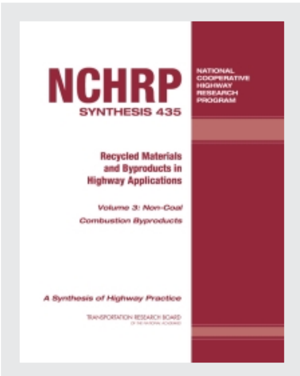

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP SYNTHESIS 435

Recycled Materials and Byproducts in Highway Applications

Volume 3: Non-Coal Combustion 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.

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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.

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NCHRP SYNTHESIS 435: Volume 3

Project 20-05, Topic 40-01

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

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

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FOREWORD

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

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

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

PREFACE

By Jon M. Williams
Program Director
Transportation Research Board

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

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

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

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

CONTENTS

CHAPTER ONE

MUNICIPAL SOLID WASTE

Minnesota defines municipal solid waste as any garbage, refuse, and other solid waste from residential, commercial, industrial, and community activities that the generator of the waste aggregates for collection, but does not include auto hulks, street sweepings, ash, construction debris, mining waste, sludges, tree and agricultural wastes, tires, lead-acid batteries, motor and vehicle fluids and filters, and other materials collected, processed, and disposed of as separate waste streams (Minnesota Statutes § 115A.03, Subd. 21). Municipal solid waste (MSW) combustion ash is the end result of burning this waste material in solid waste combustion facilities. Figure 1 shows a general schematic of a typical solid waste combustion facility and indicates the MSW byproduct collection locations within the facility. MSW fly ash, as with coal combustion fly ash, is ash removed from the air pollution control system that consists of the scrubber and fine particle removal system.

In the United States, most facilities combine air pollution control system ash byproducts into the combined ash collection location (RMRC 2008). In Europe, most facilities separate and separately manage the MSW bottom ash and MSW fly ash streams.

The two basic types of MSW solid waste combustion facilities in the United States are mass burn and refuse-derived fuel (RDF) facilities (RMRC 2008). The mass burn facilities combust unsorted solid waste, whereas the RDF facilities burn preprocessed waste. The preprocessing consists of shredding solid waste and removing ferrous metal and certain nonferrous metals prior to burning. Currently, about 15% of the total ash fraction is recovered metal material and only about 5% of all nonferrous metal is recovered from the pre-combustion MSW. Because of the difference in the waste streams being burned, the byproduct composition and characteristics will be dependent on the type of combustion facility producing the MSW byproducts.

Other MSW byproduct differences are associated with the age of the various combustion facilities. The newer facilities incorporate more advanced furnace designs and emissions controls. For example, newer facilities will add lime or lime-based reagents into the pollution control system to remove the acid gases from the gas stream. This results in both reacted and unreacted lime in the MSW fly ash. Newer emissions control systems are also more efficient in capturing finer particles in the exhaust gases, which results in changes in the physical and chemical composition of the MSW fly ashes. Additional information can be found at the following websites:

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

PHYSICAL AND CHEMICAL PROPERTIES

MSW bottom ash, approximately 90% of what is retained on the stoker or grate (bottom of boiler, Figure 1), is approximately 75% to 80% of the total combined ash byproduct. This grate material consists mainly of glass, ceramics, and ferrous and nonferrous metals and minerals. MSW bottom ash has a porous, grayish, silty sand and gravel-like appearance with small amounts of unburned organic materials and metals.

Table 1 provides information on the chemical compounds reportedly found in MSW byproducts. Table 2 shows the variation in the absorption capacity of the various MSW byproducts. The water absorption properties vary greatly between the byproducts, which will lead to very different behaviors of the byproducts in highway applications.

ENGINEERING PROPERTIES

Forteza et al. (2004) evaluated the physical and engineering properties of MSW byproducts; additional information was found on the RMRC website (2008). Table 3 summarizes this information and shows the wide range of properties that can be expected for these byproducts. Bulk specific gravities range between 1.50 and 2.22 for fine MSW bottom ash. The bulk specific gravity increases for the coarser MSW bottom ash (1.93 to 2.44). Most highway application designs are either weight or volume based. The wide range of specific gravities could lead to a high degree of variability in designs with these byproducts. Moisture content, also an important engineering consideration, can range from 22% to 66% for MSW bottom ash.

The MSW combined ash (Figure 1) tends to be slightly less variable in specific gravity, but more variable in potential moisture content when compared with MSW bottom ash. This is likely a function of the finer particle size of the combined ash, which is also likely responsible for the lower permeability of the combination ash byproduct (Table 3). Both MSW

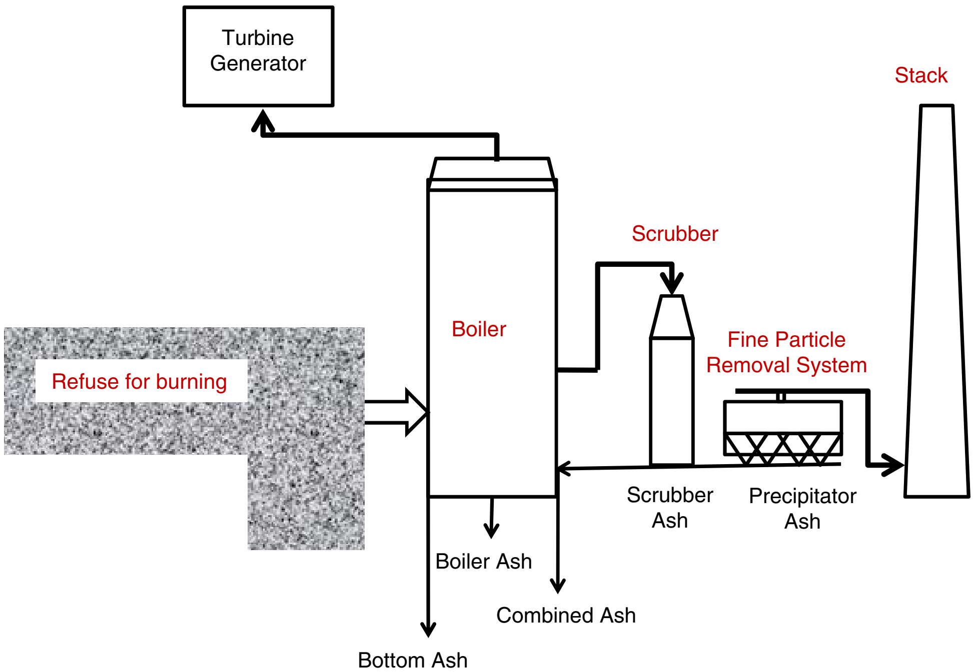

FIGURE 1 Schematic for MSW combustion process.

TABLE 1
RANGES OF MSW BYPRODUCT CHEMISTRY

Compounds	MSW Bottom Ash (%)	MSW Combined Ash (%)
SiO_2	1.68 to 27.4	13.8 to 20.5
CaO	5.12 to 10.3	5.38 to 8.03
Fe_2O_3	2.11 to 11.5	2.88 to 7.85
MgO	0.19 to 1.18	0.90 to 1.84
K_2O	0.72 to 1.16	0.84 to 1.15
Al_2O_3	3.44 to 6.48	3.26 to 5.44
Na_2O	2.02 to 4.80	2.00 to 4.62

After RMRC (2008); Chesner et al. (2000).

byproducts can produce unbound material with acceptable California bearing ration values, although the range of possible values is large. Both byproducts show a low resistance to impact damage [i.e., high LA (Los Angeles) abrasion results] and a good resistance to freeze/thaw damage (i.e., good sodium sulfate soundness results).

ENVIRONMENTALLY RELATED PROPERTIES

The predominance of metals in key constituents in MSW byproducts depends on the collection point in the combustion process. MSW bottom ash is expected to have higher concentrations of the heavier metals such as copper (Cu) and iron (Fe) than the MSW combined ashes collected from the air quality control systems (Cosentino et al. 1995a; Chesner et al. 2000). However, Table 4 shows this may not always be the case. MSW combined ashes can be expected to have higher concentrations of the more volatile trace metals such as cadmium (Cd). These two compounds have historically been the trace metals of most concern in these MSW byproducts (Chesner et al. 2000; RMRC 2008). Table 4 shows that this expectation is supported by the reported values for these trace metals.

Table 5 presents reported values for trace organic compounds and includes information for semi-volatiles, total polychlorinated biphenyls (PCBs), and dioxin/furan concentrations. In general, the MSW fly ash (not combined with other ashes) has a greater maximum concentration of

TABLE 2
WATER ABSORPTION PROPERTIES
OF MSW BYPRODUCTS

Type of Ash	Ash Fraction	Water Absorption
Bottom Ash	Coarse	4.1% to 4.7%
	Fine	12.0% to 17.0%
Combined Ash	Coarse	2.6% to 10.0%
	Fine	4.8% to 14.8%
Bottom Ash	<12.7 mm	4.50%
Combined Ash	<12.7 mm	5.70%

After RMRC (2008); TFHRC (2009).

TABLE 3
GENERAL ENGINEERING PROPERTIES OF MSW

Property	MSW Bottom Ash (Forteza et al. 2004)	MSW Bottom Ash (RMRC 2008; Chesner et al. 2000)	MSW Combined Ash (RMRC 2008; Chesner et al. 2000)
Bulk Specific Gravity	—	1.50–2.22 (Fines) 1.93–2.44 (Coarse)	1.86–2.03 (Fines) 1.96–2.24 (Coarse)
Moisture Content, % dry wt.	—	22%–66%	17%–76%
Unit Weight, lb/ft^3	—	60–86	62–73
Loss on Ignition, %	—	1.5–6.4	2.5–13.5
Sieve Size 25 mm 12.5 mm 10.0 mm 5.0 mm 2.5 mm 1.0 mm 0.5 mm 0.09 mm 0.075 mm	Est. % Passing 100 80–95 75–85 50–66 23–30 10–23 8-18 3–6 2–5	Passing 4.75 mm 42–70 Passing 0.075 mm 2–16	Passing 4.75 mm 50–70 Passing 0.075 mm 15–20
Fractured Faces	0	—	—
LA Abrasion, %	45%	55%–60% (Grading B) 41%–47% (Grading C)	44%–52% (Grading B) 36%–45% (Grading C)
Sodium Sulfate Soundness, %	—	10.4%–14.3% 1.6%–2.8% (Fines) 2.9% (Course)	2.2%–4.0% (Fines) 3.5 (Coarse)
Optimum Moisture Content, %	4.84–15.25	—	—
Maximum Density	1.67–1.79 g/cm3	79–110 lb/ft^3	79–108 lb/ft^3
CBR, %	21–103	0.1 in penetration 74–155 0.2 in penetration 104–116	— 0.2 in penetration 95–140
Sand Equivalent, %	52	—	—
Plasticity	None	—	—
Clay Lumps	0	—	—
Angle of Internal Friction	—	40°–45°	—
Proctor Compacted Permeability, cm/sec	—	10^{-3}–10^{-4}	10^{-6}–10^{-9}

After RMRC (2008).
— = data not reported.

TABLE 4
METALS FOUND IN MSW

Constituent	MSW Bottom Ash (mg/kg)	MSW Fly Ash (mg/kg)	MSA Combined Ash (mg/kg)
Ag	1.3–45	15–750	15–873
Al	47–2,000	88–9,000	160–1,000
As	3,900–12,000	3,960–270,000	22,000–250,000
Ba	0.3–61	5–2,210	7–050
Ca	22,706	2.3–1,670	—
Cd	13–1,440	20–1,900	30–670
Co	80–10,700	187–2,380	300–9,300
Cr	1,000–133,500	900–87,000	3,200–72,000
Cu	0.003–2	0.9–73	<0.13–160
Fe	750–16,000	11,000–65,800	2,300–14,400
Mg	400–26,000	2,150–21,000	1,400–22,000
Mn	50–3,100	171–8,500	250–1,350
Na	1,800–42,000	9,780–49,500	5,900–11,000
Ni	<430	10–1,970	20–340
Pb	98–6,500	200–2,600	371–22,400
Se	Not detectable—3.4	0.48–16	<1.2–12
Si	1,300–12,400	1,783–266,000	150,000–630,000
Zn	200–12,400	2,800–152,000	960–18,800

After Cosentine et al. (1995a); Chesner et al. (2000).
— = data not reported.

TABLE 5
ENVIRONMENTALLY RELATED CHEMICAL COMPOUNDS REPORTED IN MSW

Trace Organics Compound	MSW Bottom Ash (mg/kg)	MSW Fly Ash (mg/kg)	MSA Combined Ash (mg/kg)
Bis (2-Chloroethyl) Ether	—	—	—
1,3-Dichlorobenzene	—	—	—
1,4-Dichlorobenzene	—	—	—
Bis (2-Chloroisopropyl) Ether	—	—	—
N-Nitroso-N-Propyl	—	780	—
Hexachloroethane	—	—	—
Nitrobenzene	—	—	—
Isophorone	—	—	—
Bis (2-Chloroethoxy) Methane	—	—	—
1,2,4-Trichlorobenzene	—	—	—
Naphthalene	49–580	270–9,300	ND
Hexachlorobutadiene	—	—	—
2-Chloronaphthalene	—	—	—
Dimethyphthalate	—	—	—
Acenaphthylene	15–390	ND–3,500	ND
2,6-Dinitrotoluene	—	—	—
Acenaphthene	28	ND	ND
2,4-Dinitrotoluene	—	—	—
Fluorene	ND–150	0–100	ND
Diethylphthalate	ND–23	6,300	ND
4-Chlorophenyle Phenyl-Ether	—	—	—
N-Nitrosodiphenylamine	—	—	—
1,2-Diphenylhydrazine	—	—	—
4-Bromphenyl Phenylether	—	—	—
Hexachlorobenzene	—	—	—
Phenanthrene	28–540	21–7,600	ND–310
Anthracene	12–14	1–500	ND
Di-n-Butyl Phthalate	69–360	ND	ND–430
Fluoranthene	27–230	0–6,500	ND–170
Benzidine	—	—	—
Pyrene	27–220	0–5,400	ND
Butyl Benzyl Phthalate	82–180	ND	ND
Benzo(a)Anthracene	—	—	—
3,3-Dichlorobenzidine	—	—	—
Chrysene	ND–37	0–690	ND
Bis (2-Ethyhexyl) Phthalate	580–2,100	85	ND–250,000
Di-n-Octyl Phthalate	ND–65	ND	ND–2,000
Benzo(b)Fluoranthene	—	—	—
Benzo(k)Fluoranthene	ND–51	ND–470	ND
Benzo(a)Pyrene	ND–51	ND–400	ND
Indeno (1,2,3-cd) Pyrene	—	—	—
Dibenzo(ah)Anthracene	—	—	—
PCBs	Total	ND–180	ND–250
Dioxin/Furan	2,3,7.8=TCDD	0.008	ND–18
Araclor 1221	—	—	—
Araclor 1232	—	—	—
Araclor 1248	—	—	—
Total	ND–180	ND–250	—
2,3,7.8=TCDD	0.008	ND–18	<0.1–0.5
Total Phenols	—	—	—

— = data not reported.
ND = not detectable.

semi-volatiles and dioxin/furans than either the MSW bottom or MSW combined ash (Chesner et al. 2000).

Table 6 provides information on the leaching properties of the MSW byproducts. It can be noted that the results depend on both the type of MSW byproduct and the leaching test method. The dependency on the type of MSW byproduct is the result of different trace metal contents and particle sizes associated with each of the byproducts, which in turn is a function of the collection location in the combustion process. Leaching results are also dependent on the pH of the solution used for a given test method. The synthetic acid rain method simulates anticipated leaching in acid rain environments. Trace metals are more soluble in acidic solutions and tend to be less soluble in neutral or alkaline solutions. Therefore, it is necessary that estimates of leaching potential consider the pH of the water in the local environment where the byproducts will be used.

Table 7 provides estimates of the more volatile compounds that could be found in the leachate. Results were found for only the toxic characteristics leaching procedure (TCLP).

TABLE 6
LEACHING INFORMATION FOR MSW

Constituent	Bottom Ash TCLP (mg/L)	Fly Ash TCLP (mg/L)	Combined Ash-(A)-SAR (mg/L)	Combined Ash-(B)-SAR (mg/L)	
Ag	<0.025	<0.025	—	<0.025	—
As	<0.2–0.3	<0.2	0.014	<0.25	0.0013
Ba	0.26–0.73	0.5–3.4	0.24	0.12–0.7	3.23
Cd	<0.025–1	<0.025–5	0.002	<0.05	—
Cr	<0.1–0.2	<0.1	0.0004	<0.05	0.0031
Pb	<0.1–11	<0.2–19	0.059	<0.025	20.6
Hg	<0.0002	<0.0002	0.0051	0.0017	0.00312
Se	<0.1	<0.1	0.0059	<0.01	0.0063
Cu	—	—	—	<0.05–0.34	—
Fe	—	—	—	<0.05	—
Ni	—	—	—	<0.4	—
V	—	—	—	—	
Zn	—	—	—	<1.0	—
SO4	—	—	—	—	—
TDS	—	—	—	—	—

Chesner et al. (2000).
— = data not reported.

TABLE 7
LEACHATE PROPERTIES REPORTED FOR MSW

Constituent	Bottom Ash TCLP (mg/L)	Fly Ash TCLP (mg/L)
Benzene	<0.05	<0.005
Carbon tetrachloride	<0.05	<0.005
Chlordane	<0.01	<0.003
Chlorobenzene	<0.05	<0.005
Chloroform	<0.05	<0.005
o-cresol	—	—
m-cresol	—	—
p-cresol	—	—
Total cresol	<0.12	<0.12
2,4,-D	<0.0025	<0.0025
1,4-Dichlorobenzene	<0.04	<0.04
1,2-Dichloroethane	<0.05	<0.05
2,4-dinitrotoluene	<0.04	<0.013
Endrin	<0.001	<0.001
Heptachlor	<0.0005	<0.0005
Hexachlorobenzene	<0.2	<0.013
Hexachlor-1,3 butadiene	<0.04	<0.04
Hexachloroethane	<0.04	<0.04
Lindane	<0.005	<0.005
Methoxychlor	<0.025	<0.005
Methyl Ethyl Ketone	<0.1	<0.01
Nitrobenzene	<0.04	<0.04
Pentachlorophenol	<0.2	<0.2
Pyridine	<0.04	<0.04
Tetrachloroethylene	<0.05	<0.005
Toxaphene	<0.025	<0.025
Trichloroethylene	<0.05	<0.005
2,4,5-Trichlorophenol	<0.08	<0.08
2,4,6-Trichlorophenol	<0.04	<0.04
2,4,5-TP (Silvex)	<0.0025	<0.025
Vinyl chloride	<0.1	<0.01

Chesner et al. (2000).
— = data not reported.

MUNICIPAL SOLID WASTE BYPRODUCTS PRODUCTION AND USAGE

The original (1994) agency survey on the use of byproducts showed that Connecticut, Florida, Massachusetts, Minnesota, Missouri, New Hampshire, New Jersey, and New York had reported using MSW byproducts. By 2000 (Chesner et al. 2000), Missouri was dropped from the list and Pennsylvania and Tennessee were added. As of 2000, only Pennsylvania and Tennessee gave bidders the opportunity to use these byproducts as alternates (Chesner et al. 2000). The remaining states identified in the 1994 survey were only using MSW byproducts on a case-by-case basis in 2000. Of the 30 states that reported the production of MSW combustion ash byproducts as of 2000, 13 were producing low quantities (<100,000 tons per year) (Oregon, Utah, Texas, Oklahoma, Arkansas, Iowa, Wisconsin, Mississippi, Alabama, Georgia, South Carolina, North Carolina, and New Hampshire) (Chesner et al. 2000). Eight states (Washington, California, Illinois, Indiana, Michigan, Tennessee, Maryland, and Maine) were producing quantities from 100,000 to 500,000 tons per year and nine states (Minnesota, New York, Massachusetts, Rhode Island, Connecticut, New Jersey, Pennsylvania, Virginia, and Florida) were producing quantities greater than 500,000 tons per year.

A comparison of the information on state usage and production shows that while there was a large supply of MSW byproducts in 2000, there was also little use in highway applications although a number of states had experimented with such uses.

CHAPTER TWO

AGENCY SURVEY RESPONSES

The 2009 agency survey responses indicated that there has been a steady decrease in states using these MSW byproducts. The matrix used to collect MSW combustion byproduct information from state agencies in the 2009 survey (Table 8) included three choices of MSW byproducts (rows) and six major categories of highway applications (columns). A short definition of the terms was included in the response instructions. The respondents could check all choices that applied to their agency. Of the 30 states that indicated a source of MSW combustion ash byproducts in 2000, only Wisconsin and Minnesota indicated that they were actively using MSW byproducts in highway applications in 2009. Wisconsin used the MSW bottom ash in flowable fill applications, while Minnesota used the MSW combination ash in hot mix asphalt (HMA) applications. Since 1994, Kentucky has used MSW bottom ash in embankments; however, as of 2000 they did not have a source of MSW byproducts. It is possible that the RMRC 2008 survey results will help identify if Kentucky has recently acquired a source of such byproducts.

TABLE 8
SUMMARY OF THE NUMBER OF STATES USING MSW BYPRODUCTS IN HIGHWAY APPLICATIONS

Question: Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the specific type of combustion byproduct that has been used in your state, check the combustion ash, unknown type at the bottom of the list.

- MSW bottom ash: municipal solid waste combustor ash that remains at the bottom of the ash stream.
- MSW combined ash: any collection of particulate from municipal solid waste combustion process.

Municipal Solid Waste	Number of States Using MSW in Highway Applications								
	Asphalt Cements or Emulsions	Crack Sealants	Drainage Materials	Embank.	Flowable Fill	HMA	Surface Treatment	PCC	Soil Stability
MSW Bottom Ash	0	0	0	2 (KY, ND)	1 (WI)	0	0	0	0
MSW Combination Ash	0	0	0	0	0	0	0	0	0
Combustion Ash, Unknown Type	0	0	0	0	0	0	0	0	0

Embank. = embankment.

CHAPTER THREE

APPLICATIONS FOUND IN THE LITERATURE

BOUND APPLICATIONS

Asphalt Cement and Asphalt Concrete

The only research published over the last decade on MSW byproducts in asphalt and asphalt concrete applications was based on studies conducted in Oman and Taiwan. In Oman, Hassan (2005) used MSW bottom ash as a partial replacement of fine aggregate (passing the 4.75 mm sieve) in asphalt concrete mixes with 0%, 5%, 10%, 15%, 20%, 30%, and 40% by total weight of aggregate. Testing included characterization of physical properties for the MSW bottom ash (gradation and specific gravity) and leachate testing. Asphalt concrete mix testing included evaluations of optimum asphalt content by the Marshall method, moisture sensitivity (tensile strength ratio), and raveling (Cantabro method).

Results showed that the Marshall flow number became insensitive to asphalt content at MSW bottom ash contents of 10% or higher. Increasing percentages of byproduct resulted in significant increases in air voids and voids in mineral aggregate, with corresponding decreases in bulk specific gravity of the compacted samples. Significant increases in raveling potential (Cantabro test) were seen once the percentage of MSW byproduct reached 30%. Moisture sensitivity began to increase for mixes with percentages of 20% and higher. Based on these results, the authors recommended limiting the use of MSW byproduct to 15% and 20% for surface and base course mixes, respectively.

In Taiwan, Chen et al. (2008) evaluated the influence of MSW bottom ash as an aggregate substitute in asphalt concrete mixes on physical properties and the leaching potential of mixtures. The physical property testing showed a higher resistance to rutting and increase sensitivity to moisture (low tensile strength ratios). The authors recommended limiting the use of MSW bottom ash to 20% in binder or base courses and to 10% in surface mixes (percent by weight of mix). The toxicity characteristic leaching tests showed, after mixing with asphalt cement, that the concentrations of heavy metals and toxicity levels were significantly reduced. It should be noted that no assessment of cracking potential was included in the study.

Portland Cement Clinkers

A Japanese laboratory study used two types of processed MSW prior to burning: raw MSW and washed MSW (Nabajyoti et al. 2007). Both byproducts were evaluated for volatile emissions from the MSW during the clinker production. Results showed the production process generated considerable amounts of sodium (Na), potassium (K), lead (Pb), zinc (Zn), and cadmium (Cd). Researchers noted toxic elements such as Pb and Cd remained captured in the clinker. The evaluation of the cement produced from the raw MSW ash was more reactive than the cement produced from the washed MSW ash. The use of MSW in clinker reduced the demand for $CaCO_3$ from 70% (conventional clinker) to 50% when the byproduct was used.

Research conducted in Greece by Sikalidis et al. (2002) investigated using MSW byproducts in the production of clinkers. First, the MSW was separated into two fractions. The heavy fraction consisted of mainly earthen materials, stones, broken ceramics, glass, and other similar materials. The light fraction consisted mainly of paper, wood, light plastics, leather and cloth pieces, various fibers, and other similar combustible materials. The dried and crushed heavy fraction was introduced into the rotary kiln at approximately 1100°C, which is about the location in the kiln where the other raw materials are added. The light fraction was used with a mixture of pet-coke to heat the rotary kiln (jets need to be designed especially for this fuel source blend). An economic analysis showed a modified kiln that could treat about 500 tons per day of MSW and that producing about 433 tons per day of mortar would be economically profitable for processing the lightweight MSW.

Portland Cement Replacement

Italian researchers Polettini et al. (2001) investigated the mechanical behavior (setting time, unconfined compressive strength, shrinkage/expansion) of four different sources of Italian MSW fly ash byproducts (i.e., combustion ashes from air pollution control devices) used in portland cement mixes. Authors noted that MSW bottom ash, generally composed of aluminosilicate with small amounts of heavy metals, was not considered a hazardous material in the European Waste Catalogue. However, the MSW fly ash was considered hazardous because of concentrations of heavy metals, chlorinated organic compounds, and soluble salts.

Researchers found that the high concentrations of heavy metals, chlorides, and sulfates significantly altered the hydration behavior (setting time, strength gain over time) of the portland cement. A suggestion for an upper limit on MSW fly ash was 20% by weight maximum allowable content. It was noted that even at low concentrations the inclusion of the MSW fly ash significantly delayed the strength gain of the composite cement.

Filipponi et al. (2003) noted that MSW bottom ash is considered nonhazardous waste according to the European Waste Catalogue and would be acceptable material to use in concrete applications. These researchers evaluated different portland cement concrete (PCC) mixes that were prepared by blending MSW bottom ash with portland cement in varying proportions and with different water to cement ratios. In general, the MSW bottom ash was not reactive (i.e., did not contribute to cementitious properties); authors suggested treatment of the byproduct to improve pozzolanic reactions.

Italian researchers Bertolini et al. (2004) evaluated both MSW fly ash and MSW bottom ash in PCC. The MSW fly ash was subjected to a washing treatment to reduce the chloride content. The MSW bottom ash was ground with one of two methods: dry or wet grinding in a ball mill. MSW byproducts were used as a cement substitute at 30% replacement by weight. The chemical composition of the byproducts, cement, and other additives were determined with inductively coupled plasma and x-ray defraction. The workability of the fresh concrete was evaluated using both the standard slump test and the VeBe test. Hardened properties were determined for compressive strength (4-in. cubes), chloride by potentiometric titration after grinding penetration (6-in. cubes, 1.18-in. diameter cores), and corrosion rate in solutions with pH from 11 to 13.5.

Various compounds found in MSW ash are reviewed in Table 9. Although there was variation in the oxide percentage between the sources of MSW bottom ash, there were significant differences between either of the bottom ashes and the MSW fly ash. The particle size distribution after dry ball mill grinding had a D_{50} size of approximately 0.015 mm, which reduced to 0.003 mm after wet ball mill grinding. Fresh concrete properties showed a significant reduction in slump (almost zero) with 30% MSW fly ash. After compaction on a vibratory table, the MSW fly ash 28-day compressive strength was only slightly lower compared with a control PCC with 30% coal combustion fly ash.

Fresh concrete with the MSW dry grind bottom ash was similar to that of the control mix. During setting, the MSW bottom ash concrete showed significant expansion owing to the development of hydrogen gas. The authors attributed this to the presence of metallic traces of aluminum in the MSW bottom ashes, which, when in contact with the high pH in the solution, produces a high rate of corrosion. This reaction produces hydrogen gas, which was entrapped in the concrete before setting occurs. Experiments with just the MSW bottom ash in a solution of 14 pH water showed that 1 g of MSW bottom ash produced 0.15 liter of gas. Fresh mixes prepared with the wet ground MSW did not show this expansion reaction. The byproduct in this case was added to the mix in slurry form (1:1 for the MSW-water ratio). The water in the slurry was considered in overall volumetric mix design for the PCC. The authors suggested that a few days of rest after grinding may be sufficient to eliminate the expansive nature of the bottom ash.

Hardened PCC properties of the control and wet ground MSW bottom ash had similar 28-day compressive strengths, with the byproduct mix having the potential for a higher long-term compressive strength than the control. In all cases there was a significant loss of compressive strength when using the MSW fly ash in the PCC (3190 psi and 8702 psi, respectively). Resistivity of wet ground MSW bottom ash had a higher electrical resistivity at 30 days than either the control PCC or the control PCC with 30% coal fly ash (300, 80, and 160 μm, respectively). Chloride penetration was slightly lower for the wet ground MSW bottom ash than either the control or control with 30% coal fly ash at a depth of 10 mm (0.04%, 0.1%, and 0.15% by concrete mass, respectively,

TABLE 9
PERCENT OF MAJOR ELEMENTS, NOT INCLUDING CHLORIDE, CALCULATED IN TERMS OF OXIDES

Compounds	Oxides (%)				
	Cement	Fine Aggregate	MSW Fly Ash	MSW Bottom Ash (Source 1)	MSW Bottom Ash (Source 2)
Al_2O_3	4.71	6.15	10.72	10.29	6.36
Na_2O	0.32	0.19	11.34	2.46	1.72
K_2O	0.85	0.19	6.94	0.71	0.40
SO_3	3.48	0.79	8.49	1.21	3.43
CaO	62.7	6.53	37.32	13.25	15.89
Fe_2O_2	1.93	4.49	2.6	14.17	6.53
MgO	1.99	1.7	3.3	2.02	1.99
MnO_2	1.07	0.05	0.05	0.06	0.16
P_2O_5	0.15	1.07	1.55	1.08	1.77
TiO_2	0.19	0.39	—	0.38	0.85
SiO_2	23.74	78.45	14.71	53.41	61.9

After Bertolini et al. (2004).
— = date not reported.

after 6 months, 1-day cycles). The authors concluded that the wet ground MSW bottom ash could be expected to behave like a pozzolanic reaction.

Research in Slovenia by Jurič et al. (2006) evaluated the influence of MSW bottom ash on the physical properties of the paste (i.e., binder) and PCC. The workability (slump) of the PCC was reduced by about 50% when 15% MSW bottom ash was included in the paste. The density (unit weight) of the fresh concrete increased when the byproduct was included in the PCC. The hardened concrete properties showed a decrease in the 28-day flexural and compressive strength of the mortar by 4.35 to 2.9 psi (0.03 to 0.02 MPa) per percent of MSW bottom ash used in the mix (percent by weight). The authors recommended that the amount of byproduct in the cement be limited to 15% for use in low-strength concrete mixtures.

Mortars

French researchers evaluated the mechanical strength of mortars with MSW fly ash, as well as the environmental impact of these mortars (Aubert et al. 2006). Two proprietary treatments of the MSW fly ash were used to minimize problems with swelling of the mortar when MSW fly ash is used. The first treatment, REVASOL™, was based on a wash, phosphation, and calcinations of the MSW fly ash. The second treatment was a variation of the first and added sodium carbonate (Na_2CO_3) to the wash water to dissolve the metallic aluminum and sulfates. Both processes reduced swell; however, a poor stabilization of antimony and chromium is achieved.

Portland Cement Concrete

French researchers, Pera et al. (1997), evaluated the use of MSW bottom ash as an alternative aggregate in PCC. The MSW bottom ash material used passed the 20 mm sieve and was retained on the 4 mm sieve. The authors noted the MSW bottom ash properties showed lower, but still acceptable, density and strength characteristics. They also noted that the water absorption capacity was higher than typical construction aggregates. When used in PCC mixtures, the MSW bottom ash aggregate substitution resulted in swelling and cracking of the samples, which was attributed to a reaction between the cement and the metallic aluminum. A treatment with sodium hydroxide was proposed to avoid this problem. Experimentation with this approach showed that a substitution of MSW bottom ash at up to 50% of the gravel content could be obtained while minimizing swelling.

Berg and Neal (1998), U.S. researchers, found that MSW bottom ash could be considered a marginal aggregate for PCC applications. The MSW byproduct met most of the PCC-related ASTM standards such as aggregate gradation. However, the high angularity and brittle nature of the byproduct was thought to generate problems with use in PCC. They also found the sulfate and chloride concentrations to be high enough to create potential sulfate attack issues and problems if used with reinforcing steel.

French researchers, Aubert et al. (2004) evaluated the development of a physio-chemical treatment for MSW fly ash, referred to as the REVASOL™ process. The process allowed for the reduction of the soluble fraction, fixes heavy metals, and eliminates dioxins. These researchers evaluated both engineering properties (compressive strength, durability) and leaching potential of conventional concrete prepared with treated MSW fly ash. Mixes that were investigated in this study were a control mix, two mixes with treated MSW fly ash (12% and 50%) substituted for cement, and two mixes with sand substituted for cement (12% and 50%) for comparison.

Workability decreased with the increasing percentage of substitution of the treated MSW for cement. The workability of the 12% treated MSW and 12% sand fresh concrete were similar, with slumps of about 2.5 in. At the 50% levels, the treated MSW and sand mixes had slumps of 2 and 3 in., respectively; the control mix had a slump of 4.5 in.

Porosity of the hardened concrete was measured using three methods:

1. *Gas permeability:* Hardened concrete (28 days, 68°F, 100% relative humidity) specimens are sawed to eliminate surface defects and skinning, then tested dry once steady-state conditions are established according to the French AFPC–AFREM recommendations using a Cembureau permeameter.
2. *Water accessibility:* Uses the difference between the mass of a specimen dry to the mass after saturation with water.
3. *Total porosity:* Uses the bulk and absolute densities of the concrete to determine the percentage of potentially permeable voids.

The results are included in Table 10. At either 50% of sand or 50% MSW bottom ash, the permeability, porosity, and total porosity increased substantially.

Leaching tests were conducted on monolithic PPC samples (Figure 2). When the MSW is encapsulated in hardened concrete, only the chromium, copper, lead, and tin show a slight increase in the concentration in the leachate. As expected, the concentrations increased with the increasing percentage of MSW bottom ash in the mix. All concentrations were below the threshold values for the monolithic concrete samples.

Aubert et al. (2004) also evaluated the potential environmental impact when the PCC is recycled. These researchers crushed concrete to simulate recycling PCC and then reassessed the leaching potential (Figure 3). Once the concrete was crushed, all elemental concentrations increased substantially in both the crushed control and crushed MSW PCC materials. The concentrations of chromium, lead, and arsenic

TABLE 10
PERMEABILITY OF PCC MIXES

Mix	Gas Permeability ($10^{-16}m^2$)	Water Porosity (%)	Total Porosity (%)
Control	3.3–4.6	14.2–15.1	14.2–16.7
Sand, 12%	1.9–5.1	12.7–14.2	14.5–16.2
MSW, 12%	1.6–4.6	13.4– 16.9	15.9–17.2
Sand, 50%	35.8–68.0	18.5–20.7	21.5–25.4
MSW, 50%	17.9–35.6	18.1–22.5	22.7–25.0

After Aubert et al. (2004).

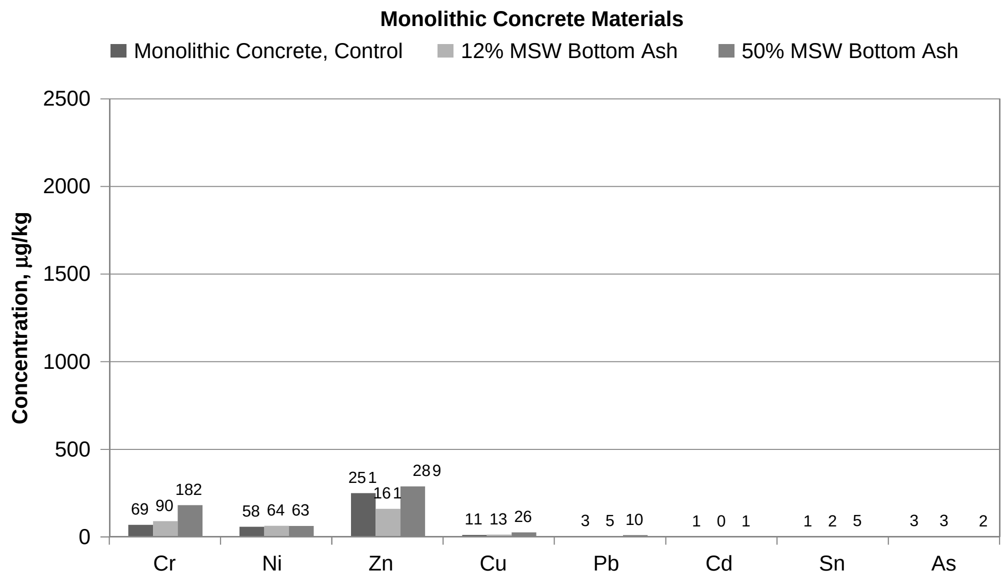

FIGURE 2 Elements leached from monolithic concrete samples (after Aubert et al. 2004).

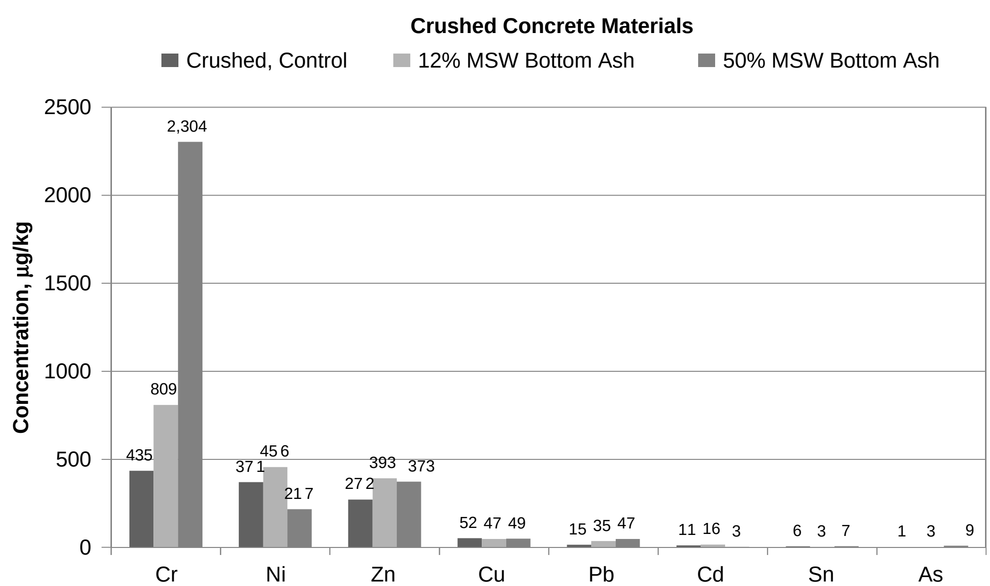

FIGURE 3 Elements leached from crushed concrete (after Aubert et al. 2004).

increased significantly over those in the control crushed PCC materials. Only the chromium exceeded the legal thresholds in the case of the crushed concrete. As with the monolithic samples, the concentrations in the leachate increased with the increasing percentage of MSW in the PCC.

Japanese researchers Horiguchi and Saeki (2004) evaluated the use of a MSW ash in the preparation of a special cement (Eco-cement) for use in controlled low strength materials (CLSM) mixes. The authors reported that acceptable leaching, strengths and flowability properties could be achieved with this specialty cement.

Stabilized Base

Danish researchers Cai et al. (2004) used MSW bottom ash and treated flue gas cleaning products and mixed each byproduct with 2.5% cement to determine the compressive strength and leaching potential over a 64-day period. The byproduct mixes had lower but acceptable strength characteristics. Heavy metal leaching results showed that the MSW bottom ash mixes had up to 100 times that of the reference (control) mixes. The results also showed Cl and Na were increased by a factor of from 20 to 100; from 2 to 10 times for K, calcium (Ca), and sulfate (SO_4); and from 5 to 50 times for copper (Cu) (50 times), Cd, Pb, and Zn (5 times). The results from Cr and nickel (Ni) were similar to the control mix.

UNBOUND APPLICATIONS

For Florida Department of Transportation (FDOT) research for MSW use in highway applications the byproducts, in general, were classified as either a well-graded or poorly graded sand (SW or SP by Unified Soil Classification System) (Cosentino et al. 1995a, b, c). Cosentino et al. (1995 a, b, c) noted that the MSW combined ash met FDOT criteria for use as highway subgrade materials. A demonstration project was constructed to evaluate engineering properties and leachate characteristics. Results for this project showed that moisture–density compaction properties, permeability, and unconfined compressive strength were a function of the compaction energy and moisture content with similar behavior of conventional fill materials. The stress–strain characteristics were similar to those for sand.

Leachate testing showed initial increases in concentrations of silver (Ag), arsenic (As), Ca, Cr, and Pb decreased over time. Although the concentrations were higher than in the control materials, none of the values exceeded the drinking water standards.

Aggregates

Researchers in Spain, Izquierdo et al. (2008) evaluated the use of MSW bottom ash as an aggregate substitute in unbound pavement layers under both laboratory and field conditions (Table 11). Although the mechanical properties of the MSW aggregates were found to be acceptable, the environmental issues were considered the most important factor to be addressed. These researchers used two leaching tests that were the single-batch Dutch availability test, NEN 7341, and the two-batch European method EN 1247. The pH from the field evaluation of the MSW byproduct increased from 7.3 to 9.2 and was slightly lower than the laboratory values predicted. The leachate also had high initial conductivity values indicating the release of elements occurring in salts. Trace

TABLE 11
SUMMARY OF SPANISH REQUIREMENTS AND MSW BOTTOM ASH PROPERTIES

Property	Spanish Requirement for Bottom Ash for Various Applications		
	Embankment and Landfill	Base and Subbase	Gravel–Cement
Particle Size, 0.08	Tolerable: <25% passing Adequate: <35% passing Select: <25% passing	0.08 mm% (2/3)(0.4 mm%)	5.4% max
Gradation Curve Shape	—	Granulometric curves ranging from S1 and S6	S3
Maximum Size	Tolerable: at least 75% passing 15 cm Adequate: 100% passing 10 cm Select: 100% passing 8 cm	Less than one-half of the compacted thickness	12.5 mm
LA Abrasion	—	<50%	45%
Proctor Values	Tolerable: > 1.45 g/cm^3 Adequate: > 1.75 g/cm^3 Select: —	No requirement	Opt. moist. 12.3% at 1.8 g/cm^3
CBR	Tolerable: > 3 Adequate: > 5 with less than 2% swell Select: > 10 and no swell	>20	90% 30 95% 56 100% 97
Sand Equivalent	—	>30% for medium and heavy traffic >25% for light traffic	52%
Plasticity	Tolerable: LL < 40 or LL < 65 and PI < 0.6 LL 9 Adequate: LL < 40 Select: LL < 30 and PI < 10	Non-plastic	Non-plastic
Organic Matter by Potassium Permanganate Method	Tolerable: <2% Adequate: <1% Select: —	—	1%

After Forteza et al. (2004).
— = data not reported; CBR = California bearing ratio.

metals showed very low release and the researchers concluded the trace metals in MSW were not a concern.

Base and Subbase

Cosentino et al. (1995 a, b, c) noted that the MSW combined ash met the FDOT criteria for use as highway subgrade materials. A demonstration project was constructed to evaluate engineering properties and leachate characteristics. The project showed that MSW combination ash provided high strength and was relatively free draining. The environmental analysis showed concentrations of As, barium (Ba), Cd, Cr, Pb, mercury (Hg), selenium (Se), and Ag concentrations were below surface water and drinking water standards with the exception of Se. This was a concern for stockpiling or using the byproducts in unbound applications.

Research in the Netherlands by Comans et al. (2000) studied the potential of a new technique to reduce the leaching potential of Cu and molybdenum (Mo). The technique was designed to increase adsorption properties of the MSW bottom ash matrix by the inclusion of sorbent minerals added to the MSW byproduct. The most likely candidates for reducing leaching potential were found to be Fe(III) and Al(III) salts and in situ precipitation of the metal(hydr)oxides. A durable reduction in the pH to near neutral of the MSW bottom ash was also found to be a major factor in controlling the leaching of Cu and Mo.

A U.S. literature review by Chesner et al. (2000) noted that one or more of the following states were exploring the use of MSW byproducts as partial aggregate replacements in stabilized and granular bases as of 2000: Connecticut, Florida, Massachusetts, Minnesota, New Hampshire, New Jersey, and New York. International use of MSW combustion ash was limited to MSW bottom ash in these applications in the Netherlands, Denmark, Germany, and France.

French research by Bruder-Hubscher et al. (2001) evaluated the environmental impact of MSW bottom ash in two field test sections. Results monitored over three years showed minimal impact when compared with test sections constructed with natural materials.

In Spain, Forteza et al. (2004) evaluated the use of MSW byproducts in road base applications. These researchers evaluated the physical and engineering properties of the MSW byproducts to determine if they could be substituted for aggregates in bases. The MSW bottom ash had acceptable aggregate and soil-related properties (see previous section). The environmental parameters evaluated were pH, conductivity, chloride content, sulfates, aluminum (Al), As, Ca, Cd, Cr, Cu, Fe, Hg, K, magnesium (Mg), manganese (Mn), Na, Ni, Pb, tin (Sn), and Zn. The authors concluded that trace metals did not pose an environmental problem.

By Spanish standards, MSW bottom ash met all requirements for soils classified as adequate. The Spanish embankment and landfill classification system had requirements for tolerable, adequate, and select soils. Table 3 provides the engineering properties of the bottom ash and the Spanish requirements for embankments and landfills as well as for base and subbase materials.

Swedish research by Åberg et al. (2006) evaluated the leaching potential trace metals and chlorides when MSW bottom ash is used as a base material under asphalt concrete pavements. One full-scale field section was constructed using MSW bottom ash and another section using gravel (control section). The highest mobility metals and anions in the leachate were Cl, Cu, and Cr; the Cl and Cu concentrations decreased with time (over 12 months). The mobility of the Cr decreased over time. The concentrations of lead were very low over the 12-month monitoring period, and the authors attributed this to iron oxides. Prediction models (regression equations) were useful in predicting Ni, Pb, Zn, and Cu concentrations, but were less reliable for predicting Cd and Cr. The lack of accuracy was attributed to changes in pH and liquid to solid ratio values between the laboratory and field testing conditions. The regression equations used in the analysis were:

$$\mathrm{Log10}(\mathrm{Cd}) = 4.2 - 0.22x - 0.04y - 0.004xy - 0.03x^2$$

$$\mathrm{Log10}(\mathrm{Cr}) = 7.7 - 1.9x + 0.11x^2$$

$$\mathrm{Log10}(\mathrm{Cu}) = 10.8 - 1.9x - 0.02y + 0.11x^2$$

$$\mathrm{Log10}(\mathrm{Pb}) = 11.0 - 2.3x + 0.12x^2$$

$$\mathrm{Log10}(\mathrm{Zn}) = 6.9 - 0.23x - 0.03x^2$$

$$\mathrm{Ni}^{0.5} = 126 - 21.4x - 1.2y + 0.12xy + 0.87x^2$$

Where:

x = pH
y = liquid/solid ratio

Another Swedish research project was conducted by Lidelow and Lagerkvist (2006) that evaluated full-scale field test sections; these were monitored for three years. The main elements in the leachate included Al (12.8–85.3 mg/l), Cr (2–125 µg/l), and Cu (0.15–1.9 mg/l) from the MSW bottom ash sections. The crushed rock sections showed concentrations of Zn (1–780 µg/l). The initial release of compounds from the MSW bottom ash sections included Cl^- (about 20 g/l). After three years, the Cu and Cl^- were similar in concentration to the crushed rock sections. However, the Al and Cr was still more than one order of magnitude higher in the MSW bottom ash sections compared with the crushed rock sections after three years. During rain events, diluted salt compound concentrations increased. Researchers noted that the laboratory results for evaluating the leachate from the crushed rock materials did not agree with the field results. However, the results agreed fairly well for the MSW bottom ash materials.

French researchers Bouvet et al. (2007) specifically evaluated the leaching of Pb from MSW bottom ash when used in roadway base applications. Findings from this study indicated that the release of lead when water conditions have a neutral pH (about 7) was very low (<2%). The release percentage increased with a water pH of 4 and ranged from 4% to 47%.

In Denmark, Hjelmar et al. (2007) placed and evaluated six large-scale field test sections placed in October 2002. Three of the sections used different MSW bottom ashes as sub-base materials under asphalt concrete test sections. Comparisons between the water quality from the field sections and laboratory studies showed good agreement in results for salts but less agreement for some trace elements. The differences between the laboratory and field results were attributed to differences in the pH of the water between laboratory and field experiments.

In Spain, Vegas et al. (2008) conducted a detailed characterization of material properties for three byproducts: construction and demolition waste, slag, and MSW bottom ash. The findings indicated that fresh MSW bottom ash could be suitable for roadway base material as long as it does not contain high concentrations of soluble salts. The authors noted fresh MSW bottom ash had higher concentrations of soluble salts than weathered MSW bottom ash.

Other Spanish researchers, Izquierdo et al. (2008), also compared the results of leaching evaluations (NEN 7341, EN 12457) and found reasonable agreement between the lab and field. In addition, these researchers developed estimates of depletion periods of extractable fractions for a number of elements in field conditions. Compounds that were readily depleted included Na, K, or Cl^- salts with more than 50% of the compounds leaching out in the early stages of testing. The elements lead and vanadium (V) also followed this trend. Other elements that showed delayed depletion (i.e., needing additional extractions) including Al, titanium (Ti), Cu, cobalt (Co), Ni, Zn, Cr, As, and Se. The authors related this delayed leaching to the ionic strength of the initial leachate. Slightly soluble salts of Ca, Mg, and rubidium (Rb) were found to have progressive depletion. Other elements with progressive depletion behavior included tungsten (W) and antimony (Sb). Slow (delayed) depletion behavior was noted for SO_4^{2-}, strontium (Sr), Ba, bromine (B), Mo, and silicon (Si).

Embankments and Flowable Fill

The RMRC website (2008) indicated that European experience in MSW use in embankments encompassed more than 20 years, whereas the United States has only evaluated use in fills as demonstration projects. Internationally, the Netherlands, Denmark, France, and Sweden have used MSW bottom ash in a limited number of embankment applications. Only Denmark was identified as having some experience with this byproduct in either backfills or flowable fills (Chesner et al. 2000).

Life-Cycle Cost Assessment

Life-cycle cost assessment programs differ from life-cycle cost analysis programs in that they consider both financial costs as well as resource, energy consumption, environmental impact, construction, operation, and maintenance (including the use of roadway salts) over the life of the pavement. Birgisdottir et al. (2005, 2006) used the ROAD-RES (Denmark) program for life-cycle cost assessment, developed at the Technical University of Denmark, to evaluate two different scenarios. The first scenario was the control with only natural materials and the second scenario used MSW bottom ash as a replacement for gravel in the sub-base layers. This evaluation showed only marginal differences in the environmental impacts (primarily emissions from fuel consumption) and resource consumption. Ground-water contamination leaching potential was linked to the use of road salt rather than the MSW bottom ash.

CHAPTER FOUR

DOCUMENT ASSESSMENT SURVEY

Most of the recent literature on the use of MSW byproducts in highway applications was found in international reports and papers. The NCHRP 4-21 report in 2000 indicated that the Netherlands, Denmark, Germany, France, and Sweden had some experimentation work in progress. These countries have also consistently been publishing research over the past decade. In addition, the Netherlands, Spain, Greece, Italy, and Japan have begun to report MSW byproduct research in highway application. Figure 4 shows the general locations for world-wide research found in the literature. Figure 5 summarizes the highway applications using MSW byproducts contained in the literature. A number of documents were found that considered uses in unbound applications, especially base and soil stabilization applications. Bound applications evaluated by researchers included asphalt concrete and PCC. The assessment of the type and quantity of information in the literature included documents referenced in the body of this chapter as well as addition documents listed at the end of the reference section.

FIGURE 4 Geographical locations of MSW in highway application research.

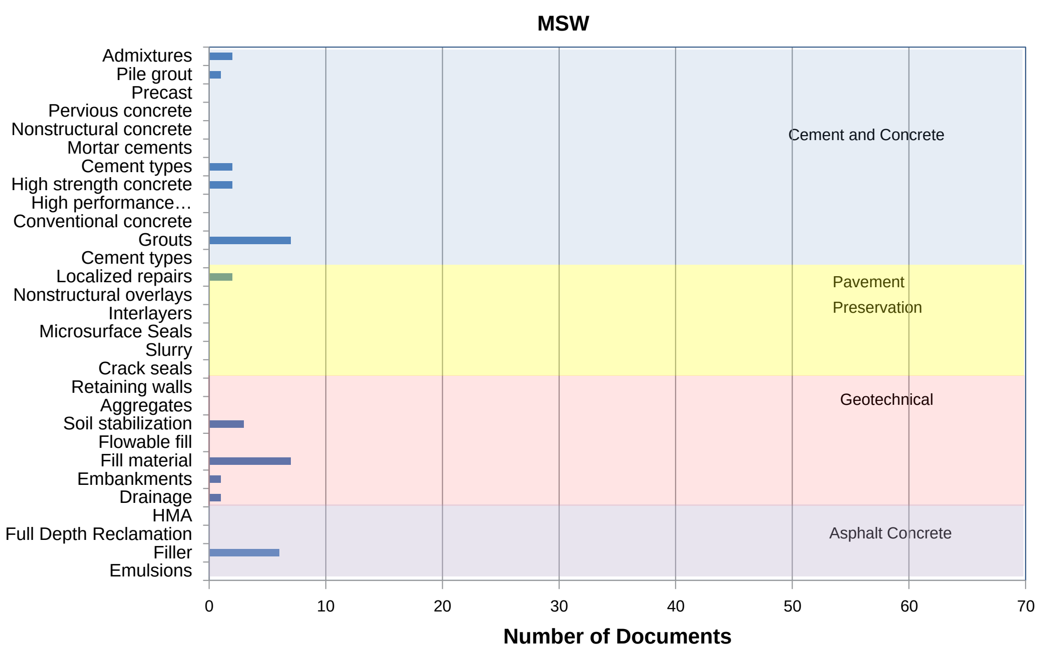

FIGURE 5 Highway application information available in the MSW byproduct literature.

CHAPTER FIVE

SEWAGE SLUDGE ASH BYPRODUCTS

Sewage sludge ash is the byproduct generated by the combustion of dewatered water treatment plant sewage sludge in one of two types of incinerator facilities. One type of facility is the multiple hearth; approximately 80% of the systems in the United States are this type. The second type of system, which is less frequently used in the United States, is a fluidized bed configuration (RMRC 2008). The multiple hearth facility is typically comprised of a circular steel furnace with a number of solid refractory hearths and a central rotating shaft. The dewatered sludge, usually with about 20% solids, is introduced into the furnace. Cooling air is used to prevent overheating; spent air is recirculated (i.e., combustion air; see Figure 6). The flue gases are scrubbed (air pollution control system) and particles removed.

The fluidized bed facility configuration consists of a vertical cylindrical vessel with a grid in the lower portion to support a bed of sand. The dewatered sludge is introduced into the vessel above the sand bed, and combustion air flows upward and fluidizes the mixture of hot sand and sludge (RMRC 2008).

PHYSICAL AND CHEMICAL PROPERTIES

Sewage sludge ash is mostly silty with some sand-like material, with most of the particles less than the 0.075 mm sieve. Sewage sludge ash has a low percentage of organic compounds. Table 12 shows some estimates found for oxide compound percentages reported by Chesner et al. (2000) and on the RMRC website (2008). As with other combustion ash byproducts, there is a wide range of concentrations in sewage sludge ash. Table 13 shows the range of concentrations of trace constituents of interest reported in sewage sludge ash.

ENGINEERING PROPERTIES

General materials properties were found in the literature (RMRC 2008). Table 14 shows that the particle size is consistent with a typical mineral filler size that is predominately passing the 0.075 mm sieve. In some cases, a significant fraction may be retained on the 0.21 mm sieve (27% for the Khanbiluardi source). The typical moisture content is well below 1%. The specific gravity of the byproduct is toward the upper end of those typically seen in construction aggregates (2.44 to 2.99), and the corresponding water absorption capacity is less than 2%.

ENVIRONMENTALLY RELATED PROPERTIES

Chesner et al. (2000) reported that a wide range of constituents can be expected in leachate from sewage sludge ash (Table 15). Higher concentrations of trace metals can be expected from facilities processing sewage sludge waste from industrial sources than from domestic waste water treatment plants. Trace metal concentrations such as Cd, Cu, and Zn in sewage sludge ash are usually found in higher concentrations than found in natural fillers or aggregates (RMRC 2008).

Chesner et al. (2000) reported no trace volatile organic information was found in their literature review. Table 16 shows very few organic compounds reported as leaching out of sewage sludge ash (distilled water in testing).

PRODUCTION AND USAGE

The 1994 agency survey showed that six states were evaluating using sewage sludge ash in highway applications (Minnesota, Illinois, New York, Vermont, New Hampshire, and New Jersey). In 2000, Chesner et al. reported that sewage sludge ash was being produced in 33 states. Michigan, Ohio, Pennsylvania, New York, Massachusetts, Connecticut, New Jersey, Virginia, and California were producing more than 50,000 tons per year. Alaska, Washington, Minnesota, Iowa, Missouri, Louisiana, Tennessee, Florida, Georgia, North Carolina, West Virginia, and New Hampshire were producing between 10,000 and 50,000 tons per year. Oregon, Nevada, Texas, Kansas, Nebraska, Wisconsin, Indiana, Arkansas, and South Carolina each produced less than 10,000 tons per year. Chesner also reported only Oregon, Minnesota, Ohio, and New York were exploring the potential use of sewage sludge by 2000.

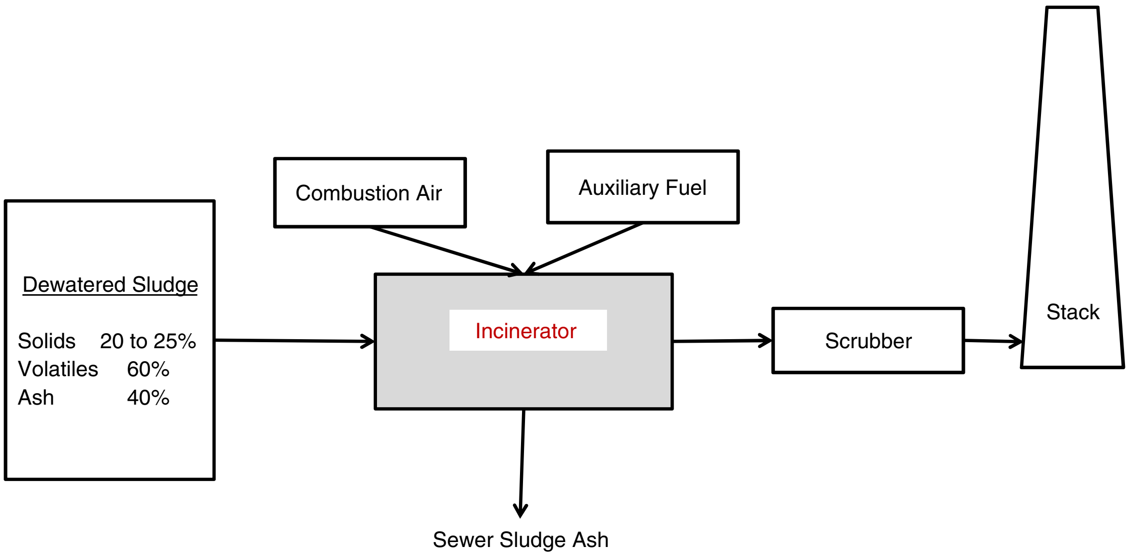

FIGURE 6 Schematic of sewage sludge combustion process (RMRC 2008).

TABLE 12
TYPICAL CHEMICAL COMPOUNDS IN SEWAGE SLUDGE ASH BYPRODUCTS

Compound	Range of Percent Content, % (Chesner 2000; RMRC 2008)
SiO_2	14.4–57.5
Al_2O_3	4.6–22.1
Fe_2O_3	2.6–24.4
CaO	8.6–36.9
MgO	0.8–2.2
Na_2O	0.1–0.7
K_2O	0.07–0.7
SO_2	0.01–3.4
P_2O_5	3.9–15.4
TiO_2	—

Chesner et al. (2000).
— = no data reported

TABLE 13
TRACE CONSTITUENTS OF INTEREST REPORTED IN SEWAGE SLUDGE ASH

Constituent	mg/kg
Mo	60–120
Na	1,000–8,000
Ni	16–2,800
Pb	89–2,000
Si	56,0000–257,000
Ti	287–8,000
V	1,897
Zn	1,950–27,000

Chesner et al. (2000).

TABLE 14
ENGINEERING PROPERTIES OF SEWAGE SLUDGE ASH

Property	Values from Different References, Percent Passing			
Gradation (% passing)	Wegman	Khanbiluardi	Waste Commission	Gray
4.76 mm (No. 4 sieve)	99	100	100	100
2.38 mm (No. 8 sieve)	99	98	100	100
2.00 mm (No. 10 sieve)	—	—	100	100
2.00 mm (No. 10 sieve)	—	—	100	—
0.85 mm (No. 20 sieve)	—	—	100	—
0.42 mm (No. 40 sieve)	99	73	98	—
0.21 mm (No. 80 sieve)	—	—	83	—
0.149 mm (No. 100 sieve)	85	53	—	—
0.074 mm (No. 200 sieve)	66	38	56	47–93
- (0.0902 mm)	10–13	—	—	2–13
0.02 mm	—	—	20	—
0.005 mm	—	—	12	—
>0.001 mm	—	—	2	—
Loss on Ignition (%)	1.4			
Moisture Content (% by total weight)	0.28			
Absorption (%)	1.6			
Specific Gravity	2.44–2.99			
Bulk Specific Gravity	1.27–1.82			
Plasticity Index	Non-plastic			
Permeability (ASTM D2434—cm/s)	1×10^{-4} to 4×10^{-4}			

RMRC (2008).
— = no data reported.

TABLE 15
CONSTITUENTS OF INTEREST IN LEACHATE FOR SEWAGE SLUDGE

Constituents	Concentration, mg/kg
Ag	241
Al	11,000–85,000
As	<6.5
B	3,000–4,310
Ca	100–3,600
Cd	3–50
Co	40–1,200
Cr	100–3,600
Cu	4,000
Fe	10,000–164,000
Hg	0.005–0.04
K	3,000–16,000
Mg	6,000–20,000
Mn	1,000–8,000
Mo	60–120
Na	1,000–8,000
Ni	89–2,000
Pb	16–2,800
Si	56,000–200,000
Ti	287–8,000
V	1,897
Zn	1,950–27,000

Chesner et al. (2000).

TABLE 16
LEACHATE INFORMATION FOR SEWAGE COMBUSTION BYPRODUCTS

Leachate Compound	TCLP (mg/L)	EPTox (mg/L)	DID (mg/L)	ASTM (mg/L)
Benzene	4.93	2.88	5	8.9
Carbon tetrachloride	—	—	—	—
Chlordane	—	—	—	—
Chlorobenzene	—	—	—	—
Chloroform	—	—	—	—
o-cresol	—	—	—	—
m-cresol	—	—	—	—
p-cresol	—	—	—	—
Total cresol	—	—	—	—
1,4-dichlorobenzene	—	—	—	—
1,2-dichloroethane	—	—	—	—
2,4-dinitrotoluene	—	—	—	—
Endrin	—	<0.0001	—	—
Heptachlor	—	—	—	—
Hexachlorobenzene	—	—	—	—
Hexachlor-1,3,butadiene	—	—	—	—
Hexachloroethane	—	—	—	—
Lindane	—	0.00012	—	—
Methoxychlor	—	<0.0004	—	—
Methyl ethyl ketone	—	—	—	—
Nitrobenzene	—	—	—	—
Pentachlorophenol	—	—	—	—
Pyridine	—	—	—	—
Tetrachloroethylene	—	—	—	—
Toxaphene	—	<0.00003	—	—
Trichloroethylene	—	—	—	—
2,4,5 trichlorophenol	—	—	—	—
2,4,6-trichlorophenol	—	—	—	—
2,4,5-TP (Silvex)	—	—	—	—
Vinyl chloride	—	—	—	—

Source: NCHRP 4-21.
— = no data reported.

CHAPTER SIX

AGENCY SURVEY RESPONSES

Agency use of sewage sludge ash in 2009 was captured in the agency survey conducted for this synthesis. The question on the survey regarding the use of sewage sludge ash was: “Is your state using, or has ever used, these byproducts in highway applications? If you are not sure of the specific type of combustion byproduct that has been used in your state, check the Combustion ash, unknown type at the bottom of the list.

- Sewage sludge ash: ash from combustion of dewatered sewage sludge.”

No state agencies reported using sewage sludge ash in any highway applications.

CHAPTER SEVEN

BOUND APPLICATIONS

ASPHALT CONCRETE

Research conducted in Bahrain by Al Sayed et al. (1995) used sewage sludge ash as a replacement for mineral filler in asphalt concrete mixes; the binder was a 60/70 Pen asphalt. Marshall mix design parameters showed the use of the byproduct mix, compared with the control mix, decreased the stability, increased the flow, increased voids in mineral aggregate, and decreased the Marshall quotient (ratio of Marshall stability after moisture conditioning to original stability). There was little difference on air voids for mixes with similar asphalt contents.

MORTAR

Cyr et al. (2007) used an experimental program that was designed to evaluate the influence of ternary binders (75% cement, 22.5% Metakaolin, and 2.5% sewage sludge ash) on the physical and environmental characteristics of concrete mortars intended for use in nonstructural concretes (e.g., sidewalks, curbs, and gutters). At this level of byproduct content, little changes to the physical and environmental properties were seen. The use of the Metakaolin was noted to significantly decrease the soluble fractions and heavy metals released from the binder matrix.

CONTROLLED LOW STRENGTH MATERIALS

Horiguchi et al. (2007) explored using sewage sludge ash in CLSM mixtures. The authors researched a potential in situ method for estimating the strength gain of the CLSM by applying a simple cone penetration method referred to as the Yamanaka Cone Penetration test. The fresh CLSM mixtures showed adequate early strength gain and workability, although the authors reported decreasing compressive strength with increasing percent of ash byproduct. Adjustments to the cement content were used to compensate for the influence of the byproduct on strength.

NONSTRUCTURAL PORTLAND CEMENT CONCRETE

Research in Korea by Mun (2007) evaluated sintered lightweight aggregate produced from the sewage sludge (dried and crushed to 0.15 mm sieve size), which was experimentally manufactured with various mass ratios of clay to sewage sludge in a rotary kiln. The concept of producing lightweight aggregates was to first melt the raw materials at a high temperature until the desired viscosity properties were obtained (i.e., when a gas was generated). The melted raw materials were expanded, then formed into lightweight aggregates when the gas pressure was slightly higher than that required to resist the viscosity of the melted raw materials.

The authors noted the CaO and MgO contents accounted for a sudden change in viscosity at high temperatures. Because both the sewage sludge ash and clay had contents of less than 10%, no sudden change in properties was expected (or seen). The authors also noted that when the ratio of Al_2O_3 to SiO_2 was high, the melting point and viscosity tended to be high. Since this ratio was low for the sewage sludge ash used in this study, the melting point also tended to be low. The high caloric value content of the sewage sludge was also expected to accelerate the sintering process.

Chemical properties of the individual components used in the process were found to be similar to those found in the clay used to produce the lightweight aggregate (Table 17). Table 18 shows the trace metal concentrations found in the sewage sludge. The concentrations were noted as being lower than those found in most other industrial wastes. The authors also noted the heavy metals are solidified during the sintering process. This expectation was met if the trace metal contents for sewage sludge ash (Table 18) were compared with trace metals found in MSW byproducts (see Table 13).

The physical properties of the synthetic lightweight aggregate properties were comparable to commercially available imported nonstructural lightweight aggregate from Europe (Table 19). Very little difference in toughness was found, as measured with each of three methods (LA abrasion, crushing values, and impact values). Higher ratios of clay to sewage sludge ash only showed very slight decreases in aggregate toughness.

Table 20 shows results from two leachate tests for two different clay-to-sewage sludge ratios (100:100 and 100:500). Most of the results showed elements that were not detectable. The elements that were detectable were present only in small quantities.

Mun used three clay-to-sewage sludge ratio lightweight aggregates and one commercial lightweight aggregate to prepare conventional PCC mixtures (Table 21). PCC with

TABLE 17
PROPERTIES FOR SEWAGE SLUDGE COMPARED WITH CLAY AS REPORTED BY MUN (2007)

Property	Sewage Sludge	Clay
Water Content, %	83.08	—
Organic Compound Content, %	10.17	7.13
Inorganic Compound Content, %	6.75	92.87
Calorific Value, kJ/kg	13,808	—
Components, %		
SiO_2	52	66.73
Al_2O_3	20.94	19.28
TiO_2	0.94	0.98
Fe_2O_3	8.98	6.62
MgO	2.21	1.63
CaO	4.05	0.43
Na_2O	1.3	0.95
K_2O	3.11	3.13
MnO	0.12	0.13
P_2O_5	5.31	0.11

TABLE 18
HEAVY METAL TRACE CONTENTS IN SEWAGE SLUDGE

Trace Metals	mg/kg
As	71.21
Cd	5.92
Co	15.68
Cr	83.61
Cu	710.5
Mn	1094.02
Mo	113.46
Ni	88.62
Pb	126.82
Ti	1204.33
Zn	1648.02

After Mun (2007).

TABLE 19
LIGHTWEIGHT AGGREGATE PHYSICAL PROPERTIES

Type of Lightweight Aggregate	Clay: Sewage Sludge (by mass)	Abrasion Loss (%)	Crushing Value (%)	Impact Value (%)
Manufactured Lightweight Aggregate	100:100	18.2	31.3	29.9
	100:200	18.2	32.5	31.3
	100:300	18.5	35.5	32.1
	100:400	19.8	35.8	33.3
	100:500	20.2	36.1	33.9
Commercial Lightweight Aggregate	—	19.6	35.1	33

After Mun (2007).
— = not reported.

TABLE 20
LEACHING CONTENTS OF HEAVY METALS FROM LIGHTWEIGHT AGGREGATES

Trace Metals	Extraction Procedure Toxicity (EPT) Test		Korean Standard Leachate Test (KSLT)	
	Leaching Content for Various Clay:Sewage Sludge Ratios (mg/L)			
	100:100	100:500	100:100	100:500
As	ND	ND	ND	ND
Cd	ND	ND	ND	ND
Co	ND	ND	ND	ND
Cr	ND	ND	ND	ND
Cu	ND	ND	ND	ND
Mn	0.36	0.35	0.28	0.31
Mo	0.70	ND	ND	ND
Ni	4.53	5.28	1.06	1.07
Pb	ND	ND	ND	ND
Ti	ND	ND	ND	ND
Zn	0.49	0.50	0.28	0.34

After Mun (2007).
ND = not detectable.

TABLE 21
PROPERTIES OF CONCRETE USING LIGHTWEIGHT AGGREGATES

Type of Lightweight Aggregate	Clay:Sewage Sludge Ash (by mass)	Compressive Strength (psi)	Flexural Strength (psi)	Density (lb/ft^3)	Water Absorption (%)	Thermal Conductivity (BTU)
Manufactured Lightweight Aggregate	100:100	2466	522	93.6	9.6	0.42
	100:300	2379	479	90.5	10.2	0.38
	100:500	2306	479	88	10.5	0.34
Commercial Lightweight Aggregate		2234	449	89.3	11.8	0.36

After Mun (2007).

100:100 ratio lightweight aggregate showed about an 11% improvement in compressive and flexural strengths as compared with the commercially available lightweight aggregate. The density increased and the water absorption decreased. The thermal conductivity also increased. The 100:100 PCC had the highest density and the corresponding highest thermal conductivity of all of the mixes tested. The conclusions from this research indicated that acceptable lightweight aggregates could be manufactured using clay and sewage sludge ash manufactured lightweight aggregates.

CHAPTER EIGHT

DOCUMENT ASSESSMENT SURVEY

Only a limited number of documents were found that contained information about the use of sewage sludge ash in highway applications. Most of these documents represented international research (Figure 7). The two main applications evaluated in this research were PCC and filler for HMA (Figure 8). The assessment of the type and quantity of information in the literature included documents referenced in the body of this chapter as well as additional documents listed at the end of the reference section.

LIST OF CANDIDATE BYPRODUCTS

There is a short list of non-coal combustion byproducts that have been used in highway applications. These include:

- MSW (raw; RFD)
- MSW bottom ash
- MSW combination ash (from boiler ash and air pollution control systems)
- Sewage sludge (raw)
- Sewage sludge ash.

MSW, raw, has been sorted into two sizes and used as RFDs. The raw sewage sludge has been sintered (burned) with clay to produce lightweight aggregates. The MSW bottom ash byproduct was the most researched of these byproducts. However, there was little work on-going in the United States by state agencies for using any of the materials in highway applications. The MSW air pollution control systems byproducts were a combination of various systems in the combustion facility (e.g., scrubber and precipitation ash). Unlike in the United States, most European facilities separated their air pollution component ashes. This resulted in a number of references reporting research using MSW fly ash, since most of the literature found was from international studies. This made it difficult to compare the international research to practices in the United States.

TEST PROCEDURES

A number of test methods associated with the testing of non-coal combustion byproducts and highway applications in which they are used are listed in Table 22. This table has been sorted by material test methods for aggregates, asphalt, byproducts (general classification), HMA, leaching tests, lime, PCC, PCC paste, PCC mortar, soils, and solids. Eighteen test methods were found referenced in the literature. There were multiple test methods used for aggregate toughness (LA abrasion, crushing value, impact value), sieve analyses, as well as specific gravity and absorption. One asphalt test for softening point was found in the documents. Eleven test methods are included in the general byproducts category. Most of these methods were from other countries; most of the documents were not in English. Three test methods were found that were used to evaluate HMA mix properties (maximum density, Marshall stability, and moisture sensitivity). Eleven test methods that detailed leachate tests are included in the list. These test methods were from EPA (United States), EN (European standards), ISO (International standards), DIN (German standards), and UNE (Spanish standards). Two standards were found for lime specifications (ASTM and British Standards). Six standards were related to portland cement paste, mortar, or concrete. Six, mostly ASTM, standards were identified for testing soils and five methods, mostly European, for solids.

MATERIAL PREPARATION AND BYPRODUCT QUALITY CONTROL

Few specific materials handling issues were documented in the literature and none were cited in state agency responses to the survey. The only MSW information found in material handling was related to separating the raw MSW prior to use as a RFD. The only reference to material preparation of sewage sludge was found in the research that used this byproduct to burn with clay to produce lightweight aggregates. For this usage, the sewage sludge was dried and crushed to 0.15 mm sieve size prior to sintering (burning) with the clay.

MATERIALS HANDLING ISSUES

None were noted in the literature or in the survey responses.

TRANSFORMATION OF MARGINAL MATERIALS

An interesting Korean study used dried and crushed sewage sludge and combined it with various percentages of clay in a rotary kiln to produce a synthetic lightweight aggregate. It was interesting to note the chemical composition of the dried sewage sludge was found to be similar to that of clay. The toughness of the synthetic aggregate

FIGURE 7 Geographical location of sewage sludge ash in highway applications research (stars indicate general international locations for published research).

was as good, or better, than that of commercially available European lightweight aggregate. Most of the trace metals of concern were not detectable in leachate testing of the synthetic aggregates.

DESIGN ADAPTATIONS

No specific requirements for design adaptations were noted in the literature or on the agency survey responses.

SITE CONSTRUCTION ISSUES

No specific requirements for design adaptations were noted in the literature or on the agency survey responses.

FAILURES, CAUSES, AND LESSONS LEARNED

The research evaluated in the literature review is summarized in Table 23.

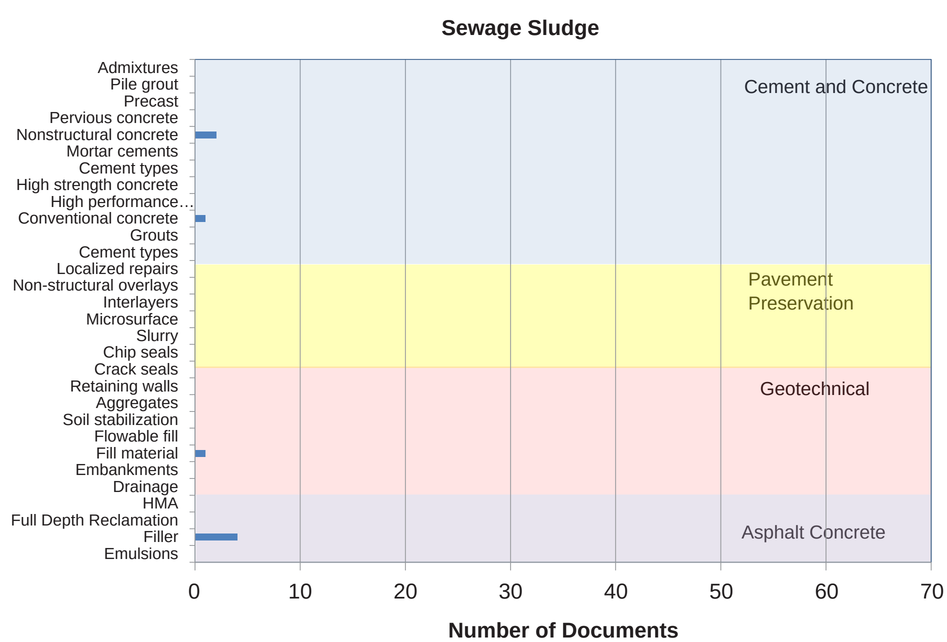

FIGURE 8 Highway application information available in sewage sludge ash literature.

TABLE 22
LIST OF TEST METHODS USED TO EVALUATE NON-COAL COMBUSTION BYPRODUCTS AND ASSOCIATED HIGHWAY APPLICATIONS

Material	Test Method	Title	Short Description
Aggregate	ASTM C29	Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate	Density, voids
	UNE-EN 933-3	Standards in French	Flakiness index
	UNE-EN 1097-2	Standards in French	LA abrasion
	KS F 2508	Method of Testing for Abrasion of Coarse Aggregate by Use of the Los Angeles Machine	LA abrasion
	KS F 2541	Testing Method for Determination of Aggregate Crushing Value	Crushing value
	KS F 2581	Testing Method for Determination of Aggregate Impacting Value-Method of Test for Production Control of Aggregate	Impact value
	ASTM D2216	Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass	Moisture content
	UNE 103204	Standards in French	Organic matter content
	ASTM C117	Standard Test Method for Materials Finer Than 75 mm (No. 200) Sieve in Mineral Aggregates by Washing	Passing 0.075 mm sieve
	UNE-EN 933-5	Standards in French	Percent crushed and broken surfaces
	UNE-EN 933-8	Standards in French	Sand equivalent
	ASTM C136	Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates	Sieve analysis
Aggregate	BS 812	Testing aggregates. Method for determination of particle size distribution. Sieve tests.	Sieve analysis
	UNE-EN 933-1	Standards in French	Sieve analysis
	ASTM C127	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate	Specific gravity and absorption
	ASTM C128	Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate	Specific gravity and absorption
	KS F 2503	Testing Methods for Density and Absorption of Coarse Aggregate	Specific gravity and absorption
	UNI 8520	Natural aggregates: alkali reactivity, organic matter content, screen analysis, absolute gravity and water absorption	Suite of aggregate tests
Asphalt	BS 2000-132	Methods of test for petroleum and its products	Softening point
Byproduct	ANC-WTC method	Acid neutralization capacity	
	IRSA-CNR	Quartering	Homogenization
	NEN 7341	Availability (Dutch)	Mixing
	Ball milling	<150 mm in inert environment	Particle size reduction
	UNE 103502	Standards in French	CBR
	NLT 172	Standards in Spanish	Clean coefficient
	NLT 115	Standards in Spanish	Gypsum content
	Article 331	Spanish General Technical Specifications for Road Construction PG3	Roadbed material specification
	Article 300	Spanish General Technical Specifications for Road Construction PG3	Roadbed material specifications
	NLT 114	Standards in Spanish	Soluble salt content
	UNE1744-1	Standards in French	Total sulfur compounds
	Article 510	Spanish General Technical Specifications for Road Construction PG3	Unbound structural layers
HMA	AASHTO T283	Standard Method of Test for Resistance of Compacted Hot Mix Asphalt (HMA) to Moisture-Induced Damage	Moisture sensitivity
	ASTM D2041	Standard Test Method for Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures.	Specific gravity
	ASTM D1559	Test Method for Resistance of Plastic Flow of Bituminous Mixtures using Marshall Apparatus	Stability

(*continued on next page*)

TABLE 22
(*continued*)

Leaching	EPA SW-846 Method 3051	Test Methods for Evaluating Solid Waste	Alternative to Method 3050
	EN 26595	Water quality: Determination of total arsenic—Silver diethyldithiocarbamate spectrophotometric method	Arsenic
	ISO 5961	Water quality: Determination of cadmium by atomic absorption spectrometry	Cadmium
	EN 1233	Water quality: Determination of chromium—Atomic absorption spectrometric methods	Chromium
	ISO 8288	Water quality: Determination of cobalt, nickel, copper, zinc, cadmium and lead—Flame atomic absorption spectrometric methods	Cobalt, nickel, copper, zinc, and lead
	EPA SW-846 Method 3050	Test Methods for Evaluating Solid Waste	Alternative to Method 3051
	DIN 38414-4 (1984)	German standard methods for the examination of water, waste water, and sludge: sludge and sediments (group S); determination of leachability by water	Leaching
	EN 12457	Compliance leaching test for granular wastes	One and two stage laboratory leaching test
	ISO 5667-3	Water quality—Sampling Part 3: Guidance on the preservation and handling of water samples	Sample preservation
	EPA SW-846 Method 3052	Test Methods for Evaluating Solid Waste	Total digestion method
	UNE 103201	Standards in French	Water soluble sulfates
Lime	ASTM C25	Standard Test Method for Chemical Analysis of Limestone, Quicklime, and Hydrated Lime	Loss on ignition
	BS 6463	Quicklime, hydrated lime, and natural calcium carbonate. Methods for physical testing.	Chemistry
PCC	EN 197-1	Cement, Composition, Specifications and conformity criteria for common cements	Cement specifications
	ASTM C109	Unconfined Compressive Strength at 1, 2, 7, 28, and 56 Day	Compressive strength
	UNI 6132	Compressive mechanical resistance	Compressive strength
PCC Mortar	ASTM C305	Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency	Mixing paste
PCC Paste	EN 196-1 (1994)	Methods of testing cement—Part 1: Determination of strength	Binding abilities
	ASTM C 191	Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle	Set time—Vicat
Soil	ASTM D6951	Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications	DCP
	ASTM D2922	Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth) (Withdrawn 2007)	Density
	ASTM D698	Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard	Density
	ASTM D4643	Standard Test Method for Determination of Water (Moisture) Content of Soil by Microwave Oven Heating	Moisture content
	UNE 103103/103104	Standards in French	Plasticity (Atterberg)
	ASTM D854	Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer	Specific gravity
Solids	EPA SW-846 Method 1310	Test Methods for Evaluating Solid Waste	Extraction Procedure Toxicity (EP Tox)
	EPA SW-846 Method 1311	Test Methods for Evaluating Solid Waste, Physical/Chemical Methods	TCLP leaching
	EPA SW-846 Method 1320	Test Methods for Evaluating Solid Waste	Multiple Extraction Procedure
	EPA SW-846 Method 1312	Test Methods for Evaluating Solid Waste	Synthetic Precipitation Leaching Procedure (SPLP)
	ASTM D3987-06	Standard Test Method for Shake Extraction of Solid Waste with Water	Water leach test

CBR = California bearing ratio.

TABLE 23
SUMMARY OF INFORMATION ON MSW AND SEWAGE SLUDGE LITERATURE

Byproduct	Application	Reference	Engineering	Environmental	Findings
MSW, Raw	Clinker, portland cement	Nabajyoti et al. (2006)	Cement prepared with raw MSW was more reactive (i.e., more pozzolanic) than the washed MSW. The byproduct reduced the demand for $CaCO_3$ from 70% to 50%.	Cd, K, Na, Pb, and Zn generated during clinker production.	Washed MSW did not show as much pozzolanic behavior as did the raw MSW. Calcium carbonate demand was decreased.
	Clinker	Sikalidis et al. (2002)	Fractionated MSW into coarse sizes (earthen materials, stones, broken ceramics, glass, and other similar materials) and could be used in the production of the cement clinker.	—	Produced acceptable cement clinker
	Refuse derived fuel	Sikalidis et al. (2002)	The fine fraction (mostly paper, wood, light plastics, leather and cloth pieces, various fibers and similar combustible materials) used with rotary kiln.	—	Economically feasible with a modified kiln with production of about 500 tons/day and a production rate of 433 tons/day of mortar.
MSW Bottom Ash	HMA	Hassan (2004)	HMA stiffer (higher Marshall stability, lower flow), increased raveling, air voids, and VMS with increasing percentages of byproduct.	None noted	Limit use to 15% to 20% in base and surface HMA
		Chen et al. (2008)	HMA more resistant to rutting but had increased moisture sensitivity	Leachate concentrations after mixing the byproduct in the HMA were significantly reduced for heavy metal and toxicity.	Limit use to 20% in binder courses and 10% in surface mixes
	Portland cement replacement	Filipponi et al. (2002)	MSW was not reactive and did not contribute to the cementitious material.	—	Treat MSW to improve pozzolanic reactions
		Berolini et al. (2004)	Dry ground: generated an increase in paste/mortar expansion due to gas formation prior to hardening of the cement/mortar.		Dry ground MSW bottom ash produced undesirable expansive reactions.
			Wet ground: When added in a slurry the expansive reaction was minimized when sufficient time was allowed for gas formation to dissipate in the slurry.	—	High variability in MSW bottom ash byproducts may produce variability in controlling expansive reactions.
MSW Bottom Ash	PCC aggregate	Pera et al. (1997)	Lower densities and compressive strengths were noted. Problems were noted with swelling and cracking of the samples.	—	Substitution of gravel with up to 50% MSW bottom ash could be achieved without significant problems with expansion.
			Expansion problems are function of reaction between the portland cement and the metallic aluminum in the byproduct		
		Berg and Neal (1998)	MSW bottom ash met most PCC aggregate property requirements. It had high angularity but brittle behavior (low toughness). Sulfate and chloride concentrations sufficiently high to cause potential problems with sulfate attack and corrosion problems with reinforcing steel.	—	—
	Stabilized base	Cai et al. (2004)	MSW bottom ash mixed with 2.5% cement produced lower but acceptable flexural and compressive strengths. Density increased with use of byproduct.	Leachate testing showed an increase in Cl and Na by from 20 to 100 times the control; Ca, K, and SO_4 2 to 10 times higher; Cu 50 times higher; Cd, Pb, and Zn 5 times higher; Cr and Ni were similar to control.	Significant increase in metals and salts in the leachate.
	Base and subbase	Izquierdo et al. (2007)	MSW bottom ash has acceptable aggregate properties.	Byproduct increased pH from 7.3 to 9.2 was slightly lower than laboratory study. Leachate had initial amount of salts with an indication of depletion over time. Trace metals released very slowly.	Environmental issues were found to be most important property. Salts produced high values of conductivity that decreased with depletion of salts. Trace metals were found not to be of concern because of their low release rate.
		Comans et al. (2000)	—	Treatment of the byproduct to reduce Cu and Mo leachate showed Fe(III) and Al(III) were most likely effective in treatment. A durable reduction in pH to neutral conditions also controlled Cu and Mo leaching.	Cu and Mo leaching decreases with pH near neutral. Fe and Al help reduce Cu and Mo leaching.
		Bruder-Hubscher et al. (2001)	—	Found minimal impact on leachate over 3 years of monitoring under field conditions.	Acceptable for base materials under pavements
		Forteza et al. (2004)	Acceptable aggregate properties were found for use in embankment, landfills, base, and subbase.	—	Acceptable engineering properties for various unbound applications

(*continued on next page*)

TABLE 23
(*continued*)

Byproduct	Application	Reference	Engineering	Environmental	Findings
MSW Bottom Ash	Base	Aberg et al. (2006)	—	Cl, Cu, Cr had the highest concentrations in the leachate; concentrations decreases over the 1 year of monitoring. Pb was very low, which was attributed to iron oxides. Prediction models were useful for predicting Ni, Pb, Zn, and Cu; less accurate for Cd and Cr.	Prediction models were found to be useful for estimating leachate concentrations for a number of elements. Independent variables were pH and liquid to solid ratios. Most concentrations decreased with time (i.e., elements were depleted).
	Base	Bouvet et al. (2007)	—	Pb concentrations in leachate were low when pH was neutral. Concentrations increased substantially with pH of 4.	Pb concentrations increase with decreasing pH below neutral.
	Base	Hjelmar et al. (2007)	—	Good agreement in field section leachate testing with laboratory results for salts; less agreement was obtained for trace metals.	Differences between field and laboratory results are a function of pH.
	Base	Vega et al. (2007)	—	Fresh MSW bottom ash will generate higher concentrations of soluble salts than weathered MSW bottom ash.	Stockpiling (weathering) MSW bottom ash can decrease the amount of soluble salts seen in the leachate.
	Base	Izquierdo et al. (2008)	—	Readily depleted compounds included Na, K, and Cl salts; over 50% leached out early in the study. Similar trends were seen for Pb and V. Delayed depletion in concentrations was seen for Al. Ti, Cu, Co, Ni, Zn, Cr, As, and Se.	Salt concentrations depleted quickly while trace metals depleted slowly.
MSW Combined Ash	Aggregate substitute	Cosentino et al. (1994)	Byproduct met requirements for either a well-graded or poorly graded sand (SW, SP). Moisture–density and stress–strain behavior was similar to conventional base materials.	—-	MSW combined ash has similar engineering properties as SW or SP soils.
	Base and subbase	Cosentino et al. (1995)	—	Higher concentrations of As, Ba, Cd, Cr, Pb, Hg, Se, and Ag were seen; values were still below drinking water standards.	Higher concentrations of heavy metals seen, but values acceptable by drinking water standards at that time.
MSW Fly Ash	Portland cement replacement	Polettini et al. (2001)	High concentrations of heavy metals, chlorides, and sulfates altered set time (hydration) and strength gain with time.	—	Heavy metals increased set time and decreased strength gain.
	Mortars	Aubert et al. (2006)	Treated with 2 versions of a proprietary treatment, REVASOL™, to minimize expansive reaction problems.	One of the treatments minimized the expansive reaction but failed to stabilize the antimony and chromium content.	Expansion problems function of aluminum and sulfates present in the byproduct, which was mitigated by the treatments.
	PCC	Aubert et al. (2004)	Workability (slump) decreased with increasing percentages of either sand or MSW fly ash in the fresh PCC; porosity increased with increasing percentages of either substituted material.	Monolithic PCC samples with and without MSW fly ash: Cr, Cu, Pb, and Sn showed a slight increase in leachate concentration.	No observed environmental issues when encapsulated in PCC; all concentrations were below the threshold values.
				Crushed PCC with and without MSW fly ash: As, Cr, and Pb increased significantly over those in the control crushed PCC materials.	Good potential for recyclability as only the chromium exceeded the legal thresholds in the case of the crushed concrete.
	PCC-CLSM	Horiguchi and Saeki (2004)	Slump and strengths properties were noted as acceptable.	Leaching results were also noted as acceptable.	Lower but acceptable fresh and hardened properties when used to produce low strength concrete.
Sewage Sludge Ash	Mineral filler	Al Sayed et al. (1995)	Marshall mix design results showed decreased stability and increased flow and VMA. Air voids were similar to control mixes.	—	Sewage sludge ash resulted in loss of stability and increased VMA.
	Mortar	Cyr et al. (2007)	Suitable concrete properties for non-structural concrete (2.5% of cementitious materials)	Metakaolin (calcined clay) was responsible for significant decrease in soluble salts and trace metals released from binder matrix.	Sewage sludge ash, when combined with calcined clay, reduces salts and metals in leachate.
	PCC–CLSM	Horiguchi et al. (2007)	Adequate early strength gain and workability were achieved. Compressive strengths were decreased with increasing percentages of ash, which could be corrected by adjusting the water to cement ratio	—	Adequate for use in CLSM
	PCC–Non-Structural	Mun (2007)	Sewage sludge and clay were sintered (burned) in a rotary kiln to produce lightweight aggregates with LA abrasion and strength as good as or better than commercially available lightweight aggregates.	The chemical composition of the sewage sludge was similar to that of clay; concentrations of trace metals were very low, if present in detectable amounts.	Synthetic lightweight aggregates produced from sewage sludge–clay materials have good potential for commercially useful lightweight aggregates.

BARRIERS

The main barriers to using MSW byproducts in highway applications are:

- Presence of a number of soluble salts and trace metals that needed to be either bound or depleted prior to use.
- Additional environmental monitoring needed to monitor the impact on water quality
- Reduction in desirable engineering or construction properties.
- Inadequate experience with byproducts in highway applications in the United States.
- Unknown variations in byproducts from difference waste facilities.

The main barriers to using sewage sludge, raw or ash, in highway applications includes:

- Lack of research on their use in highway applications
- Lack of experience by agencies.

COSTS

All of the available information found focused on the potential for use and demonstrations projects. No information was found on the costs associated with using this category of byproducts in highway applications.

GAPS

Gaps in the research include:

- Lack of experience in the United States
- Lack of cost information
- Estimates of financial costs associated with preparing the byproducts for use in highway applications
- Estimates of environmental impacts in U.S. highway applications
- Health and safety information associated with byproduct handling
- Stockpiling information and guidelines (safety, environmental issues)
- Inadequate chemistry information on byproducts (particularly sewage sludge, raw and ash)
- Information on byproduct variability.

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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