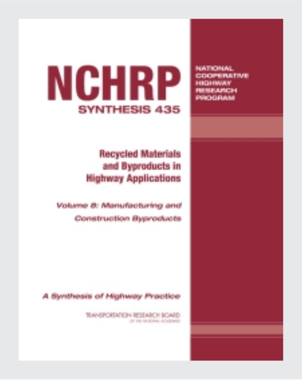

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 435

Recycled Materials and Byproducts in Highway Applications

Volume 8: Manufacturing and Construction 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 8

Project 20-05, Topic 40-01

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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 CEMENT KILN DUST

VOLUME EIGHT: MANUFACTURING AND CONSTRUCTION BYPRODUCTS

This volume contains the survey information for the following byproducts::

- *Kiln dust, cement:* airborne particles from the portland cement rotary kiln.
- *Kiln dust, lime:* airborne particles from the lime production process.
- *Kiln dust, combination:* blending of both cement and lime kiln dusts.
- *Paper pulp, lime mud:* residual materials from paper mills.
- *Roofing shingles, fiberglass-backed (also called fiberglass felt-backed):* byproduct from production of fiberglass-backed roofing material.
- *Roofing shingles, paper-backed (also called organic felt-backed):* byproduct from production of paper-backed roofing material.
- *Roofing shingles, tear-offs:* construction debris from reroofing or demolition of existing structures.
- *Foundry sand:* high-quality sand recycled after metal castings of products.
- *Waste glass:* post-consumer glass byproducts.
- *Sulfur:* byproduct primarily from petroleum and gas processes.
- *Sulfate waste, fluorogypsum:* byproduct from the production of hydrofluoric acid from fluorspar.
- *Sulfate waste, phosphogypsum:* byproduct of phosphoric acid production.

Additional information on the individual byproducts can be found at the following websites:

- Recycled Materials Resource Center: www.rmrc.unh.edu/
- Turner–Fairbanks Highway Research Center: http://www.fhwa.dot.gov/research/tfhrc/.

CHAPTER ONE

CEMENT KILN DUST

BACKGROUND

Cement kiln dust (CKD) is generated during the production of the cement clinker and is a dust particulate mixture of partially calcined and unreacted raw feed, clinker dust, and ash, enriched with alkali sulfates, halides, and other volatiles (Adaska and Taubert 2008). According to EPA (2010), the definition of cement kiln dust is: “a fine-grained, solid, highly alkaline material removed from the cement kiln exhaust gases by scrubbers (filtration baghouses and/or electrostatic precipitators). The composition of CKD varies by plants and over time at a single plant. Much of the material comprising CKD-reacted raw material, including a raw mix at various stages of burning, and particles of clinker.”

Cement is produced using a rotary kiln to turn raw materials (limestone, clay, iron ore, and silica) into a sintered product referred to as a clinker. Gypsum is added at the end of the process to manage the rate of hydration. A rotary kiln is fundamentally a long, slowly rotating cylinder tilted at a slight angle with the burner at the lower end. The raw materials enter the top end of the cylinder, are heated, then exit and cool. The sintered material at the end is referred to as “clinkers.”

Kilns were first introduced in the 1890s and became popular in the first part of the 1900s as improvements were made to provide continuous production and a more consistent final product in larger quantities (“Understanding Cement” 2010). There are three main types of kilns:

- Long-wet kiln
- Long-dry kiln
- Precalciner kiln.

The original kiln style, the long-wet kiln, feeds the raw material in as slurry and the length of the cylinder can be up to 656 ft long and 20 ft in diameter (Figure 1). The length is required because the material needs sufficient time to dry out the slurry water, which until recently was difficult to blend and add dry (“Understanding Cement” 2010). Once in the kiln, the materials are calcined then sintered to form the clinker. Some of these kilns are still in use.

Newer dry kiln configurations add the dry, blended raw materials after passing through a pre-heating tower, using heat from recycling hot kiln gases (Figure 2). The heat exchange is accomplished by feeding the finely ground raw material, called raw meal, into the top of the preheater tower, then passing through a series of cyclones in the tower through which the hot gases are circulated (“Understanding Cement” 2010). The high surface area and small particle size provide efficient heat transfer and approximately 30% to 40% of the decarbonation of the raw meal before it enters the kiln. Because the material enters preheated, the length and the diameter of the cylinder can be smaller but still produce the same quantity of clinker per hour.

The precalciner kiln, the newest technology, is similar in concept to the dry kiln, but with the addition of a second burner, or precalciner (Figure 3). With the additional heat, about 85% to 95% of the material is decarbonated before entering the kiln (“Understanding Cement” 2010).

The particulates for all types of the cement kilns are captured from the exhaust gases using air pollution control devices such as cyclones, baghouses, and electrostatic precipitators (Adaska and Taubert 2008). The particles captured in this process are the CKD. Many cement plants recycle the CKD back into the kiln to optimize the process, save a small quantity of virgin raw materials, and avoid landfilling costs. The CKD is not reused by the plant when there are equipment limitations for handling the dust or it would make the cement product noncompliant with specifications.

PHYSICAL AND CHEMICAL PROPERTIES

Different types of cement kilns generate CKD materials with different physical and chemical properties (Adaska and Taubert 2008). Long-wet and long-dry kiln CKD is typically partially calcined kiln feed fines enriched with alkali sulfates and chlorides. Alkali by-pass with precalciner kilns produce CKD that is more calcined with a coarser size and concentrated with alkali volatiles (Table 1). These CKD byproducts also have the highest amount by weight of calcium oxide and the lowest loss on ignition (LOI) (Table 2).

The type of burner fuel will also influence the CKD composition. Gas- or oil-fired kilns contain higher proportions of soluble K_2O compared with coal-fired kilns. The amounts of trace metals are not significant (Adaska and Taubert 2008; EPA 2010). Previous research by PCA (1992) reported that concentrations for eight Resource Conservation and Recovery Act (RCRA) metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) were well below the regulations at that time.

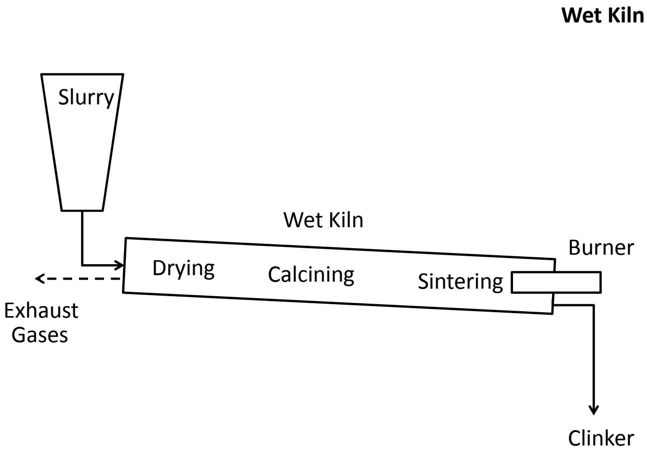


FIGURE 1 Long-wet kiln (after "Understanding Cement" 2010).

When trace metals are present, they include antimony, barium, lead, manganese, strontium, thallium, and zinc (EPA 2008). Minor trace metals include beryllium, copper, hexavalent chromium, mercury, nickel, silver, and thallium. Concentrations of trace metals vary widely between sources of CKD. The trace metals are low enough to not be a concern. The EPA (2008) developed a materials characterization paper in support of the advanced notice of proposed rulemaking identifying CKD as a nonhazardous material that is considered solid waste as long as stockpiles are managed properly.

Traditionally, those agencies using CKD in highway applications focused on using byproducts from cement plants shortly after production. However, there are significant amounts of CKD that have been landfilled over the years. There is some movement to attempt to use these weathered stockpiles of CKD in highway applications to minimize the demands on raw materials. Fresh CKD and landfilled CKD can be expected to have different properties owing to environmental exposure.

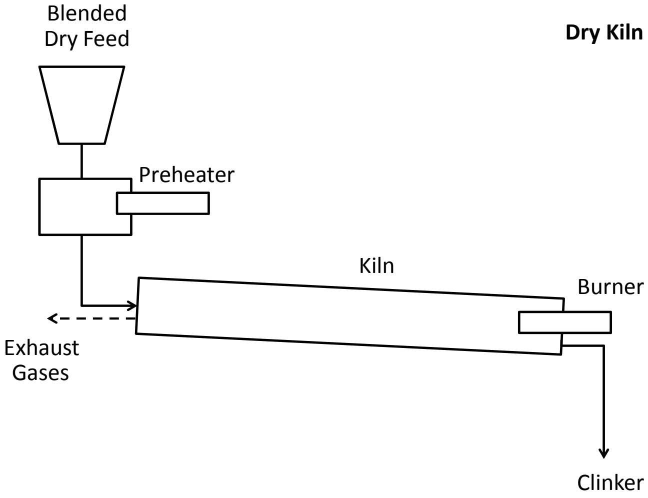


FIGURE 2 Dry kiln (after "Understanding Cement" 2010).

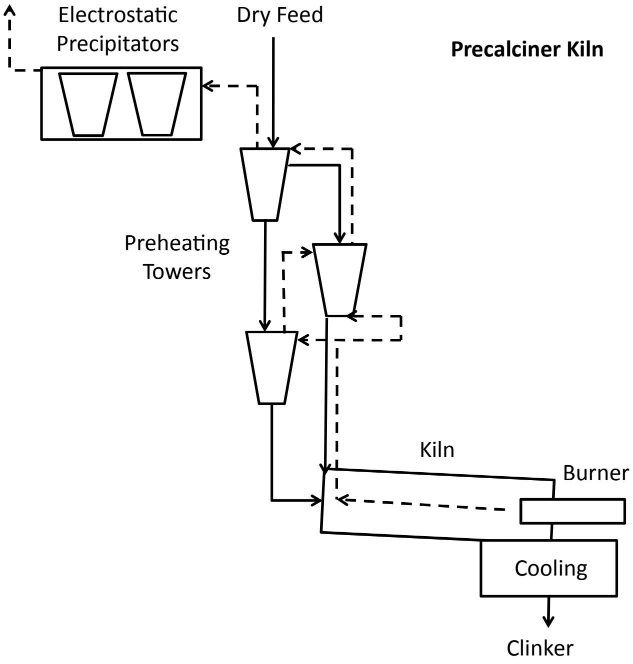


FIGURE 3 Precalciner kiln (after "Understanding Cement" 2010).

Fresh Cement Kiln Dust Properties

Recent and extensive data on CKD chemistry was reported by Williams (2005) for a project that included an in-depth analysis of cement producers scattered throughout the United States and Canada. Approximately 18 companies and their subsidiaries, representing 100 cement plants, were identified and contacted. Of these plants, 12 companies provided the chemical composition of CKD for a total of 32 plants (Table 3). The between-plant coefficient of variation (CV) was under 10% for only the SiO_3 and Al_2O_3. The CV for the CaO, Fe_2O_3, and TiO_2 was between 22% and 32% and ranged from 47% up to 143% for the other compounds. The loss on ignition CV was 35%. The coefficient of variations highlight the wide range of chemical and LOI properties between cement plants and the importance of evaluating the chemical properties of the CKD to be used on each project. By contrast, the variability over time within one plant (Table 4) was

TABLE 1
EXAMPLES OF KILN TYPE INFLUENCE ON PARTICLE SIZE

Particle Size, mm	% by Weight		
	Long-wet kiln	Long-dry kiln	Alkali by-pass from preheater/precalciner
>0.1	5.0	0	2.0
<0.045	85.0	99.2	84.5
<0.003	77.3	98.8	66.0
<0.007	43.0	87.2	14.0
<0.001	12.0	12.0	3.0
<0.0006	7.5	5.6	2.0
Median Size, mm	9.4	3.0	2.2

After Todres et al. (1992); Adaska and Taubert (2008).

TABLE 2
EXAMPLES OF COMPOSITION OF CKD FROM DIFFERENT OPERATION SOURCES

Constituent	% by Weight			
	Long-wet kiln	Long-dry kiln	Alkali by-pass from preheater/precalciner	Typical type I cement
SiO_2	15.02	9.694	15.23	20.5
Al_2O_3	3.8	3.39	3.07	5.4
Fe_2O_3	1.88	1.1	25	2.6
CaO	41.01	44.91	61.28	63.9
MgO	1.47	1.29	2.13	2.1
SO_3	6.27	6.74	8.67	3
Na_2SO_4	0.74	0.27	0.34	<1
K_2O	2.57	2.4	2.51	<1
Loss on Ignition	25.78	30.24	4.48	0–3
Free Lime (CaO)	0.85	0.52	27.18	<2

Todres et al. (1992); Adaska and Taubert (2008).

TABLE 3
CHEMICAL COMPOSITION BY CEMENT KILN PLANT

Cement Producer	Plant	Sample Location	Percent by Weight (%)												
			CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	Mn_2O_3	SrO	LOI
A	1	—	62.04	15.61	4.89	2.00	1.45	8.04	0.45	4.85	NR	NR	NR	NR	25.52
	2	—	48.21	15.88	4.61	1.87	0.71	3.60	0.58	11.92	0.36	0.08	0.05	0.04	9.77
	3		52.19	15.75	3.90	2.06	3.16	11.44	0.34	5.65	NR	NR	0.03	NR	1.78
	4	1	54.11	14.53	5.30	2.10	2.08	12.70	3.28	NR	0.19	0.15	NR	NR	14.71
		2	56.29	14.41	5.49	2.26	2.13	12.99	4.03	NR	0.22	0.10	NR	NR	13.59
		3	48.21	13.46	4.96	2.18	2.43	12.77	3.78	NR	0.20	0.13	NR	NR	13.53
		4	57.17	13.24	5.15	2.13	2.37	13.06	4.46	NR	0.18	0.14	NR	NR	12.70
		5	54.56	13.29	4.95	2.13	1.98	14.27	6.90	NR	0.19	0.12	NR	NR	15.88
		combined	55.55	14.50	5.53	2.21	2.36	10.65	5.45	NR	0.31	0.16	NR	NR	17.62
		cond tower	56.90	12.00	4.38	2.00	2.33	10.60	3.21	NR	0.25	0.12	NR	NR	15.30
		recovery	51.20	12.10	4.69	1.82	1.82	9.72	2.84	NR	0.22	0.15	NR	NR	NR
		waste	53.70	11.30	4.01	1.78	2.12	11.00	2.64	NR	0.20	0.12	NR	NR	NR
B	1	—	62.09	17.62	4.90	2.58	1.93	5.79	0.56	3.76	NR	NR	NR	NR	4.94
	2	—	49.00	13.00	4.04	2.02	0.67	8.10	0.26	3.51	NR	NR	NR	NR	18.10
	3	—	44.00	10.50	4.03	1.92	0.69	7.30	1.19	8.70	NR	NR	NR	NR	19.84
	4	—	41.93	12.66	3.17	0.78	1.75	6.15	0.40	9.71	NR	NR	NR	NR	23.44
	5	—	51.39	16.33	3.69	1.78	2.51	12.27	0.56	11.47	NR	NR	NR	NR	NR
C	1	—	47.75	15.16	4.56	1.84	2.09	10.15	0.99	9.81	NR	NR	NR	NR	1.77
D	1	—	39.41	16.57	3.51	2.22	2.42	2.35	0.09	0.71	0.18	0.00	0.04	0.02	32.16
E	1	—	48.05	14.56	5.59	3.31	0.78	6.06	0.32	1.61	0.28	0.13	NR	NR	22.96
F	1	—	48.16	13.15	5.69	1.07	2.36	2.64	0.45	1.74	0.07	0.21	NR	NR	NR
G	1	waste	44.64	11.48	3.72	1.47	3.15	5.14	0.44	2.03	0.19	0.04	NR	NR	25.78
		return	45.02	12.91	3.56	1.61	3.42	5.14	0.42	1.61	0.19	0.05	NR	NR	23.68
H	1	—	0.00	15.55	5.39	0.40	0.00	5.83	0.01	1.35	NR	NR	NR	NR	18.52
	2	—	65.55	13.90	4.95	1.92	1.37	5.26	0.39	6.42	0.22	0.09	0.02	0.05	35.41
	3	—	38.10	17.50	3.60	0.23	4.40	5.20	0.50	8.40	NR	NR	NR	NR	22.00
I	1	—	43.20	14.04	3.16	2.08	1.42	2.36	0.09	0.95	0.23	0.23	NR	NR	33.19
J	1	—	49.62	16.62	3.93	2.32	2.30	6.30	0.37	2.45	0.21	0.21	0.11	0.03	15.26
	2	—	51.67	14.75	3.31	1.77	2.30	7.24	0.39	2.74	0.16	0.07	0.03	0.04	15.22
	3	—	40.18	14.54	3.85	1.69	2.47	5.78	0.70	4.20	0.19	0.05	0.04	0.03	25.74
	4	—	59.77	16.97	5.20	2.26	0.92	8.64	0.44	3.88	0.24	0.20	0.22	0.17	1.08
	5	—	52.08	15.60	3.82	2.14	0.97	6.85	0.25	2.87	0.15	0.15	0.17	0.16	14.56
	6	—	49.05	15.55	3.00	1.97	1.34	4.53	0.31	3.57	0.16	0.04	0.06	0.05	20.22
	7	—	44.92	11.85	4.12	2.27	0.58	10.24	1.02	6.07	0.46	0.18	0.03	0.16	15.35
	8	—	43.43	15.04	3.52	1.67	2.59	6.84	0.25	3.89	0.21	0.15	0.05	0.02	20.75
	9	—	43.74	13.50	4.39	2.42	0.82	7.04	0.43	3.90	0.23	0.16	0.02	0.06	21.09
K	1	—	57.10	18.70	5.40	2.90	0.77	8.10	0.18	3.46	0.28	NR	NR	NR	19.50
	2	baghouse 1	73.16	14.94	5.92	3.32	1.29	0.39	0.02	0.48	0.25	NR	NR	NR	NR
		baghouse 2	72.98	15.14	5.91	3.30	1.29	0.40	0.00	0.48	0.25	NR	NR	NR	NR
		kiln feed	67.41	20.67	5.62	3.68	1.29	0.20	0.04	0.57	0.30	NR	NR	NR	NR
	3	—	50.96	18.23	5.30	2.47	1.95	6.16	0.43	8.94	0.21	0.12	NR	NR	16.01
L	1	min	50.00	11.20	5.00	1.50	0.70	3.70	0.20	3.00	NR	NR	NR	NR	16.00
		max	59.00	16.00	6.00	3.00	1.00	4.80	0.30	4.80	NR	NR	NR	NR	22.00
	2	—	60.00	17.00	5.00	2.80	1.09	7.20	0.18	3.30	0.38	0.22	NR	0.06	1.60
Statistics		No. Plants	44	44	44	44	44	44	44	35	32	28	13	13	37
		Average	50.99	14.71	4.56	2.07	1.76	7.16	1.14	4.37	0.23	0.13	0.07	0.07	17.47
		Std Dev.	11.41	2.18	0.86	0.69	0.89	3.62	1.63	3.22	0.07	0.06	0.06	0.06	8.33
		CV	22.4%	14.8 %	18.9%	33.4%	50.6%	50.6%	143.2%	73.7 %	32.0%	46.9%	93.0%	81.3%	47.7%
		Min.	0.00	10.50	3.00	0.23	0.00	0.20	0.00	0.48	0.07	0.00	0.02	0.02	1.08
		Max.	73.16	20.67	6.00	3.68	4.40	14.27	6.90	11.92	0.46	0.23	0.22	0.17	35.41

After Williams (2005).
CV = coefficient of variation; NR = not reported.

TABLE 4
MONTHLY CHANGE IN CKD CHEMICAL COMPOSITION IN PLANT H2

Month		Percent by Weight, %												
	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO	Mn_2O_3	Cl	LOI
1/04	67.11	16.46	5.63	1.69	1.56	3.37	0.39	3.62	0.25	0.08	0.06	0.02	0.00	34.68
2/04	66.96	15.80	5.60	1.56	1.56	3.39	0.58	3.77	0.24	0.09	0.05	0.02	0.00	34.98
3/04	66.99	15.86	5.54	1.79	1.66	3.79	0.30	3.66	0.24	0.09	0.05	0.03	0.00	34.97
4/04	69.27	16.18	5.79	1.66	1.66	3.20	0.18	2.29	0.26	0.09	0.06	0.02	0.00	34.35
5/04	69.63	16.72	5.70	1.95	1.58	3.14	0.21	2.14	0.26	0.10	0.05	0.02	0.00	34.00
6/04	71.50	16.78	5.60	2.03	1.58	2.51	0.16	1.78	0.25	0.09	0.07	0.02	0.00	34.09
7/04	67.85	15.16	5.15	2.07	1.41	4.05	0.23	4.06	0.23	0.09	0.06	0.02	0.00	35.99
8/04	65.77	13.76	5.00	1.92	1.39	5.38	0.30	6.23	0.21	0.09	0.06	0.02	0.00	35.17
9/04	66.46	13.86	4.98	1.96	1.34	5.32	0.27	5.91	0.23	0.10	0.05	0.02	0.00	35.41
10/04	66.57	14.32	5.14	1.98	1.40	4.52	0.25	5.34	0.23	0.09	0.05	0.02	0.00	35.41
11/04	65.17	14.03	4.96	1.93	1.37	5.19	0.62	6.65	0.22	0.09	0.04	0.02	0.00	NR
12/04	64.00	13.39	4.71	1.79	1.37	6.01	0.42	7.81	0.21	0.09	0.04	0.02	0.00	NR
Average	67.27	15.19	5.32	1.86	1.49	4.16	0.33	4.44	0.24	0.09	0.05	0.02	0.00	34.91
Std. Dev.	2.06	1.26	0.36	0.16	0.12	1.11	0.15	1.94	0.02	0.01	0.01	0.00	0.00	0.63
CV	3.1%	8.3%	6.8%	8.6%	8.1%	26.7%	45.9%	43.6%	7.3%	5.7%	16.6%	13.9%	—	1.8%

After Williams (2005).
CV = coefficient of variation.

less than 10% for seven compounds, and all but two were below 27%. There was also reasonably low variation between properties initially reported by the plant, those reported by the plant at the time of sampling, and those found when tested by an independent third party (Table 5).

Landfilled Cement Kiln Dust Properties

Sreekrishnavilasam et al. (2006) and Sreekrishnavilasam and Santagata (2006) evaluated the properties of landfilled CKD for a stockpile that had been generated over 12 years at one cement plant. Older CKD byproducts were located in the lower depths of the landfill. Three borings were used to evaluate the water content, LOI, free lime content, and pH at various depths in the landfill (0 to 78 ft), representing various ages of the stockpile. The first two borings (B1 and B2) were obtained between 0 and 50 ft located on the top terrain of the landfill. The third boring was taken from the lower terrain and represented properties from about 15 ft to 75 ft in depth. Testing of the weathered CKD showed that the water contents in the stockpile ranged from 0% to about 65%, and the LOI ranged between 30% and 37%. The LOI values were at the high end of those reported in previous studies of fresh CKD and suggested that the reactivity of the landfilled CKD should be limited. The pH varied between 10.7 and 12.8 (Table 6).

The chemical evaluation by x-ray defraction (XRD) showed a number of peaks for quartz and calcite for all of the samples. The landfilled CKD also showed a number of ettringite peaks along with similar calcite and quartz peaks. The ettringite was the result of the hydration reactions over time in the landfill. The free lime of the fresh CKD from this plant showed a low free lime content; therefore, the low free lime content in the landfill CKD was not unexpected.

Particle size distribution analysis was conducted using a hydrometer test in water with sodium hexamethaphosphate as a dispersing agent. The landfilled CKD had a slightly higher mean particle size than the fresh CKD, which was attributed to the expansive reactions (e.g., ettringite) and change in morphology as seen in the scanning electron microscopy (SEM) photographs. Results indicated the properties of the landfilled

TABLE 5
COMPARISON OF CHEMICAL COMPOSITION OF CKD USED IN TESTING FOR VALUES QUOTED BY THE PLANT, SAMPLING, AND WHEN USED

ID	Sample	Date	Percent by Total Weight, %												
			CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO	Mn_2O_3	LOI
LH	Quoted	9/04	41.93	12.66	3.17	0.78	1.75	6.15	0.4	9.71	NR	NR	NR	NR	23.44
	Received	2/05	38.56	15.46	1.77	1.25	1.3	4.23	0.27	7.62	NR	NR	NR	NR	28.24
	Tested	7/05	39.01	12.58	4.45	2.28	1.7	7.46	0.29	10.96	0.17	0.08	0.06	NR	25.9
HH	Quoted	12/04	65.55	13.9	4.95	1.92	1.37	5.26	0.39	6.42	0.22	0.09	0.02	0.05	35.41
	Received	2/05	70.25	14.75	5.14	1.89	1.47	2.64	0.17	2.51	0.23	0.08	0.02	0.04	35.26
	Tested	7/05	51.94	10.62	3.94	2.68	1.02	2.26	0	1.87	0.19	0.03	2	NR	35.28
HL	Quoted	9/04	62.09	17.62	4.9	2.58	1.93	5.79	0.56	3.76	NR	NR	NR	NR	4.94
	Received	3/05	51.94	13.27	4.04	1.97	1.55	3.79	0.57	6.13	0.28	0.09	0.11	NR	9.87
	Tested	7/05	44.64	13.35	3.83	2.57	2.44	3.64	0.8	5.46	0.19	0.05	0	NR	8.07
LL	Quoted	5/04	47.75	15.16	4.56	1.84	2.09	10.15	0.99	9.81	NR	NR	NR	NR	1.77
	Received	4/05	47.47	14.11	4.3	1.82	1.96	13.35	0.94	9.74	NR	NR	NR	NR	NR
	Tested	7/05	38.89	13.43	3.86	2.25	1.99	13.85	1.36	8.77	0.15	0.11	0.04	0	1.4

After Williams (2005).
First letter represents high or low value of CaO.
Second letter represents level high or low of LOI.
Quoted: results reported by the plant during the survey.
Received: results reported by the plant at time of sampling.
Tested: results reported by an independent laboratory on the as-received CKD.
NR = not reported.

TABLE 6
OXIDE COMPOSITION OF FRESH AND LANDFILLED CKD

Sample	Fresh CKD	Fresh CKD	Boring Samples from CKD Stockpile						Stockpiled Statistics	
			B2-C	B1-F	B2-F	B3-B	B2-I	B3-D	Mean	Std. Dev.
Approximate Depth in Boring, ft	—	—	17	31	31	41	51	60	—	—
Water Content, %	—	—	2	37	21	24	5	2	—	—
LOI, %	—	—	33	34	32.7	—	34.3	33	—	—
pH	—	—	11.6	12.1	12.5	—	11.8	12.7	—	—
Composition, % by weight										
CaO	50.4	45.93	53.19	42.96	46.3	42.14	44.59	44.54	46.15	3.98
SiO_2	NA	9.30	8.70	7.62	7.82	7.10	7.99	12.37	8.80	1.91
Al_2O_3	2.66	3.20	2.87	2.50	2.66	2.43	2.56	2.82	2.67	0.18
Fe_2O_3	1.09	1.06	1.11	0.96	1.05	1.00	1.11	1.57	1.17	0.22
MgO	0.7	1.11	1.02	0.83	0.88	0.99	0.91	1.93	1.14	0.41
SO_3	3.50	2.30	4.92	4.62	3.76	4.17	4.12	2.59	3.91	0.81
Na_2O	0.18	0.13	0.23	0.30	0.12	0.23	0.08	0.11	0.15	0.09
K_2O	2.16	1.22	2.39	2.14	1.43	2.32	1.39	1.19	1.74	0.53
LOI	33.62	33.3	33	33.86	33.64	34.1	34.8	33.16	33.74	0.65
Total Alkali	1.6	0.93	1.80	1.71	1.06	1.76	0.99	0.89	1.34	0.41
Total Reactive Oxides (sodium equivalent)	15.14	12.36	18.59	7.49	11.99	6.49	9.24	12.00	11.66	4.36

After Sreekrishanavilasam et al. (2006).
Oxide values expressed in percentage by mass; mean and standard deviation refer to tube samples alone.
— = indicates no data.
LOI = loss on ignition; NA = not available.

CKD were relatively consistent throughout the 12 years of the operation, although there were noticeable differences in the composition as a result of hydration over time.

USAGE AND PRODUCTION

As of 2006, fewer than 20 of the 118 cement plants in the United States managed 90% of the CKD disposed on-site (Adaska and Tauber 2008; PCA 2008). The CKD produced, beneficially reused, and landfilled has changed significantly over the last two decades (Table 7); the practice of CKD landfilling is being phased out as more plants are retrofitted to allow in-processing recycling. The peak amount sent to landfills was around 1995. By 2006, less than half of the amount of clinker-produced CKD was going to landfills. The quantity of CKD used in beneficial reuse applications was starting to increase each year. Improvements in the reduction of CKD produced during the clinker production

TABLE 7
HISTORICAL CKD PRODUCTION AND USE

Year	Plants Responding to Survey	CKD Beneficially Reused On or Off Site	CKD Sent to Landfills	CKD Reclaimed from Landfills	Annual Clinker Production	CKD Sent to a Landfill/Clinker Produced, kg/ metric ton
		1,000 metric tons				
1990	84	752	2,656	—	44,360	60
1995	94	651	3,147	—	61,729	51
1998	95	769	2,500	13	67,105	37
2000	92	575	2,223	79	68,263	33
2001	102	925	2,329	231	75,683	31
2002	101	665	1,990	103	77,637	26
2003	102	718	1,995	116	79,357	25
2004	102	918	1,993	69	83,945	24
2005	102	988	1,429	205	85,568	17
2006	101	1,160	1,403	361	86,687	16

After Adaska and Taubert (2008).

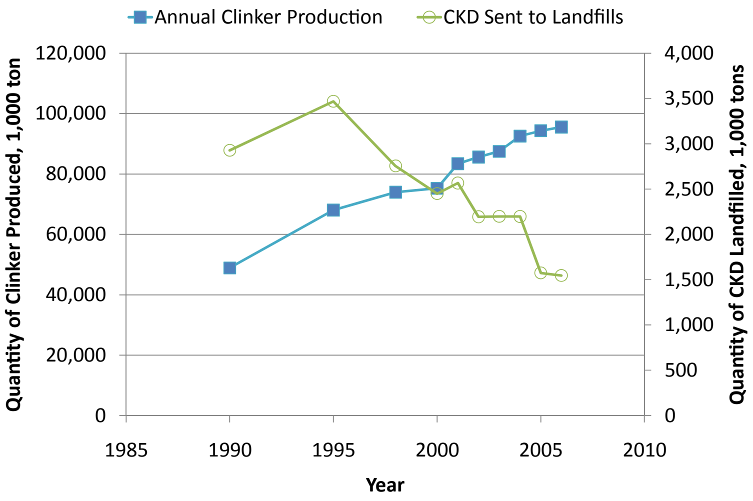


FIGURE 4 Improvements in technology result in more clinker production and less CKD sent to landfills (after Adaska and Taubert 2008).

can be seen in Figure 4. The clinker production quantity increased significantly from 1990 to 2006; however, the amount of CKD landfilled significantly decreased over the same time. Although beneficial reuses accounted for some of the decrease, improvements in cement production technologies also appeared to have a significant impact.

In 2006, ten states represented 76% of the beneficially reused CKD in the United States; the states were Oklahoma, Texas, Pennsylvania, Ohio, Illinois, Indiana, California, Arkansas, Maryland, and Missouri. There were a range of beneficial reuse applications for CKD (Table 8). In some areas, the previously landfilled CKD was also being used, although at much lower levels.

The U.S. cement industry has adopted a year 2020 voluntary target for a 60% reduction from the 1990 baseline for the amount of CKD landfilled per ton of clinker produced (PCA 2008).

LITERATURE REVIEW

This section summarizes information obtained from the literature and is organized as follows:

- CKD regulatory history
- Applications—bound
- Applications—unbound
- Environmental issues.

The objective of this section is to provide the reader with a brief background on the evolution of the regulatory actions, currently researched applications for this byproduct, and a sampling of currently reported material properties and application product characteristics.

TABLE 8
BENEFICIAL USES OF CKD

Application	Production Byproduct	Recovered from Landfill	Total Used in Application
	1,000 metric tons		
Potential Use in Highway Applications			
Cement Additive/Blending	202	2	204
Soil/Clay Stabilization/Consolidation	588	23	611
Pavement Manufacturing	13	2	15
Concrete Products	0	0	0
Used in Structures or Highways	803	27	830
Returned to Kiln	0	126	126
Nonhighway Application Uses			
Wastewater Neutralization/Stabilization	13	3	16
Waste Stabilization/Solidification	235	101	336
Mine Reclamation	168	0	168
Agricultural Soil Amendment	37	31	68
Sanitary Landfill Liner/Cover Material	17	0	17
Beneficial use Not Provided	4	0	4
Other Uses	2,080	315	2,395

After Adaska and Taubert (2008).

Cement Kiln Dust Regulatory History

Adaska and Taubert (2008) provided the history of legislation in the United States for the regulation of CKD byproducts.

- In 1976, the RCRA required EPA to develop regulations governing the identification and management of hazardous wastes.
- In 1980, the Solid Waste Disposal Act amendments amended RCRA (referred to as the Bevill Amendment) and exempted three special wastes including CKD from hazardous waste regulation until further study could be completed. This legislation required that EPA submit a report to Congress evaluating the status of CKD management and potential risk to human health and the environment.
- In 1993, the EPA Report on CKD was submitted to Congress. The conclusions from the report were that CKD posed little risk to human health and the environment.
- In 1995, the EPA issued a final regulatory determination for CKD that recommended a more tailored set of standards be developed for managing CKD to minimize any risk resulting from the mishandling of the byproduct.
- In 1999, the EPA published Standards for the Management of Cement Kiln Dust; Proposed Rule, which classified CKD as nonhazardous as long as specific management standards are met. If not, then it is to be classified as a "listed waste" and would need to comply with RCRA Subtitle C management standards.
- In 1999, the American Portland Cement Association submitted formal comments opposing the use of federal authorities for CKD management.
- In 2000, the EPA elected to retain the Bevill exclusion.
- In 2001, the American Portland Cement Association filed a petition requesting that EPA withdraw the CKD proposed rule and reinstate the Bevill status for CKD.
- In 2002, the EPA published a notice of data availability that explained they were considering a new approach to CKD management whereby it would finalize the proposed CKD management standards as RCRA Subtitle D (solid waste) rule and temporarily suspend the proposed RCRA Subtitle C (hazardous waste) portion rule for 3 to 5 years to assess how CKD management practices and state regulatory programs evolve.
- In 2010, the EPA and industry were working together to resolve CKD issues.

Applications—Bound

Clinkers

Adaska and Taubert (2008) noted that some cement producers have started to remove CKD from their on-site historical landfills to augment the raw materials used during cement production.

Blended Cements

Shah and Wang (2004) investigated the influence of different combinations of CKD and fly ash, grinding equipment and methods, chemical additions, and elevated curing temperatures on blended cements. Three activation methods were used for accelerating CKD-FA binder hydration: chemical (2% and 5% by weight of binder of NaOH), thermal (curing temperatures of 38% and 50%), and mechanical (simple blending, ball and mill grinding, grinding aid, and high-speed mixing). Testing included XRD and thermal gravimetric analysis (TGA) for chemical evaluations, and compressive strength for application properties. Results showed a combination of NaOH addition and elevated curing temperature was not beneficial to strength development. The blended cements and these activation combinations resulted in a loss of strength. The elevated curing temperature was much more effective than NaOH on improving activation. An optimum combination of CKD-FA ratio, 2% NaOH, and a curing temperature of 100°F produced a blended cement strength that was comparable to that of ordinary portland cement.

Ryou (2004) evaluated three different methods of mechanically improving reactivity (ball mill, vibratory mill, and attrition mill) of CKD (65%) and Class F fly ash (35%). The ball mill was a hollow cylinder that could be rotated on the mill rollers at different speeds. A tumbling media was used to impact the material as the cylinder rotates. The vibratory mill grinding was also a cylindrical container that held grinding media, but shook the materials in a horizontal or vertical direction at a high rate of speed. The impact energy varied with the amplitude of the movement. Typical settings were a rate of 1,200 rpm and amplitude of 0.5 in. The attrition mill imparted higher energy than either of the other two methods. A central shaft with arms continually stirred the particles and spherical media to provide a grinding action. Intense rolling and in-line impacts were produced by the differential velocity of the media moving around the agitator arms into the cavity behind the trailing edge.

Results showed differences between types of grinding. As expected the no-grinding option showed the lowest levels of reactivity and compressive strength (Table 9). The ball grinding at either 4 or 8 h only slightly improved the reactivity. The attrition mill showed only a slight improvement in properties, similar to the 4 h in the ball mill. Four or eight hours of vibratory grinding produced the best improvement in reactivity. Materials from this method of grinding had the smallest mean diameter particle size (about 0.003 mm).

Controlled Low Strength Materials

Al-Harthy et al. (2004) investigated the use of CKD in the production of flowable fill [i.e., controlled low strength material (CLSM)] in Oman using water from regional oil production

TABLE 9
INFLUENCE OF CKD PARTICLE SIZE ON COMPRESSIVE STRENGTH

Grinding Method	Hours of Grinding	Cubes			Max. Rate of Heat Evolution, kJ/kg-hr	Time to Max. Rate, hour	Percent Finer Than 0.0005 mm, %	Mean Particle Size, mm
		Compressive strengths, psi						
		3 days	7 days	28 days				
Grinding (ball mill)	0	4	8	33	2.9	18.80	1.57	0.12
	4	20	52	77	3.8	14.70	1.84	0.09
	8	14	47	55	3.7	14.60	2.96	0.05
Vibratory Mill	4	33	68	119	7.7	14.50	5.10	0.00
	8	46	78	130	6.6	16.60	5.16	0..3
Attrition Mill	4	9	28	68	3.0	13.20	2.72	0.09
	8	9	30	68	3.2	15.40	3.25	0.08

After Ryou (2004).
65% CKD + 35% fly ash + water (w/cm = 0.5)
Blends were mixed before grinding but without water.

activities. Water is considered a valuable commodity in Oman and using contaminated water in construction projects reduces the demand for fresh water. Flowable fill was produced using several sources of water with different properties (Table 10). The results showed that oily production water resulted in lower compressive strengths than when using ground water. However, the 28-day compressive strengths were still above the minimum requirement of 2 to 24 psi for flowable fill. No differences were seen in slumps with the different water sources.

Pierce et al. (2003) and Williams (2005) investigated the flow consistency and setting time of CLSM materials with CKD. Both the CaO and LOI values were used to select four CKDs to be used in the laboratory study (Table 11). The low CaO content CKD range was about 39% and the high content CaO was between 44% and 52%. An LOI value of less than 8.1% was considered low and values greater than 25% were labeled as high. Particle surface area and particle size range parameters are shown in Table 12. The high LOI CKD samples generally had higher surface areas and smaller particle sizes than the low LOI CKDs.

Initial Vicat set times of the paste were approximately 480 min for the LH and HL (the high and low values of CaO),

TABLE 10
PROPERTIES OF WATER USED TO PRODUCE CKD CLSM MIXTURES

Source of Sample	Time of Sample Collection	Parameter Concentration					
		pH	TDS (mg/L)	Chloride (mg/L)	Hardness (mg/L)	Alkalinity (mg/L)	Sulfate (mg/L)
Tap Water	2001	8.6	278	75	94	58	278
	2002	8.3	398	86	182	114	65
Bahja Ground Water	2001	6.7	8,770	5,100	670	55	8
	2002	8.2	233	93	17	16	5
Bahja Production Water	2001	7.4	66,300	44,500	13,000	59	281
	2002	7.3	9,720	4,790	1,320	94	662
Rima Ground Water	2001	7.9	10,960	5,420	1,730	134	826
	2002	7.4	9,850	4,820	2,250	169	759
Rima Production Water	2001	8.0	11,540	5,850	880	240	323
	2002	8.5	586	223	13	72	5
Marmul Ground Water	2001	8.0	1,360	331	558	100	281
	2002	8.0	1,540	383	588	147	548
Marmul Production Water	2001	7.3	4,900	2,040	166	606	233
	2002	8.3	4,220	2,080	146	80	<1
Nimr Ground Water	2001	7.6	7,080	3,080	1,680	209	982
	2002	7.8	7,050	3,160	1,670	219	782
Nimr Production Water	2001	7.3	423	4,000	490	399	330
	2002	7.9	8,200	138	23	95	15

After Al-Harthy et al. (2004).
TDS = total dissolved solids.

TABLE 11
CHEMISTRY FOR CKD BYPRODUCTS USED IN CLSM MIXTURES

ID	Date	% Total Weight												
		CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	SrO	Mn_2O_3	LOI
LH	7/05	39.01	12.58	4.45	2.28	1.7	7.46	0.29	10.96	0.17	0.08	0.06	NR	25.9
HH	7/05	51.94	10.62	3.94	2.68	1.02	2.26	0	1.87	0.19	0.03	2	NR	35.28
HL	7/05	44.64	13.35	3.83	2.57	2.44	3.64	0.8	5.46	0.19	0.05	0	NR	8.07
LL	7/05	38.89	13.43	3.86	2.25	1.99	13.85	1.36	8.77	0.15	0.11	0.04	0	1.4

After Williams (2005).
First letter represents high or low value of CaO.
Second letter represents high or low level of LOI.
NR = not reported.

and between 780 and 1,380 for the HH and LL pastes (the high and low level of LOI). Ordinary portland cement usually achieved initial set in about 120 min by comparison. Final Vicat set times were between 1,200 and 1,680 min for the LH, HH, and HL pastes and greater than 1,680 for the LL paste. The final set time for ordinary portland cement was about 240 min. Hydration temperatures of the pastes were 74°F and 128°F for the LH and HL pastes, and 74°F and 108°F for the HH and LL pastes.

Testing for the fresh CLSM properties included the determination of the percent bleeding (ASTM D940), flowability (ASTM D6103), nonstandard inverted slump cone (ASTM C1611), and unit weight (ASTM D6023). The results are shown in Table 13. The bleeding evaluation, while not standard for CLSM mixtures, was used in this study. In this test, the volume of excess water that accumulated on the surface of fresh mix placed in a graduated cylinder was measured. Flowability was assessed by placing the fresh mix in a nonabsorbent cylinder (ASTM method) or an inverted slump cone on a clean, flat surface, then raising the container, and the largest diameter of the spread was determined. The bleeding decreased and the flowability decreased with increasing CKD. The unit weight increased with increasing CKD content.

Fresh and hardened CLSM properties were determined for blends using Type I portland cement, Class F fly ash, sand, and city water. The level of the combined fly ash and CKD was held constant at 20%. Mixes varied the percent of fly ash, and hence the CKD, in 5% increments. Ratios of CKD to fly ash were: 3:1, 1:1, 1:3, and a 100% CKD. Water-to-cement ratio held constant at 0.85, but was adjusted as needed to maintain flowability. The set and hardening times of the CLSM mixes were determined using the pocket penetrometer, penetration resistance (ASTM C403), and the Kelly ball (ASTM D6024).

TABLE 12
CKD PROPERTIES USED IN LABORATORY STUDY

Source	Specific Surface Area (m^2/kg)	D_{95}, µm	D_{85}, µm	D_{50} , µm	D_{10}, µm
Cement	300–500	45	35	13	2
LH	3,300	13	8	3	0.7
HH	3,900	30	5	2	0.6
HL	1,690	200	70	11	1
LL	230	200	170	30	5.2

After Williams (2005).
Fineness determined using ASTM C204 (Blaine Fineness).
First letter represents high or low value of CaO.
Second letter represents high or low level of LOI.

The combination of CKD and cement showed the fastest set times using either the pocket penetrometer or the penetration resistance (Table 14). The rate of set was co-dependent on the levels of CaO and LOI percentages as well as the combination of CKD and fly ash. In other words, what combination works with one source of CKD may not work with another. This study showed that the best combination for the fastest rate of set was the highest CaO content with the lowest LOI CKD combined with fly ash. What data were available for the Kelly ball testing generally agreed with the pocket penetrometer and penetration resistance testing (Table 15).

The compressive strengths with time are shown in Table 16. The compressive strengths were the highest for the high CaO and low LOI CKD, but decreased with increasing CKD content. The concentration of CKD needed to achieve strength of 200 psi maximum (PCA 2010) decreased with increasing CaO content. CKD with high LOI provided adequate strengths, but lower concentrations were needed to gain strengths of around 150 to 200 psi. Williams (2005) used these data to develop a prediction equation for estimating the CLSM 28-day strength (Table 17):

$$\sigma_{28\text{day}} = c(\text{CaO}) + l(\text{LOI}) + f(F) + b_{\text{CKD}}(B)$$

Where:

$\sigma_{28\text{ day}}$ = 28 day compressive strength, MPa;
CaO = calcium oxide content, %;
LOI = loss on ignition;
F = fineness, m^2/kg;
B = CKD content, percent of total mix, %; and
c, l, f, and b_{CKD} = coefficients selected from Table 17.

TABLE 13
FRESH CLSM PROPERTIES

Mix	CKD:Fly Ash	w:cm	Bleeding, %	Flowability				Unit Weight, pcf
				Inverted slump cone		ASTM D6130		
				in.	in.	in.	in.	
LH	5:15	0.80	2.4	13.0	13.0	31	30	128
				13.5	13.5			
	10:10	0.83	0.4	9.5	9.5	21	20.5	130
				10.5	10.5			
	15:5	0.85	0.2	7.8	7.8	18.5	18.5	134
				8.3	8.3			
	20:0	1.00	0.6	8.5	8.5	20	22	126
				8.5	8.3			
				9.0	9.5			
HH	5:15	0.80	2.7	11.5	11.5	34	32	129
				11.5	11.5			
	10:10	0.80	1.4	11.5	11.5	27.5	29	130
				11.0	11.0			
	15:5	0.80	0.2	10.0	10.0	23.5	23.5	133
				10.0	10.0			
	20:0	0.88	0	10.0	10.5	22	22.5	131
				9.0	9.0			
HL	5:15	0.74	3.4	11.5	10.5	23	23.5	132
				11.5	11.0			
	10:10	0.74	2.3	8.5	8.5	20	19.5	134
				8.5	8.5			
	15:5	0.80	0.7	8.5	8.5	ó	ó	133
				8.3	8.5			
	20:0	1.01	0.2	8.0	8.0	21	20.5	128
				8.5	8.5			
LL	5:15	0.70	3	9.0	10.0	22	23	130
				9.5	9.5			
	10:10	0.78	2.1	10.0	10.0	22	23	132
				9.5	9.5			
	15:5	0.89	0.6	8.3	8.3	19.5	20.5	130
				8.5	8.3			
	20:0	1.07	1.1	8.5	8.5	21	21	125
				8.0	8.3			

After Williams (2005).
First letter represents high or low value of CaO.
Second letter represents high or low level of LOI.

TABLE 14
RATE OF SET DATA FOR CKD CLSM

ID	Mix	Pocket Penetrometer		Penetration Resistance	
		1 tsf, hours	4 tsf, hours	102 psi, hours	400 psi, hours
LH	CKD + FA	<24	<23	<25	20–28
	CKD	<20.5	114	<23	never
HH	CKD + FA	17–24	42–44	<33	41–70
	CKD	never	never	never	never
HL	CKD + FA	10–16	19–26	<21	16–23
	CKD	14	31	<22	45
LL	CKD + FA	28–35	57–72	<72	70–85
	CKD	29	67	<67	100

After Williams (2005).
First letter represents high or low value of CaO.
Second letter represents high or low level of LOI.

TABLE 15
KELLY BALL INDENTATION DIAMETER AFTER 5 DROPS

ID	CKD:Fly Ash	Indentation after Various Times, inches			
		24 hours	48 hours	72 hours	96 hours
LH	5:15	3.5	3.4	—	—
	10:10	3.9	3.5	—	3.1
	15:5	—	—	4.5	—
	20:0	—	—	2.9	—
HH	5:15	—	4	3.5	3.1
	10:10	—	—	3.5	—
	15:5	—	—	—	—
	20:0	—	3.1	2.5	—
HL	5:15	—	2.8	2.0	—
	10:10	—	—	2.8	2.5
	15:5	—	—	3.4	3
	20:0	—	—	4.0	—
LL	5:15	—	—	3.6	—
	10:10	—	—	4.0	—
	15:5	—	—	4.25	—
	20:0	—	—	4.25	—

After Williams (2005).
First letter represents high or low value of CaO.
Second letter represents high or low level of LOI.
— = indicates no data.

TABLE 16
INFLUENCE OF CALCIUM OXIDE AND LOSS ON IGNITION OF CKD BYPRODUCTS ON COMPRESSIVE STRENGTH OF CONCRETE

ID	CKD:Fly Ash	Estimated Compressive Strength, psi				
		7 Days	14 Days	28 Days	56 Days	90 Days
LH	5:15	124	145	173	165	180
	10:10	109	131	155	167	195
	15:5	70	90	110	140	148
	20:0	—	—	—	—	—
HH	5:15	67	100	120	140	160
	10:10	70	80	97	120	140
	15:5	58	68	70	78	89
	20:0	—	—	10	10	10
HL	5:15	200	375	720	1550	1750
	10:10	180	360	595	1150	1750
	15:5	90	200	310	565	720
	20:0	70	100	150	200	250
LL	5:15	75	225	530	725	—
	10:10	45	100	400	460	—
	15:5	30	80	210	445	—
	20:0	25	60	75	140	—

After Williams (2005); estimated from figures.
First letter represents high or low value of CaO
Second letter represents high or low level of LOI.
— = indicates no data.

TABLE 17
RANGE OF REGRESSION COEFFICIENTS FOR RANGE OF MATERIAL PROPERTIES IN THE WILLIAMS (2005) STUDY

Coefficient	Range	Guidance for Selecting Coefficient
c	6.1–18.0	High % CKD (>10%) = lower coefficients Low % CKD (<10%) = higher coefficients
l	14.0–51.4	
f	0.087–0.333	
b_{CKD}	6.3–21.9	

TABLE 18
VOLUME AND MASS CHANGES IN VARIOUS CLSM MIXES

Mix	CKD:Fly Ash	Diameter Change (3 in.), %					Mass Change, %			
		7 days	14 days	28 days	56 days	90 days	14 days	28 days	56 days	90 days
LH	5:15	—	—	—	1.22	1.22	0.9	0.03	0.84	0.36
	10:10	—	—	—	1.13	1.04	0.28	–0.53	0.24	0.31
	15:5	—	—	1.39	1.3	1.74	0.33	–0.32	0.26	–0.04
	20:0	—	—	6.6	6.77	6.51	—	7.57	8.65	9.02
	1:20:0	—	—	0.95	0.78	0.78	0.29	0.39	0.42	0.43
HH	5:15	—	0.87	0.78	1.22	1.04	0.54	0.74	0.72	0.13
	10:10	—	0.52	0.78	0.52	0.87	0.85	1.56	1.34	1.10
	15:5	—	0.52	0.78	0.78	—	–0.24	–0.24	0.56	0.02
	20:0	—	—	0.61	0.26	0.26	—	—	—	—
HL	5:15	0.78	1.04	—	1.04	1.13	0.91	1.15	1.23	1.06
	10:10	0.78	1.04	1.13	0.95	1.04	0.47	1.06	1.02	0.50
	15:5	1.04	1.30	1.04	1.30	1.04	0.39	0.27	0.21	0.39
	20:0	0.95	1.04	1.04	1.04	1.04	0.61	0.28	0.29	0.18
LL	5:15	0.78	0.95	0.95	1.13	—	1.45	1.53	1.11	—
	10:10	0.78	1.22	1.65	1.91	—	0.37	1.49	1.20	—
	15:5	0.87	1.13	1.65	1.56	—	0.41	1.16	1.93	—
	20:0	0.52	0.69	1.48	1.82	—	1.61	2.19	2.74	—

After Williams (2005).
First letter represents high or low value of CaO.
Second letter represents high or low level of LOI.

The change in CLSM sample volume was also evaluated (Table 18). The volume changes increased with time and none of the samples showed any shrinkage. All of the mixes, except the low CaO/high LOI mixes, had volume changes of less than 2%. The change in sample mass shows that the low CaO/high LOI mixes lost mass, except at a ratio of 20:0, which gained the most mass. At 20:0 of the low CaO/high LOI, there was over 6.5% swell after 28 days and the highest percent increases in mass, which was attributed to water adsorption. All of the other mixes generally gained mass with time.

Adaska and Taubert (2008) found in their literature review that CLSM slump and bleeding and strength decreased with increasing CKD content, although these mixes showed less bleeding than fly ash mixes. Longer set time for CKD and lower strengths compared with fly ash were also noted. Without fly ash and with a high LOI, CKD mixes did not harden; the LOI has the greatest impact on hardened properties.

Portland Cement Concrete

Udoeyo and Hyee (2002) investigated five percentages of a single source of CKD. Results showed the slump decreased and setting times increased with increasing percentages of CKD. The compressive strength, splitting tensile, and modulus of rupture decreased with increasing percent of CKD.

Research in Saudi Arabia by Daous (2004) used local CKD, cement, and fly ash from the combustion of heavy fuel oil to determine if this combination of materials could be used in the Middle East. The mortar cube testing showed adequate strength for 70% portland cement and 30% CKD.

Hot Mix Asphalt

Taha et al. (2002) evaluated the influence of cement by-pass dust on asphalt binder and mix properties when used as mineral filler. When mixed with the asphalt, both filler materials (lime, CKD) used in the study decreased penetration and ductility with a corresponding increase in softening point with increasing mineral filler (Table 19). The CKD–asphalt binder appeared to have more ductility and a higher softening point than the lime–asphalt binder (Table 20). At 13% CKD the hot mix asphalt (HMA) mix properties met the specification requirements for both the wear and binder courses. At 5% CKD the voids in mineral aggregate (VMA) was under the

TABLE 19
INFLUENCE OF LIME AND CKD ON ASPHALT BINDER PROPERTIES

Binder Properties	Asphalt	Filler Content, %									
		Lime					CKD				
		2	5	7	10	15	2	5	7	10	15
Penetration, dmm	62	55	47	45	45	41	44	45	47	46	45
Ductility, cm	115	110	78	72	60	50	108	105	95	65	83
Softening Point, °C	41	47	50	53	56	57	41	45	43	48	50
Specific Gravity	1.03										

After Taha et al. (2002).
Values estimated from graphs in document.

TABLE 20
HMA MARSHALL MIX DESIGN PROPERTIES

Properties	Control Mix (lime filler)	5% CKD	13% CKD	Ministry of Transportation Spec.	
				Wearing course	Binder course
Stability, lb	4,496	3,822	4,047	3,417 min	2,698 min
Flow, 0.01 in.	8	9	10	8–16	8–16
Air Voids, %	4.5	4.5	4.5	3.5–5.5	4–6
Voids in Mineral Aggregate, %	14.2	13.9	16.7	15 min	14 min
Voids Filled with Asphalt, %	70	68	72	63–75	55–70

After Taha et al. (2002).

minimum value needed for either the wear or binder courses. The VMA was similar to the control mix, which also did not meet the specification; however, it is not clear that these are statistically significant. In this study, the use of the CKD helped improve the mix properties so that the mix met the specification requirements by increasing the VMA values.

Surface Treatments

Oikonomou and Eskioglou (2007) in Greece evaluated the influence of various sources of mineral filler in an emulsion used for slurry seals. The mineral fillers included in the study were ordinary portland cement, fly ash, ladle furnace slag, CKD, and marble dust. The CKD had a free CaO content of 3.8%.

Testing evaluated mixing time, cone consistency, set time, cohesion, wet track abrasion for chip retention, wet stripping, and excess asphalt. The mixing time indicated how long the emulsion could be stirred before the emulsion began to break (i.e., emulsion separates from water). The cone consistency test was used to indicate the flow of the mix on a plate when poured from a standard mold. The cohesion test measured the cohesion at the interface between a rotating neoprene cylinder and the slurry seal test specimen at different times. Times of 30 min for set time properties and 60 min for resistance to damage from initial traffic were used. Wet track abrasion test loss evaluated the ability of the slurry seal to withstand traffic by measuring the loss of material with continued abrasion. Wet stripping checked the compatibility of the slurry seal system with the aggregate. Excess asphalt under loaded wheel conditions ensured that the mix did not show excess binder (flushing) under traffic.

Results showed that the CKD provides the longest construction time window before breaking (highest mixing time) and acceptable, but lower, cohesion than seen for ordinary portland cement (Table 21). All of the mineral fillers provided acceptable values compared with the specification requirements.

Applications—Unbound

Stabilized Soils

Stabilized soils are used for:

- Drying up construction sites
- Providing working platforms
- Reducing soil plasticity index (PI) and clay/silt-sized particles
- Improving compactability
- Reducing shrinkage/swell of expansive soils
- Improving strength and stability
- Reducing moisture susceptibility
- Utilizing local or recycled materials.

TABLE 21
INFLUENCE OF DIFFERENT MINERAL FILLERS ON EMULSIONS FOR SLURRY SEALS

Test	Mineral Filler Type at 2% by Weight of Aggregate					ASTM Specification	International Slurry Seal Assoc. (ISSA)	
	OPC	HCFA	LFS	CKD	MD		Specification	Test method
Mixing Time, s	134	125	122	137	108	60–180	>120	TB106
Cone Consistency, cm	2.7	2.3	2.8	2.6	2.1	2–3		
Set Time, s	175	143	151	196	228	<1 h		
Cohesion, 30 min, kg cm	17	14	15	15	13		>12	TB139
Cohesion, 60 min, kg cm	25	26	28	23	22		>20	TB130
WTAT, 1 h soak, g m^{-2}	312	321	336	314	362	<807	<538	TB100
WTAT, 6 d soak, g m^{-2}	540	506	512	532	544		<807	
Wet Stripping, %	>95	>95	>95	>95	>95		>90	TB114
Excess Asphalt by CWT, g m^{-2}	392	429	382	416	371		<538	TB109

After Oikonomou and Eskioglou (2007).
OPC = ordinary portland cement; HCFA = high calcium fly ash; LFS = ladle furnace slag; CKD = cement kiln dust;
MD = marble dust; WTAT = wet track abrasion test.

TABLE 22
OKLAHOMA DOT SOIL MODIFICATION TABLE (2009)

Type of Additive Selected for Stabilization of Soil	Percent Modification Needed for Different Soil Classifications, %				
	Soil Group Classification—AASHTO M145				
	A-4	A-5	A-6	A-7	
				A-7-5	A-7-6
Portland Cement	3	3	3		
Fly Ash	9	9	9		
CKD, Precalciner Plant	4	4	4		
CKD, Other Type	8	8			
Hydrated Lime*	NA	NA	3	3**	3**

*Reduce quantity by 20% when quicklime is used.
**Use 4% when the liquid limit is greater than 50.
NA = not available.

The selection of treatment depends on the specific goals for a specific project, soil type, material availability, traffic loads, pavement design needs, environmental conditions (e.g., drainage, ground water table, and precipitation), and costs. Mix design is a key component of selecting appropriate stabilizer.

The Oklahoma Department of Transportation (DOT) (2009) developed a soil modification mix design method that could be used for designing CKD stabilized soil in AASHTO M145 soil groups A-4, A-5, A-6, and A-7. The mix design method provided two methods for design. The first was an abbreviated laboratory test procedure selecting an optimum percentage from the Soil Modification table. The second method described a complete laboratory test procedure for designing stabilized soils. The end results produced general recommendations for each type of additive with each soil type (Table 22).

In addition, soluble sulfates were measured using OHD L-49 (Method of Test for Determining Soluble Sulfate Content in Soil) and, if the content was greater than 500 ppm, additional samples needed to be tested. Modification with calcium-based additives might not be appropriate for values greater than 1,000 ppm. Modification was not recommended if greater than 8,000 ppm.

Soil dispersion was determined using the crumb test, ASTM D6572, which was originally called an aggregate coherence test, with seven different categories of soil–water reaction. There were only four categories (grades) of soil dispersion. If a grade of 3 or 4 was found, then the soil needed to be evaluated with the Pinhole Test procedure, ASTM D4647, which modeled the action of water flowing along a crack in an earth embankment. If the soil was dispersive, the agency representative was notified. In this case, all exposed surfaces required special treatment to prevent erosion.

The full mix design used a sample prepared with the additive with minus No. 40 soil material at a moisture content equal to the plastic limit, covered and cured for 48 h, then dried and prepared for testing (AASHTO T87). The Atterberg limits were determined and a plot of PI versus additive percentage was prepared. The percent modification that reduced the PI by 2% per 1% of additive was selected as the optimum percent.

Once the amount of additive was estimated, the target density and optimum moisture content were determined (AASHTO T99). Method D in this standard was used if the soil had more than 5% retained on the 19 mm sieve and Method A if 5% or less was retained on the 4.75 mm sieve; otherwise, Method C was used. The report included information about the AASHTO group classification of untreated soil, soluble sulfate content of soil, recommended percent of type of additive, density, and optimum moisture content for both the untreated and treated soil.

Khoury and Zaman (2007) evaluated the impact of 0 to 30 days of freeze/thaw cycles, after 28 days of curing, on stabilized aggregates for base materials using CKD, Class C fly ash, and fluidized bed ash. The percent added to each mix was held constant for each stabilizing material: 15% for CKD, 10% for each of the other two. Properties of the three additives are shown in Table 23.

TABLE 23
PROPERTIES OF STABILIZING ADDITIVES USED
IN THE KHOURY AND ZAMAN (2007) STUDY

Property	CKD	Class C Fly Ash	Fluidized Bed Ash
Compounds, % by weight			
$SiO_2 + Al_2O_3 + Fe_2O_3$	19	62	35
CaO	44	27	41
MgO	1.5	5.4	2.7
SO_3	2.5	2	19
$CaCO_3$	64	—	41
Other Properties			
Free Lime	2 to 3	—	18.2
Loss on Ignition, %	29	0.2	5.3
Percent Fineness	—	11.5	55
Specific Gravity	2.74	2.69	2.87

— = no data reported.

Testing focused on determining the resilient modulus values for the mixtures since this material property is used in mechanistic-empirical pavement design methods. Results were dependent on the particular combination of stabilizing material and aggregate source (Table 24). The CKD provided twice the initial modulus for limestone 2 as compared with limestone 1. The authors noted that both the fly ash and fluidized bed ash were more effective than the CKD with either of the limestone. The CKD provided higher modulus values for the sandstone aggregate mix compared with the other two additives.

Miller and Azad (2000) noted in their literature review that in 1991 Kamon and Nontananandh suggested that a cementitious stabilizer should have a hydration modulus between that of alite and belite. Because CKD satisfies this requirement, it would act as a cementitious material. Typically, CKD had about one-third of the oxides as present in portland cement and approximately 6% to 10% of the total analytical calcium oxide was free lime (Table 25).

Three Oklahoma natural soils were selected for the study (Table 26). The main variable was the level of plasticity (low, medium, high). Soils 2 and 3 reach a pH maximum of 12.3 at 15% CKD; soil 1 needs approximately 40% CKD to reach the same level. A higher pH is equated with greater chemical activity as a result of the cation exchange capacity of the clay fraction. The authors suggested that this was a function of the nature of the clay size fraction. They also noted that an upper limit of 15% was most likely the practical upper limit for cost-effective stabilization (based on authors experience).

Results showed that pH and unconfined compressive strength decreased with increasing PI when using the same percent and source of CKD. At a PI of either 33 or 40 (CH or CL), the compressive strength was between 200% and 400% of the untreated soil. At a PI of 21, the unconfined compressive strength increased by about 600% to 1,300% for 7- to 28-day curing, respectively. Similar trends were seen with increasing pH; unconfined compressive strength increased with increasing pH. Changes in PI were more pronounced for the higher PI soils with the addition of 5% CKD.

Parsons et al. (2004) evaluated the use of CKD from the three types of cement kilns for the Kansas DOT. Data from local consultants was provided to the University of Kansas by industry. These data were then sorted into one of two categories of information; the first was for precalciner kilns and the second grouped both the long-wet and long-dry kilns together. The long-wet and long-dry data were combined because previous research showed that the material properties were similar (Table 27). The precalciner CKD had much higher free lime content than the long-wet or long-dry kilns; therefore, it was expected to perform more like a lime stabilized soil.

Materials and testing included the evaluation of lime, fly ash, cement, CKD (pre-calcined), and Permenzyme as stabilizers for eight different types of soils meeting one of the Unified Soils Classifications (CH, CL, ML, SM, or SP). Test methods used in the study were grain size analysis (ASTM D422), Atterberg limits (ASTM D4318), specific gravity (ASTM D854), pH lime stabilization (ASTM D6276), moisture-density relationships (ASTM D698), swell (KDOT spec), freeze/thaw (ASTM D560), wet-dry conditioning (ASTM 559), and unconfined compression (ASTM D1633 and D5102). The CKD content was determined based on pH and Atterberg limit results and the percent of quicklime according to ASTM D6276. The fly ash content was fixed at 16% and the percent of cement was determined by the amount needed to lower the PI below 10, or capped at a maximum of 9% for cost reasons. The proportion of the sand- and fine-sized particles in each soil type is shown in Table 28.

Properties of soils modified with and without CKD are shown in Table 29. The CKD provided similar or slightly lower strengths than either the fly ash or lime. The pH initially increased with increasing percent of CKD. Although the percent of CKD needed to attain the maximum pH varied with the soil type, the pH was consistently greater than 12 at 5% CKD for all mixtures. The CKD significantly increased the pH of the soil, slightly higher than lime (pH = 12.45). The CKD with the exception of one source of CH soil reduced the swelling potential. The CH soil used in this study contained sulfates and none of the additives worked well with this soil. For the other soils, the reductions in swelling when using the CKD were either similar to or slightly better than any of the other admixtures. Permeability of the CKD tended to decrease or remain steady with time (except for CH soil). Unconfined compressive strength after leaching showed an estimated retained strength of between 60% and 105% of the original strengths (except for CH soil). Most of the CKD samples did not survive the full 12 cycles of wet-dry testing; similar results were obtained for the other additives. Only four of the eight samples survived the 12 cycles of freeze/thaw testing.

Recommendations from the Parsons et al. (2004) study were that the CKD is an effective stabilizer for subgrade soils. Suggestions for using CKD in projects included:

- Specify a free lime content of the CKD if it is used as a lime replacement. An alternative would be to pay the contractor based on the tonnage of free lime contained in the CKD.
- Use pH testing with Atterberg limits for additional guidance for determining the optimum CKD content.
- Evaluate the effectiveness of the CKD on reducing swell to confirm effectiveness, particularly with high plasticity soils.
- Conduct strength testing, because it will be important if the subgrades are to be a substantial contributor to the strength of the pavement system.

TABLE 24
MODULUS VALUES FOR CKD STABILIZED LIMESTONE AGGREGATE

Stresses			Resilient Modulus, ksi for 15% CKD										
			Limestone 1			Limestone 2				Sandstone			
			Aggregate: 97% CaO_3 0.9 to 1.2% MgO_3 0.25 to 6.2% SiO_2 34% for LA abrasion			Aggregate: 87% $CaCO_3$ — 10% SiO_2 26% for LA abrasion				Aggregate: — — 94% SiO_2 22% for LA abrasion			
Confining Stress, σ_3	Deviator Stress, σ_d	Seating Pressure, σ_s	No. freeze/thaw cycles			No. freeze/thaw cycles				No. freeze thaw cycles			
			0	8	15	0	8	15	30	0	8	15	30
951	475	193	11,582	7,069	2,873	30,226	19,140	12,698	3,190	22,172	14,924	9,667	3,914
951	951	193	12,292	7,262	2,956	31,942	19,010	13,243	3,521	25,121	16,936	10,197	4,079
951	1,433	193	15,227	7,586	3,169	34,416	21,077	14,938	3,748	29,861	18,196	10,411	4,189
951	1,909	193	15,689	7,751	3,535	38,005	33,857	15,702	4,113	33,210	19,940	11,141	4,665
717	475	193	11,382	6,353	2,508	29,751	18,679	12,182	2,873	21,442	14,986	8,034	3,362
717	951	193	11,837	6,725	2,976	30,323	19,175	12,113	3,473	23,750	15,571	8,909	3,528
717	1,433	193	13,187	6,835	3,569	32,762	21,400	13,608	4,155	27,167	17,659	10,335	4,134
717	1,909	193	14,827	7,090	3,886	35,284	34,395	12,498	4,603	31,322	19,581	11,493	4,665
475	475	193	11,155	6,222	2,715	29,558	18,534	11,782	3,087	21,517	15,000	8,220	3,280
475	951	193	11,658	6,511	3,073	29,847	19,450	11,768	3,555	23,481	15,213	9,053	3,624
475	1,433	193	12,740	6,614	3,652	32,183	21,194	13,229	4,217	27,209	17,377	10,452	4,286
475	1,909	193	14,600	7,021	4,051	34,236	32,927	12,312	4,733	29,668	19,140	11,720	4,685
241	475	193	11,086	6,029	2,770	26,919	18,830	11,493	3,287	42,311	15,048	8,103	3,266
241	951	193	11,630	6,380	3,142	28,139	19,719	12,588	3,727	22,999	15,234	8,923	3,569
241	1,433	193	12,643	6,428	3,693	28,277	22,262	11,610	4,327	27,643	17,411	10,397	4,196
241	1,909	193	16,316	6,911	4,106	32,631	34,932	12,223	4,940	28,483	19,030	11,720	4,878
0	475	193	11,107	5,919	2,804	27,340	18,693	11,196	3,280	21,449	15,234	7,979	3,231
0	951	193	11,527	6,153	3,149	28,876	18,596	12,312	3,672	23,268	15,482	8,819	3,528
0	1,433	193	12,374	6,325	3,672	28,924	20,022	11,389	4,375	26,788	17,328	10,342	4,162
0	1,909	193	14,421	6,869	4,113	35,470	31,115	11,961	4,954	27,994	17,445	11,706	4,678

After Khoury and Zaman (2007).
Cured for 28 days before freeze/thaw testing.

TABLE 25
COMPARISON OF PHYSICAL AND CHEMICAL PROPERTIES
OF TWO KANSAS CEMENT KILNS

Property	Precalciner Kiln	Long-Kiln
SiO_2, %	17.62	11.0–14.0
Al_2O_3, %	4.9	3.5–5.0
Fe_2O_3, %	2.58	1.5–2.5
CaO, %	62.08	—
MgO, %	1.93	—
Na_2O, %	0.56	0.1–1.0
K_2O, %	3.76	2.0 –10.0
SO_3, %	5.79	8.00–12.0
Volatiles, %	—	0.3–1.0
Available Lime Index, % CaO	33.7	—
Water-Soluble Chlorides, % Cl	—	—
Moisture Content, %	0.07	—
Loss on Ignition, %	4.94	—
Retained on No. 325 sieve, %	16.9	—
Passing 0.075 mm, %	—	55–75
Specific Gravity	2.95	—
pH	—	12.4–12.9

After Parsons et al. (2004).
— = indicates no data.

TABLE 26
SOIL PROPERTIES USED IN MILLER AND AZAD (2000) STUDY

Properties	Plasticity Index Levels		
	High	Medium	Low
USCS Classification	CH	CL	ML
% Finer Than 0.075 mm	98	94	52
% Finer Than 0.002 mm	51	42	21
Liquid Limit, %	55	48	23
Plasticity Index, %	40	33	6
Activity	0.78	0.79	0.29
Specific Gravity	2.82	2.72	2.67
Optimum Moisture Content, %	23.3	16.0	14.0
Maximum Dry Unit Weight, lb/ft^3	101.2	111.4	118.4
pH	7.6	5.3	7.7
Sulfate Content, SO_4^{-2}, mg/kg	137	171	ND
Organics, % by weight	1.62	0.86	0.36

ND = not detectable.

TABLE 27
COMPARISON OF PHYSICAL AND CHEMICAL PROPERTIES
OF TWO KANSAS CEMENT KILNS

Property	Precalciner Kiln	Long-Kiln
SiO_2, %	17.62	11.0–14.0
Al_sO_3, %	4.9	3.5–5.0
Fe_2O_3, %	2.58	1.5–2.5
CaO, %	62.08	—
MgO, %	1.93	—
Na_2O, %	0.56	0.1–1.0
K_2O, %	3.76	2.0 –10.0
SO_3, %	5.79	8.00–12.0
Volatiles, %	—	0.3–1.0
Available Lime Index, % CaO	33.7	—
Water-Soluble Chlorides, % Cl	—	—
Moisture Content, %	0.07	—
Loss on Ignition, %	4.94	—
Retained on No. 325 sieve, %	16.9	—
Passing 0.075 mm, %	—	55–75
Specific Gravity	2.95	—
pH	—	12.4–12.9

After Parsons et al. (2004).

TABLE 28
NATIVE SOIL PROPERTIES AND PERCENTAGES OF ADDITIVES

Properties	Unified Soils Classification System (USCS) Designation							
	CH	CH	CH	CL	ML	CL	SM	SP
Native Soil Properties								
% Sand	5	12	5	8	12	34	70	96
% Fines	95	88	95	92	88	66	30	4
Liquid Limit	70	53	65	36	30	35	20	—
Plasticity Index	45	31	36	16	4	16	3	—
AASHTO Designation	A-7-6	A-7-6	A-7-6	A-6	A-4	A-6	A-2-4	A-3
Unit Weight, lb/ft^3	94	105.4	96.9	108	98	104	120	107
Optimum Moisture Content, %	25.7	20.3	25.3	18.5	13.7	19.9	9.9	2
Unconfined Compressive Strength at Optimum, lb/ft^2	6,400	4,600	4,600	4,800	6,600	4,415	5,638	—
Maximum Unconfined Compressive Strength, lb/ft^2	8,600	7,500	6,400	7,500	6,600	6,200	5,638	—
Moisture at Maximum Unconfined Compressive Strength, %	18.9	18.6	23.5	17	13.7	17.6	9.9	—
Specific Gravity	2.78	2.77	2.72	2.74	2.75	2.69	2.68	2.66
Swell, %	4.4	2.5	2.8	1.4	1	1.4	0.4	NR

After Parsons et al. (2004).
Sand refers to particles passing the 4.75 mm sieve (no. 4) and less than about 10% passing the 0.75 mm sieve (no. 200).
Fines refer to particles passing the 0.075 mm sieve (no. 200).
NR = not reported.

- Evaluate the sulfate in the CKD and soils. Soils or CKD materials with sulfates could potentially react with free lime and form expansive minerals, resulting in additional swelling where none previously existed. The percentages of sulfates in the CKD should be reported as part of the chemical analysis of the CKD.

Adaska and Taubert (2008) noted that CKD could be used to stabilize highly expansive clay soils when combined with fly ash and limestone aggregates that produced a noncement concrete. The LOI was a significant factor in the effectiveness of CKD for stabilizing these soils. The CKD improved the unconfined compressive strength and reduced the PI when the LOI was low. A high LOI resulted in lower unconfined compressive strengths and higher PI. The higher LOI implied a higher amount of bound water and less CaO available to react. The CKD also improved freeze/thaw resistance and provided an alternative to quicklime for subgrade stabilization. CKD has been reported in the literature to perform better than quicklime when the results were compared over time. Fresh CKD worked as well as hydrated lime. Larger quantities of CKD were needed compared with the hydrated lime for stabilization. CKD from stockpiles, rather than fresh from the

TABLE 29
PROPERTIES OF CKD STABILIZED SOILS

Properties	Soil Type							
	CH	CH	CH	CL	ML	CL	SM	SP
Liquid Limit								
Before leaching	54	54	56	42	35	48	NP	NP
After leaching	NP to 49	44	NP	NP	NP	NP	NP	NP
Plasticity Index								
Before leaching	13	17	17	10	6	12	NP	NP
After leaching	NP to 11	9.5	NP	NP	NP	NP	NP	NP
Max. Dry Unit Weight lb/ft^3	54	91	89.5	92	84.5	86	110	110
Opt. Moisture Content, %	23	21	20	23	17	24	16	5.5
Opt. Unconfined Compressive Strength, lb/ft^2	17,500	18,000	12,250	23,000	12,250	15,750	14,000	780
Max. Unconfined Compressive Strength, lb/ft^2	17,700	20,000	14,400	23,250	16,850	15,750	14,000	780
Moisture at Max. Unconfined Compressive Strength, %	23.5	23.5	23.0	24.5	23.0	24.0	16.0	5.5
Swell, %	1.4	7.1	1.0	0.2	none	0.1		none
Permeability with Time, cm/s								
7 days	1.91E-05	3.80E-05	1.50E-06	2.30E-06	1.20E-05	1.10E-05	4.30E-08	2.60E-03
14	1.39E-05	1.80E-05	3.20E-08	2.70E-06	3.20E-06	5.75E-06	3.90E-08	2.80E-03
21	1.35E-05	1.70E-05	4.80E-08	4.50E-06	3.30E-06	5.15E-06	4.60E-08	2.90E-03
28	7.10E-06	7.00E-06	2.30E-07	2.85E-06	2.65E-06	1.20E-05	4.00E-09	3.50E-03
Freeze/Thaw Cycles to Failure	11	10	2	12	12	12	12	4
Wet-Dry Cycles to Failure	NR	1	NR	7	2	3	12	NR

After Parsons et al. (2004).
NP = not provided. NR = not reported.

cement plant, had a lower free lime content that resulted in poor reactivity.

Peethamparan et al. (2008) evaluated CKD from four different kiln types. One cement facility used a long-dry kiln with limestone, shale, sand, and iron ore as raw materials. A second source of CKD was from a long-dry kiln with a preheater that used limestone, clay, bottom ash, and iron scale as raw materials. The facility with the long-wet kiln used limestone, clay, sand, fly ash, and blast furnace slag, whereas the precalciner kiln used limestone, clay, bottom ash/fly ash, found sand/sludge, and iron waste in their cement production. The chemical properties of each CKD are shown in Table 30. Testing for differences in chemistry and morphology was conducted using XRD, thermal gravimetric analyses, differential TGA, and SEM. The properties of the mix measured the heat of hydration and unconfined compressive strength.

Significant amounts of calcium hydroxide, syngenite, and ettringite were identified in hydrated free lime content CKDs. The amount of ettringite increased with increased curing periods. These reaction products were either low or nonexistent in CKD with lower free lime. The high free lime content CKD was also responsible for a higher strength gain compared with the lower lime content CKD. The authors attributed this to the increased formation of ettringite and the secondary C-S-H during hydration. The high free lime content was also responsible for higher temperatures during hydration. Both compressive strength and heat of hydration provided a good indication of the performance of the CKD used as a stabilizer in soils. Although not as effective at increasing the strength of the stabilized soil, the lower free lime content CKDs in the kaolinite improved the strengths from 100% to 300% after 7 days of curing.

Peethamparan et al. (2009) evaluated the mechanisms for CKD stabilized Na-montmorillonite clays after more than 90 days of moist curing using XRD, SEM, and energy-dispersive x-ray spectroscopy (EDX). The results showed that extensive physicochemical changes occurred during curing. Calcium hydroxide was initially produced, but was quickly absorbed by the clay. SEM photographs showed that fractured surfaces of the bulk clay microstructure were significantly modified over time. The pH of the clay–CKD system was initially elevated to more than 13, but dropped over time to a stable value of 12.5 despite the absence of detectable calcium hydroxide. Some gypsum was produced by the anhydrite in the CKD and water reaction, which led to ettringite formation. The C-S-H reaction products were identified locally on the fracture surfaces of the CKD–clay system. The authors assumed that this was a function of the reaction of adsorbed calcium hydroxide with silica from the clay.

Base and Subbase

Texas Transportation Institute Report TTI-2003-1 is a synthesis that was prepared for TxDOT, which provides a good summary of pre-2001 information (Button 2003). The conclusions at the end of this synthesis were:

TABLE 30
PROPERTIES OF CKD FROM FOUR TYPES OF CEMENT KILN PROCESSES

Chemical Composition by XRF	Long Dry	Precalciner	Dry and Dry Preheater	Long Wet	Type I Cement	Kaolinite Clay
	Percent by Weight (%)					
SiO_2	12.18	16.42	11.91	15.39	20.48	45.73
Al_2O_3	4.24	3.62	2.17	4.66	4.21	37.36
TiO_2	0.22	0.23	0.15	0.57	0.36	—
P_2O_5	0.08	0.09	0.09	0.09	0.09	—
Fe_2O_3	1.71	2.31	2.08	2.34	2.41	0.79
CaO	46.24	55.00	46.05	37.35	63.19	0.18
MgO	1.24	2.68	2.20	2.10	4.00	0.098
Na_2O	0.51	0.17	0.33	0.81	0.19	0.059
K_2O	4.89	2.89	1.43	7.00	0.28	0.33
Na_2O equivalent	3.72	2.05	1.27	5.36	0.37	—
Mn_2O_3	0.05	0.44	0.04	0.07	0.14	—
SrO	0.04	0.03	0.07	0.02	0.04	—
SO_3	14.62	12.69	4.21	5.80	2.76	—
Cl	0.59	0.74	0.35	3.26	—	—
LOI	14.22	3.92	29.63	27.65	1.76	—
Free CaO	13.85	29.14	5.32	3.26	1.58	—
Water-soluble Na_2O	0.28	0.06	0.12	0.59	0.04	—
Water-soluble K_2O	2.95	1.68	0.93	6.33	0.16	—
Raw Materials	Limestone Shale sand Iron ore	Limestone Clay Bottom ash/fly ash Foundry Sand/sludge Iron waste	Limestone Clay Bottom ash Iron scale	Limestone Clay sand Fly ash Blast furnace slag	—	—

After Peethamparan et al. (2008).

- CKD can be used to stabilize subgrade soils and bases; the combination of CKD and fly ash significantly increase the compressive strength because of the pozzolanic reactions.
- High-quality bases for pavements can be obtained using CKD, but testing is needed to optimize the performance.
- Full-depth reclamation HMA recycling successfully uses CKD to produce a base layer.
- Specifications should set minimums for key components for testing or certification, or warranty performance.
- Soluble sulfates and alkalis can lead to undesirable swelling.
- Some cement plants may burn hazardous waste as kiln fuel, which may lead to hazardous materials in the kiln dust.
- The CKD needs to be kept dry to preserve the reactivity of the material.
- There is very little, or no, free lime or magnesia in stockpiled CKD. Aged stockpiled CKD should not be used as a component of stabilized base or subgrade soil unless conditioned by the addition of commercial lime to enhance short-term strength development.
- Additional research is needed to assess the suitability of kiln dust as a pozzolan activator in stabilized base and soil applications.
- Specifications are needed to define the physical and chemical properties that will provide acceptable performance.
- Environmentally related properties are needed along with management guidelines.

Environmental Considerations

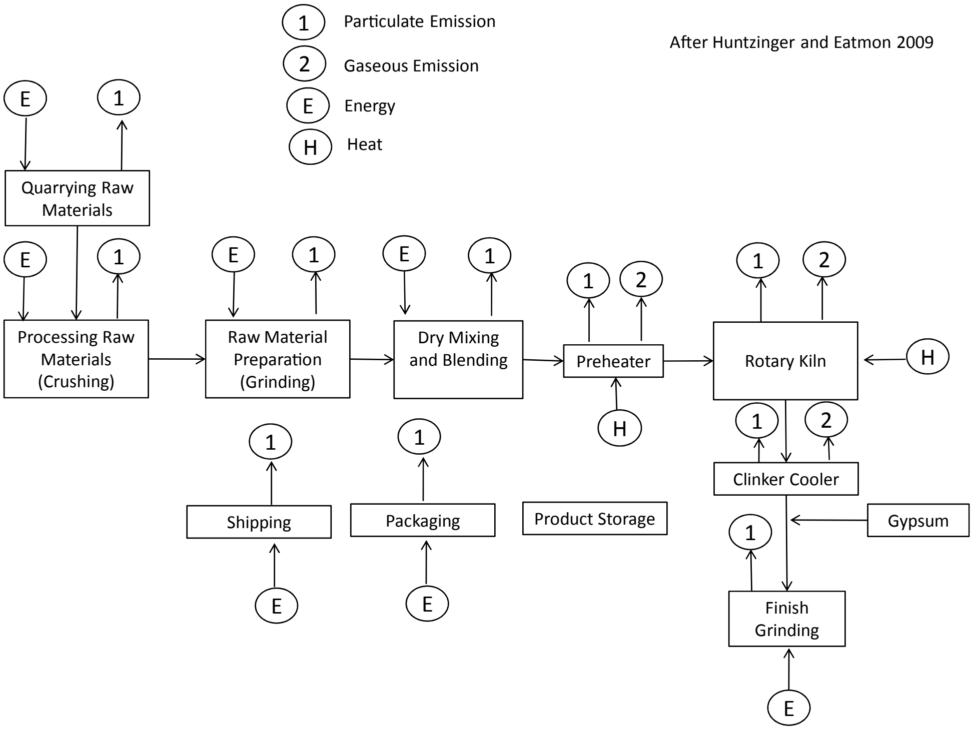
Approximately 5% of global CO_2 emissions originate from the production of cement and is the third largest source of carbon emission in the United States. Life-cycle assessment is a method of evaluating the environmental impacts of technologies from “cradle to grave” and may be performed on both products and processes.

Huntzinger and Eatmon (2009) conducted a life-cycle assessment of portland cement manufacturing that compared the traditional manufacturing process with alternative technologies and raw materials. LCA methodology consisted of four major steps (Figure 5):

- Determination of the assessment scope and boundaries
- Selection of inventory of outputs and inputs
- Assessment of environmental impact data compiled in the inventory
- Interpretation of the results and suggestions for improvement.

The life-cycle assessment was conducted for four manufacturing processes:

- Production of ordinary portland cement
- Blended cement (natural pozzolans)
- Cement where 100% of waste CKD was recycled into the kiln process
- Portland cement produced when CKD was used to sequester a portion of the process related to CO_2 emissions.



After Huntzinger and Eatmon 2009

FIGURE 5 Flow chart for life-cycle assessment for cement kiln dust (after Huntzinger and Eatmon 2009).

CKD recycling was used by a majority of the cement producers. Although a number of plants could reuse 100% of their CKD, the amount that was recycled ultimately depended on the chemistry of the CKD. For this study, the authors assumed 100% recycling of the CKD. The scope of this research was limited to the processes shown in the previous figure rather than the "cradle to grave" so that the focus of the analysis was on only the environmental impact of changing the four plant variables. The environmental impact of packaging and transportation default values in the Eco-indicator95 in the SimiPro software was used for this information.

The life-cycle inventory used five major nonfuel raw materials consumed in the processes. The amount of material per ton of cement manufactured considered in the analysis is shown in parentheses:

- Calcium oxides (1.41 tons),
- Aluminum oxides (0.139 ton),
- Silica (0.034 ton),
- Ferrous oxides (0.015 ton), and
- Calcium sulfate (0.05 ton).

The SimaPro 6.0 software was used for the analysis.

Energy usage varied widely depending on the plant. To control all variables except for the use of CKD, a blend of fuels was assumed as coal (70%), fuel oil (15%), and natural gas (15%). The natural pozzolans were considered environmentally benign because they were typically the waste byproduct (e.g., fly ash and rice husks) of another process. The impact for the activities associated with these materials such as the collection procedures and transportation were considered to be the financial and environmental responsibility of those recyclers. A substitution of 25% by weight was assumed.

CKD was considered to have the theoretical potential to sequester 0.4 ton of CO_2 per ton of cement. Previous batch and column studies showed that CKD could readily sequester greater than 80% of the theoretical capacity at ambient temperatures and pressures. Results indicated that using the CKD for CO_2 sequestering decreased the cement processing environmental impact score by 5%, which was the best of the choices.

SPECIFICATIONS

Lafarge (2008) cited the general reasons for using CKD as providing direct cementation of soils, containing reactive silica, providing ion exchange, and decreasing the moisture content of soils. A starting estimate of the dry weigh of CKD needed for the reduction of moisture was obtained by:

$$W_{\text{CKD}} = \frac{\left(W_i - W_f\right) W_{\text{dry soil}}}{\left(1.1604\, W_f + 0.1604\right)}$$

Where:

W_{CKD} = dry weight of CKD;
W_i = initial in situ moisture content;
W_f = final moisture content; and
$W_{\text{dry soil}}$ = dry weight of in situ soil used.

An example of a Michigan DOT project where CKD was used for the I-75 Ambassador Bridge was summarized. Michigan DOT had no specification for CKD in subgrade stabilization and asked Lafarge to develop such a specification. It was developed based on the anticipated uniformity of CKD properties within a given source, but with potentially widely variable properties between CKD sources. The specification was developed recognizing the need to be sufficiently broad to allow for more than one source of CKD to compete for the project. A review of existing specifications indicated few examples were available for CKD and those that were found appeared to be based on existing Type C fly ash specifications. Since the CKD and Type C fly ash were very different in chemical and physical properties, the specification limited the amount of SO_3 in the CKD to 10% without needing justification. The original justification for the limit appeared to be a response to concerns with alkali silica reactivity (ASR) when using fly ash.

Lafarge conducted an 18 month study and found levels of SO_3 as high as 15% in the CKD produced blends, with various soil types showing acceptable expansions. Testing of the source material was considered to be critical; therefore, any problems with expansive behavior were identified for a given combination of CKD and soil. The final specification recommended the following:

- CKD must conform to ASTM D5050-96.
- Soil classification needed to be per AASHTO M145 and ASTM D2487.
- Moisture and density testing per AASHTO T99 for both untreated and treated soils.
- California bearing ratio (CBR) lab results must be above 10% using ASTM D1883.
- Atterberg limits needed to be performed according to ASTM D4318.
- Unconfined compressive strength must have a minimum of 125 psi at 7 days (ASTM D5120).

AGENCY SURVEY RESULTS

The most common use for CKD was in soil stabilization (Table 31). Other applications that used CKD were in portland cement concrete (PCC) and HMA. Eleven states indicated they had used CKD in highway applications (Table 32 and Figure 6). Three states have used a combination of cement and lime kiln dusts.

The most common comment to the success or failure of a project was in identifying the correct soil for CKD stabi-

TABLE 31
RESULTS FOR AGENCY SURVEY FOR CEMENT KILN DUST BYPRODUCTS USED IN HIGHWAY APPLICATIONS

Question: Manufacturing or Misc. Construction Byproducts: Is your state using, or has ever used, these byproducts in highway applications?
* Kiln dust, cement: airborne particles from the portland cement rotary kiln
* Kiln dust, lime: airborne particles from the lime production process
* Kiln dust, combination: blending of both cement and lime kiln dusts

Type of Sand Byproduct	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embank.	Flowable Fill	HMA	Pavement Surface Treatment (nonstructural)	PCC	Soil Stability
Cement Kiln Dust	0	0	0	0	0	2	0	3	7
Combination Kiln Dust	0	0	0	0	0	0	1	1	1

Embank. = embankment.

TABLE 32
STATES USING CKD BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

No. of Applications	States	
	Cement kiln dust	Comb. dust
2	OR	—
1	CO, IL, IN, IA, KY, MO, NE, NM, NY, TX	IA, MA, NY

lization (Table 33). Texas noted that identifying sulfate and chloride contents was essential to using CKD in areas that will come in contact with reinforcement.

DOCUMENT ASSESSMENT SURVEY

Twenty-two documents were identified and reviewed for this byproduct. The summary of applications addressed in these documents showed that the most commonly researched uses were in PCC, geotechnical, and HMA products (Figure 7). The documents include research from national and international sources (Figure 8).

The agencies reported focusing more on the use of CKD in geotechnical applications than either concrete or HMA. This suggests that these areas may benefit from increased use of this byproduct.

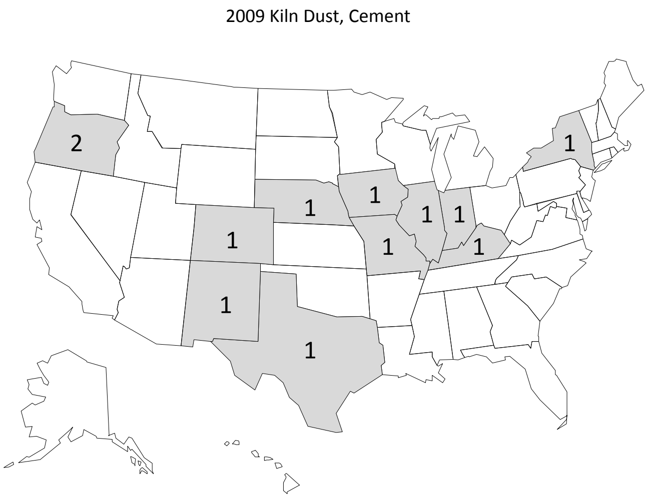


FIGURE 6 States currently using CKD in highway applications.

SUMMARY OF CEMENT KILN DUST INFORMATION

List of Candidate Byproducts

The list of the most commonly researched and used byproducts include:

- CKD, long-wet or long-dry kiln
- CKD, precalciner kiln.

The CKD byproducts are separated by the type of kiln used to collect the byproducts since the physical and chemical properties of the CKD are dependent on the type of kiln.

Test Procedures

The test methods used to evaluate byproducts and highway applications are shown in Tables 34 and 35.

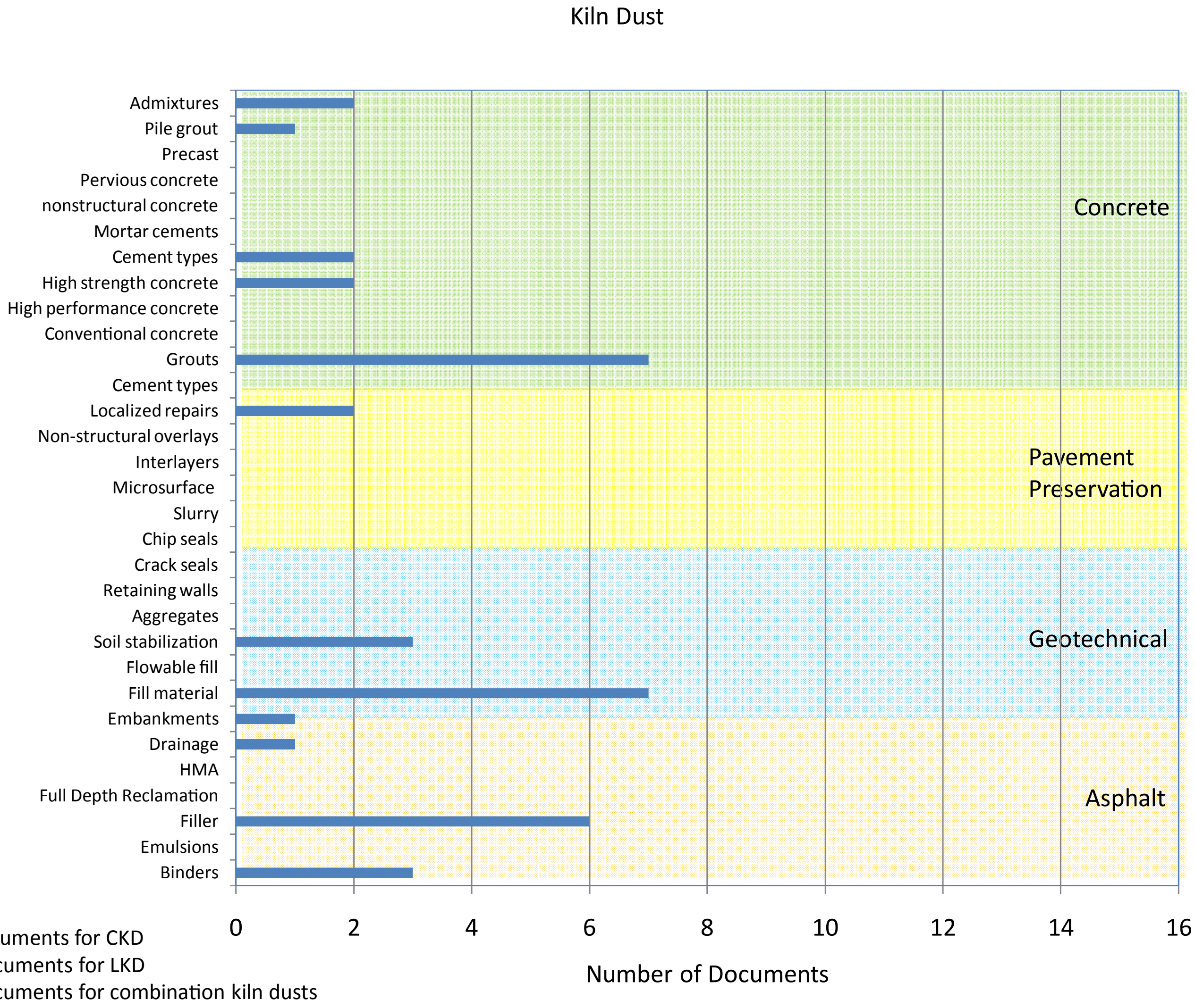
Material Preparation and Byproduct Quality Control

The following byproduct post-processing and quality control (QC) points need to be considered when using CKD in highway applications:

- Periodic composition testing to be done to track historical changes in CKD byproduct over time. Changes in technology, burner fuel, and/or sources of raw materials can change the properties of the CKD.
  - CKD for PCC applications is most effective when there is a high concentration of CaO and a low LOI.
- Post-processing of the CKD can improve reactivity by post-processing grinding of the CKD.

TABLE 33
SUMMARY OF COMMENTS BY STATES ON THEIR EXPERIENCE WITH USING CKD IN HIGHWAY APPLICATIONS

State	Comment
CO	Cement kiln dust did not perform well in the soil we were trying to stabilize.
KY	Kiln dust used for soil stabilization can be successful, but it depends on the type of soil involved (critical).
PA	CKD has proven to be an excellent soil stabilizer.
TX	The Amarillo District was happy with the performance of cement kiln dust used in soil stabilization and base applications. You need to be very conscious of the sulfate and chloride contents of the cement kiln dust especially in areas with reinforcement.



18 documents for CKD
3 documents for LKD
8 documents for combination kiln dusts

FIGURE 7 Summary of information contained in the reviewed literature.

FIGURE 8 CKD research locations.

Materials Handling Issues

The following materials handling and stockpiling points need to be considered:

- CKD byproduct could designate the type of kiln that generated the byproduct.
- Age of stockpiles needs to be tracked and the age of the CKD be included in the byproduct information provided to the user of the byproduct.
- Fresh CKD is best if kept dry prior to use in a highway application.

Transformation of Marginal Materials

No additional post-processing uses for transforming CKD into alternative products were noted in the literature or survey responses.

Design Adaptations

The following need to be considered when using CKD in highway applications:

- CKD generally reduces the strength of PCC products. A combination of CKD and fly ash helps minimize the loss of strength. The best strengths are obtained when the CKD has a high CaO content and a low LOI.
- CKD or CKD–fly ash decrease PCC workability and may require the use of superplasticizers in the PCC mix design.
- The use of CKD improves soil properties such as plasticity and strength. Adding fly ash with the CKD proves further improvement. The increased strength of the soil is to be considered in designing applications.
- The pH of water in contact with CKD stabilized soils will be increased. This could be considered during the project selection and design phases.

Construction Issues

CKD reactions will be slower in cold conditions; reactivity is improved with elevated curing temperatures.

Failures, Causes, and Lessons Learned

None were described in the literature or the survey responses.

Barriers

The following barriers were identified:

- The loss of reactivity of the CKD over time (weathered stockpiles) limits the use of landfilled CKD.
- CKD chemical composition information from byproduct supplier.
- CKD material specifications for individual highway applications (e.g., CaO and LOI properties for PCC producer).

Costs

- Cost of landfilling needs to be high enough to encourage CKD producers to initiate specific stockpiling and post-processing for highway applications.
- About 15% CKD appears to be an upper limit for balancing cost-effectiveness with desirable material properties.

Gaps

The following gap was noted:

- Further education for agencies for appropriate project selection (e.g., identification of soil properties good for stabilization with CKD) is needed.

TABLE 34
AASHTO TEST METHODS USED WITH CKD BYPRODUCTS IN HIGHWAY APPLICATIONS

AASHTO Method	Title
M145	Classification of soil and soil-aggregate mixtures for highway construction purposes
T86	Investigations and sampling soils and rock for engineering purposes
T87	Standard method of test for dry preparation of disturbed soil and soil-aggregate samples for test
T88	Standard method of test for particle size analysis of soils
T89	Standard method of test for determining the liquid limit of soils
T90	Standard method of test for determining the plastic limit and plasticity index of soils
T99	Standard method of test for moisture-density relations of soils using a 2.5 kg (5.5 lb) rammer and a 305 mm (12 in.) drop

TABLE 35
ASTM TEST METHODS USED WITH CKD BYPRODUCTS IN HIGHWAY APPLICATIONS

ASTM Method	Title
C204	Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus
C403	Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
D1633	Standard Test Methods for Compressive Strength of Molded Soil-Cement Cylinders
D1833	Standard Test Method for CBR of Laboratory Compacted Soils
D2487	Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System)
D422	Standard Test Method for Particle Size Analysis of Soils
D4318	Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils
D4647	Standard Test Method for Identification and Classification of Dispersive Clay Soils by the Pinhole Test
D5050	Standard Guide for Commercial Use of Lime Kiln Dusts and Portland Cement Kiln Dusts
D5102	Standard Test Method for Unconfined Compressive Strength of Compacted Soil-Lime Mixtures
D5120	Standard Test Method for Inhibition of Respiration in Microbial Cultures in the Activated Sludge Process
D560	Standard Test Methods for Freezing and Thawing Compacted Soil-Cement Mixtures
D6023	Standard Test Method for Density (Unit Weight), Yield, Cement Content, and Air Content
D6024	Standard Test Method for Ball Drop on Controlled Low Strength Material (CLSM) to Determine Suitability for Load Application
D6103	Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)
D6130	Standard Test Method for Determination of Silicon and Other Elements in Engine Coolant by Inductively Coupled Plasma-Atomic Emission Spectroscopy
D6267	Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization
D6572	Standard Test Methods for Determining Dispersive Characteristics of Clayey Soils by the Crumb Test
D698	Standard Test Methods for Laboratory Compaction Characteristics of Soils Using Standard Effort
D854	Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer

CHAPTER TWO

ROOFING SHINGLES

From the late 1800s to the 1970s roofing shingles were manufactured by saturating a thick organic mat such as cotton, waste paper, and wood fibers with asphalt and topped with protective stone coating (Seattle Roof Broker 2010; Figure 9). Although the shingles came with 15- to 20-year warranties, they were typically left in place from 30 to 35 years. In the 1970s, the conversion was made from organic to fiberglass backing. However, the 1974 oil embargo, the economic recession in the 1980s, and durability concerns in hot moist climates forced roofing shingle manufacturers to adjust shingle composition. This led to a reduction in the fiberglass mat (expensive) and an increase in mineral filler content in the asphalt to extend the binder volume, save money, and improve durability. This resulted in declining asphalt content in the newer shingle products compared with the older recycled asphalt shingles (RAS) materials.

There are several categories of roofing materials that are available for recycling. These include:

- Roofing manufacturing byproducts
- Tear-offs
- Built up roofing (BUR).

Additional information can be found at the following websites:

- Shingle Recycling: http://www.shinglerecycling.org/content/technical-reports
- National Association of Home Builders: http://www.nahbrc.com/index.aspx.

TYPES OF POSSIBLE BYPRODUCTS

Roofing Shingles (Manufacturer)

Roofing shingles are produced by saturating the backing felt material, which is either organic (cellulose or wood fiber) or fiberglass (VANR 1999). This is followed by coating the material on both sides with additional asphalt. The asphalt is treated with exposure to air (air blown or bubbled) to increase the viscosity and reduce the temperature susceptibility. Powdered limestone (70% passing the 0.075 mm sieve) or other fine granulated materials are also added to the asphalt as a stabilizer and viscosity enhancing material. When the desired thickness of asphalt has been applied, a granular material is used to finish the surface, usually crushed rock coated with ceramic metal oxides with some coal slag at the headlap of the shingle. The particles are reported as being hard and angular with a uniform size that is primarily between 2.36 and 3.0 mm. The back of the shingle is coated with fine sand (<0.425 mm) to prevent sticking together during packaging and transporting.

There are 77 plants in the United States that produce approximately 12.5 billion square feet of shingles per year (Brock 2007). About 65% of the new shingles are used for reroofing projects and only 35% for new roofs. Manufacturing roofing shingle byproducts are comprised of factory scrap from the production process.

Tear-Offs

Roofs are commonly replaced after 20 years, but this can be done by overlaying the old shingles with new ones (California Integrated Waste Management Board 2009). Although most building codes limit maintenance to one reroof without tearing off the old materials, more than two layers of roofing materials can be encountered. This results in a range of shingle ages in the same reroof or demolition job in the construction industry waste stream and is commonly landfilled. Most of the older roofing materials are organic-backed materials. The asphalt in the tear-offs has aged over the years of environmental exposure and the amount of granular material is also lower than in the manufacturing byproduct because of weathering. Tear-offs usually contain other contaminates such as nails, paper, wood, and other miscellaneous debris (RMRC 2008a; CIWMB 2009).

Built Up Roofs (BUR)

These roofing systems have been in use for more than a century (NRCA 2010) and consist of alternating layers of binder and reinforcing fabrics. Sometimes the first layer (base sheet) is mechanically fastened to the roof. If the first layer is directly applied to the roof deck or insulation it is considered to be fully adhered. The reinforcing fabric is also referred to as roofing felts or ply sheets, which are either organic or fiberglass mats. The binder in built up roofs (BUR) can be hot-applied asphalt binders, hot-applied coal tar, or cold-applied solvent-based asphalts. The surfacing for BUR roofs include aggregates such as gravel, slag or mineral granules, glass-fiber or mineral surfaced cap sheets, hot mopped-asphalt, aluminum, or

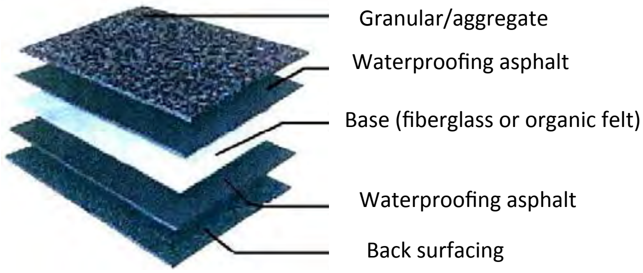


FIGURE 9 Typical composition of roofing shingles (after Gevrenov 2007).

elastomeric coatings. Standards used to specify BUR materials include:

- ASTM D226, Standard Specification for Asphalt Saturated Organic Felt Used in Roofing and Waterproofing
- ASTM D312, Standard Specification for Asphalt Used in Roofing
- ASTM D450, Standard Specification for Coal Tar Pitch Used in Roofing, Damp Proofing and Waterproofing
- ASTM D2178, Standard Specification for Asphalt Glass Felt Used in Roofing and Waterproofing
- ASTM D4990, Standard Specification for Coal Tar Glass Felt Used in Roofing and Waterproofing.

RECYCLED ASPHALT SHINGLES PROCESSING

Regardless of the source of shingle, RAS needs to be post-processed by shredding, sizing, and cleaning in order to be used in highway applications. The steps in processing RAS for use in highway applications are (Figure 10):

- Grinding
- Sizing
- Grading
- Contaminate removal (tear-offs)
- Stockpiling.

Brock (2007) described various methods of shredding shingle byproducts that have been tried over the years with variable success including crushers, hammer mills, and rotary shredders. Brock (2007) noted that currently most shingles were shredded by large wood chippers with 500 hp, which produced about 50 to 75 tons of RAS per hour. To ensure that the RAS met the ½ inch minus particles size, the material needed to pass through the shredder a second time (Figure 10).

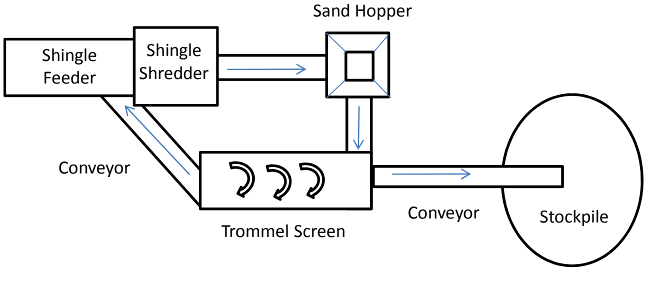


FIGURE 10 Typical grinding operation set-up (after Brock 2007).

Grinding was easier in the winter when the shingles were cold and more brittle, which helped minimize agglomeration. The oxidation of the roofing asphalt helped with reducing the agglomeration of the shredded material (VANR 1999). A Minnesota recycler found that grinding manufacturing byproduct was easier if the material had been weathered by being stored in a stockpile for a year before grinding. Manufacturing byproducts were reportedly more difficult to process than the aged roofing material, which had hardened with age and was less likely to agglomerate during grinding (VANR 1999). Some shredding processes used water to cool the cutting heads and limit dust production.

Schroer (2007) noted that an additional feature that was needed in the tear-off RAS grinding process was a removal system for nails and other ferrous materials. This was accomplished by fitting the conveyor belts with magnets; a minimum of three or four was suggested. A final detection system of a metal detection device and manual sorting was also suggested as the final QC process. Wood could be removed either by hand or floated off in a water floatation unit. Air blowers to remove paper and lightweight debris were an alternative method for removal.

Sand may or may not be needed to prevent clumping of the RAS. A trommel screen can be used to either divert oversized particles back to the shredder or to the final stockpile. Schroer (2007) also noted that RAS can be pre-blended with reclaimed asphalt pavement (RAP) in a metered process to produce a composite blend that will resist re-agglomeration.

Schroer (2007) noted that a dust control plan was needed for the grinding operation that should include the ability to provide optimum amounts of sprayed water at critical grinding stages, shrouds, negative air (i.e., suction), and standard employee health and safety protection equipment and procedures.

For stockpiling, shingles needed to be either processed shortly before using, covered and kept dry, or post-processed to dry out, particularly if they were to be used in HMA applications (Decker 2002; Schroer 2007). Stockpiled RAS also tended to re-agglomerate in stockpiles, especially during the warm summer season. Blending ground RAS with sand or RAP helped prevent agglomeration; however, some agencies, such as Minnesota DOT (MnDOT), did not allow preblending of stockpiles.

Schroer (2007) and Gevrenov (2007) suggested siting was important to the feasibility of processing and using RAS. The location of the recycling operation may require state and local permits such as air, water, zoning, and possibly solid waste. Good location choices would consider the location of

TABLE 36
TYPICAL REPORTED COMPOSITION OF SHINGLES

Component	VANR (1999)		Sengoz and Topal (2005)	CIWMB (2009)	
	Organic shingles	Fiberglass shingles	Fiberglass shingles	Organic shingles	Fiberglass shingles
Asphalt	30%–35%	15%–20%	32.5%	30%–36%	19%–22%
Backing	5%–15%	5%–15%	2.5%	2%–15%	2%–15%
Mineral Filler	10%–20%	15%–20%	20% $CaCO_2$	8% to 40% with 90% smaller than 0.15 mm and 70% smaller than 0.08 mm Typically limestone, silica, dolomite, etc.	
Mineral Granules	30%–50%	30%–50%	35% basalt	20% to 38% of sand sized particles Ceramic coated natural rock	

competing landfills and transfer stations. A location near the HMA contractor's plant was always a good choice. Usage location should be close to RAS location. Decker (2002) noted that urban distances for economical hauls were usually within 25 to 40 miles of the recycler. Decker (2002) noted that grinding will typically require two operators for safe operation.

PHYSICAL AND CHEMICAL PROPERTIES

Physical and chemical properties of RAS depend on the manufacturer and the roofing application (VANR 1999). Examples of the variation in the reported material content of shingles are shown in Table 36. The asphalt content of the shingles is dependent on the type of backing; fiberglass backing requires less asphalt than organic backing. The amount of mineral granules varies from 20% to 50%.

Brock (2007) reported on the composition of new RAS as the percent of material per 100 square feet of shingles (Table 37) compared with a sample of tear-offs. The organic shingle manufacturing process used significantly more asphalt and less mineral filler than fiberglass-backed shingles, which agreed with previously reported data. Newly manufactured fiberglass RAS had a mat content (2%), while only newly manufactured organic and recycled organic tear-off RAS had a felt content (10% to 12%). The tear-off RAS had similar properties to the organic-backed RAS. This was a function of the predominance of organic-backed shingles used in the older roofing systems.

TABLE 37
ROOFING SHINGLE COMPOSITION

Component	Percent of Component in 100 ft^2 of Shingles		
	Organic	Fiberglass	Tear-offs
Asphalt	30	19	31
Filler	26	40	25
Granules	33	38	32
Mat	0	2	0
Felt	10	0	12

After Brock (2007).

Roofing shingle binder, like paving grade asphalt binders, aged with time and exposure to ultraviolet (UV) light and oxidation. The effect of aging of shingle properties was summarized by Bauman (2005; Table 38).

Gevrenov (2007) provided a summary of the use of asbestos in the manufacturing process (Table 39). The asbestos content was one of the main environmental concerns when using tear-offs in highway applications.

Tear-offs contained a range of roofing products in the mix. This variability was increased when the new roof was installed over the old material. In some cases, older backing materials used asbestos in the felt manufacture.

Shingles manufactured between 1940 and 1973 contained asbestos fibers, which may be a concern when using tear-offs in highway applications (Marks and Petermeier 1997). As noted by the Vermont Agency for Natural Resources (VANR) (1999) there were inconsistencies in the literature on the presence of asbestos in RAS.

ENGINEERING PROPERTIES

The preferred size of the shredded roofing material will vary by agency. The Texas DOT requires that 100% of the shingle shreds pass the 19 mm sieve and 95% pass the 12.5 mm sieve (VANR 1999). The Georgia DOT requires that 100% of the shingle shreds pass the 12.5 mm sieve; this agrees with the FHWA recommendation of less than 12.5 mm. Other

TABLE 38
GENERAL WEATHERING AND AGING CHARACTERISTICS OF TEAR-OFFS

Shingle Type	Misc. Attributes	Weather	Aging
Organic Felt Backing (cellulose, wood fiber)	Tear resistant	Less brittle in cold weather	Components break down, crack, and curl
Fiberglas Felt Backing	Lighter, cheaper ($45–$60/sq)	More cohesive in heat	Components break down, crack, and curl
Laminated Shingles	Thicker more expensive ($100/square)	More durable than traditional shingles	Slower break down
Roll Roofing (organic)	Similar to organic shingle		
Roll Roofing (fiberglass)	Similar to fiberglass-backed shingle		

After Bauman (2005).
Source: Reference USA Business Disc, Info USA Library Division, www.referenceusa.com.
"Elements of Roof Repair," Canadian Home Workshop, by Martin Zibauer.
Asphalt Shingle and Coating Manufacturing: 2002 (issued Jan. 2005).

engineering properties will depend on the amount, size, and application for the RAS.

ENVIRONMENTALLY RELATED PROPERTIES

There are several possible exposure pathways for RAS contaminates to the environment that are grinding (e.g., inhalation) emissions into the air as the material moves through hot highway applications (e.g., HMA plant), and leaching into water supplies (Gevrenov 2007). Contaminates of concern are asbestos and polyaromatic hydrocarbons (PAHs).

Asbestos

The Georgia DOT reported the use of asbestos in shingles as late as the 1980s (VANR 1999). The California Integrated Waste Management Board (CIWMB) reported that the asbestos content of shingles manufactured in 1963 was 0.02%, which decreased to 0.00016% in 1997 (VANR 1999). Other roofing products such as sealants used around pipes and chimneys could also contain asbestos; however, if it is present, it was in very low concentrations of 0.8% (Marks and Petermeier 1997). Communications between the VANR and members of the roofing industry indicated that asbestos was confined to commercial built-up roofing, older roofing coatings, and roofing cement; asbestos content was considered rare.

Because of the health concerns, the Iowa DOT tested shingles for asbestos content starting in 1994. A total of 368 samples were tested, with only 3 samples testing positive. In 1996, the EPA of Region VII in Kansas City responded to an inquiry by the Iowa DOT indicating that the National Emission Standards for Hazardous Air Pollutants (NESHAP) regulation identified and controlled asbestos-containing materials (Marks and Petermeier 1997). The letter also indicated that tear-offs coming from four or fewer units would be exempt from the NESHAP standard; however, shingles coming from a recycling facility would require testing for asbestos content. Any material containing more than 1% asbestos could not be used for roadways.

In 1996, the Iowa Department of Natural Resources (DNR) provided guidelines for landfills on the acceptance of tear-off

TABLE 39
USE OF ASBESTOS IN ROOFING SHINGLE MANUFACTURING

Years Manufactured	Product
1891 through 1983	Asphalt–asbestos shingles, rag–felt shingles, fibrous roof coating, shingle tab cement, roof putty
1906 through 1984	Asphalt roof coating and other miscellaneous materials
1920 to 1968	Roof paint, roll roofings with asbestos-containing base sheets, caulking compounds, plastic cements, taping, and finishing compounds
1930 through 1977	Paper and felt
1941 through 1981	Roofing and shingles
Early 1930s through 1976	Adhesives, coatings, sealants, and mastics
Dates not available	Asphalt–asbestos roof felt
	Asphalt–asbestos shingles, asbestos finish felt, mastic
	Roofing asphalt
	Asbestos surface coating for shingles
	Asbestos surface coatings for shingles

After Gevrenov (2007).

TABLE 40
SUMMARY OF ANALYTICAL RESULTS

Material Analyzed	Number of Samples with Given Level of Asbestos Detected				
	None	Trace	2%	5%	Total samples tested
Shingles	1,625	8	3	0	1,636
Felt	109	0	0	1	110
Ground Products	23	1	0	1	25
Total	1,757	9	3	2	1,771
% of Total	99.2	0.5	0.17	0.11	100

After Zickell (2003).

shingles. The DNR stated that landfills "are prohibited from accepting any shingle wastes that will be crushed, broken, or ground on-site per federal NESHAP regulations. . . . unless the generator or hauler provides lab certification that the shingle waste does not contain asbestos-containing material."

Zickell (2003) reviewed a large number of tests to determine the extent of asbestos in tear-offs (Table 40). Of 1,771 samples tested, only 3 shingle, 1 felt, and 1 ground product samples showed asbestos content of 2% or greater. This was 0.2% of all samples tested.

Schroer (2007) listed environmental concerns, other than asbestos, as air emissions impacts from tear-off RAS in HMA plants, PAH and other particulates, runoff from whole shingles and RAS stockpiles, and runoff from RAS used as ground cover or dust control.

The CIWMB (2009) noted that asbestos was not present in current roofing products, but that the tear-off RAS may contain very small amounts in the waste stream up until about 2016. The CIWMB noted the following regulations for asbestos that might be considered when using tear-off byproducts in California:

- U.S. EPA
- California EPA
- Air Resources Board
- Department of Toxic Substances Control.

Other regulations that need to be considered are those from the Occupational Safety & Health Administration (OSHA), which regulates friable and nonfriable asbestos over 0.1%; CalOSHA; and other city and county health department requirements.

Polyaromatic Hydrocarbons

Because asphalts naturally contain PAH compounds, it follows that shingle byproducts will as well (Gevrenov 2007). Research has shown that PAHs were not readily leached from shingles, and studies of PAH in leachate from virgin roofing asphalt, RAP, and runoff from asphalt pavements originally showed PAH levels below laboratory detection limits. However, some of the regulatory limits have decreased, which implies that additional data are needed to detect the new, lower concentration levels.

COSTS

Although the tabs from RAS have alternative uses, the factory scrap is commonly landfilled at costs ranging from $18 per ton to as much as $100 per ton. Haul distances can be up to 300 miles (Brock 2007). Marks and Petermeier (1997) reported that the disposal fee in Iowa for landfills accepting roofing tear-offs was $40 per ton. The asbestos testing was estimated at $12 per ton and grinding at about $18 per ton, leaving a margin for profit (or reduced costs) of $10 per ton. Their conclusion was that it was cost-effective to use the tear-offs for dust control for rural aggregate roads.

Bauman (2005) reported that in Massachusetts the disposal costs could be as much as $115 per ton but the recycling fees are from $75 to $85 per ton, making recycling financially advantageous (Table 41).

Gjerde (2004) noted that Minnesota contractors were seeing a savings in virgin asphalt and aggregate costs from $0.50 to $1 per ton of finished HMA. The shingle processing costs were from $12 to $15 per ton of whole shingle scrap feedstock at a production rate of 20 to 30 tons per hour and maintenance costs were a significant factor in the shingle processing. Another Minnesota recycled shingle provider charged $15 per ton to accept shingles (manufacturer byproduct), which they then processed for use in HMA applications (Krivit 2008). Other costs that needed to be considered in the overall recycler costs were the modifications to operations that need to a include dust shroud installation, and added repair and maintenance costs as shingles were abrasive and shortened the life of the grinder.

Krivit (2008) noted that Minnesota tipping fees from 2007 ranged from $16.00 to $43.00 per ton, with the average being $32.20. Krivit noted previous research that showed a tipping fee of $50 per ton appears to be the price that stimulated the industry to take additional action for the byproduct reuse. Using 5% RAS (manufacturer) resulted in a cost savings of

TABLE 41
EXAMPLE OF SHINGLE PRODUCTION COSTS
IN MASSACHUSETTS

Shingle Type	2002 Sales
Organic Felt Backing (cellulose, wood fiber)	$280,053
Fiberglas Felt Backing	$392,652 (225 lb) $540,167 (other) $932,819 (total)
Laminated Shingles	$1,382,881
Roll Roofing (organic)	$387,561
Roll Roofing (fiberglass)	$182,728

After Bauman (2005).

TABLE 42
COMPONENT COSTS AND POTENTIAL SAVINGS IN ASPHALT

Component	Unit Cost Per Ton	Organic	Fiberglass	Tear-offs
		Value of Components		
Asphalt	$400	$120.00	$76.00	$124.00
Filler	$10	$2.60	$2.80	$2.50
Granules	$10	$3.33	$2.66	$3.20
Mat	$10	$0.00	$0.14	$0.00
Felt	$10	$1.00	$0.07	$1.20
Total	$440	$126.93	$81.67	$130.90
Opt. HMA Binder Content	Value of Asphalt in RAS to Contractor			
4%		$5.68	$3.86	$5.76
5%		$7.10	$4.83	$7.19
6%		$8.32	$5.80	$8.62

After Brock (2007).
Value of binder to contractor based on using 5% RAS.

between $0.50 and $1.00 per ton of HMA (typical non-RAS HMA cost $30/ton in Minnesota), which translated into a savings of between 1.5% and 3.3% in cost.

The National Asphalt Pavement Association (NAPA 2004) noted 5% of RAS typically reduced the demand for virgin asphalt by 0.5% of total weight of mix. At $197.5 per ton in October 2004 for asphalt (per Texas Bituminous Index) would result in a savings of $7.16 per ton of HMA. At the April 2010 cost of asphalt of $500.45 per ton, 5% RAS would save $18.14 per ton of HMA.

Zickell (2003) noted that the grinding, sorting, testing, housing, regulatory, and administrative costs exceeded $39 per ton. When the tipping fee was in excess of $50 per ton, it was cost-effective for the facility to recycle the waste stream. The sales of fiberglass-backed shingles were about double that of the organic-backed. However, the newer laminated shingle byproduct was the current best-selling product. The author stated that an additional category of byproducts with a different range of properties will be needed in the coming years.

Brock (2007) estimated the potential for cost savings to the HMA contractor when using various types of RAS (Table 42). Because of the different components in the various types of shingles, the total unit cost of the components varied. Also, because the optimum HMA binder content was different for each combination of aggregate, additives, and binder, the savings to the contractor for using RAS also varied. This table shows that using either the organic-backed or tear-off RAS provided the most binder replacement savings to the contractor. However, this can be expected to gradually change with time as more fiberglass-backed RAS enters the tear-off waste stream.

USAGE AND PRODUCTION

A review of the literature in 1999 by VANR showed the annual production of manufacturing RAS ranged from 0.5 to 1.0 million tons per year. Tear-offs removed from buildings each year generated between 7 and 9 million tons per year.

Bauman (2005) reported that Massachusetts estimated the annual market for post-consumer shingles as:

- 82,653 tons, assuming 10% post-consumer shingles in road surface and base.
- 27,334 tons, if shingles consumed in the state included 10% post-consumer content.
- A combined diversion of 47.5% of the estimated volume of shingles generated in the state.
- More than 210,000 tons of shingles discarded per year.

Gjerde (2004) reported that roofing manufacturers in Minnesota generated between 40,000 and 50,000 tons of roofing shingle scrap annually. Between 20% and 40% of this scrap was recycled into highway applications in 2003. At the same time approximately 400,000 tons per year of tear-offs were 100% landfilled. Two of the three roofing manufacturers had contracts to manage their shingle waste, which Gjerde reported as being well accepted in HMA applications by counties, cities, townships, and private customers.

Krivit (2008) reported the production of RAS in Minnesota to be about 70,000 tons of manufacturing byproduct each year with the use in HMA at about 40,000 to 60,000 tons per year. There were 227,000 tons of tear-offs generated each year, with about 166,000 tons per year being landfilled. Krivit proposed that Minnesota strive to obtain a recovery rate of 50% of the tear-off material by 2012 as a goal for Minnesota's recycled shingle byproduct program (see Table 43).

AGENCY SURVEY RESULTS

RAS was most commonly used in HMA applications. Two states were using the byproducts in asphalt cement or emulsion applications. Three states listed "other" uses, which were noted as being in geotechnical applications (see Figures 11a–c).

Table 44 shows the states using each roofing byproduct in one or more applications. Maine and Virginia were the only

TABLE 43
USE OF ROOFING SHINGLE BYPRODUCTS IN HIGHWAY APPLICATIONS

Question: Manufacturing or Misc. Construction Byproducts: Is your state using, or has ever used, these byproducts in highway applications?

- Roofing shingles, fiberglass backed: byproduct from production of fiberglass-backed roofing material
- Roofing shingles, paper backed: byproduct from production of paper-backed roofing material
- Roofing shingles, tear-offs: construction debris from reroofing or demolition of existing structures

Type of Roofing Shingle Byproduct	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embankments	Flowable Fill	HMA	Pavement Surface Treatments (non-structural)	PCC	Soil Stabilization
Roofing Shingles, Fiberglass Backed	1	0	0	0	0	14	0	0	0
Roofing Shingles, Paper Backed	0	0	0	0	0	13	0	0	0
Roofing Shingles, Tear-offs	1	0	0	0	1	12	0	0	1
Roofing Shingles, Unknown Type	1	0	0	0	4	1	0	0	0
Roofing, Built Up Roofing	0	0	0	0	0	0	0	0	0

states using roofing byproducts in two applications. Each of the other states only used these byproducts in a single application. Fewer agencies were using tear-offs than either of the manufacturing byproducts. No states were considering or using BUR byproducts in any highway applications.

Agency comments note that the performance of HMA with roofing byproducts is either satisfactory or slightly improved in the case of rut resistance (Table 45). A number of agencies are currently working on specifications and/or special provisions for allowing RAS in HMA. Some agencies that currently allow RAS use report limited use by the contractors.

Applications—Bound

Hot Mix Asphalt

Decker (2002) provided a detailed evaluation of shingle byproduct processing and introduction of the shingle byproducts into the HMA plant. He noted his experience with two types of shredding methods, which were a conventional milling head and an anvil method. The shredding methods had a problem processing the granular material as neither is designed as an aggregate crusher. The anvil approach appeared to minimize the oversized material, which results in a lower amount of rejected material. Shredding production rates depended on the type of shredder, with typical rates ranging from 25 to 100 tons per hour. Care was needed so that other rock contaminates were not included in the material to be shredded, because this will significantly decrease the life of the shredding equipment. Grapple hooks were found to be the best method of introducing the shingles into the shredder. This minimized contamination and provided better control of the material being fed into the shredder.

Water could be used to cool the shredder head and for dust control. However, this could be a problem for HMA production since a 1% increase in moisture content will increase the production costs by about 10% because of the additional drying time needed. Stockpiled shredded RAS agglomerated over time and, once shredded, the shingle stockpile needed to be kept clean. Decker recommended not shredding any more than can be used in a two-week period to minimize additional moisture content that could slow production.

Introduction of the shingles into the HMA production could be accomplished by blending with RAP or crusher fines and added through the RAP port in the HMA plant (Decker 2002). This location in the HMA plant would keep the RAS away from the flames used for drying. The RAS should be in the plant long enough for the roofing asphalt to get soft, which requires some experimentation with the plant operation to determine the optimum time. Mix temperatures might need to be raised by about 5°F to accomplish the softening. The HMA plant also needed to be cleaned more frequently when using RAS in the mixes.

In Turkey, Sengoz and Topal (2005) investigated the use of tear-offs in HMA. The percents of byproduct used in the study mix were 1%, 2%, 3%, 4%, and 5% and the

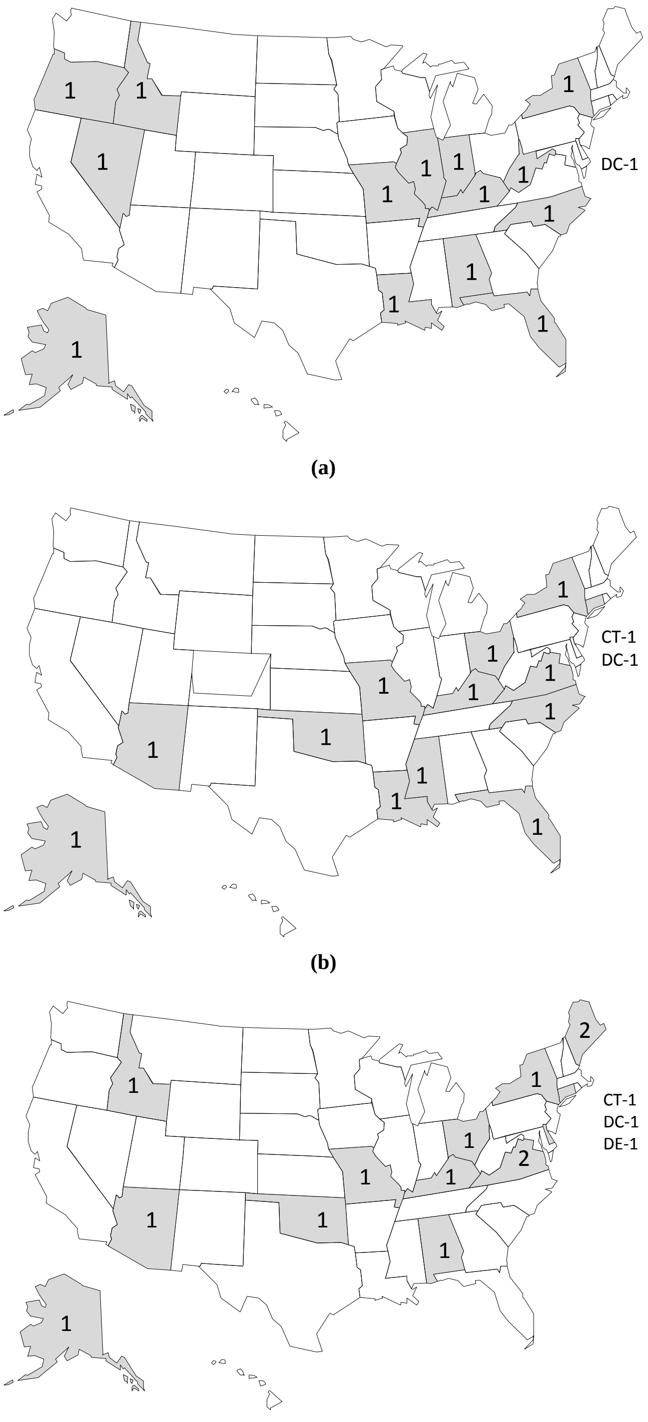


FIGURE 11 State agencies using roofing shingle byproducts: (a) roofing shingles fiberglass backed; (b) roofing shingles, paper backed; (c) roofing shingles, tear-offs.

HMA mixes were evaluated to determine a desirable level of roofing byproduct. Results showed that the Marshall stability decreased with an increasing percent of RAS. At a shingle content of 3% or higher, the stability values were lower than for the control mix, but the flow values did not noticeably change. Air voids were lower for mixes with shingle, which was attributed to the RAS being easier to compact and the filler effect from the RAS. The optimum asphalt content was reduced by 0.5% asphalt at 1% of shingle content. This indicated that a cost savings as a function of the reduced amount of asphalt needed could be obtained. Rut testing was conducted using mixes with 1% of byproduct using the French Laboratoire Central des Ponts et Chaussées (LCPC) loaded wheel rut tester. Table 46 shows an improvement in the rutting resistance of the mix, even at the low 1% of addition.

Schroer (2007) listed the factors associated with using RAS in HMA that will ultimately influence the performance of the application as:

- Aggregation of the RAS
- Properties of the final blended binder
- Type of binder in the RAS
- Type of virgin binder
- Where the RAS is introduced into the HMA drum mixer
- Mix temperature
- Moisture content of the RAS and other aggregates
- Retention time in the HMA drum.

Low temperature cracking problems generated by stiffening the binder with the addition of RAS can be countered by using less RAS (i.e., 2% or 3% instead of 5%), using a softer grade of virgin asphalt, and setting a minimum amount of virgin binder to be used, regardless of the performance grade (PG) of the binder.

Maupin (2008) noted that the incentive for using recycled materials in Virginia came from Virginia Senate Bill 469 in the mid-1990s, which directed the formation of a Recycled Materials in Highway Construction Advisory Committee to provide recommendations for the use of recycled materials in highway applications. This resulted in the development of a draft specification for RAS to be used in HMA, which focused on manufacturing waste because it would provide more consistent material properties than tear-offs. The recent fast increase in the cost of asphalt encouraged a North Carolina contractor to request approval to use RAS in HMA in 2006.

Test sections were constructed over 4.1 miles of rural two-lane road with a surface mix containing 5% manufacturing shingle byproducts. For comparison, additional test sections containing 10% RAP (no RAS) in the surface mix were placed.

The mix was a 9.5 mm HMA with a PG 64-22 binder designed with a gyratory compactor using 65 gyrations by the contractor. A limited number of visual inspections were performed to determine that the size of the RAS met the 0.5 in. maximum requirement. The mix variables used in the study are shown in Table 47. The Superpave gyratory mix design volumetrics are shown in Table 48.

TABLE 44
AGENCIES USING ROOFING SHINGLE BYPRODUCTS IN HIGHWAY APPLICATIONS

Number of Applications	States				
	Fiberglass backed	Paper backed	Tear-offs	Unknown type	Built up roofing (BUR)
2	—	—	ME, VA	—	—
1	AK, AL, DC, FL, ID, IL, KY, LA, MO, NC, NV, NY, OH, OR, WV	AK, AZ, CT, DC, FL, KY, LA, MO, MS, NC, NY, OH, OK, VA	AK, AZ, CT, DC, DE, ID, KY, MO, NY, OH, OK	AL, MO, SC, VT, WI	—

TABLE 45
AGENCY COMMENTS ON USING RAS IN HIGHWAY APPLICATIONS

State	Comment
AL	Roofing shingles (manufacturing waste) is routinely used in HMA. Tear-off shingles are allowed by specification, but are not currently being used by contractors. The performance of HMA pavements containing roofing shingles has been satisfactory.
FL	Shingles have only been used a few times. Economics and performance have prevented widespread use.
IA	Just starting with tear-off shingles using 5% limit at this time.
KY	The availability of roofing shingles for incorporation into HMA has been sporadic in Kentucky. This inconsistent supply hinders the usage of roofing shingles by those few contractors that are equipped to use this material. Also, the incorporation of higher contents of roofing shingles (e.g., more than 5%) normally requires a softer virgin asphalt binder. Some softer virgin binder grades (e.g., PG 58-28) are difficult to obtain in this region.
MO	Most agencies have trouble with acceptance of processing tear-off shingles, while it was brought to MoDOT by a contractor and the Department of Natural Resources.
NC	No problem with shingles in HMA; however, there are environmental concerns with using tear-off shingles.
NH	Currently working on a specification to allow the use of recycled asphalt shingles on our highway project.
NJ	Have allowed the use of roofing shingles (pre-consumer) in HMA-base and intermediate courses for more than 15 years; however, there is not wide use.
SC	The recycled materials (RAP and shingles) show additional rutting resistance in laboratory tests.
	QC requires very close monitoring of stockpiled shingle material, especially tear-off shingles, by the contractor.
TX	Special provision recently approved allowing use of post-manufactured and post-consumer recycled shingles.
WA	The shingle industry has not satisfactorily answered why this product cannot be reused into new shingles.

Laboratory testing included determination of the core density (AASHTO T166) and ignition oven testing was used to determine the asphalt content of the mix. Results indicated similar volumetrics for both mixes.

Field testing included the use of nuclear density testing using a thin lift gauge and a 60-s count to establish the required rolling pattern. This testing was in addition to the standard density testing requirements. VDOT required the density be at least 92.5% of the maximum theoretical specific gravity.

TABLE 46
RUT TESTING RESULT FOR HMA WITH 1% TEAR-OFF RAS

Number of Passes	LCPC Rut Depths, in.	
	60/70 Pen AC with 1% RAS	60/70 Pen AC HMA Mix
300	0.07	0.17
1,000	0.11	0.28
3,000	0.13	0.41
10,000	0.16	0.64
30,000	0.29	—
50,000	0.41	—

After Sengoz and Topal (2005).
LCPC = Laboratoire Central des Ponts et Chaussées.

Fatigue testing (AASHTO T321) at 400 and 800 microstrain with failure defined as a loss of 50% of the initial stiffness as well as the endurance limit were also determined. The endurance limit is defined as the strain at which the specimen can endure an infinite number of cycles and is a value projected from the fatigue testing data (Table 49). The results showed no practical difference in the endurance limits between the mixes. Rut testing (VTM 110) was accomplished using a loaded wheel rut tester, which limits the maximum rut depth to 0.25 in. The RAP mixes were borderline, whereas the shingle mixes were rated as satisfactory by VDOT.

Permeability testing (VTM 120) limits the maximum allowable permeability to 150×10^{-5}. Permeability was an average of 83×10^{-5} and 98×10^{-5} cm/s for the RAP and shingle mixes, respectively. Two of 10 RAP cores exceeded this limit, while 4 of 10 shingle cores exceeded the limit. The cores with the highest permeability also had the highest air voids. The conclusion was that the air voids need to be less than 9% in order to meet the maximum permeability limit.

TABLE 47
VARIABLES IN FIELD SECTIONS

Mix	Percentage	Material	Source
RAP Mix	42	78M	Vulcan Materials, Skippers, Va.
	10	Fine RAP	Rose Brothers, Murfreesboro, N.C.
	19	Coarse sand	Rose Brothers, Grit Pit, Rich Square, N.C.
	29	Regular screenings	Vulcan Materials, Skippers, Va.
	5.5	PG 64-22 binder	Koch Materials, Newport News, Va.
	0.25	Adhere HP	Armaz, Vanceboro, N.C.
Shingle Mix	45	78M	Vulcan Materials, Skippers, Va.
	5	RAS	Certain Teed Corporation, Oxford, N.C.
	27	Coarse sand	Rose Brothers, Grit Pit, Rich Square, N.C.
	23	Regular screenings	Vulcan Materials, Skippers, Va.
	5.8	PG 64-22 binder	Koch Materials, Newport News, Va.
	0.25	Adhere HP	Armaz, Vanceboro, N.C.

After Maupin (2008).
78M = aggregate size designation; Adhere HP = anti-stripping additive.

Moisture sensitivity was evaluated by determining the tensile strength ratio. Both mixes contained about 70% of crushed granite known to be susceptible to stripping and 25% sand with no known stripping problems. A liquid antistrip (0.25%) additive was used in both mixes. Both mixes performed satisfactorily.

Superpave binder testing on the Abson (AASHTO T170) recovered binder (Table 50) was performed. The virgin binder used was a PG 64-22 and the recovered binder was graded as a PG 70-22 with the shingle mix having greater warm temperature stiffness, but not enough to change the grading. This difference could account for the better rut resistance of the shingle mix.

Comments on the construction of the pavement noted that both mixes were slightly tender during rolling. The finish roller needed to be delayed until the mixes had cooled sufficiently so that the material was not pushed during rolling. Performance observations after 18 months in service showed both sections were performing well, with negligible signs of distress cracking. A cost/benefit assessment indicated that an estimated 50,000 tons of HMA could be supplied to the Hampton Roads District per year, with a cost savings of as much as $2.69 per ton. Recommendations from the research were to develop a provisional specification to allow manufacturing shingle byproducts in HMA and to assess the possibility of using tear-offs in the future.

TABLE 48
VOLUMETRIC PROPERTIES: MIX SAMPLES AND PAVEMENT CORES

Property	Recycled Asphalt Pavement Mix	Shingle Mix
Mix Design, 65 Gyrations		
VTM, %	3.6	3.6
VMA, %	16.1	15.9
VFA, %	77.8	77.5
Roadway, Post-construction		
Air voids, %	7.9	8.0

After Maupin (2008).
VTM = voids in total mix; VMA = voids in mineral aggregate; VFA = voids filled with asphalt.

Schultz (2010) evaluated mix design methods and needed Oregon DOT specification changes for mixes using RAP and RAS. Oregon DOT was allowing the use of up to 30% RAP without adjusting the PG grade of the asphalt, and above 30% the use of blending charts was needed to select the grade. In 2009, the Oregon legislature introduced a bill that would require the use of up to 5% RAS in HMA. The major concern of Oregon DOT engineers was that too much RAP and/or RAS would significantly reduce the performance of the pavements resulting in early failures and/or undesirable increases in maintenance, repair, or rehabilitation costs.

This research was to be used to address this concern. The research program evaluated the impact RAP, RAS, and RAP/RAS combinations would have on the Superpave PG binder specification grade. In the Superpave binder specification, the grades change in six degree Celsius increments and the

TABLE 49
FATIGUE AND RUT TEST RESULTS

Mix	Sampling Time	Endurance Limit at 50 x 10^6 cycles, με	Rut Depth, in.
RAP	Morning	182	0.28
	Afternoon	167	0.28
Shingle	Morning	152	0.25
	Afternoon	222	0.20

After Maupin (2008).

TABLE 50
BINDER PROPERTIES FOR FIELD TEST SECTIONS WITH AND WITHOUT SHINGLE BYPRODUCT

Binder Properties	Virgin Binders		Mix with 10% RAP (recovered)	Mix with 5% RAS (recovered)
	RAP mix	Shingle mix		
No Lab Aging				
G*/sin δ, kPa > 1.0	1.282 at 64°C	1.333 at 64°C	—	—
	0.630 at 70°C	0.663 at 70°C	—	—
Rolling Thin-Film Oven				
G*/sin δ, kPa > 2.20	4.014 at 64°C	3.648 at 64°C	4.546 at 64°C	6.943 at 64°C
	1.884 at 70°C	1.710 at 70°C	2.252 at 70°C	3.447 at 70°C
	—	—	1.145 at 76°C	1.758 at 76°C
Pressure Aging Vessel				
G*sin δ, kPa < 5,000	3026 at 22°C	3255 at 22°C	2413 at 25°C	2298 at 25°C
	2113 at 25°C	2259 at 25°C	1682 at 28°C	1647 at 28°C
Creep Stiffness, MPa < 300	128 at −12°C	129 at −12°C	126 at −12°C	113 at −12°C
	—	—	257 at −18°C	243 at −18°C
m-value, > 0.300	0.319 at −12°C	0.314 at −12°C	0.322 at −12°C	0.312 at −12°C
	—	—	0.287 at −18°C	0.283 at −18°C

After Maupin (2008).

temperatures represent the environmental conditions under which the binder will need to perform. For example, a PG 58-22 needs to be stiff enough to resist rutting when the average summer temperature is 58°C and resist thermal cracking at −22°C in the winter. The critical high temperature indicates that the test temperature above which the binder has a complex modulus divided by sinδ (i.e., G*/sinδ of less than 2.2 kPa). The critical low temperature indicates the lowest temperature the mix can withstand without significant thermal cracking occurring.

The data from this research program showed that the binder for RAS mixes with various percentages of RAS will be very rut resistant (Table 51). However, they also showed significant early thermal cracking distresses at mild temperatures. For example, at 40% RAS the critical low temperature was −14°C and increased to 43°C or warmer at 80% RAS. The typical low temperature requirement for the Oregon climate was approximately −28°C to −31°C. Therefore, at 40% RAS, the mix could be expected to exhibit significant thermal cracking.

Schultz (2010) also compared the Oregon data with similar research conducted by both Ohio and Minnesota (Table 52). Since each grade change represents a shift in the temperature of 6°C, a change in the high temperature of two grades would represent a grading change from PG 58-xx to PG 70-xx. Conversely, a one grade change in the low temperature would mean a PG xx-22 would be changed to a PG xx-16. The findings showed that mixes with RAS should limit the amount of RAP to low levels or the grade of the virgin binder changed to a softer binder. Conclusions from the Schultz (2010) study were that the use of RAS increased both the high and low PG grade temperatures relative to the virgin binder. The use of both RAS and RAP in the same mix also increased both temperatures, up to about 30% RAP, when there was no further increase in the low temperature grading. The high temperature grade increased for the 30% to 40% RAP-only mixes and was similar to mixes with only 5% RAS (i.e., no RAP). The study identified a need for:

- Improved batching and mixing procedures for RAP/RAS mixes;
- Development of an improved binder extraction procedure;
- A modified method for determining asphalt content using the ignition oven;

TABLE 51
CRITICAL HIGH AND LOW TEMPERATURES FOR VARIOUS PERCENTAGES OF RAS

Virgin Binder Grade	Percent of Reclaimed Material in Mix									
	Percent Virgin Binder Replacement from RAS									
	0% (i.e., no RAS)		20%		40%		60%		80%	
	Critical Temperature, °C									
	High	Low	High	Low	High	Low	High	Low	High	Low
PG58-22	59	−28	73	−25	108	−17	105	−1	123	8
PG52-28	56	−31	64	−28	80	−19	99	14	126	Too stiff
PG58-28	60	−30	73	−24	78	-14	107	2	123	43

No RAP; after Schultz (2010).
PG grade changed one grade for every 6°C change in critical temperature.

TABLE 52
CHANGE IN PG GRADE REPORTED IN OHIO AND MINNESOTA RESEARCH

Mixture	RAP, %	RAS, %	Change in High Temp Grade	Change in Low Temp Grade	Resulting PG Grade
Ohio DOT Study	10	5 (tear-offs)	0	0	—
	20	5 (tear-offs)	2	1	—
MnDOT Study	15	5 (tear-offs)	2	0	—
	15	5 (manufacturer)	2	1	—
Oregon Study	0	0	–1	0	PG 64-28
	0	5	3	1	PG 88-22
	10	5	0	0	PG 70-28
	20	5	2	1	PG 82-22
	30	5	3	2	PG 88-16
	40	5	3	2	PG 88-16
	50	5	2	2	PG 82-16

McGraw et al. (2007); Schroer (2007); Schultz (2010).

- QC/quality assurance (QA) procedures for RAP/RAS mixtures, procedure for selecting PG grade of virgin binder for RAP and/or RAS mixes;
- Performance mix testing;
- A pilot study for field evaluation.

Cold-Applied Asphalt

Re-pave, produced by a Florida company, is a shingle product marketed as a pothole patching material, tried by New Jersey, but not currently available in bulk quantities for New Jersey use. This product is marketed commercially for residential use in 3.5 gallon buckets and can be found at home centers and hardware stores for residential use.

Applications—Unbound

Aggregate/Dust Control

Marks and Petermeier (1997) reported on Iowa's experience with RAS as a roadway surface to control dust problems on a rural Benton County roadway. Tear-off roofing was collected and tested during 1994 and 1995 for asbestos content, then ground up at a rate of 40 tons per hour using a 2-in. screen. Initial work with a 1-in. screen resulted in a slow production rate of only 15 tons per hour. The grinding unit was equipped with a water spray system for dust control. The discharge conveyor was fitted with a magnetic roller to remove most of the nails in the shingles.

A total of 500 tons of ground RAS was spread on the crushed stone surface and a motor grader was used to mix the crushed stone and RAS into a mixture with a uniform texture. The finished surface mix was about 2.5 in. thick with a friable surface. In December 1995, the surface looked "open" and a fog seal using a CSS1 emulsion diluted with 1,000 gal. of water was applied (0.3 gal./yd^2). This treatment of the rural roadway remained mostly dust free for more than two years.

Three other states (Minnesota, North Carolina, and Maine) were identified in the Vermont agency report (VANR 1999) as having tried ground RAS as a dust control for unpaved surfaces. Minnesota results indicated less dust was generated and the need for reapplication of dust suppressants was reduced. The driving conditions were improved on the unsurfaced roads. A North Carolina contractor was reportedly marketing scrap shingles as low-cost driveway and parking area surface treatment. A contractor in Maine was using tear-off byproducts in a combined mix of RAS, aggregates, and asphalt emulsion to produce a base or subbase material.

Benefits noted for using tear-offs for dust control included that processing the shingles was only 75% of the cost of landfilling, shingle binder bound the aggregate that resulted in less loss of granular surfacing into the ditches, improved lateral control of vehicles, and a smoother, quieter ride.

Hooper and Allen (Ahmed et al. 2009) developed a composite of RAS, RAP, and gravel (10:30:60) as surface mix. This mix was placed and compacted on a series of municipal roads and sprayed with calcium chloride solution. Over two years the composite resisted rutting and erosion.

Soil Improvement

Hooper and Marr (2005) conducted a study to determine the effects of adding RAS to soils on engineering properties. The results showed dependence of improvement was linked to the soil type being modified. The unbound materials used in the study were crushed stone gravel, silty sand, clean sand, and clay. The results showed weak soils such as clay benefited from the addition of 25 mm minus RAS by an improvement in strength. Strong materials such as crushed gravel, showed a loss of strength when RAS was added.

Shrestha et al. (2008) evaluated the use of tear-offs in road base and unpaved gravel roads. The materials in the

TABLE 53
INFLUENCE OF VARYING PERCENTAGES OF MEDIUM-SIZED RAS ON RAS–CKD–SOIL (SP) PROPERTIES

Percent Shingles	Unconfined Compressive Strength, N/mm^3	Splitting Tensile Strength, N/mm^3	% Tensile Strength Improvement Compared with CKD–Soil Only
2.5	1.2	0.13	—
5	1.9	0.25	50
10	2.2	0.30	70
15	1.9	0.30	65
20	1.8	0.30	40

After Ahmed et al. (2009).

study included two sizes of ground RAS: maximum size of the 75 mm and 40% passing the 4.75 mm, 100% passing the 4.75 mm sieve. The five types of aggregates used were crushed limestone, crushed natural gravel with 72% crushed particles, and three recycled concrete aggregates (RCA).

The results showed that the maximum dry density decreased with the addition of RAS, but the decrease was not accompanied by a significant change in the optimum moisture content. The effect on strength was dependent on the initial CBR value of the unmodified aggregate or RCA base. The smaller size RAS (ground) improved the CBR values more than the larger sized RAS. This led to the decision to use only the ground RAS in the remainder of the experimental design. Adding ground RAS to materials with low CBR values improved the strength with the optimum improvement occurring at 5% RAS, after which the strength decreased with increased shingle content. Adding RAS to materials with initially high CBR values (crushed limestone and one RCA) decreased the strength of the mixes. Permeability was relatively unchanged by the addition of the RAS to the base materials with the exception of the crushed limestone. In this case the permeability was noticeably decreased at 5% ground RAS.

General observations were that the higher the fines contents of the base materials, the more influence the RAS had on material properties. Materials that depend strongly on interlocking, angular particles to achieve their properties were adversely influenced by the addition of RAS.

Ahmed et al. (2009) in Ontario, Canada, investigated combining CKD and RAS to improve the properties of fine grained soils. Materials used in the study were CKD, RAS, and soil that was poorly graded (SP). The CKD was used to improve the strength and the RAS was used to improve the tensile strength of the composite soil–CKD. One source of CKD was used with three different sizes of RAS that were a small (passing 2.36 mm sieve), a medium (passing 4.75, but retained on 2.36 mm), and a large (passing 9.5 mm but retained on 4.75 mm). Testing evaluated the compressive and tensile strength, permeability (ASTM D2434), and CBR (soaked, unsoaked). The capillary rise indicating an increase in the frost susceptibility as the capillary water level rise increases was also evaluated.

Results indicated that the soil–CKD (10%)–shingle (medium) compared with soil–CKD mix (Table 53) slightly improved the compressive strength of the mix up to a maximum of 10% RAS, after which the strengths decreased. Significantly improved tensile strength was seen, with the optimum strength occurring at 10% RAS. Results for soil–CKD (10%)–RAS (different sizes) compared with soil–CKD (Table 54) showed that the unconfined compressive strength increased with decreasing size. The tensile strength increased with increasing size of shingle, which was opposite of the compressive strength. CBR testing of soil–CKD–RAS (small), both the soaked and unsoaked, increased in value up to 10% RAS. Unsoaked CBR values for the 10% shingle mix were about 45, compared with soil–CKD CBR value of 20. Soaked CBR values were about 40 compared with 16, respectively. Capillary rise was represented by the time it took for the water to reach a certain height within the sample where long times mean less frost susceptibility. Results showed an increase in time with increased shingle content. Up to 60 min, any size

TABLE 54
INFLUENCE OF VARYING RAS SIZED (10%) ON RAS–CKD–SOIL (SP) PROPERTIES

Shingle Size	Unconfined Compressive Strength, N/mm^3	Splitting Tensile Strength, N/mm^3	% Tensile Strength Improvement Compared with CKD–Soil Only	% Unconfined Compressive Strength Improvement Compared with CKD–Soil Only
Small	2.2	0.24	75	48
Medium	2.1	0.28	67	105
Large	1.7	0.3	41	118

After Ahmed et al. (2009).
Note: estimated values from graphs in report.

of shingle significantly increased the time needed for a given height of capillary rise. After 60 min, the larger the shingle size the slower the rise. Permeability showed no noticeable differences between the soil–CKD mix and soil–CKD (10%)–shingle (small) with various shingle contents or with the same content, but with differing sizes.

The conclusion from the research was that a combination of CKD and RAS improves the properties of silty subgrade soils. Although the CKD increased the compressive strength with increasing percentages, it had little influence on the tensile strength. When RAS was added to the mix, the tensile strength of the soils was significantly improved. The optimum shingle content was 10%. At 10%, the addition of the RAS improved the CBR, tensile strength, and compressive strength compared with the soil–CKD mixes. Larger shingle sizes had more of an influence on the tensile strengths, whereas the small size had the opposite effect. The addition of RAS reduced the frost heave potential while not significantly influencing the permeability,

SPECIFICATIONS

As of 1999, five states had standard specifications for using manufacturing RAS byproducts, generally up to 5% by weight of aggregate, in HMA; Minnesota, Maryland, Georgia, North Carolina, and Indiana. The NAHB Research Center (1999) identified the stakeholders in recycling roofing shingle byproducts as roofers, manufacturers, haulers, recyclers, governments and paving contractors.

Schroer (2005) reported on the Missouri DNR efforts to use tear-offs in HMA applications. The project was a combined effort between DNR, MoDOT, a local recycler, and a paving contractor. The MoDOT specification for RAS in HMA was used for the pilot project. This specification limited the amount of debris to no more than 3% by weight in the byproduct material before introduction into the HMA plant. A separate limit of no more than 1.5% wood was proposed for the specification. Asphalt properties of a virgin asphalt PG64-22 were required for the final HMA. At 5% RAS, the maximum allowable RAS, the contractor was required to use a softer PG58-28. Other (lower) percentages of RAS would require the contractor to submit a proposed job mix formula to MoDOT for consideration.

The CIWMB (2006) fact sheet for RAS contained information on state specifications and standards such as the AASHTO MP15 for asphalt shingle use in HMA. This standard allowed for the use of either pre- or post-consumer shingle byproducts. The AASHTO PP53 was a companion recommended practice. Other specifications identified in this document are summarized in Table 55. Only two specifications (those of Michigan and Brampton in Ontario, Canada) allowed either manufacturer or tear-offs. Other states did not specify the type (Missouri, Ohio).

TABLE 55
SUMMARY OF SPECIFICATIONS

State	Shingle Byproduct	Amount
Georgia	Manufacturing	5%
Maryland	Manufacturing	5%
Michigan	Either	50% recycling specification; does not specifically address RAS in specification
Minnesota	Manufacturing	5%
Missouri	Not specified	5%
New Jersey	Manufacturing	5%
North Carolina	Manufacturing	5%
Ohio	Not specified	Certain percentage
Indiana	Manufacturing	5%
City of Brampton, Ontario	Either	3%

After CIWMB (2006).

Schroer (2007) noted on the subject of regulatory compliance that the recycler and contractor needed to be pro-active and assertive in planning, anticipate agency requirements, use precedents from existing recycling programs as a format, and document adequate market demand to avoid comments about “speculative” stockpiling.

Schultz (2010) recommended the following changes to the current Oregon DOT Standard Specification Section 00745-Hot Mixed Asphalt Concrete (HMAC SP745):

1. Either pre-consumer or tear-off RAS can be used.
2. No more than 5% RAS by total weight of mixture should be allowed. The maximum allowable percentage of asphalt binder replacement (i.e., either RAS or RAP binder) shall be restricted to 20% for base courses and 15% for wearing courses in HMAC containing RAS but not RAP.
3. The maximum allowable percentage of binder replacement from a combination of RAS and RAP should be restricted to 30% for base courses and 25% for wearing courses.
4. Process RAS by grinding at ambient temperature so that 100% of the shredded pieces are less than ½ inch in any dimension and that 90% are less than ⅜ inch in any dimension.
5. A minimum of one sample per 100 tons of RAS shall be obtained and tested for asbestos.
6. Limit deleterious materials such as nails, glass, rubber, soil, brick, tars, paper, plastic, wood chips, metal flashing, etc., to 3.0%, by weight, of the stockpiled RAS as determined on material retained on the 4.75 mm (No. 4) sieve.

7. Limit lighter material such as paper, plastic, and wood to a maximum of 1.5%, by weight, of the stockpiled RAS as determined on material retained on the 4.75 mm (No. 4) sieve.
8. Fine aggregate may be added to the RAS in a quantity not to exceed 4% by weight of RAS to keep the material workable and to prevent conglomeration of the shingle particles in the stockpile.
9. Take the necessary steps to ensure that excessive moisture is not retained in the RAS stockpiles; only allow a maximum of 5% moisture.
10. When RAS is used in conjunction with RAP, no more than 20% reclaimed materials by total weight of mixture should be used.
11. For high traffic facilities with little tolerance for construction disruption, no more than 15% of RAS should be allowed. Restrict the maximum RAS to 30% for base courses and 25% for wearing
12. For HMA mixtures containing only RAS, the amount of asphalt cement in the RAS needs to be established in the mix design.
13. For HMAC mixtures containing RAP and RAS, the RAS shall be added to the RAP and tested to establish the asphalt content of the combined reclaimed materials.
14. Adjustments for RAS content need to be within 1% of the original job mix formula.

New provisional AASHTO specification R2005A-TS-2c (AASHTO 2010) and recommended practice (M2005A-TS-2c) for RAS in HMA were under review (Gevrenov 2007). These provisional standards addressed the need for detailed QC/QA guidance including RAS types, definitions, sources, and sampling. They also included guidance for RAS gradations, addition rates of RAS into HMA, deleterious substances, and methods of sampling and testing.

The draft of R2005-TS-2c (AASHTO 2010) Recommended Practice for Design Considerations when using RASs in new HMA provided recommendations relative to four areas:

1. Design consideration when using RAS in HMA
2. Determining the shingle aggregate gradation
3. Determining the virgin PG and percent of the virgin asphalt binder in new HMA
4. Determine the shingle asphalt binder availability factor.

The shingle asphalt binder availability factor is calculated from the following equation:

$$F_c = \frac{\left(P_{vav} - P_{var}\right)}{\left(P_s\right)\left(P_{sab}\right)}$$

Where:

F_c = shingle asphalt binder availability factor;
P_{vav} = binder content of virgin mix without shingles, %;
P_{var} = design binder content of the new mix asphalt with recycled shingles, %;
P_s = recycled shingle asphalt in the new HMA, %; and
P_{sab} = shingle asphalt binder present in RAS, %.

This draft practice indicated that after 0.75% by weight of asphalt binder contributed by the RAS the virgin asphalt PG grade specified may need to be changed. Because the size of the RAS was expected to influence the amount of binder contributed to the mix by the RAS, the mix design needed to account for the size to be used in the mix. The point of introduction of the RAS into the HMA plant needed to be selected so that damage to the RAS from excess heat was minimized. This needed to be balanced with sufficient heating to soften the RAS binder.

The RAS aggregate gradation should be determined after extraction by either AASHTO TP2 or ASTM D228 (section 13 or 14). The AASHTO method was for the extraction and recovery of the RAS binder. If the binder did not need to be recovered, the ASTM method was recommended, which was the standard for the design consideration when using RASs in new HMA.

The required PG (i.e., critical temperature) for the virgin binder was determined:

$$T_{va} = T_{sb} - \frac{T_{sb} - T_{fbb}}{1 - P_{sb}}$$

Where:

T_{va} = critical temperature of the virgin asphalt binder;
T_{sb} = critical temperature of the shingle asphalt binder;
T_{fbb} = critical temperature of the final blended binder (i.e., desired PG temperature); and
P_{sb} = percentage of shingle asphalt binder present in the final blended binder.

The value of P_{sb} was calculated as:

$$P_{sb} = \frac{F\left(P_s\right)\left(P_{sab}\right)}{\left(P_{fbb}\right)}$$

Where:

P_s = percent of RAS;
P_{sab} = percent of shingle asphalt binder in shingles;
P_{fbb} = percent of final blended binder present in the new HMA; and
F = shingle asphalt binder availability factor determined using

$$F_c = \frac{P_{vav} - P_{var}}{P_s P_{sab}}$$

Where:

F_c = initial estimate of percentage of asphalt in blended mix;
P_{vav} = design binder content of virgin HMA without RAS; and
P_{var} = design binder content of HMA with RAS.

The practice noted that this estimate will result in an overestimate of the critical design temperature of the virgin asphalt.

The Illinois Tollway Congestion Relief Plan memorandum (Kovacs 2010) construction bulletin no. 20-01 was issued in January 2010. This bulletin provided guidelines for the use of tear-off RAS asphalt shingle recycling facility operators. Tear-offs were defined as roofing waste removed from residential buildings with four or fewer housing units. Asbestos testing was required prior to shredding the tear-offs. The document contained training slides for both the recycled shingle supplier and for their sorting personnel.

ENVIRONMENTAL BENEFITS

Krivit (2008) reported that the EPA preliminary assessment of using shingle byproducts would result in an energy savings. For 300,000 to 400,000 tons of shingles recycled each year, an energy savings of between 60 and 80 million KWH per year could be achieved. For the same amount of shingles, the savings in greenhouse gases would be 44 to 50 tons of CO_2 (0.27 to 0.29 lb of CO_2 equivalents per ton of shingles).

BARRIERS

The CIWMB (2006) fact sheet for RAS noted several barriers to the increased use of shingle byproducts in California. The most widely used specifications were either the California DOT (Caltrans) or the Standard Specifications for Public Works Construction (called the Greenbook). Caltrans did not allow shingle byproducts and shingle byproducts were also not allowed in the Greenbook. Work required by Caltrans to use byproducts included laboratory testing, preparation of a draft of Special Provisions, field testing and monitoring of test sections, and finalizing a Special Standard Provision. Work required to alter the Greenbook included the necessary submission by the local government(s) of field and laboratory test results to the Greenbook committee for evaluation. The most promising market at the current time was identified as working through local government public works. In California, the local government public works typically use either Caltrans or the Greenbook, but were free to use any specification of their choosing or to develop their own for local projects using local funds.

Bauman (2005) developed a short list of factors influencing the increased use of shingle byproducts, the anticipated impact of each factor, and the likely outcome for each factor and impact (Table 56). The factors identified as significant to increased usage were byproduct purchasing practices, tear-off disposal practices, byproduct material variability, and application performance.

Bauman (2005) lists the following key lessons learned from the survey on the use of tear-off RAS:

- If recycling is cheaper than disposal, the contractors will do it.
- Successful implementation experiences are needed.
- Highlight the advantages to agencies and contractors. Identify other byproduct generators that can join the effort to promote recycling.

Schroer (2007) identified key barriers to increased use of RAS as the lack of clear industry standards and specifications, inconsistent state regulations, inadequate information and technology transfer, and a lack of national leadership by private industry and government. Schroer noted that separation of the tear-off RAS could be done either at the roofer's job site or at a central processing shingle recycling facility. The author suggested that there be a required certification to document the chain of custody, a pre-approved customer list developed of certified suppliers, and that a permanent file of all supply certificates be maintained.

Krivit (2007) prepared a best practices guide for roofing contractors to facilitate their ability to recycle tear-offs. Best practices focus on three major categories:

1. Development of a supply QC/QA program.
2. Optimize operations to produce RAS that meets or exceeds specifications for end markets.
3. Development of a marketing plan based on multiple outlets.

The suggested the best practice for the roofer was to layer the tear-off materials with the RAS on the bottom of the dumpster, followed by the roofing felt, then wood materials.

Krivit (2008) developed a white paper to provide a bridge between technical research and development efforts and larger policy options for improved use of shingle byproducts. Phase I of the study for the Solid Waste Management Coordinating Board and the Minnesota Pollution Control Agency identified asphalt shingles as a high priority commodity that could be potentially recovered from the construction, demolition, and industrial waste stream as it comprises up to 15.2% of total waste sorted. In 2008, the Solid Waste Management Coordinating Board consolidated its new and post-consumer shingle recycling efforts into a comprehensive project (Phase II of the study).

A history of the development of a recycling market for byproducts for RAS was included (Table 57). Changing

TABLE 56
FACTORS THAT ARE CONSIDERED AS INFLUENTIAL FOR INCREASED USE OF TEAR-OFF RAS

Factor	Impact	Outcome
Purchasing Practices	Making institutional (i.e., agency) buyers aware of post-consumer content products and its performance against competitors is a key factor in entering the market. Worth noting: Mass Highway has not seen post-industrial content being used in pavement, although the specification allows for it. The highway spec. does not currently allow for post-consumer content in base or surface courses.	Highly significant. The next section focuses on the single largest buyer.
How Material Is De-installed	Unlike other types of renovation, this is largely a one material (or two material) job. Source separation is relatively easy. If a laborer can tarp area to minimize yard waste and prevent trash from going into the load, all other contaminants (ice and water shield, shingle wrapping) are removed by MRF. The rest is ground into dust.	Significant. Source separation is easy, but this corner of the industry is very traditional, so change will come slowly.
The Complexity of the Material	Shingles are composed of asphalt, stone dust, an organic felt or fiberglass backing, and adhesive. Unfortunately, sorting shingles into product types so that they can be used as feedstock for new shingles is not cost-effective.	Significant for manufacturers accepting the material. This is a longer-term consideration.
Predictable Supply of Feedstock	Established shingle recyclers have their own markets and are able to aggregate volume in order to supply companies with the needed volume. Many aggregate companies also produce pavement and have a contracting division, which allows them to leverage cost savings for state jobs. Longer term, shingle recycling becomes more the rule than the exception, and manufacturers will have the confidence to invest in post-consumer feedstock processing.	Less significant (but highly significant for shingle manufacturers). As long as the manufacturing process can adjust for volumes of post-consumer material in its “recipe,” this does not have to be a show stopper.
Performance of Post-consumer Material	Shingles generally last 20 years or more. Weather exposure decreases stone content and increases brittleness. Studies showed that the binding attribute of shingles was not diminished with time, although elasticity is (and is important for pavement).	Not significant in the usability of the resulting feedstock. “Recipe adjustments” have accommodated the effects of aging.

After Bauman (2005).
MRF = material recovery facilities.

the specification from “job-by-job approval” to “use unless explicitly prohibited” significantly increased the use of shingle byproducts. Once contractors started using RAS, the higher RAS binder percentage in the total binder resulted in premature cracking of one project, hence the 2006 amendment.

Phase 2 was an outreach project designed to address the information needs of the private contractors and local agencies. This phase developed a guide to the use of RAS in road construction in 2002, which was a joint effort by MnDOT and the Minnesota Office of Environmental Assistance (now an office in the Minnesota Pollution Control Agency). This phase traced the lack of locally available RAS to a limitation on the use of shingle byproducts and led to the next phase of research into using tear-off RAS, which was significantly more available.

Phase 3 was a co-sponsored research project between MnDOT and Recycled Materials Resource Center (RMRC) to investigate the use of RAS in other applications such as a dust control material, unbound aggregate supplement to base, and in a 5% concentration in HMA.

TABLE 57
HISTORY OF SHINGLE SCRAP RECYCLING SPECIFICATION DEVELOPMENT

Approximate Date	Activity
1990–1996	MnDOT conducts original Phase 1 research projects
1996	MnDOT adopts first manufacturer’s shingle scrap materials specification for use on a job-by-job approval by the project engineer required basis
1998 (circa)	MnDOT develops draft guideline on file with Bituminous Engineer
2003	MnDOT amends specification to allow HMA producers the discretion to use manufacturer’s shingle scrap by changing approval process from job-by-job approval to allow the use unless explicitly prohibited by the project engineer
2006	MnDOT amends specification to require a minimum of 70% virgin asphalt as the percent of the total binder within higher volume highways
2007	MnDOT develops special provision, mix design specifications allowing tear-off RAS in HMA according to the project QC/QA specifications

After Krivit (2008).

SUMMARY OF ROOFING SHINGLE INFORMATION

List of Candidate Byproducts

The list of the most commonly researched and used byproducts included:

- Roofing manufacturer,
- Tear-off shingles, and
- Built-up roofing.

Test Procedures

The test methods found in the literature and survey responses are shown in Table 58.

Material Preparation and Byproduct Quality Control

The following post-processing and QC points needed to be considered:

- Grinding of RAS could be easier and minimize agglomeration of particles in colder weather conditions.
- Shingles could be ground when needed rather than stockpiled for long periods of time.
- Sand (up to 4%) could be added during the grinding process to minimize agglomeration.
- Water may be needed to cool the cutting heads:
  - Moisture content determinations of the RAS stockpiles were needed before use.
- Metals needed to be removed as the material is stockpiled.
- Individual stockpiles could be used for each type of RAS byproduct.
- Asbestos content testing may be needed for tear-off RAS. This was not a concern for current manufacturing byproducts.

Materials Handling Issues

The following materials handling points needed to be considered:

- Dust mitigation needed to be addressed during RAS grinding operations.
- Recycling operations might require state and/or local permits.

Transformation of Marginal Materials

Recent research focused on the use of RAS as a means of improving the stability of poor soils and as a method of dust control.

Soil Improvement

The use of 5% finer ground RAS significantly improved the CBR values of soils with initially low values. Improvements were seen in CBR, compressive strengths, and especially tensile strengths of the modified soils. The most improvement was seen when the soil had high fines content.

A combination of RAS and fly ash worked well with silty subgrade soils. RAS was not a good choice for use with base materials with initially higher CBR value (e.g., crushed limestone).

Dust Control

In one study, ground tear-offs were spread on a gravel base and mixed with a motor grader resulting in about 2.5 in. of surface mix, which was somewhat friable. An emulsion fog seal was used to preserve the surface. Another three states used similar applications to reduce dust and provide improved driving conditions.

TABLE 58
ASTM AND AASHTO TEST METHODS USED TO EVALUATE ROOFING SHINGLE BYPRODUCTS AND HIGHWAY APPLICATION PRODUCTS

Test Method	Title
AASHTO TP2	Method for the quantitative extraction and recovery of asphalt binder from hot mix asphalt (HMA)
AASHTO T321	Standard test method for determining the resilient modulus of bituminous mixtures by indirect tension
AASHTO T170	Standard method of test for recovery of asphalt binder from solution by Abson method
ASTM D226	Standard specification for asphalt saturated organic felt used in roofing and waterproofing
ASTM D312	Standard specification for asphalt used in roofing
ASTM D450	Standard specification for coal tar pitch used in roofing, damp proofing, and waterproofing
ASTM D2178	Standard specification for asphalt glass felt used in roofing and waterproofing
ASTM D4990	Standard specification for coal tar glass felt used in roofing and waterproofing
ASTM D2434	Standard test method for permeability of granular soils (constant head)
ASTM D228	Standard test methods for sampling, testing, and analysis of asphalt roll roofing, cap sheets, and shingles used in roofing and waterproofing

Design Adaptations

The following points needed to be considered during the design processes:

- Any sand added to the RAS during grinding needed to be considered in mix designs.
- Moisture contents of RAS stockpiles needed to be accounted for when used to stabilize soils.
- The use of RAS increased the combined binder PG grade, implying that a lower PG grade upper temperature and possibly a lower PG grade cold temperature could be required for the virgin binder:
  - RAS increased the viscosity and stiffness.
  - Changes in binder properties owing to the addition of 5% RAS were similar to changes seen when using 30% to 40% RAP only (Schultz 2010).

Construction Issues

The following points needed be considered in the construction of projects using RAS byproducts:

- Moisture content of RAS could require longer dwell times in HMA plants.
- HMA with RAS showed some tendency to be tender during rolling:
  - Rolling occasionally needed to be delayed.

Failures, Causes, and Lessons Learned

No significant major experiences were reported in the literature or in the agency surveys.

Barriers

The following barriers were found in the literature and the survey responses:

- Lack of documented application performance
- Lack of material specifications
- Lack of agency experience, particularly with tear-offs
- Potential for additional testing for asbestos when using tear-offs
- Additional testing of RAS stockpiles, particularly for tear-offs
- Increased testing for QC programs.

Costs

The following information was found with regard to the costs associated with using RAS in highway applications:

- Tipping fees varied widely across the country. Based on material values and operating costs in the early 2000s, the most commonly reported tipping fee was about $50/ton, with the cost of grinding, sorting, testing, housing, regulation, and administration about $40/ton.
  - The cost of processing RAS accounted for 75% to 80% of the average tipping fees.
- Organic-backed manufacturer RAS and tear-offs provided a cost savings of about 5% per ton of HMA at 4% RAS content (Brock 2007). Fiberglass-backed RAS produced a savings of about 3% per ton of asphalt.
  - Difference in cost savings was the result of the higher asphalt content used for the organic (paper)-backed shingles that are prevalent in the older shingle products.
- Recycling equipment maintenance costs were a significant factor in the costs of operation.

Gaps

The following gaps were found in the literature and survey responses:

- Education and training for agencies were needed for agencies and contractors (technology transfer).
  - A comparison of agency responses to information on specifications suggested it was unclear if agencies differentiated between paper-backed and organic-backed manufactured byproducts. Because these byproducts have different materials properties, agencies and contractors might consider this when developing specifications and QC/QA programs.
- RAS specifications for individual byproducts and hybrid application materials were needed.
- Improved laboratory standards were needed for sample preparation and HMA testing with RAS, RAP, and/or RAS/RAP mixes.
  - Adaptations for asphalt content by ignition oven, binder extraction methods, and QC/QA testing procedures were needed when more than one recycled product was used.

CHAPTER THREE

WASTE PAPER MILL SLUDGE

BACKGROUND

Waste paper mill sludge is the byproduct of the paper production process. The major byproducts from the pulp and paper waste stream are (Bird and Talberth 2008):

- Waste water treatment plant (WWTP) residuals
- Boiler and furnace ash
- Causticizing residuals.

The primary residuals, approximately 40% of the WWTP, including de-inking residuals (paper recycling operations), consisting mostly of processed wood fiber and inorganic or mineral materials (e.g., kaolin clay, $CaCO_3$, and TiO_2). Secondary (activated waste sludge) is mostly bacterial biomass (nonpathogenic) and makes up about 1% of the WWTP residuals. Dewatering the WWTP residual produces a byproduct of between 30% and 40% solids and once dewatered, the material is not considered hazardous as defined by RCRA. A few facilities can dry the WWTP to produce a byproduct with 70% to 95% solids. Chlorinated organic compounds tend to concentrate in the solids that can be an environmental concern.

Boiler and furnace ash (energy recovery) is produced from wood, coal, or a combination of wood, coal, and other solid fuels (most common) used in the pulp and paper processes. Causticizing residues have three components: lime mud, green liquor dregs, and slaker grit. Lime mud (calcium carbonate and water) is burned in a lime kiln to regenerate the byproduct to lime (CaO). This byproduct may also contain unreacted calcium hydroxide, unslaked calcium oxide, magnesium, and sodium. The lime mud is about 70% to 80% solids.

Green liquor dregs are composed of nonreactive and insoluble materials remaining after the inorganic process chemicals (smelt) from the recovery furnace are mixed with water. The dregs are removed by gravity clarification, resulting in a byproduct with 45% to 55% solids. The major components are carbonaceous material along with calcium, sodium, magnesium, and sulfur.

Slaker grits are produced by mixing lime (burned or unburned) with the green liquor dregs and contain between 70% and 80% solids. The solid portion is approximately 50% fibers and up to 50% minerals with a pH about 12, which is neutralized before disposal. The solids can also contain titanium oxide and calcium sulfate.

USAGE AND PRODUCTION

United States

Production in the United States generates about 16.5 million dry tons of solid wastes and byproduct solids that are used and/or disposed of in a number of ways (Table 59). There are about 6.1 million dry tons of WWTP residuals produced annually. For the 104 U.S. mills, this works out to an average byproduct production of about 28,660 dry tons per year per plant. However, WWTP rates of production vary widely between mills, ranging from 31 to 309 pounds per ton of pulp produced. Causticizing residuals production, as of 1995, was 1.8 million dry tons per year and consisted of lime mud (59%), green liquor dregs (28%), and slaker grit (14%).

The Wisconsin Department of Natural Resources (DNR) (2010) summarized the beneficial usage of paper sludge byproducts. These byproducts were regulated under the wastewater program, so that there were no generators requesting initial or annual certification under DNR Chapter NR538. The wastewater program only accounted for a portion of the total pulp and paper processing waste either generated or used beneficially. One recycler that received paper mill sludge from a group of mills reported the annual amount of sludge processed by the facility as approximately 1.2 million tons of which approximately 445,000 tons were beneficially used (38% of sludge).

The Wisconsin Paper Council reported to the DNR that about 1.73 million tons of paper mill sludge was produced annually in the state, with about 1.15 million tons being beneficially used (66%). These numbers included material land spread and used in energy recovery at the facilities.

European

Dunster et al. (2005) noted that European pulp and paper mills produce more than 1 million tons per year from recycling operations. Paper sludge was thought to be a significant resource but not without significant modifications. The major post-processing needed was dewatering. Waste paper sludge was considered to have potential as a value-added component for lightweight concrete products and nonaerated blocks. Limited research showed it reduced density but also reduced compressive strength. It was suggested that the usefulness could be improved with chemical bonding to form

TABLE 59
DISPOSAL OF WASTE PAPER SLUDGE BYPRODUCTS

Use	Percent of Byproduct per Use, %					
	WWTP residuals		Boiler and furnace ash	Causticizing residuals		
	U.S.	Europe		Lime mud	Green liquor dregs	Slaker grits
Landfill or Lagoon	50	10	65	70	95	91
Land Application	10	40	10	9	3	6
Incineration for Energy Production	20	30	—	—	—	—
Reuse in Mill				1	0	3
Other Beneficial Use	10	20	25	2	2	1

After Bird and Talberth (2008).

aggregates. The authors recommended examination of the feasibility of adapting, binding, or otherwise modifying the paper sludge or paper sludge ash as an aggregate replacement.

PHYSICAL AND CHEMICAL PROPERTIES

Wastewater Treatment Plant

Little was found in the literature with regard to the material or chemical properties of the WWTP residuals. IRC (2010) noted the WWTP can provide paper fiber content that will reduce the hydraulic conductivity (permeability) of a treated soil.

Lime Mud

The University of Maine publication *Beneficial Use of Solid Waste in Maine* (2006) provided a summary of lime mud properties reported in the literature, which only provided limited information. Particle sizes reported in previous research for Wisconsin mill paper sludge showed that the lime mud had a 94% $CaCO_3$ content, with 100% passing the 0.15 mm sieve. A subsequent study reported that only 88% passed the 0.15 mm sieve. When the lime mud was taken from the dewatering storage facility the moisture content was about 17%, with a bulk density of 66.55 lb/ft^3. When used in soil modification, the sodium levels increased with the addition of lime mud. The magnesium levels were raised at a slower rate than when using limestone, whereas the calcium level rose faster than with limestone. A 1993 study by Dorris evaluated the longest linear dimension using an image analysis technique. The results generally showed that the lime mud particles were larger and more spherical than hydrated lime but were less reactive.

TABLE 60
TYPICAL CONCENTRATIONS OF NUTRIENTS AND MINERALS IN LIME MUD FROM PULP AND PAPER MILLS COMPARED WITH AGRICULTURAL LIME

Minerals	Lime Mud*	Agricultural Lime
Nitrogen, %	0–0.2	0.01
P_2O_5, %	1–1.2	0.06
K_2O, %	0.2–1.4**	0.13
Calcium, %	28–50**	31
CCE, %	91–100	NA
Magnesium, %	0.2–1.0**	5
Sulfur, ppm	0.19***	NA
Boron, ppm	7.91***	NA
Copper, ppm	3–66	10
Zinc, ppm	4–93	113

After IRC (2010).
*Data from Morris et al. (2000) except where noted.
**Data from South Carolina mills. Camberato et al. (1997).
***Data from Alabama mills. Muse and Mitchell (1995).
NA = not available.

Clemson University (2010) research showed that although lime mud reacts faster than agricultural lime, it was not typically used because of the need to dredge from holding ponds, dry the material, and crush it so that it can be spread with conventional dry lime spreaders.

IRC (2010) reported that as long as lime mud had a beneficial use it was not considered a hazardous material by the Georgia DNR. Typical mineral and trace metal contents for lime mud are shown in Tables 60 and 61. Moisture contents of the lime mud were typically around 30%, but could be as high as 50%, which were difficult to spread for soil stabilization. The application rates needed to be adjusted for water content. The pH was also found to increase with increasing lime mud concentrations, hence its usefulness for soil stabilization.

TABLE 61
TRACE METAL CONTENT IN LIME MUD

Minerals	Lime Mud*	Agricultural Lime
Arsenic, ppm	1.71**	<1–3
Cadmium, ppm	bd–0.5	<0.1–1.1
Lead, ppm	bd	1.3–130
Mercury, ppm	<0.05**	<0.01–0.02
Molybdenum, ppm	bd–0.1	0.3–0.5
Nickel, ppm	3.3–71	7.0–17
Selenium, ppm	bd–7.6	<1

After IRC (2010).
*Data from Morris et al. (2000) except where noted.
**One sample from a Georgia mill.
***Data from McBride and Spiers (2001).
bd = below detection.

TABLE 62
PAPER PROCESSING BOILER ASH USES IN HIGHWAY APPLICATIONS

Market or Beneficial Uses	Description
Manufactured Soil Component	Wood ash is more appropriate for land application. Ashes provide alkalinity to soil.
Cement and Brick Feedstock	Boiler ash from wood and WWTP residues is suitable for cement and brick manufacture.
Concrete Additive	Coal fly ash is used as an additive in concrete for highways and other applications. A state DOT approved use of coal wood fly ash for use in concrete after short- and long-term evaluation of the product. With wood fly ash added, concrete is stronger, more durable, more resistant to water erosion in saltwater conditions, and is less expensive. Coal wood bottom ash is used as aggregate in concrete blocks.
Flowable Fill (CLSM)	CLSM is a self-compacting soil replacement and has become a popular material for projects such as structural fill, foundation support, pavement base, and conduit bedding.
Soil Stabilization	Can be used as potting or liming agent
Earthen Construction	Boiler ash may increase the strength of the structure if it is cementitious.
Asphalt Aggregate/Road Building Component	Coal or wood bottom ash is used as aggregate in asphalt mixes.

After Bird and Talberth (2008).
CLSM = controlled low strength material.

APPLICATIONS

Applications for the beneficial reuse of WWTP residuals include use in clinker production, as a cement additive, and in roadbed construction, soil improvement, and erosion control. WWTP has also been preliminarily investigated in the production of synthetic aggregates. The basic raw materials in WWTP are consistent with those traditionally used in cement clinker production. Early research suggests that the wood fiber content can potentially serve as a concrete admixture to potentially improve durability, pumpability, and salt-scaling resistance while reducing shrinkage cracking. However, the concrete may need a high range water reducer to mitigate an increase in water demand and loss of compressive strength. When used in roadbed, soil improvement, and erosion control, the WWTP needs to be post-process-treated, otherwise trace amounts of heavy metals may not meet soil environmental standards. Synthetic lightweight aggregates can be produced by mixing with fly ash and pelletizing in a rotary kiln.

Boiler ash, like other burned ash byproducts (e.g., fly ash and boiler ash) can be used in road construction and concrete brick manufacture (Table 62). As with the other byproducts, the physical and chemical properties are dependent on fuel source. Significant differences have been noted in dioxin and furan levels between ash from inland mills and ash from salt-laden coastal mill fuels.

Causticizing residuals have been used for soil stabilization and erosion control. The potential uses identified by Bird and Talberth (2008) are shown in Table 63.

Cement and Concrete

Vegas et al. (2006) reported that Spain produced about 441,000 tons of paper mill sludge per year, which would yield about 165,400 tons a year of pozzolanic material. The paper mill sludge used in the study consisted mainly of calcite, kaolinite, talc, and other philosilicates (illite, chlorite). There

TABLE 63
PAPER PROCESSING CAUSTICIZING RESIDUAL USES IN HIGHWAY APPLICATIONS

Market or Beneficial Uses	Description
Cement and Brick Feedstock	The basic raw materials required to make cement are calcium, silicon, aluminum, and iron. Causticizing materials have high percentages of calcium, aluminum, and iron.
Manufactured Soil Ingredient	Causticizing residuals provide lime to soil.
Soil Stabilization/Earthen Construction	Lime slaker grits have been used as an additive.
Road Dust Control	Lime slaker grits have also been shown to be effective as a dust suppressant on unpaved roads.
Asphalt Additive	Lime mud, lime slaker grits, and green liquor dregs have been used successfully as a substitute for fine aggregate in roads.

After Bird and Talberth (2008).

was a significant kaolinite content (20.83%) that is the precursor of reactive metakaolin, which can be obtained under certain temperature and kiln time conditions. Typically, higher kaolinite content resulted in a more reactive calcined product.

The study evaluated a blend of 90% cement and 10% calcined paper sludge. Calcined materials were produced using three temperatures (700°C, 750°C, and 800°C) and one of two kiln times (2 or 5 h) and ground to a maximum particle size of 0.045 mm before use in the cement mixtures. Results showed that the pozzolanic activity declined with increasing calcination so the optimum activation of the paper mill waste was found to be achieved with calcining for 2 h at 700°C. Initial set times were 127.5 min for the control and 97.5 min for the blend.

Science Daily (2009) reported research in Portugal that showed pulp waste could be useful in cement production. The preliminary research evaluated clinkers made with 0.13% and 0.25% grits and dregs and compared them with conventional clinkers. Gas emissions measured during clinker production showed no significant effect as a result of including the paper byproducts in production. This research used the process as more of a disposal process rather than clinker enhancement.

Hot Mix Asphalt

Torres (2007) reported on research conducted by the Forest Products Research and Development Institute of the Department of Science and Technology (FPRIDI-DOST), which investigated the use of paper mill sludge in stone matrix asphalt. The dried, ground, and sieved sludge material was used as the fiber additive. The processed sludge was mixed with aggregates and asphalts and then used to prepare standard Marshall mix design samples. The results showed that at between 5% and 6% asphalt, mixtures with 0.3% to 0.5% paper mill sludge would provide mixes that would meet the requirements of the stone matrix asphalt for both medium and high traffic level roadways. Successful implementation of the post-processing of the sludge could provide a beneficial use for 92,600 tons of sludge that is currently landfilled.

AGENCY SURVEY RESULTS

Only Kentucky reported they had used paper pulp or lime mud in HMA applications. No comments were provided on its experiences.

SUMMARY OF WASTE PAPER SLUDGE INFORMATION

List of Candidate Byproducts

The list of the most commonly researched and used byproducts include:

- WWTP residuals
- Boiler and furnace ash
- Causticizing residuals.

About 50% of these byproducts were used in land application, for energy production (incineration), or landfilled. There had been limited research for use in highway applications and only one agency reported using this byproduct.

Potential future use of these byproducts will likely focus on soil modification (lime mud), cement or concrete additives, or aggregate replacement (bottom ash).

Test Procedures

No specific test methods were cited in the literature for using this byproduct in highway applications. It is anticipated that traditional environmental (leaching), material (physical, chemical), and application test methods would be used.

SUMMARY OF OTHER TOPICS

There was too little usage in highway applications to provide information for the following topics:

- Materials Preparation and Byproduct Quality Control
- Materials Handling Concerns
- Design Adaptations
- Construction Concerns
- Failures, Causes, and Lessons Learned
- Barriers
- Costs
- Gaps.

CHAPTER FOUR

FOUNDRY SANDS

BACKGROUND

Foundry sand is a uniformly graded, high-quality sand byproduct from the ferrous and nonferrous metal casting industry (FIRST 2004a). The metal casting industry uses the foundry sand in two ways. The first is as a molding material to form the external shape of the cast part. The second is used as a core material to fill the internal void space in products such as engine blocks. Because sand grains do not naturally adhere to each other to hold the desired mold shape, binders are added to the sand. Spent (recycled) foundry sand (RFS) can include other materials from foundry processes such as cleaning and grinding operations, slag, and dust collector equipment (i.e., bag houses) (Partridge and Alleman 1998).

Binder systems can be either clay-bonded systems (green sand) or chemically bonded systems (resin sands) (FIRST 2004a). Partridge and Alleman (1998) summarized the types of binders used in various types of casting operations (Table 64). Green sands are used to produce about 90% of the casting volume in the United States and consist of 85% to 95% silica, 4% to 10% bentonite clay, 2% to 10% carbonaceous additive, and 2% to 5% water. The carbon content gives the sand a black color. Resin sands are used in core making, where high strengths are needed to withstand the heat of the molten metal and in mold making. Most of the chemical binders consist of an organic binder (e.g., oil, cereal, and wood proteins; Hughes 2002) that is activated by a catalyst, although some systems use an inorganic binder such as portland cement or sodium silicate. The most common chemical binder systems are phenolic-urethanes, epoxy-resins, furfyl alcohol, and sodium silicates (FIRST 2004a). The resin sands tend to be somewhat coarser in texture than the green sands.

Additional information can be found at the following websites:

- American Foundry Society: www.afsinc.org
- Recycled Materials Resource Center (RMRC): www.rmrc.unh.edu/
- Turner–Fairbanks Highway Research Center (TFHRC): http://www.fhwa.dot.gov/research/tfhrc/.

Most foundries have two sand systems. One system is for external modeling lines and a second one for feeding the internal core lines. After the metal is poured and the cast product is cooled, the green sand is shaken off of the part, recovered, and reconditioned for reuse in the molding process. Used cores are reclaimed during the cooling and shaking processes. The reclaimed material is crushed and reintroduced into the green sand systems to replace a portion of the sand lost in the process. Broken and/or excess cores or those that do not break down when crushed are discarded. The flow chart for a typical foundry is shown in Figure 12. Examples of amount of typical individual byproducts by the molding type are shown in Table 65.

It may be important to separate the sand streams at the foundry because of the different material characteristics needed for external and core molding. These sands may be contaminated with metal and/or large chunks of burned cores, referred to as core butts, which will need further crushing, separation, and screening before recycling.

COSTS

Bhat and Lovell (1997) estimated the in-place cost of a flowable fill at around \$40/yd^3, which was considerably higher than the cost of conventional soil backfill. Assuming the cost of cementitious material (portland cement and fly ash) to be \$60/ton, the cost of sand to be \$4/ton, the combined cost of the fill would be \$8.64/ton. If the clean sand is replaced by RFS at a cost of \$1.50/ton but requires about 50% more cement, the cost of the fill could be reduced by 25% to \$6.44/ton.

Transportation costs were generally the highest cost factor in recycling foundry sands (FIRST 2004a). Hughes (2002) noted that RFS consortiums generated significant cost savings for small to medium sized foundries. For example, a recovery facility was established in 1985 to manage the RFS from 33 iron, brass, and steel foundries in Pennsylvania. This consortium accepted nonhazardous foundry sand, slag, refractories, and dust from foundries within 100 miles of its land fill. The facility charged a fee for each haul that was considerably lower than the average statewide tipping fee of \$35 per ton. The use of a recycling facility was estimated to save the foundries more than \$15 million in tipping fees since the monofill began operation in 1990. About 75% of the RFS was recycled for use in HMA. The remaining 25% of the waste stream was comprised of metal, refractory, core butts, and slag, which are diverted to other recycling markets.

TABLE 64
SUMMARY OF FOUNDRY SAND BINDER TYPES AS A FUNCTION OF THE TYPE OF CASTING TYPE

Type	Name	Binders and Additives
Inorganic Option	Green sand	Clays, water, starch, and sea coral
	Alumina phosphate	Aluminum phosphate resin and metal oxide hardeners
Cold Set/No-Bake Options	Furan	Furfural alcohol resins, urea, phenol, and aryl sulfonic acids
	Phenolic urethane	Phenol formaldehyde resin, isocyanates, and liquid amines
	Sodium silicate	Liquid sodium silicate and liquid organic ester
Cold Box Options	Phenolic urethane	Phenol formaldehyde resin, polymeric isocyanate, and gaseous amine
	Silicate-CO_2	Liquid sodium silicate, coal dust, clays, and CO_2 gas
Heat Activated Options	Hot box	Furfural alcohol or phenolic resin, urea, formaldehyde, and acid catalyst
	Shell molding	Phenol formaldehyde resins, calcium stearate, Vinsol, iron oxide, and hexamethylene tetra-amine
	Air set	Various oil resins
	Core oil	Unsaturated oil resins, oxygen sources, and solvents

Partridge and Alleman (1998).

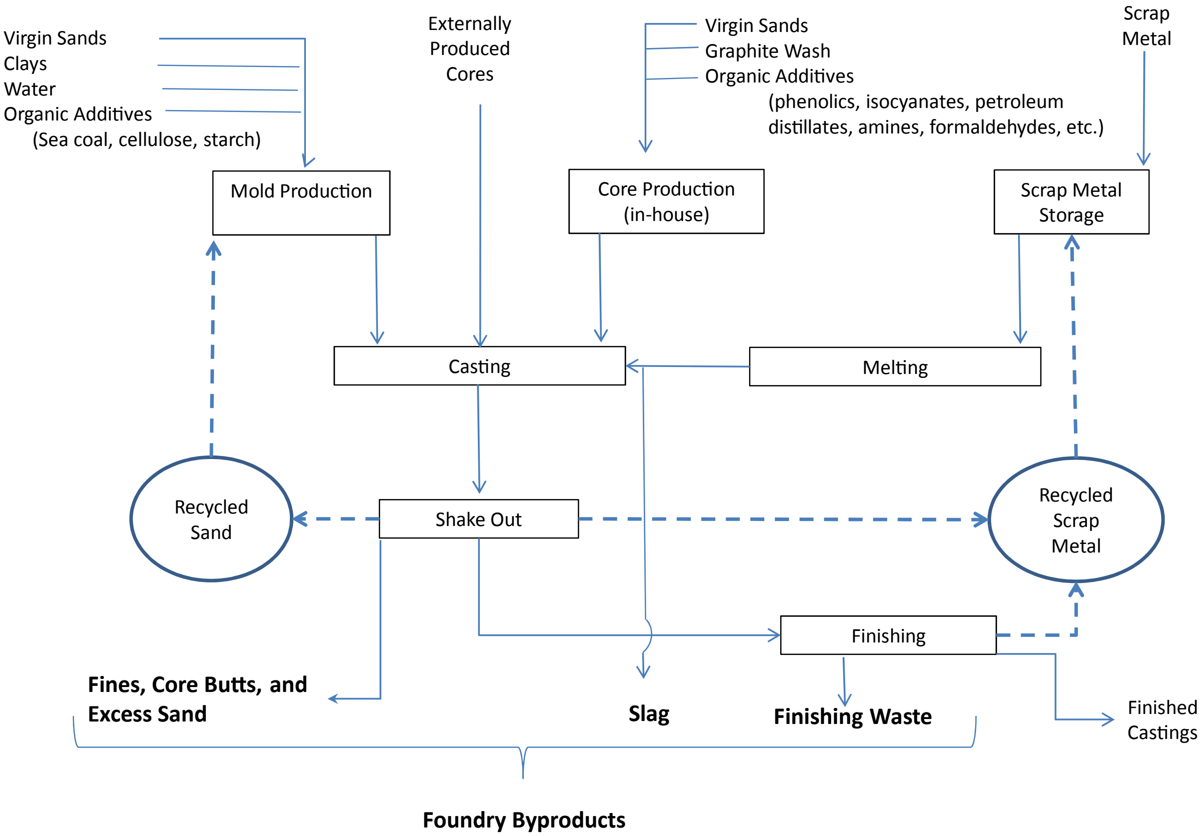


FIGURE 12 Flow chart for the generation of foundry sand byproducts (after Partridge and Alleman 1998).

TABLE 65
ESTIMATED POUNDS OF FOUNDRY WASTER PER TON OF METAL CASTING

Waste Type	Foundry Type					
	Malleable	Ductile iron	Gray iron	Steel	Aluminum	Brass and bronze
Refractories	40	50	80	140	20	40
System Sand	1,250	2,190	670	2,790	280	100
Core Sand	310	100	30	550	1,370	140
Cleaning Room Waste	60	90	80	270	20	30
Slag	100	400	220	350	—	—
Coke Ash	—	60			—	—
Dust Collector Discharge	20	—	190	30	—	—
Miscellaneous	2	—	110	5	5	5
Totals	1,785	2,890	1,380	4,135	1,695	315

After Bhat and Lovell (1997).

FIGURE 13 The ten states with major sources of recycled foundry sand (dark shading) (after FIRST 2004a).

USAGE AND PRODUCTION

There are approximately 2,300 foundries spread throughout the United States; each state has some form of foundry industry (IRC 2010). Figure 13 shows the top ten foundry production states in the United States. Most of the foundry production is centered around the Great Lakes and in both Texas and California (FIRST 2004a).

Foundries typically send about 28.2% of their spent foundry sand to beneficial reuse programs (IRC 2010). The uses for different spent foundry sands are shown in Table 66.

TABLE 66
TYPICAL REUSES FOR RFS

Primary Material	Primary Application	Secondary Application
Ferrous Foundry Sands	Structural fill	Granular base
Aluminum Foundry Sands	Cement manufacturing	Granular base

After IRC (2010).

Physical and Chemical Properties

The original, pre-consumer foundry sand properties are shown in Table 67 (FIRST 2004b). Pre-consumer foundry sand can meet the requirements of the Unified Soil Classification System as SP, SM, or SP-SM, and by the AASHTO classification system for A-3, A-2, or A-2-4. Foundry sands are typically nonplastic or low plasticity sand with a silt or clay content ranging from 0% to 12%. Foundry sands with 6% to 10% clay typically have a liquid limit greater than 20% and a plastic index (PI) greater than 2.

Typical physical properties of RFS and natural sands were reported by Bhat and Lovell (1997) in Table 68. The RFS median particle size (d_{50}) was about half of that for river sand used in the study and the fineness modulus was between 40% and 50% smaller. The water content varied substantially. The LOI was also variable and significantly larger for the RFS compared with the pre-consumer foundry sand. The ion concentration in the leachate was much greater in the RFS compared with either the river sand or the pre-consumer foundry sand. The RFS occasionally had a higher maximum void ratio ($e_{\max}$) and lower minimum void ratio ($e_{\min}$) than the river sand used for comparison. The maximum and minimum dry unit weight and specific gravities were somewhat lower for the RFS than for the control river sand. The water absorption of the RFS can exhibit a wide range of characteristics; this was related to the amount of moisture held by the material.

Engineering Properties

Foundry sands (pre-consumer) without clay typically have internal friction angles between 30° and 35° as determined with direct shear testing (FIRST 2004b; Tables 69 and 70).

TABLE 67
TYPICAL PHYSICAL PROPERTIES OF FOUNDRY SAND

Property	Pre-Consumer Foundry Sand (FIRST 2004a)			Spent Foundry Sand (TFHRC 2010)
	ASTM standard	Foundry sand with clay (5%) FS#1	Foundry sand without clay FS#2	
Bulk Density, lb/ft^3	C29	60–70	80–90	—
Moisture Content, %	D2216	3–5	0.5–2%	0.1 to 10.1
Specific Gravity	D854	2.5–2.7	2.6–2.8	2.30 to 2.55
Dry Density, pcf	D698 Standard Proctor	110 to 115	100 to 110	—
Water Capacity, absorption	ASTM C128	—	—	0.45
Optimum Moisture Content, %	D69	8 to 12	8 to 10	—
Permeability Coefficient, cm/s	D2434 AASHTO T215	10^{-3} to 10^{-7}	10^{-2} to 10^{-6}	10^{-3} to 10^{-6}
Plastic Limit/Plastic Index	ASTM D2434 AASHTO T90	—	—	Non-plastic

FIRST (2004b); RMRC (2009); TFHRC (2010).

TABLE 68
PHYSICAL PROPERTIES OF RFS

Property		Material				
		River sand	Pre-consumer foundry sand	RFS		
				Source 1	Source 2	Source 3
d_{50}, mm		0.75	0.32	0.36	0.39	0.26
Coefficient of Uniformity		2.83	2.24	2.41	6.3	5.0
Fineness Modulus		2.98	1.50	1.57	1.78	1.38
Water Content, %		0.5	0.25	0.9	10.4	1.3
Loss on Ignition, %		6.0	0.1	3.8	7.8	2.1
Ion Concentration in Leachate, mg/L	Cl^{-1}	NA	NA	17.6	60	9.4
	SO_4^{-2}	NA	NA	63.9	340.2	120.9
e_{max}		0.69	—	0.91	1.78	1.01
e_{min}		0.45	—	0.73	1.06	0.67
γ_{dmax}, lb/ft^3		118	—	94	75	95
γ_{dmin}, lb/ft^3		101	—	85	55	79
Specific Gravity		2.69	2.66	2.53	2.42	2.50
Bulk Specific Gravity, SSD		2.62	2.64	2.48	2.25	2.45
Water Absorption, %		1.6	0.5	1.5	5.5	1.6

After Bhat and Lovell (1997).
NA = not applicable. — = indicates no data.

For pre-consumer foundry sands with sands, the angle of internal friction is from 32° to 41° with cohesion values from 0.6 to 1.82 psi. Post-consumer foundry sand engineering properties reported on the TFHRC website (2010) show similar, but somewhat different, ranges of values. TFHRC reports a very good resistance to abrasion but a wide range of resistance to freeze/thaw damage ($MgSO_4$ soundness).

Environmentally Related Properties

One or more of four leachate tests commonly used to evaluate RFS leachate characteristics were the extraction procedure (EP) toxicity method, Toxicity Characteristic Leaching Procedure (TCLP) method, AFS method, and ASTM method. Metals of interest include arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver. Organics are a concern because many of these compounds are added to the foundry sands (Bhat and Lovell 1997).

Partridge and Alleman (1998) provided a summary of previously reported research that assessed the leaching potential of organics from nine binder and core making processes. The major casting processes represented in the study were phenol formaldehyde, phenolic urethane, furan hot box, furan no-bake, phenolic ester, core oil, phenolic isocyanate, and furan warm box (Table 71). Organic chemicals detected for any one of four regulatory EPA lists were reported. The four EPA lists of compounds were the priority pollutant list identifying chemicals, which were environmentally hazardous and found in water (88 compounds, excluding pesticides and PCBs), the TCLP chemical list (38 compounds, excluding pesticides), the drinking water standards (DWS),

TABLE 69
TYPICAL PRE-CONSUMER FOUNDRY SAND ENGINEERING PROPERTIES

Materials	Internal Friction,°		Cohesion, psi		Permeability, cm/sec
	Loose	Dense	Loose	Dense	
Green Sand with Clay (6%–12%)	32°–34°	37°–41°	0.60–0.75	1.44–1.82	2.8×10^{-5} to 2.6×10^{-6}
Clean Green Sand Without Clay	30°	35°	—	—	3×10^{-3} to 5×10^{-3}
Chemically Bonded Sand	—	—	0.06	1.04	4.5×10^{-3} to 5.9×10^{-4}
Natural Sand	29°–30°	36°–41°	—	—	10^{-3} to 10^{-4}

After FIRST (2004b).

TABLE 70
TYPICAL SPEND FOUNDRY SAND PROPERTIES

Property	Test Method	Results
Micro-Deval Abrasion Loss, %	—	<2
Magnesium Sulfate Soundness Loss, %	ASTM C88	5 to 47
Friction Angle	—	33° to 40°
California Bearing Ratio, %	ASTM D1883	4 to 20

TFHRC (2010).

TABLE 71
MEASURABLE ORGANIC COMPOUNDS IN RFS FROM NINE CASTING PROCESSES

Chemical Compound	Quantization Limit, ppb	Maximum Concentration, ppb
Acetone	100	200
Benzene	2	11
Benzoic Acid	ND	400
2,4-Dimethylphenol	20	120
Ethylbenzene	0.4	24
1,1,1-Trichloroethane	2	49
Naphthalene	1	480
2-Methylnaphthalene	1	320
Phenol	30	540
Dimethylphthalate	40	61
Phenanthrene	30	38
Tetrachloroethene	2	7
Toluene	0.5	61
Cresols	30	150
Xylenes	0.4	140

After Partridge and Alleman (1998).
ND = not determined.

and the proposed solid waste disposal facility criteria under Subtitle D of the RCRA act. The only compounds exceeding any of these standards were benzene, which was higher than the DWS maximum contaminating levels for three of the nine RFS. Tetrachloroethene concentrations were at the trigger level used when DWS have not been established. The authors noted these concentrations in leachate testing would likely never exceed limits in actual field testing. Both the core oil and phenolic urethane binder systems leached the greatest number of organic chemicals.

The literature review summarized by Partridge and Alleman (1998) provided information from an early 1990s Wisconsin–Madison research study that evaluated RFS from three foundries. None of the sands were hazardous according to the RCRA criteria. A top priority parameter of greatest concern was iron with concentrations higher than DWS in TCLP leachates when compared with results for virgin soil. Other parameters of interest included fluoride, pH, and total dissolved solids. Secondary priority parameters included arsenic, chromium, copper, manganese, zinc, phenolics, and sulfates.

The Industrial Resources Council (2010) reported on studies of RFS byproducts that showed little uptake of trace metals from iron and aluminum foundry sands. However, there were some concerns with trace metals in RFS from brass and bronze foundries. Trace metal concentrations in most clay-bonded iron and aluminum RFS were similar to those found in naturally occurring soils, while leachate may contain trace metal concentrations that may exceed drinking water standards, the leachate results were found to be similar to those of other construction materials such as native soils or gravels (IRC 2010). This information led to the EPA endorsing the use of properly managed ferrous and aluminum RFS as a construction material.

Hughes (2002) also noted that TCLP testing indicated RFS was nonhazardous. Synthetic Precipitation Leaching Procedure (SPLP) testing showed that leachate from HMA design blends without RFS had higher concentrations than when RFS was included. HMA plant emissions testing when using a mix with 10% RFS was found to not be statistically different for HMA mixes without RFS.

APPLICATIONS

Partridge and Alleman (1998) reported the results for a survey on the use of recycled foundry sand in highway applications of ten states with foundry production operations (Table 72). The common applications were reported as concrete, HMA, and road base.

Applications—Bound

Cement

FIRST (n.d.) provided a case study for the use of RFS in the manufacture of cement in Mason City, Iowa. In this case, the portland cement producer received approximately 75,000 tons per year of the RFS from a waste management firm in Michigan, which was supplied by eight regional foundries located in Iowa, Minnesota, Wisconsin, and Illinois. Costs for the RFS recycling facility included transportation to the plant, testing for chemical and physical properties, and crushing and processing sand.

Flowable Fill

Bhat and Lovell (1997) investigated the use of RFS, along with Type F fly ash, in flowable fill in Indiana. Desirable properties

TABLE 72
SUMMARY OF RFS USE IN THE UNITED STATES

Application	IA	IL	IN	MI	MN	NJ	NY	OH	PA	WI
Landfill Daily Cover				x			x	x		x
Highway Embankment				x				x		x
Roadway Subbase	x		x	x	x	x		x		x
Parking Lot Subbase				x	x	x		x		x
Concrete and Asphalt		x	x	x	x		x	x	x	x
Foundation Subgrade Fill	x							x		x
Flowable Fill							x	x		x
General Fill		x	x	x				x		
Other		x	x					x		x

Partridge and Alleman (1998).

of the flowable fill were local availability, easily delivered and placed, weather resistant, self-compacting, and an unconfined strength below 150 psi so that it can be easily excavated with a backhoe in case repairs or reconstruction were needed. The American Concrete Institute modified flow test was used to evaluate flowability. This test involved placing a 3-in.-diameter by 5-in.-tall open-ended cylinder on a smooth, level, surface, then filling with the material, quickly lifting the cylinder and measuring the diameter of the circular section formed. A spread of 8 to 9 in. or greater was considered to be self-leveling.

The angularity of the fine aggregate was evaluated with the flow cone sand test. This test showed that for a given flowability, the use of the RFS significantly increased the water demand needed to achieve a given flow compared with either the river sand or pre-consumer foundry sand mixes. The presence of the fly ash in the mix was needed to improve the flowability. At low fly ash contents, a lubricant effect was achieved as a result of the round shape of the fly ash. At high fly ash concentrations, the fly ash tended to flocculate and the viscous forces appeared to dominate.

Other testing included an evaluation of penetration resistance (ASTM C403), bleeding (measured by collecting the free water on the surface of a sample), and the surrounding drainage conditions. The factors that influenced the early strength of the mixes were cement content, environmental curing conditions, the nature of the fly ash, and the drainage conditions surrounding the flowable fill materials. Higher cement content mixes had higher early strengths, and flowable fill material with drainage around the perimeter gained strength more quickly than undrained conditions.

The Bhat and Lovell research also evaluated the constant head permeability (ASTM D5045), pH, and toxicity of the flowable fill. The permeability was similar for all of the mixes, ranging between 2.6×10^{-6} and 1.2×10^{-5}. The pH of both the bleed water and pore solution ranged between 10.0 and 11.7. Toxicity testing, using MicroTox™ showed mixed results that led to a conclusion by the researchers that more testing was needed before a conclusion could be drawn.

FHWA (2003) described the Abrams Creek Improvement project in Cleveland, Ohio, which used RFS to encase four 10-ft-diameter concrete pipes. The pipes were placed only 1 ft apart during a major extension of a runway at the Cleveland Hopkins International Airport. Once placed, the pipes and fill had 65 ft of fill placed over the top of the drainage system. The close proximity of the pipes as well as the deep fill required the strong bedding for the pipe. RFS was delivered to the concrete ready mix plant where it was mixed with 150 lb/yd^3 of cement and 60 gal/yd^3 of water to produce flowable fill with strength of between 125 and 300 psi at a cost of \$30/yd^3.

HMA

Hughes (2002) noted that the RFS properties differed based on the type of original foundry sand (i.e., green, resin). The chemically bonded RFS was drier and had lower fines content than green RFS. Important information required by the HMA producer were identification of the type of RFS and how the sand streams were separated, comingled, etc. Hughes noted there were a number of independent recycling operators who addressed the majority of these concerns in their operations. Regardless of who collected the RFS, post-processing was needed prior to use in HMA applications. The RFS needed to be reprocessed into a consistent, high-quality product comparable to virgin sand. There were three steps needed in post-processing RFS:

1. Removal of general refuse and other contaminates
2. Removal of metals
3. Processing and sizing.

This required the installation of reprocessing systems to provide contaminate-free, and screened to provide marketable gradations. Most foundries that post-process their RFS invested in screening, crushing, and magnetic separation units.

Resizing green RFS resulted in a an excess of minus 0.075 mm fines that needed to be monitored so that the maximum percent 0.075 mm was not exceeded for HMA applications. This also required the post-processor to address fugitive dust controls.

Hughes noted that small to medium size foundries typically did not have the capital to invest in post-processing operations. A cost-effective method of recycling for these facilities was to have a partner handling multiple spent sand streams from a collective of foundries. A sufficient incoming supply of material was needed for the HMA producer to maintain a consistent rate of production.

FIRST (2003) provided a case study for gray iron RFS from a foundry in Michigan City, Indiana, that was used in HMA. The foundry paid the haul costs and the contractor to use the RFS. About 4,000 tons of RFS was used in the project, with a cost savings of 75% (about $50,000 savings for the foundry) over the typical tipping fee costs. The RFS made up about 10% by weight of the HMA aggregate. The RFS represented four types of sand: green sand (<10%), no-bake (<25%), cold box (about 25%), and warm box (about 40%). Comments from the contractor suggested the RFS improved the smoothness of the finished surface. Reported RFS properties are shown in Table 73.

TABLE 73
RFS PROPERTIES

Property	Value
Density, lb/ft^3	100–110
Bulk Specific Gravity	2.61
Sodium Sulfate Soundness, %	6.9
Water Absorption, %	0.4
Uncompacted Void Content,%	33.2

After FIRST (2003).

Applications—Unbound

Embankment and Fill

Partridge and Alleman (1998) evaluated the performance of foundry sand from a gray iron foundry that used a phenolic urethane binder as the core binder in embankments in Indiana. Both RFS and control embankments were placed with geotechnical and environmental monitoring instrumentation. Evaluations of the geotechnical properties of the RFS embankment showed that although RFS performed as a natural sand structural fill with acceptable strength and deformation characteristics, it was not as freely draining as the natural sand.

Environmental information was collected using Microtox™ and Nitrotox bioassay, ion chromatography, and inductively coupled plasma testing for metals. Bioassay results indicated the RFS did not have a higher toxicity than those expected from natural sands. Ion migration was measured in the RFS lysimeters, but the concentrations were below reuse regulatory criteria. Metal concentrations were generally below Indiana regulatory reuse Type III criteria and typically below drinking water standards. When metal concentrations in the monitoring wells exceeded the criteria, excess concentrations occurred in both up- and down-gradient wells. This was interpreted by the researchers as background metal concentrations rather than contributions from the RFS.

Partridge and Alleman noted barriers that included a lack of decision-based scientific tools (e.g., life-cycle cost analysis or risk-based analyses), liability exposure from state and federal regulations from using a regulated byproduct, lack of foundries commitment to reuse, post-processing needs and QC, and a formal marketing strategy.

FHWA (2003) reported that the Ohio DOT used RFS to repair an embankment on Ohio SR-271. The RFS was selected because it was deemed to have the necessary strength and permeability properties. The RFS was successfully compacted at the optimum moisture content. Independent testing laboratory results for the RFS are shown in Table 74.

TABLE 74
TESTING AND PROPERTIES OF RFS EMBANKMENT IN OHIO

Property	AASHTO	Results	Spec. Criteria
Grain Size Analysis	T 11-91 T 27-93	Pass	ODOT 203
Sodium Sulfate Soundness	T 104-94	3%	NA
Liquid Limit	T 89-96	NA	NA
Plastic Limit & Plasticity Index	T 90-96	Nonplastic	NA
Moisture-Density Relationship	T 99-95	γ_d = 107.0 pcf	>120 pcf
Direct Shear Test	T 236-92	N = 350	>340
Resistivity	T 288-91	5,600 Ω-cm	NA
pH	T 289-91	9.2	NA
Sulfate Level	T 290-95	87.8	NA
Chloride	T 291-94	35	NA

FHWA (2003).
NA = not available; ODOT = Ohio DOT.

In another application, the Ohio DOT used RFS as a fill for the extension of Oak Tree Boulevard in the city of Independence. Fill was needed for an approximately 2,000 ft long by 600 ft wide by a depth of up to 50 ft ravine. About half of the fill for this project was the RFS. The primary use of the RFS was because it was immediately and locally available. A clay-like dike at the open end of the embankment was constructed to contain the fill and a 3 ft clay cap was placed over the completed embankment. Proper compaction was obtained as long as the moisture content was maintained.

Base and Subbase

FIRST (2005) reported a case study using about 23,000 cubic yards of RFS as subbase fill for an airport runway constructed in Shawano, Wisconsin, in 2005. The original assumption on the part of the recycler was that the cores would break down during compaction. During construction of the subbase this did not occur and large fragments were found in the byproduct supply. The recycler ended up screening the RFS before placement. This additional work resulted in an in-place cost per cubic yard of about $5. Compared with a typical borrow cost in the area of $8 per cubic yard, this still resulted in a cost savings to the owner.

During construction, the RFS needed to be pre-wet before compaction to meet the required compaction requirements (Table 75). A significant amount of water was needed and it was important that compaction be done correctly the first time, because previously compacted RFS did not behave like the loose RFS. A performance review of the project after the first winter showed no differential heaving, a problem in the area, and no excessive joint movement.

Specifications

Partridge and Alleman (1998) summarized state industrial waste classification systems and environmental test procedures after a survey of 14 major foundry states' environmental regulatory criteria (Table 76). Most of the surveyed states classified RFS as either a solid or residual waste. Six of the 14 states used multiple tiers within a classification category. Thirteen of the 14 states used the TCLP method for determining leachate and seven of these states also require additional chemical testing beyond TCLP.

TABLE 75
COMPACTION REQUIREMENTS SET FOR SHAWANO, WISCONSIN, AIRPORT RUNWAY

Compaction Requirements, %	Depth Required, in.
100	0–18
95	8–18
90	18–32
85	32–44

After FIRST (2005).

FHWA (2003) reported that the Ohio DOT used a general specification for embankment construction using recycled materials that contains specific guidance on the use of foundry sand. Guidance included directions to place the RFS on a prepared foundation in horizontal loose lifts not to exceed 8 in. and compact the lifts to a stable, durable condition with at least eight passes of a vibratory steel wheel roller with a minimum weight of 10 tons or centrifugal equivalent. The compaction of the lifts needed to achieve 98% of the maximum density. The sides and top of the RFS needed to be covered with natural soil with a minimum vertical cover of 3 ft, measured from the subgrade elevation, and a minimum horizontal cover of 8 ft, measured from the final slope line.

The Indiana DOT (2007) developed a specification for RFS use in one of two borrowed specifications upon approval from the Geotechnical section. This specification required the contractor to submit an MSDS and a copy of the Indiana Department of Environmental Management waste classification certification for Type III or IV residual sands prior to use. An example of the RFS certification form is shown in Figure 14 and their Indemnification Clause in Figure 15.

The specification put limits on the placement of the RFS near water sources at not closer than:

- 100 ft horizontally of a stream, river, lake, reservoir, wetland, or other protected environmental resource area.
- 150 ft horizontally of a well, spring, or other ground source of potable water.

Other restrictions on placement *locations not to be* used were:

- Adjacent to metallic pipes or other metallic structures.
- Encasement material.
- Mechanically stabilized earth wall applications with metal reinforcement.

Safety considerations limited the release of fugitive dust and loss of material during transporting. Spraying with water, limewater, or other sealing type sprays could be used for dust control. The RFS needed to be encased in the same work day as it was placed.

Barriers

The Foundation Industry (2007) conducted a survey of foundries to determine the extent of their recycling programs and to identify barriers to the increased use of RFS recycling programs. The most commonly cited reason for limited recycling programs was the lack of a local market for spent (post-consumer) sand (Table 77). Quantities generated and storage-related issues were the next two most cited reasons

TABLE 76
SUMMARY OF STATE INDUSTRIAL WASTE CLASSIFICATION SYSTEMS AND BENEFICIAL REUSE TESTING REQUIREMENTS

State	Industrial Waste Classification System				Test Procedures and Standards for Beneficial Reuse						
	Solid waste category	Special waste category	Residual waste category	Multiple tiers within category	State hazardous classification	TCLP or acid-based test	ASTM D3987 or neutral based test	Use of individual state test systems	Identification of specific test levels	Additional chemical testing beyond TCLP or neutral leachate tests	Bulk analysis
Alabama	x	x				x			x		
California		x			x	x		x		x	x
Georgia	x					x					x
Illinois		x		x			x		x	x	
Indiana	x	x		x		x	x		x	x	
Iowa	x					x			x		
Massachusetts	x	x				x					x
Michigan	x			x		x	x		x	x	
New York	x					x					x
Ohio	x		x	x		x	x		x		
Pennsylvania			x			x			x	x	x
Tennessee	x					x	x		x		
Texas	x			x		x	x		x	x	x
Wisconsin	x			x		x	x		x	x	x

After Partridge and Alleman (1998).

RECYCLED FOUNDRY SAND (RFS) SOURCE CERTIFICATION

This is to certify recycled foundry sand (RFS) stockpiles geographically located as follows:
RFS ____
____

RFS was produced by the ________________________ __________________ Company located in ____________________(City), and _________________ (State) and was shipped for use on Indiana Department of Transportation projects is Type _________________ (III or IV) material according to IDEM's restricted waste criteria and that the material has passed Microtox™ (ITM 215) test criteria. If any metal concentration exceeds 80% of the allowable limits for a Type III the foundry shall provide the Department with an acceptable indemnification clause. The _________________ RFS source also agree that processes and stockpiles associated with the production of such RFS may be inspected and sampled at regular intervals by properly identified representatives of the Department or a duly assigned representative.

________________ (Date of Signing) ________________________________ (RFS Producer)
______________________________(Title) ______________________________(Signature)
State of _____________________________) SS:
County of _____________________)
Subscribed and sworn to before me by ___________________________________ of the firm of
________________________________ this __________ day of ________________ 20__.
_______________________________ Notary Public
My Commission Expires: ______________________
This certification has been reviewed and approved by:
_____________________________Date________________
(Materials and Tests Division representative)

FIGURE 14 Example of Indiana's RFS source certification form (Indiana DOT 2007).

RECYCLED FOUNDRY SAND (RFS) INDEMNIFICATION CLAUSE

______________ RFS producer shall indemnify, defend, exculpate, and hold harmless the State of Indiana, it officials, and employees from any liability of the State of Indiana for loss, damage, injury, or other casualty of whatever kind or to whomever caused, arising out of or resulting from a violation of the federal or Indiana Occupational Safety and Health Acts (OSHA), the Resource Conservation and Recovery Act (RCRA), the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), or any other environmental law, regulation, ordinance, order or decree (collectively referred to hereinafter as "Environmental Laws"), as a result of the supply, testing, and application of residual sand or other materials supplied under this Contract by ________________ source, whether due in whole or in part of the negligent acts or omissions of: (1) _________________ Foundry, its agents, officers, or employees, or other persons engaged in the performance of the contract; or (2) the joint negligence of them and the State Of Indiana, its officials, agents, or employees.

This contract shall include, but not be limited to, indemnification from: (1) any environmental contamination liability due to the supply, testing, and application of residual sand in road base, embankments, or other projects designated by the Department as agreed to by the parties, and (2) any liability for the clean up or removal of residual sand, or materials incorporating such sand, pursuant to any Environmental Law.

The RFS producer also agrees to defend any such action on behalf of the State of Indiana, to pay all reasonable expenses and attorneys fees for such defense, and shall have the right to settle all such claims. Provided, however, that no liability shall arise for any such fees or expenses incurred prior to the time that ______________ Foundry shall have first received actual and timely written notice of any claim against the State which is covered by this Indemnification Agreement. If timely written notice of any claim hereunder is not received by _______________ Foundry, and _________________ Foundry is thereby prejudiced in its ability to defend or indemnify, then to the extent of such prejudice, this Indemnification Agreement shall be void.

This Indemnification Agreement does not create any rights in any third party, and is solely for the benefit of the State Of Indiana and its agents, officials, and employees.

FIGURE 15 Indiana's RFS indemnification clause (2007).

TABLE 77
REASONS FOR NOT REUSING FOUNDRY SAND

Reason for Not Reusing	Percent of Respondents
No local market for spent sand	40.1
Does not generate enough for project	24.2
No place to store sand in sufficient quantities	22.9
Do not want to risk future liability claims	15.3
Characteristics prevent reuse	14.0
State regulation and paperwork make it too time-consuming or state regulations do not allow reuse	9.6
Did not know it could be beneficially used	6.4

Foundry Industry (2007).

for limited recycling followed by liability concerns and undesirable material properties. Another limitation identified in an Indiana state foundry evaluation indicated that intra-foundry competition could also limit recycling. For example, the larger foundries in Indiana had a lock on supplying foundry sand to cement kilns, which prevented the smaller foundries from marketing to this industry.

Reuse Programs

In 2006, the EPA published a toolkit for developing reuse programs for foundry sand. The structure, state review, and approval for beneficial use should include information for waste classification, case-by-case determinations, and hybrid applications. Ongoing testing guidance should be given for periodic and event-base, or event-based-only cases. This toolkit provided the following standardized definitions to be used for reuse program development.

- **Approval:** A state agency's endorsement of proposed beneficial reuse activities. This state endorsement may be in written format, although some states endorse proposed activities without a formal written response to generators or end-users.
- **Case-by-case determinations:** states review proposed reuse activities on an individual basis.
- **Waste classification:** States establish categories that are defined by ranges of contaminant thresholds for specific reuses and/or waste types. In general, byproducts with low concentrations of constituents of concern are less restricted in their reuse activities. Conversely, byproducts with higher concentrations are more restricted. These categories standardize the review process for proposed reuse activities and streamline the approval process.
- **Event-based testing:** Establishes the frequency of sampling and testing to confirm that the foundry sand's composition has not changed. In this case, generators or end-users must test the sand when a specific incident occurs, such as a change in the foundry process generating the waste sand.

Prior to starting the reuse program design, the types of foundries from which the sands originate needed to be identified. Iron, steel, and aluminum foundries were the most common, but some regions of the country had other foundries for copper, brass, bronze, beryllium, cobalt zinc, lead tin nickel, magnesium, and titanium casting. The level of agency and contractor involvement in the approval process needed to be identified, as this had an impact on work load and responsibilities (Table 78).

Nearby industries that could potentially use RFS needed to be identified. The main activities were commonly stabilized or bound materials (e.g., portland cement, asphalt, and concrete products), geotechnical (confined) applications (e.g., road bases, structural fills, and embankments), and other products such as soil amendments, manufactured soil, and top dressing.

Sampling and test method requirements needed to be defined as well as the constituents to test QC and QA programs developed. The frequency of testing needed will be a function of the consistency of the byproduct. Byproducts with consistent physical and chemical properties required less frequent testing.

Once this information had been assembled, six steps were defined for the development of a reuse program:

1. Define program structure
2. Identify siting or location restrictions:
   a. Define siting standards that need to be established for reuse activities (e.g., environmental resources to be protected such as ground water, wetlands, etc.; minimum distances, and bans)
   b. Demand on agency resources.
3. Identify state reviews needed to initiate projects
4. Obtain state approval for beneficial uses
5. Develop initial sampling and testing results
6. Develop a program for periodic and/or event-based sampling, testing, and reporting.

The type(s) of program structures were considered in Step 1. The choices made in Step 1 carried over to Step 3. The type of program structure defined the extent of the required initial and ongoing level of resource commitment to reuse programs.

A waste classification structure established reuse standards that varied by the type of byproduct. This type of program required more agency and industry resources up front, but minimized the ongoing resource commitments. These types of classifications were usually based on constituent levels that were stringent enough to ensure environmental safety for all possible uses. For example, Illinois and Indiana set the maximum allowable leaching concentrations for arsenic, but used different category designations and levels (Table 79).

A case-by-case program structure typically created a basic set of standards that all of the byproducts must meet to be eligible for beneficial reuse. The hybrid structure combined the waste classification categories with the case-by-case reviews to help streamline the process for reuse applications within the waste classification categories while being flexible enough to consider other applications individually. Table 80 provides an overview of the wide range of reuse programs used by state agencies. The range of types of programs and responsibilities highlight the reason both agencies and contractors list regulations as a barrier to increased use. When trying to create a market for byproducts, reclaimers were faced with a number of classification systems and regulations that needed to be met within a given market area.

TABLE 78
LEVELS OF RESPONSIBILITIES AND IMPACTS ON RESOURCES FOR AGENCIES AND INDUSTRY

Activity	Responsibility	Agency Burden				Industry Burden			
		None	Low	Med.	High	None	Low	Med.	High
Review of Proposed Reuse Activity	Industry required to keep records of sampling and testing results	x							x
	Agency reviews initial sampling and testing		x					x	
	Agency reviews sampling and testing on a case-by-case basis for environmental impacts			x				x	
	Agency reviews sampling and testing plus additional information regarding environmental impacts (i.e., ground water contamination, off-site releases, air pollution, etc.)				x			x	
Written Submissions of Approval	No written approval to generators needed	x					x		
	Agency submits written approval to generators or end-uses for some, but not all reuse applications (dependent on volume used)		x				x		
	Agency submits written approval to generators or end-uses for all reuse activities				x				x
Ongoing Oversight	Industry conducts periodic and event-based sampling and testing but does not report the results to the agency unless a significant change occurs	x				x			
	Industry conducts event-based sampling and testing and reports the results to the agency		x				x		
	Industry conducts periodic and event-based sampling and testing and reports the results to the agency			x				x	
	In addition to periodic and event-based sampling and testing and reporting, industry reports additional information regarding reuse activities				x				x

After EPA (2006).

AGENCY SURVEY RESULTS

Three agencies had used recycled foundry sands in embankments, two in flowable fill, and one in drainage materials (Table 81). The only use for recycled sand blasting waste was in HMA applications. Table 82 shows only five states reporting that they had experience using recycled foundry sand in highway applications. No states were currently using sands from sand blasting operations (Figure 16).

Only two states provided comments about their experience with foundry sands (Table 83). Alabama noted it is allowed for soil aggregate mixtures as long as their existing specification could be met. Utah, that did not use RFS in highway applications, highlighted properties that made foundry sand high quality for casting, were not always considered high quality for highway applications. The uniform size and round shape made it difficult to meet well-graded aggregate specifications and angular fines requirements for bases and HMA.

TABLE 79
EXAMPLES OF DIFFERENT WASTE CLASSIFICATIONS FOR ARSENIC IN BENEFICIAL REUSE APPLICATIONS

Illinois		Indiana	
Category	Threshold	Category	Threshold
Beneficially Usable	0.05 mg/L	Type IV	0.05 mg/L
Potentially Usable	0.1 mg/L	Type III	0.50 mg/L
Low Risk	0.25 mg/L	Type II	1.3 mg/L
Chemical Waste	>0.35 mg/L	Type I	5.0 mg/L

After EPA (2002).

SUMMARY OF FOUNDRY SAND INFORMATION

List of Byproducts

The list of the most commonly researched and used byproducts include green sands and core sands.

The foundry sand byproducts could be separated by their use in the casting process, which could alter physical and chemical properties. These differences were a function of the

TABLE 80
SUMMARY OF STATE REUSE PROGRAMS FOR SPENT FOUNDRY SAND AS OF 2002

State	Classification System	Allowable Reuses	Sampling and Testing Requirements	Other
Alabama	Single-tiered waste classification	Applications prohibited	Generators certify waste quarterly or when process changes	Generators maintain records
California	Approvals and designation determined by Department of Toxic Substances Control (DTCS), Water Boards, and, California Integrated Waste Management Board	RCRA and state-determined hazardous wastes standards used	Leachate testing required	Depends on application
Illinois	4-tiered classification beneficial reuse	Depends on classification	Generator-provided leachate testing from each waste stream	Generator certification
Indiana	4-tiered classification beneficial reuse	Depends on classification	Generator-provided leachate testing to classify	Additional testing may be required; stockpile site restrictions; dust controls
Iowa	Concentration criteria for intended reuse application	Dependent on concentration levels	Leachate and pH testing	RFS use does not require a permit; a foundry sand management plan needs to be submitted
Louisiana	Source of byproduct and types of facilities (5 levels)	Solid waste regulations define uses	Applicant must conduct a detailed analysis for specific compounds	Third party certification; completion of application for use; site location information
Maine	Application for use of secondary materials and special waste	Defined by regulation and on case-by-case basis	Applicant needs to submit sampling and analytical work plan	Meet or exceed requirements for materials that will be replaced with byproduct; no use in environmentally sensitive areas; annual report of activities; licensee submission of application
Massachusetts	Volume of material in application	Applicant needs to describe benefits and demonstrate safe handling, storage, use, and end products	Application needs to contain physical and chemical properties	Draft beneficial use regulations in progress
Michigan	Petition for classification as either inert material or low-hazard industrial waste	Depends on classification	Applicant needs to submit TLCP, SPLP, or other test results as required with annual re-tests submitted	Submit description of material, schematic of processes and raw materials used, maximum and annual amounts generated monthly and annually, documentation supporting non-hazardous classification, and description of proposed use
Minnesota	Case-by-case	Case-by-case	—	Draft beneficial use regulations in progress
New York	16 materials identified in regulation; foundry sand not on list Also allow case-by-case	Defined by regulation Not allowed if decontamination or special handling/processing before use is required	Leachate testing and sampling plan	Case-by-case requires a description of the byproduct and proposed use; demonstration of safety; byproduct control plan
Ohio	4-tier waste classification	Depends on concentration thresholds	Applicant submission of leachate testing; annual tests submitted to agency	Minimization of byproduct volume preferable; cannot create a nuisance; storage subject to nuisance and erosion regulations; cannot place in environmentally sensitive areas

Pennsylvania	General permits issued on either regional or statewide basis	Applicant applies for one of three permit types: beneficial use as pipe bedding; beneficial use in concrete or asphalt applications, or as a beneficial use in road bed construction	Applicant submission of byproduct characterization and leachate concentrations	Applicant submission of annual report, demonstration of beneficial contribution, notification to local agency of intent to use, acceptable storage and use of byproduct, protection of water quality, and maintain on-site records for 5 years
Rhode Island	Applicant requests variance from Solid Waste Regulations; variances expire after 1 year; positive results may allow a renewal for a period of 3 years	Case-by-case	Applicant submits testing plan	Applicant must minimize environmental hazards, demonstrate reuse is a viable substitute for raw materials, demonstrate no adverse impact on health and natural resources, assess market extent, describe in-place controls, demonstrate reuse is not simply an alternative method of disposal, and describe any post-processing
Tennessee	Contaminate thresholds for nontoxic designation; division approval for others	Depends on designation	—	Generator maintains records, byproducts approved by division need to designate generator and proposed use, estimated volume of byproduct to be used, proposed silt/runoff control and site specifics
Texas	3-tier waste classification	Depends on classification	None if classified as non-waste; non-hazardous requires leachate testing, analysis of hydrocarbons, and verification of absence of PCBs	Generators maintain on-site records
West Virginia	Guidance on beneficial use; application process	Guidelines contain reuse applications	Submission of sampling and analysis plan	Required plan approval from Solid Waste Management
Wisconsin	5-tiered waste classification system	Depends on classification	Leachate testing; frequency depends on quantities	Applicant submission of initial and annual certifications, public notification (quantity-based), written notification to DNR (quantity-based), leachate monitoring for certain transportation facilities

After EPA (2007).

TLCP = toxicity characteristic leaching procedure; SPLP = synthetic precipitation leaching procedure; PCB = polychlorinated byphenols; DNR = Department of Natural Resources.

TABLE 81
RESULTS FOR AGENCY SURVEY FOR FOUNDRY SAND BYPRODUCTS USED IN HIGHWAY APPLICATIONS

Question: Manufacturing or Misc. Construction Byproducts: Is your state using, or has ever used, these byproducts in highway applications? * Sand blasting waste: sand along with finishing materials after resurfacing * Sand, foundry: high quality sand recycled after metal castings of products									
Type of Byproduct	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embank.	Flowable Fill	HMA	Pavement Surface Treatment (non-structural)	PCC	Soil Stability
Sand Blasting Waste	0	0	0	0	0	1	0	0	0
Sand, Foundry	0	0	1	3	2	0	0	0	0

Embank. = embankment.

type of additive used with the original foundry sand, the type of metal being cast, and the specific casting process used.

Test Methods

The test methods in Table 84 have been used to evaluate foundry sand and highway application products that use foundry sand. Both AASHTO and ASTM standards are shown in this table.

Materials Preparation and Byproduct Quality Control

Material preparation and QC found in the literature and agency surveys included:

- The casting cores have been hardened by additives such as epoxies, resins, organic binders (e.g., portland cement and wood proteins) to form the inside of the part. This component of spent foundry sand was used to form the inside shapes of the part and needed further crushing, separation, and screening before recycling.
- Post-processing needed to include the removal of general refuse and other contaminates, metals, and sizing.
- Green sands were used to form the external modeling lines and were reclaimed and reused by the foundry until they failed to meet foundry sand requirements

Materials Handling Concerns

No specific handling concerns were noted in the literature or agency survey.

TABLE 82
STATES USING FOUNDRY SAND BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

Number of Applications	States	
	Sand blasting waste	Sand, foundry
2	—	WI
1	NC	IA, IN, OH, PA

Design Adaptations

The following design adaptations were found when using RFS:

- Spent foundry sands typically required higher portland cement contents that needed to be addressed during the mix design.
- Fly ash was needed in PCC mix designs to compensate for a loss of workability as a result of the RFS.
- Fill designs needed to account for less freely draining material.
- When constructing embankments with RFS, the following recommendations were made by the FHWA (2003):
  - Place the byproduct on a prepared foundation in horizontal loose lifts not to exceed 8 in.
  - Compact the lifts to a stable, durable condition with at least eight passes of a vibratory steel wheel roller with a minimum weight of 10 tons or centrifugal equivalent. The compaction of the lifts needs to achieve 98% of the maximum density.
  - Cover the sides and top of the RFS with natural soil with a minimum vertical cover of 3 ft, measured from

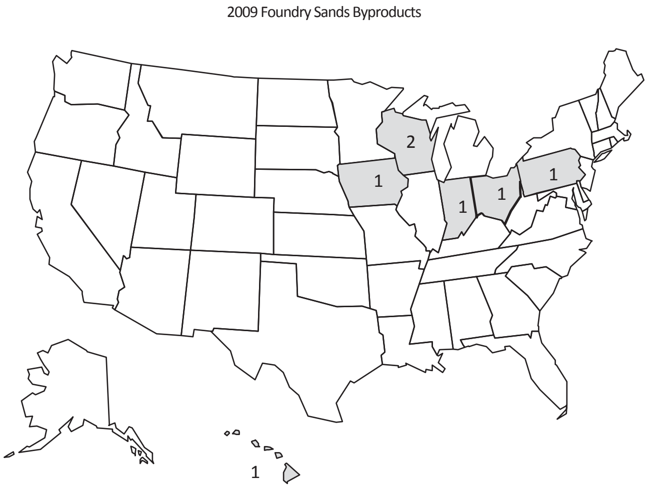


FIGURE 16 States using foundry sand in highway applications.

TABLE 83
SUMMARY OF COMMENTS ON USING FOUNDRY SAND IN HIGHWAY APPLICATIONS

State	Comment
AL	Foundry sand is allowed in granular soil materials (Section 821 of ALDOT Standard Specifications) and in soil aggregate materials (Section 823) provided it meets the testing/specification requirements.
	Foundry sand stockpiles are required to be inspected/approved on an individual basis. Issues with consistency of foundry sand properties and its potential for chemical reactions is also a concern.
UT	Foundry sand is not "High Quality Sand" in the construction world. In its native gradation the single sizes often do not provide a stable material for compaction purposes. It could be if intermixed with other sizes, but typically the single size gradations and shape are not stable. Therefore, to place and use, the gradation has to be modified. This costs money and doesn't make it always as attractive in a low-bid environment. Again, it gets down to the issue of suppliers wanting us to use their product as is rather than modifying their product and/or quality control to provide us the product we want.

TABLE 84
TEST METHODS USED TO EVALUATE BYPRODUCTS AND HIGHWAY APPLICATION PRODUCTS

Test Methods	Title
AASHTO Methods	
T112	Standard method of test for lightweight pieces in aggregate
T215	Standard method of test for permeability of granular soils
T90	Standard method of test for determining the plastic limit and plasticity index of soils
ASTM Methods	
C128	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregates
C142	Standard Test Method for Clay Lumps and Friable Particles in Aggregates
C29	Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)
C403	Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
C88	Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate
D1883	Standard Test Method for CBR of Laboratory Compacted Soils
D2216	Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass
D2434	Standard Test Method for Permeability of Granular Soils (Constant Head)
D3987	Standard Test Method for Shake Extraction of Solid Waste with Water
D69	Standard Test Methods for Friction Tapes
D698	Standard Test Methods for Laboratory Compaction Characteristics of Soils Using Standard Effort
D854	Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer

the subgrade elevation and a minimum horizontal cover of 8 ft, measured from the final slope line.

Construction Concerns

Construction concerns that need to be considered when using RFS include:

- Additional crushing and compaction efforts that may be needed if the spent foundry sand cores were not crushed prior to use in base applications.
- Proper moisture content was needed to achieve the desired in-place density in unbound applications. A significant amount of water may be needed so that compaction is achieved the first time around. RFS was difficult to re-wet because of the clay additive.

Failures, Causes, and Lessons Learned

The lessons learned when using RFS in demonstration projects include:

- When used in unbound applications, the RFS needed to be pre-wet and at optimum moisture content on the first round of compaction as the clay additive content tends to prohibit further compaction after re-wetting.
- RFS cores needed to be crushed before use in unbound applications as it was difficult to crush them during compaction.

Barriers

Barriers noted included:

- Lack of decision-based scientific tools (e.g., life-cycle cost analysis or risk-based analyses)
- Liability exposure from state and federal regulations from using a regulated byproduct
- Lack of foundries committed to reuse
- Post-processing needs
- Lack of QC for the RFS
- No formal marketing strategy
- A number of classification systems and regulations that need to be met within a given market area.

Costs

Regional recycling facilities reduced the cost of the byproducts. A recycling facility provided a single disposal location for smaller foundry operations, post-processing operations for useable byproducts with consistent properties, and adequate quantities for a given application product.

CHAPTER FIVE

WASTE GLASS BYPRODUCTS

Post-consumer glass cullet can usually be separated by color: amber, green, and clear. The Northeast Resource Recovery Association identifies suitable sources of recycled crushed glass as glass or ceramic bottles, glass jars, ceramic tableware and cookware, vases, ceramic flowerpots, plate glass, mirror glass, and residential incandescent light bulbs. Waste glass from material recovery facilities can be identified by several names: cullet, recycled glass, soda lime glass, crushed glass, or processed glass aggregate. This byproduct is recovered from glass containers and from breakages and inferior products made during glass manufacturing. The majority of post-consumer containers can be sorted into three categories based on color, which is defined by the chemical composition needed to produce the color:

- Flint glass: colorless glass food, beverage, beer, liquor, and wine bottles.
- Amber glass: brown beer and liquor bottles.
- Green glass: green wine and beer bottles.

Another source of waste glass is from the glass manufacturing process, which includes such materials as broken, obsolete, and/or off specification glass from the manufacturing of plate, window, and analytical glassware (Wartman et al. 2004). Glass from automobiles, lead crystal, TV monitors, lighting fixtures, and electronics applications are excluded owing to their composition and coatings.

Glass cullet can be provided by the material recovery facilities as unwashed larger broken glass particles, unwashed but crushed glass cullet, and as-washed glass cullet. Washing the byproduct removes most of the contaminates such as paper, plastics, and metals that would be considered contaminates in most highway applications.

PHYSICAL AND CHEMICAL PROPERTIES

One example of the physical properties of glass cullet, not crushed, used by the Ramsey County Public Works Department in Minnesota is shown in Table 85 (Krivit 1999). The American Geophysical Institute (AGI) visual evaluation is a subjective method of defining the percent of contaminates in the cullet. In the case of unwashed cullet, the percent of contaminates could be well above the recommended limits of 5% (TFHRC 2010). The contaminates influenced a number of the other physical properties such as the moisture content, specific gravity, permeability, and biological and chemical content.

Wartman et al. (2004) reported unwashed, crushed glass cullet properties for two sources used in their Pennsylvania study (Table 86). The moisture content of around 5.5% was a function of the debris content, which was up to about 5.5%. The median particle sizes from these sources ranged from 2.2 to 3 mm, with most of the particles between the 4.75 and 0.075 mm sieves; there was a maximum of 5% of minus 0.057 mm.

The chemical composition of glass cullet will depend somewhat on the color of the glass (Table 87). The main compound in glass cullet, regardless of color, was silica oxide. This high silica content was one of the main concerns when using glass cullet as aggregate substitutes in PCC because of potential ASR expansion. The sodium oxide compound was the primary alkali component.

ENGINEERING PROPERTIES

Acceptable highway application physical properties can be obtained when the cullet is post-processed by washing and crushing. Research by the Florida DOT (Cosentino et al. 1995 a, b) showed that post-processed glass cullet could be used to produce a number of standard aggregate gradations (Table 88). Physical properties such as permeability, soil classifications, maximum dry density, and porosity depended on the final gradation of the gullet. The resulting gradations could be classified as either A-1-a or A-1-b by AASHTO standards and by SP or SW (poorly graded or well-graded fine to coarse sand) by Unified Soil Classification System.

The ability of the glass cullet aggregate to carry a load was very low, regardless of the gradation [i.e., CBR and limestone bearing ratio (LBR) values below 5]. The specific gravity also became much more consistent (2.40 to 2.55) when the cullet was washed, regardless of gradation. This led to slightly lower unit weights for the glass cullet when compared with those for typical soils (100 to 110 lb/ft^3).

Wartman et al. (2004) investigated the engineering properties for the two Pennsylvania sources of unwashed, crushed

TABLE 85
MIXED GLASS CULLET PROPERTIES
(NOT CRUSHED)

Property	Value
AGI Visual Method (MnDOT), %	35
LOI, %	3.35
Moisture Content, %	0.1 to 2.8
Permeability, cm/s	0.41
Compacted Density, lbs/ft^3	87
Specific Gravity	1.96 to 2.41
Difference in BOD, mg/l (glass compared with sand)	26
Average difference in COD, mg/l (glass compared with sand)	58
Di-n-butyl phthalate, μg/l	9.6

Krivit (1999).
AGI = American Geophysical Institute; BOD = biological oxygen demand; COD = chemical oxygen demand.

sources of glass cullet (Table 89). These materials met the soil classification requirements for an SW soil. Toughness is higher than for typical aggregates but below most state upper limit specifications of 30% to 40%. The laboratory evaluation for freeze/thaw resistance (sodium sulfate soundness) was consistent and low for up to 120 cycles. The constant head hydraulic conductivity at 90% modified Proctor density showed results similar to those of typical SW soils indicating the glass cullet should be relatively free draining. Direct shear testing gave high angles of internal friction; the authors noted dilatancy behavior that increased with increasing confining stresses. A cohesion value, *C*, from the testing was assumed to be 0, but the triaxial testing showed that a small value was obtained. This was attributed to contamination by "gummy" substances such as labels on the glass cullet and an angle of internal friction of around 45°.

TABLE 86
EXAMPLE OF UNWASHED, CRUSHED GLASS CULLET PROPERTIES FROM A PENNSYLVANIA STUDY BY WARTMAN ET AL. (2004)

Test		As-Received			
		Source 1		Source 2	
		Ave.	Range	Avg.	Range
Water Content, %		2.36	2.03–2.60	4.22	3.49–5.32
Debris Content, %		0.34	0.0–0.75	1.82	0.62–3.41
Specific Gravity		2.48		2.49	
Minimum density, lb/ft^3		71.8	71.1–72.4	79.2	76.8–81.1
Gradation Information	Maximum density, lb/ft^3	111.7	110.7–112.3	108.6	108.5–109.2
	Median grain size, D_{50}, mm	2.24	1.85–2.62	3	2.70–3.30
	Coefficient of uniformity	6.2	4.3–10.0	7.2	5.4–7.0
	Sand content, (0.075 to 4.75 mm), %	91.3	89.5–93.0	70	66.5–74.0
	Fines content (<0.075 mm), %	3.2	0.0–5.0	1.2	0.2–2.0
Sieve Analysis	Sieve Size, mm				
	10	100		100	
	4.75	97		70	
	2.0	50		26	
	8.6	23		15	
	0.43	14		8	
	0.25	10		4	
	0.13	8		2	
	0.075	5		1	

TABLE 87
CHEMICAL COMPOSITION OF GLASS CULLET BY COLOR

Compound	Chemical Composition, % (Oliveira et al. 2008)			Chemical Composition, % (Park et al. 2004)		
	Flint glass	Amber glass	Green glass	Flint glass	Amber glass	Green glass
Na_2O	9.94	10.37	10.54	—	—	—
MgO	0.75	0.81	1.18	—	—	—
Al_2O_3	2.57	3.00	2.54	2.18	1.74	1.81
SiO_2	74.07	73.27	72.25	71.3	72.1	73.04
Cl_2O	—	—	—	—	—	—
K_2O	1.14	1.10	1.15	—	—	—
CaO	11.53	11.36	12.35	—	—	—
TiO_2	—	—	—	—	—	—
Fe_2O_3	—	—	—	0.596	0.310	0.040
SO_3	—	—	—	0.053	0.130	0.220
Cr_2O_3	—	—	—	0.44	0.01	–
$Na_2O + K_2O$	—	—	—	13.07	14.11	13.94
CaO + MgO	—	—	—	12.18	11.52	10.75

Flint = colorless glass.

TABLE 88
EXAMPLE OF GLASS CULLET AFTER POST-PROCESSING TO MEET ASTM D448 GRADATIONS

Properties		Post-Processed			
		No. 8	No. 9	No. 10	No. 89
Coefficient of Uniformity		2.3	2.3	14.3	9.3
Coefficient of Gradation		1.3	1.2	0.8	1.4
D_{10}		3	1.5	0.075	0.5
Soil Classification	USCS	GP	SP	SP	SW
	AASHTO	A-1-a	A-1-a	A-1-b	A-1-a
Modified Proctor Density, lb/ft^3	Minimum	85	85	60	83
	Maximum	102	105	87	111
Max. Dry Density, lb/ft^3		95.61	96	81	111
Coefficient of Permeability, k, cm/s		6.46	3.54	0.003	0.87
Specific Yield, n_e, %		35.14	34.0	8	20
Time to 85% Saturation, hour		<0.01	0.01	61	<0.1
Direct Shear	Unit weight, lb/ft^3	88–93	91–101	95–108	91–103
	Angle of internal friction, ^{o}	45–51	37–45	34–46	40–45
Bearing Capacity	Unit weight, lb/ft^3	89–95	83–97	84–98	88–107
	CBR	0.9–2.7	0.8–2.8	0.8–1.7	0.4–3.3
	LBR	1.1–3.4	1.0–3.5	0.6–2.1	0.5–4.0

Cosentino et al. (1995 a,b).
CBR = California bearing ratio; LBR = limestone bearing ratio (Florida); D_{10} = particle size associated with 10% passing that size.

ENVIRONMENTALLY RELATED PROPERTIES

Krivit (1999) reported environmental testing for 13 metals that were analyzed with no detectable amounts released from the glass samples. Ninety-two semi-volatile compounds were analyzed and only di-n-butyl pthalate had any trace amounts. The high biological oxygen demand concentrations resulted in MnDOT placing limitations for proximity of the cullet to water sources.

The NCHRP 4-21 Report (Chesner et al. 2000) summarized the trace metal concentrations in waste glass (Table 90) and the trace metals in leachate (Table 91). No trace organics for waste glass were included in this report.

Wartman et al. (2004) reported that their results from the TCLP or SPLP testing had values significantly lower than those for identifying hazardous wastes (Table 92). The only compounds that exceeded drinking water standards were barium, cadmium, selenium, and silver. Some variability was noted between the two sources that were attributed to miscellaneous waste stream differences such as glass color, chemical content of label ink, specialty glass chemistries, and waste thermometers (i.e., mercury content).

TABLE 89
EXAMPLE OF ENGINEERING PROPERTIES FOR GLASS CULLET (UNWASHED, CRUSHED) AS REPORTED BY WARTMAN ET AL. (2004)

Test		As-Received			
		Source 1		Source 2	
		Ave.	Range	Avg.	Range
Soils Classifications, USCS		SW	—	SW	SW
LA Abrasion, %		24	—	25	—
Sodium Sulfate Soundness, 120 cycles		6.38	—	7.1	—
Hydraulic Conductivity, cm/s		1.61×10^{-4}	—	6.45×10^{-4}	—
Modified Proctor	Maximum dry unit weight, lb/ft^3	116.9	—		111.4
	Optimum moisture content, %	9.7	—	11.2	—
Standard Proctor	Maximum dry unit weight, lb/ft^3	106.9	—		105.7
	Optimum moisture content, %	12.8	—	13.6	—
Direct Shear Internal Friction at Various Normal Stresses, ^{o}	0–60	—	61–63	59–62	—
	60–120	—	58–61	55–59	—
	120–200	—	63–68	47–55	—
Consolidated Drained Triaxial Internal Friction, ^{o}		—	48	47	—

TABLE 90
TRACE METAL LEACHATE CONCENTRATIONS

Constituent	TCLP (mg/L)	SPLP (mg/L)
Ag	<0.1	—
As	<0.1	—
Ba	0.27	—
Cd	<0.002	0.004
Cr	<0.01	0.0023
Cu	<0.056	0.011
Hg	<0.004	0.0008
Pb	<0.005	0.0092
Se	—	—

Chesner et al. (2000).

TABLE 91
TRACE METALS

Metal	Concentration (mg/kg)
Cr	3.1
Cu	1.7
Fe	597
Hg	<0.15
K	272
Mg	2,700
Mn	5.4
Mo	0.94
Na	439
Ni	<0.77
Pb	2.9
Se	<0.77
V	16.8
Zn	244

Chesner et al. (2000).

USAGE AND PRODUCTION OF WASTE GLASS

Chesner et al. (2000) reported on the production of waste glass in all states. States that were producing more than 500,000 tons per year were California, Connecticut, Florida, Illinois, New York, Ohio, Pennsylvania, and Texas. States with the lowest production of waste glass in 2000 were Alaska, Hawaii, Idaho, Maine, Montana, North Dakota, New Mexico, New Hampshire, Nevada, South Dakota, Utah, Vermont, and Virginia. All of the other states were producing between 100,000 and 500,000 tons a year. The Northeast Resource Recovery Association (2009) annual reported that a total of 10,862 tons of mixed glass was recycled.

The NCHRP 4-21 report (Chesner et al. 2000) noted only limited use of glass byproducts in HMA applications by Canada and Great Britain. As of 2000, only Sweden was using fine glass byproducts in PCC applications, and only on a limited basis.

AGENCY SURVEY RESULTS

Glass cullet was commonly used by agencies in HMA and embankment applications (Table 93). At least one agency used glass cullet in all of the other seven applications included in the survey. Table 94 shows that only six states reported using or having used waste glass in more than one highway application. Fifteen states use this byproduct with a single application. Figure 17 shows the geographical distribution of the states

TABLE 92
TOXICITY CHARACTERISTIC (TCLP) AND SYNTHETIC PRECIPITATION (SPLP) LEACHING PROCEDURE RESULTS

Metal	Standards		TCLP (mg/L)		SPLP (mg/L)	
	U.S. EPA drinking water standard[a]	Hazardous waste designation[b] (mg/L)	Source 1	Source 2	Source 1	Source 2
Ag	0.05	5	0.02	0.02	0.02	0.02
As	0.05	5	0.10	0.10	0.10	0.10
Ba	2	100	0.151	0.10	0.10	0.10
Cd	0.005	1	0.01	0.01	0.01	0.01
Cr	0.1	5	0.03	0.0772	0.03	0.03
Hg	0.002	0.2	0.0002	0.0002	0.00024	0.0002
Pb	0.015	5	0.10	0.128	0.10	0.10
Se	0.05	1	0.20	0.20	0.20	0.20

Wartman et al. (2004).
Note: All data in milligrams per liter (mg/l).
[a] U.S. EPA (1999).
[b] *SW-846*, Chapter 7.4 (Revision 3, Dec. 1994).

TABLE 93
RESULTS FOR AGENCY SURVEY FOR GLASS PROCESSING BYPRODUCTS USED IN HIGHWAY APPLICATIONS

Manufacturing or Misc. Construction Byproducts: Is your state using, or has ever used, this byproduct in highway applications?
*Waste glass: post-consumer glass byproducts

Type of Glass Byproducts Used in Highway Applications	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embank.	Flowable Fill	HMA	Pavement Surface Treatment (non-structural)	PCC	Soil Stability
Any Type	2	1	4	9	2	8	2	3	1

Embank. = embankment.

indicating experience with this byproduct by the respondent filling out the survey. Only Alaska, Hawaii, and Idaho indicated some experience in the western half of the United States.

LITERATURE REVIEW

Applications

The original use for glass cullet was as an aggregate substitute for natural aggregates used in highway applications. Recent research has begun to focus on the use of glass powder (mostly passing the 0.075 mm sieve) as a pozzolanic replacement for cement. The information in this section documents recent national and international research.

Bound—Mortar

Xie et al. (2003) evaluated the use of glass and glass-fly ash for ASR using ASTM C 1250. At 10% glass cullet substitution for natural aggregate, the ASR expansion was dependent on the size of the glass aggregate. However, the expansion of the glass-fly ash combination was not a function of glass cullet particle size. Rather, the expansion was found to be a function of the percent of the glass cullet. Glass-fly ash mortars could use a replacement of up to 100% without exceeding expansion limits.

Oliveira et al. (2008) evaluated the pozzolanic reaction of finely ground glass cullet in cement mortars in Portugal. A chemistry analysis was conducted for glass, sorted by color and then ground into a fine powder. This testing showed that the glass powder satisfied the basic chemical requirements of a pozzolan but did not comply with additional requirement for alkali content (Na_2O), which was high. The high alkali content was a concern when the byproduct was used in mortar and PCC applications because of the possibility of detrimental ASR expansion. The authors noted the glass cullet should be washed before grinding because previous research indicated false reactivity predictions may be obtained when testing unwashed glass cullet powders.

TABLE 94
STATES USING GLASS BYPRODUCTS IN HIGHWAY APPLICATIONS IN 2009

No. of Applications	States
9	ID
3	PA
2	MA, MN, NY, VT
1	AK, CT, FL, HI, IA, ME, NC, NH, NJ, SC, VA,WI

A jaw crusher and ball mill were used to crush the glass cullet, which was then sieved into three fractions: 0.15 to 0.075 mm, 0.075 to 0.0045 mm, and less than 0.045 mm. Grinding time optimization was determined using the Blaine specific surface at the end of various grinding times (every hour for 10 h). There was a good linear correlation between an increase in specific surface with time in the ball mill with values starting at about 65 m^2/kg at time 0 and increasing to about 250 m^2/kg at 9 h. The finely ground glass was used as a cement replacement at 10%, 20%, 25%, 30%, and 40% of each color and size. The shape of the glass powder was characterized using SEM photographs. These images indicated all of the powders had an angular shape.

Testing of the mortar mixes included compressive and flexural strength (EN 198-1) and ASR evaluation with mortar

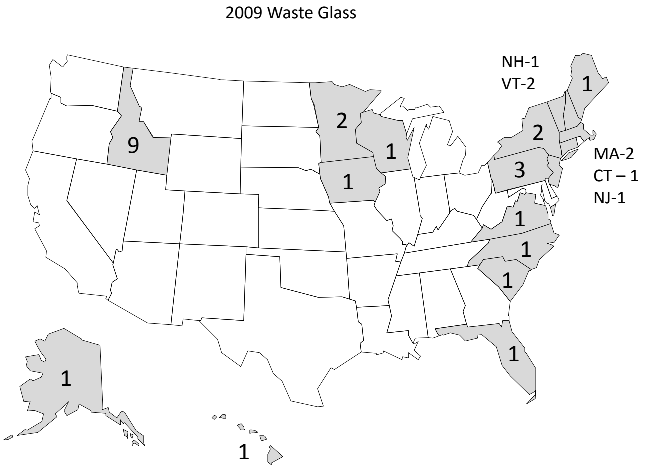


FIGURE 17 Agencies reporting use of glass byproducts in highway applications.

TABLE 95
MATERIAL PROPERTIES FOR STUDY OF GLASS POWDER IN PCC MIXES

Material	ASTM Type F	Fly Ash, F	Powered Glass	ASTM Type C	Fly Ash, C
Pozzolanic Content, %	>70	61.2–76.4	73	50–70	64.5
SO_3, %	<5	0.7–9.4	None	<5	2.4
Loss on Ignition, %	<6	0.2–15.2	None	<6	0.2
Na_2O, %	<1.5	0.8–1.7	5–16	<1.5	0.5

After Polley (1996).

bars (ASTM C1260). Increasing the percent of glass powder as a cement replacement resulted in a corresponding decrease in compressive strength for the 0.15 to 0.075 mm fraction. Compressive strength was similar for both the amber and flint colored glass; the green glass powder had only a slightly higher strength at 28 days. This was attributed to the slightly higher specific surface of the green glass (about 445 m^2/kg) compared with the amber and flint color (about 355 m^2/kg). At 90 days, the strengths were similar for all of the mixes.

Pozzolanic activity was higher for the amber glass than the control mix. The activity increased with decreasing fraction size, but decreased with increased percent of glass powder, regardless of color. There was some indication the green powdered glass was slightly more reactive than the amber. The percent of expansion (ASR test) decreased with the increasing percent of powder. At 40% of either the amber or flint colored glass powders the percent expansion was similar to the control. The green glass powder had an expansion of about 0.0053% compared with about 0.0038%. Conclusions were that 30% of 0.075 to 0.045 mm fraction of powdered glass could be used as a cement replacement without any detrimental ASR effects.

Bound Applications—Portland Cement Concrete

Polley (1996) studied using glass cullet and glass powder in PCC mixes. Glass cullet was used in conjunction with and without fly ash. Several properties for the glass powder and other PCC materials are compared in Table 95. The specific gravity of the glass cullet was reported as 2.15 with 0.0% water absorption. Glass powder had a slightly higher pozzolanic content than either of the fly ashes, but a significantly higher alkali content (i.e., Na_2O).

Table 96 shows the various combinations of glass aggregates and glass powders used in this study. The coarse glass gradation included a range of particles between the 12.5 mm (100% passing) and 90% retained above the 1.18 mm. The finer glass gradations usually had 100% passing the 1.18 mm and 90% retained on 0.75 mm. The pozzolanic content (ASTM C618) was reported as about 73%, and from about 5% to 16% Na_2O (alkali) for the crushed glass.

The slump was dependent on the percent of crushed glass aggregate in the PCC. As the percent of glass cullet increased, the water to cementitious material ratio needed to increase to maintain a consistent slump. An increase in the percent of powdered glass, holding the percent of crushed glass constant, showed a decrease in slump with the increasing percent of glass powder. Crushed glass greater than about 3 mm in size and visibly identifiable as crushed glass required heavy gloves to handle the mix safely. The surfaces of the particles were difficult to get coated with the paste. Commercially crushed glass was typically less than 1.5 mm in size and resembled sub-angular sand rather than crushed glass and produced mixes much easier to handle. During field trials, mixes with only the finer glass gradations were identifiable as “workable and finishable.” In general, glass aggregates decreased workability and the coarse gradation had more loss of workability than fine glass gradations. There was a corresponding increase in water demand. The author noted that the glass has little influence on the amount of air entrainment needed. Greater amounts of high range water reducer (HRWR) were needed to get the desired slump; the amounts were similar to those increases needed when just using fly ash.

Compressive strength/failure planes for the low alkali-fine glass gradations had similar fracture patterns as the control. At 365 days of curing, these mixes showed a sharp failure plane with shearing of the coarser glass particles evident. Mixes with glass aggregate and with/without glass powder reduced the strength by about half. The glass aggregate reduced the strength improvement over time that was typically developed

TABLE 96
COMBINATIONS OF COARSE GLASS AND FLY ASH MIXES

Ratios of Mix Components		Strength, psi*	
Experimental mix	Control mix	Experimental mix	Control mix
CA/FA	FA/F1	5,729	3,887
12/0	0/0	6,121	2,930
12/25	0/25	5,729	3,263
36/25	0/0	6,121	2,190
90/0	0/0	5,729	1,595
90/25	0/0	6,121	1,436
24/0	0/0	5,729	3,365
24/25	0/25	6,121	2,495
24/25	0/25	6,121	3,249
24/25	0/25	7,614	6,585
20/20	0/25	7,614	7,687

Values estimated from graphs; after Polley (1996).
*Long-term strength (6 to 12 months), adjusted to 6% air voids.
CA = washed, coarse glass; fine glass aggregate was a consistent 35% of the total glass aggregate in the mix; FA = fly ash; F1 = fine glass powder.

by fly ash. The tensile strengths of the PCC mixes with glass aggregates were similar to those for the control mixes.

The freeze/thaw impact on the retained stiffness showed that the glass aggregate, either fine or coarse, resulted in increased freeze/thaw damage compared with the control, with 10% to 15% reduction in stiffness at 100 cycles compared with essentially no loss for the control.

ASR testing (ASTM C1260) showed that mixes with the glass aggregate increased the expansion by at least 3 to 4 times that of the control mix at 14 days, with the maximum expansion occurring for mixes with 50% glass aggregate. The reactivity had a pessimism with regard to the percent of glass in the mix.

In Korea, Park et al. (2004) evaluated glass aggregate as a replacement for fine aggregate for each of three colors of glass (amber, green, and flint). The PCC mixes contained air entrainment and latex polymer admixtures. Testing included slump, air content, and compacting factor for the fresh concrete and ASR, and compressive, tensile, and flexural strength for the hardened concrete.

Fresh concrete test results showed that the air contents were not significantly influenced by the type of glass, but did exhibit a linear increase in air content with an increase in the percent of glass aggregate. The slump and compacting factor showed the opposite trends; that is, they decreased with increasing glass content. The authors suggested that the more angular shape of the glass aggregate was responsible for the decreased workability and increased air voids.

The hardened concrete properties showed increasing relative expansion (ASR reactivity) with increasing glass content. Compressive strength decreased with glass aggregate contents above 30%. The styrene-butadiene-styrene (SBR) increased the compressive strength of the mixes for a given level of glass aggregate up to 10% SBR. Higher concentrations of the SBR then resulted in a significant decrease in compressive strength. Flexural strengths generally followed the same trends as the compressive strengths. Flexural strengths were well-correlated (nonlinearly) compressive strengths using the equation:

$$Y = -0.0004X^2 + 0.1622X$$

Where:

Y = flexural strength, and
X = compressive strength.

Tensile strengths were well correlated (nonlinearly) with the compressive strengths using the equation:

$$Y = -0.001X^2 + 0.1089X$$

Where:

Y = flexural strength, and
X = compressive strength.

Shayan and Xu (2006) in Australia evaluated glass powder as a pozzalanic material in concrete in field trials of slabs. Mixed glass powder (88% < 0.010 mm; surface area of 800 m^2/kg) and sand-sized glass cullet were used as a cement replacement at 0%, 20%, and 30% to construct 10 slabs (Table 97). A water/cement (w/c) ratio of 0.49 was used for all mixes. The ratios of cement:coarse aggregate:fine aggregate was 1:2.68:2.02. Both the w/c ratio and the blending ratios were held constant and the natural aggregates were substituted at various percentages of the appropriate coarse and fine glass cullet.

Compressive strength target of 5,800 psi was reached by only the 20% glass power at 28 days (Table 98). However, all mixes approached a compressive strength of 7,977 psi at 404 days, despite the 30% reduction in portland cement. Drying shrinkage was below 0.075% for all mixes. Dynamic modulus (ultrasonic pulse velocities) were all above 6,000 ksi at 404 days. Some indication of reduced permeability was noted, but the authors stated that more testing was needed before any

TABLE 97
EXPERIMENTAL VARIABLES FOR GLASS POWDER PCC MIXES REPORTED BY SHAYAN AND XU (2006)

Concrete	Description	Cement	SF	GLP	Coarse Agg.	Coarse Sand	Fine Sand	Crushed Glass	Water
Mix 1	Reference mix	380	0	0	1019	576	192	0	185
Mix 2	10% SF in binder	342	38	0	1019	566	189	0	185
Mix 3	20% GLP in binder	304	0	76	1019	564	188	0	185
Mix 4	30% GLP in binder	266	0	114	1019	558	186	0	185
Mix 5	10% SF in binder; 50% CGS	342	38	0	1019	283	94	356	185
Mix 6	20% GLP in binder; 50% CGS	304	0	76	1019	282	94	355	185
Mix 7	30% GLP in binder; 40% CGS	266	0	114	1019	335	112	281	185
Mix 8	30% GLP in binder;75% CGS	266	0	114	1019	141	47	523	185
Mix 9	No GLP; 50% CGS	380	0	0	1019	288	96	363	185
Mix 10	100% cement; 50% CGS, 30% GLP by mass of cement replaced fine sand	380	0	114	1019	288	36	306	185

GLP = fine glass powder; CGS = crushed glass sand; SF = silica fume; Agg. = aggregate.

TABLE 98
RESULTS FOR GLASS POWDER PCC MIXES EVALUATED BY SHAYAN AND XU (2006)
IN AUSTRALIA (VALUES ESTIMATED FROM GRAPHS IN REPORT)

Concrete	Description	Slump, in.	28-Day Density, lb/ft^3	Compressive Strength at Various Times, psi			Dynamic Modulus, ksi		
				90 Days	220 Days	404 Days	90 Days	220 Days	404 Days
Mix 1	Reference mix	3	150.3	7,324	7,687	7,687	7,397	7,687	8,122
Mix 2	10% SF in binder	3	146.1	6,019	7,252	7,252	6,019	6,092	6,237
Mix 3	20% GLP in binder	3	142.5	6,817	6,164	8,630	7,107	7,542	7,687
Mix 4	30% GLP in binder	2	145.3	5,076	5,729	5,802	5,366	6,237	6,962
Mix 5	10% SF in binder; 50% CGS	3	145.2	5,511	5,874	7,542	6,237	6,309	6,672
Mix 6	20% GLP in binder; 50% CGS	3	142.5	6,527	7,397	7,687	5,584	6,672	6,817
Mix 7	30% GLP in binder; 40% CGS	2	144.5	6,672	6,527	6,599	6,237	6,527	6,817
Mix 8	30% GLP in binder; 75% CGS	2	139.3	6,382	7,542	7,614	5,656	5,947	6,237
Mix 9	No GLP; 50% CGS	3	145.4	6,527	7,397	8,412	6,237	6,164	6,527
Mix 10	100% cement; 50% CGS, 30% GLP by mass of cement replaced fine sand		144.5	6,817	7,542	8,412	6,092	6,237	6,672

SF = silica fume; GLP = fine glass powder; CGS = crushed glass sand.

conclusions could be reached. No ASR expansion was noted in any of the glass powder mixes. The authors attributed this to the glass powder behaving like a pozzolan and therefore the alkali was not available for reactivity. SEM and EDX analyses showed that the fine glass powder particles appeared to have been consumed by the paste and converted to silicon- and calcium-rich phases that also retained large amounts of sodium. Conclusions were that the alkali originally contained in the glass was bound in the paste and crystalline materials that resulted from the pozzolanic reaction of the glass powder; it was likely no longer available for ASR product formation. Only a limited amount of possible ettringite formation (expansive reaction) in the alkali rich areas was observed.

In the United Kingdom, Taha and Nounu (2008) evaluated PCC mixes with glass powder and glass aggregate. Two supplemental cementitious materials, SCM, granulated ground blast furnace slag (GGBFS), and metakolin, were used as portland cement substitutions at 60% and 10%, respectively. The glass powder used had an average particle size of 0.045 mm and a single level of glass powder (20%) was used to replace the portland cement. Mixed glass aggregates had a particle size of less than 5 mm and were implemented as-received without any post-processing. This byproduct was used at two percentages: 50% and 100% aggregate replacement. Physical material properties are shown in Table 99. Table 100 provides a comparison of the XRF chemical analysis for the materials.

Glass aggregate in fresh PCC mixes showed a decrease in consistency and wet density with increasing glass aggregate percentages. The loss of consistency was attributed to the lack

TABLE 99
MATERIAL PROPERTIES REPORTED IN TAHA AND NOUNU
STUDY (2008)

Material	Relative Density (ton/m^3)		Water Absorption (%)
	Oven dry	SSD	
Cementitious materials			
Cement	3.14	—	—
GGBS	2.9	—	—
Metakaolin	2.6	—	—
Glass Powder	2.51	—	—
Coarse aggregate (crushed limestone)			
20 mm	2.66	2.67	0.6
10 mm	2.66	2.68	0.66
Fine aggregate (sand)			
Sea Dredge	2.6	2.63	1.0
Recycled Glass	2.5	2.51	0.6

SSD = saturated surface dry.

TABLE 100
XRF CHEMICAL ANALYSIS FOR TAHA AND NOUNU STUDY (2007)

Oxide (%)	Cementitious Materials				Sand	
	Portland cement	GGBS	Metakaolin	Glass powder	Sea dredge sand	Glass cullet
CaO	64.5	40.9	0.06	8.61	7.11	10.63
SiO_2	20.4	35.2	55.3	72.3	78.6	72.1
Al_2O_3	5.63	13.2	40.9	1.04	2.55	1.78
Fe_2O_3	2.85	0.39	0.71	0.17	2.47	0.36
MgO	1.09	7.86	0.28	3.89	0.46	1.26
Na_2O	0.18	0.29	0.15	13.31	0.42	12.4
K_2O	0.64	0.5	2.08	0.52	0.64	0.64
TiO_2	0.27	0.55	<0.05	<0.05	0.15	0.06
Mn_2O_3	0.06	0.55	<0.05	<0.05	0.1	<0.05
SrO	0.09	0.09	<0.05	<0.05	<0.05	<0.05
P_2O_5	0.16	<0.05	0.15	<0.05	0.09	<0.05
Cr_2O_3	<0.05	<0.05	<0.05	<0.05	<0.05	0.09

of fines in the glass cullet mixes. Workability was reduced because of the sharp edges and harsh texture. Segregation and bleeding were both obvious for the glass cullet mixes. Glass powder improved the workability and consistency because of the improved texture and shape of the powder particles. The wet density was still slightly reduced. The highest values of hardened properties were consistently obtained using the PCC with metakaolin SCM.

All of the mixes had 28-day compressive strengths of more than 8,000 psi. PCC mixes with the GGBFS had the lowest. The glass powder improved the compressive strengths over that of the GGBFS mixers. The glass aggregate (100%) combined with the 20% glass powder mixes had slightly lower tensile strengths when compared with the control, but slightly higher values for the static modulus.

In Portugal, Oliveira et al. (2008) evaluated finely ground glass as a replacement for aggregates in PCC. Reference mix was 1:0.29:1.87:3.14 of cement, fly ash, fine aggregate, and coarse aggregate with a w/c ratio of 0.6. Fine glass sand was used as a natural sand replacement at 25%, 50%, and 100% dosage rates.

Testing included slump, compressive strength, expansion (ASR), and capillary sorptive, as well as water and oxygen permeability. Water and permeability testing were conducted using a permeability cell that can measure the flow of oxygen through a 5 cm diameter by 4 cm high cylindrical sample. Once the oxygen flow rate was determined, the water permeability was determined. Capillary sorptive testing was conducted by drying 7.5 × 7.5 × 15 cm bars at 140°F until the weight loss was negligible. The bars were then submerged in water and the wet weight measured at the saturated surface dry condition. Various submersion times were used (10, 20, 30, 40, 50, 60, 70, 90, 130, and 150 min). Results became linear after a few minutes of testing. The sorptivity coefficient, *k*, was determined using the equation:

$$\frac{W}{A} = k\sqrt{t}$$

Where:

W = the amount of water adsorbed, kg;
A = cross section of the specimen in contact with the water, m^2;
t = time in min; and
k is the sorptivity coefficient of the specimen in $kg/m^2/min^{0.5}$.

Hardened PCC had compressive strengths that increased with age for all mixes, as expected. Mixes with amber glass sand had increasingly higher strengths with the increased percent of glass sand. Authors noted that these results were the opposite of those reported by other researchers who found glass aggregate had lower strengths than the control mix and using a high alkali content cement further decreased the strength. This was attributed to the possible influence of replacing cement with 30% fly ash in this study and changes in the amount of cement relative to the surface area of the glass aggregate. Expansion of bars in NaOH solution was below the limit of 0.1%. Sorptivity decreased with age at the time of testing for all mixes. Both 25% and 50% glass sand reduced sorptivity from about 0.24 at 28 days to about 0.18. At 100% glass sand it decreased to about 0.14 at 28 days. Oxygen permeability increased over the control for mixes with both 25% and 50% glass sand, and then decreased for the 100% glass sand mixes. At 28 days, the control oxygen permeability was about 2.25 compared with 2.50, 2.75, and 1.75, respectively. Water permeability followed a similar trend.

Conclusions included a recommendation for using a HRWR to maintain adequate workability and use fly ash to mitigate the ASR expansive reaction to use glass sand as an aggregate substitute.

Unbound

Ho et al. (1995) reported on the research work used to develop the Florida specifications for glass byproducts in highway fill. Two sources of Florida glass cullet were evaluated in this study. Testing included a range of ASTM and Florida standards as-written including sieve analysis (ASTM D136), specific gravity (ASTM D854), direct shear (ASTM D3080), CBR (ASTM D1883), limestone bearing ratio (FDOT FM-5-515), BOD (Method 5210B five day), DO (Method 4500-OC), total phosphorous (EPA single reagent method and persulfate digestion), total dissolved solids and total suspended solids, fixed and volatile suspended solids, and total Kjeldahl nitrogen.

A number of test methods were modified to specifically address glass cullet properties that differed from conventional aggregates. Maximum density was determined using a combination of Marshall and Proctor compaction hammers. The minimum density was determined using ASTM D4254 (vibratory compaction).

Constant head permeability (ASTM D2434) was modified because the test method as written maxes out the flow at 0.02 cm/s, which was constantly exceeded by the glass cullet samples. Changes included increased inflow and outflow outlets, sample diameter, and height. Four openings in the perimeter of the sample (with pinchcocks and commercial window screening) were used to replace the standard filter cloth.

Leaching solid waste (ASTM D4874) was modified and was performed using 2, 4, and 6 ft columns. A 1:1 volumetric ratio of glass to water was needed to obtain good results for the highly permeable glass cullet materials.

The specification recommendations at the end of this study included:

- Gradation requirements with a minimum of 97% passing the ½ inch sieve and a maximum of 2% passing the 0.075 mm.
- Contaminates should be no more than 1% by weight of glass cullet.
- Stockpile storage with time sufficient to minimize leachable materials and leachate must meet treated water standards.
- Glass cullet will not be placed directly on synthetic liners, geogrids, or geotextiles or left exposed to the air for extended periods of time.
- Fill will be covered with a minimum of 1 ft of topsoil or more as needed for vegetation requirements.
- Glass cullet will be compacted to a minimum density of not less than 100 lb/ft^3.
- Standard health and safety requirements need to be met.

The researchers found that glass cullet could be safely handled when it was sized to meet ASTM D448 No. 8 or finer. It was also found to be good for drainage material because of its good frictional characteristics and resistance to breakage under high confining pressures. However, the low CBR and LBR values precluded it from being recommended for use as a base or subbase course. Florida considered glass cullet as clean debris so no special permits are needed to use the byproduct as long as it was washed prior to use. The shake extraction test was used to determine organic pollutants.

In 1999, the U.S. Corps of Engineers (COE) produced a fact sheet that discusses the frost heave potential when using glass cullet in highway applications. Its Cold Regions Research Engineering Laboratory found that in freeze/thaw testing using materials with less than 1% passing the 0.075 mm sieve had very low frost susceptibility. Adding 30% by weight to gravel did not influence wear resistance (abrasion testing) or frost susceptibility. In one case, 30% glass cullet reduced the frost susceptibility.

Krivit (1999) of the Ramsey County Public Works Department in Minnesota provided a list of the six Ramsey County demonstration projects using recycled glass as an aggregate supplement, as well as project-specific comments. The author noted the bid language ". . . shall use . . ." is preferable to ". . . will be permitted . . ." to provide sufficient incentive for the contractor to use, even when there are little to no cost increases to the contractors. The downside to the required use language was that it may place an undue burden on the agency for determining the suitable availability of the glass cullet as a feedstock.

The glass supply was noticeably contaminated with sod, cans, whole bottles, and miscellaneous scrap metal. This resulted in loads of recycled materials being rejected. The recycled material supplier needed to institute additional QC procedures to ensure that there was no cross contamination of waste streams. Engineers, field inspection staff, and the construction contractor were generally not satisfied with the 100% use option. Reasons included:

- Inadequate material control
- Excess moisture content
- Safety concerns with larger size glass cullet particles
- Difficult to compact
- Offensive odor
- Construction machines behaved differently on 100% glass
- Possible future subsidence
- Poor byproduct delivery timing.

Available supply quantities were limited to approximately 8,000 tons of recycled glass per year from the one source used for the demonstration projects. Other sources might be available but very few recycling centers were considered capable of producing high-quality mixed broken glass for use as aggregate substitutes. At a 5% ratio, only 160,000 to 300,000 tons of blended aggregate could be produced per year,

TABLE 101
LIST OF PILOT PROJECTS CONSTRUCTED IN FLORIDA USING GLASS CULLET

Project Number	Project #1	Project #2	Project #3	Project #4	Project #5	Project #6
Sponsor	Ramsey County PWD	Ramsey County PWD	Ramsey County PWD	Super Cycle, Inc.	Ramsey County PWD	City of St. Paul
Month, Year	1992–1993	May–July 1997	August 1997	July 1997	June 1998	July 1998
Grade (application)	Class 5 (aggregate base)	Class 6 (throughout 6" aggregate base)	(aggregate base)	Bituminous base and Class 5 “Glasphalt” and aggregate base	Select granular borrow (first 2" to 3" of subgrade)	Granular borrow (first 2" of subgrade)
Project	Aldrich Arena parking lot	Larpenteur Avenue, Phase I	County Road D and Edgerton	County recycling center, parking lot and tipping pad	Larpenteur Avenue, Phase II	Residential paving, “Thomas/ McKubin”
Glass Pre-Processing	Unknown	Pre-crushed, screened (1/2" minus)	Pre-crushed, screened (1/2" minus)	Pre-crushed, screened (1/4" minus)	Screened, hand-picked	Screened, hand-picked
Pre-Blended	Unknown	Yes	No	Yes (into bituminous and aggregate base)	No	No
Ratio (glass to traditional aggregate)	Unknown	5%	100%	5% (nominal)	100% of first subgrade lift	100% of first subgrade lift
Approved By:	Ramsey County	Ramsey County and Mn/DOT	Ramsey County only	Super Cycle and Frattalone Paving	Ramsey County only	City of St. Paul
Spec. Wording	None	“… may use…”	“… shall use…"	“… shall use…”	“… shall use…"	“… shall use…”
Amount of Glass Used	Unknown	715 tons	108 tons	10 tons est.	128 tons (net)	122 tons
Performance Results Glass Supplier	No change NRG (Newport RDF Facility)[a]	No change Super Cycle	No change Super Cycle	No change Super Cycle	Some change (some additional quality control needed) Super Cycle	No change Super Cycle
Aggregate Producer	Unknown	Carl Bolander & Sons, Inc.	Super Cycle	Commercial asphalt	Super Cycle	Super Cycle
Cost Differential to Contractor	Unknown	$0 per ton	$0 per ton	Unknown	$0 per ton	$0
$ Paid Glass Supplier	$0	$0 per ton	About $1 per ton	$0	About $1 per ton	About $1 per ton
Cost to Process	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Environmental Impacts	Unknown	None	Minimal risk	None	Minimal risk[b]	Min. safety risk[c]

Krivit (1999).

[a] “Glass” supplied by NRG, Inc. (a subsidiary of NSP) the owner–operator of the Ramsey–Washington Counties' Resource Recovery Facility located in Newport, Minnesota.

[b] Project #5 involved a negligible increased risk of contaminated storm water run-off (see report text and Mn/DOT report for more details).

[c] Project #6 involved a negligible increased safety risk as the result of the stockpiling of glass pile overnight by the road construction contractor in a nonsecured residential area.

PWD = Public Works Department; RDF = refuse-derived fuel.

which is substantially lower than the annual production of millions of tons of aggregates per year. Table 101 lists the pilot projects constructed with glass cullet.

In Minnesota, Sibley County was paying $60 a ton for landfill glass and had a concurrent problem finding cost-effective sources of aggregates. This agency explored the use of a 10:1 ratio of gravel to glass. Both materials were fed through an aggregate crusher that produced about 100 tons of Class 5 road gravel mix. MnDOT tested the aggregate and noted the increased quality of the gravel (no test results provided) and a 1,200 ft test strip was constructed on the CSAH 6 roadway. The specification required that unwashed reclaimed glass be free draining, with a minimum depth of ground water or bedrock of 4 ft, minimum distance of 150 ft from any surface water body, and a maximum slope of 4% to any surface water body.

Based on the success of pilot projects, MnDOT and the Minnesota Office of Environmental Assistance developed a new specification that included the use of reclaimed glass as an option for Class 7 aggregates as a base course. Car windshields, other car glass, light bulbs, porcelain, laboratory glass, and glass from televisions and computers were excluded. Other specification details included a requirement for crushing operations to produce a well-graded byproduct, combined gravel/glass material must meet MnDOT specification 3138, and it shall not be used as a surfacing aggregate or shoulder surface. Reclaimed glass was limited to no more than 5% of contaminates (e.g., paper, foil, metal, corks, and wood debris).

Guidelines for estimating debris were also developed and based on the following normal aggregate sampling procedures. These guidelines recommended that when stockpiling whole bottles before blending, sample the glass within the glass pile before crushing (about 40 lb), after crushing (about 10 lb), before blending, and then conduct one visual inspection every 50 cubic yards of glass.

The steps in the recommended visual inspection procedure were:

- Select an 8 to 10 in. test pan that is about 2 in. deep.
- If whole bottles are sampled, break them into 1 in. minus size so that it will fit in the test pan.
- Place 1 to 3 lb of glass in the test pan and level the sample.
- Estimate the amount of unattached debris in the glass and compare with a reference chart for visual observations.

Safeguards and material properties were controlled by asking suppliers for a letter of certification. Glass suppliers needed to meet environmental requirements and work together with counties, recyclable collection companies, and recyclable processors to ensure the QC of the byproduct. More than 15 Minnesota counties were beginning to use glass cullet in this application.

In Pennsylvania, Wartman et al. (2004) determined the geotechnical properties of glass cullet and waste industrial glass. The authors defined glass cullet as post-consumer glass comprised of mixed colored glass fragments resulting from the breakage of glass containers, predominately food, juice, beer, and liquor bottles that could not be reused by bottle manufacturers. Waste industrial glass including such materials as broken, obsolete, and/or off-specification glass from the manufacturing of plate, window, and analytical glassware was also considered as part of the glass cullet definition. Glass from automobiles, lead crystal, television monitors, lighting fixtures, and electronics applications were excluded because of their composition and coatings.

The properties of the glass cullet used for this research showed variable levels of contaminates depending on the source (two were evaluated), including bottle labels, metal, and plastic caps (between 0.8% and 3.4%). A summary of the results is in Table 102.

The glass cullet, as-received, had variable levels of contaminates, depending on the source, including bottle labels, metal, and plastic caps (between 0.8 and 3.4%). The glass cullet toughness was higher than for typical aggregates but below

TABLE 102
MATERIAL PROPERTIES FOR THE PENNSYLVANIA PROJECTS

Test		As-Received		Post-Compaction	As-Received		Post-Compaction
		Source 1			Source 2		
		Ave.	Range		Avg.	Range	
Water Content, %		2.36	2.03–2.60	—	4.22	3.49–5.32	0.62–3.41
Debris Content, %		0.34	0.0–0.75	—	1.82	—	—
Specific Gravity		2.48	—	—	2.49	—	—
Minimum Density		1.15	1.14–1.16	—	1.27	1.23–1.30	1.72–1.75
Gradation Information	Maximum density	1.79	1.77–1.80	–	1.74	–	—
	Median grain size, D50, mm	2.24	1.85–2.62	1.6	3	2.70–3.30	—
	Coefficient of uniformity	6.2	4.3–10.0	6.5	7.2	5.4–7.0	—
	Sand content, (0.075 to 4.75 m), %	91.3	89.5–93.0	87	70	66.5–74.0	—
	Fines content (< 0.075 mm), %	3.2	0.0–5.0	6.2	1.2	0.2–2.0	—
Sieve Analysis	Sieve size, mm						
	10	100	—	100	100	—	100
	4.75	97	—	97	70	—	77
	2	50	—	55	26	—	41
	8.6	23	—	32	15	—	23
	0.43	14	—	21	8	—	14
	0.25	10	—	17	4	—	9
	0.13	8	—	11	2	—	7
	0.075	5	—	7	1	—	4
Soils Classifications	USCS	SW	—	SW	SW		SW

Wartman et al. (2004).
SW = well-graded sand.

TABLE 103
ENGINEERING PROPERTIES FOR THE PENNSYLVANIA PROJECTS

Tests		As-Received			
		Source 1		Source 2	
		Ave.	Range	Ave.	Range
LA Abrasion, %		24	—	25	—
Sodium Sulfate Soundness		6.38	—	7.1	—
Hydraulic Conductivity (cm/s)		1.61×10^{-4}		6.45×10^{-4}	
Modified Proctor	Maximum dry unit weight, lb/ft^3	116.9	—	111.4	—
	Optimum moisture content, %	9.7	—	11.2	—
Standard Proctor	Maximum dry unit weight, lb/ft^3	106.9	—	105.7	—
	Optimum moisture content, %	12.8	—	13.6	—
Direct Shear Internal Friction at Various Normal Stresses, ^{o}	0–60	—	61–63	—	59–62
	60–120	—	58–61	—	55–59
	120–200	—	63–68	—	47–55
Consolidated Drained Triaxial Internal Friction, ^{o}		—	48	47	—

Wartman et al. (2004).

most state upper limit specifications, and the freeze/thaw resistance was good with no more than 7.1% loss after 120 cycles (Table 103). Constant head hydraulic conductivity at 90% modified Proctor density showed results similar to those of typical SW natural soils indicating the glass cullet should be relatively free draining. Direct shear testing showed dilatancy behavior, which increased with increasing confining stresses.

Direct shear testing showed that a small value was obtained for cohesion that was attributed to contamination by “gummy” substances such as labels on the glass cullet. Testing considerations were needed for small punctures in the membrane. The initial membrane was greased and a second membrane was then slipped over the first. A correction factor was applied to account for the additional stiffness of the two membranes.

Environmental testing was conducted using both the TCLP and SPLP. Some variability was noted between the two sources, which was attributed to miscellaneous waste stream differences such as glass color, chemical content of label ink, specialty glass chemistries, and waste thermometers (i.e., mercury content). The test results are shown in Table 104.

Barriers noted included contracting mechanisms, existing nonperformance (material specific)-based specifications, and unnecessary cross referencing of specifications. An example was provided for one Philadelphia recycler who accepted glass and accumulated approximately 1,000 tons per month of glass

TABLE 104
TOXICITY CHARACTERISTIC SYNTHETIC PRECIPITATION LEACHING PROCEDURE RESULTS FOR PENNSYLVANIA STUDY

Trace Metal	U.S. EPA Drinking Water Standard[a] (mg/L)	Hazardous Waste Designation[b] (mg/L)	TCLP (mg/L)		SPLP (mg/L)	
			Source 1	Source 2	Source 1	Source 2
Arsenic	0.05	5	0.10	0.10	0.10	0.10
Barium	2	100	0.151	0.10	0.10	0.10
Cadmium	0.005	1	0.01	0.01	0.01	0.01
Chromium	0.1	5	0.03	0.0772	0.03	0.03
Lead	0.015	5	0.10	0.128	0.10	0.10
Mercury	0.002	0.2	0.0002	0.0002	0.00024	0.0002
Selenium	0.05	1	0.20	0.20	0.20	0.20
Silver	0.05	5	0.02	0.02	0.02	0.02

Wartman et al. (2004).
Note: All data in milligrams per liter (mg/L).
[a] U.S. EPA (1999).
[b] *SW-846*, Chapter 7.4 (Revision 3, Dec. 1994).

cullet, but had difficulty in identifying reuse applications. The recycler ended up land filling the material at a cost of $18 a ton. New York City suspended glass collection in 2002 because of a lack of reuse applications. The lack of standard test methods for characterization of material properties was also a problem. These authors would rather see the use of performance specification limits. Another example was of a local municipal engineer who also served as the recycling coordinator, who could not approve of the use of crushed glass for septic field drainage because that regulation was under the control of the Department of Environmental Protection, which in turn required the use of DOT approved aggregates.

Barriers related to specifications included material property values specified for natural materials only; considerations of different values for recycled material were not considered. For example, minimum density requirements (e.g., embankment soil requirements) failed to account for lower specific gravities of glass byproducts. Also, some specifications placed arbitrary limits, or limits based on old research, on the amount of glass. In some cases, the total exclusion of glass in the embankment material was also a barrier.

The Environmental Works (2003) in Washington reported that Washington has allowed aggregate blends with up to 15% glass cullet in ballast, shoulder ballast, crushed surface base coarse, aggregate for gravel base, gravel backfill for foundations (classes A and B), gravel backfill for walls, gravel backfill for pipe bedding, gravel backfill for drains, backfill for sand drains, sand drainage blankets, gravel borrow, bedding material for rigid and flexible pipe, foundation materials (classes A, B, and C), and bank run gravel for trench backfill. Also, 100% glass aggregate was allowed by WSDOT for backfill for walls, pipe bedding, sand drains, sand blanket, and bedding material for flexible pipe.

This report noted difficulties with using glass cullet in PCC applications that were related to ASR reactions. The use of blast furnace slag was noted as a possibility for reducing this problem, which would reduce the total alkalis in the mixture. Handling concerns focused on the potential hazards associated with fugitive dust (eye contact and inhalation). Bottle glass was derived from an amorphous or noncrystalline silica, but was classified by OSHA only as a “nuisance” dust. Dampening the cullet helped mitigate the dust problems.

Johnson (2006) provided a presentation on the Montana recycling programs. Glass cullet was post-processed using a pulverizer that was mounted on a trailer with its own generator that operates on biodiesel (Figure 18). This unit produced glass cullet both ⅜ and ⅛ inch minus byproducts. The resulting glass cullet had a rounded, rather than angular, glass particle that improved the handling safety of the byproduct.

FIGURE 18 Portable glass crushing unit used for Montana pilot projects. http://www.astswmo.org/files/meetings/2006Annual Meeting/Montana’s%20Glass%20Aggregate%20compressed %20file.pdf.

Barriers that needed to be overcome included haul distance, haul costs, low tipping fees, byproduct perception, project funding, and low quantities in one location. These barriers were overcome by establishing partnerships between federal, state, county, city, non-profits, and tribal agencies. Pilot projects included a glass parking lot, septic tank drain field, landscaping material, and flooring. Parking lot combined a GravelPave® matrix of co-joined recycled plastic rings, placed on top of a geotextile fabric and then filled with ⅜ inch minus glass cullet.

Skumatz and Freeman (2007) provided a summary of the uses for glass cullet in a number of applications (Table 105). Eight applications were noted for road, rail, and maintenance work. Another two geotechnical applications were also included.

Clean Washington Center (1996) noted that the historical use of glass in HMA applications had been limited to county roadways with maximum speeds of 40 mph, residential streets, and parking lots. The use of glass was also limited by the cost of collecting, sorting, sizing, and transporting the byproduct. Limitations noted in the document mentioned that glass particles tended to align parallel to the road surface, which resulted in reduced skid resistance. There was more of a tendency strip (i.e., have less of a bond between the asphalt and aggregate surfaces) owing to the smooth glass surfaces.

Fulton (2008) reported on the use of glass cullet as an aggregate replacement in New Zealand since 2005. Factors that were expected to provide impetus for increased use of glass cullet included:

- Limited permits for aggregate production being issued
- Need to reduce landfill use
- More costly to dump clean fill than to buy lower grade quarry material
- Growing public emphasis on sustainable practices.

TABLE 105
SUMMARY OF USES FOR GLASS CULLET

Uses	Program	Results
Base Material	Some states have set specifications for road aggregates that provides for up to 10% of reclaimed glass being blended with other aggregates as a Class 5, 6, or 7 road base materials.	It is common, well proven, and safe. Research has shown that recycled glass can actually improve the quality of gravel in an aggregate mix for road base, and can be used up to 100% as a base in some cases. Aggregate contractors use the same machines to crush glass as they use to produce aggregate. Can enhance permeability of road surface, and decrease stream runoff. Costs savings depend on aggregate prices.
Road Cover for Landfill	Use the pulverized glass at the landfill in two capacities: (1) Larger pieces can be used as a road base; (2) Smaller "sand" size glass can be used as a dust control device.	Both uses are successful. As a dust control, it works better than water because it reflects the sun and keeps the ground from drying out as quickly. As a road base, the permeability of the glass is an advantage.
Glasphalt	Use 5%–10% reclaimed glass mix with asphalt and aggregate for road surface.	Has been used for over 30 years on country roads, highways, and even airport runways. Lifetime, wear, slippage, and cracking have proven to be comparable to conventional surface materials. Reports of glass "popping" out of surface in heat, same as rocks, but more citizen complaints around glass. Satisfactory with the public in some communities, although not in all.
Airport Runway	10% reclaimed glass aggregate used for airport runway and apron surface	Installed a 3,000 x 40 ft runway about eight years ago that has worked well. Used approximately 400 tons of glass in the construction of the runway. Passes inspection of state, and, over time, skid resistance has actually increased.
Salt/Sand Mix for Roads in Winter	Mix with sand, salt, or magnesium chloride to apply to the roads and sidewalks in the winter.	Very successful as a non-slip application, it increases traction significantly for both roads and sidewalks.
Striping	Use glass as reflective material in road stripes or cross walks	Very successful, but not using much tonnage. Some DOTs have discovered that paint adheres better to glass than other aggregates. Glass also lasts longer and retains sparkle longer than other materials.
Pipe Bedding or Septic System Mounds	Lay below pipes when installing or build septic mounds	Works well and studies have found it to be technically sound. Good potential for recycled because color mix, labels, and residual sugars are not an issue. Good drainage qualities.

Skumatz and Freeman (2007).

The benefits were noted as the reduced cost of transporting glass to landfill or distant disposal sites, reduced use of landfill air space, reduced amount of virgin aggregate consumed, and improved environmental awareness/attitudes. The costs listed as associated with glass cullet use were the costs of curbside collection, crushing glass, and mixing with aggregate.

Two methods of incorporating the glass into the aggregate were evaluated. The first fed glass into the raw feed of the parent aggregate. The amount of nonglass debris was considerable with the first option. The larger pieces of glass posed a safety risk during placement. The second method involved crushing the glass separately then blending during aggregate crushing. The glass was screened over the 10 mm sieve, which eliminated most of the debris and improved the visual appearance of the byproduct. The oversized particles were periodically rejected and were primarily pulverized plastic and metal. Higher wear of the crushing plant as a result of the high silica content of the glass was noted. The daily outputs were low compared with 100% crushing of rock. The final gradations and the target values needed for the specification are shown in Table 106.

One possible advantage to glass cullet–aggregate blends was a reduced amount of water needed for obtaining the optimum water content, which may be beneficial in water restricted areas. Performance to date showed no difference between pavement sections with or without the blended base.

DOCUMENT ASSESSMENT SURVEY

Twenty-eight documents were reviewed for the use of glass cullet in highway applications. Between 23% and 28% of the documents contained information about either the byproduct or application properties, or manufacturing processes. Thirteen percent of the researchers reported chemical properties for their studies. Only 5% or less reported data for air and water quality testing. Cost information was presented in only 7% of the documents. Figure 19 provides information on the worldwide locations recently reporting glass cullet studies. Figure 20 provides a summary of the content in the literature.

TABLE 106
PROPERTIES OF MATERIALS USED
IN AUSTRALIAN STUDY

Gradation	0% Glass	5% Glass	Specification
37.5	100	100	100
19	73	74	66–81
9.5	51	54	43–57
4.75	35	38	28–43
2.26	24	25	19–33
1.18	17	18	12–25
0.6	12	12	7–19
0.3	8	8	3–14
0.15	6	4	0–10
0.075	4	4	0–7
CBR	210	270	80 min.
Clay Index	2.7	2.8	3.0 max.

Fulton (2008).

http://en.wikipedia.org/wiki/File:BlankMap-World6.svg

FIGURE 19 Locations of glass cullet research.

SUMMARY OF GLASS BYPRODUCT INFORMATION

List of Byproducts

The byproduct categories needed for glass cullet are:

- Processed glass aggregate (amber, green, flint colors)
- Powdered glass.

Test Procedures

The following ASTM test methods were identified in the glass cullet in highway application literature and the agency survey (Table 107).

Materials Preparation and Byproduct Quality Control

Information for handling and controlling the quality of the byproduct included:

- Post-processing by washing and crushing can produce acceptable physical properties.
  - Material variability is significantly reduced. For example, the specific gravity becomes much more consistent (2.40 to 2.55) when the cullet is washed, regardless of gradation.
  - Contamination by “gummy” substances such as labels on the glass cullet needs to be removed.
  - Reclaimed glass is typically limited to no more than 5% of contaminates (e.g., paper, foil, metal, corks, and wood debris).
  - Contaminates are attributed to miscellaneous waste stream differences such as glass color, chemical

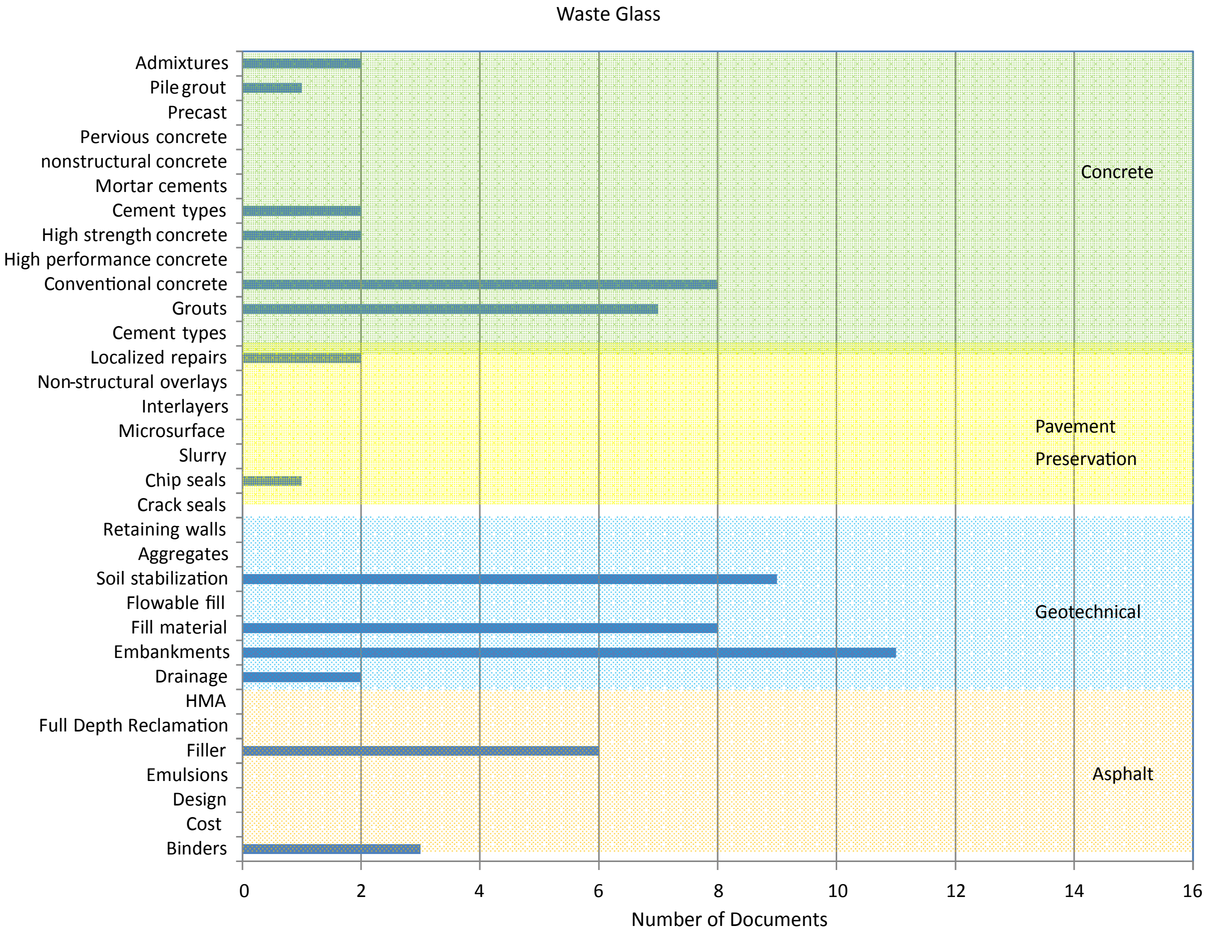


FIGURE 20 Summary of uses for glass cullet in highway applications found in the literature.

TABLE 107
TEST METHODS USED TO EVALUATE GLASS CULLET AND THEIR USE IN HIGHWAY APPLICATIONS

Test Method	Title
AASHTO M318	Standard Specification for Glass Cullet Use for Soil-Aggregate Base Course
ASTM Standards	
C1250	Standard Test Method for Nonvolatile Content of Cold Liquid-Applied Elastomeric Waterproofing Membranes
C1260	Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method)
C136	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates
C204	Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus
C618	Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete
D1883	Standard Test Method for CBR (California Bearing Ratio) of Laboratory-Compacted Soils
D2434	Standard Test Method for Permeability of Granular Soils (Constant Head)
D3080	Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions
D4254	Standard Test Methods for Minimum Index Density and Unit Weights of Soils and Calculation of Relative Density
D448	Standard Classification for Sizes of Aggregate for Road and Bridge Construction
D4874	Standard Test Method for Leaching Solid Material in a Column Apparatus
D6023	Standard Test Method for Density (Unit Weight), Yield, Cement Content, and Air Content (Gravimetric) of Controlled Low-Strength Material
D6103	Standard Test Method for Flow Consistency of Controlled Low Strength Material (CLSM)
D854	Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer

content of label ink, specialty glass chemistries, and waste thermometers (i.e., mercury content).

- Crushing operations are needed to produce a well-graded byproduct, which can be combined gravel/glass material, and the combination must meet specification requirements.

Transforming Marginal Materials

Recent research started to focus on the use of glass powder (mostly passing the 0.075 mm sieve) as a pozzolanic replacement for portland cement. The glass powder satisfied the basic chemical requirements of a pozzolan but did not comply with additional requirement for alkali content (Na_2O), which was high. However, the expansive reactions could be minimized by adding either fly ash or slag to the PCC mixes.

Handling Concerns

The following handling issues needed to be addressed when using glass cullet in highway applications:

- Crushed glass greater than about 3 mm in size are visibly identifiable as crushed glass and require heavy gloves to handle the mix safely.
  - Glass cullet can be safely handled when it is sized to meet ASTM D448 No. 8 or finer.
- Handling concerns focus on the potential hazards associated with fugitive dust (eye contact and inhalation).
- Stockpile storage time sufficient to minimize leachable materials is needed.

Design Adaptations

Most of the design adaptations were focused on adjustments needed in the design of PCC mixes:

- Expansion is a function of the percentage of the glass cullet and needs to be considered in the design phase of the project.
- As the percent increased, the water to cementitious material ratio needs to increase to maintain a consistent slump.
- Air content increases linearly with an increase in the percent glass aggregate and may require adjustments to the mix design. However, some research indicates the glass has little influence on the amount of air entrainment needed.
- A HRWR is needed to maintain adequate workability. Greater amounts of HRWR are needed to get the desired slump; the amounts were similar to those increases needed when just using fly ash.
- Fly ash can be used to mitigate the ASR expansive reaction. Blast furnace slag can also help with the expansive reaction.

HMA designs needed to address:

- HMA mixes designed for low traffic volume and slower speed roadways.
- Lower skid resistance of glass in the surface mixes when determining the most appropriate pavement layer for the mix.
- Mix designs to assess the sensitivity of HMA mixes to moisture (i.e., stripping potential).

Unbound designs needed to address:

- Low CBR and LBR values preclude glass cullet from being recommended for use as a base or subbase course.
- Decreases in the ability of the material to allow free draining when using unwashed glass cullet needs to be considered when designing embankments and fill.

- A minimum depth of ground water or bedrock of 4 ft, minimum distance of 150 ft away from any surface water body, and a maximum slope of 4% to any body of water.
- Glass cullet should not be placed directly on synthetic liners, geogrids, or geotextiles, or be left exposed to the air for extended periods of time.

Construction Concerns

Construction issues were:

- Workability may be reduced that will result in more time and effort needed to finish PCC surfaces.
- Segregation and bleeding can be obvious problems with fresh PCC mixes.

Failures, Causes, and Lessons Learned

Lessons learned from field projects included:

- Only the finer glass gradations were identifiable as “workable and finishable.”
- The glass supply was noticeably contaminated with sod, cans, whole bottles, and miscellaneous scrap metal. This resulted in loads of recycled materials being rejected. The recycled material supplier needed to institute additional QC procedures to ensure that there was no cross-contamination of waste streams.
- Engineers, field inspection staff, and the construction contractor were generally not satisfied with the 100% use in unbound options. Reasons included:
  - Material control was inadequate
  - Excess moisture content
  - Glass that was not pre-crushed exhibited sharper edges and was a concern for worker safety because of potential infections from cuts, unknown hazards (e.g., medical waste), etc. It also resulted in flatter pieces that were more difficult to compact.
  - Offensive odor
  - Possible future subsidence.
- Poor byproduct delivery timing stalled the construction process.
- Construction machines behave differently on 100% glass

Barriers

Barriers noted included:

- Contracting mechanisms
- Existing nonperformance (material specific)-based specifications
- Unnecessary cross referencing of specifications
- Haul distance
- Haul costs
- Low tipping fees
- Byproduct perception
- Project funding
- Low quantities in one location.

Costs

The benefits were noted as the reduced cost of transporting glass to landfill or distant disposal site, reduced use of landfill air space, reduced amount of virgin aggregate consumed, and improved environmental awareness/attitudes. The costs listed as associated with glass cullet use were the costs of curbside collection, crushing glass, and mixing with aggregate.

CHAPTER SIX

SULFUR AND SULFATE WASTE

SULFUR BYPRODUCTS

Background

A major byproduct from the oil and gas industries is brimstone, which is essentially elemental sulfur (Shell 2010). Sulfur, in the form of sulfuric acid, is also a byproduct of ferrous and nonferrous metal smelting. The use of sulfur as a binder to produce a construction material has been explored for more than a century (McBee et al. 1985). These early efforts used the sulfur as the binder in mortars and concretes to produce acid-resistance mixes with good strength. Research in the mid-1930s discovered that thermal properties of the sulfur mixes could be improved by adding an olefin polysulfide, marketed under the name of Thiokol. In the 1940s, sample preparation and specifications for sulfur polymer concrete were standardized by ASTM as ASTM C1312 and C1159.

Sulfur was first used in asphalt cements in the early 19th century as a product that was minimally sensitive to temperature changes and weathered well. The original use fell out of favor when air-blown asphalts began to be marketed. The substitution of sulfur for a portion of the asphalt cement was investigated in the late 1930s; however, additional development of sulfur-extended asphalts did not come along until the mid-1970s when the oil embargo increased the cost of crude oil and the availability of asphalt cement was limited. Uses of sulfur as an extender (i.e., replacement) for asphalt cement in HMA were researched.

Highway applications for sulfur include sulfur extended asphalt (SEA) and SC. Sulfur, a naturally occurring component in asphalt, can be substituted for the more expensive portland or asphalt cement. Sulfur was most commonly combined with polymers and aggregates to produce sulfur polymer concrete starting in the early 1990s. The main uses were as a rapid repair mix and to encapsulate hazardous materials (Mattus and Mattus 1994). Additional information can be found at the following website: Sulfur Institute: http://www.sulphurinstitute.org/.

Initial evaluations of the physical properties of sulfur showed the internal structural characteristic transition upon heating at about 212°F (100°C), which results in a decrease in volume (Mattus and Mattus 1994). When subjected to thermal cycling, the sulfur tended to disintegrate if some form of stabilizing admixture was not used. Shrinkage problems were overcome by using 5% of dicyclopentadiene and oligomers of cyclopentadiene (used in equal amounts to make the 5% admixture). This combination of sulfur and polymers was designated as sulfur polymer cement (SPC). When the SPC was combined with aggregates, the material was referred to as SC.

The physical propertied of sulfur polymer concrete at one day are comparable to those of conventional PCC at 28 days (Table 108). Although the air voids for both types of concrete are similar, the air voids in the sulfur polymer concrete are not interconnected as they are in conventional PCC. This property makes the sulfur mix impermeable.

Engineering Properties

Thermal coefficient of expansion for sulfur was reported as 46 µin./in.-°C between 25°C and 95°C and increased to 1,000 µin./in.-°C between 95°C and 108°C (McBee et al. 1985).

Environmentally Related Properties

Research was conducted to evaluate the potential for biological degradation as some bacteria attack elemental sulfur (Mattus and Mattus 1994). Tests at the Brookfield National Laboratory found no bacterial (e.g., thiobacilly bacteria) or fungi activity after 21 days, incubation at 95°F to 99°F (35°C to 37°C), relative humidity greater than 85%, and in the presence of nutrient agar to sustain growth. However, under certain specific circumstances such as cooling towers and in the presence of pyrite containing rock, sulfur polymer concrete was susceptible to bacterial attack. The bacterial attack resulted in the formation of sulfuric acid (metabolic byproduct).

Use and Production

Petroleum refining increased an average of 1.08% per year for 1971 through 2000. During the same period, the technological advances in emissions controls at refineries resulted in a 6.89% increase in recovered sulfur (Ober 2002; Schneider 2006). The trend in production of recovered sulfur is shown in Figure 21.

Costs

As of 2006 there was at least 15 million tonnes of stored sulfur from oil-sand oil upgraders, oil refineries, and natural gas processing plants (Schneider 2006). The storage of sulfur was an expense to these industries because of the cost of treating and neutralizing acidic water runoff. The cost of storage was as much as $3.00 per tonne in 2006 (Schneider 2006).

TABLE 108
REPORTED PROPERTIES OF SULFUR POLYMER CONCRETE COMPARED WITH CONVENTIONAL PCC

Property	Sulfur Polymer Concrete	Conventional Portland Cement Concrete
Mix Component		
Sulfur Polymer Cement, %wt	14 to 18	0
Water, %wt	0	6 to 9
Mineral Filler, %wt	6 to 9	0
Portland Cement, %wt	0	12 to 18
Sand, %wt	38 to 42	30
Coarse Aggregate, %wt	33 to 37	45
Hardened Properties		
	Properties at 1 day	Properties at 28 days
Compressive Strength, psi	7,000 to 10,000	3,500 to 5,000
Tensile Strength, psi	1,000 to 1,500	500
Flexural Strength, psi	1,350 to 2,000	535
Elastic Modulus, 10^6 psi	4.0	4.0
Moisture Absorption, %	0.0 to 0.1	0.3 to 3.0
Air Void Content, %	3.0 to 6.0	4.0
Impact Strength, compressive, ft-lb	100 to 119	81
Impact Strength, flexural, ft-lb	0.3 to 0.5	0.2
Linear Shrinkage, %	0.08 to 0.12	0.06 to 0.10
Coefficient of Thermal Expansion, µin./in.	14.0 to 14.7	
Specific Gravity	2.4 to 2.5	2.5

After Mattus and Mattus (1994).

Literature Review

Bound Applications—Sulfur Concrete

Benefits to using sulfur in concrete (Micropowder 2010) were identified as:

- Sulfur polymer concrete:
  - Gains strength rapidly (about 80% within a few hours of placement)
  - Resistant to acids such as sulfuric acid, hydrochloric acid, and nitric acid
  - Durable in corrosive environments
  - High density
  - Resists cracking
  - Resists plastic deformation.

Disadvantages to using sulfur polymer concrete were:

- Material will not burn on its own but still meets the criteria for the U.S.DOT regulations as flammable material.
- Viscosity rises sharply when the temperature is more than about 320°F (160°C). The additional polymerization in the sulfur makes the liquid that is "gummy and unpourable."
- Above 320°F (160°C) hydrogen sulfide gas or sulfur dioxide forms are poisonous and flammable.

Mattus and Mattus (1994) investigated sulfur to encapsulate low specific gravity materials such as fly ash. These researchers noted that if the sulfur and fly ash was kept hot

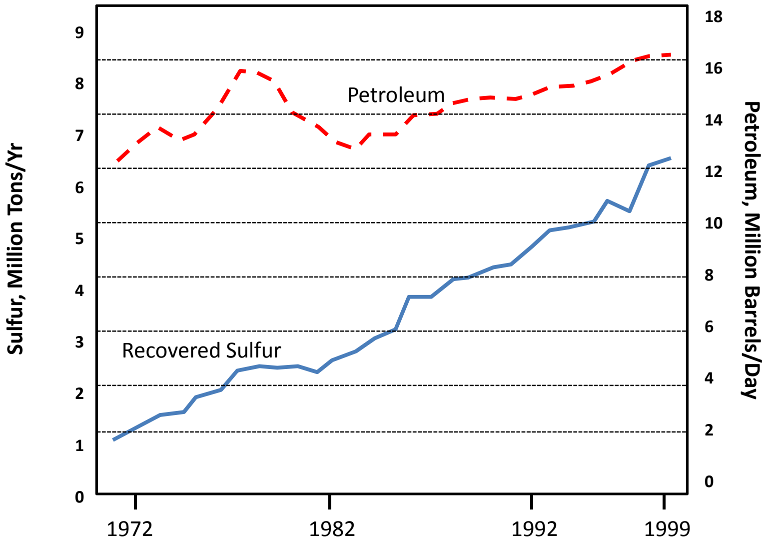


FIGURE 21 Production of sulfur from refinery processes (after Ober 2002).

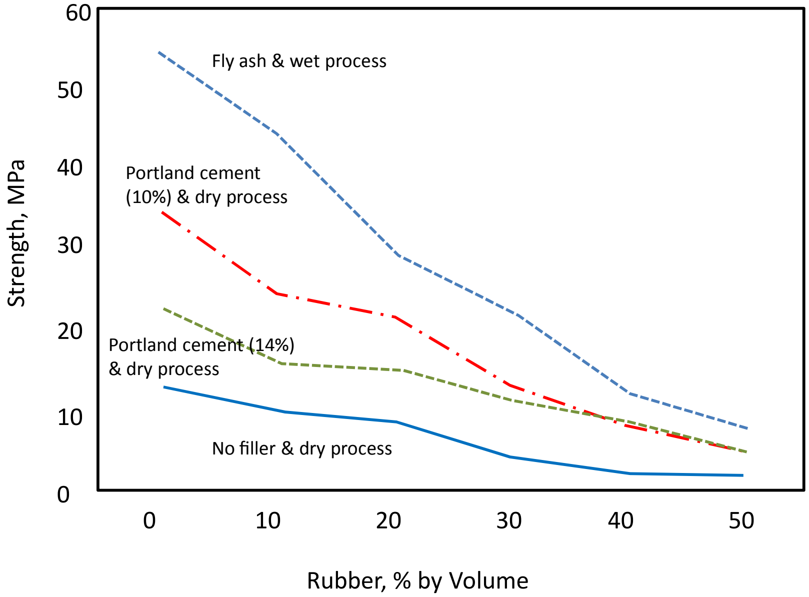


FIGURE 22 Influence of crumb rubber and sulfur as binder and aggregate replacements in conventional PCC (after Xi et al. 2004).

(i.e., liquid) for a period of time, the fly ash floated to the top of the hot sulfur. Preferred materials in need of immobilization were inorganic, low solubility compounds (e.g., sludges, precipitates, and incinerator ash). Combining sulfur with organic materials ion exchangers and highly soluble compounds was not recommended.

Construction concerns noted the need for a mixer with a heated mixer and paddle. A weir was needed for flow control as valve control was not successful. Mixing speed needed to be controlled and slow enough to prevent air entrainment. One concern was too rapid cooling of the mix under field conditions as the impermeability of the sulfur polymer concrete was compromised as a result of void formation. The nonsulfur solids needed to have very low moisture contents for proper mixing and hardened properties.

Xi et al. (2004) explored the use of crumb rubber and sulfur to prepare sulfur rubber concrete (SRC). Preparation of the SRC preheated all of the materials to 130°C to 146°C (i.e., sulfur, natural aggregates, rubber particles, and mineral fillers). The rubber was used to replace a portion of the finer natural aggregates. Two general sizes of crumb rubber were used with the large size having an average size of 4.12 mm. The small particles had an average size of 1.85 mm. The percent of replacement ranged from zero to 50%. Two types of mineral filler were evaluated (fly ash and portland cement). Materials were combined at different mixing temperatures and processing techniques (wet and dry). The wet process for preparing SRC involved mixing the sulfur with rubber particles and holding the blend at mixing temperature for a period of time. The dry process mixed the rubber particles with the aggregates before mixing.

The results showed the combination of fly ash filler and sulfur modified with crumb rubber using the wet process produced the highest strength of any of the mixes (Figure 22). Regardless of the method of adding the rubber or type of filler the strength decreased with increased rubber content.

Adeh et al. (2008) evaluated the use of sulfur, additives, mineral fillers, and aggregates in the development of a SC mixture. The research studied the influence of blending temperatures on mortar strengths (Table 109). Three different approaches were used to blend the sulfur and olefinic additive. The first of the three methods blended the materials at 130°C to 140°C and mixed for 3 h. The second method blended the two materials at 150°C to 160°C for 3 h.

As of 2010, Shell (2010c) was marketing a proprietary product, Thiocrete. Shell noted that Thiocrete had a lower carbon footprint when compared with conventional portland cement products. Even though Thiocrete was mixed at high temperatures during production, the total process used less energy than conventional cement production.

TABLE 109
INFLUENCE OF BLENDING TIME ON COMPRESSIVE STRENGTHS OF SULFUR MODIFIED MORTARS

Compressive Strength (3 days) of Mortars with Different Blending Temperatures Used for Blending Sulfur and Olefinic Additive, kg/m^3	
140°C	160°C
203	104
208	112
246	82
372	126
320	
268 Average	106 Average

After Adeh et al. (2008).

Bound Applications—SEA

Mahoney et al. (1982) reported the results from placing SEA mixes at the Washington State University test track at Pullman, Washington. The test track used a circular layout where the loading wheel revolves around the center point of the circle. The test track was capable of accommodating 12 test sections. This study used two thicknesses, one surface mix, three types of base top lift, two types of base bottom lift, and two types of subgrades.

Mix designs were conducted for three ratios of sulfur to asphalt (0:100, 30:70, and 50:50). Based on an equivalent volume basis, the optimum binder contents were established as 5.5% for the 0:100 ratio (i.e., control mix), and 6.5% and 7.4% for the 30:70 and 50:50 ratios, respectively. Researchers noted the kneading compactor used in the Hveem mix design method resulted in lower air voids when compared with Marshall compaction at the perceived optimum binder content. This would result in a lower optimum asphalt content set for the SEA mixes.

The results from the track testing and data analysis showed that the control and SEA mixes had similar fatigue characteristics, but the SEA mixes could accommodate higher bending strains at low levels of repetitions.

SEA has been used periodically over the last century (McBee et al. 1985). In 1938, SEA was used to produce a stable mix using 25% sulfur as an asphalt replacement. This early investigation did not become popular because it was not cost-effective until the oil embargo in the 1970s when the increased cost and decreased availability of asphalt cement became a concern. At this time, two approaches were explored for using sulfur as a paving material. The first approach used sulfur as a replacement for the asphalt cement, while the second evaluated its use as a structuring agent that would allow the use of lower quality aggregates. Societe Nationale Elf-Aquaitaine in Canada developed a proprietary method for pre-blending asphalt and sulfur before introduction into the HMA plant. The U.S. Bureau of Mines developed a process that used a shearing action within the HMA plant.

In the first decade of 2000, Shell started to market sulfur pellets for blending SEA binders. Three critical temperatures to be considered when using Thiopave in mixes were 240°F, which was the temperature at which the pellets melted; 300°F, which was the temperature at which H_2S generation was likely; and 265°F, which was considered the ideal discharge temperature. For safety reasons, the sulfur extended asphalt mix (SEAM) required the use of warm mix technology that was provided by the use of the wax product.

Benefits to using sulfur in asphalt cement mixes (Shell 2010a; Mattus and Mattus 1994) included:

- Increased stiffness without becoming brittle at cold temperatures
  - Use of softer, lower viscosity asphalt cements in cold climates while minimizing rutting problems during hot summer seasons.
- Better performance than conventional HMA in extremely hot or cold climates.
- Improved overall structural capacity of the pavement system.
- Can be reheated since the hardening process is thermo-setting.
- Cleaning operations are limited to making sure sulfur polymer concrete is not contaminated with other materials.

McBee et al. (1985) evaluated a number of SEA mixes. One asphalt cement (AR 2000) was modified using six levels of percent volume of sulfur (0%, 15%, 25%, 35%, 50%, and 75%). The original viscosity versus temperature relationship was decreased significantly when the asphalt was replaced with the sulfur. However, the amount of the decrease was dependent on the volume of sulfur. As the volume of sulfur increased, the difference decreased between the unmodified and modified asphalts at any given temperature.

In the production of asphalt cement concrete, the amount of each component was proportioned into the plant using weights of each component. The weight of the SEA binder to be added to achieve the optimum binder content needed to be adjusted to account for the sulfur specific gravity with the following equation:

$$\text{\% Weight of SEA} = A\left(\frac{100R}{100R - S(R-G)}\right)$$

Where:

A = asphalt content in conventional design, %wt;
R = sulfur to asphalt substitution ratio;
S = sulfur to be used in SEA binder, %wt; and
G = specific gravity of asphalt cement.

Testing of the SEA mixtures showed significant changes to the properties of the paving material. When the volume of sulfur in the compacted sample increased, the specific gravity, air voids, Marshall stability, and dynamic modulus increased.

The economic advantage for using sulfur as a replacement for asphalt cement was lost in the 1980s and remained lost until about 2008. There has been a resurgence of interest in using sulfur that has led to more advanced methods for introducing the byproduct into the HMA plant.

Stuart (1990) documented and compared the performance of SEA roadways to conventional HMA pavements that had been constructed from 3 to 7 years before. Cores were obtained from 18 projects. The sulfur was added to the mix in one of three ways (colloid mill preblending, in-line liquid blending, and direct liquid feed). Cores were taken from

TABLE 110
SUMMARY OF PAVEMENT CONDITION FOR SEA AND CONVENTIONAL HMA PAVEMENTS

State	Age	Blending Method	PCI		Deduct Values for Pavement Distresses							
					Rutting		Combined cracking		Bleeding		Potholes	
			AC	SEA	AC	SEA	AC	SEA	AC	SEA	AC	SEA
CA	4.3	C	100	100	0	0	0	0	0	0	0	0
CB-1	3.2	B	100	100	0	0	0	0	0	0	0	0
CB-2		B	100	100	0	0	0	0	0	0	0	0
DE	6.4	B, C	90	85	29	0	29	47	0	0	0	0
GA	4.6	C	87	90	16	0	16	10	0	0	0	4
ID-1	4.0	B	100	100	0	0	0	0	0	0	0	0
ID-2			95	100	0	0	0	0	0	0	0	0
KS	5.0	C	0	0	—	—	—	—	—	—	—	—
LA	6.0/7.2	B	90	87	0	0	5	11	0	0	0	12
ME–Benton 1	4.1	C	—	—	—	—	—	—	—	—	—	—
ME–Benton 2	4.1	C	87	92	0	0	47	28	0	0	0	0
ME–Benton 3	4.1	C	87	84	0	0	47	44	0	0	0	0
ME–Crystal	6.2	C	88	80	11	37	8	0	0	0	0	0
MN	7.0	C	49	79	0	0	51	61	72	0	0	26
MS	4.4	C	100	100	0	0	0	0	0	0	0	0
ND-1	4.4	C	82	80	20	14	6	4	0	0	0	0
ND-2	5.2	B	85	83	4	19	11	8	0	0	0	0
NM	3.7	B	95	100	0	0	6	0	0	0	0	0
TX–College Station	7.4	A	57	80	31	9	58	24	0	0	37	16
TX–Pecos	4.2	B	100	100	0	0	0	0	0	0	0	0
TX–Nocogdoches	5.2	C	80	85	0	0	13	24	24	0	0	0
WI	3.6	B	47	83	48	17	5	0	0	0	0	0
WY	3.7	C	82	80	15	0	49	49	0	0	0	0

After Stuart (1990).
A = colloid mill preblending.
B = in-line blending (liquid).
C = direct feed (liquid).

each of the projects. In some cases, more than one location was cored. A pavement condition survey was completed so that the pavement condition index (PCI) could be calculated (Table 110). The PCI implements the distress deduct values using a standard formulation. The PCI values varied by project and location but were not statistically different owing to the replacement of the asphalt cement with the sulfur.

Laboratory testing included the determination of core properties for diametral resilient modulus, diametral creep, moisture susceptibility, and stress-controlled-repeated load fatigue cracking (diametral) testing. The results showed no significant difference because of the sulfur on the resilient modulus properties of the mixes. There was also no significant difference in the creep modulus at 41°F (5°C); however, at 77°F (25°C) the sulfur significantly reduced the permanent deformation measured during creep modulus testing. At 104°F (40°C), sulfur slightly decreased creep modulus at short loading times and slightly increased the stiffness at longer loading times (i.e., better rut resistance). Sulfur decreased both the tensile strength ratio and the resilient modulus ratio in the older pavement cores. The values were 79.8% and 79.1% for the retained tensile strength and retained resilient modulus, respectively, for the conventional mixes, but only 67.4% and 54.9% for the sulfur mixes. The fatigue testing showed that results were similar for about 50% of the mixes and when sulfur did impact the fatigue life the sulfur decreased the fatigue life.

The composition of the mixtures was validated using solvent extraction to recover both the binder and the aggregates. Extraction could be accomplished using trichloroethylene (TCE) with the reflux method or TCE with a centrifuge if the solvent was heated to 150°F (65.5°C). The Abson recovery method was used to obtain binder samples from the cores. This recovery method significantly softened the SEA binder. Binder testing showed that the sulfur in the SEA tended to settle out while being reheated for test sample preparation. When vacuum viscosities were determined, the sulfur left a film on the sides of the glass tubes, which was difficult to remove. The SEA binder results were too variable to draw all but one conclusion. The viscosity of the 40% sulfur SEA was initially softer than the conventional asphalt by about one specification grade.

In 2007, a sulfur extended asphalt mix using 40% of Thiopave by weight of binder was placed in Qatar A conventional and HMA pavement was placed as the control section Shell (2010a). Indirect tensile stiffness testing was used to evaluate the change in stiffness over a range of temperatures. Below 86°F (30°C) the surface mixes were close in stiffness while the base course mix was about 25% higher than the control. At or above this temperature the stiffness of the base course SEA mix was about 75% higher than the control and the surface course SEA mix was about 25% higher than the control. Information reported by Shell (Palmer 2010)

TABLE 111
INFLUENCE OF THIOPAVE ON MIX PROPERTIES

Test Temperature, °C	AC 20 Stiffness, GPa			AC25, GPa		
	Thiopave	Control	Stiffness ratio	Thiopave	Control	Stiffness ratio
10	6.4	6.0	1.07	6.5	6.2	1.05
20	6.0	5.0	1.20	6.0	5.2	1.15
30	5.0	3.2	1.56	5.0	3.3	1.52

After Shell (2010d).

showed that Marshall stability of the conventional HMA was just over 1,800 lb at either 1 or 14 days. The Thiopave SEAM had a stability that was more than 10% greater than the conventional mix at 1 day and more than 80% higher at 14 days.

Laboratory research in France in 2007 evaluated the low temperature sulfur extended asphalt mix properties (Shell 2010a). The study used three penetration grades without and with 40% Thiopave. The thermal stress restrained specimen test (TSRST) was used to show that the sulfur modifier did not significantly alter the cold temperature properties of the base asphalt. Additional research with two asphalts used in the construction of Chinese test sections (Shell 2010d) showed that the stiffness modulus ratio increased with increased temperature (Table 111).

Additional research on Thiopave in asphalt concrete at the National Center for Asphalt Technology (NCAT) used stiffness modulus master curves to show the influence of the sulfur additive on material properties. The results of the testing showed that Thiopave provided more resistance to rutting than conventional HMA at slower loads and/or higher temperatures (Shell 2010d).

Transportation Research Laboratory (TRL) in the United Kingdom evaluated the impact of Thiopave on pavement deflections and design. The analysis showed the Thiopave pavement structure could potentially extend the pavement life by up to 40%. The data and analysis was also used to estimate the reduction in layer thickness that could be achieved while still maintaining a stiffness and pavement life similar to conventional mixes. A computer program, BISAR, was used to calculate expected stresses, strains, and deflection in any layer or position. The BISAR inputs were elastic modulus, Poisson’s ratio, layer thickness, and loading characteristics (i.e., imposed stress, radius of loaded area, and coordinates of loads). The results showed the HMA layer could be reduced by 10% while still achieving similar load carrying capabilities to the conventional HMA.

Environmental issues about the recyclability of SEA mixtures were evaluated at Tonghi University in China. The research used cold recycling of Thiopave RAP with emulsions to produce the recycled mix. The recycled SEAM was considered similar in properties to that of a conventionally used cold mix (Shell 2010e). No work using hot recycling was assessed for potential environmental and worker safety concerns. Shell noted that the use of Thiopave reduced greenhouse gas production (Shell 2010c) since it was produced at lower temperatures than conventional HMA.

Al-Mehthel et al. (2010) reported on the results from three test sections during construction in Saudi Arabia. The first section was placed on the Khursaniyah access road (0.33 km long, two lane road, 30:70 blend, and conventional), the second on the Shedgum–Hofuf road (0.25 km, two lanes, SEA full depth, SEA wear course, and conventional), and the third on Dhahran–Jubai expressway (500 m long, one lane wide, and 30:70 blend wear course). The Khursaniyah access road was constructed in March 2006 and pavement condition surveys were conducted in September 2006, June 2007, October 2007, September 2008, January 2009, and June 2009. No signs of distresses were observed and the PCI was consistently around 95. The Shedgum–Hofuf road was opened to traffic in early 2009 and the first pavement condition survey was conducted in December 2009. Only minor rutting in the wheel paths was noted from heavily loaded trucks. The Dhahran–Jubail expressway, a heavily trafficked roadway (2,679,465 annual vehicles), had a PCI of 98 in December 2009.

Air monitoring at the Khusaniyah construction site is reviewed in Table 112. The sulfur dioxide concentrations ranged from 0 to 8 ppm close to the source (auger), but were lower and acceptable at either the driver and foreman

TABLE 112
RESULTS FROM AIR EMISSIONS TESTING

Location of Probe	SO_2, ppm			H_2S, ppm			Remarks
	Max.	Mean	Min.	Max.	Mean	Min.	
Probe 29 to 49 cm over Auger	3.118	0.56	0.156	3.17	2.00	0.26	450°C H_2S/SO_2 analyzer
	8.0	1.89	0.0	—	—	—	S710 analyzer
Probe at Elevated Levels	0.39			0.47			Probe at driver level (2.5 m)
	0.404			0.51			Probe at foreman level (18 m)

After Al-Mehthel et al. (2010).

locations. The construction temperatures ranged from 255°F to 297°F (124°C to 147°C).

Shell Sulphur Solutions (Palmer 2010) developed a new product, Thiopave, which can be used to replace about 20% to 25% with sulfur. The percent of replacement depended on the mix design and type of project. Thiopave was described as a proprietary pelletized sulfur form that was added to the HMA plant. An organic compaction agent (wax) was also used to improve workability at lower temperatures. The recommended order of addition of materials into the plant was as follows:

1. Hot aggregate
2. RAP
3. Virgin asphalt cement
4. Wax
5. Baghouse dust
6. Thiopave pellets.

SULFATE WASTE

Sulfate rich byproducts, fluorogypsum and phosphogypsum, are the result of the production of hydrofluoric and phosphoric acid. The *fluorogypsum* byproduct (RMRC 2008; TFHRC 2010) is the result of combining fluorspar and sulfuric acid and is discharged in a slurry that solidifies over time in the holding ponds, which then needs to be crushed and separated if the byproduct is to be used. The resulting byproduct is sulfate rich with a mostly well-graded sand silt particle size (Table 113). *Phosphogysum* (RMRC 2008) is a solid byproduct from phosphoric acid production and is a byproduct from a wet process which used hydrochloric acid to treat phosphate rock. The process is outlined in Figure 23.

TABLE 113
TYPICAL CHEMICAL COMPOSITION
OF FLUOROGYPSUM

Constituents and Properties	Coarse Sulfate	Fine Sulfate
% by Weight		
Sulfate ($CaSO_4$)	71	65.6
Fluoride (F)	1.6	2.5
Free Water	8.6	10.4
Combined Water	14.9	15.2
Acidity		
pH	4.5	4.6

After TFHRC (2009).

FLUOROGYPSUM BYPRODUCTS

About 100,000 tons of byproduct is produced annually from locations in Delaware, New Jersey, Louisiana, and Texas. The deposits of byproduct are hard and require extraction using typical quarrying processes. The end result is a byproduct with a top size of about 1/5 in. and fines that are comprised primarily of sand-sized calcium sulfate particles. The specific gravities are similar to typical construction aggregates (between 2.06 and 2.50); however, the moisture content

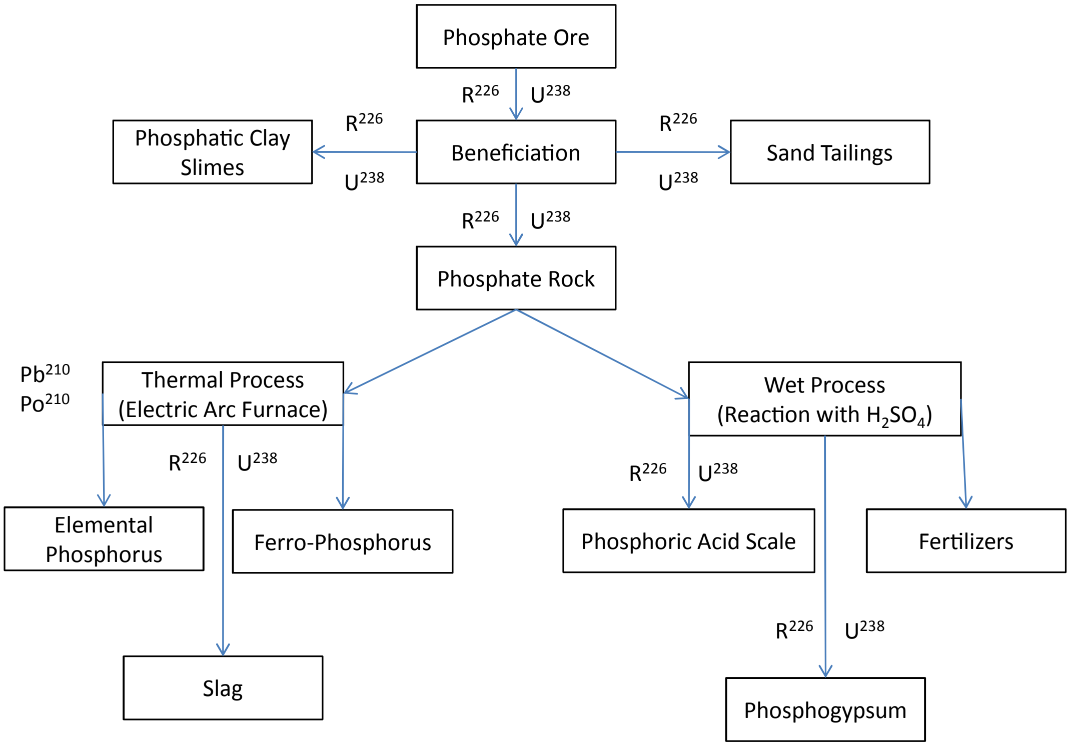


FIGURE 23 Schematic of phosphate process (after Deshpande 2003).

TABLE 114
TCLP RESULTS FOR FLUOROGYPSUM

Constituents and Properties	Values
TCLP	
Ba, mg/L	0.09
Cr, mg/L	0.11
Pb, mg/L	1.56
Ca, mg/L	422
Acidity	
pH	4.6

After Vipulanandan (1996).

varies widely. The coarser fractions have a moisture content range of from 6% to 9%, whereas the fine fraction moisture ranges from 6% to 20%.

In 1996, Vipulanandan et al. (1996) reported the internal angle of friction, cohesion, and unit weight of this byproduct as 40°, 14 psi, and 96 lb/ft^3, respectively. Gradation parameters for D_{15}, D_{50}, D_{85}, C_u, and C_c were 0.012, 0.045, 0.20, 6.9, and 0.87, respectively. The material was described as angular and well graded. The Atterberg limits were 39 for the plastic limit and 47 for the liquid limit giving a plasticity index of 8. The unconfined compressive strength was 64 psi with a wet density of 117 lb/ft^3. Table 114 shows results from the TCLP leachate testing.

PHOSPHOGYPSUM BYPRODUCTS

Phosphate ore is comprised of one-third each of quartz sands, clay mineral, and phosphate particles. Fourteen phosphate rock producing mines were active in 2001 and were located in Idaho (3), Florida (8), and one each in Utah and North Carolina. Florida produces approximately 30 million tons of phosphogypsum annually, most of which is stored. In 1989, the EPA prohibited the use of this byproduct for any purpose unless the proposed use would be at least as protective of human health as leaving it in the stack (Rush et al. 2005).

PHYSICAL AND CHEMICAL PROPERTIES

Phosphoric acid is produced from finely ground phosphate rock that contains relatively high concentrations of naturally occurring radioactive impurities of radium^{226} and uranium^{238} (Deshpande 2003). Deshpande investigated the possibility of stabilizing the phosphogypsum by binding it in blended cement. This research focused on defining the appropriate proportions of phosphogypsum, class C fly ash, and portland cement Type II combinations for PCC in marine applications. The specific objectives of the research were to develop blended cement proportions with acceptable physical and engineering properties, minimize dissolution of Ca, SO_4, Ra, and toxic metal concentrations in saltwater, and be economical. Blends with the following proportions were evaluated: 73:25:2, 67:30:3, 63:35:3 of phosphogypsum:fly ash: cement. The 73:25:2 blend proved to be the most economical at an estimated cost of $10.62 per ton (2001 year basis).

TABLE 115
RADIONUCLIDE CONCENTRATIONS IN PHOSPHOGYPSUM

Radionuclide	Concentration (pCi/g)	Half-Life (Yr)
U^{238}	6	4.9 × 109
U^{234}	6.2	2.4 × 105
Th^{230}	13	8.0 × 104
Pb^{210}	26	2.2 × 101
Ra^{226}	33	1.622 × 103
Po^{210}	26	3.78 × 101

After USEPA (1993); Deshpande (2003).

The radionuclide concentrations are shown in Table 115 and the oxides of the raw phosphogypsum are shown in Table 116; values for fly ash and cement are included in this table for comparison and the physical properties provided in Table 117. Trace metals were below the EPA standards (Table 118).

Leachate concentrations in the raw phosphogypsum exceeded the TCLP limits, but were below the limits when bound in cement (Tables 119 and 120). No information was provided about the leaching potential of recycled (crushed) blended cements.

APPLICATIONS—BOUND

Blended Cement

Guo et al. (2001) reported on the results of blended phosphogypsum, fly ash, and cement blocks used in marine environment after 1.5 years of submersion. All of the composite blocks survived with no signs of degradation. SEM, wavelength dispersive microprobe, and XRD suggests a reaction between the composites and the saltwater result in precipitation of calcite on the block surface. This deposit provides encapsulation of the composites that helps protect the blocks from saltwater attack and dissolution.

Deshpande (2003) conducted a literature review that identified a number of research projects designed to use phosphogypsum in highway applications. Applications identified in this report included roadway bases, embankments (Thimmegowda 1994), flowable fill (Gandham 1995), cement stabilized soils (Joshi 1997), synthetic lightweight fill (Holmstrom and Swan 1999). The Deshpande research focused on using the blended cements to form fill replacement materials to minimize coastal erosion.

Hot Mix Asphalt

Tao and Zhang (2006) presented findings using blended calcium sulfate (BCS), the fluorogypsum byproduct in

TABLE 116
CONSTITUENTS OF PHOSPHOGYPSUM AND OTHER BLENDED CEMENT MATERIALS

Constituent	Phosphogypsum			Components for Blended Cement	
	Louisiana	Texas	Florida	Fly ash (Type C)	Cement (Type II)
% by Weight					
CaO	29–31	32.5	25–31	27.24	63.85
SO_4	50–53	53.1	55–58	—	—
SiO_2	5–10	2.5	3–18	34.46	21.43
Al_2O_3	0.1–0.3	0.1	0.1–0.3	17.83	4.34
Fe_2O_3	0.1–0.2	0.1	0.2	6.58	5.14
P_2O_5	0.7–1.3	0.65	0.5–4.0	—	—
MgO	—	—	—	6.07	0.9
Fe	0.3–1.0	1.2	0.2–0.8	—	—
Acidity					
pH	2.8–5.0	2.6–5.2	2.5–6.0	12.2	—

After Taha and Seals (1992); Deshpande (2003).

TABLE 117
TYPICAL TRACE METALS IN PHOSPHOGYPSUM

Trace Element	Concentration (mg/L)
Arsenic (As)	1.0–5.0
Barium (Ba)	50
Cadmium (Cd)	0.3–0.4
Chromium (Cr)	2.0–5.0
Lead (Pb)	2.0–10.0
Mercury (Hg)	0.02–0.05
Selenium (Se)	1
Silver (Ag)	0.1–0.2
U_3O_8	5.0–0.0

After Deshpande (2003).

TABLE 118
PHYSICAL PROPERTIES OF RAW PHOSPHOGYPSUM

Properties	Values
Specific Gravity	2.32 to 2.35
Free Moisture, %	1 to 18
Fineness (passing the 0.075 mm)	74% to 75%
Plasticity	Little to no plasticity
Maximum Dry Density, lb/ft^3	91.7 to 104.3
Unified Soil Classification System	Silty soil (ML)

After Deshpande (2003).

cementitious blends, in pavements. The maximum dry unit weight of the BCS was 109 lb/ft^3 at an optimum moisture content of 12%. The BCS was stabilized with GGBFS (Grade 120) at 10% by weight. Curing conditions for samples to be tested required that the samples be wrapped in plastic and placed in a 100% humidity, 70°F curing room.

The samples without the GGBFS showed high initial strength (dry), but decreased substantially when exposed to moisture. Construction problems with particle degradation can be expected. The original BCS gradation was initially similar to the control limestone gradation, but became significantly finer after compaction.

The unconfined compressive strength of the GGBFS/BCS samples had unsoaked and soaked values of approximately 1,000 and 850 psi, respectively, at 28 days. Durability testing showed a fairly consistent rate of mass loss per cycle of about 5 grams per cycle and a volumetric strain (expansion) of less than 0.8% after 100 days.

TABLE 119
SUMMARY OF TRACE METALS IN BOUND PHOSPHOGYPSUM, FLY ASH, AND CEMENT SAMPLES

PG:Class C Fly Ash:Portland Type II Cement	Mean Metal Conc. in the TCLP Leachate (mg/L) ± Stand. Dev. for *n* = 3					
	Cr	Cu	Zn	Fe	Pb	Cd
73%:25%:02%	0.073 ± 0.023	0.188 ± 0.147	0.045 ± 0.012	0.986 ± 0.370	0.292 ± 0.173	0.044 ± 0.013
67%:30%:03%	0.069 ± 0.021	0.177 ± 0.097	0.044 ± 0.014	0.991 ± 0.348	0.281 ± 0.136	0.042 ± 0.011
63%:35%:02%	0.063 ± 0.019	0.173 ± 0.115	0.043 ± 0.012	0.930 ± 0.376	0.278 ± 0.126	0.043 ± 0.009
62%:35%:03%	0.078 ± 0.021	0.211 ± 0.128	0.048 ± 0.009	0.972 ± 0.348	0.339 ± 0.141	0.046 ± 0.009
EPA Toxicity Limits[1]	5.0	—	—	—	5.0	1.0

After Deshpande (2003).
1: 40 CRF 261.24 (USEPA 1999).
— = not applicable.

TABLE 120
SUMMARY OF TRACE METALS IN BOUND PHOSPHOGYPSUM, FLY ASH, AND CEMENT SAMPLES

PG:Class C Fly Ash:Portland Type II Cement	TCLP Leachate Concentration (mg/L)			
	As	Cd	Pb	Se
73%:25%:02%	0.24	0.16	0.16	0.32
67%:30%:03%	0.22	0.12	0.28	0.30
63%:35%:02%	0.18	0.10	0.16	0.14
62%:35%:03%	0.16	0.14	0.20	0.17
Raw Phosphogypsum	1.0–5.0	0.3–0.4	2.0–10.0	1.0
EPA Regulatory Limits[1]	5.0	1.0	5.0	1.0
MCL in Drinking Water	0.05	0.01	0.05	0.05

After Deshpande (2003).
[1] 40 CRF 261.24 (USEPA 1999).
MCL = maximum contaminate level (USEPA Safe Water Drinking Act, revised in 1999).

In 2009, Zhong et al. published research that reported on the use of BCS in roadway applications. The authors noted that this material has been used for more than 10 years as a base layer in Louisiana pavements. The major concern when using this material in bases was the moisture sensitivity of the byproduct. High moisture contents could result in construction problems with achieving the desired in situ densities and with long-term performance as support for the pavement structure. Three test sections were evaluated in an accelerated pavement testing facility. The testing indicated that the GGBFS stabilized BCS section significantly outperformed both the other BCS and control sections. Falling Weight Deflectometer testing indicated that the HMA layer thickness could be reduced, thereby resulting in a cost savings.

SUMMARY OF SULFATE BYPRODUCT INFORMATION

Sulfate byproducts include fluorogypsum and phosphogypsum. Only a limited amount of information was found for these byproducts. No specific test methods were found in this information. Louisiana was the only state that has evaluated blended calcium sulfate, the fluorogypsum byproduct in cementitious blends, as a base material. These byproducts needed to be bound to minimize undesirable leachates. No additional information was available with regard to materials handling, QC, design changes, or construction guidelines.

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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