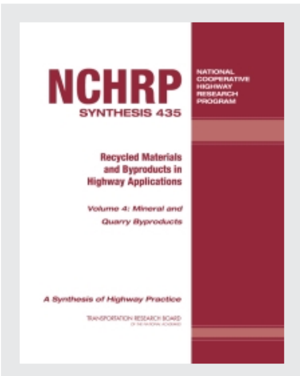

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 435

Recycled Materials and Byproducts in Highway Applications

Volume 4: Mineral and Quarry Byproducts

A Synthesis of Highway Practice

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation 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 Transportation Research Board of the National Academies 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 the National Research Council 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 and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation 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 the responsibilities of the National Research Council and the Transportation 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.

NCHRP SYNTHESIS 435: Volume 4

Project 20-05, Topic 40-01

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical panel selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Jon M. Williams
Program Director
Transportation
Research Board

Recycled materials and industrial byproducts are being used in transportation applications with increasing frequency. There is a growing body of experience showing that these materials work well in highway applications. This study gathers the experiences of transportation agencies in determining the relevant properties of recycled materials and industrial byproducts and the beneficial use for highway applications. Information for this study was acquired through a literature review, and surveys and interviews with state department of transportation staff. The report will serve as a guide to states revising the provisions of their materials specifications to incorporate the use of recycled materials and industrial byproducts, and should, thereby, assist producers and users in "leveling the playing field" for a wide range of dissimilar materials.

Mary Stroup-Gardiner, Gardiner Technical Services LLC, Chico, California, and Tanya Wattenberg-Komas, Concrete Industry Management Program, California State University, Chico, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

The report is presented in eight volumes, the first of which is available in hard copy and on the Internet. The next seven volumes are available through the Internet only and can be found at: http://www.trb.org/Publications/NCHRPSyn435.aspx. The eight volumes are:

Volume 1 *Recycled Materials and Byproducts in Highway Applications—Summary Report*
Volume 2 *Coal Combustion Byproducts*
Volume 3 *Non-Coal Combustion Byproducts*
Volume 4 *Mineral and Quarry Byproducts*
Volume 5 *Slag Byproducts*
Volume 6 *Reclaimed Asphalt Pavement, Recycled Concrete Aggregate, and Construction Demolition Waste*
Volume 7 *Scrap Tire Byproducts*
Volume 8 *Manufacturing and Construction Byproducts*

CONTENTS

1 CHAPTER ONE MINERAL BYPRODUCTS
Physical and Chemical Properties, 1
Engineering Properties, 1
Environmentally Related Properties, 3
Production and Usage, 3
United States, 3
International, 3

4 CHAPTER TWO COSTS AND BENEFITS
United Kingdom Program, 4
Australian Sustainability Program, 4

7 CHAPTER THREE AGENCY SURVEY RESULTS

9 CHAPTER FOUR APPLICATIONS
Bound Applications, 9
Portland Cement and Concrete, 9
Controlled Low Strength Materials, 9
Supplementary Cementitious Materials, 9
Synthetic Materials, 9
Performance of Mineral or Quarry Byproducts in Highway Applications (Agency Survey), 11
Document Assessment Survey, 12

13 CHAPTER FIVE QUARRY BYPRODUCTS
Physical and Chemical Properties, 13
Engineering Properties, 13
Environmental Properties, 16
Production and Usage, 16
United States, 16
International, 17
Legislation—United Kingdom, 17
Cost Information, 17

18 CHAPTER SIX AGENCY SURVEY RESULTS

20 CHAPTER SEVEN APPLICATIONS
Bound Applications, 20
Portland Cement Substitution, 20
Portland Cement Concrete, 20
Self-Consolidating Concrete, 21
Hot Mix Asphalt, 21
Stabilized Base, 21
Unbound Applications: Base and Subbase, 21
Modification of Fine Quarry Byproducts, 22
Performance of Quarry Processing Byproducts, 23

24 CHAPTER EIGHT DOCUMENT ASSESSMENT SURVEY
Chapter Summary, 24
List of Candidate Byproducts, 24
Test Procedures, 24
Materials Preparation and Byproduct Quality Control, 24
Materials Handling Concerns, 24
Transformation of Marginal Materials, 27
Design Adaptations, 27
Site Construction Concerns, 27
Failures, Causes, and Lessons Learned, 27
Barriers, 27
Costs, 27
Gaps, 28

29 REFERENCES

31 APPENDIX A OPEN-ENDED COMMENTS FROM AGENCY SURVEY

CHAPTER ONE

MINERAL BYPRODUCTS

Mineral processing includes waste rock, mill tailings, coal refuse, wash slimes, and spent oil shale (RMRC 2008; TFHRC 2009).

- ***Waste rock*** is material removed along with overburden from surface mining operations that, by itself, has little or no useful mineral content.
- ***Mill tailings*** are very fine particles that are rejected from the grinding, screening, or raw material processing.
- ***Coal refuse*** is rejected material from the processing and washing of coal.
- ***Wash slime*** byproducts are derived from phosphate and aluminum production that use water to clean the parent material. Wash slimes are typically stored in holding ponds. The mineral portion of the slime is difficult to dry, which is a significant barrier to its use. Even after some drying the moisture content of the byproducts is high.
- ***Spent oil shale*** is what is left over after oil shale is processed for oil content. This was developed by the industry in the 1970s during the Oil Embargo.

Petavratzi and Wilson (2009) noted there was not a consensus on definitions and proposed groupings for mineral byproducts (Table 1) that would also be applicable to quarry byproducts. Groupings are based on the level of byproduct processing and preparation, and are referred to as “fit-for-purpose” definitions. These were developed to address the United Kingdom objectives prescribed for mineral planning requirements.

Additional information can be found at the following websites:

- National Stone, Sand, and Gravel Association: www.nssga.org
- Recycled Materials Resource Center: www.rmrc.unh.edu/
- Turner–Fairbanks Highway Research Center: http://www.fhwa.dot.gov/research/tfhrc/.

PHYSICAL AND CHEMICAL PROPERTIES

Mineral byproducts are usually derived from grinding and washing processes, with chemicals from the ore treatment or cleaning process contaminating the waste. Most of the final waste products are deposited in settling ponds, a process that also deposits a significant amount of water along with the mineral waste.

As expected, the properties of waste rock and mill tailings will vary with the source and mining processes for a given location and mineral extraction. Table 2 shows examples of the range of gradations that can be found for different sources of mill tailings (Chesner et al. 2000; RMRC 2008). Most mineral byproducts, but not all, can be described as fine aggregate with between 42% and 90% passing the 0.075 mm sieve.

The range of oxides in the mineral processing byproducts is demonstrated by the examples shown in Table 3. Depending on the parent rock characteristics and the individual plant processes, acidic leachate from sulfide-based metallic ores, low-level radiation from uranium host rock, or radon gases produced by uranium and phosphate rocks can cause environmental concerns that need to be carefully evaluated for each source of mineral processing byproduct. For example, byproducts from gold mines can contain cyanide left from the extraction process. Byproducts from sulfide ore sources can be radioactive, while some taconite tailings have been shown to have asbestos. Sulfur-containing minerals such as pyrite and marcasite can result in acidic leachate.

ENGINEERING PROPERTIES

Generally, the absorption of waste rock byproducts is typically greater than 1% for lead, zinc, copper, and iron ore tailings, with compacted maximum dry density ranges from 100 to 140 lb/ft^3 (Chesner et al. 2000; RMRC 2008). Because of the wide range, and limited use, of mineral byproducts, little additional generic engineering property information is available. A couple of examples of relevant engineering properties are shown in Table 4.

When necessary, the pH value of the byproduct in water could be evaluated to determine if there is the potential for corrosivity. Effluent with pH values that are not essentially neutral (about 7.0) may need to be treated to prevent infrastructure damage (e.g., protects pipes) and to protect habitat ecology.

The deleterious substances in the mineral byproducts also need to be evaluated to prevent problems in highway applications. For instance, a high percentage of siltstone can show a substantial problem with weathering and can disintegrate under certain environmental conditions.

Another component that needs to be considered in mineral processing byproducts is the sulfate content. If high

TABLE 1
SUGGESTED MINERAL BYPRODUCT GROUPINGS BY USE

Group	Description	Example	Potential End Uses
Type 1	Unprocessed waste—large-volume, low-value industrial minerals; commonly used in construction applications; market would be located in close proximity to use	Quarry scalpings; quarry blocks; colliery spoil	Fill, low-grade road stone, armour stone, brick clay
Type 2	Processed waste—reclaimed minerals: only a small amount of processing is required; market largely local; a small amount of secondary waste will be produced	Silica sand waste; limestone waste; building stone waste	Silica sand, kaolin, brick clay, mineral filler, aglime, aggregate
Type 3	Processed waste—added-value products: contain small amounts of valuable minerals; potentially complex processing is required; major capital investment; international market; large volumes of secondary waste	Lead/zinc waste; pegmatite waste; silica sand waste	Fluorite, barite, feldspar, rare earths, mica, heavy minerals
Type 4	Beneficiated wastes—contain small quantities of highly valuable minerals; complex processing requirements; large volumes of secondary waste; international market	Specific mine wastes	Gemstones, other high-value metals

After Petavratzi and Wilson (2009).

TABLE 2
EXAMPLE OF GRADATION RANGES FOR MINERAL PROCESSING BYPRODUCTS

Sieve Size, mm	Sieve No.	Cumulative Percent Passing					
		Copper Tailings Kennecott, Magna, UT	Gold Tailings Homestake Lead, SD	Iron Ore Tailings Kaiser–Eagle Mtn., CA	Lead–Zinc Tailings ASARCO Mascot, TN	Molybdenum Tailings Climax Henderson, CO	Taconite Tailings Hanna Hibbing, MN
19.00	3/4 in.	—	—	99.7	—	—	—
12.50	1/2 in.	—	—	83.4	—	—	—
9.50	3/8 in.	—	—	65.1	—	—	—
6.40	1/4 in.	—	—	46.8	—	—	100
2.00	No. 10	—	—	17.6	—	100	97
0.84	No. 20	—	—	7.9	99.6	99.5	92.5
0.65	No. 28	—	—	5.7	N.R.	98.5	N.R.
0.50	No. 35	99.4	—	4.1	91.6	95.8	86.5
0.38	No. 48	98	—	2.8	N.R.	89.5	83
0.23	No. 65	95.4	100	1.9	69.2	81.1	79
0.15	No. 100	92.4	97.6	1.4	58.2	70.7	74
0.11	No. 150	90.2	94.6	0.9	47.4	60.3	68
0.075	No. 200	87.8	90.3	0.7	41.4	50	62.5
0.053	No. 270	N.R.	82.4	—	N.R.	44.2	53
0.044	No. 325	N.R.	72.1	—	N.R.	41.5	46
0.037	No. 400	N.R.	N.R	—	N.R.	35.5	N.R.

After TFHRC (2009).
— = data not reported; N.R. = not recorded.

TABLE 3
CHEMICAL COMPOSITION OF SELECTED SAMPLES OF MILL TAILINGS
(percentage by weight)

Oxides	Copper Tailings, Phelps Dodge, Ajo, AZ	Gold Tailings, Homestake Lead, SD	Iron Ore Tailings, Kaiser Eagle Mtn., CA	Lead–Zinc Tailings, USSRM Co., Midvale, UT	Molybdenum Tailings, Climax, Henderson, CO	Taconite Tailings, Eveleth, Eveleth, MN	Coal Refuse
SiO_2	67.3	52.8	48.6	53.91	75–80	64.6	37–62
Al_2O_3	16.3	1.6	—	2.27	7–12	0.25	16–32
FeO	2.1	34	18.8	11.4	0.2–3	11.57	43–29
CaO	5.8	1	5.74	7.14	0.1	3.57	0.1–4.6
MgO	—	8.2	4.64	2.16	—	4.15	0.6–1.6
Na_2O	—	0.5	—		4–8	—	0.2–1.3
K_2O	—	—		—	—	—	2.1–4.7
CO_2	—	—	—	—	—	7.57	—

After TFHRC (2009).
— = data not reported.

TABLE 4
EXAMPLE OF ENGINEERING PROPERTIES REPORTED FOR COPPER TAILINGS, MILL TAILINGS, AND COAL REFUSE (Duval, Arizona)

Property	Value		
	Copper Tailings	Mill Tailings	Coal Refuse
Minus 0.075 mm, %	31.7	—	—
Plasticity Index	Non-plastic	—	—
AASHTO Soil Classification	A-2-4	—	—
Specific Gravity	2.71	—	—
Internal Friction Angle, °	—	28–45	25–42
Maximum Dry Density, lb/ft^3	—	100–140	80–120
Optimum Moisture Content, %	—	10–18	6–15
Permeability, cm/sec	—	10^{-2} to 10^{-4}	10^{-4} to 10^{-7}
Rainfall Erosion, %	2.3	—	—
Color	Grey	—	—

After RMRC (2008) and TFHRC (2009).
— = data not reported.

sulfate-containing byproducts are used in concrete applications, sulfate damage to the structure can be a durability problem.

ENVIRONMENTALLY RELATED PROPERTIES

The environmental issues and concerns with any of the mineral byproducts will also vary depending on the chemical content of the parent rock and, in particular, the chemicals used in extracting the desired minerals. Mineral byproducts may pose environmental concerns with acidic leachate (sulfide-based metallic ores), low-level radiation from uranium sources, or radon gas produced from uranium and phosphate mineral sources (RMRC 2008). Byproducts from uranium ore may also be radioactive. Waste byproducts from leaching processes to recover a higher yield of copper, gold, and uranium can have cyanide contaminates (used in the leaching process). Processing of sulfide ores can also present issues with high arsenic levels. Residual mineral content, such as iron, can also cause discoloring as a result of iron staining.

PRODUCTION AND USAGE

United States

In 1994, the following 14 states reported that they were using mineral processing byproducts: Montana, Nevada, North Carolina, Ohio, Pennsylvania, New Jersey South Dakota, Tennessee, Texas, Virginia, Washington, West Virginia, Wisconsin, and Utah. An additional three states, Nevada, New York, and Oklahoma, indicated they were both researching and using these byproducts in highway applications.

By 2000, the annual quantities of total mineral processing byproducts produced were estimated at approximately 1 billion tons per year. Quantities of coal refuse were about 120 million tons per year. Wash slime quantities were estimated at 100 million tons of phosphate slimes and 5 million tons of alumina mud. Because of economic issues, conditions have not been favorable for the production of spent oil shale (RMRC 2008). The annual production for mill tailings was approximately 500 million tons per year, with each state producing at least some of these byproducts. In 2000, the highest production levels of mineral byproducts were found in the western United States. Arizona, California, Idaho, Michigan, Minnesota, Montana, Nevada, and New Mexico are states with the highest levels of productions (Chesner et al. 2000).

International

Canada has a limited use of mineral byproducts in asphalt concrete and embankments. Some current research by Australian researchers (McClellan et al. 2008) has focused on the sustainability concepts for identifying uses for mineral processing byproducts, which is described in the following section.

CHAPTER TWO

COSTS AND BENEFITS

International research and byproduct application programs have been developed that provide the framework for a formalized process of identifying byproducts and applications that enhance the sustainable use of resources, are more environmentally friendly, and reduce costs.

UNITED KINGDOM PROGRAM

The Petavratzi and Barton (2007) study objectives were to develop a screening protocol and a "Waste-Product Pairing (WPP) Database" for a variety of mineral wastes with uses in construction sectors. The deliverables of this study focused on helping a range of stakeholders evaluate:

- Issues of geographical distribution;
- The level of specific information required to allow waste producers to engage with particular product manufacturing sectors;
- Provide at "strategic" levels the generic information needed for planning policy, strategy, and initiatives aimed at stimulating waste utilization; and
- The required level of detail at the "implementation" level.

Figure 1 shows the conceptual model used by Petavratzi and Barton (2007) to develop the WPP Database. The purpose of Phase One is to conduct waste minimization and environmental audits that can be used to aid in the identification, characterization, and identification of the quantities of byproducts. Independent audits need to be conducted by both the byproduct producers and the byproduct users. Phase Two requires both parties to gather information needed to determine preliminary matches between producers and users. Key criteria for matches will be developed in this phase. Specific case studies are explored in Phase Three. This is a rigorous and iterative process that compares and contrasts adverse factors to benefits gained from the pairing. Factors consider technical issues and feasibility (e.g., environmental and financial costs of transport, processing, etc.) of the pairing. Phase Four evaluates the particular details needed to move the pairing from concept to implementation.

AUSTRALIAN SUSTAINABILITY PROGRAM

Australian researchers McClellan et al. (2008) have conducted a number of research projects directed at the sustainable development programs for the mineral processing industry. The Co-operative Research Centre for Sustainable Resource Processing (CSRP) is developing a collection of toolkits for embedding sustainability into the design and operation of mineral processing plants.

The methodology for this particular assessment tool is presented as steps designed to pose questions that need to be answered at each point in the process. The steps and key questions included in the process are:

- ***Project description:*** What is the project about? What can it be compared with? Who is involved?
- ***Characterization:*** What aspects of the sustainability does the project impact?
- ***Quantification:*** What are the measures of the impacts?
- ***Extrapolation:*** How would wider implementation affect industry sustainable development performance?
- ***Valuation:*** What is the value of the benefits in monetary and nonmonetary terms?
- ***Presentation:*** Summary of results.

The key focus of sustainability, as defined by McClellan et al. (2008), is water and energy consumption. In Australia, water usage by mineral processing consumes only 2% to 3% of the country's water resources. However, because mineral processing plants are usually located in rural, dry areas of the country, their impact on the local water supply can be significant. The step in the assessment process needs to consider local water management programs so that restrictions and benefits can be reasonably considered. The authors note that the typical trend of reporting water usage in mineral processing operations only indicates water use-to-production ratios industry-wide. This information is not useful for sustainability assessments as it does not reflect individual operational differences on a plant-by-plant basis. The authors also note there is a similar disconnect when it comes to reporting financial information (i.e., cost per produced quantity of product). This cost ratio does not have the ability to reflect different cost structures within companies. The hierarchical process is needed that integrates *individual* unit operations in a given plant to an industrial ecological perspective toward sustainability and water management objectives.

McClellan et al. (2008) suggest that energy impact assessments will be tied to a carbon footprint pricing scheme. The need to reduce greenhouse gases is driving industries to improve technology through the improvement of process effi-

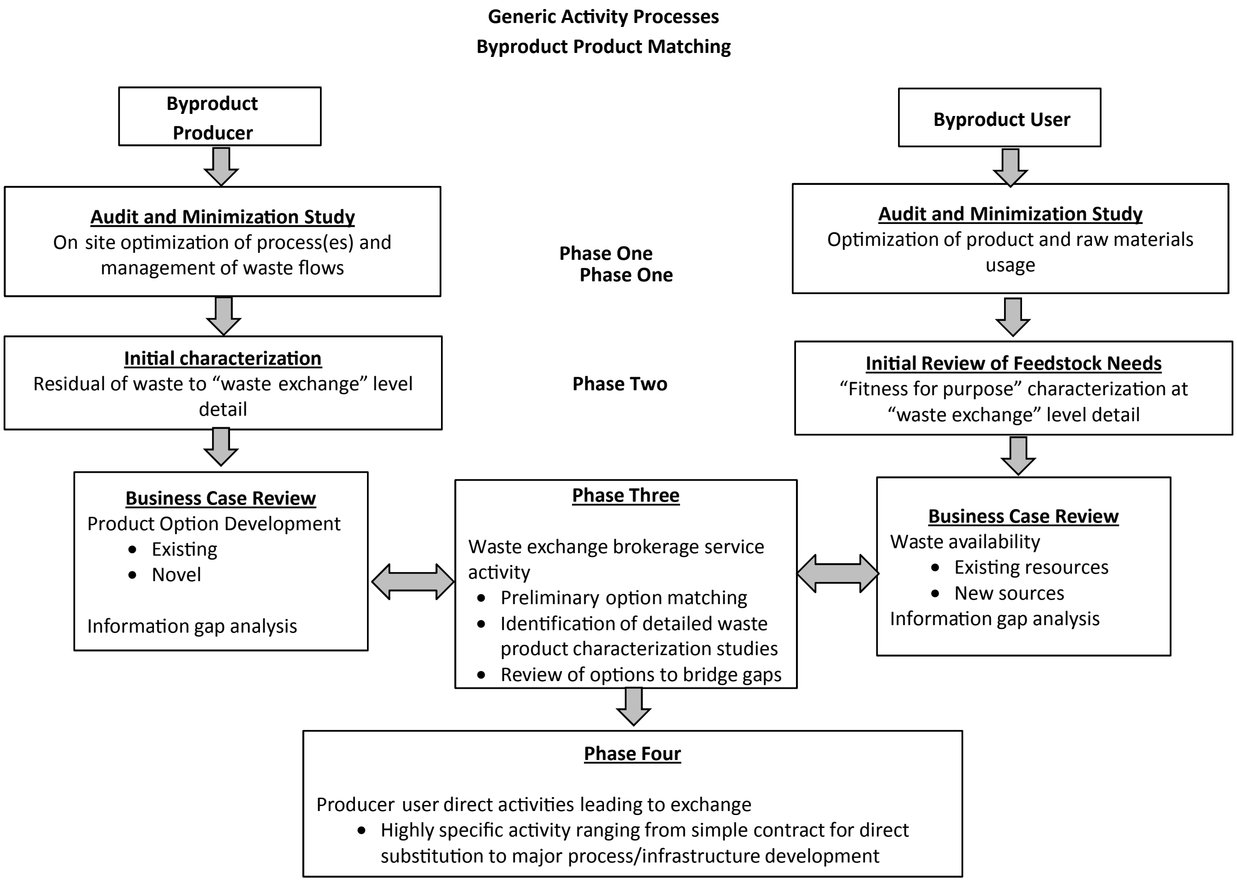

FIGURE 1 Conceptual model used to develop sustainability assessment database (after Petavratzi and Barton 2007).

ciencies and through process modifications, fuel switching, waste process heat utilization, alternative energy sources, biomass feedstock, geo-sequestration, and bio-sequestration. The ideal application of sustainable operations is to define regional synergies, where byproducts (i.e., materials, water, energy) from one industry can be reused by one or more nearby industries. The CSRP is currently developing two software-based tool kits to be used in a practically oriented process:

- ***Regional Synergy Opportunity Tool:*** Identifies potential synergy opportunities in an industrial region. This is a three-stage process. The first uses input and output flows for most major industries within the region to identify and rank potential synergies. Second, a more detailed assessment of potential synergies is made based on water consumption, energy usage or production, and material byproducts. Third, a screening analysis is conducted to evaluate sustainability.
- ***Technology Assessment Tool:*** Assesses the technology needs and opportunities for selected regional synergies. This is an analytical framework to evaluate, capture, recover, manage, and utilize.

Figure 2 provides an example from McClellan et al. (2008) developed for evaluating the sustainability of bauxite residue management, a byproduct that is anticipated to have some uses, but also face storage or disposal issues. This figure shows three hierarchical levels:

- ***Headline Performance Indicators:*** this indicator includes strategic planning and reporting, community well-being, social and cultural values, environmental integrity and benefits, lifetime costs and revenue, and resource use efficiency.
- ***Key Performance Indicators:*** there are 23 Key Performance Indicators shown in Figure 2.
- ***Performance Measures:*** the number of performance measures is case-dependent. In Figure 2 the measures in this example are risk assessment and environmental risk once in place.

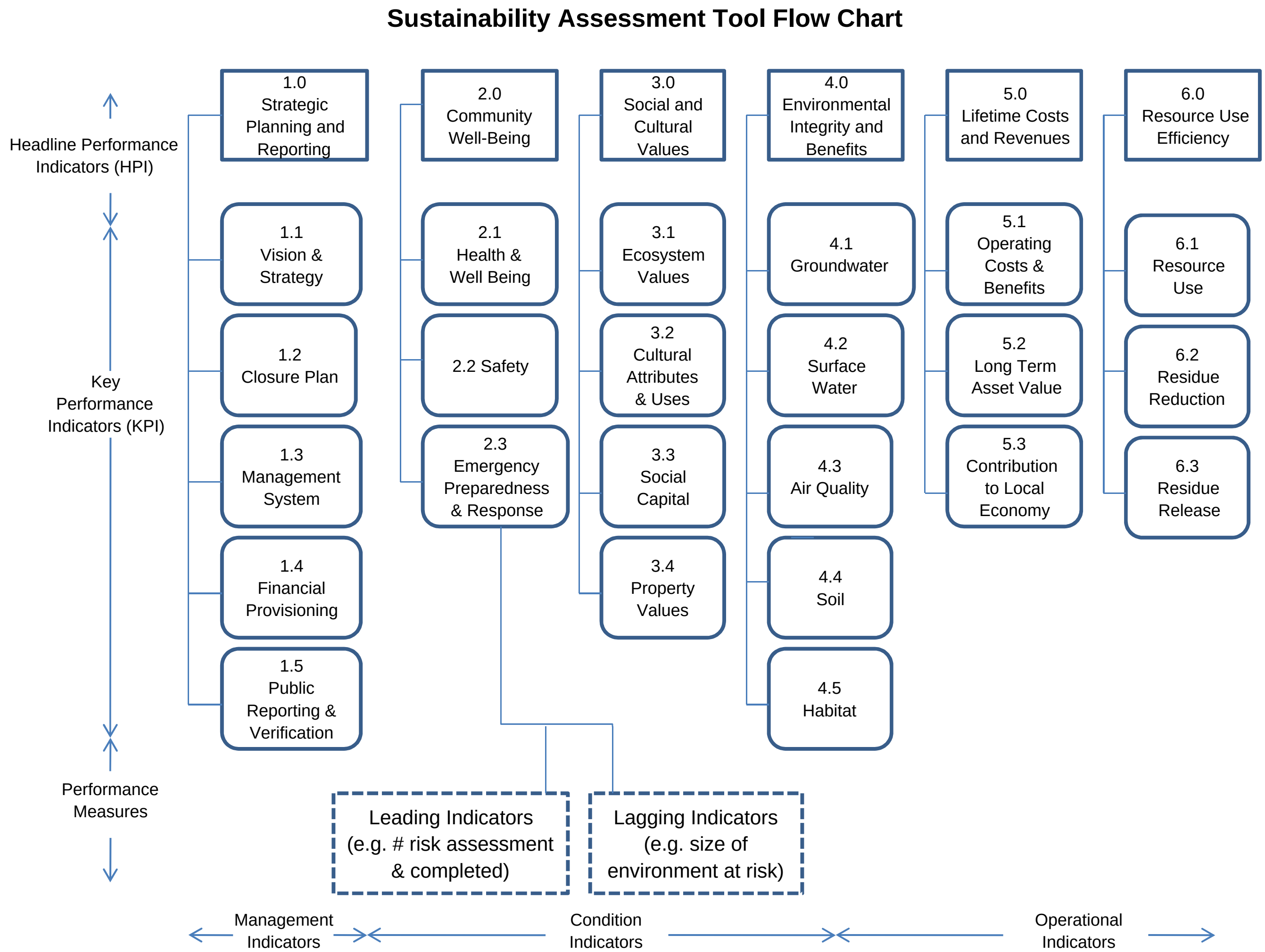

FIGURE 2 Flow chart for sustainability assessment (after McClellan et al. 2008).

CHAPTER THREE

AGENCY SURVEY RESULTS

The survey questions, along with a summary of the agency responses, are shown in Table 5 and Figure 3 a, b. None of the states reported use of coal refuse byproducts. The most used mineral processing byproduct was waste rock in embankments, followed by use in hot mix asphalt (HMA). Mill tailings were more likely to be used in HMA mixtures. States using each of the three byproducts in highway applications are shown in Table 6. Kentucky, Minnesota, and New York use mill tailings in two applications. Kansas, Missouri, Mississippi, and Wisconsin had a single application that used mill tailings. Idaho, Georgia, and New York used waste rock in multiple highway applications.

TABLE 5
NUMBER OF AGENCIES USING MINERAL PROCESSING BYPRODUCTS IN HIGHWAY APPLICATIONS

Question: Mineral Processing and Quarry Byproducts: Is your state using, or has it ever used, these byproducts in highway applications? If you are not sure of the type of material used in your state, check the mineral or quarry byproduct, unknown type box at the end of the list.

- Coal refuse: reject material from coal preparation or washing
- Mill tailings: extremely fine particles rejected from grinding, screening, or processing of raw material
  Waste rock: waste from surface mining operations

Byproducts	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embank.	Flowable Fill	HMA	Pavement Surface Treatment (non-structural)	PCC	Soil Stability
Coal Refuse	0	0	0	0	0	0	0	0	0
Mill Tailings	0	0	0	3	1	5	1	0	0
Waste Rock	0	0	2	11	1	7	2	2	0

Embank. = embankment; HMA = hot mix asphalt; PCC = portland cement concrete.

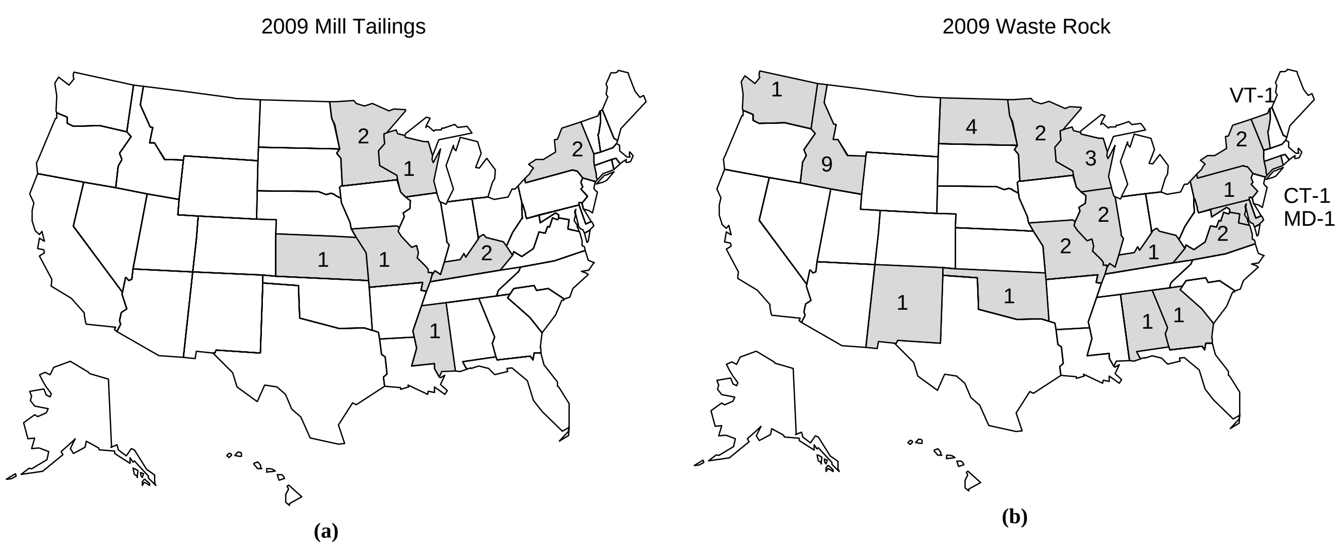

FIGURE 3 Locations for mineral processing byproduct research: (a) mill tailings; (b) waste rock.

TABLE 6
STATES USING MINERAL BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

Number of Applications	States		
	Coal Refuse	Mill Tailings	Waste Rock
9	—	—	ND
6	—	—	WI
2	—	KY, MN, NY	IL, MN, MO, NY, VA
1	—	KS, MO, MS, WI	AL, CT, GA, KY, MD, NM, OK, PA, VT, WA

— = not applicable.

CHAPTER FOUR

APPLICATIONS

General information on the TFHRC (2009) website indicates waste rock, cleaned of overburden and deleterious materials, has been used as riprap for erosion control, rock fill for embankments, and as granular base courses for pavement applications. Mill tailings were reported to be used as granular base courses, embankment fill, aggregate for chip seals, fine aggregates in HMA overlays, and in portland cement concrete (PCC). For the bound applications, it may be necessary to provide additional sizing operations to obtain the required application gradations. Historical use of coal refuse was reported to have the potential for spontaneous combustion as a result of older, poor, refuse disposal practices and the carbonaceous content of the byproduct. Modern practices place the coal refuse in thin, well-compacted layers with all exposed surfaces covered with several feet of earth fill to reduce the presence of oxygen needed to support combustion.

Only a limited number of current research projects and highway applications for mineral processing byproducts were found in the literature. Applications under evaluation focus on bound applications.

BOUND APPLICATIONS

Portland Cement and Concrete

Research conducted at the University of Leeds by Petavratzi and Barton (2007) evaluated the potential for using a range of byproducts, including mineral processing byproducts, in the product of clinkers and for use in blended cements. The authors developed a list of tests needed for the byproduct, kiln feed, and the end product (Tables 7 and 8).

Controlled Low Strength Materials

Research in England by Bouzalakos et al. (2008) explored the use of mineral processing solids in wash water as a viscosity-modifying additive in the preparation of controlled low strength material (CLSM). Two precipitates were evaluated: (1) ochreous (red to yellow iron ore) mine water sludge, and (2) jarosite (basic hydrous sulfate of potassium and iron) residue from zinc extraction. Table 9 shows key material properties determined for each of the CLSM components. Both of the mineral processing byproducts have high specific gravities (as compared with the sand), high and variable surface areas, high loss on ignition percents, variable slurry pH values, and smaller mean particle sizes than fly ash.

The unconfined compressive strength at 28 days was below the upper limit of 290 psi to permit excavation of the CLSM. The ochreous byproduct mixes showed decreased setting time; however, setting time was delayed for the jarosite byproduct formulations. The slower setting time was attributed to higher concentrations of heavy metals, specifically lead (Pb) and zinc (Zn), in the jarosite. The low pH of the jarosite also delayed setting. Both porosity (34% to 45%) and hydraulic conductivity (10^{-6} to 10^{-7} m/s) were high because of the high water contents needed to achieve flowability; results were similar to nonbyproduct CLSM mixes in the study. Leaching tests showed that the least encapsulated trace metals were barium (Ba), Cr, Pb, and Zn. The lower concentrations of trace metals in the ochreous byproduct resulted in lower concentrations in the leachate from the CLSM, which make it more useful in highway applications.

Supplementary Cementitious Materials

In Australia, Ray et al. (2007) investigated the potential for using perlite mineral processing byproducts as a supplementary cementitious material in portland cement applications. Four mortar mixes were evaluated: control, 10% perlite, 10% fly ash, and 10% silica fume. The water-to-cementitious material ratio was held constant at 0.43, and the superplasticizer was consistently 50 grams. The initial evaluation included a chemical evaluation of the perlite byproduct (Table 10). The compressive strengths of the perlite and fly ash mortars were similar from 1 to 28 days of curing and the control and silica fume mortars were similar but with consistently higher compressive strengths (Table 11). These results, combined with thermogravimetric testing, indicated that the perlite byproduct had a similar reactivity to that of the fly ash mortars.

Synthetic Materials

Australian researchers Drechsler and Graham (2005) reported on an innovative use for tailings as underground backfill when combined with a geopolymer technology. Geopolymers were defined as a group of alkali-activated alumino-silicate binders that are formed by mixing silica-rich and alumina-rich materials with a solution of alkali or alkali

TABLE 7
TESTING RECOMMENDATIONS FOR USING BYPRODUCTS IN AN ALTERNATIVE CEMENT CLINKER RECIPE

Testing on Byproduct	Testing on Kiln Feed	Testing on End Product	
		Physical and Chemical Properties	Engineering Properties
Particle Size	CaO	Cement chemistry	Compressive strength, psi
Mineralogy	SiO_2	Chlorine content, Cl, % by mass	Initial setting time, minutes
Chemistry	Al_2O_3	Sulfate content, SO_4, % by mass	Soundness, mm
Other Constituents	Fe_2O_3	Alkali content, NaO_2 equivalent	Durability
Total Sulfur	MgO	Water soluble hexavalent chromium	
Chloride Content		Phosphate content	
Heavy Metals		Fineness	
Loss on Ignition		Apparent and bulk specific gravity	
Moisture Content		Surface area	
		Insoluble residues, % by mass	
		Loss on ignition, % by mass	
		Color	

After Petavratzi and Barton (2007).

TABLE 8
TESTING RECOMMENDATIONS FOR BYPRODUCTS AS AN ALTERNATIVE MATERIAL IN BLENDED CEMENT

Testing on Byproduct	Testing on Blended Cement	
(CaO + MgO)/SiO_2 Ratio	Physical Properties	Engineering Properties
Byproduct Chemistry	Moisture content	Compressive strength, psi
Other Constituents	Particle size	Initial setting time, minutes
Reactive CaO, %	Density	Heat of hydration
Free CaO, %	Fineness	Soundness
Free Lime, %	Sulfate content	Insoluble residue
Reactive SiO_2	Chloride content	Pozzolanicity
$CaCo_3$, %	Alkali content	Water soluble chromium
Methylene Blue Adsorption	Phosphate content	Durability
Specific Surface (BET), m^2/g	MgO, %	Color
Total Organic Carbon		
LOI, %		

After Petavratzi and Barton (2007).
LOI = loss on ignition.

TABLE 9
MATERIAL PROPERTIES FOR INDIVIDUAL COMPONENTS USED IN THE PREPARATION OF CLSM

Property	Ochreous Minewater Sludge	Jarosite Residue	Fly Ash	Silica Sand	Portland Cement	Hydrated Lime
Water Content, % by Weight	75	88	14	—	—	—
pH (slurry)	8.7	4.6	10.2	7.1	12.6	12.0
Specific Gravity	3.10	2.74	1.96	2.37	2.77	2.25
BET Surface Area, m^2/g	300.00	35.00	0.75	1.00	0.30	25.00
Mean Particle Size, mm	0.003	0.0137	0.0312	0.25	—	—
Median Particle Size, mm	0.0018	0.00925	0.0211	0.38	—	—
LOI, % by Weight	15.4	26.5	6.0	—	1.2	13.3

After Bouzalakos et al. (2008).
— = not available.
LOI = loss on ignition.

TABLE 10
CHEMICAL COMPOSITION OF PERLITE MINERAL PROCESSING BYPRODUCT

Compounds	Mass, %
SiO_2	70.3
Al_2O_3	13.32
Fe_2O_3	1.28
CaO	1.24
MgO	0.13
Na_2O	4.36
K_2O	2.06
CrO_3	<0.01
TiO_2	0.09
MnO	0.02
P_2O_5	0.04
SrO	0.02
BaO	0.06
LOI	7.9

After Ray et al. (2007).
LOI = loss on ignition.

salts, which results in a mixture of gels and crystalline compounds that harden into a strong new matrix. These products are reported to have a high early strength and low shrinkage properties as well as resistance to freeze-thaw, acid, fire, sulfate, and alkali–aggregate reaction (data not provided). Geopolymer products can be produced from either calcined and noncalcined sources. The final matrix should have the ability to bind tailing contaminates such as heavy metals. A comparison of typical portland cement and the geopolymer cement contents is shown in Table 12.

Most of the tailings in Australia are composed of high concentrations of silica, alumina, and clay particles. A number of operators mix tailings with portland cement to provide stabilized materials for dams and backfills. The geopolymers in combination with slags to provide activation have been successfully used to replace the portland cement (Table 13).

Pacheco-Torgal et al. (2008) explored the use of tungsten mine waste mud, which was used to produce a type of PCC binder, referred to as "geopolymeric binder," which is essentially a synthetic cementitious binder. These researchers based their designation on the definition of geopolymer defined by Davidovitz in 1978 as the ability to transform, polycondense, and adopt a shape rapidly at low temperatures like "polymers." The process is based on a chemical reaction under highly alkaline conditions on Al-Si (aluminum-silicon) minerals yielding polymeric

TABLE 12
USUAL COMPOSITION LIMITS FOR PORTLAND AND GEOPOLYMER CEMENTS

Oxide	Portland Cement Content (%)	Geopolymer Cement Content (%)
CaO	60 to 67	11
SiO_2	17 to 25	59
Al_2O_3	3 to 8	18
Fe_2O_3	0.5 to 6.0	—
MgO	0.5 to 4.0	3
K_2O, Na_2O	0.3 to 1.2	9
SO_3	2.0 to 3.5	—

After Drechsler and Graham (2005).
— = no data provided.

Si-O-Al-O bonds with the empirical formula Mn[-(Si-O_2) *z*-Al-O]*n* wH_2O, where *n* is the degree of polymerization, *z*, is 1, 2, or 3, and *M* is an alkali cation such as potassium and sodium.

The tungsten byproduct was thermally treated at 950°C for two hours so that a dehydroxylated state was obtained. X-ray defraction testing showed that the mine waste mud consisted primarily of muscovite and quartz. The thermally treated (calcined) mine waste mud composition was primarily silica and alumina, with some arsenic and sulfur contamination, and high contents of iron and potassium oxide. The iron produced binder with a red color. Findings showed that standard paste testing such as flowability (flow table) and set times (Vicat) were not useful with the synthetic binder owing to different material properties. The water absorption properties of mixes with the synthetic binder were very low because of the compact structure of the mix. The modulus of elasticity decreased for mixes with the synthetic binder.

PERFORMANCE OF MINERAL OR QUARRY BYPRODUCTS IN HIGHWAY APPLICATIONS (AGENCY SURVEY)

The agency survey included an open-ended question asking the respondents to comment on experiences with either good or poor performance of mineral or quarry byproducts. The responses were sorted so that responses for mineral processing byproducts are shown in Table 14. The comments indicated that the few states using waste rock and mill tailings consider the performance of the applications to be good. In the case of HMA applications, the responses

TABLE 11
COMPRESSIVE STRENGTH OF MORTAR MIXES

Mortar Mixes	Compressive Strength, psi			
	1 Day	3 Day	7 Day	28 Day
Control	387	5,671	4,569	3,466
10% Perlite	126	4,859	3,785	4,424
10% Fly Ash	122	4,656	3,785	3,844
10% Silica Fume	141	5,540	4,264	5,584

After Ray et al. (2007).

TABLE 13
COMPARISON OF PORTLAND AND GEOPOLYMER UNDERGROUND BACKFILL PRODUCT

Portland Cement Technology	Geopolymer Technology
Backfill mix design: 2.5% ordinary portland cement 4.5% bottom fly ash 57% dolomite quarry 35% tailings	Backfill mix design: 3% geopolymer reagent 97% tailings
Balance of tailings to storage facility	No tailing to storage facility
Large water demand	Elimination of quarry operations
Large environmental impact	Reduction in environmental legacy
Backfill 25% of mining costs	Reduced mining costs

After Drechsler and Graham (2005).

TABLE 14
AGENCY SURVEY RESPONSES FOR PERFORMANCE EXPERIENCE

Question: Comment on your experience with the *performance* of the application(s), which used any mineral or quarry byproducts.		
Performance Categories	Performance Comments	States with Comments
Performance—Good	*Waste Rock:* More fractured faces; plastic fines and overburden need to be removed	MO, NY
	Mill Tailings: Lead "chat" millings very good source for building VMA for Superpave mixes; work like standard fines	KS, KY, NY
Specifications—Existing	*Riprap:* Needs to meet existing LA abrasion and sodium sulfate soundness requirements	AL

VMA = voids in mineral aggregate.

Mineral Processing Research

FIGURE 4 Locations for mineral processing byproduct research.

indicate it is easier to meet the current Superpave mix design criteria for fine aggregates. It appears the states are using existing application specification requirements (i.e., aggregate specifications for riprap, Superpave for HMA). No comments were received about poor performance. The actual responses received from the agencies are included in Appendix A.

DOCUMENT ASSESSMENT SURVEY

Only nine documents in the last nine years were found that deal directly with mineral processing byproducts in highway applications. The majority of the research on mineral processing byproducts was conducted outside of the United States (see Figure 4).

CHAPTER FIVE

QUARRY BYPRODUCTS

Quarry fines are the result of quarrying activities (Figure 5): extraction, rock preparation, and additional processing procedures such as screening and treatment (Petavratzi and Wilson 2009). Most excess material can be reused in restoration of the quarry; however, there are significant amounts of quarry processing byproducts still left that need to be managed. Quarrying limestone and dolomite usually produces 20% to 25% fines and sandstones/gritstone up to 25%. Quarry scalping is considered to be the coarse clay-contaminated material from the pre-screening extracted rock (before the primary crusher).

The RMRC and Turner–Fairbanks Highway Research Center (TFHRC) websites (RMRC 2008; TFHRC 2009) identified three quarry processing byproducts:

- Screenings,
- Settling pond fines, and
- Baghouse fines.

Screenings are defined on this website as the finer fraction of crushed stone that accumulates after primary and secondary crushing and separating on the 4.75 mm screen. Settling pond fines (often referred to as simply “pond fines”) are defined as the fine material collected after washing aggregates and recovery of the aggregates retained on the 0.60 mm screen. The combination of water and minus 0.60 mm fines are discharged into settling ponds or basins where the fines are left to settle out (gravity). Another term, pond clay, has been used to identify material collected from washed natural sands and gravels. Baghouse fines represent the material collected by dry processing plant dust collection systems (i.e., air quality technology).

Other definitions for quarry processing byproducts were found in the literature. Manning and Vetterlein (2003) noted that the European Aggregates Standards tend to construe the definition of fines for concrete and general use as passing the 4 mm sieve, passing the 2 mm sieve for asphalt, and passing the 0.63 mm for fillers. However, in many European quarry locations, the term “fines” refers to the undersized materials from the crushing plant that is wasted.

Petavratzi and Wilson (2009) noted that quarry fines, quarry dust, and quarry wastes are terms that are used interchangeably. These authors defined quarry fines as material passing the 6 mm sieve and are intentionally produced by quarrying activities to meet specific application requirements. Quarry dusts are defined as material passing the 0.075 mm sieve and are a specific subset of quarry fines. Dusts are usually collected from air pollution control systems. They noted that there is a need for the development of standardized definitions.

PHYSICAL AND CHEMICAL PROPERTIES

The range of gradations reported on the TFHRC website (2009) is shown in Table 15 for screenings, pond fines, and baghouse fines. It can be noted that gradations, particle shape, and other physical properties will be a function of the parent material (e.g., mineralogy fracture planes), crushing equipment, and size separation equipment. Although compounds and mineralogical properties depend on parent materials, some examples of composition are shown in Table 16.

Screening of moisture content ranges from 5% to 10% and represents water content absorbed from environmental conditions. Pond fines can have a moisture content of up to 80%. Depending on how the baghouse fines are stored, the moisture content will range from very low to 10% (from environmental moisture).

Key aggregate properties identified by the Florida Department of Transportation were gradation, moisture content, mineralogy, amount of material passing the 0.075 mm sieve size, hydrometer gradation of fines, and acid insoluble fraction (McClellan and Eades 2002). Washed sieve analysis gradations for a variety of Florida limestone sources are shown in Table 17. Table 18 shows the percentage of sand-, silt-, and clay-sized particles.

The physical and chemical properties of Florida limestone sources were determined (McClellan and Eades 2002). Properties included moisture content and acid insolubles (Table 19). The acid insoluble testing showed varying mixtures of quartz, clay (smectite and kaolinite), pyrite (FeS_2), rutile (TiO_2) and goethite (FeOOH) where the most common component was quartz, followed by clays, particularly smectite, then pyrite, rutile, and goethite. Limestone has a greater percentage (11.4% average) than limestone/dolomitic fines (2.1% average).

ENGINEERING PROPERTIES

No specific engineering-related properties were reported either in the NCHRP 4-21 report (Chesner et al. 2000*)* or on the RMRC website (2008) for the quarry processing byproducts identified on the TFHRC or RMRC websites.

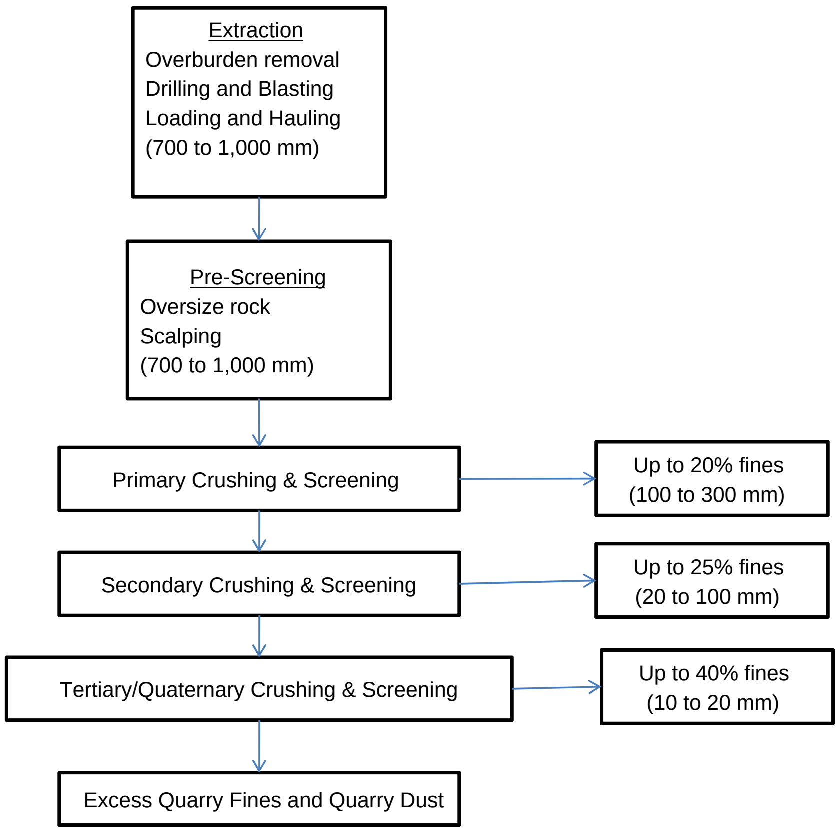

FIGURE 5 Flowchart for a typical quarry operation (RMRC 2008).

TABLE 15
TYPICAL GRADATIONS FOR QUARRY PROCESSING BYPRODUCTS

Sieve Size, mm	Percent Passing			
	Screenings	Pond Fines		Baghouse Fines
		Sand Screw	U.S. Bureau of Mines Fines	
4.75	100	—	—	—
2.36	82–86	—	—	—
1.18	51–71	100	100	—
0.600	31–57	99.2–100	97.2–100	—
0.300	18–33	97.7–100	90.2–100	—
0.150	10–19	90.3–98.1	77.6–99.6	—
0.075	6–12	65.0–89.1	56.8–94.6	100
0.045	—	47.1–75.9	42.6–83.5	89–100
0.030	—	—	—	43–100
0.020	—	—	—	18–100
0.010	—	—	—	8–99
0.005	—	—	—	3–93
0.003	—	—	—	2–75
0.001	—	—	—	1–10

After TFHRC (2009).
— = no data provided.

TABLE 16
TYPICAL OXIDES AND MINERALOGIES FOR DOLOMITIC AND DIABASE POND FINES

Compounds	Compound Percentage for Each Pond Fine Gradation			
	Screenings	Bulk	Retained on 0.11 mm (No. 140)	Passing 0.11 mm (No. 140)
Compounds				
SiO_2	75.25	74.98	77.44	73.37
Al_2O_3	13.63	13.31	13.43	14.16
K_2O	5.34	5.01	4.75	5.30
Na_2O	32.00	2.81	2.49	3.02
CaO	1.28	2.07	1.00	2.77
Fe_2O_3	1.22	1.28	1.28	1.27
MgO	0.33	0.44	0.40	0.47
MnO	0.07	0.03	0.03	0.04
Mineralogy				
Quartz	23.0	25.1	31.5	20.9
K-Feldspar	35.0	33.7	27.1	38.0
Plagioclase	39.2	35.7	31.1	38.7
Muscovite	1.4	3.7	8.7	0.0
Biotite	1.4	0.9	1.6	0.4
Diopside	0.0	1.2	0.0	2.0

TABLE 17
GRADATION INFORMATION FOR VARIOUS SOURCES OF
FLORIDA LIMESTONE FINES

Sieve Size	Washed Sieve Gradation Analysis, Cumulative Percent Passing							
	Source 1	Source 2	Source 3	Source 4	Source 5	Source 6	Source 6	Source 7
40 mm	65	90	88	90	52	47	94	48
60 mm	58	85	78	86	38	25	88	32
100 mm	37	66	63	78	29	14	81	19
200 mm	17	25	28	66	21	7	69	10
325 mm	13	9	13	50	13	6	60	8

McClellan and Eades (2002).

TABLE 18
GRADATION AND MINERALOGY INFORMATION FOR DIFFERENT SOURCES OF
FLORIDA LIMESTONE FINES

Florida Limestone Source	General Composition			Clay Mineralogy (<2 microns)
	Sand (%)	Silt (%)	Clay (%)	
Source 1	78.5	7.0	14.5	D > Q > S
Source 2	56.5	38.3	5.1	D >> Q > S
Source 3	26.4	52.2	21.4	D >> C > Q > S
Source 4	10.8	70.5	18.7	D >> C > Q > S
Source 5	84.9	9.6	5.6	C >> Q > S
Source 6	67.7	22.1	10.3	C >> Q > S
Source 7	79.1	9.7	11.1	C >> Q > S
Source 8	41.5	43.8	14.7	C >> Q > S

McClellan and Eades (2002).
C = calcite, D = dolomite, G = goethite, K = kaolinite (clay), P = pyrite, Q = quartz, R = rutile, S = smectite (clay).

TABLE 19
SUMMARY OF MOISTURE AND ACID INSOLUBLE CONTENTS IN FLORIDA SOURCES OF LIMESTONE

Florida Limestone Fines	No. of Samples	Moisture Content (%) Average	Moisture Content (%) Std. Dev.	Acid Insoluble (%) Average	Acid Insoluble (%) Std. Dev.	Acid Insoluble Fraction by XRD
Source 1	6	18.7	14.2	1.5	0.5	Q >> S > H Q >> S > R Q >> R, Q >> S Q >> S > R > H
Source 2	5	19.8	8.2	0.9	0.2	Q >> K > S Q >> S > P > R P > Q, Q >> S > P
Source 3	11	21.0	9.8	3.6	1.4	Q > S Q > S > P > R Q >> S > P > R Q > S > P S
Source 4	18	12.7	8.5	1.8	0.8	Q > S > G S > Q > P >> G > R Q > P > S Q > S Q > S > P Q >> S > P > G Q >> S > P > R S > Q > P Q > P > S > G

McClellan and Eades (2002).
C = calcite, D = dolomite, G = goethite, K = kaolinite (clay), P = pyrite, Q = quartz, R = rutile, S = smectite (clay), H = not defined in original document, XRD = X-ray diffraction

Most of the engineering information found in the literature is embedded in discussions of the application properties (see following section).

ENVIRONMENTAL PROPERTIES

No environmental issues (i.e., air and water quality) were reported in the NCHRP 4-21 (Chesner et al. 2000). However, if screenings and baghouse fines are used, standard regulations covering containment of fugitive dust can be expected to apply. Because pond fines are obtained from a wet source fugitive dust will not be a concern.

PRODUCTION AND USAGE

United States

More than 3,000 stone quarry operations are located across the United States. Every state, except for Delaware, has quarry operations. An estimated production of more than 175 million tons is generated each year. The leading aggregate and stone producing states include Pennsylvania, Texas, Florida, Illinois, Virginia, Tennessee, Missouri, Georgia, North Carolina, Kentucky, and Ohio. The TFHRC website (2009) estimated that baghouse fines byproducts are stockpiled at 65 million tons/year resulting in an estimated 4 billion tons stockpiled and/or landfilled (TFHRC 2006).

As of 2000, states with quarry byproduct production rates of more than 5 million tons per year were Florida, Georgia, Kentucky, Illinois, Missouri, North Carolina, Ohio, Pennsylvania, Tennessee, Texas, and Virginia. States with production rates between 500,000 and 5 million tons/year were Alabama, Alaska, Arizona, Arkansas, California, Colorado, Connecticut, Hawaii, Indiana, Iowa, Kansas, Maryland, Michigan, Minnesota, Montana, Nevada, New Jersey, New York, Oklahoma, Oregon, South Carolina, South Dakota, Washington, Wisconsin, and Utah. States with production rates of less than 500,000 included Idaho, Mississippi, New Hampshire, Louisiana, Maine, Nebraska, New Mexico, North Dakota, Rhode Island, Vermont, and Wyoming. Of the states with sources of quarry byproducts, only Arkansas, Colorado, Georgia, Massachusetts, and Missouri, reported general use in highway applications in 2000. Texas and Wyoming provide the option as an alternative to bidders, whereas Illinois, Montana, New York, Vermont, and Rhode Island only approve quarry byproduct use on a case-by-case basis.

Florida ranked third in the nation in crushed stone production with an annual rate of approximately 90 million tons per year (McClellan and Eades 2002). The aggregate products in Florida are primarily limestone, dolomite, shell, and marl, with the limestone accounting for 95% of the production. Quarry byproducts, coarse fraction of quarry byproducts (passing 9.5 mm and retained on 0.075 mm) and fines (passing 0.075 mm), are considered under-utilized materials in Florida. Aggregate producers typically find a market for about 78% of the coarse aggregate byproducts, but only 34% of the fines. The estimated production is 154 million tons of coarse sizes and 146 million tons of fine sizes over a 10-year period.

TABLE 20
ESTIMATED PRODUCTION OF AGGREGATE, QUARRY WASTE, AND QUARRY FINES IN THE UNITED KINGDOM

Rock Type	Annual Production (millions of tonnes)		
	Saleable Aggregate	Quarry Waste	Quarry Fines
Sandstone	10	1.1	3.3
Limestone	67.3	7.5	18.8
Igneous and Metamorphic Rock	44.6	5	11.2
Sand and Gravel	82.4	9.2	20.6
Total	204.3	22.8	53.9

After British Geological Survey (2007).

The following equation can be used to estimate the annual production of fines:

$$APF_i = \left[CP_i + \left(n * API\right)\right]WA$$

Where:

APF_i = annual production of fines, in millions of tons, for year i;
CP_i = year specific annual stone production, in millions of tons, for year i;
n = number of years in the future;
API = annual production increase (1.86 million tons/year for the 29-year period used to develop the equation); and
WA = weighted average of byproduct fines production (29.1% for the study used to develop the equation).

International

In 2000, reported international use of quarry byproducts were listed as HMA use in Austria, Belgium, and Canada. Austria and Belgium were also reported as using quarry byproducts in either cold-mix surface treatments or stabilized bases (Chesner et al. 2000).

The British Geological Survey (2007) reported the 2005 generation of quarry production and byproducts as shown in Table 20. The quarry waste is about 10% and quarry fines are about 25% of the saleable aggregate.

Petavratzi and Wilson (2009) compiled a comprehensive report on the use, properties, and potential applications for United Kingdom quarry byproducts. The authors reported that primary aggregate products are limestone, dolomite, and chalk quarrying operations that generate around 20% to 25% fines. Sandstone and gritstone quarries produce up to 35% fines, sand and gravel fines generation vary between 5% and 15%, and igneous rocks produce between 10% and 30% fines. Several software programs are available that can be used for modeling quarry operations. These programs are designed to help optimize the production of the primary product while minimizing the fines.

Legislation—United Kingdom

Petavratzi and Wilson (2009) included information on various recent U.K. legislations that are expected to impact the use of quarry byproducts. The first is the Aggregates Levy (Statutory Instrument 2003), which applies to primary sales of aggregates. The purpose of the legislation is to create a viable market for recycled and secondary aggregates by increasing the cost of the primary materials. It is also expected to:

- Promote environmentally friendly extraction and transport
- Address the environmental impacts of past aggregates extraction
- Compensate local communities for the impact of aggregates extraction.

This legislation applies to quarry fines and is seen as a barrier to increased use of the byproducts.

The Mining Waste Directive (EU Directive 2006 I/EC) will require the implementation of a waste management plan and all noninert waste producers will require a permit to operate. This directive will require quarry operators to more efficiently manage their byproducts and expand secondary uses. The Directive was implemented as national law by May 2008 and mine waste facilities would be subject to the new provisions by 2012.

COST INFORMATION

Bottero et al. (2006) conducted a cost–benefit analysis on the possible environmental and economic benefits of using mineral byproducts in the building industry in Italy. Researchers found that for their local conditions the use of mineral byproducts was advantageous compared with not using such byproducts. Aggregate Manager (2008) found that capital improvement to the quarry operation feeding an on-site asphalt concrete plant resulted in a fuel cost savings of between 10% and 20%, while at the same time significantly improving the marketability and usefulness of the screenings from the operations. Both usability and fuel saving came from converting a wet wash process to an air classification system.

CHAPTER SIX

AGENCY SURVEY RESULTS

The 2009 agency survey questionnaire was used to collect information on the type and highway application usages across the United States. The matrix provided for responses, along with the number of responses, is shown in Table 21. The majority of the states indicated that they are using quarry processing byproducts in either HMA or pavement surface treatment applications. These byproducts are also being used in PCC, flowable fills, and embankment applications, but much less frequently. Given the selection of "unknown type" by some respondents, it appears that no distinction of the source of fine aggregates is required by some state agencies.

Table 22 shows that the most commonly used quarry processing byproducts are screenings and baghouse fines. Only six states, Connecticut, Illinois, Indiana, Maryland, South Carolina, and Wisconsin, and Ontario, Canada, use pond fines in any highway applications.

The states using pond fines or screenings in highway applications tend to be concentrated in the eastern part of the country (Figure 6). States using baghouse fines tend to be fairly well distributed throughout the country.

TABLE 21
STATES USING QUARRY BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

Number of Applications	States			
	Baghouse Fines	Pond Fines	Screenings	Unknown Type
9	—	—	—	ID
6	—	—	—	GA
5	—	—	ND	
4	—	—	SC, VA	
3	—	SC	CO, KY, MS, NY, VT, WA, WI	
2	VA, WI	—	CT, FL, GA, IL, IN, IA, NC, NE, PA	NY
1	AL, CT, DC, FL, GA, KY, MN, MS, NJ, NM, NV, NY, OK, TX, VT, WA, WV	CT, IL, IN, MD, OH, WI	AL, AR, DC, DE, LA, MD, ME, MO, OH, OR, TX	CT, IL, NM

— = no data provided

TABLE 22
RESULTS FOR AGENCY SURVEY FOR QUARRY PROCESSING BYPRODUCTS USED IN HIGHWAY APPLICATIONS

Quarry Byproducts:_ Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the type of material used in your state, check the mineral or quarry byproduct, unknown type box at the end of the list.
- Pond fines: fines obtained from washing crushed aggregate
- Screenings: smaller aggregate fractions left after primary and secondary crushing operations

Byproduct	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embank.	Flowable Fill	HMA	Pavement Surface Treatment (non-structural)	PCC	Soil Stability
Baghouse Fines (aggregate production)	1	0	0	0	0	17	2	1	0
Pond Fines	0	0	0	1	1	4	2	1	0
Screenings	0	0	6	5	8	25	11	7	1
Mineral or Quarry Byproduct, Unknown Type	1	1	2	3	3	5	1	2	2

Embank. = embankment.

FIGURE 6 Location of research for quarry processing byproducts in highway applications: (a) baghouse fines; (b) screenings; (c) pond fines.

CHAPTER SEVEN

APPLICATIONS

McClellan and Eades (2002) noted that the quarry byproducts of interest to the Florida Department of Transportation included engineered backfills, flowable fills, fillers for PCC, and synthetic aggregate production.

A comprehensive report by Petavratzi and Wilson (2009) provided a wide range of information on the use of quarry byproducts in a variety of highway and non-highway applications. For highway applications, they identified key quarry byproducts as defined in the British standard BS EN 12620. Defined geometrical properties included gradation, flakiness index, shell content, fines content, and clay content. Physical properties included assessments of the Los Angeles abrasion, resistance to wear, polished stone value, aggregate abrasion value for highway surfaces, and magnesium sulfate soundness. Important chemical properties were identified as water soluble chloride ion, acid soluble sulfates and total sulfur, and carbonate content.

The mineralogy of the quarry byproducts has the same mineral content as the soil and solid rock present at the quarry, although their physical and chemical characteristics may have been altered during processing. Factors influencing quarry fines properties include the toughness needed to resist the abrasion and impact associated with construction operations such as conveyor belts, milling and mixing, haulage roads, stockpiling and tipping, blasting design, velocity of conveyor belts, mill type, time-scales of operations, drop heights during tipping, and stockpiling.

BOUND APPLICATIONS

Portland Cement Substitution

Stubstad (2008) evaluated replacing a 25% portion of Type II/V portland cement with varying percentages of Type F coal fly ash and limestone byproducts. The limestone was interground with cement prior to testing. Workability of fresh concrete was also investigated. Five limestone contents were investigated: 0 (control), 1.6%, 2.2%, 2.85%, and 4.5%, and three sources of cement in three different testing laboratories. The percent of limestone byproduct was based on total CO_2 of the cement; the assumption being that the limestone was the only contributor to this compound.

Results show compressive strength increased by about 5% to 7% when limestone was included (91 day). Drying shrinkage decreased with the increasing percentage of limestone. Shrinkage was reduced by about 5% with 1.6% limestone; at 2.85% limestone, it was reduced by about 10%. Permeability increased with the increasing percentage of limestone; results were also strongly dependent on the cement source. At 1.6% limestone, the permeability increased by about 8%, at 2.5% limestone, the permeability increased by 22%.

Portland Cement Concrete

Quarry byproducts have been used in a number of PCC applications including cement production, traditional PCC, CLSM, and self-consolidating concrete (SCC). Raman et al. (2007) evaluated the partial replacement of natural mining sand with quarry waste in flowing concrete (SCC). These researchers found that the flakiness of their source of quarry waste resulted in a slight loss of compressive strength, and the quarry waste concrete had a higher initial surface absorption compared with the control mix. This may also be a function of the flakiness making the final compaction of the mix more porous. The quarry waste replacement did not significantly alter the nondestructive hardened concrete properties (e.g., dynamic modulus).

Shah et al. (2007) investigated the use of ornamental stone byproduct (in Turkey) and using marble and granite byproducts as coarse aggregates in traditional concrete. They found no statistical difference between byproduct and control mixes. Hardened properties for byproduct mixes showed better bonding between materials and cements.

Research in Turkey by Binici et al. (2008) considered the use of marble and granite rock quarry byproducts from ornamental stone industries for use as recycled aggregates. Marble and granite byproducts were used as substitutes for coarse aggregates; limestone was used in the control mixes. Fine aggregates used were river sand and/or granulated ground blast furnace slag (GGBFS). Superplasticizers were used to obtain the desired workability. The marble mixes showed the most resistance to abrasion, and when combined with GGBFS, showed the best resistance to chloride penetration. The granite mixes also had significantly more resistance to chloride penetration, and both marble and granite mixes had increased compressive strengths at 28 days.

TABLE 23
PROPERTIES OF MATERIALS USED IN RAMAN ET AL. (2007) SCC STUDY

Properties	Crushed Granite Stone	Natural Mining Sand	Quarry Waste	Ordinary Portland Cement	Silica Fume	Type C Malaysian Fly Ash
Specific Gravity	2.62	2.60	2.63	3.15	2.20	2.26
Water Absorption Capacity, %	0.90	1.20	0.60	—	—	—
Maximum Aggregate Size, mm	19.00	4.75	9.5	0.023	0.015	0.020
Fineness Modulus	—	3.01	3.20	—	—	—
Flakiness Index, %	28	18.0	55	—	—	—
Aggregate Crushing Value, %	—	—	49	—	—	—
Specific Surface Area, m^2/kg	—	—	—	325 (Blaine)	26,000 (N_2 absorp.)	440 (Blaine)

Tap water: chlorine was negligible; Superplasticizer: specific gravity of 1.21, solid content of 40%.
Air entraining agent: specific gravity of 1.02, solid content of 8%.
— = data not provided.

Self-Consolidating Concrete

Canadian research by Raman et al. (2007) used quarry byproducts as a partial (20% by weight) replacement for natural mining sand to produce flowing concrete (i.e., SCC) with a water to cement ratio of 0.45. Values of the individual materials' physical and volumetric properties were obtained (Table 23). Researchers reported ranges of fresh concrete properties (Table 24) and compressive properties over time were also obtained (Table 25). The SCC with the quarry byproduct sand replacement (20%) reduced the compressive strength somewhat. The mix with the silica fume and quarry byproducts increased the compressive strength somewhat. The mix with fly ash and quarry byproducts achieved similar compressive strengths by 28 days.

Dynamic modulus of elasticity was similar for all of the mixes, with the control having the lowest of all the mixes. The ultrasonic pulse velocity showed similar trends. The use of quarry byproduct in any of the mixes resulted in a slight increase in initial surface absorption because of the increased porosity in the concrete covering the reinforcing bars. Silica fume provided additional strength gains to compensate for the inclusion of the quarry byproduct.

Felekoglu (2007, 2008) evaluated the use of quarry dust limestone power that was used to develop SCC mixes. This Turkish research indicated that the quarry byproduct can be used to economically and produce acceptable SCC compressive strength.

TABLE 24
FRESH SCC PROPERTIES

Test	Range of Results for Study	Typical Values for SCC
Slump, mm	230 to 245 mm	>190 mm
Slump Flow, mm	520 to 550 mm	>500 mm
V-Funnel, L/s	0.355 to 0.425 L/s	>0.0333
Air Voids, %	1.6 to 2.2	—

After Raman et al. (2007).
SCC = self-consolidating concrete.

Hot Mix Asphalt

Research in Turkey by Akbulut and Gürer (2007) explored the use of marble quarry byproducts in HMA mixes using 60/70 penetration graded binders. Aggregate properties determined for the project include LA abrasions, aggregate impact value, flakiness, and freeze/thaw resistance. All aggregates had acceptable properties. Marshall mix designs were used to determine the acceptability of the HMA mixtures. One of the marble sources was found to be acceptable for surface course mixes; all of the mixes were acceptable for lower lifts.

Stabilized Base

Nelson et al. (1994) investigated the use of emulsion-stabilized limestone screenings for Linn County, Iowa. Findings showed that a low-maintenance roadway could be constructed by placing a seal coat on top of 6 in. of emulsion-stabilized limestone screenings base. If the residual asphalt content is too low (3.5% compared with 4.5% for this study), an economical roadway cannot be obtained (performance not sufficient). Reducing the base thickness to 4 in. is also not cost-effective. Higher traffic facilities would need a 2-in. HMA overlay over the stabilized base to achieve a lost-cost, low-maintenance roadway.

UNBOUND APPLICATIONS: BASE AND SUBBASE

Brazilian researchers De Rezenda and Carvalho (2003) used quarry byproducts as 8 in. of base material under 1.2 in. of surface treatment (double chip seal) in a 1998 low traffic volume roadway field study. The quarry byproduct was classified as GM by the Unified Soil Classification System and A-2-4 by AASHTO classification with 65.9% gravel size, 12.0% sand, and 22.1% fines (silt and clay). The California bearing ratio (CBR) was 27 for the byproduct. The in situ testing of the base material included dynamic cone penetration that was between 1 and 9 mm per blow, which would correlate with in situ CBR values of more than 100 for the lower values and between 34 and 83 for the higher millimeters per blow values. Laboratory resilient modulus testing indicated values of an average of 44 ksi.

TABLE 25
COMPRESSIVE STRENGTHS FOR VARIOUS PCC MIXTURES

PCC Mixture Combinations	Compressive Strength at Various Days, psi			
	7	14	28	56
Self-Consolidating Concrete (control)	4,192	4,757	5,265	5,540
Quarry Byproduct	3,844	4,424	4,859	5,004
Silica Fume and Quarry Byproduct	4,525	4,960	5,410	5,743
Fly Ash and Quarry Byproduct	3,844	4,728	5,250	5,613

After Raman et al. (2007).

Testing of in situ properties for stress–strain characteristics (Pencel pressuremeter test; RocTest 2009) showed that the properties of the quarry byproduct base were sensitive to the water content, which fluctuated from season to season. Higher water contents resulted in lower strength parameters. Plate bearing tests (10-in. diameter) also showed moisture-sensitive base support characteristics. Recommendations were that the quarry byproduct was acceptable for use in roadway construction. Because the field study was conducted for a low traffic volume roadway, more testing on higher traffic volume roadways was recommended.

Cresswell (2007) reported on studies in the United Kingdom that used crushed rock fines (95%, 90%, and 85%) mixed with paper sludge (5%, 10%, and 15%) to fabricate synthetic aggregates. The crushed rock washings were the byproduct of cleaning scalpings after crushing the parent rock. The average gradation had 99.5% passing the 0.30 mm and 80% passing the 0.075 mm sieves. The mineralogy was primarily plagioclase and K-feldspar with quartz, mica, and kaolin. The relative density decreased from 2.23 to 2.1 with the increasing percentage of paper sludge used to fabricate the aggregate. The water absorption increased from 1.95 to 6.19 with the increasing percentage of paper sludge.

MODIFICATION OF FINE QUARRY BYPRODUCTS

Florida researchers, McClellan and Eades (2002), evaluated four processes to produce synthetic aggregates from the agglomeration of the minus 0.075 mm materials obtained from producing quarried materials. The two wet processes used for the project were drum granulation and pan granulation. The two dry processes used were roll-press flaking and roll-press briquetting. All four of these methods have been used to prepare agricultural liming agents. The cost of the wet processes is slightly higher than the dry processes because of the need for more instrumentation, piping and ductwork, auxiliary facilities, and buildings. Capital recovery was estimated as 30% higher for the wet processes.

A key factor in the development of synthetic aggregate is in identifying a binding agent with the ability to produce synthetic aggregates with acceptable crushing strength. Sodium silicate, portland cement, and calcium sulfate hemihydrates ($CaSO_4 * ½ H_2O$) were evaluated as potential binders. The method of forming the synthetic aggregates influenced the particle sizes. For aggregates fabricated using the California pellet mill and fines/cement binder, more than 75% of the fines/cement aggregate was retained on the 4.75 mm sieve, whereas about 12% was retained on the 2.38 mm sieve. Less than 4% was retained on any of the other individual screens. The pug mill mixing with the fines/sodium silicate or fines/cement binder produced finer more well-graded size distributions. Between 25% and 35% were retained on each of the 4.75 mm, 2.36 mm sieves, and between 12% and 18% on each of the 1.18 mm and 0.60 mm sieves. The crushing strength of the synthetic aggregates was between 6.0 and 14.7 lb. The aggregates prepared with the sodium silicate performed poorly owing to problems with solubility. When a single method of production (pug mill) with the various binders was evaluated, both the binder type and source of fines influenced the gradation of the synthetic aggregate.

Portland cement mortar cubes were prepared with the synthetic aggregates and both Ottawa and Florida DOT sands as the control fines. Table 26 shows that the sodium silicate binder, regardless of the source of fines, had the lowest com-

TABLE 26
COMPRESSIVE STRENGTH OF MORTAR CUBES WITH VARIOUS SANDS AND SYNTHETIC AGGREGATES

Time, days	Mortars with Sand Standards		Synthetic Aggregates					
			Sodium Silicate Binder			Portland Cement Binder		
	Ottawa	FDOT	Fines D	Fines H	Fines I	Fines D	Fines H	Fines I
3	3,446	3,913	587	950	955	1,733	2,767	2,179
7	3,454	5,804	1,063	963	1,088	2,767	3,638	3,188
14	4,013	7,342	1,238	1,330	1,413	2,938	4,017	2,946
28	4,450	7,156	1,432	971	1,500	2,983	4,200	3,167

After McClellan and Eades (2002).

TABLE 27
AGENCY SURVEY RESPONSES FOR PERFORMANCE EXPERIENCE

Question: Comment on your experience with the *performance* of the application(s) which used any mineral or quarry byproduct.		
Performance Categories	Performance Comments	States with Comments
Performance—Good	*Screenings:* meet AASHTO No. 10 for bike trails; good angularity for HMA fines; easier to meet specification requirements for fine aggregate	KY, LA, NE, NY, PA, TX
	Baghouse fines: additional fines used in foamed asphalt	IA, KY
	General comments: performing well; successful; good to excellent; meet performance-based specifications	CO, DC, ME, MS, VA, WA
Usage—High	*Screenings:* Commonly used in HMA	AR, MO
Specifications—Existing	*HMA:* use existing HMA specifications when using screenings and baghouse fines; considered in mix design stage	AL, TX
	PCC: considered in mix design stage	AL

TABLE 28
SUMMARY OF KEY FINDINGS FOR THE EUROPEAN STATE OF THE ART

	Generation of Fines
1	Fiscal changes, such as the introduction of the Aggregate Levy, may in some circumstances inhibit the exploitation of fines, creating additional problems for those responsible for their management.
2	Engineering design changes, including those linked to regulation, lead to changes in the portfolio of products derived from hard rock aggregate production, with consequent changes in fines production. In particular, increased use of high polished stone value aggregate in road surfaces increased the product of fines.
	Marketing of Fines
3	Although some operations are able to deliver fines to responsive markets, others are either inappropriately located or unable for other reasons to do so.
4	Additional characterization of fines may be needed as part of a marketing exercise, particularly to demonstrate consistency of product.
5	Additional processing of fines may be required to generate products suitable for specific markets.
6	New (or revised) specifications may be needed so that fines can map onto requirements for specific products and so achieve recognition as a quarry product.
	Exploitation of Fines
7	Opportunities exist to increase the proportions of quarry fines used in construction products, provided specifications exist and can be met.
8	Opportunities exist to use fines in response to soil protection requirements, to compensate for soil erosion and to generate soil substitutes.
9	A market-led approach is needed, which will require quarry producers to become familiar with the needs and practices of nonconstruction users of fines.

After Manning (2003).

pressive strengths when compared with mortars with sand standards or with the fines/portland cement binder. There appears to be some dependency of mortar cube strength on the source of fines; Fines H/cement mortar had about twice the strength as the Fines D/cement cubes. The Fines H/cement compressive strengths were near that for the Ottawa sands at 14 and 28 days.

PERFORMANCE OF QUARRY PROCESSING BYPRODUCTS

The agency survey included an open-ended question asking the respondents to comment on experiences with either good or poor performance of mineral or quarry byproducts. The responses were sorted so that responses for quarry products are shown in Table 27. All of the responses to this question indicated that the performance of applications is good to excellent. States are using current application specification requirements to incorporate quarry processing byproducts. Both Arkansas and Missouri indicated that they routinely use screenings in HMA applications. The actual responses from each agency are included in Appendix A.

Manning and Vetterlein (2003) provided a summary of the state of the art for the European quarry industry. The key findings from this report (Table 28) address topics related to the generation of fines, the marketing of fines, and the exploitation of fines (i.e., potential uses).

CHAPTER EIGHT

DOCUMENT ASSESSMENT SURVEY

CHAPTER SUMMARY

A total of 26 documents were found using quarry processing byproducts in highway applications. These research projects represent work conducted in a number of countries around the world (Figure 7).

The major concentration of research focused on PCC applications, followed by geotechnical and HMA (Figure 8).

LIST OF CANDIDATE BYPRODUCTS

The following general categories were identified for mineral processing byproducts and included in the TFHRC and RMRC websites (2008):

- Waste rock
- Mill tailings
- Coal refuse
- Wash slime
- Spent shale oil.

Categories identified for quarry processing byproducts included:

- Screenings
- Pond fines
- Baghouse fines.

Several definitions and/or descriptions of material properties for each category were found in the literature that could address this lack of fit for different byproducts. Both the United Kingdom and Australian researchers indicated that one of the first major steps needed is clear definitions of quarry processing byproduct categories. Definitions found on the RMRC and TFHRC websites define categories depending on where they are obtained in the quarrying process. Suggestions from the international community included definitions based on the intended uses for the byproducts.

TEST PROCEDURES

The test methods used by researchers to characterize the physical and chemical properties of the byproducts as well as used to define the hybrid application properties are shown in Table 29. The test methods are grouped by the material property being evaluated.

A total of 24 standards were cited for aggregate properties; all were British Standards (BS EN) except for one ASTM and one Turkish standard. This reflects the large number of international documents included in the literature review. Seventeen standards were identified for evaluating portland cement, mortar, or concrete (fresh and hardened) properties. Of these standards, eight were British standards, six were ASTM standards, one was from AASHTO, one was a California test method, and one was for a new nonstandardized PCC test (V-funnel). All seven of the test methods for asphalt cements were ASTM standards; however, none of these binder tests were for the Superpave performance grading specification testing. All of the test methods refer to tests used for either penetration or viscosity grading systems that are only still used in the United States for a limited number of applications (e.g., emulsions). Of the three soils-related standards, two were translations of Dutch test methods and one method referred to an ASTM standard.

In general, specified test methods require the byproducts to meet existing application specification requirements. This is consistent, regardless of country.

MATERIALS PREPARATION AND BYPRODUCT QUALITY CONTROL

Concerns related to byproduct materials preparation include:

- Removing overburden and deleterious materials from waste rock before using in highway applications;
- Removing plastic fines;
- Resizing by crushing or sieving to obtain desired application gradations;
- Dewatering byproduct slurries prior to use in most highway applications; and
- Testing for leaching potential, which will be particularly important for byproducts with known sources of sulfur compounds and radioactive elements.

MATERIALS HANDLING CONCERNS

No particular concerns were found in the literature or noted in the agency responses.

FIGURE 7 Location of research for quarry processing byproducts in highway applications.

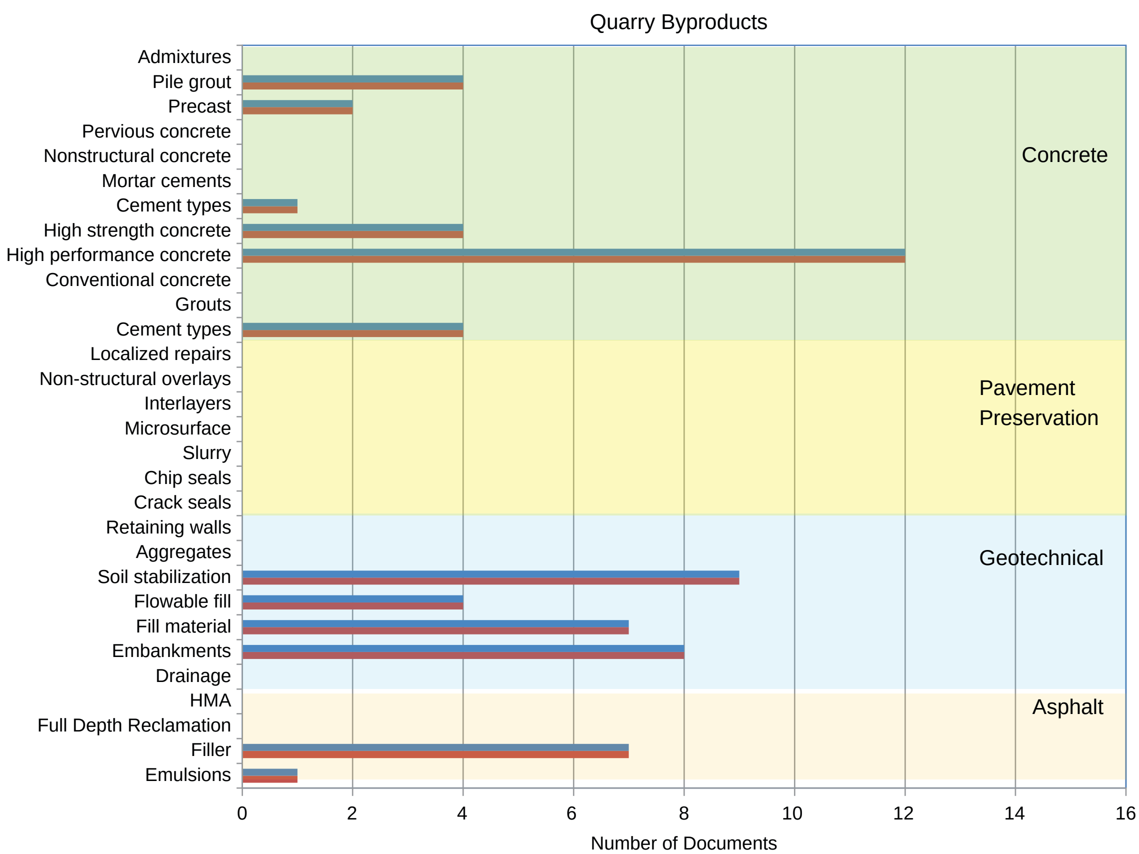

FIGURE 8 Information on quarry processing byproducts in highway applications in the literature.

TABLE 29
SUMMARY OF TEST METHODS USED BY RESEARCHERS TO INVESTIGATE EITHER MINERAL OR QUARRY PROCESS BYPRODUCTS

Material	Test Method	Title
Aggregate	ASTM D2419	Standard Test Method for Sand Equivalent Value of Soils and Fine Aggregate
	BS EN 1097 Part 1-9	Test methods—physical and mechanical properties of aggregates
	BS EN 12620	Aggregates for concrete
	BS EN 13043	Aggregates for bituminous mixtures and surface treatments
	BS EN 13139	Aggregates for mortar
	BS EN 13242	Aggregates for unbound and hydraulically bound mixtures
	BS EN 13383	Armourstone
	BS EN 13450	Railway ballast
	BS EN 1367 Part 1-5	Test methods—thermal and weathering properties of aggregates
	BS EN 13955	Part 1: Lightweight aggregate for concrete, mortar and grout
	BS EN 13956	Part 2: Lightweight aggregate for bound and unbound materials
	BS EN 1744	Test methods—chemical properties of aggregates
Aggregate	BS EN 932 Part 1-6	General test methods (i.e., sampling petrography, repeatability-reproducibility etc.) for aggregates
	BS EN 933 Part 1-10	Test methods—geometrical properties of aggregates
	BS PD 6682-1	Aggregates for concrete
	BS PD 6682-2	Aggregates for asphalt and chipping
	BS PD 6682-3	Aggregates for mortar
	BS PD 6682-4	Lightweight aggregates for concrete and mortar
	BS PD 6682-5	Lightweight aggregates for other uses
	BS PD 6682-7	Aggregates for armourstone
	BS PD 6682-8	Aggregates for railway ballast
	BS PD 6682-9	Test method for aggregates
	TS 706 EN 12620	Turkish standard for concrete aggregate
Asphalt Cement	ASTM D113	Standard Test Method for Ductility of Bituminous Materials
	ASTM D36	Standard Test Method for Softening Point of Bitumen
	ASTM D4402	Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer
	ASTM D5	Standard Test Method for Penetration of Bituminous Materials
	ASTM D6	Standard Test Method for Loss on Heating of Oil and Asphaltic Compounds
	ASTM D70	Standard Test Method for Density of Semi-Solid Bituminous Materials (Pycnometer Method)
	ASTM D92	Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester
PCC	AASHTO T160	Standard Test Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete
	ASTM C1202	Standard Test Method for Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration
	ASTM C143	Standard Test Method for Slump of Hydraulic Cement Concrete
	ASTM C150	Standard Specification for Portland Cement
	ASTM C1556	Standard Test Method for Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion
	ASTM C1581	Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage
	ASTM C39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
	BS 1881: Part 106	Concrete adhesion tester pull off tester standards
	BS 1881: Part 203	Testing concrete. Recommendations for measurement of velocity of ultrasonic pulses in concrete
	BS 1881: Part 209	Testing concrete. Recommendations for the measurement of dynamic modulus of elasticity
	BS 1881: Part 5	Testing concrete. Methods of testing hardened concrete for other than strength
	BS EN 196-3	Methods of testing cement. Determination of setting time and soundness
	BS EN 197-1	Cement. Composition, specifications and conformity criteria for common cements

TABLE 29
(*continued*)

Material	Test Method	Title
PCC	BS ISO 11599	Determination of gas porosity and gas permeability of hydraulic binders containing embedded radioactive waste
	Caltrans CT 527	California test for shrinkage of cement mortar
	BS PD 6682-6	Aggregates for unbound and hydraulically bound mixtures
	V-funnel	Not standardized as a test method
Soil	ASTM D422	Standard Test Method for Particle-Size Analysis of Soils
	EA NEN 7371	Leaching characteristics of granular building and waste materials (Dutch standard)
	EA NEN 7375	Leaching—Determination of the leaching of inorganic components from monolithic materials and designed with a diffusion test—Solid ground and stone materials (Dutch Standard)

TRANSFORMATION OF MARGINAL MATERIALS

Several instances of manufacturing synthetic aggregates were found in the literature. Florida researchers adapted existing agricultural technologies for producing synthetic aggregates manufactured from limestone fines (passing the 0.075 sieve) and binder (e.g., cement). The results showed a good match between the binder and limestone materials that has the potential to be used in PCC applications (McClellan and Eades 2002). Cresswell (2007) used a combination of crushed rock fines with paper sludge (binder) to produce synthetic aggregates with some initial success.

DESIGN ADAPTATIONS

More environmental testing is needed prior to using some sources of mineral processing byproducts. No specific requirements for structural or construction adaptations were found in the literature or noted in the agency responses. It appears that existing specifications for material and application properties are used with or without the inclusion of byproducts.

SITE CONSTRUCTION CONCERNS

No particular concerns were found in the literature or noted in the agency responses.

FAILURES, CAUSES, AND LESSONS LEARNED

No particular concerns were found in the literature or noted in the agency responses.

BARRIERS

A number of barriers have been identified throughout the available literature, including:

- Lack of definition and terms of byproducts cause user confusion.
- Limited knowledge about quarry fines and understanding of local sources of byproduct (McClellan and Eades 2002; RMRC 2008).
- Local availability of byproducts not easily found.
- Need feasibility study to define technical and economic viability (McClellan and Eades 2002; Petavratzi and Wilson 2009).
- Lack of understanding of compositional consistency and temporal variability.
- Undefined storage and handling guidance.
- No best practices guidelines for utilization and for different applications.
- Environmental regulations defined by each state rather than at the national level.
- Consumption of natural resources such as water for processing and cleaning fines.
- Limited understanding of potential markets.
- Limited physical and mineralogical information.
- Difficulty in arranging for transportation of byproducts by means of railways (Zanko et al. 2003).
- May require additional cement (portland or asphalt) because of absorption.

The District of Columbia, Iowa, and Texas indicated that no real barriers existed, and Maryland reported it perceived only minimal barriers. Agency responses to barriers are summarized in Table 30. With the exception of haul distance, all of the state's concerns agree with those outlined in the literature.

COSTS

Increased cost issues found in the literature or indicated in the agency responses included:

- Trucking costs associated with long haul distances,
- Additional byproduct preparation such as overburden and plastic fines removal, and
- Additional testing requirements to satisfy EPA requirements.

No specific cost studies were found in the literature, but several conceptual flow charts and programs for matching

TABLE 30
AGENCY RESPONSES TO BARRIERS TO FURTHER USE OF QUARRY BYPRODUCTS

Question: Comment on *barriers* to the use of combustion byproducts in highway applications that have been either overcome or still exist		
Barrier Category	Reasons for Classification as Barrier	States with Barrier Responses
Availability	Lack of availability or only limited sources of byproducts in state	NE, NV, WA
Cost	Require increase in binder content (either asphalt or cement); trucking costs	NE, OH
Performance	Unknown performance	DE
Regulations	EPA: heavy metal considerations; byproducts independently reviewed for environmental and engineering properties prior to use	MD, NY
Specifications	Limits on substitution for portland cement limit amount used	IA

byproducts with products for environmental and cost benefits were noted. It is expected that the cost of any byproduct will need to be at most as costly as landfilling.

GAPS

Gaps in the research and information available to the agencies include:

- Standardization of byproduct definitions
- Readily available information on byproduct locations and availability
- Information on byproduct physical and mineralogical properties
- Statistics on source variability of properties
- Availability of environmental test results
- Best practices for using byproducts in individual highway applications.

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APPENDIX A

Open-Ended Comments from Agency Survey

State	Mineral and Quarry Processing Byproducts	
	Performance	Barriers
AL	Waste rock may be allowed for riprap provided the LA abrasion and sodium soundness requirements are met. Baghouse fines/screenings in HMA or PCC must be considered and addressed in the mix designs.	
AR	Commonly used in ACHM mixes in the state	
AZ	We have not used any of the above products on an ADOT project to my knowledge.	
CO	The screenings are performing well.	Uniformity of the materials is an issue.
DC	Good to excellent	No barriers in using byproducts
DE	Use fines in HMA often	
FL	Works fine in locations where natural sands are not available. In general the Department would prefer to use natural sands, but in some locations it is just not feasible to truck materials to replace the screens. In HMA applications, baghouse fines and screenings are used routinely with no adverse affects.	We have restricted the use of screens to several locations in the state. The screens do not provide the same durability qualities that our natural sands provide.
IL	We work very closely with our aggregate producers; unless the quality is extremely severe, we try to use anything they produce.	
IA	Used for additional fines in foamed asphalt full depth reclamation; worked okay.	None
KS	Lead “chat” millings are a very good source of VMA builder for Superpave mixes.	
KY	The performance of HMA and pavement surface treatments containing baghouse fines, mill tailings, and screenings has been satisfactory.	Depending on the quantity and nature of the baghouse fines and screenings utilized in HMA, the resulting volumetric properties may be adversely affected. Aggregate fines often decrease the air void content and voids-in-the-mineral aggregate in HMA.
LA	Certain granite fines/screenings have been used successfully in HMAC mixes.	
MD	Used as common borrow, no record available, site is stable	Minimal barrier; however, each material is individually reviewed for environmental and engineering bases prior to use for highway system.
ME	Satisfactory	
MO	Screenings or manufactured sand from screenings is included in almost every HMA mixture in the state. The performance has been good except when plastic fines from shale or overburden are not removed during processing.	Many times these contain other undesirable materials such as lead in some mining waste.
MS	Good performance	
ND	Waste screening or rock is usually used in bases or other projects that use different aggregate gradations.	
NE	We use the finer screenings (man sands) in our hot mix asphalts and they provide good fine aggregate angularity for mixes.	Not available throughout the state, so hauling/costs can be high
NV	NDOT allows up to 2% of baghouse fines generated to be reintroduced into the HMA mixing drum.	Limited availability in the geographic area
NY	Mill tailings, screenings, and waste rock behave very much like natural materials of the same size, except they frequently have more fractured faces.	Depending on their source, they may contain metals or other materials that pose environmental concerns. Some mine tailings may also have extremely high specific gravities, changing densities and therefore design parameters.
OH	Not a lot. See the comments on barriers.	Generally to use most of these materials you have to be willing to use more asphalt cement or portland cement. The smaller the particle the greater the surface area that has to be coated. That means the final roadway material costs more and can sometimes have strength, stability and/or handling and placement problems. In Ohio screenings aren’t used in portland or asphalt concrete because we have adequate fines in the aggregate mixtures to begin with. Could they be used as fill/embankment. Yes, but that means trucking costs and higher bid costs for an embankment. In a low bid environment not likely till the material is cost competitive.

State	Mineral and Quarry Processing Byproducts	
	Performance	Barriers
PA	Screenings for bike path surface treatments meeting AASHTO No. 10 have performed well.	
SC	Screenings have been used for fine-grained leveling courses and bases. These applications are part of our standard specifications.	
TX	HMA produced with screenings and baghouse fines have performed well when meeting specification requirements.	No significant barriers
VA	VDOT has had equal success with all mineral processing and quarry byproducts checked above.	Wasted rock is not durable and does not hold together very long.
WA	Used following performance based specs has been good.	Lack of product

Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation