05	13.82	12.34	24
Nebraska	14.64	11.99	13.54	11.74	26
Nevada	14.14	9.45	9.09	10.17	29
New Hampshire	8.77	10.58	7.63	8.45	35
New Jersey	17.66	17.39	17.78	18.63	14
New Mexico	8.78	11.76	15.50	14.67	19
New York	39.28	29.22	41.90	43.50	3
North Carolina	11.15	10.50	11.60	10.01	30
North Dakota	10.52	7.57	10.14	8.82	34
Ohio	37.77	40.85	43.85	43.19	4
Oklahoma	6.68	5.22	6.04	4.54	44
Oregon	18.25	21.80	35.33	19.63	13
Pennsylvania	16.20	18.50	17.57	17.48	17
Rhode Island	1.65	1.68	2.28	2.33	47
South Carolina	4.62	5.25	6.02	5.25	43
South Dakota	13.77	14.00	13.63	13.46	22
Tennessee	7.97	8.19	8.63	7.97	39
Texas	29.16	32.65	26.22	31.40	8
Utah	10.22	10.03	12.37	9.41	33
Vermont	1.76	2.08	2.32	3.72	46
Virginia	10.59	15.32	17.19	9.86	31
Washington	31.92	31.30	29.00	28.16	9
West Virginia	5.47	5.25	5.45	5.83	42
Wisconsin	34.35	38.75	41.52	42.54	5
Wyoming	5.63	8.00	7.19	8.18	37
All	840.69	877.00	916.81	872.31	

* Data from *Minerals Yearbook 1967* (99).

TABLE C-2

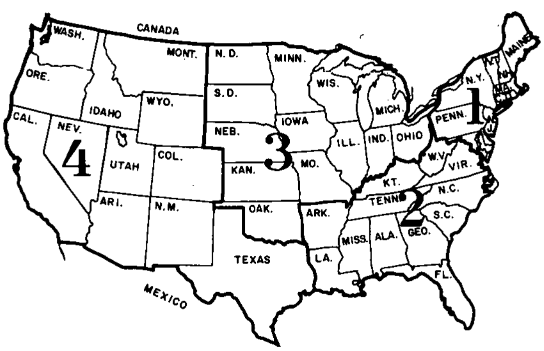
TOTAL CONVENTIONAL STONE AGGREGATE PRODUCTION, BY STATE *

STATE	PRODUCTION (MIL. TONS) 1964	1965	1966	1967	RANK
Alabama	15.85	17.99	20.74	18.37	17
Arizona	3.76	2.47	2.27	1.91	37
Arkansas	20.24	21.24	19.11	17.45	18
California	45.81	42.57	43.05	37.19	5
Colorado	3.22	4.79	7.03	2.99	34
Connecticut	5.86	5.87	5.62	5.10	30
Delaware	.18	.18	.21	.21	48
Florida	33.16	35.73	35.02	33.97	8
Georgia	22.82	23.42	24.69	23.42	16
Idaho	1.14	1.83	2.69	1.99	36
Illinois	42.99	47.07	26.16	48.46	3
Indiana	22.32	24.57	24.32	26.98	12
Iowa	23.94	25.89	27.73	26.13	13
Kansas	14.14	15.27	14.03	13.55	23
Kentucky	21.87	26.03	22.67	24.81	14
Louisiana	5.46	7.45	8.09	7.60	28
Maine	1.41	1.10	1.09	1.16	44
Maryland	13.35	14.55	13.87	14.48	21
Massachusetts	6.52	6.17	6.52	6.20	29
Michigan	34.65	34.71	37.86	36.43	7
Minnesota	3.59	4.37	4.90	4.16	33
Mississippi	1.55	2.36	1.53	1.88	38
Missouri	31.49	36.25	35.24	36.58	6
Montana	7.34	5.51	4.15	4.85	31
Nebraska	3.78	4.20	5.05	4.85	32
Nevada	.79	1.25	2.00	1.37	42
New Hampshire	.20	.15	.21	.47	47
New Jersey	12.33	12.23	12.45	12.61	25
New Mexico	2.76	1.91	2.65	1.39	41
New York	29.14	30.80	34.13	33.39	9
North Carolina	17.94	18.83	22.38	24.51	15
North Dakota	.03	.36	.17	.60	45
Ohio	37.71	42.26	45.00	45.46	4
Oklahoma	13.99	16.42	15.33	16.36	20
Oregon	16.12	21.21	33.29	13.20	24
Pennsylvania	58.83	56.81	59.09	60.16	1
Rhode Island	.45	.44	.54	.48	46
South Carolina	6.11	5.95	8.13	8.13	27
South Dakota	2.12	1.55	2.19	1.87	39
Tennessee	26.50	28.89	31.26	31.46	10
Texas	40.24	39.52	43.58	49.42	2
Utah	3.10	2.33	2.25	1.83	40
Vermont	2.07	2.59	2.65	2.76	35
Virginia	30.41	36.35	34.15	31.32	11
Washington	10.50	12.46	13.25	14.45	22
West Virginia	7.48	8.48	9.74	9.44	26
Wisconsin	13.90	15.34	16.15	17.12	19
Wyoming	2.15	1.59	1.39	1.25	43
All	721.31	769.31	805.52	779.88	

* Data from *Minerals Yearbook 1967* (99).

1. Aggregate production increases in excess of 5 percent per year are encountered.
2. The percentage of aggregate for highway consumption to total aggregate production for the region is greatly increased over 40 percent.
3. Conventional aggregate is transported into the region from one of the other three regions.
4. Supplemental aggregates are manufactured and used for highway construction.
5. Low-quality aggregates are beneficiated and used.

Figure C-6 shows that all of these possibilities exist for the region. That is, because the area does not lack quality materials, they could be produced given the demand. To meet the demand, however, the average annual yearly con-



AASHO Region 1 — Maine, Maryland, New York, Delaware, New Hampshire, Rhode Island, Vermont, Pennsylvania, Massachusetts, District of Columbia, Puerto Rico, New Jersey, Connecticut.

AASHO Region 2 — Mississippi, Tennessee, North Carolina, Florida, Georgia, Alabama, South Carolina, West Virginia, Louisiana, Virginia, Arkansas, Kentucky.

AASHO Region 3 — Minnesota, Nebraska, Iowa, Ohio, Illinois, South Dakota, Michigan, Wisconsin, Kansas, Oklahoma, Indiana, North Dakota, Missouri

AASHO Region 4 — Alaska, Hawaii, Texas, Colorado, Utah, Idaho, Washington, Montana, Arizona, Wyoming, California, Nevada, New Mexico, Oregon.

Figure C-1. American Association of State Highway Officials (AASHO) Regions. (After ARBA, Ref. 5.)

ventional aggregate production rate increase would need to exceed 12 percent to met the 1975 requirement and 7 percent to meet the 1985 requirement.

The situation in Region 2 is more critical than that in Region 1. Table C-6 indicates that the supply will exceed the demand, assuming the total conventional aggregate production rate increases at 5 percent yearly. Yearly production increases of this magnitude may not be possible, because some areas of the region are already lacking quality aggregate (Fig. C-6). Thus, to meet the projected demand many areas of the region will have to:

1. Increase the proportion of aggregates for highway consumption to total aggregate production.
2. Transport quality aggregates into the aggregate-deficient areas of the region.
3. Manufacture and use supplemental aggregates.
4. Beneficiate and use low-quality materials.

The situation for Regions 3 and 4 is similar to that for Region 2. That is, over-all the regions are capable of meeting future demands for aggregates for highway consumption provided the yearly production rate increase of approximately 5 percent and the percentage of aggregate for highway consumption to total aggregate production of approximately 40 percent or more can be met. However, Figure C-6 shows that some local areas of each region will have difficulty meeting the aggregate production quantities because of an existing quality aggregate deficiency. To meet the projected demand, such areas will have to select one of the alternatives as stated for Region 2.

Because it will not be possible for all areas of the United States to increase production of conventional aggregates at an annual rate of 5 percent, increased use of beneficiated low-quality materials and manufactured aggregates will be necessary.

TECHNICAL CAPABILITIES TO MEET DEMAND

The technical capability currently exists or can be developed to provide all the aggregates needed in the future. Furthermore, aggregates can be manufactured with special properties desired for certain uses, such as skid resistance and night visibility. Additional high-quality aggregates can still be obtained, poor-quality aggregates can be upgraded or used for selected purposes, and aggregates of various qualities can be manufactured from earth materials and waste products.

Additional Aggregate Sources

In some portions of the country, where the current sources of aggregates are being depleted, additional high-quality aggregates may be obtained by mining. The depth to which mining is feasible is determined by economic considerations. No new technology needs to be developed.

Excellent aggregates are being dredged from rivers and lakes, but sea-dredged aggregate production can be expanded. Again, no new technology is needed to obtain the aggregates. However, because such aggregates contain salt and shells, some research is needed to determine suitable limits for these potentially deleterious materials.

TABLE C-3

TOTAL CONVENTIONAL AGGREGATE PRODUCTION (SUPPLY), BY AASHO REGION

AASHO	SAND AND GRAVEL (MIL. TONS)				STONE (MIL. TONS)			
REGION	1964	1965	1966	1967	1964	1965	1966	1967
1	146.62	156.56	148.44	146.78	120.34	120.89	136.28	127.02
2	96.42	104.20	122.29	113.42	209.39	232.72	237.51	232.54
3	302.10	313.01	328.37	312.39	244.65	268.26	274.13	278.55
4	295.55	303.23	217.71	299.72	136.93	137.44	157.60	131.77
All	840.69	877.00	916.81	872.31	721.31	769.31	805.52	779.88

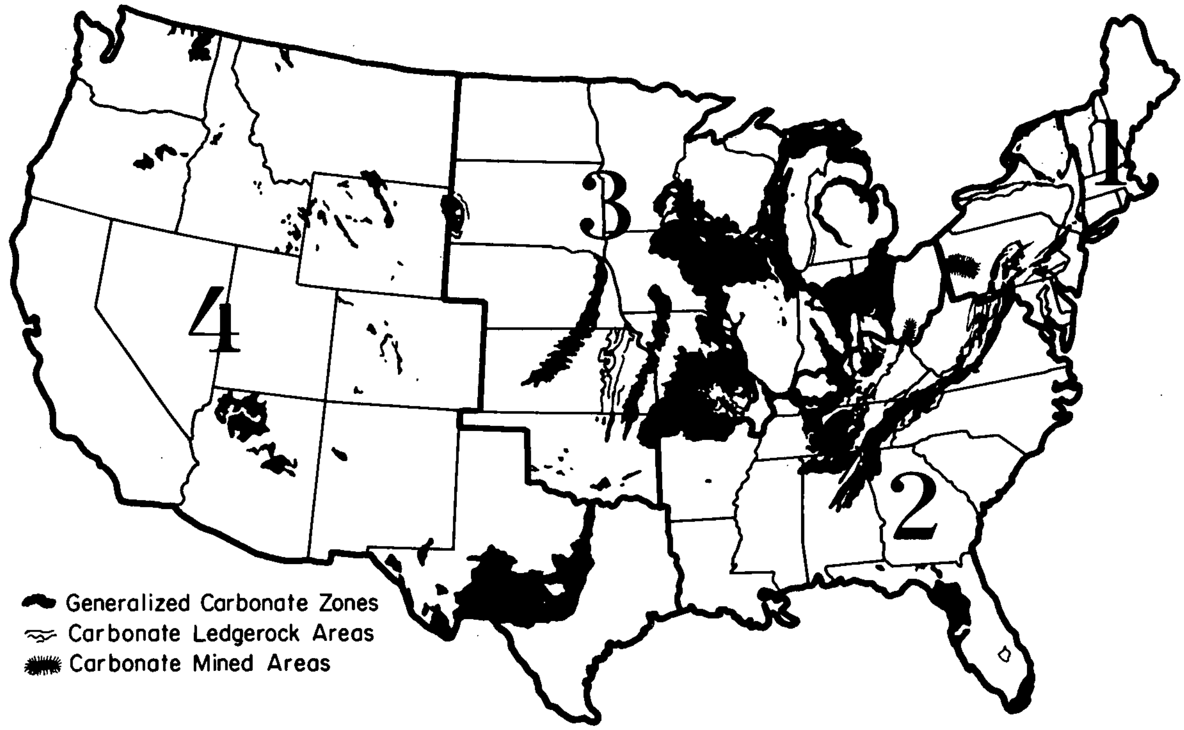


Figure C-2. Distribution of generalized potential crushed carbonate stone areas. (After Witczak, Ref. 110.)

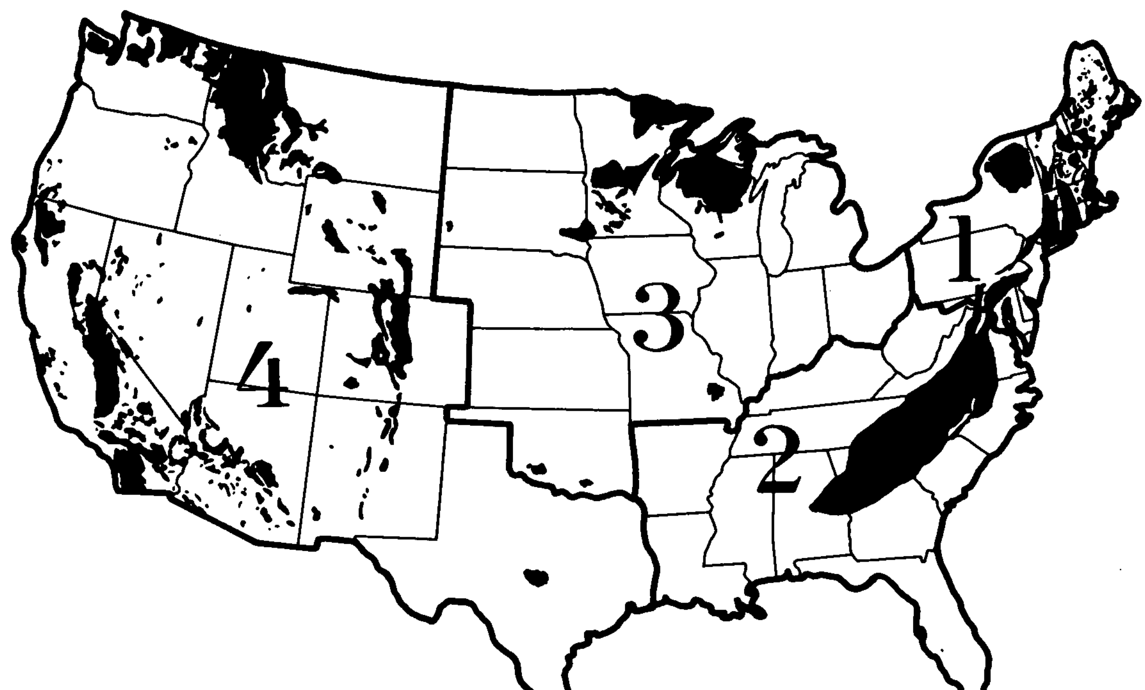


Figure C-3. Distribution of generalized potential crushed granitic/metamorphic complex stone areas. (After Witczak, Ref. 110.)

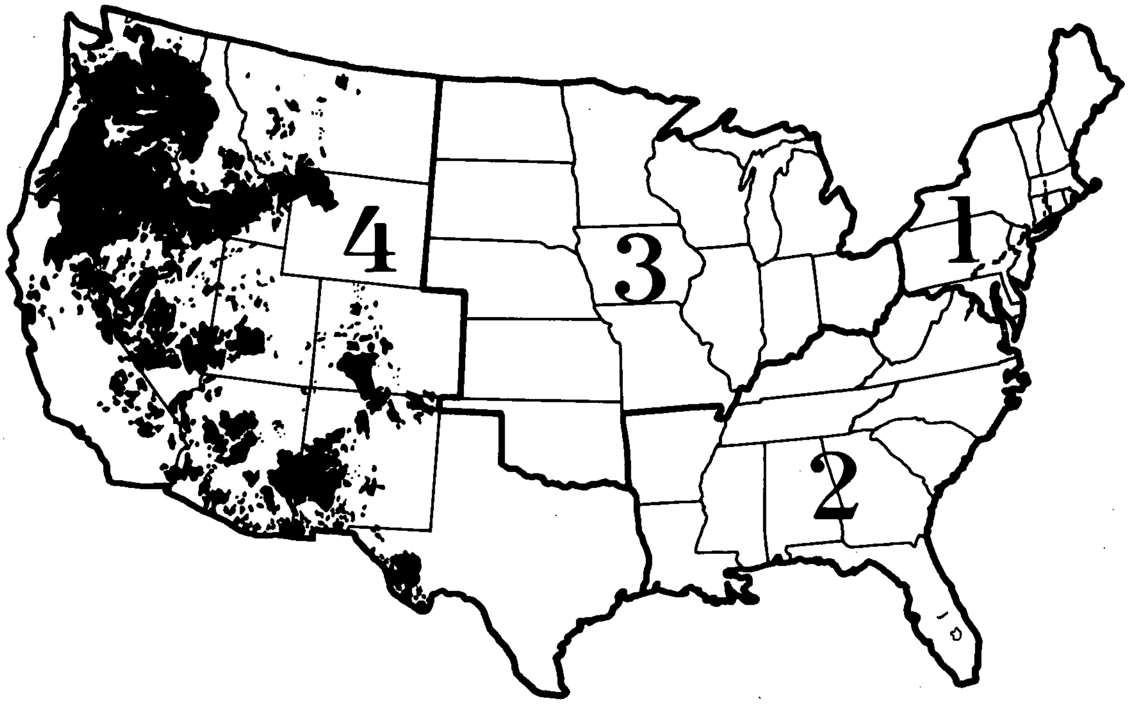


Figure C-4. Distribution of generalized potential crushed igneous (exclusive of granite) stone areas. (After Witczak, Ref. 110.)

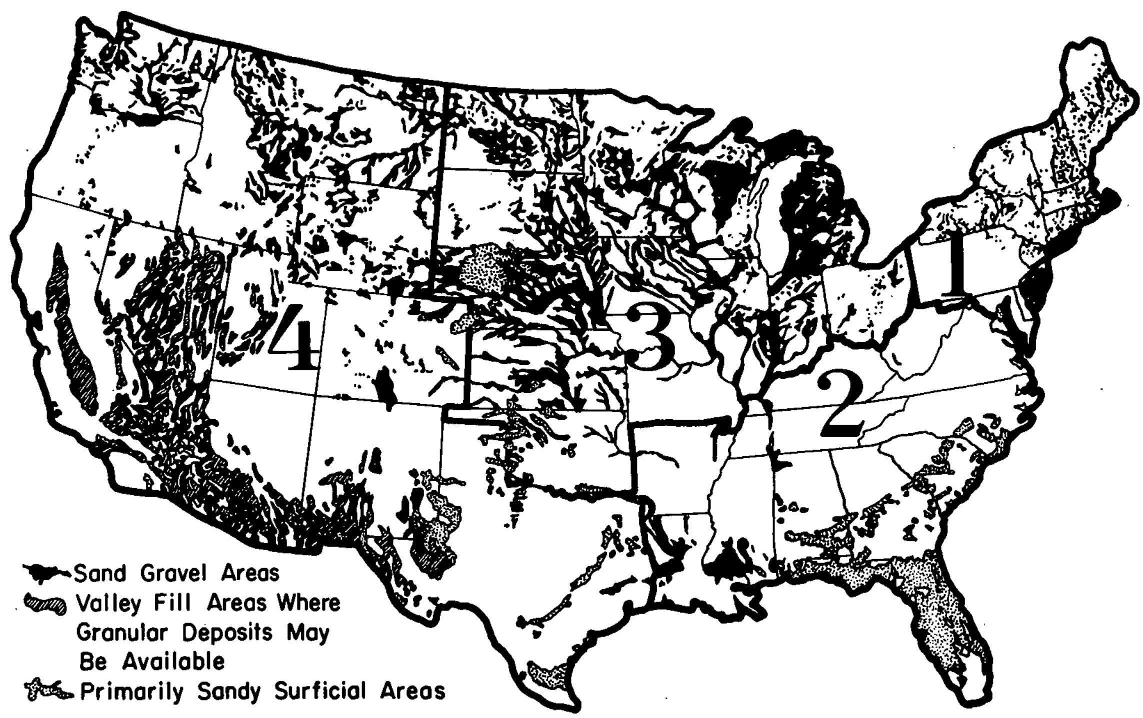


Figure C-5. Distribution of generalized potential sand gravel areas. (After Witczak, Ref. 110.)

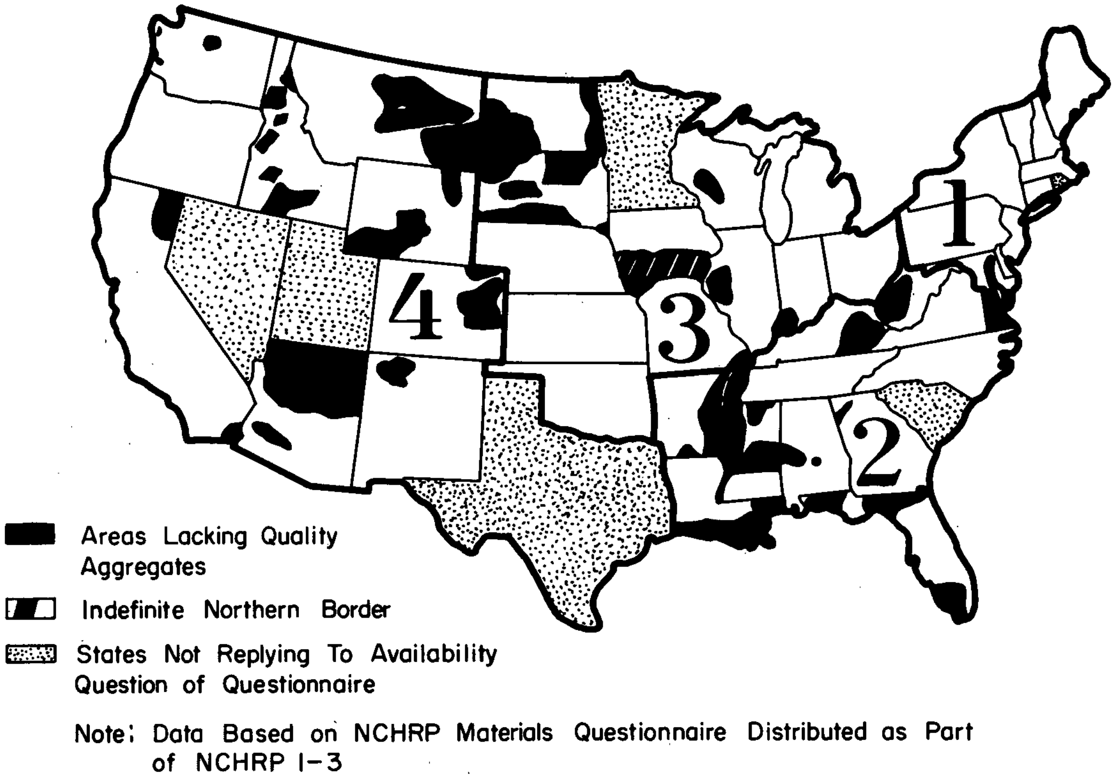


Figure C-6. Areas lacking quality aggregates. (After Witczak, Ref. 110.)

Beneficiation

Low-quality aggregate can be upgraded by mechanical or chemical beneficiation methods, or may be used for selected purposes or in special designs. Current methods of mechanical beneficiation are sufficient to upgrade many poor aggregates to the required quality; but where natural aggregates have continued to decrease in quality in recent years more sophisticated beneficiation methods, often borrowed from the ore-processing industry, are being introduced.

Chemical processes for beneficiation have not been widely used and additional technology needs to be de-

TABLE C-4

HIGHWAY AND TOTAL AGGREGATE CONSUMPTION [a]

YEAR	TOTAL PRODUCTION [b] (MIL. TONS): SAND AND GRAVEL	CRUSHED STONE	IRON AND STEEL SLAG [c]	TOTAL	HIGHWAY CONSUMPTION [d]: MILLION TONS	PERCENT OF TOTAL PRODUCTION
1956	625	504	32	1161	443 [e]	38
1961	752	613	27	1392	555	40
1966	934	811	29	1774	660	37
1975	1330	1260	33 [f]	2623	1199	46
1985	1970	2060	37 [f]	4067	1447	36
Avg.						39.4

[a] After ARBA (*5*).
[b] Data through 1966 were obtained from *Minerals Yearbook*, Bur. of Mines, U. S. Dept. of the Interior; projections for 1975 and 1985 are based on a continued growth rate equal to the average for 1956–61 and 1961–66 periods, except as noted.
[c] Excludes expanded slag lightweight aggregate used almost exclusively in building construction.
[d] Consumption in highway construction and maintenance through 1966 is based on AASHO surveys and is projected for 1975 and 1985 on the basis of highway needs as reported to Congress by AASHO.
[e] Assumes maintenance added 10 percent to construction use of 403 million tons.
[f] Estimates projected on basis of moderate increase in iron and steel production.

TABLE C-5

PROJECTED AGGREGATE DEMAND FOR HIGHWAY CONSUMPTION, BY AASHO REGION

AASHO REGION	DEMAND [a] (%)	MILLION TONS 1975	1985
1	31	371.7	448.6
2	17	203.8	246.0
3	28	335.7	405.2
4	24	287.8	347.2
All	100	1199	1447

[a] After ARBA (*5*).

veloped. Surface-active agents and other chemicals, even in trace amounts, may yield significant improvement to poor aggregates and should be investigated. For example, small quantities of lime may be used to improve the adhesion characteristics of some aggregates to asphaltic materials.

Poor-quality natural aggregates may be upgraded by coating or impregnation with either organic or inorganic materials. Further research is required before any aspect of this approach can be considered practical.

New binders can be developed that permit the use of aggregates not now suitable. Also, some aggregates may be used in the usual manner and the finished product impregnated, coated, or otherwise sealed to prevent the ingress of elements that cause deterioration.

Supplementary Aggregates

Aggregates suitable for all uses are being obtained from natural deposits or processed from naturally occurring materials. The processed aggregates are usually lighter in weight, except for air-cooled slag, than the natural-occurring aggregates. The industry has the capacity, or can obtain it, to maintain the supply needed as long as the natural resources last.

Clays, shales, and slates can be used to manufacture aggregates; there is virtually no geographical region in the United States where one or more of these raw materials does not occur in an almost inexhaustible supply. These materials need not be naturally floating, as fluxing and/or gas-forming agents can be added to produce a material with adequate bloating qualities.

Aggregates with desirable properties can be made from combinations of calcareous and argillaceous materials in rotating kilns in the same manner as cement clinker is produced. Shale, clay, or fly ash may be added to produce quality aggregates. Such aggregates may not be lightweight, but particle shape and the nature of the particle surface can be controlled. Much development work needs to be done in this area.

Aggregates made from sintered fly ash are being used in limited quantities. Large quantities of fly ash exist and its transformation to an aggregate may contribute significantly to the reduction of an aggregate shortage in some areas, particularly near large cities.

There are many processes by which the ceramics industry can manufacture suitable aggregates from materials that exist in large quantities. These aggregates can be of various shapes, hardnesses, textures, compositions, and colors, each designed to serve a specific purpose.

In many instances, the rubble from an existing pavement might be used, and it has been in some cases, for aggregate in a new pavement. Further development of equipment is needed to make this a more practical approach.

There are many waste materials, such as tires, sewage, bottles, and cans, that can be used as aggregates. Use of some of these materials for aggregates requires new techniques not widely available today, such as encapsulating in plastic or asphaltic material. Such materials need not be processed to permit use as aggregates for all purposes. Even though universal aggregates are convenient, they are not necessary. Selective use of aggregates is one effective means of extending the aggregate supply.

TABLE C-6

PROJECTED SUPPLY AVAILABLE VS ANTICIPATED DEMAND FOR HIGHWAY CONSUMPTION, BY AASHO

AASHO REGION	1975 SUPPLY [a] (MIL. TONS)	DEMAND [b] (MIL. TONS)	DIFF. (%)	1985 SUPPLY [a] (MIL. TONS)	DEMAND [b] (MIL. TONS)	DIFF. (%)
1	174.0	371.7	−53.2	283.5	448.6	−36.8
2	219.8	203.8	+7.8	358.2	246.0	+45.6
3	368.1	335.7	+9.6	599.2	405.2	+48.0
4	290.1	287.8	+0.9	473.2	347.2	+36.3
All	1052	1199	−12.3	1714	1447	+18.4

[a] Data in Table C-3 for 1966 were projected assuming a constant average annual increase in total aggregate production of 5 percent; the average percentage of total aggregate production (39.4) was then applied to the total production value to obtain the highway consumption value.

[b] Projected demand was obtained from Table C-5.

Summary

The technical capabilities of the plastic, ceramics, chemical, mining, and metal processing industries have never been fully applied to solving the problem of an aggregate shortage. In short, much of the technology needed to provide the United States with a virtually unlimited aggregate supply is already available or can be developed in the foreseeable future. The rapidity with which new techniques are brought into aggregate production for highway use will be determined by economical considerations.

QUALITY NEEDED

Aggregates of a given quality that can be used for all purposes, including bases, asphaltic concrete, and portland cement concrete, are convenient, but not necessary. In some areas, the effective aggregate supply can be increased by appropriate selection of aggregates for the various uses or by design changes to reduce required aggregate quantities or to permit the use of otherwise substandard aggregates without beneficiation.

Selective Use

A pavement can be divided into three components—wearing surface, base, and in-place soil. In structures, a similar classification can be made, philosophically at least, in that there exists a foundation, a substructure support, a slab, a wearing surface, etc.

In general, the quality of the aggregate required (i.e., the restriction placed on various characteristics) decreases as the depth below the wearing surface increases. Although the lower portions of a structure or pavement are more "massive," there is a parity between volume and required quality. In general, the best materials are placed near the top in heavy-duty roads. Fortunately, these are not necessarily the materials used in greatest volumes. Large volumes are required for the lower layers, but the quality of material required in these "base" layers can be lower than that of the upper layers. Thus, selective use of existing quality aggregates should be practiced.

SPECIFICATIONS AND DESIGNS

Many specifications for aggregates are written to be applied nationwide, and as such may not be ideally suited for a particular region or a particular use.* Such specifications are by their very nature usually more restrictive than necessary for many uses and require the use of high-quality materials in places where lesser-quality aggregates would perform adequately.

Caution must be used in preparing specifications for any supplementary aggregates that are developed so as not to restrict their use. It cannot automatically be assumed that specifications for currently used aggregates can be applied to newly developed aggregates.

Some aggregates contribute to D-cracking in portland cement concrete pavements and, hence, are avoided. However, the same aggregates might possibly be used in pavements that would not exhibit the D-cracking phenomenon if the geometric designs of the base and surface are changed to provide more complete drainage.

Mixture designs and proportions might also be altered to allow the use of lesser-quality aggregates.

* This has sometimes been appreciated by those who wrote the specifications, as is indicated, for example, by Note 1 to the scope of ASTM Method C-33, "Standard Specification for Concrete Aggregates," which reads: "These specifications are regarded as *adequate* to ensure satisfactory materials for *most* concrete. It is recognized that, for certain work or in certain regions, they may be either more or less restrictive than needed."

APPENDIX D

BENEFICIATION OF EXISTING AGGREGATES

One method of extending the existing aggregate supply is through beneficiation of aggregates too low in quality to be otherwise used. Such aggregates can be improved for specific or general use by:

1. Coatings.
2. Impregnation.
3. Blending.
4. Mechanical processes.

The choice of the method of improvement will depend on the particular aggregate and its deficiency and intended use. The capabilities of the ceramic, plastic, mining, and other related industries have not been fully exploited to resolve this problem.

In the following discussion, it should be kept in mind that aggregates produced by the processes discussed in Appendix E can also be upgraded by the processes mentioned here. For example, it is logical to assume that a number of processes can be used to produce aggregates that will not meet the standards necessary for highway construction. This might include pelletizing clayey soils and reclamation of rubble from old construction, as examples. It is entirely logical to assume that these aggregates can be upgraded by one or several of the processes given here.

COATINGS

Aggregates can be coated by physical, chemical, thermal, or combined processes. The coatings may prevent intrusion of harmful materials, increase the general strength characteristics, increase resistance to wear, increase skid resistance, increase resistance to weathering, and promote bond between the aggregates and the matrix.

Ceramic surfaces can be developed on some aggregates simply by heating the aggregate to moderate temperatures (850 to 1,450 F) in rotary kilns. For this treatment to be effective, the mineralogical composition of the aggregate must be such that the aggregate surface can be sintered or fused. Many aggregates are not susceptible to this type of treatment, in which case fluxing agents can be used to provide the ceramic surface when heated.

A number of fluxing agents have been developed that, when applied to the aggregate particles and heated to temperatures of from 850 to 2,000 F, will produce waterproof, insoluble, weather-resistant surface coatings for the aggregate particles. Jewett (*28, 91, 17*) has patents on processes and formulas for coating aggregate particles. The type of surface obtained by such processing depends on the flux used and the temperature to which the aggregate is heated. The amount of fluxing agent required varies with the type of flux and the aggregate gradation, but generally varies between 80 and 200 lb of flux per ton of aggregate.

An additional advantage of the ceramic coating process is that the aggregates can be color coded for surface applications. Also, the adhesion characteristics between the aggregate particles and a binding matrix can be greatly improved by the proper choice of flux.

Aggregates can also be coated with thin plastic films of thermosetting and thermoplastics materials. Coating of aggregates with the thin plastic films protects them from the elements, thereby increasing the soundness, and may increase their abrasion resistance. These coatings are not likely, however, to significantly improve the compressive strength of the aggregate particles.

Organic compounds, and specifically linseed oil, have been used to improve the durability of concrete, apparently by reducing the absorption of salts into the concrete pores (*83*). This same technique might also significantly improve the resistance of aggregates to breakdown due to environmental conditions. Care must be taken, however, to ensure that if these aggregates are to be used with a binder, such as in concrete or with bituminous materials, the linseed oil or other organic compounds do not reduce the adhesion, thus promoting stripping of the binder. Attempts have been made to make a surface-active agent from linseed oil by converting it into monoglyceride (*83*) or by emulsifying it with resinous materials. Data are not available to evaluate the effectiveness of these materials.

Use of surface-active agents is another method of improving the performance of aggregates. Such agents are useful in promoting adhesion between the aggregate particles and the binder, especially bituminous binders. Many commercial products might be used for this purpose, such as:

1. Silicones.
2. Long- and medium-chain amines.
3. Cationic and anionic salts, depending on the residual charge on the aggregates.
4. Linseed oil products.

Other adhesion promoters, such as chlorophenylalkyl-substituted carboxylic acids, which have been used to promote adhesion in paints, may also be effective in promoting bond between the aggregates and the matrix.

Ceramic coatings that wear unevenly, or alternate layers of coatings with varying hardnesses, may be used to improve skid resistance in aggregates.

IMPREGNATION

Impregnation of aggregate particles can greatly reduce their absorption capacity and thus would probably increase their soundness. If porous aggregates are impregnated with gaseous or liquid-phase monomeric plastics, and polymerized by radiation or by chemical treatment, significant increases in the strength, impact resistance, and resistance to freeze-thaw of the aggregate may result (*57*).

Experience with impregnation of portland cement concrete may be applicable to porous aggregates. Methyl methacrylate, styrene, and to some extent acrylonitrile, have been effective in increasing the strength and resistance of concrete to frost action (*57*). Polyesters and epoxies can also be used for this purpose, but are much more expensive than the other resins mentioned. Other monomeric plastics will also likely serve the same purpose, but data are not available in the literature to evaluate their effectiveness.

BLENDING

For some uses aggregates may be upgraded to the necessary standards by blending in other aggregates or materials with specific characteristics. Silica sand and particles of cast iron are examples of materials that can be used to increase polishing resistance and improve the skid-resistance characteristics of pavement surfaces.

Substantial quantities of cast-iron particles may be obtained by melting low-quality scrap steel, such as old automobiles, and cooling the molten mass by an appropriate quenching process that will produce metal particles in acceptable sizes for inclusion in the pavement surface layer.

MECHANICAL

Several methods of mechanically beneficiating aggregates are in general use. These include crushing, washing, heavy-media separation, sieving, and blending. Other mechanical methods can also be applied, such as selective crushing, in which only the soft, deleterious materials are crushed and can be removed by washing or heavy-media separation. If rubble is considered as a suitable replacement for aggregates, it can probably be upgraded significantly by selective separation and removal of certain portions such as plaster, wood, and the softer portions that are not suitable for highway construction.

APPENDIX E

SUPPLEMENTARY MATERIALS TO EXISTING AGGREGATES

For many decades the use of synthetic or manufactured aggregates for construction purposes has been suggested. Efforts were being made to incorporate such materials into highway and building construction at a time when the apparent shortage of aggregate was not critical. As a result, such efforts were not well received.

The accelerated pace of highway and building construction today has rapidly diminished the high-quality, natural aggregate resources of the United States. In some areas, the shortage of conventional aggregates is acute and is causing engineers to take another look at "manufactured" supplemental aggregates.

Raw materials for producing aggregate replacements include clays, shales, marls, and industrial wastes such as fly ash and mine tailings. One or more of these materials is available in regions that do not have supplies of conventional aggregates. The problem with these materials often is that they are too small in particle size for conventional aggregate replacements and may be subject to deterioration in strength upon exposure to water. However, there are several possible methods of overcoming these difficulties.

Of some importance to be considered in the manufacture of synthetic aggregates is the possibility of making them better for a given purpose than any available natural aggregate. For example, it appears possible to produce aggregate with a controlled pore structure, controlled chemical composition, and controlled particle shape, as well as other properties. The manufacture and use of such materials could result in improved highway performance.

Development of supplementary aggregate materials must also recognize the need for continuity of supply. The highway industry has in the past developed means of using a waste product, which, after the development stage, either became depleted or was patented and available only at a premium cost. Continuity of supply is particularly important in the development of long-term performance criteria and user competence.

EXISTING SYNTHETIC AGGREGATE SOURCES

A comprehensive review of the existing synthetic aggregate situation through 1964 was presented in *NCHRP Report 8* (*21*). Although six years have elapsed since preparation of that report, few significant changes or additions have been forthcoming; however, the current aggregate situation indicates that supplementary aggregates will increase both in kind and in amount used.

The following methods, both existing and potential, for production of manufactured aggregates are not presented according to any order of preference:

1. Heat treatment of suitable clays and shales.
2. Pelletizing and sintering of raw materials.
3. Pelletizing of raw materials and coating.
4. Mechanical processing of certain wastes:
   - (a) Building and highway rubble.
   - (b) Ceramic waste:
     - (1) Devitrified waste.
     - (2) Glass cullet.
     - (3) Waste ceramic ware.
   - (c) Waste from cast-iron enameling.
   - (d) Wastes from structural clay products:
     - (1) Broken bricks.
     - (2) Broken pipe.
     - (3) Broken tile.
   - (e) Metallurgical slags.
   - (f) Ash clinker:
     - (1) Incineration of sewage sludge.
     - (2) Incineration of garbage.
   - (g) Scrap iron and steel.
5. Heat treatment of nonbloating materials, including sand, soil, and loess.
6. Manufacture by nuclear methods.
7. Heat treatment of waste materials:
   - (a) Coal mine tailings.
   - (b) Fly ash.
   - (c) Collected mineral dusts.
8. Chemical and thermochemical processing of raw materials or solid wastes from conventional aggregate production:
   - (a) Mixing with agent, pelletizing, and curing:
     - (1) Lime.
     - (2) Lime-fly ash.
     - (3) Cements (phosphate, silicate, portland, etc.)
     - (4) Plastics.
   - (b) Mixing with agent, casting brick, curing, and crushing to size.
9. Mechanical processing of marine deposits:
   - (a) Reef shell.
   - (b) Beach sand.
10. Beneficiation of a low-quality aggregate.
11. Combinations of two or more of the previously listed sources.

These methods can be reduced to the following broad categories:

1. Heat treatment of raw minerals.
2. Chemical and thermochemical processing of raw minerals or solid wastes from conventional aggregate production.

3. Pelletizing of raw minerals and beneficiation to suitable quality.
4. Utilization of solid wastes.
5. Beneficiation of low-quality aggregate.
6. Utilization of marine deposits.

Several methods within each of these broad categories have been used to yield manufactured aggregates in the past. Additional methods that utilize the same basic principles of manufacture have been conceived and are potential sources of manufactured aggregate. No method using a basic principle other than those listed previously appears to be forthcoming in the near future.

HEAT TREATMENT

For many years supplementary aggregates have been made in rotary kilns or on sintering grates. These aggregates are usually lightweight and are made from self-bloating clays, shales, or slates.

Nonbloating raw materials can be used for the manufacture of normal-weight aggregates or can be made to bloat by the fuels used.

Combinations of calcareous and argillaceous materials can be used to manufacture aggregates in much the same manner as cement clinker is made. These aggregates have certain desirable properties, such as increased bond with the paste.

In-situ earth materials can be transformed into suitable aggregate material by heat generated from an underground nuclear blast. This approach does not require any preheat treatment of the raw materials; however, it does require greater post-heat treatment than other processes.

CHEMICAL AND THERMOCHEMICAL PROCESSING OF RAW MINERALS

The principle of chemical and thermochemical processing of raw minerals to form a larger agglomerate of minerals that possesses desired properties has been used for some time in the construction industry. A notable example is the sand-lime brick industry, which produces a high-strength brick by autoclaving a mixture of sand and lime. In this process, a chemical combination of calcium with silica occurs to form a calcium silicate that cements the mixture together. This principle can be extended to the production of supplemental aggregates.

Suitable aggregates might be made by mixing a chemically active ingredient such as lime, phosphate, silicate, or cement with a base raw mineral. The base mineral could be any of a number of earthen materials, including sands, clays, soil, loess, or combinations of these, or a waste material such as fly ash. The mixture could then be compacted into aggregate-size agglomerates by pelletizing techniques and stockpiled for curing. The method of curing would be dictated by the reactivity of the base minerals and the type of chemically active ingredient used, and might vary from several days to several weeks. Some combinations (cement, water, and base) would react under atmospheric conditions, whereas other combinations (lime and sand) might require autoclaving.

If pelletizing to the desired aggregate size is not convenient, large bricks could be made and then crushed and screened to the desired sizes.

The aggregate industry produces, along with its various products of crushed stone and gravel, appreciable quantities of solid wastes (*84*). Stringent specifications for higher-quality products are increasing the production of this solid waste material, which represents from 2 to 20 percent of total conventional aggregate production (*84*). Disposal of this waste is a problem, particularly in metropolitan areas. As a result, effective uses are being sought. It may be possible and desirable to use the solid wastes from conventional aggregate production as the raw material for the production of a manufactured aggregate by chemical or thermochemical processing.

PELLETIZING RAW MINERALS AND BENEFICIATION TO SUITABLE QUALITY

One source of a high-quality aggregate that does not utilize excessive temperature would be production of a low-quality aggregate and then beneficiation to the desired quality. The low-quality aggregate could be produced by:

1. Pelletizing suitable raw materials, including soils and clays, by extrusion or balling techniques.
2. Chemical processing of soils.

After formation of the low-quality aggregate, one of the several beneficiation techniques presented in Appendix D could be used to upgrade the agglomerate to the desired quality.

There is a need to make the agglomerate particles resistant to disintegration by exposure to highway environments. Clays and many shales disintegrate or slake upon exposure to water. This process causes a complete loss of strength of clay agglomerates. Smaller losses in strength occur through pick-up of moisture from a humid environment by dry clay lumps. Dry clay alone may have good strength, with values above 4,000-psi crushing strength and 1,000-psi modulus of rupture. The strength will in large part be determined by the clay mineral composition. Exposure to water drastically reduces the strength of the dry clay particle; therefore, primary concern in making aggregate from clay should be directed toward stabilizing the clay lumps against water attack.

The relative ease of producing a low-quality material from the abundant supply of raw material makes this approach quite attractive.

WASTE UTILIZATION

As the nation's solid wastes grow at an accelerated rate, a major threat is posed to the environment. One way of handling a part of the problem of solid waste is to collect it, burn it, and dispose of the resulting ash. It has been estimated that the ash residue is 10 percent of the incinerated solid waste (*29*).

Sources of ash include domestic power plants and municipal incinerators. Production of such ash wastes exceeds 20 million tons per year. Currently, only 4 percent of this material is being used (*29*). Thus, there is a large potential raw material source for aggregate production near developed areas that may have high demands for construction materials but that have a low production of conventional aggregates because of exhausted supplies or restrictive zoning.

The ash residue from solid wastes and other collected mineral dusts could be transformed into supplemental aggregate by either a heat treatment or a thermochemical process. It may even be possible to use a solid waste incineration process as a heat source to improve the economics of production.

A number of solid wastes can not be disposed of by incineration. Included in this category are rubble from buildings and replaced highways, battery cases, rubber tires, scrap iron and steel, ceramic wastes (such as broken tile and glass), metallurgic slags, and clinkers. Some of these wastes have been used for construction purposes on a limited basis.

Some waste residues may be incorporated in impervious media such as asphalts or plastics. Wastes so incorporated should have very low leach rates in water, emit little or no odors, and should not settle or shrink. These products may be used directly or combined with other insoluble aggregates, such as limestone and sand, for road surfacing or the manufacture of building blocks.

At Oak Ridge National Laboratories, the possibility of using discarded tires as a constituent and commercially acceptable building material was investigated. In small-scale tests, used tires were shredded, diced, ground, and mixed with asphalt to produce materials that could be useful in the paving and construction industries or in other areas where asphaltic mixtures are used.

Unfortunately, with regard to aggregate production, the supply of some waste materials is small and, except in unusual circumstances, cannot justify the facilities needed to convert them to suitable aggregates. Other wastes occur in such quantities and in sufficiently continuous supply that they warrant the research effort and facilities needed to transform them into suitable aggregates.

Reclaimed rubble from highways has been successfully used for pavement construction in Texas. However, much development is needed to increase the efficiency of the equipment for processing the rubble.

The cement content of some rubble may be detrimental for use in portland cement concrete; therefore, stabilization techniques to reduce shrinkage may have to be investigated. Although it may be possible in processing to separate the cement from the aggregates in the rubble, some of the rubble might be more satisfactory as subbase and base materials than in concrete products and, thus, be less costly to recycle.

BENEFICIATION OF LOW-QUALITY AGGREGATE

Many available natural aggregates have serious deficiencies, such as poor abrasion resistance or reactive constituents. Furthermore, some aggregates of low quality may be manufactured inexpensively.

It may be possible and practical to utilize all of these low-quality aggregates in highway construction if they are beneficiated as suggested in Appendix D.

MARINE DEPOSITS

In several states, especially those bordering the Gulf of Mexico, large quantities of reef shell and beach sand occur in areas where there is a scarcity of conventional aggregates. Results of research indicate that these materials do not meet existing quality specifications, but nonetheless produce concrete of suitable strength for certain purposes. Such aggregates do not meet usual grading, particle shape, and abrasion loss requirements.

Use of reef shell and beach sand has been recommended in those constructions where strength greater than 2,500 psi in compression and 550 psi in flexure, and high abrasion resistance, are not required *(76)*. These materials have been used for base construction, as well as in portland cement concrete and bituminous concrete surfacing. Their use sometimes permits the utilization of otherwise unsatisfactory fine-grained materials. Although some difficulties might be encountered in their use, modification of conventional practice and careful selection of mixture compositions can result in a system that has satisfactory performance characteristics.

The results of research efforts on marine deposits illustrate the need for modification of some existing specifications to permit use of supplemental aggregates that have been shown to result in suitable end-product performance.

TECHNICAL FEASIBILITY OF A SUPPLEMENTAL AGGREGATE SOURCE

The feasibility of using any supplemental aggregate in highway construction is determined by its cost and field performance. Thus, each aggregate should be evaluated for the area in which its use is considered. A given material may not be suitable for all areas or for all construction purposes in a given area. It is impossible, therefore, to generalize the potential utility of various types of manufactured materials without detailed information concerning their potential uses.

APPENDIX F

DESIRABLE PROPERTIES OF AGGREGATES

Manufacturers of supplemental aggregates for highway use must give careful attention to the control of the quality of the aggregate they produce. The supplemental aggregates must possess the necessary properties that (1) will permit a pavement to function as the support subsystem for the motor vehicle by providing the support and surface conditions necessary for the safe, economical, and comfortable operation of vehicles on the pavement; and (2) will allow the aggregate to be satisfactorily manipulated and handled during construction of the pavement.

The specific properties that a supplemental aggregate must have to fulfill these functions are discussed in this appendix. The information is provided as a guide to the producers of supplemental aggregates who are unfamiliar with conventional aggregates, but who need to know the specific properties that are required of the supplemental aggregate they are contemplating producing. This is not a comprehensive treatise of aggregates written for the highway engineer; other publications and research have dealt with this topic. Included herein, however, are explanations and definitions of the needed aggregate properties so that persons may obtain an initial overview of what is required in a highway aggregate. If additional detailed data are desired, they must be obtained elsewhere.

The aggregate is not the only physical element of the pavement system that influences the ability of the system to fulfill its intended functions. The binder (portland cement, asphalt cement, etc.) and the interaction between the binder and the aggregate have a significant influence on the performance of the pavement system. Although important, the influence of such factors is not considered herein. Only those properties of the *aggregate* that influence the behavior of pavements are discussed.

Although many of the needed properties of the aggregate, such as strength, are required at some level regardless of how the aggregate is used, the actual levels of all the needed properties are influenced by how the aggregate is used in the pavement system. Aggregates used in portland cement concrete must have levels of some properties that are different than those of aggregates used in producing asphaltic concrete and in some cases different properties are involved; e.g., reactive aggregate may be a serious problem in portland cement concrete, but is not a problem in asphaltic concrete. When possible, then, the importance of different aggregate properties to a specific type of construction is noted.

Just to identify the properties that a good aggregate must possess is not enough; it is also necessary to be able to quantify each property. This means that standard tests must be used or new tests must be developed that can be used either to measure the properties or to obtain an indication of the quality of the aggregate with respect to a certain property.

The ideal aggregate is seldom available. Thus, after tests that measure aggregate properties are developed, for each such test criteria must be established that will be able to differentiate between satisfactory and unsatisfactory aggregates. Such criteria are difficult to establish, as they are related to the performance of the pavement and the quality of aggregates available in the area. The problem is to describe the level of performance that is required for a given situation and area, and to determine the degree to which it is economically available. It is then necessary to appraise the available aggregates and either use what is available or manufacture new aggregates that possess the desired performance level.

In this appendix the various functions of a pavement are discussed. Subsequently, the properties that an aggregate must possess in order that the pavement system may fulfill its various functions are determined. Finally, each property is defined and discussed in detail. Tests that are used to measure the properties are not discussed; nor are acceptability criteria for use with the various tests given. Appropriate tests and criteria are dependent on the level of performance desired and on economic considerations, and therefore may vary from place to place and from time to time.

FUNCTIONS OF THE PAVEMENT SYSTEM

To the driver of or a passenger in a motor vehicle, the primary function of a pavement system is to provide the support and surface conditions necessary for the safe, economical, and comfortable operation of the vehicle, with due consideration to the operational characteristics of the vehicle. The highway engineer is interested in pavement systems that have the properties to provide these functions economically. He is also interested in the durability property of the pavement system and of the pavement materials in the system because of the influence they have on economic considerations.

The characteristics of a pavement system required to provide acceptable performance (economics) of its functions for a reasonable period of time (durability) are as follows. A discussion of these characteristics as related to the properties needed in an aggregate is given in a later section.

1. Adequate internal strength and stability to distribute surface pressures to the subgrade and to prevent extensive surface deflection.
2. Resistance to deteriorating effects of weather and chemical actions.

3. Resistance to deteriorating effects produced by traffic.
4. Resistance to the effects of internal forces, such as expansion, contraction, and warping.
5. Limitations to temporary or reversible internal changes in load-carrying capabilities introduced by environmental elements.
6. Aggregate and binder compatibility.
7. Retention of a pavement surface that will assume acceptable standards of performance. For the surface to have this characteristic, consideration must be given to the following surface properties:
   (a) Skid resistance.
   (b) Surface roughness.
   (c) Glare and light reflection.
   (d) Loose material.
   (e) Tire wear.
   (f) Rolling resistance.
   (g) Noise level.
   (h) Electrostatic properties.
   (i) Appearance.

CONSTRUCTION REQUIREMENTS

Even though aggregates may have the desirable properties that allow the pavement system to perform satisfactorily, they also must possess certain characteristics that are dictated by construction procedures. For example, the integrity of aggregates used in the construction of hot-mixed asphaltic concrete must be retained at high temperatures (300 F), because the temperature of the aggregate is increased during drying operations. Once the mixture is compacted and "cooled" in the pavement system, the probability of the aggregate being heated to these temperatures again is almost negligible. The aggregate must possess those properties that will allow the aggregates to be satisfactorily manipulated and handled during shipment and storage of the aggregate, mixing of the aggregate with binder or other types of aggregates, placement of the mixture in the pavement, and compaction and/or curing of the pavement mixtures.

AGGREGATE PROPERTIES FOR SPECIFIC HIGHWAY USES TO MEET FUNCTIONS OF SYSTEM

Table F-1 summarizes the various properties of an aggregate that influence a specific function of the pavement or that are needed to satisfy construction requirements. The relative importance of a specific aggregate property, by various types of pavement materials, is also given. Numerical ranges of the properties are not given, as the range will depend on the test used to measure the specific property and the desired level of performance as influenced by economics.

DEFINITION AND DISCUSSION OF NEEDED AGGREGATE PROPERTIES

A quality that is indicative of a specific characteristic of a material is a *property*. There are a number of properties of a material that identify its behavior under different conditions. For instance, there are elastic properties, magnetic properties, chemical properties, physical properties, mechanical properties, etc. A property may or may not be identified by a numerical quantity, but preferably it should be.

Various aggregate properties, identified in Table F-1, are defined and discussed in this section. For the discussion, the properties have been grouped in the following categories:

1. Physical.
2. Mechanical.
3. Chemical.
4. Thermal.
5. Electrical.
6. Optical.
7. Aesthetic.

Supplemental aggregates need not possess all of the listed properties, nor do they necessarily have to be of the highest quality in each of the properties. The important properties and the quality needed in supplemental aggregates depend on the uses of the aggregate in the pavement, the type of binder used, the performance desired, and economics. These requirements should be established by the contracting agency for each particular construction application.

Two general properties of the aggregate must always be considered. They rarely cause a problem, however, and many times they are forgotten. These two properties relate to:

1. Freedom from contamination with deleterious substances (deleterious substances that contaminate the aggregate, such as sticks, dissimilar metal pieces, paper, clay lumps, coal, should be minimized).
2. Aggregate uniformity (aggregate particles should be uniform within a given batch and from batch to batch).

Physical Properties

The physical properties of a material identify or describe the material in terms of the fundamental dimensions of length, mass, and time. As examples, some physical properties of a material are size, shape, specific gravity, and pore structure. Physical properties identified as being important for aggregate for use in highway construction are discussed in the following.

Particle Grading

Particle grading is the distribution of different particles of aggregates among various sizes; e.g., the relative amounts of ⅜-in. to ½-in. size, ¼-in. to ⅜-in. size, etc.

The grading of the aggregate influences both the mass stability of the pavement and the roughness of its surface. Regardless of the type of paving material, the better the grading, the greater will be the strength of the mixture. The optimum grading is usually the particle size distribution that allows the maximum amount of aggregate to be included in a unit volume of pavement. One exception is the macadam base, which is composed of large, essentially one-size aggregate (1 in. to 2 in.). When the surface of the pavement is composed of large, protruding aggregates,

TABLE F-1

AGGREGATE PROPERTIES FOR SPECIFIC HIGHWAY USES TO MEET FUNCTIONS OF SYSTEM

FUNCTION	AGGREGATE PROPERTY	RELATIVE IMPORTANCE OF PROPERTY[a] IN SPECIFIC MATERIAL		
		PCC	BIT. CONC.	BASE
1. Adequate internal strength and stability to distribute surface pressures to the subgrade and to prevent extensive surface deflections	1. Mass stability	NA	I	I
	2. Particle strength	I	I	I
	3. Particle stiffness	I	I	I
	4. Particle surface texture	I	I	I
	5. Particle shape	I	I	I
	6. Grading	I	I	I
	7. Maximum particle size	I	I	I
2. Resistance to deteriorating effects of weather and chemical actions	1. Resistance to attack by chemicals, such as salts	I	U	NA
	2. Solubility	I	U	I
	3. Slaking	I	I	I
	4. Resistance to wetting-drying	I	U	I
	5. Resistance to freezing-thawing	I	U	I
	6. Pore structure	I	I	I
3. Resistance to deteriorating effects produced by traffic	1. Resistance to degradation	I	I	I
4. Resistance to effects of internal forces, such as expansion, contraction, warping	1. Volume change, thermal	I	N	N
	2. Volume change, wetting and drying	I	N	N
	3. Pore structure	I	N	N
	4. Thermal conductivity	I	N	U
5. Limitations to temporary or reversible internal changes in load-carrying capabilities introduced by environmental elements	1. Resistance to temporary strength change	I	I	I
6. Aggregate and binder compatibility	1. Chemical compounds reactivity	I	I	N
	2. Organic material reactivity	I	N	N
	3. Coatings	I	I	N
	4. Volume stability, thermal	I	N	N
	5. Base exchange	I	I	I
	6. Surface charges	N	I	N
	7. Pore structure	U	N	N
7. Retention of a pavement surface that will assure acceptable standards of performance. To have this characteristic, consideration must be given to the following surface properties:				
(a) Skid resistance	1. Particle shape	I	I	NA
	2. Particle surface texture	I	I	NA
	3. Maximum particle size	N	I	NA
	4. Particle strength	I	I	NA
	5. Wear resistance	I	I	NA
	6. Particle shape of abraded fragments	I	I	NA
	7. Pore structure	I	I	NA
(b) Surface roughness	1. Maximum particle size	I	I	NA
	2. Grading	I	I	NA
(c) Glare and light reflection	1. Reflection	I	I	NA
	2. Glare	I	I	NA

TABLE F-1 (Continued)

(d) Loose material	1. Resistance to degradation	I	I	NA
	2. Specific gravity	N	N	NA
(e) Tire wear	1. Particle shape	I	I	NA
	2. Particle surface texture	I	I	NA
	3. Maximum particle size	I	I	NA
(f) Rolling resistance	1. Maximum particle size	U	I	NA
	2. Particle shape	I	I	NA
(g) Noise level	1. Maximum particle size	U	I	NA
(h) Electrostatic properties	1. Electrical conductivity	U	I	NA
(i) Appearance	1. Particle color	N	N	NA
	2. Oxidation and hydration reactivity (stains and popouts)	I	N	NA
8. Retention of properties during the construction process that support all other functions of the system	1. Maximum particle size	I	I	I
	2. Resistance to degradation	I	I	I
	3. Integrity during heating	N	I	N

[a] I = Important; N = Not important; U = Importance unknown; NA = Not applicable.

the rough surface can be improved by filling the voids between the large aggregate with finer aggregate. The gradation also influences the workability of binder-aggregate mixtures; mixtures with well-graded aggregates can be handled easily and the surface can be smoothly finished.

Particle Shape

Angular particles are generally preferred. In bituminous mixes and unbound base materials, angular, cubical particles are desired to permit development of aggregate interlock and thus increase the shear strength of the mixtures. However, aggregate of any shape can be used in portland cement concrete to obtain high strength, provided the water/cement ratio is adjusted. Angular aggregates are also desirable at the surface of the pavement to promote high skid resistance. But these same angular particles can be detrimental in that they may increase tire wear and the rolling resistance of the pavement surface.

Maximum Particle Size

Maximum particle size is the size of the screen opening of the sieve on which not more than a stated maximum amount of the aggregate may be retained; or, if the aggregate size range is stated in terms of two sieves (as ½ in. to ¾ in.), the larger of the two stated sizes of sieves.

Although most paving mixtures (except macadams) can be satisfactorily constructed with a wide range of maximum aggregate sizes, some desirable characteristics of the pavement are improved by using large-size aggregates. For instance, the strength of the mixture generally is increased and skid resistance of the pavement at high speeds is greater when large-size aggregates (>½ in.) are present. However, large-size aggregates at the surface of the pavement increase the noise generated, the amount of tire wear, and the rolling resistance. During mix production large-size aggregate usually accelerates the wear and breakage of parts in the mixer and the dryer; during laydown they may cause segregation to take place; and during finishing they can produce a harsh mixture that is difficult to handle and to finish smoothly.

The maximum size of the aggregate may be a very important consideration in the production of supplemental aggregates. In many geographical areas there is a dearth of large-size aggregates, but an abundance of small-size conventional aggregates (e.g., sand with a top size of approximately 0.08 in. or No. 10 sieve). Larger-size aggregates are needed for combination with these fine materials so that the strength of the mixture may be increased, for economic reasons, etc. Thus, production of large-size supplemental aggregate is almost a must. Fine-size aggregates are usually not a problem if large-size aggregates can be produced, because the large-size aggregates can probably be economically reduced to smaller size.

Particle Surface Texture

Particle surface texture is the degree of roughness or irregularity of the external surfaces of an aggregate particle.

Normally, rough-surfaced aggregates are preferred, although smooth-surfaced aggregates can be used satisfactorily in some paving materials. The strengths of bituminous mixtures and unbound aggregate bases are increased when rough aggregates are used. Also, rough aggregates are needed in surface mixtures to help provide high skid resistance. When rough surface texture is removed through wear, the skid resistance is decreased. Aggregates with any texture can be used in portland cement concrete provided the mixture is properly proportioned. A paradox exists, however, in the type of surface texture needed to prevent stripping of bituminous materials from aggregates. During mixing, a smooth aggregate can be well-coated with the bitumen; but the bitumen can be stripped easily from smooth aggregates. It is generally thought that a rough surface texture contributes more to the prevention of stripping than does a well-coated smooth aggregate. Thus, rough-surfaced aggregates generally are preferred.

Pore Structure

The pore structure is the structure (size, volume, and shape) of the void spaces within the aggregate. Pores can be impermeable (i.e., an enclosed cavity) or permeable (extend to an opening on the surface of the aggregate). Pores can also be continuous, so that large volumes of permeable voids are formed, or they may be dispersed, small-volume voids.

Large volumes of permeable pores are normally not desired in conventional aggregate. When an aggregate is subjected to repeated cycles of freezing-thawing and/or wetting-drying, a deteriorating effect may be produced. If the aggregate, when subjected to these conditions, can absorb large volumes of salt solutions and water into the pores, the deterioration can be greatly accelerated. Large-volume permeable pores also can absorb binder material and this extra binder increases the cost of the paving mixture. It is desirable, then, that the pores be not only of low volume but also well dispersed and not continuous.

In conventional aggregate, there are several advantages in having pores in the surface of the aggregate. Normally, surface pores contribute to the sharpness of the surface texture, resulting in greater skid resistance of the pavement surface. Also, the water that is absorbed by aggregates used in portland cement concrete is available for release at a later time, with a concomitant improvement in the curing conditions. Although it is recognized that these advantages exist, supplemental aggregates do not have to contain permeable pores, provided rough surface texture can be obtained.

Specific Gravity

The specific gravity of an aggregate is the ratio of the weight of a given volume of the aggregate to the weight of an equal volume of water.

In an aggregate, specific gravity (G) is not, in itself, an important property; an aggregate with $G = 2.70$ is not necessarily better than an aggregate with $G = 2.55$. However, deleterious particles present in an aggregate may be lighter than the good aggregates and separation can be based on the difference in specific gravity.

Lightweight synthetic aggregates ($G < 1.6$) have one advantage over heavier aggregates. Considerably less damage is produced by loose lightweight aggregates than by heavier aggregeates if they are flung into the air. Thus, if lightweight aggregates can be produced with all other desirable properties, they would be preferable for use in pavement surfaces.

Mechanical Properties

The mechanical properties of a material identify the behavioral characteristics of the material when subjected to applied forces. There are a number of mechanical properties, but some of the more common ones are strength, stiffness, ductility, and hardness. Those mechanical properties desirable in an aggregate are discussed in the following.

Mass Stability

Mass stability is that property which permits an aggregate mass to remain stable and to retain its load-carrying capabilities under various types of loading.

Mass stability is a desired over-all property of the pavement that is influenced by a number of properties related to the aggregate and the binder, such as particle gradation, shape, and surface texture. Loss of mass stability leads to surface rutting and/or cracking of the upper layers of the pavement system.

It may be that in the development of supplemental aggregates mass stability can be obtained without the aggregates themselves having all of the properties usually desired in the individual particles. If this can be done, the individual particles need not have all of the desirable properties of an aggregate.

Particle Strength

Particle strength is the magnitude of the tensile and/or compressive stress that can be supported before failure occurs.

In general, aggregate particles should have high strength. A good-quality portland cement concrete can be made, however, with "soft" aggregate particles, inasmuch as a major portion of the strength of concrete is contributed by the cement matrix. This may not be true when other binders are used.

It is currently difficult to determine aggregate strength. Because aggregates are individual pieces, it is difficult to measure the strength of the particles because of varying shape and size. Also, there is some question as to whether the strength of individual particles or the strength of the compacted aggregate mass should be evaluated. Current practice usually uses the Los Angeles abrasion test to indicate the strength of the aggregate particles, as well as their resistance to abrasion.

Most aggregates are brittle; therefore, it has been suggested that perhaps a surface energy concept could be applied to establish the "strength" of the aggregate particles. However, this concept may not be universally applicable, as nonbrittle particles may be more desirable for portland cement concrete aggregates than brittle particles.

Particle Stiffness

Particle stiffness is the resistance of an aggregate to deformation, as usually indicated by the modulus of elasticity of the material (the ratio of the applied compressive or tensile stress to corresponding strain).

Many of the comments pertaining to the strength property are applicable to the stiffness property. Although particle stiffness is desirable, it has rarely been measured and is seldom used in design because of the problem of handling particles of varying size and shape.

Engineers usually like to have an aggregate with high stiffness for most pavement materials. However, some engineers believe that an aggregate with low stiffness would be desirable in portland cement concrete. If an aggregate is very stiff, microcracking of the cement paste surrounding the particle can occur during curing and during the plastic shrinkage stage of the hydration process. These microcracks may lead to poor performance when the concrete is subjected to repeated loadings.

Wear Resistance

Wear resistance is the ability of the surface of the aggregate to resist being worn away by rubbing and friction produced by externally applied forces which result in the polishing, wearing, and rounding of the aggregate.

Aggregates used in pavement surface layers should have resistance to polishing and wear by the motor vehicle tires and should wear nonuniformly to promote the skid resistance of the pavement surface. Because the rate of polishing is related primarily to the types of minerals in the aggregate, a high percentage of hard, well-bonded mineral grains in a softer matrix should be present in the aggregate if the aggregate is to resist the abrasive smoothing actions of the tires.

Resistance to Degradation

Resistance to degradation is the ability of the aggregate to resist breakdown into smaller pieces when subjected to applied forces such as those produced by heavy wheel loads, mixer blades, etc.

Degradation is different from wear. When wearing occurs, the small pieces that abrade off the aggregate are brushed aside by moving tires and no longer influence the behavior of the pavement system. However, when degradation takes place, the broken pieces of aggregate (usually larger than those abraded off during wearing) remain and contribute to the behavior of the pavement surface. Degradation as defined in this section does not include breakdown due to chemical processes.

As the pavement deflects and rebounds under moving loads, aggregate within the pavement system also moves. When such movement is large, aggregate edges can be worn off, fracturing of the aggregate can take place, and a general degradation of the aggregate can occur. If degradation occurs, consolidation of the pavement system may result, with associated cracking and breakup of the upper layers of the system. The property is especially important in poorly compacted unbound bases and subbase materials.

The degradation property is also important in aggregates at the surface of the pavement. If surface aggregates degrade, loose particles may be thrown into the air by the vehicle tires, with resulting hazards to the vehicle or its occupants, or to other vehicles or persons. Degradation that takes place while the aggregate-binder mixture is being mixed, or while being compacted during the construction process, can detrimentally change the original gradation of the aggregate.

Particle Shape of Abraded Fragments

Particle shape of abraded fragments is the spatial shape of the small fragments that are broken and worn away from the aggregate during abrasion.

Abrasion of the aggregate may not be detrimental per se; whether or not it is depends on the characteristics of the particle abraded from the surface of the aggregate. If the particle is rounded in shape and very small in size, polishing of the aggregate may result, with a reduction in the skid resistance of the pavement surface. However, if rough aggregates are worn so that "slivers" are broken loose, new sharp fractures may be developed that allow the aggregates to retain their surface roughness and their high skid resistance.

Chemical Properties

The chemical properties of a material identify it chemically and/or indicate the transformation the material can undergo due to a chemical process. Acidity, corrosion resistance, and solubility are examples of chemical properties.

Whenever an aggregate undergoes a change due to a chemical action, the forces providing the change are usually from sources external to the pavement system. In some instances, however, serious deterioration can be produced by chemical action initiated by compounds that are components of the binder. Thus, the aggregate should be chemically compatible with the binder.

Solubility

Solubility is the tendency of an aggregate to be dissolved by a liquid.

Water is always present around a pavement, so the aggregate should not be soluble in water. In some localities, water with unusual chemical contents (e.g., runoff from coal mine slag heaps) may be present and the aggregate also should not be soluble in these solutions.

Slaking

Slaking is the crumbling of the aggregate into visible pieces (particles) when water or other liquids destroy the bond between the particles.

A condition similar to the dissolving of the aggregate is the slaking off of large pieces of the soaking aggregate (e.g., hard clay lumps are not used as aggregates because they slake when immersed in water for a period of time). Aggregates should not slake in water or other liquids that may be present in the pavement.

Base Exchange

Base exchange is the replacement of one type of cation adsorbed on the aggregate surface by another type of cation.

Certain cations can be added to the surface of aggregates by adsorption. These cations aid in the release of alkalies from zeolites and adsorbed clay in the aggregate. Consequently, the alkalies can react with portland cement concrete in the same manner as the action described under "Chemical Compound Reactivity." Aggregates should have surface properties that prevent detrimental base exchanges.

Surface Charge

The adhesion of bituminous binders to the aggregate is influenced to a considerable extent by the polarity of the charge on the surface of the aggregate. Water can be strongly attracted to a highly polarized aggregate. This attraction could be so strong that the asphalt may not be able to displace the water and coat the aggregate, or water may strip off the bituminous binder already coating the aggregate. Thus, proper surface electrical charges that will produce good adhesion are needed on the surface of the aggregate.

Coatings

A coating is a deposit of mineral and/or chemical substances on the surface of the aggregate.

Instances have occurred in which natural aggregates have been coated with precipitated salts. Aggregates also may be coated with materials such as dust and clay. If coatings are firmly bound to the aggregate and are nonreactive with either the aggregate or the binder, the coatings may be quite acceptable. However, coatings should not be permitted if they prevent good adhesion between the aggregate and the binder or if they react with the aggregate or the binder.

Volume Change—Wetting and Drying

Some conventional aggregates shrink or swell with changes in the moisture content of the aggregate. It is desirable that aggregates have little or no volume change with variations in moisture content, because such volume change (swelling or shrinkage) may produce disruptive forces that may fracture the pavement mixtures. The magnitude of volume change due to wetting and drying is generally related to the volume of permeable pores in the aggregate.

Resistance to Attack by Chemicals

Resistance to attack by chemicals refers to the ability of the aggregate to resist deteriorating attacks from chemicals, such as salts, that may be carried into the pavement system in a solution.

Many aggregates react with salts, such as calcium or sodium chloride, that are placed on the pavement surface for winter maintenance. This reaction can be accelerated by cyclic freezing and thawing. The resulting disruptive stresses can produce pavement deterioration. Aggregates should be resistive to deterioration produced by highly soluble chemicals if their presence is anticipated.

Resistance to Freezing-Thawing

Aggregates can deteriorate (a general flaking process takes place) when the aggregate is subjected to repeated cycles of freezing and thawing. This process occurs because the water present in the pores of the aggregate produces disruptively high internal hydrostatic pressures. The resistance of the aggregate to freeze-thaw action is influenced by the volume and size of accessible pores in the aggregate. Aggregates, when used in areas where there is a large fluctuation of temperature around the freezing point of water, should be resistant to these types of destructive forces.

Resistance to Wetting-Drying

The swelling and shrinking that may accompany increases and decreases in the moisture content of an aggregate may produce large internal tensile stresses, which may cause cracking and flaking of the aggregate. This phenomenon should not be permitted in those pavements and materials where water can gain access to the aggregate, such as unbound macadams and nonstabilized bases and subbases. However, when the aggregate is used with an impervious binder (such as bituminous materials), this property is not as important and less-resistant aggregates can be used.

Resistance to Temporary Strength Changes

Aggregates should retain their strength properties on a "permanent" basis. Some pavement materials lose a portion of their load-carrying capability by variation in such external factors as some climatic conditions. As an example, clay subgrade, when it becomes saturated with water, will lose considerable strength. When the clay is dried out, its load-carrying capabilities are increased. Similarly, bituminous mixtures have lower resistance to shear strength at high temperatures than at low temperatures. A temporary loss in the strength of the pavement system, initiated by some external influencing condition, should not be a result of the aggregate used.

Temporary strength changes do not take place in the conventional aggregates now used. Therefore, material engineers have not been concerned with this property. However, it is conceivable that supplemental aggregates may be developed, from certain types of materials such as plastics, that may lose strength when the temperature is increased and regain it when the aggregate is cooled. The acceptability of such aggregates depends on the magnitude of the temporary strength loss and the relative influence that the loss would have on the entire pavement structure.

Chemical Compound Reactivity

Chemical compound reactivity refers to the change in the structure of an aggregate produced by chemical reactions with the binder.

Chemical compounds (such as sulfates) in the aggregate may react with certain binders in paving mixtures. Compounds (such as alkalies) in the binder also may react with the aggregate. These chemicals can be quite detrimental to the integrity of the mixture. Regardless of the location of the detrimental compounds, aggregate and binder should be chemically compatible.

Oxidation and Hydration Reactivity

Certain minerals may exist in an aggregate that are affected chemically by oxidation and hydration from atmospheric elements. The chemical process can produce such compounds as iron oxide, which discolors the surface of the pavement. Other reactions can produce particle expansions that result in "popouts" of the surface.

Reactions such as these do not ordinarily have a serious effect on the strength or durability properties of the pavement system. They do, however, influence the aesthetics of the pavement surface. Thus, aggregates used in the surface layer of a pavement should not contain minerals that will produce surface stains and disfigurations.

Organic Material Reactivity

Organic materials may exist in aggregates. For example, crushed limestone aggregates may be naturally impregnated with bituminous material. An organic material may react with ingredients of portland cement concrete and similar mixtures to produce a decrease in strength and/or rapid deterioration. Certain organic materials should not be present in aggregates used in these mixtures.

If supplemental aggregates are produced from organic materials for use in portland cement concrete, deleteriously reactive organic compounds should be rendered nonreactive during the manufacturing process. Aggregates produced from organic material for use in bituminous mixtures, however, may be acceptable without modification.

Thermal Properties

Thermal properties identify the behavior of a material when subjected to changes in temperature. The behavior response is a result of thermal excitation of the molecules of the material. Examples of thermal properties are coefficient of thermal expansion, specific heat, and thermal conductivity. The most important thermal properties that must be considered in the selection of aggregates are thermal volume change, thermal conductivity, and integrity of the aggregate during heating.

Volume Change—Thermal

Aggregates with large coefficients of thermal expansion ($> 7 \times 10^{-6}$ per °F) may produce cracking in a rigid pavement. When a pavement is prevented from expanding or contracting due to temperature changes, high stresses can develop that may lead to fracture of the pavement slab. Thus, it is desirable that aggregates have a coefficient of thermal expansion that is compatible with the coefficient of expansion of the binder. The coefficient of thermal expansion of aggregates should also be approximately the same in all directions and at all exposure temperatures. Further, all minerals present in the aggregates should have the same coefficient of thermal expansion.

The aggregate must also be compatible with the binder used in the paving mixture. If a rigid binder has a coefficient of thermal expansion that is considerably different from that of the aggregate, differential expansion may take place and large tensile stresses can develop. Thus, the coefficient of thermal expansion of the aggregate should be approximately equal to that of the binder. If there is a significant difference in the two coefficients of thermal expansion, a viscoelastic binder or aggregate might be used satisfactorily.

Thermal Conductivity

Aggregates with low thermal conductivity are desired to decrease the depth of frost penetration through a pavement system. Conversely, aggregates that transmit heat rapidly may help to prevent the development of large differential temperatures between the top and the bottom of a rigid pavement slab. The resulting uniformity of temperature within the slab can decrease the magnitude of the warping stresses and reduce pavement cracking.

Integrity During Heating

Integrity during heating is the ability of an aggregate to retain its desirable properties when heated to high temperatures (300 F).

In the production of hot-mix bituminous concrete, the aggregate is dried by heating to temperatures of approximately 300 F. Aggregates used in such mixtures should not be affected by high temperatures so that the aggregates break apart, become weak, or have other characteristics modified by heat.

Electrical Properties

Electrical properties of a material identify its behavioral characteristics that are affected by an application of an electrical charge to the material. Magnetic, electrical conductivity, and dielectric strength are electrical properties. Only one electrical property—conductivity—appears to have any influence on the behavior of aggregates in the pavement system.

Conductivity

Aggregates should be able to conduct electricity. This property is needed for two reasons. First, a motor vehicle generates static electricity during its movement. The charge should not be allowed to build up and thus needs to be discharged through the pavement to the ground. Second, the aggregate should not contribute to the development of static electricity when a motor vehicle's rubber tires rub on the pavement surface. It is possible that this latter condition might develop if supplemental aggregates are produced from certain plastics. If the aggregate conducts electricity, the build-up in static electricity can be minimized.

Optical Properties

Optical properties of a material identify the effects that the material has on the genesis and propagation of light. Polarization and refraction are examples of optical properties. Two optical properties—reflection and glare—should be considered in selection of aggregates.

Reflection

Reflection is the returning of light waves by the surface of an aggregate.

Even though most conventional aggregates have little reflectivity, reflective aggregates are desirable to contrast the road surface and its surroundings. They can increase the delineation of the road surface when it is illuminated by the vehicle's lights. Also, reflective aggregates can reduce the amount of power needed in overhead lights used to illuminate city streets and intersections at night.

Glare

Glare is the shining of a strong, steady, and dazzling light from the aggregate.

Lights from oncoming cars and from overhead lights may create a glare on some pavement surfaces, depending on constituent material characteristics. Bright, intense light can decrease the night vision of the driver of the vehicle and create a hazardous condition. If possible, aggregate particles on the surface of a pavement should not create a glare condition.

Aesthetic Properties

Aesthetic properties of a material identify those characteristics that make the material pleasing to the eye; i.e., beauty. Some aesthetic properties are color, intensity, harmony, and texture. Of these, color may be the most important for aggregates.

Color

Color is the property of reflecting light waves of a particular length from the aggregate particles.

Aggregates for highway construction should have a pleasing color. Vivid, intense colors are distracting to the driver and should be used only when a delineated surface is desired. Although aggregates of various colors can be used, the aggregate particles used in a particular paving mixture should be of uniform color.

APPENDIX G

DISCUSSION BY A PROJECT CONSULTANT

Inorganic wastes and naturally occurring materials not presently used as aggregates for concrete may be converted to such use by heat or steam treatment or, in some cases, simply by crushing and screening. Portions of taconite and chrysotile tailings, phosphate slag, crystalline metallurgical slags, calcined clays and shales (waste brick and tile), and certain mining wastes might provide suitable aggregates without heat treatment.

In the more common cases, materials of potential value will require conversion by pyroprocessing at temperatures of 2,000 F or higher or by hydrothermal treatment at temperatures to 400 F or higher. In either case, silica, alumina, and iron are essential constituents of the raw material; for hydrothermal treatment, lime is also required.

Materials with high glass content (such as fly ash) or high glass-forming potential (such as clays and shales) are suitable for thermal treatment. At the point of fusion, glass provides the medium for chemical reaction and becomes the binder and hardener of the finished aggregate. Thus, the production of portland cement clinker and pyroprocessed aggregates involve a common ceramic technology.

All of the heating devices used in the production of portland cement can be used to produce ceramic aggregates: rotary kilns, sintering strands, shaft kilns, and Lepol kilns (sintering grate plus rotary kiln). Fluidized beds, vibrating hearths, and tunnel kilns have been proposed for the burning of clinker and aggregates. Naturally occurring shales, clays, and slates, fly ash, colliery shale, taconite tailings, and nonmetallic refuse incinerator residue may be processed in these devices.

Hydrothermal synthesis may be used to harden pelletized mixtures of cementitious and pozzolanic materials. Presence of a glassy phase is not essential in raw materials hardened under autoclave treatment; lime and silica mixtures are readily hardened in the autoclave. Presence of a glassy phase in granulated slags, fly ash, calcined shales and clays, and pumice appears to enhance markedly the reactivity of these materials with portland cement or lime under both atmospheric pressure steam and autoclave treatments. Hydrothermally processed aggregates are essentially calcium silicate-bound, but aluminum and iron compounds appear to contribute importantly to the formation of structure. Satisfactory pelletized aggregates have been made on a pilot scale using a 1 to 19 blend of portland cement and fly ash that has hardened at room temperature. Autoclaved pellets of waste lime, fly ash, and granulated slag have also been made. Many combinations can be used as long as the blended ingredients contain lime, silica, and alumina in forms that react to provide calcium silicate hydrates to harden the pellets. Finely divided crystalline slags (including phosphate slag, alumina "brown mud," calcined chrysotile, taconite tailings, pumice and pumicite, ground brick and tile, glass polishing waste, ground glass, incinerator ash and slag) and other materials can react with portland cement or lime at sufficiently high temperatures of autoclave curing. Waste carbide lime, phosphogypsum, limestone flour, and volcanic ash are other potentially suitable ingredients.

Preparation of raw materials for thermal or hydrothermal processing frequently entails beneficiation measures, the function of which is to provide optimum chemical or mineralogical composition and uniformity of composition and particle size of feed material for the hardening process. Examples of beneficiation of fly ash for sintered aggregate production are the magnetic separation of excess iron, the screening out of excess carbon particles, and size separation to provide fractions of uniform fineness. Beneficiation is the key to utilization of heterogeneous materials and makes it possible to use apparently useless raw materials by separating them into useful fractions. Beneficiation of low-grade materials becomes profitable when material rejected for one purpose becomes a marketable commodity for other uses. Again using the example of beneficiation of fly ash for aggregate production, separation provides an iron concentrate, a pozzolanic fraction, and a fraction rich in activated carbon, each of which can be marketed at higher prices than that of the principal product—sintered aggregate.

Similar examples can be cited in relation to municipal refuse incinerator residue, more than one-half of which consists of glass, slag, and ash. Potential utilization of nonmetallic incinerator residue, possibly in aggregate production, may depend on successful separation of the more valuable individual metallic components.

In the case of shales and clays, many deposits unsuitable for production of lightweight aggregates are suitable for firing to produce heavier products such as brick or tile. Shales and clays unsuited to the production of fired materials can be upgraded by the addition of small amounts of additives to lower fusion temperatures and to promote glass formation and bloating during the heat hardening treatment.

It has been stated that the most desirable synthetic aggregate may not be lightweight aggregates, but might be similar in density to naturally occurring aggregates. Nevertheless, the force of economics leans heavily toward the development of lightweight aggregates from abundant natural and waste materials. Higher volumetric yields of finished products are translated into lower processing and fuel costs and lighter weight means lower transportation costs. Furthermore, the agglomeration of particulate materials such as fly ash results in porous materials. Fluxes used to lower fusion temperatures for shales and clays produce some bloating. Aggregates having specific gravities of 1.5 to 2.0 in the dry condition might provide the best compromise of economic and technologic factors and still would be capable of providing concrete of high strength, durability, and abrasion resistance.

Apart from the use of such raw materials as crystalline slag or taconite tailings, which may be processed simply by crushing and screening, preparation of finely divided materials for thermal or hydrothermal treatment requires balling or pelletizing. Experience from the iron and steel industries in the pelletizing of ores has been carried over successfully to the pelletizing of portland cement raw mix, fly ash, clays, and shales. In many cases the binder used for agglomeration of fine particles is water, but in some cases additives are required.

Equipment used for pelletizing consists of inclined pan pelletizers (Loesche, McDowell-Wellman, Eirich), drum and drum cone pelletizers, extruders, plain or grooved rolls, and presses. All of these devices are potentially suitable for pyroprocessed aggregates, but hydrothermally treated materials may require presses or other equipment capable of providing higher compactive forces. The pelletizing operation is as much art as science, depending greatly on the skill of operators to produce pellets of controlled uniform size and compaction in order to assure uniformity of heat treatment.

For thermally hardened aggregates, pelletizer feed may contain particles as large as the No. 8 sieve opening (3/32 in.) if sufficient amounts of minus No. 200 sieve material are also present, or the material may consist entirely of subsieve sizes. If pellets in which water is the sole binder do not have sufficient green strength to survive the heat hardening process, certain additives may be employed that may also enhance the burning characteristics. Waste sulfite liquor, sewage sludge, treated solid human waste, sodium silicate, bentonite, or other clays may be used in small amounts. Some of these materials and ferric oxide, sodium hydroxide, carbon, fuel oil, and calcium carbonate may be used to reduce fusion temperature and enhance bloating. Additions of silica flour or fine sand can be used to suppress bloating and increase the density of some fired products.

For production of hydrothermally hardened aggregates, the raw materials must be in finely divided form and mixed intimately with the cementitious or lime-bearing binder to facilitate pelletizing and assure rapid calcium silicate formation. Wet or dry mixing or pugmilling and the pelletizing process provide satisfactory mixing. Fly ash is already in finely divided form, but granulated slags and calcined clays and shales must be ground; incinerator residue must be finely ground for extraction of metallics.

Final hardening of synthetic aggregates depends on adaptation of curing or firing temperatures and duration to specific materials and mixtures being processed. Thermal treatment requires critical balances of firing range and temperature, carbon, iron, and glass-forming constituents to avoid difficulties in processing. Hydrothermally processed materials must be finely divided, intimately mixed, and compacted to densities sufficient to provide high strength. Hardening must occur rapidly at temperatures up to 450 F in short curing cycles with rapid heating and cooling.

Air curing and natural or artificial carbonation may be used to harden agglomerates bound with portland cement.

Plastic-bound sand is presently formed into artificial "stone" panels in a German process in which the materials cost is about $18 per solid cubic yard. As prices of organic plastics decrease and prices of other materials increase, the time is approaching when aggregates, as well as concretes, may be competitively manufactured with plastic binders. Such binders may be hardened at elevated or ambient temperatures or, potentially, by nuclear radiation.

APPENDIX H

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