NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 8

SYNTHETIC AGGREGATES FOR HIGHWAY CONSTRUCTION

HIGHWAY RESEARCH BOARD NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL

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SYNTHETIC AGGREGATES FOR HIGHWAY CONSTRUCTION

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HIGHWAY RESEARCH BOARD OF THE DIVISION OF ENGINEERING AND INDUSTRIAL RESEARCH
NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL 1964

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 Highway Planning and Research funds from participating member states of the Association and it receives the full cooperation and support of the Bureau of Public Roads, United States Department of Commerce.

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, non-profit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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

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

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

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

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FOREWORD

By Staff
Highway Research Board

As sources of natural aggregates suitable for use in highway construction become increasingly diminished, and in some areas exhausted, the demand for new road building materials grows. Although many types of lightweight aggregates are in use throughout the construction industry, this study emphasizes possible sources of other synthetic aggregates. The information published in this report will be of benefit to highway research and materials engineers faced with the problem of locating suitable sources of synthetic aggregates.

This study is essentially concerned with investigating the feasibility of using various materials as aggregates for highway construction. It contains discussions of methods and equipment for altering the properties of existing natural materials and industry waste products. Included is a literature review and a digest of some of the more important findings uncovered in the review and from a canvass of selected industries and highway departments. In effect, it is a state-of-the-art report on the existence of synthetic aggregates and their potentials.

The report points out that there are a number of existing sources suitable for providing synthetic aggregates. The majority of these are lightweight aggregates produced by expansion or sintering of clays, shales or fly ash and those produced as a by-product of the blast-furnace industry. In view of the abundance of available information on lightweight aggregates, consideration of these materials is minimized in the report. Several potential sources for other synthetic aggregates were brought to light, however. These include heat treatment of natural soils, use of waste materials from various industries, and altering materials through chemical additives. In addition, selective use of materials on the basis of their needful contribution to the layered structure of the roadway is suggested as a possible means of obtaining maximum economic utilization of construction aggregates. For example, high-quality aggregates are needed in surface mixtures, whereas materials of lower quality may be used in base and subbase work. At present, economic considerations restrict the use of many potential sources of synthetic materials other than those existing for lightweight aggregates. However, as the shortage of existing aggregates becomes critical and the demand for new aggregates increases, it is expected that the manufacture of aggregates from a number of industrial waste products and from natural soils will become more economically feasible. New developments in sources of power, processing techniques, and transportation can contribute to the early usefulness of these materials as synthetic aggregates.

This study, conducted at the Battelle Memorial Institute, will contribute to the knowledge on the current status of new synthetic aggregates throughout the construction field and in particular the highway industry. No new processing methods were uncovered in this study and no "exotic" aggregates which are presently economical appear on the horizon. The information, together with the bibliography, is intended to serve as a basis for future investigations when the need for new sources of construction aggregates intensifies.

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SYNTHETIC AGGREGATES FOR HIGHWAY CONSTRUCTION

SUMMARY

Greater activity in highway and other construction has speeded the rate at which high-quality aggregates are consumed. This situation, coupled with an unbalanced geographical distribution of deposits, has created a supply problem in some areas, and many more areas are expected to encounter the problem in the future.

To compensate for the shortage or high cost of aggregates, less commonly used materials, such as shell and scoria, are being substituted in highway construction. Stabilized soils are also being substituted for aggregate in bases and subbases. Another approach to the problem is to use synthetic rather than naturally occurring aggregates.

A study was made to identify existing and potential materials suitable for producing synthetic aggregates, to conceive new methods of producing such aggregates, and to evaluate the present and future prospects for their use in highway construction. A large number of existing and potential synthetic aggregates were identified. Several manufactured or by-product materials, such as lightweight aggregates and blast-furnace slag, currently are used as aggregates; other by-product or waste materials that might be used after minor mechanical processing include a number of ceramic wastes, various industrial slags and clinkers, demolition wastes, and scrap iron or steel. The study considered potential methods for producing new synthetic aggregates — by sintering or fusing such fine-grained natural material as sand, clay, or soil, or such waste materials as steel-furnace dusts or mining wastes; or by chemical or thermochemical processing of mixtures such as those of sand and lime or fly ash and lime.

Synthetic aggregates offer a possible alternative to importing natural aggregates from other areas. The present worth of synthetic aggregates for highway construction thus depends on specific economic factors in the locality suffering an aggregate shortage. In time, when the aggregate shortage becomes more widespread and the importing of natural aggregates becomes too extensive and costly to be a sound practice, synthetic aggregates may provide a feasible solution to the problem. The most significant development for the future is likely to be either the use of job-site materials for making synthetic aggregates in versatile and portable processing equipment or the establishment of a widespread synthetic aggregate industry which processes widely available materials such as clays and shales. Another possibility, the development of new highway systems requiring lesser quantities of aggregates, should not be overlooked.

It is not too early to start planning, developing, and evaluating job-site materials for making synthetic aggregates with versatile and portable processing equipment, and large-scale processing of widely available materials such as clays and shales.

INTRODUCTION

The accelerated highway construction program and the expanding uses for concrete in the building field have resulted in an unprecedented demand for high-quality aggregates. The annual total consumption of aggregates has now reached 1.5 billion

tons and is expected to increase as much as 50 percent in the next ten years. This expanding rate of consumption and the continual demand for higher quality is exhausting many suitable aggregate sources. A number of areas throughout the country are already experiencing a shortage of certain types or a total lack of suitable local aggregates.

Several measures are being taken to compensate for this lack of suitable aggregates for highway construction. One approach is the use of cement-, asphalt-, or lime-stabilized soils in bases and subbases. The use of other natural materials such as shells, coral, and scoria is practicable in some locations. Another approach is the use of synthetic aggregates: aggregate-like products produced from raw or waste materials by some processing treatment.

This report summarizes the results of a study to identify existing and potential sources of synthetic aggregates, formulate new methods of producing synthetic aggregates, and evaluate present and future prospects for alleviating the aggregate shortage through use of synthetic aggregates. Information concerning possible sources of synthetic aggregates was assembled from material available at Battelle and an intensive study of the published literature; ideas for new sources of synthetic aggregates were originated at Battelle and were solicited from universities, industrial organizations, various highway departments, and governmental groups.

GENERAL NATURE OF THE PROBLEM

A recent study conducted by the Bureau of Public Roads (*1*) revealed that the annual aggregate requirements for new highway construction are about 580 million tons, and that in addition, 170 million tons are required annually for maintenance purposes. It has been estimated (*2*) that other segments of the construction industry will consume almost an equal amount. This combined total of almost 1.5 billion tons of aggregates consumed each year is expected to increase steadily over the next several years and to reach 2.5 billion tons by 1975 (*3*). The increasing demand for high-quality aggregates has caused considerable concern because the rapid depletion of some of the major sources has left many areas of the U. S. in short supply or, in some cases, completely deficient in suitable construction aggregates.

It has been reported (*4*) that at the end of 1960, there were over 3.5 million miles of roads of all types in the United States; over 2.5 million miles were surfaced. The total mileage was distributed approximately as follows: primary highways, 440,000 miles; secondary highways, 250,000 miles; country and township roads, 2,475,000 miles; and city streets and roads, 365,000 miles.

Data are not available on the specific kinds and amounts of aggregates required for various types of roads. In general, aggregates are estimated to represent from 15 percent to over 30 percent of the construction costs of a highway, depending on the location, traffic capacity, and design.

Aggregates used in reinforced and prestressed concrete highway structures, such as bridges and culverts, must be of high quality, strong, sound, chemically inert and well-graded. Their function is to provide an inert filler material in a portland cement concrete to yield a strong, durable concrete. The characteristics required in aggregates for pavements, whether portland cement concrete (rigid) or asphaltic concrete (flexible), are similar to those required of aggregates used for structural elements. In addition, aggregates for pavements must have high abrasion resistance.

The base course, the layer directly beneath the pavement proper, is a well-graded, highly compacted layer which provides a dense and strong supporting

medium for the pavement. The aggregate, though it need not be as high in quality as that used in pavements, must be capable of providing stability under severe loading conditions.

The subbase is generally a soil-aggregate mixture of "select materials." The aggregate properties of most interest are gradation, non-frost susceptibility, and volume stability.

Attempts to alleviate the shortage have taken a number of directions. Improved techniques for locating and identifying new aggregate sources are being developed with the assistance of aerial photography. Methods such as heavy media separation and elastic fractionation are used to upgrade or otherwise improve the characteristics of aggregates having questionable or undesirable properties. In highway base or subbase courses, soil-aggregate mixtures are being upgraded with stabilizing additives such as asphalt, lime, and cement. In some cases, materials such as oyster shells, scoria, and sandstone have been substituted for gravel and crushed rock.

Measures must be sought to compensate for the lack of good aggregates and the high cost of transporting aggregates over greater distances. This study was undertaken to explore the possibilities of using synthetic aggregates as an alternative to natural ones. In the following presentation, existing synthetic aggregates are considered as a potential solution to present, specific shortages, and possibilities for developing new synthetic aggregates to meet future demands are discussed.

EXISTING SOURCES

There are a number of existing sources of synthetic aggregates. Some of these have been used in highway or other construction either as substitutes for natural aggregates or in direct competition with them. Included are substantial quantities of lightweight aggregates produced by expansion or sintering of clays, shales, or fly ash, and both lightweight and dense aggregates produced from blast-furnace slag. Other existing sources of synthetic aggregates are little used for a variety of reasons.

Presently Used Sources

Lightweight aggregates produced by the heat treatment of suitable clays or shales are used extensively in concrete structures (*5-8*). The relatively high cost of these aggregates has limited their use in other phases of highway construction, but they are reported to show promise in asphaltic concrete pavements (*9*). Recently, lightweight aggregates have been produced successfully on a commercial scale by pelletizing and sintering fly ash (*10*). The projected long-range prices for sintered fly ash aggregates are intermediate between present prices for natural aggregates and lightweight bloated-clay aggregates (*11*).

Deposits of clay, slate, or shale suitable for the production of lightweight aggregates are found in most parts of the United States, and operating lightweight aggregate plants are widely distributed throughout the country (*12*). Fly ash, on the other hand, is produced primarily east of the Mississippi River and production is concentrated near metropolitan areas.

Slag from blast furnaces, a nonmetallic material produced by the steel industry, may be processed to form air-cooled, expanded, or granulated slag. These materials are used extensively in concrete products and in highway construction (*13*). Slag is an excellent material for base courses and for producing skid-resistant asphaltic wearing surfaces. The annual production of blast-furnace slag is about 25 to 30 million tons, and it is not expected to increase substantially. Because the demand

for slag now exceeds its supply, there is little prospect that it will be used more extensively in highway construction.

Potential Sources Using Mechanical Processing

A number of by-product or waste materials have many of the chemical and physical characteristics required of aggregates and need merely to be recovered, perhaps separated from deleterious materials, and crushed and sized. These include ceramic waste, slags and clinkers, structural wastes, and scrap iron or steel.

CERAMIC WASTE MATERIALS

Ceramic waste materials such as devitrified glass, glass cullet, waste ceramic ware and waste from cast-iron enameling have been suggested as a source of aggregate materials (*14*). The properties of these materials vary considerably depending on the source and the quality, but they would probably be suitable for base and subbase applications. The particles are hard, small, and angular in shape, making for good stability. Their limited quantities, however, would make them suitable only for local use.

Wastes from the structural clay products industry, such as reject or broken brick, pipe, or tile (sometimes referred to as "bitten") would be suitable as an aggregate material for road construction. These materials form coarse angular particles which exhibit excellent stability when compacted. Quite often the bitten is used in local areas surrounding a plant as a stabilizing material. Bitten in various shapes and sizes and in combination with ash clinker, has been used for years for unsurfaced country and township roads with considerable success. Crushed ceramic tile has been investigated as a potential concrete aggregate (*15*) with encouraging results.

No estimates could be found of the quantities of these materials that are available, but most plants have dump areas containing several thousand tons of accumulated bitten. The distribution of these plants would, however, limit the use of this material to local area roads with modest quantity requirements.

SLAGS AND CLINKERS

In addition to blast-furnace slag, a number of metallurgical slags are available in limited quantities at various locations in the United States. Basic open hearth slag is available in steel producing areas. Open hearth slag may contain constituents which expand when hydrated, making it unsuitable in portland cement concrete. It has been used to a limited extent in bases, subbases, and flexible pavements, and its applications are apparently being developed by the slag industry. Somewhat limited quantities and high unit weights restrict its use to areas near the source.

Other metallurgical slags, for example from copper or zinc production, are even more limited in quantity and distribution. Ash clinker and garbage clinker are the residue from the combustion of solid fuel and non-metallic household waste, respectively. They are soft, friable products, porous and light in weight. Ash clinker is commonly used in the construction industry, primarily for the production of lightweight concrete masonry units. As was previously mentioned, ash clinker, alone and in combination with bitten, has been used for years on non-surfaced roads. It is also applied to roads in winter to provide skid resistance. The available quantities of ash clinker have greatly diminished in the last few years because less coal is burned in lump form. The quantities of garbage clinker may be expected to increase, particularly in large metropolitan areas where incineration of waste

materials is increasing, but the suitability of this material as a potential aggregate is unknown.

STRUCTURAL WASTE

Structural waste materials from demolition and abandoned roads may be processed into an aggregate material. Demolition wastes are those which may be reclaimed from destruction and removal operations of buildings. Large quantities of broken brick, plaster, stucco, concrete and natural building stones are available in large metropolitan areas where slum clearance programs are being accelerated. Additional materials such as brick and stone may be obtained from abandoned roads, usually found in rural areas. These materials, depending on their quality, make an excellent base and subbase aggregate. Wastes such as the rock used in macadam roads could qualify as concrete aggregate after processing.

Large-scale clearance programs are often associated with the construction of expressways and highways. The quantities of demolition materials available obviously change from year to year and city to city, and vary with the size of the city. For large clearance areas, the quantities may easily reach many thousands of tons. Their use would be most advantageous near the point of origin.

SCRAP IRON AND STEEL

Scrap iron and steel have been used as aggregates to make high-density concretes for nuclear reactor shields (*16*). These materials are widely available and, although at present the high price they command as raw materials for steel precludes their use as highway aggregates, changes in steel production practices may lower scrap prices sufficiently to make their use as aggregates feasible in some localities in the future.

POTENTIAL NEW SOURCES

The possibilities of producing new synthetic aggregates by modifying or extending present methods and materials or by developing new methods were examined in depth. It appears that the use of synthetic aggregates as a solution to the aggregate shortage problem depends on the development of new methods for the production of synthetic aggregates from readily available, low cost raw materials. The potential new sources identified in the study may be classified into four groups: (1) aggregates produced by heat treatment of natural, fine-grained materials such as sand, clay, or soil; (2) aggregates produced by heat treatment of fine-grained, by-product or waste materials; (3) composite materials; and (4) aggregates produced by chemical or thermochemical processes.

Heat Treatment of Fine-Grained Natural Materials

The well-known heat treatment of bloating clays or shales to produce lightweight aggregates was briefly discussed previously in this report. This process yields synthetic aggregates having desirable characteristics for use in highway construction, but limitations on raw materials and high production costs severely restrict the usefulness of this source of synthetic aggregates. Several potential methods of surmounting these limitations were suggested.

It is recommended that, in addition to bloating clays or shales, other more widely available material be used. A dense aggregate might be produced by heat treatment of non-bloating materials or, if lightweight aggregate were desired, gas-generating materials might be added to cause bloating. Potential alternate raw materials include clays and shales of all descriptions, sand, soil, and loess (*6*), a

finely divided, wind-blown material located in Mississippi, Tennessee, Illinois, Iowa, Wisconsin, and parts of Kansas and Nebraska.

STATIONARY MANUFACTURING PLANTS

There is little question of the technical feasibility of producing dense or lightweight synthetic aggregates from natural fine-grained materials by pelletizing or other temporary consolidation methods and heat treating to form sintered or fused aggregates or masses processable to aggregates. Most of the clays, shales, and clay soils distributed throughout the United States could be processed with little difficulty in the rotary kilns and sintering machines presently used to make lightweight aggregates. The use of sand or the more heat resistant soils might require changes in the refractories employed or in the design of the kilns or sintering machines, but these adjustments are within the technological capabilities of the lightweight aggregate industry.

The economics of producing synthetic aggregates by heat treatment of natural materials in stationary plants is the primary factor that will determine whether or not such aggregates can be provided for highway purposes. For the present and near future, it is unlikely that the production costs will be low enough for synthetic aggregates from this source to offer any advantage over imported aggregates. However, the production of synthetic aggregates from local fine-grained, natural raw materials by heat treatment in fixed plants distributed throughout the nation may represent a technically and economically feasible solution in the long run.

PORTABLE PLANTS

An alternative to the stationary plant would be the development of portable, versatile plants for the production of synthetic aggregates by heat treatment of natural raw materials. This plant might be assembled in a given locality to provide aggregates for highway construction in that area and then dismantled and moved to other locations as needed. It is believed that suitable plants could be designed on the basis of present knowledge.

IN SITU TREATMENT

A third alternative would be the development of a versatile, traveling aggregate plant that would heat treat raw materials available on the highway site to produce a synthetic aggregate. This plant might contain several interconnected and interlocked units. A digging unit would excavate the existing material at the highway site to the depth desired. Another unit would remove from the excavated material coarse material such as rocks which require only crushing and screening to be used as aggregate and unusable material such as trees and roots. The fine-grained clay, soil, or sand remaining would be fed to the next unit to be pelletized or otherwise consolidated. From this unit, the green aggregate would be fed to the heat treating unit where it would be sintered or fused. The final unit would crush and size the synthetic aggregate and feed it to following equipment for incorporation in the highway. A simpler version of this complex machine might merely sinter or fuse in situ the top layer of a prepared clay or soil base laid down by conventional earth-moving equipment.

It is doubtful that the complex, integrated traveling plant is technically feasible except for the production of a low-quality aggregate. The production of a high-quality synthetic aggregate from raw materials of relatively constant composition is difficult even in a stationary plant where operating conditions can be readily controlled. The variable composition of the raw materials fed to the traveling plant

and the difficult control problems posed by such a complex system would undoubtedly result in a highly variable product.

An important economic factor for a traveling plant or in situ fusion of soil is the cost of heat energy. The poor heat economy associated with in situ fusion or a traveling plant using conventional fuels make these units more expensive to operate than fixed or portable processing plants. Nuclear energy, a potentially low-cost heat source, offers a possbile means of achieving a low-cost in situ treatment. However, many technical problems must be overcome before nuclear heat can be used in a direct heating application (*17*).

Heat Treatment of By-Product or Waste Materials

The previous discussion of potential methods of producing synthetic aggregates by the heat treatment of fine-grained, natural materials also applies generally to heat treatment of by-product or waste materials. A number of such materials are available in limited quantities and usually in isolated locations. Phosphate slimes, coal mine tailings, electric steel furnace dust, and smoke abatement dusts are typical examples.

Phosphate slimes are the colloidal phosphate-clay residues which result from the production of phosphate pellets. They are produced primarily in Florida, but there are also sizeable deposits in Tennessee. The estimated amount of waste slime produced during 1963 was about 20 million tons. When dewatered, dried, pelletized and fired, these slimes, which prior to dewatering normally contain about 20 percent solids, can be used to produce an excellent lightweight aggregate (*18*). The firing characteristics are very similar to those of clays used to make lightweight aggregates. The slimes have a short firing range and are self-bloating at temperatures on the order of 2,000 to 2,200 F. The primary drawback to the use of phosphatic clays is their colloidal nature which makes dewatering a costly and time-consuming operation.

Coal mine tailings, especially those associated with the waste dumps or gob piles, are another potential source of waste products suitable for the production of synthetic aggregates. These materials, more appropriately classified as low-grade shales, are available in Pennsylvania, West Virginia, Tennessee, Ohio, Kentucky, and Illinois with the heaviest concentration being in the Appalachian region. Trial examinations have yielded varying results; some samples have been too refractory while others have exhibited excellent bloating properties at temperatures of the order of 2,000 F (*6*).

Electric steel furnace dust and smoke abatement dust are extremely fine particles collected from stack gases. Although little information is available about their characteristics and properties, it is likely that they can be converted into synthetic aggregates by the pelletizing-sintering process used with fly ash.

Composite Materials

The characteristics of otherwise inadequate particles might be improved by coating them with an impervious skin. In general, any particle or material which is basically blocky or rounded in shape or may be pelletized might be coated with a fusible material. For example, aggregate particles of imperfect structure might be coated with a suitable clay slurry which would be fused at high temperatures. The interior could be a natural soil in a pelletized condition or it might have a porous honeycomb-like interior. Solid core materials such as sand grains or soft stone particles would require a coating of minimum thickness. A core of softer material, such as pelletized soil, could be surfaced with a thicker coating so that the quality

of the product would more closely resemble that of the coating material. The firing requirements would be determined by the type and thickness of the coating material.

The chemical properties of fired clay-coated particles would closely resemble those of the surface material while the density and strength would be primarily a function of the core material. The performance of the product could be controlled by proper selection of the components.

Chemical or Thermochemical Processing

The feasibility of using methods other than sintering or fusion to achieve permanent consolidation of fine-grained materials was examined. The in situ treatment of soils with cement, lime, pozzolans, or chemicals has been investigated thoroughly and was not given further consideration in this study.

One method consists of bonding soil or other fine-grained materials into aggregates with the cementing ingredients used to bond soils together for soil stabilization purposes. The fine-grained materials are blended with the cementing ingredients, the mixtures briquetted, and then cured to develop strength and hardness. The curing conditions are selected to produce the optimum characteristics attainable with the combination of filler and bonding materials used. Because this method permits greater control over compositions, mixing, and curing conditions, the resultant aggregate can be expected to be harder, stronger, and more durable than corresponding stabilized soils. However, the extra processing steps in forming and curing the aggregate introduce extra costs over that of stabilized soil.

Typical of this type of product would be sand-lime and fly ash-lime products. In both cases, hydrated calcium silicates, similar to those formed when portland cement hardens, are produced on the surface of the fine particles and bond them together to yield a relatively soft but stable product. Autoclaving, or a similar process, is used to accelerate the reaction which takes place very slowly at normal temperatures. A sand-lime reaction is presently used commercially to produce building brick. A fly ash-lime reaction, though not used commercially in the United States, yields a similar product. To produce an aggregate, the basic ingredients can be mixed and pelletized to the desired shape for processing or be processed in any convenient form and crushed to the desired size.

The resultant aggregates could be expected to be well suited for base and subbase applications, but might not be suitable for the production of high quality concrete and asphaltic mixes.

It is anticipated that aggregate products could also be manufactured from many other materials consisting of combinations of asbestos, wood particles, natural soils and various types of organic and inorganic adhesives. At present, however, in light of other methods available, they would be impractical and uneconomical.

EVALUATION OF NEW SYNTHETIC AGGREGATES

The technical feasibility of using any material in highway construction depends on the physical properties of the material and/or its performance under field conditions. Many of the materials suggested in the previous sections have been used successfully in various phases of road construction. The properties of some of the materials for which performance data are lacking are sufficiently well known that their probable performance can be estimated. However, some of the potential aggregates considered in this study have not yet been produced and their service-

ability must be judged on the basis of educated guesses about their properties. Within these limitations, estimates of the potential utility of various types of new synthetic aggregates for various phases of highway construction are given in Table 1.

All of the materials proposed are considered suitable as filler materials in base and subbase applications. Although many of the new synthetic aggregates appear to be usable for other applications, such as pavement surfaces, it is questionable whether they could match the performance of natural aggregates in permanence and durability. Thus, it is believed that these aggregates are presently best fitted for use in less critical applications such as bases and subbases so that high-quality natural aggregates may be conserved for wearing surfaces and structural elements. At present use of synthetic aggregates for primary highways is likely to be limited or prohibited on the basis of specification requirements. General use of these aggregates would probably require changes in design methods as well as specification changes.

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

TABLE 1

POSSIBLE USES OF SYNTHETIC AGGREGATES IN HIGHWAY CONSTRUCTION

ITEM	SUBBASE	BASE	PAVEMENTS		REIN-FORCED CONCRETE	PRE-STRESSED CONCRETE
			RIGID	FLEXIBLE		
Heat-Treated Materials:						
Clay	x	x	x	x	x	x
Shale	x	x	x	x	x	x
Slate	x	x	x	x	x	x
Phosphate slimes	x	x		x	x	
Coal mine tailings	x	x		x	x	
Fly ash	x	x		x	x	
Electric steel furnace dust	x	x		x	x	
Smoke abatement dust	x	x		x	x	
Sand	x	x			x	
Soils	x	x				
Clay-coated particles	x	x		x	x	x
Processed Waste Materials:						
Glass	x	x		x		
Waste ceramic ware	x	x		x		
Cast-iron enameling	x	x		x		
Brick	x	x	x	x	x	x
Clay pipe and tile	x	x	x	x	x	x
Ash clinker	x	x			x	
Garbage clinker	x	x			x	
Open hearth slag	x	x		x		
Demolition materials	x	x		x	x	x
Abandoned road materials	x	x	x	x	x	x
Scrap iron or steel	x	x	x	x	x	x
Manufactured Aggregates:						
Sand-lime compositions	x	x			x	
Fly ash-lime compositions	x	x			x	

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.

The foregoing discussion of synthetic aggregates and their use in highway construction was based on the premise that commercial aggregates are being used in extremely large quantities. This, of course, is true for present methods of highway construction. However, the evaluation has not considered possible future changes in vehicular designs and travel patterns which may affect the design of highway pavements, and consequently the aggregate requirements. One recent development of note is the use of ducted air for the suspension and propulsion of vehicles. This method of vehicular support could reduce highway loadings considerably, changing them from concentrated wheel loads of small areas and high pressures to loadings of large areas and very low pressure. The loadings on pavements could be changed to the extent that only a thin impermeable surfacing would be required to sustain traffic. Many of the design measures needed to prevent frost heave or rutting, or to achieve smooth surfaces, which presently require large quantities of high-quality aggregates might no longer be essential. The requirements of a thin impermeable surface might be satisfied, without use of aggregates, by such means as a thin metal sheet, foamed plastic, or fused soil. Fusing soil in place could also be facilitated by the use of thermonuclear heat which may become commercially available in the future. The aggregate requirements would then be restricted to drainage and structural members.

REFERENCES

1. "Study and Investigation of Uses of Material and New Designs and Methods in Public Works." Committee Print No. 4, prepared for Committee on Public Works, United States Senate, by the Bureau of Public Roads, U.S. Department of Commerce (1962).
2. HEROD, H. C., "Aggregate Industries—Review and Forecast." *Pit and Quarry* (Jan., 1964).
3. Minerals Yearbook—1962, Vol. 1, *Metals and Minerals;* prepared by Bureau of Mines, Division of Minerals.
4. Highway Statistics—1960, U.S. Department of Commerce, Bureau of Public Roads.
5. PECK, R. L., Concrete Industries Yearbook, *Pit and Quarry,* 1962.
6. "The Story of Lightweight Clay Aggregate." Reprint from *Brick and Clay Record.*
7. SHORT, A. and KINNIBURGH, W., *Lightweight Concrete.* John Wiley and Sons, New York, 1963.
8. "Lightweight Aggregate Structural Concrete." *Concrete Products, 66* (10) Oct., 1963.
9. WYCOFF, J. C., "Suitability of Lightweight Aggregate for Bituminous Plant Mix." ASTM Bulletin (Jan. 1959).
10. SNYDER, M. J., "Properties and Uses of Fly Ash." *Battelle Technical Review,* Feb., 1964.
11. WEINHEIMER, C. M., "Factors Relevant to the Conversion of Fly Ash into a Lightweight Aggregate When Using the Sintering Process." American Society of Mechanical Engineers, Preprint of Paper No. 61-WA-265.

12. "Lightweight Aggregate Plants Map." *Pit and Quarry,* 1963.
13. "Blast-Furnace Slag for Base Courses and Surfacing Material for Roads." Selected References, Highway Research Board Library, Oct. 1962.
14. KROYER, K. K. K., "Devitrified Glass as Aggregate Material for Road and Other Construction Purposes." *Chemical Abstracts, 58,* May 13, 1963.
15. "Investigation of Ceramic Aggregate for Concrete." Miscellaneous Paper No. 6-8, Waterways Experiment Station, Vicksburg, Mississippi, May, 1952.
16. ROCKWELL, THEODORE III, "Construction of Cheap Shields." AECD-3352, Jan. 1950.
17. FERGUSON, F. A., *et al.,* "High Temperature Heat Utilization in Industry." AEC Report SRIA-31. Abridged version appeared in *Minerals Processing,* Oct. 1963, pp. 31-34.

APPENDIX A

BIBLIOGRAPHY

1. GRINDROD, J., "Terlite-Lightweight Aggregate." *Pit & Quarry*, September, 1957.
2. SPECT, R. C., and HERRON, W. E., JR., "Lightweight Aggregate from Phosphate Slimes." *Rock Products*, May 1960.
3. LENHART, W. B., "Aggregates from Mine Waste." *Rock Products*, May 1950.
4. "Sand and Gravel." Mineral Information Service, Department of Natural Resources, State of California, Vol. 8, No. 3 (Dec. 1, 1955).
5. BURNETT, JOHN L., "Expansible Shales." Mineral Information Service, Division of Mines, State of California, Vol. 13, No. 5 (May 1960).
6. "Lightweight Aggregates for Concrete." Office of Housing Expediter, Washington 25, D. C.
7. "Processed Blast Furnace Slag." National Slag Association, 1961.
8. PARSONS, M. F., "A Basic Rotary Kiln Design for Lightweight Aggregate." *Pit & Quarry*, March 1960.
9. LEIFNER, A. F., "Sintering and Lightweight Aggregate." *Pit & Quarry*, March 1956.
10. WYCOFF, J. C., "Suitability of Lightweight Aggregate for Bituminous Plant Mix." ASTM Bulletin, Jan. 1959.
11. TIMMS, A. G., "Blast Furnace Slag as a Concrete Aggregate." *Modern Concrete*, Nov. 1963.
12. FISH, W. D., "The Highway Aggregates Program." *Rock Products*, Feb. 1959.
13. BELL, J. N., "Are Aggregate Producers Making the Most of the Highway Market." *Rock Products*, Part I, Feb. 1963; Part II, March 1963.
14. LERCH, W., "Aggregate Beneficiation." *Modern Concrete*, Dec. 1961.
15. MAARBJERG, K. M., "Concrete with Porous Aggregate." Second International Congress of Precast Concrete Industry, Wiesbaden, June 1957.
16. WOOLF, D. O., "Selection and Use of Aggregates for Concrete." *Journal of the American Concrete Institute*, Nov. 1961.
17. "Physical Test Results of the Virginia Highway Statewide Aggregate Survey." Virginia Department of Highways, 1954.
18. "Material Inventories." Highway Research Record No. 1, Highway Research Board (1963).
19. LAMBE, T. W., "Stabilization of Soils with Calcium Acrylate." *Journal of the Boston Society of Civil Engineers*, Vol. 38, No. 2 (April 1951).
20. GAY, T. E., JR., "Iron Industries." California Division of Mines Bulletin 176, Mineral Commodities of California.
21. GAY, T. E., JR., "Sand and Gravel." California Division of Mines Bulletin 176, Mineral Commodities of California.
22. "Laboratory Evaluation of Frost Heave Characteristics of a Slag-Fly Ash-Lime Base-Course Mixture." Technical Report 96, U. S. Army Cold Regions Research and Engineering Laboratory, Jan. 1963.
23. HEROD, H. C., "Aggregate Industries—Review and Forecast." *Pit & Quarry*, Jan. 1964.
24. ANDREWS, P. B. B., "New Peaks of Prosperity for Rock Producers." *Rock Products Mining and Processing*, Jan. 1964.
25. "Some Things You Should Know About Lightweight Aggregates." *Concrete Products*, Vol. 66, No. 7 (July 1963).
26. "Lightweight Aggregate Structural Concrete." *Concrete Products*, Vol. 66, No. 10, (Oct. 1963).
27. EVERHART, J. O., JOHNSON, J. E., and EHLERS, E. G., "Research in Expanded Aggregates." Experiment Station Bulletin, The Ohio State University, June 28, 1957.
28. FOSTER, H. D., "Manufacture of Lightweight Products." Bulletin of American Ceramic Society, Vol. 19 (1940).
29. "A Lesson on How to Make Good Use of Poor Materials." *Engineering News-Record*, Nov. 14, 1957.
30. HARRIS, H. M., STRANDBERG, K. G., and KELLY, H. J., "Resources for Making Expanded Aggregate in Western Washington and Oregon." U. S. Department of Interior, Bureau of Mines Report of Investigations, R. I. 6061.
31. MILLER, R. H., and COUTURIER, R. R., "Measuring the Thermal Expansion of Lime, Fly Ash Aggregate Compositions Using SR-4 Strain Gages." Villanova University, Preprint from Highway Research Board.
32. "Abridgments—Symposium on Nuclear Excavation." Ernest O. Lawrence Radiation Laboratory, University of California, Livermore, California, UCRL 7632, Preprint from Highway Research Board.
33. MATTHEWS, J. G., "Preliminary Report on Coated Lightweight Concrete Aggregate from Canadian Clays and Shales." Department of Mines and Technical Surveys, Mines Branch, Ottawa, Canada, Memo. Series No. 120, April 1952.
34. ANDAY, M. C., "Curing Lime Stabilized Soils." Presented at 42nd Annual Meeting of Highway Research Board, Washington, D. C., Jan. 1963.
35. "Symposium on Mineral Aggregates." Special Technical Publication No. 83, American Society for Testing and Materials, 1948.
36. WEINHEIMER, C. M., "Factors Relevant to the Conversion of Fly Ash into a Lightweight Aggregate when Using the Sintering Process." American Society of Mechanical Engineers, Preprint of Paper No. 61-WA-265.
37. KANTOR, A. J., "Fly Ash Sintering." *Pit & Quarry*, June 1957.
38. "Construction and Material Specifications." Department of Highways, State of Ohio, Columbus, Ohio, Jan. 1, 1963.
39. KELLY, F. R., Resources Agency, Division of Mines

and Geology, Department of Conservation, State of California, private communication.

40. WRIGHT, W. H., State Highway Commission of Kansas, Topeka, Kan., private communication.
41. LOSSING, F. W., State Highway Department, Jackson, Miss., private communication.
42. SWANSON, E. G., Colorado Department of Highways, Denver, Colo., private communication.
43. WOODFORD, T. W., Walter N. Hardy Company, Inc., Springfield, Mo., private communication.
44. HUMMEL, F. A., Department of Ceramic Technology, The Pennsylvania State University, University Park, Pa., private communication.
45. FRIEDBERG, A. L., Department of Ceramic Engineering, University of Illinois, Urbana, Ill., private communication.
46. HALL, W. B., Department of Ceramic and Metallurgical Engineering, Mississippi State University, State College, Miss., private communication.
47. HARMS, W. O., Ceramics Laboratory, Metals and Ceramics Division, Oak Ridge National Laboratory, Oak Ridge, Tenn., private communication.
48. WILDER, D. R., Department of Ceramic Engineering, Iowa State University, Ames, Iowa, private communication.
49. CUTLER, I. B., Department of Ceramic Engineering, University of Utah, Salt Lake City, Utah, private communication.
50. HELMER, R. A., Department of Highways, State of Oklahoma, Oklahoma City, Okla., private communication.
51. SWEET, R. W., Division of Construction, Department of Public Works, State of New York, Albany, N. Y., private communication.
52. GOLDMAN, H. B., Resources Agency, Division of Mines and Geology, Department of Conservation, State of California, San Francisco, Calif., private communication.
53. ELLISON, K. E., Department of Highways, Commonwealth of Virginia, private communication.
54. VOLIN, M. E., Institute of Mineral Research, The Michigan College of Mining and Technology, Houghton, Mich., private communication.
55. MATEOS, M., Engineering Experiment Station, Iowa State University, Ames, Iowa, private communication.
56. HANDWERK, J. H., Argonne National Laboratory, Argonne, Ill., private communication.
57. LAMBE, T. W., Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Mass., private communication.

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