ADVANCING CONCRETE PAVEMENT TECHNOLOGY SOLUTIONS

Use of Industrial Byproducts in Concrete Paving Applications

Technical Summary

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16. Abstract

Some industrial wastes (often called industrial byproducts, waste products, or waste materials) can be used as replacements for virgin aggregates or pozzolans, reducing the need for additional virgin material and saving landfill space that would otherwise be used for industrial waste disposal. These industrial wastes include fly ash from coal combustion that does not meet typical specifications or agency requirements (sometimes called "off-spec" or "near-spec" ash), bottom ash, municipal solid waste incinerator (MSWI) ash, ground glass, foundry sand, recycled concrete aggregate (RCA) or mixed rubble from construction and demolition (C&D) recycling facilities, and other materials. Research and field studies have shown that materials such as these can be beneficially used in several bound and unbound applications in concrete paving projects.

This document discusses the use of industrial wastes in concrete paving applications. Potential applications for using these wastes in highway infrastructure are identified, and design considerations are discussed. Information is provided to support evaluation of these materials for use. Approaches and considerations for agency approval of these products are also presented.

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Introduction

This document describes the use of industrial wastes (often called industrial byproducts, waste products, or waste materials) in concrete paving applications and identifies applications and considerations for using these wastes in highway infrastructure. These wastes can include fly ash, bottom ash, municipal solid waste incinerator (MSWI) ash, ground glass, foundry sand, recycled concrete aggregate (RCA), and mixed rubble from construction and demolition (C&D) recycling facilities. Some of these wastes have the potential to be used as aggregates or supplementary cementitious materials (SCMs) in concrete paving applications, reducing the need for virgin materials and saving landfill space. This document aims to provide information for highway agency and contractor engineers who are interested in exploring the beneficial use of industrial wastes in concrete paving projects.

Constructing, rehabilitating, and reconstructing the Nation's highway infrastructure are resource-intensive activities. Historically, virgin materials have been used in these activities, consuming limited resources and impacting the environment. However, some industrial wastes can be used as replacements for virgin aggregates or SCMs, reducing the need for additional virgin material and saving landfill space that would otherwise be used for industrial waste disposal. These industrial wastes include coal ash from coal combustion that does not meet typical specifications or agency requirements, sometimes called "off-spec" or "near-spec" ash. The applicable specifications, American Association of Highway and Transportation Officials (AASHTO) M 295 and ASTM International (ASTM) C618, were recently changed to include both coal fly ash and coal bottom ash, a coarser noncombustible residue from coal power plants, in one category called coal ash. Other industrial wastes include MSWI ash, ground glass, foundry sand, RCA or mixed rubble from C&D recycling facilities, and other materials. The challenges associated with use of these materials, as well as the potential benefits, vary by material and are described subsequently in this document. Research and field studies have shown that materials such as these can be beneficially used in several bound and unbound applications in concrete paving projects.

Table 1 lists estimates for the annual National production and beneficial use of selected industrial wastes that can be used, or that show promise for use, in concrete paving projects.

Table 1. National production and use of selected industrial wastes (annual unless otherwise noted)

Industrial Waste	Production	Beneficial Use	Combustion with Energy Recovery	Disposal
Coal combustion ash not meeting AASHTO M 295 and ASTM C618 [1]	—	—	—	—
Coal combustion bottom ash	9.15 million tons [2]	2.92 million tons [2]	None	6.23 million tons [2]
MSWI fly ash	0.52 to 1.638 million tons [3]	Negligible	None	0.52 to 1.638 million tons [3]
MSWI bottom ash	4.67 to 6.55 million tons [3]	Negligible	None	4.67 to 6.55 million tons [3]
Ground glass	12.250 million tons [4]	3.060 million tons [4]	1.640 million tons [4]	7.55 million tons [4]
Foundry sand	6 to 10 million tons [5]	2.6 million tons [5]	None	3.4 to 7.4 million tons [5]
Recycled concrete aggregates from C&D recycling facilities	102.2 million tons from building C&D waste [6]	N/A [6]	None	N/A [6]
Brick and clay tile from C&D recycling facilities	12.3 million tons [7]	1.5 million tons [7]	None	10.8 million tons [7]

N/A indicates that available data were not found in the literature.

[1] *Estimates were not available at the time of publication.*

[2] *ACAA (2021) provides 2019 production and use statistics.*

[3] *EPA (2021d) indicates that nearly 35 million tons of municipal solid waste (MSW) was incinerated for energy recovery in 2018. EPA (2021c) estimates that incinerator residue (total ash) is 15%–25% by weight (5%–15% by volume) of the MSW processed and that the bottom ash produced is 80%–90% by weight (5%–15% by volume).*

[4] *EPA (2021a); data from 2018*

[5] *AFS (2021)*

[6] *EPA (2020) indicates that the total production of concrete C&D waste in 2018 was 102.0 million tons from buildings, 168.3 million tons from roads and bridges, and 134.9 million tons from other sources. Of this total volume, 71.2 million tons (17.6%) were placed in landfills, 32.8 million tons (8.1%) were used in manufactured products, and 301.2 million tons (74.3%) were used as aggregates. No breakdown on the source of RCA for the landfill/use destinations was provided.*

[7] *EPA (2020); data from 2018*

Some State and local transportation agencies have been approached by proponents of the use of industrial wastes in paving applications. With shortages of conventional SCMs such as fly ash, alternative supplementary cementitious materials (ASCMs) are becoming of greater interest to agencies (Armaghani and Cavalline 2020). Additionally, in areas where natural aggregates are expensive because of reduced supply or long hauling distances, recycled and waste product materials are becoming more attractive aggregate options (Snyder et al. 2018). Industrial wastes may provide a cost savings over virgin materials if they are available locally in sufficient quantities and can be used with minimal processing and handling. Performance of these materials, however, should always be confirmed through trial batching and durability testing.

The performances of several of these materials have been demonstrated through research and field trials in concrete paving applications. Standards and guide documents exist to support their use. For example, several guide documents and standards for RCA exist, and, in fact, several State departments of transportation (DOTs) allow the use of RCA in a range of bound and unbound paving applications. A standard also exists to support the use of ground glass as an SCM, and an ASTM guide exists for evaluation of alternative SCMs (ASTM C1709). Other materials, such as coal combustion ash that does not meet the current provisions of AASHTO M 295 (ASTM C618), are the subject of ongoing work supporting their incorporation into existing standards. Standards to support the use of MSWI ash and foundry sand do not exist at the time of this writing.

Beneficial use of industrial wastes in concrete paving projects may provide environmental, social, and economic benefits. However, agencies and industry have expressed concerns regarding their use, including the following (Cackler 2018):

- Variability of waste product materials
- Availability of an adequate supply of waste product to meet the needs of a specific job
- Performance of the waste product (or of the application using the waste product) once in service
- Environmental impacts

The following may overcome these barriers:

- Characterization and testing of waste products to establish composition and monitor uniformity
- Selection of appropriate beneficial use applications
- Understanding of the performance of the waste product and/or system containing the waste product
- Implementation of measures during design, construction, and use to mitigate potential environmental impacts

This document presents an overview of selected industrial wastes that are used or show promise for use in concrete paving. For each waste product, the process that produces the waste is described, along with the processing techniques used to prepare the waste product for beneficial use or disposal. The physical and chemical characteristics of each waste product are also summarized in terms of their impact on typical use applications.

In addition to describing the production and characteristics of selected waste products, this document presents practical considerations for selecting and using industrial wastes, along with a general framework for evaluating waste products for different uses. Finally, typical agency approaches and considerations for approving industrial wastes are presented.

Types of Industrial Wastes Used in Concrete Paving Projects

Table 2 provides the typical properties of coal combustion and MSWI bottom ash, foundry sand, RCA and mixed rubble from C&D recycling facilities, and, for comparison, natural aggregate.

Table 2. Typical properties of natural aggregate, coal combustion and MSWI bottom ash, foundry sand, and RCA and mixed rubble from C&D recycling facilities

Property	Natural Aggregate [1]	Coal Combustion Bottom Ash	MSWI Bottom Ash	Foundry Sand [2]	RCA from C&D Recycling Facilities – Fine [3]	RCA from C&D Recycling Facilities – Coarse [3]	Mixed Rubble from C&D Recycling Facilities – Fine	Mixed Rubble from C&D Recycling Facilities – Coarse
Shape and texture	Well-rounded, smooth (gravel) to angular and rough (crushed rock)	Angular with a porous surface (FHWA 2016), with some subrounded and angular particles	Angular with a porous surface (FHWA 2016)	Subangular to rounded (FIRST 2004)	Angular with a rough surface		Angular with a rough surface	
Absorption capacity (%)	0.8–3.7	0.8–2.0 (FHWA 2016)	2.4–15.5 (Cho et al. 2020)	Reported to be low but may vary widely due to presence of binders and additives (Benson and Bradshaw 2011) 0.7–5.0 (Vipulanadan et al. 2005) 0.45 (FHWA 2016)	8.7–10.3 (Silva et al. 2014) [4]	3.7–8.7 (Silva et al. 2014) [4]	8.4–10.2 (Silva et al. 2014) [4]	6.6–7.8 (Silva et al. 2014) [4]
Specific gravity	2.4–2.9	2.1–2.7 (FHWA 2016)	1.5–2.8 (Cho et al. 2020)	2.30–2.79 (Vipulanadan et al. 2005) 2.39–2.55 (FHWA 2016)	2.1–2.4		N/A	
Oven dried density (lb/ft^3)	150–181	45–100 (FHWA 2016)	—	160 (FHWA 2016, bulk relative density	126–131 (Silva et al. 2014) [4]	144–146 (Silva et al. 2014) [4]	126–133 (Silva et al. 2014) [4]	132–138 (Silva et al. 2014) [4]
LA abrasion test mass loss (%)	15–30	30–50 (FHWA 2016)	36–43 (Townsend et al. 2020)	N/A	20–45		34.9–38.0 (Silva et al. 2014) [4]	
Sodium sulfate soundness test mass loss (%)	7–21	1.2–10 (FHWA 2016)	N/A	N/A	18–59		N/A	
Magnesium sulfate soundness test mass loss (%)	4–7	N/A	N/A	5–47 (FHWA 2016)	1–9		N/A	
Chloride content (lb/yd^3)	0–2	N/A	0.5–15 (Sarmiento et al. 2019)	N/A	1–12		N/A	
Loss on ignition (%)	N/A	N/A	1.9–6.3 (Cho et al. 2020)	0.45–9.5	N/A		N/A	

N/A indicates that values were not found in the literature or that published values identified in the literature represent test results for a single source or a small number of sources.

[1] Data for natural aggregate and RCA are for as-produced material, including both fine and coarse material. Data are from Snyder et al. (1994) and Chesner et al. (1998).

[2] Data from Vipulanadan et al. (2005) are from Texas foundry sands only.

[3] Data are from ACPA (2009) unless noted otherwise.

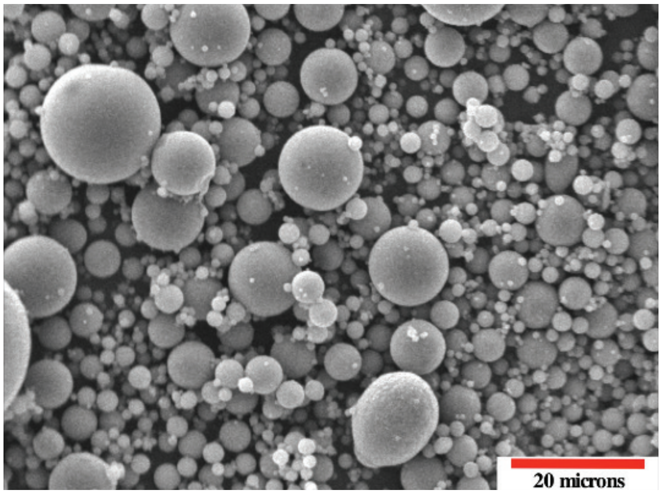
[4] Data from Silva et al. (2014) provide a 95% confidence interval for the mean of samples used in a statistical analysis of C&D waste.

Coal Combustion Ash Not Meeting AASHTO M 295 (ASTM C618)

Fly ash is a waste produced when burning finely ground coal fuel mixtures in power plants and is captured in the exhaust stream by electrostatic precipitators or baghouse systems. When used in concrete, fly ash contributes to the fresh and hardened properties by reacting with water and calcium hydroxide to form hydration products. Many of these hydration products improve the density and quality of the paste and therefore the strength and durability performance of the concrete. Fly ash has been used in concrete since the 1930s, and its use has increased over the past decades (Sutter 2020).

Part of this increased demand has been driven by the sustainability benefits associated with replacing portland cement with an SCM that would otherwise be landfilled. Beyond sustainability, the demand for fly ash is driven by its ability to improve concrete's long-term strength and durability, with benefits including reduced permeability and improved resistance to alkali-silica reactivity (ASR) and sulfate attack. Fly ash can also provide benefits associated with improved workability, reduced water demand, delayed set times, and reduced heat of hydration (Diaz-Loya et al. 2019, Tritsch et al. 2021). An image of fly ash from a scanning electron microscope is shown in Figure 1.

The purpose of a material specification is to form the basis of an agreement between a material provider and a specifier regarding the general properties of a material. It is the role of the engineer to determine the suitability of any material for a given application, and this same responsibility extends to the use of recycled materials. The information in this document applies to both newly produced and harvested coal ash products not meeting AASHTO M 295 (ASTM C618).



Larry Sutter, Michigan Technological University

Figure 1. Scanning electron microscope image of fly ash

The AASHTO standard specification AASHTO M 295, and its counterpart ASTM C618, are voluntary standards that have been used for specifying fly ash for decades. ASTM C311/C311M provides test methods for coal ash and references several other ASTM standards, which are, in some cases, modified for use with coal ash. Historically, AASHTO M 295 and ASTM C618 provided requirements for two classes of fly ash: Class C and Class F. The chemical composition of each material needed to meet specified requirements, with the key defining chemical threshold separating Class C and Class F ash being the calcium oxide content. Class F ash has a CaO content of 18% or less; Class C ash has a CaO content greater than 18%. These specifications were recently changed to include both coal fly ash and coal bottom ash in one category called coal ash, and the historic chemical and physical limits for fly ash now apply to the general class of coal ash. The classification into Class C and Class F was retained but now applies to coal ash.

The supply of fly ash conforming with AASHTO M 295 (ASTM C618) has become limited during certain time periods and within certain geographic regions (Tritsch et al. 2021, Sutter 2020). The overall supply of fly ash has been decreasing since 2008 due to reductions in the use of coal as fuel for power plants. Air quality regulations have also resulted in power plants adding activated carbon to the exhaust stream of the coal combustion chamber as a method to remove mercury and other contaminants from the exhaust. As a result, fly ash produced by these plants may adversely affect the performance of air-entraining admixtures (AEAs), making it difficult to predict the proper dosages of AEA that adsorb to the carbon by conventional means such as the loss on ignition (LOI) test (Diaz-Loya et al. 2019). Other treatments performed at power plants include injecting ammonia into the exhaust stream of the combustion chamber to reduce NOx emissions. This leads to the presence of ammonia in the ash and, in turn, safety issues on construction sites.

Historically, fly ash that does not meet AASHTO M 295 (ASTM C618) had been placed in a landfill or impoundment. Additionally, some fly ash that did meet AASHTO M 295 (ASTM C618) was landfilled because there was not a local market for its use. Commonly, bottom ash was disposed of in landfills or impoundments as well, often comingled with fly ash. Landfilled and/or impounded ashes are increasingly being recovered, or "harvested," for use and are being used to increase the supply. Because of comingling, it was necessary to change the standard specifications to recognize that harvested coal ash may be a combination of these two materials.

However, there are several challenges associated with harvesting ash in a way that provides a uniform material. Moisture content, uniformity of the deposit, and potential commingling of materials other than coal ash in a landfill or impoundment are common concerns. To address these challenges, some mechanical, thermal, and chemical processing of the harvested ash is needed. Processing of the harvested ash includes drying in almost every case, and sizing, grinding, and blending as needed. When unburned carbon is present, beneficiation to reduce the carbon fraction may be used, including carbon burn-out, chemical treatment (i.e., the use of carbon blockers), electrostatic carbon removal, supercritical water oxidation, and ozone treatment (Tritsch et al. 2021). Harvested ash is being used increasingly and has been approved for use by several State DOTs. It should be noted that AASHTO M 295 and ASTM C618 were also recently changed to include bottom ash as a standalone SCM, not comingled with fly ash. Sources of coal bottom ash are becoming available in geographic regions where ash has historically been ponded or impounded.

Coal Combustion Bottom Ash

In addition to fly ash, coal-burning power plants also produce bottom ash, which is collected from beneath the combustion chamber using a conveyor system or water jets and conveyed to decanting basins or other storage. Bottom ash, which comprises about 20% of the ash stream, is a dark, less-glassy material (compared to fly ash from the same coal). It has a chemical composition similar to that of fly ash but with a coarser particle size (typically sand-sized particles).

In physical appearance, a ground coal bottom ash resembles some conventional aggregates, but bottom ash particles are typically lighter in weight and are more brittle (Singh et al. 2016). These characteristics can negatively impact the mechanical properties and durability performance of concrete containing bottom ash if the bottom ash is used as an aggregate replacement.

The chemical composition of bottom ash varies based upon the type of coal used and the combustion process, but components are primarily SiO_2, Al_2O_3, Fe_2O_3, and CaO with smaller quantities (typically less than 5% by weight) of MgO, Na_2O, and K_2O (FHWA 2016). Table 3 provides examples of bottom ash compositions. Bottom ash produced in circulating fluidized bed boiler power plants often contains a higher amount of calcium as an oxide and as a sulfate than ash produced using other combustion technologies (Conn et al. 1999), potentially affecting the performance of concrete containing bottom ash.

The absorption of coal combustion bottom ash is higher than that of many conventional aggregates and is reported to range from 0.8% to 35.0% (Rodriguez-Alvaro et al. 2021). The coefficient of permeability ranges from 0.04 to 0.004 in./sec. The California bearing ratio (CBR) has been reported to range from 40% to 70% (FHWA 2016). Bottom ash has successfully been used in concrete mixtures as an aggregate, although means to compensate for the increased water absorption are needed. Ground coal bottom ash has also been shown to perform well as an SCM in concrete mixtures when processed to have a fineness similar to that of fly ash (Menéndez et al. 2014, Cheriaf et al. 1999, Mangi et al. 2019, Chindaprasirt et al. 2009, Jaturapiktakkul and Cheerarot 2003, ul Haq et al. 2014, Oruji et al. 2017, Oruji et al. 2019).

Table 3. Bottom ash composition found in literature

Component	Oxide Content (% wt)					
	BA1	BA2	BA3	BA4	BA5	Average ± Standard Deviation
SiO_2	56.0	52.5	49.97	48.12	38.8	49.08 ± 6.46
Al_2O_3	26.7	17.65	26.95	23.47	21.3	23.21 ± 3.90
Fe_2O_3	5.8	8.3	8.34	10.55	12.1	9.02 ± 2.41
MgO	0.6	0.58	1.12	3.45	1.7	1.49 ± 1.19
CaO	0.8	4.72	8.28	11.65	16.5	8.39 ± 6.07
Na_2O	0.2	—	0.14	3.45	1.0	1.20 ± 1.55
K_2O	2.6	—	0.78	3.45	2.5	2.33 ± 1.12
SO_3	—	3.62	0.11	1.76	2.4	1.97 ± 1.46
LOI	4.6	4.01	1.85	4.02	2.9	3.46 ± 1.10

— Analysis not provided

Sources: Menéndez et al. 2014, Cheriaf et al. 1999, Mangi et al. 2019, Chindaprasirt et al. 2009, Jaturapiktakkul and Cheerarot 2003

Coal combustion bottom ash is typically comingled with fly ash and other materials in landfills. To be used, ash harvested from landfills needs to be processed to reduce moisture content and to ensure that the ash has not agglomerated. Processing typically includes drying, de-agglomeration, and sieving, grinding, and/or air cyclone treatment to ensure that the ash meets AASHTO M295 (ASTM C618) and uniformity requirements related to performance.

MSWI Products

Municipal solid waste incineration residues include MSWI bottom ash, MSWI fly ash, and MSWI air pollution control residues. MSWI bottom ash is discharged from incinerators and collected in a water quenching tank. MSWI fly ash is composed of particles that leave the furnace and are separated from the exhaust stream before the injection of sorbents to treat the gaseous effluent. The air pollution control residues are collected in devices such as electrostatic precipitators and scrubbers, and this material therefore includes a combination of MSWI fly ash, sorbents, gas condensates, and reaction products (Cho et al. 2020).

MSWI bottom ash is the waste produced in the greatest amount in MSWI plants (85% to 95% by weight). MSWI bottom ash is porous, grayish in color, and composed of glasses, ceramics, minerals, and ferrous and nonferrous materials, along with unburned materials and organic carbon. It consists of primarily of the oxides SiO_2, CaO, Fe_2O_3, and Al_2O_3, with Na_2O, K_2O, MgO, and TiO_2 present in smaller concentrations (Cho et al. 2020).

MSWI fly ash typically comprises only about 3% (by weight) of incineration waste. It consists primarily of SiO_2, CaO, and Al_2O_3, along with large amounts of Cl, Na, and K and heavy metals such as Zn and Pb (Cho et al. 2020). MSWI fly ash is typically finer than MSWI bottom ash and often has a high LOI (approximately 13%). Its specific gravity typically ranges from 1.7 to 2.4 (Cho et al. 2020). Due to the presence of highly soluble salts, Cl, and heavy metals, MSWI fly ash is not typically considered for direct use in construction applications without beneficiation techniques. These techniques can include extraction and separation using water or acids, chemical stabilization, solidification, or thermal treatment (Chandler et al. 1997).

In the United States, many MSWI plants combine the three MSWI residues—bottom ash, fly ash, and air pollution control residues—into a single stream, often referred to as “combined MSWI ash.” In Europe, these three sources of MSWI residue are separated, and beneficial use is more common. For example, approximately 80% of bottom ash produced in the Netherlands is used in civil engineering applications after it is beneficiated (Crillesen et al. 2006).

Ground Glass

Millions of tons of glass are produced annually in the United States, including an estimated 12.3 million tons of container glass (EPA 2020). Lesser amounts of plate glass and electrical glass (e-glass) are also produced. Container glass products are fairly uniform in composition but vary in color, making recycling this type of glass into new glass products difficult (Mirzahosseini and Riding 2014). Plate glass, also known as soda-lime glass, is clear or tinted float glass used for windows and automobile windshields. E-glass, which was first developed for electrical insulation applications, results from the production of reinforcement fiberglass. These three glass types comprise over 90% of the glass produced annually in the United States (Wintour 2015).

Material recovery facilities and bottle redemption programs are the primary sources of recycled glass. Thermal, wet, and mechanical processes exist to clean the glass prior to grinding for use as a pozzolan or in other applications such as new glass items, fiberglass, and filtration media (Kaminsky et al. 2020).

Glass is amorphous and is very high in silica, with other major elements being sodium, potassium, and calcium. The presence of additional elements varies with the type of glass. For example, container glass and plate glass are high in sodium and potassium and low in aluminum, while the distinguishing feature of e-glass, or glass fiber powder, is a significantly lower sodium and potassium content.

Ground glass pozzolan (GGP) is glass that has been reduced in particle size to a fine material and has been shown to exhibit pozzolanic behavior (Maraghechi et al. 2014). To behave as a pozzolan, it is generally agreed that the glass needs to be ground to a fineness at which its specific surface area is greater than 210,000 in.^{2}/lb (Mirzahosseini and Riding 2014). Compared to other pozzolans, GGP provides several advantages when used in concrete, including fairly uniform chemistry and reactivity and lower water demand. Due to the controlled processes used to produce different glass types, the potential for toxic materials is low, and the composition of each glass type is fairly uniform. Recovery facilities support widespread availability and sourcing of GGP (Kaminsky et al. 2020).

Table 4. Chemical composition of glass powders compared to OPC and Class F fly ash

Contents (%)	OPC	Fly Ash (Class F)	Soda-Lime Glass Powder	LCD Glass Powder	Glass Fiber Powder
SiO_2	20.72	63.92	67.13	67.34	47.7
Al_2O_3	4.73	21.81	2.82	18.92	10.4
Fe_2O_3	3.72	6.69	0.01	0.56	0.3
CaO	61.94	2.36	9.49	9.42	19.6
MgO	3.07	0.93	1.83	1.53	2.3
SO_3	2.31	0.39	0.01	0.02	0.02
Na_2O	0.01	0.75	8.44	0.05	Not reported
K_2O	1.00	1.56	1.08	Not detected	Not reported
$Na_{eq}O$*	0.67	0.89	2.36	0.54	0.70

** Equivalent alkali when 20% of portland cement is replaced with fly ash and liquid crystal display (LCD) glass powder or soda-lime glass powder.*

Sources: You et al. 2019, Rashidian-Dezfouli and Rangaraju 2018

Table 4 shows the chemical compositions of ground glass powders produced from different types of source glass and compares these compositions with those of a Class F fly ash and an ordinary portland cement (OPC). The specific gravity of ground glass typically ranges from 2.4 to 2.8 (Mohajerani et al. 2017). Other characteristics of ground glass are highly dependent on the source material and processing, although its Blaine's fineness has been reported as 10,200 cm^2/g in one study, and its LOI has been reported as 1.0% in another (Rashidian-Dezfouli and Rangaraju 2018).

Foundry Sand

Foundry sand is a high-silica sand used in foundries with sand-cast molding systems. The most common metal casting technique includes molding in "green sand," which is a composite material consisting of high-grade industrial sand bound together with bentonite clay (4% to 6%) and mixed with a small amount of carbonaceous material and water. Green sands are dark colored and are finer than most construction-grade sands.

The gradation of foundry sands is typically fairly uniform, with about 85% to 95% of the particles sized between the No. 30 and No. 100 sieves and 5% to 12% of the particles smaller than the No. 200 sieve. The material typically includes a significant amount (between 1% to 44%) of clay lumps and friable particles (FHWA 2016). Standard proctor compaction tests on foundry sands typically indicate a maximum density of 107 to 117 lb/ft^3 at an optimum moisture content of 9.6% to 27.1%. The coefficient of permeability has been found to range from 0.004 to 4×10^{-6} in./sec, and the internal friction angle is reported to be 33 to 40 degrees in the direct shear and triaxial shear tests (FHWA 2016).

RCA and Mixed Rubble from C&D Recycling Facilities

Construction and demolition recycling facilities are often stationary plants that process waste from many different sources. The types of waste processed at these facilities can include concrete, concrete masonry, brick, hardscaping material, and other materials such as roofing materials, insulation materials, metals, plastics, and other construction products that may be integrated into the waste stream. Therefore, the recycled aggregates produced at C&D recycling facilities often vary widely in composition and quality, and the characteristics of these aggregates can be highly variable. A sample of recycled aggregate from a C&D waste facility is shown in Figure 2.

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Figure 2. Recycled aggregate produced at a C&D waste facility

Unlike RCA produced from transportation agency sources with a known performance history (such as pavements and transportation structures), aggregates produced at C&D recycling facilities can include material from multiple sources or types of concrete components, some of which may not have met stringent performance standards. C&D facilities often do not separate concrete by source and typically do not characterize the concrete before crushing. Aggregates produced at C&D recycling facilities can also include undesirable levels of contaminants such as glass, plastics, wood, and other debris that can influence the aggregates' performance in new pavement applications. Aggregate produced from both concrete and masonry materials is often called mixed rubble. Some specifications indicate that mixed rubble contains less than 90% by mass of concrete and natural aggregate (Silva et al. 2014). When C&D recycling facilities practice source separation techniques, recycled aggregates composed predominantly of concrete (RCA) can be produced.

The properties of RCA from C&D recycling facilities depend highly on the properties of the source concrete (Silva et al. 2014). The crushing process can also influence RCA properties, including size, shape and roughness, particle density, crushing strength, and absorption (Cardoso et al. 2016). The type of crusher, size of crusher, operating speed, and other factors influence the RCA produced. Additionally, using multiple crushers in stages can result in higher particle densities and lower absorption for the coarse fraction of the material. However, this practice also results in greater production of fine RCA that tends to include a larger fraction of mortar, which results in higher absorption.

Mixed rubble and RCA produced from concrete of an unknown history or quality are not suggested for use in new concrete mixtures for paving applications (Snyder et al. 2018). However, RCA and mixed rubble produced at C&D recycling facilities have been successfully used in unbound applications in some concrete paving projects. Guidance on the use of RCA in unbound applications is presented in Snyder et al. (2018), along with case studies describing challenges and benefits. When selective demolition and source separation techniques are used during the demolition and recycling process, the consistency of the recycled aggregates produced can be improved and contaminants in the recycled aggregates can be reduced (Silva et al. 2014). Certain processing and handling techniques can also be used during the production process to improve the quality and consistency of the final product (Cardoso et al. 2016).

Other Materials

Other industrial wastes that have been tested in the laboratory or field for use in concrete paving applications include rice husk ash, sugar cane ash, plastics, and other materials. The reader is referred to other publications for additional information (Stroup-Gardiner and Wattenberg-Komas 2013, Venkatanarayanan and Rangaraju 2015, Arce et al. 2019, FHWA 2016).

Applications for Use and Design Considerations

Concrete paving applications for industrial waste product materials can be classified into unbound and bound uses, as shown in Table 5. Unbound uses refer to applications where the material is in service in granular form and not stabilized within a binder. Bound uses refer to applications where the material is stabilized with a binder (such as cement) or encapsulated within a cementitious material.

Unbound Applications

Many industrial wastes can be used in unbound fill, base, and shoulder applications if they are available in adequate supply and exhibit acceptable engineering properties and an acceptable level of variability (with producers responsible for demonstrating consistency). To provide suitable performance in unbound applications, recycled aggregates need to have a particle size distribution (gradation) and shape that is appropriate for the specific application, as well as adequate strength, stiffness, toughness, permeability, and resistance to damage from freezing and thawing.

Requirements for these properties and performance characteristics vary based upon agency specifications and the intended applications. Engineering properties required for fill, base, and unbound shoulder applications vary by agency due to climate and geographic considerations, historical experience, risk tolerance, and a host of other factors. However, agency specification provisions often address gradation, shear strength, CBR, creep, compressibility, and resistance to freeze-thaw damage and sulfate attack. In roadway bases and unbound shoulders, the resilient modulus, permeability, and hydraulic conductivity of a material may also be of interest. Many agencies require waste products to meet the same requirements as virgin materials, although some agencies make provisions to allow for changes in some properties. For example, some States allow RCA to have a slightly higher loss in abrasion tests.

Since most unbound applications are exposed to water, the potential for materials to leach heavy metals or other contaminants should be assessed using the Environmental Protection Agency's (EPA's) Leaching Environmental Assessment Framework (LEAF). LEAF methods and information, including resources such as modeling software and agency leaching studies, are provided online by the EPA, and the reader is referred to this website for access and current information (EPA 2022). Materials exhibiting unacceptable levels of contamination should not be considered for recycling. For recycled aggregates, AASHTO M 319 provides limits on contaminants, recommendations for stockpile management practices to avoid contamination, and suggestions for assessing recycled aggregates to facilitate testing and acceptance.

Industrial wastes suitable for use in unbound applications are summarized below. Pertinent properties related to unbound uses and the performance of these materials in laboratory and field studies are discussed for each waste product.

Table 5. Potential paving applications for industrial wastes

Application		Waste Product							
		Off-Spec Coal Ash	MSWI Bottom Ash	MSWI Fly Ash	Foundry Sand	C&D RCA	C&D Rubble	Off-Spec Fly Ash	Ground Glass
Unbound applications	Fill material	R	R	—	R	R	R	A	—
	Base material	R	R	—	R	R	R	A	—
	Shoulders	R	R	—	—	R	R	A	—
Bound applications	Single-lift portland cement concrete	R, A	R	—	—	—	—	A	A
	Two-lift portland cement concrete	R, A	R	—	—	—	—	A	A
	Cement-treated base layers	R, A	R	R	—	—	—	A	A

Note: "A" indicates potential use as an ASCM; "R" indicates potential use as a replacement for virgin aggregate.

Coal Combustion and MSWI Bottom Ash

Coal combustion bottom ash and MSWI bottom ash have both been found to have engineering properties suitable for use in fill materials (FHWA 2016, ACAA 2013, Crillesen et al. 2006).

Coal combustion bottom ash has been found to be a useful material in a variety of roadway applications. According to the American Coal Ash Association, in 2013 approximately 39% of coal bottom ash was used as structural fill, roadway base material, raw material for cement and concrete production, and snow and ice control products (ACAA 2013).

Coal combustion bottom ash has also been used successfully in concrete mixtures as an aggregate, with the material's lower specific gravity providing reduced unit weights for the mixture (Rodriguez-Alvaro et al. 2021). The higher absorption of coal combustion bottom ash needs to be accounted for in mixture design to prevent workability issues. However, the increased absorption capacity could also provide internal curing benefits if the material is prewetted prior to mixing (Rodriguez-Alvaro et al. 2021).

MSWI bottom ash can be used as a subgrade amendment for roadway construction, since its shear strength, elastic modulus, and bearing capacity have been found to be similar to those of natural sand (Santagata et al. 2014). When blended with sand (Mohamedzein et al. 2006) and clayey soils (Bhavya et al. 2015), MSWI bottom ash has been found to produce a blended material with significantly improved engineering properties. MSWI bottom ash has also shown promise for use in embankment fill, providing adequate shear strength, compressibility, drainage characteristics, and stability in most types of embankments (Soleimangeigi et al. 2014).

Though field applications of MSWI bottom ash are not common, in one study MSWI bottom ash was used to replace virgin aggregate in a pavement subbase and performed satisfactorily (Wiles and Shepherd 1999). Additionally, bottom ash is used in Denmark as a replacement for aggregate in pavement base material beneath asphalt or concrete surface layers (Crillesen et al. 2006).

Although laboratory and field trials have shown strong promise for the use of both coal combustion and MSWI bottom ash in roadway projects, these materials are not commonly used in practice due to concerns about leachates, particularly heavy metals (Cho et al. 2020). Studies have shown that aging and weathering processes can reduce the potential for the release of heavy metals such as zinc, lead, cadmium, and chromium because these processes often bind these heavy metals in stable compounds (Santos et al. 2013).

Foundry Sands

Foundry sands can be transported, placed, and compacted using conventional construction techniques and show promise for use in fill and base applications (Abichou et al. 1999, AFS 2021).

In embankments and bases, foundry sands have been found to provide adequate shear strength and a higher compressibility and strain rate than local soils (Goulias et al. 2016). However, foundry sands have shown a creep response similar to that of compacted natural soils (Yin et al. 2018).

Kleven et al. (2000) found that foundry sand mixtures used as subbase material in roadway applications exhibited CBR values ranging from 4 to 40, with a CBR value of around 20 achieved with standard effort at optimum water content. Unconfined compressive strengths ranged from 10 to 27.5 psi, and the resilient moduli of compacted foundry sand samples were similar to that of a reference subbase material (a Wisconsin DOT Grade 1 subbase) but less than that of a reference base material (a Wisconsin DOT Grade 2 crushed gravel).

Studies have been performed to evaluate the leaching potential of foundry sands, since they can contain heavy metals, phenols, and polycyclic aromatic hydrocarbons (PAH) (FIRST 2004). A range of studies reviewed by Vipulanandan et al. (2005) indicated that toxicity characteristic leaching procedure (TCLP) tests often showed that a wide variety of organic compounds were present in foundry sand leachates, but most were present at low concentrations, and no samples produced concentrations above toxicity limits. The EPA has supported the use of foundry sands and operates a site supporting their beneficial use (EPA 2021b).

RCA and Mixed Rubble from C&D Waste

Studies have shown that the properties and characteristics of recycled aggregates from C&D waste greatly influence the performance of unbound base layers constructed using them (Cardoso et al. 2016). Therefore, recycled aggregates need to be tested to determine their physical and mechanical properties before they are used. When these properties are known, understood, and properly considered in base layer design and construction, RCA and mixed rubble from C&D recycling can be used as unbound pavement base material (either alone or blended with natural aggregate) in pavement applications (Silva et al. 2014).

The CBR values of recycled aggregates from different types of C&D waste have been found to vary widely (from 66 to 198 for RCA and 62 to 152 for mixed rubble), although the CBR values of some RCAs from C&D waste have been found to exceed those of some natural aggregates (Cardoso et al. 2016). The resilient modulus for aggregate blends containing recycled aggregate from C&D waste has been found to decrease with an increase in the proportion of recycled aggregate in the blend. The permeability of unbound bases constructed with recycled aggregates from C&D waste varies strongly with gradation and can be either higher or lower than that of control materials (Cardoso et al. 2016).

The resistance of recycled aggregate from C&D waste to freeze-thaw damage and sulfate attack should be evaluated prior to use in unbound bases. AASHTO T 103 has been successfully used to assess the freeze-thaw resistance of recycled aggregate from C&D waste. However, the mortar fraction contained in these recycled aggregates may react with sodium and magnesium sulfate solutions, yielding misleading results; therefore, alternate procedures are suggested (Snyder et al. 2018). Some studies have shown that RCAs from C&D waste exhibit much lower freeze-thaw resistance than natural aggregates, but this may be a function of the quality of the source concrete (Cardoso et al. 2016).

If recycled aggregates from C&D waste are used to construct unbound base and fill, the equipment and approaches used for placement and compaction may not differ greatly from those used for conventional materials. However, the mortar content in RCA and mixed rubble produced from C&D waste usually results in a higher optimum water content needed for compaction and decreases the maximum dry density. The compaction energy imparted to RCA produced from C&D waste may produce additional fines (caused primarily by degradation of the mortar fraction), and vibration is more desirable than impact energy for consolidation (Cardoso et al. 2016). Use of a standard compactive effort in lieu of compaction to density could help avoid overcompaction and degradation of material and production of additional fines (Snyder et al. 2018).

Several case studies describing the use of recycled aggregates from C&D waste in unbound applications are detailed in Cardoso et al. (2016). Based on International Roughness Index (IRI) measurements and the results of falling weight deflectometer (FWD) tests, some pavement systems using RCA have shown improved performance over natural aggregate bases, indicating that RCA may provide a longer service life than natural aggregate, possibly due to secondary cementing effects.

Bound Applications

Industrial wastes can also be used in a range of bound applications in concrete pavements. The chemical composition and fine particle size of some of the waste products described above make them suitable for use as ASCMs. Other waste products that have a larger particle size are suitable for use as aggregates in cement- and asphalt-treated base layers, single-lift and two-lift concrete pavements, and concrete and asphalt shoulder mixtures. Due to the leaching potential of some industrial wastes, their use in bound pavement layers is an enticing beneficial use application, since either the potentially harmful components are bound into the matrix of the new material, or the new material is not permeable enough to allow leaching of soluble components.

Industrial wastes suitable for use as either ASCMs or aggregates in bound applications are summarized below. Pertinent properties related to bound uses and the performance of these materials in laboratory and field studies are discussed for each waste product.

Use of Waste Products as ASCMs

Coal Combustion Ash Not Meeting AASHTO M 295 (ASTM C618)

As discussed above, a significant amount of coal ash being produced does not meet the current provisions of AASHTO M 295 (ASTM C618). As supplies of coal ash become limited, there is increasing interest in using off-spec ash, which may still provide performance benefits in various applications despite not meeting AASHTO M 295 (ASTM C618). The use of harvested ash is also becoming increasingly necessary for the concrete industry to offset the limited availability of other SCMs that improve concrete durability. Harvested ash currently needs to meet all requirements of AASHTO M 295 (ASTM C618), though harvested off-spec ash can be beneficiated to meet specification requirements and to create a more consistent product (Tritsch et al. 2021).

Used alone or blended with other materials, off-spec coal ash can possess the chemical and physical characteristics needed to provide benefits for concrete and stabilized bases (Diaz-Loya et al. 2019, Kaladharan et al. 2019). Off-spec coal ash has been found to be a suitable material for use in stabilizing soils, with high-CaO off-spec ash showing better performance than fly ash meeting AASHTO M 295 (ASTM C618) in stabilizing some soils (Yilmaz et al. 2018).

Several research studies are underway that aim to improve the test methods used to characterize fly ash and the performance of fly ash in concrete and stabilized bases (FHWA 2022). Work performed as part of NCHRP 10-104 (NCHRP 2022) and other studies will also inform revisions to the chemical and physical requirements of AASHTO M 295 (ASTM C618).

Ground Glass

Extensive research has shown that ground glass is an effective ASCM, and GGP is now specified by ASTM C1866, Standard Specification for Ground-Glass Pozzolan for Use in Concrete. Two types of glass pozzolan are specified. Type GS glass is soda-lime glass, and Type GE is e-glass. Both types have been shown to increase concrete and mortar strengths and reduce permeability. Type GE glass has been shown to be effective in mitigating ASR, while Type GS is less effective at mitigating ASR given its high alkali content. Currently, Type GS glass is not recommended for use with aggregates prone to ASR without first verifying performance using ASTM C1293.

Many research studies have focused on beneficial use applications for soda-lime glass since this type of glass is typically the most prevalent type of waste glass (Mahajerani et al. 2017). Studies have shown improved durability performance for mortars and concretes containing ground glass, including reduced absorption, susceptibility to sulfate attack, and ASR (Shi et al. 2004, Zidol et al. 2020). Reduced chloride penetration resistance has also been observed (Shayan and Xu 2006, Zidol et al. 2020), as well as reduced carbonation potential (Zidol et al. 2020).

Other sources of waste glass besides Type GS and Type GE glass have also been studied and have shown promise for use in pavement applications. For example, liquid crystal display glass has a more consistent composition than soda-lime glass and is high in alumina and silica. A study of concrete produced using powdered liquid crystal display glass indicated that this type of glass could provide strength similar to that provided by Class F fly ash at later ages. The study also showed significant improvements in concrete durability, including increased resistance to wear, lower susceptibility to ASR (due to alkali binding), increased resistance to chloride ion penetration, and improved freeze-thaw durability (You et al. 2019).

Field studies have shown that concrete produced using ground glass performs adequately (Shayan and Xu 2006). In practice, concrete containing Type GE GGP has been used in a range of architectural and landscaping uses, as well as in sidewalks in New York City. Concrete containing GGP has also been planned for use in structural high-rise applications and in bridges (Kaminsky et al. 2020). The New York State DOT allows ground glass to be used as mineral filler in concrete (NYSDOT 2014).

The potential for using ground glass with waste glass aggregate in geopolymer-stabilized road bases was recently studied, and the materials exhibited promising performance in the laboratory (Xiao et al. 2020).

Use of Waste Products as Replacement for Natural Aggregate

Coal Combustion Bottom Ash, MSWI Bottom Ash, and MSWI Fly Ash

Research has shown that coal combustion bottom ash can be used as an ASCM or as a partial replacement for natural sand in concrete mixtures, producing durable concrete with mechanical properties similar or even superior to those of conventional concrete. One study showed that concrete mixtures in which up to 100% of natural sand was replaced with coal combustion bottom ash gained strength at a slightly lower rate than that of control mixtures at early ages. However, by 28 days the experimental mixtures had equivalent or superior strength to that of the control mixtures (Singh et al. 2016). Coal combustion bottom ash has also been shown to have pozzolanic properties, particularly if ground finely. One study on the use of bottom ash as an aggregate substitute in new concrete attributed the observed reduction in permeability and shrinkage to the pozzolanic activity of the bottom ash particles (Singh et al. 2016).

MSWI bottom and fly ashes have also been studied for use as replacements for cement or aggregates in concrete mixtures, cement-stabilized bases, and asphalt mixtures (Cho et al. 2020). Studies have generally shown that MSWI fly ash performs adequately as a cement replacement, but workability is often reduced due to the absorption of the material, and adjustments to mixture proportions need to be made to achieve the desired strength and other properties. MSWI ash has also been studied for use as a feed material for cement production (Cho et al. 2020).

Foundry Sands

Foundry sands have been used in bound applications as a soil amendment, in flowable fills, and in new portland cement concrete and asphalt mixtures (Abichou et al. 1999, Goulias 2016).

Several State DOTs including those in Iowa, Pennsylvania, Wisconsin, and Ohio have (or previously had) specifications allowing the use of foundry sand in flowable fills (Vipulanandan et al. 2005). More recently, a survey of 15 States indicated that only 3 States (Wisconsin, Ohio, and Alabama) use foundry sand in flowable fill or in self-consolidating concrete (Goulias et al. 2016).

An FHWA publication, *Foundry Sand Facts for Civil Engineers*, provides practical information on the use of foundry sands in embankments, road bases, hot-mix asphalt, flowable fills, and portland cement concrete. For each of these applications, information is provided on engineering properties, mixture development, testing and specification, construction practices, and environmental impacts (FIRST 2004).

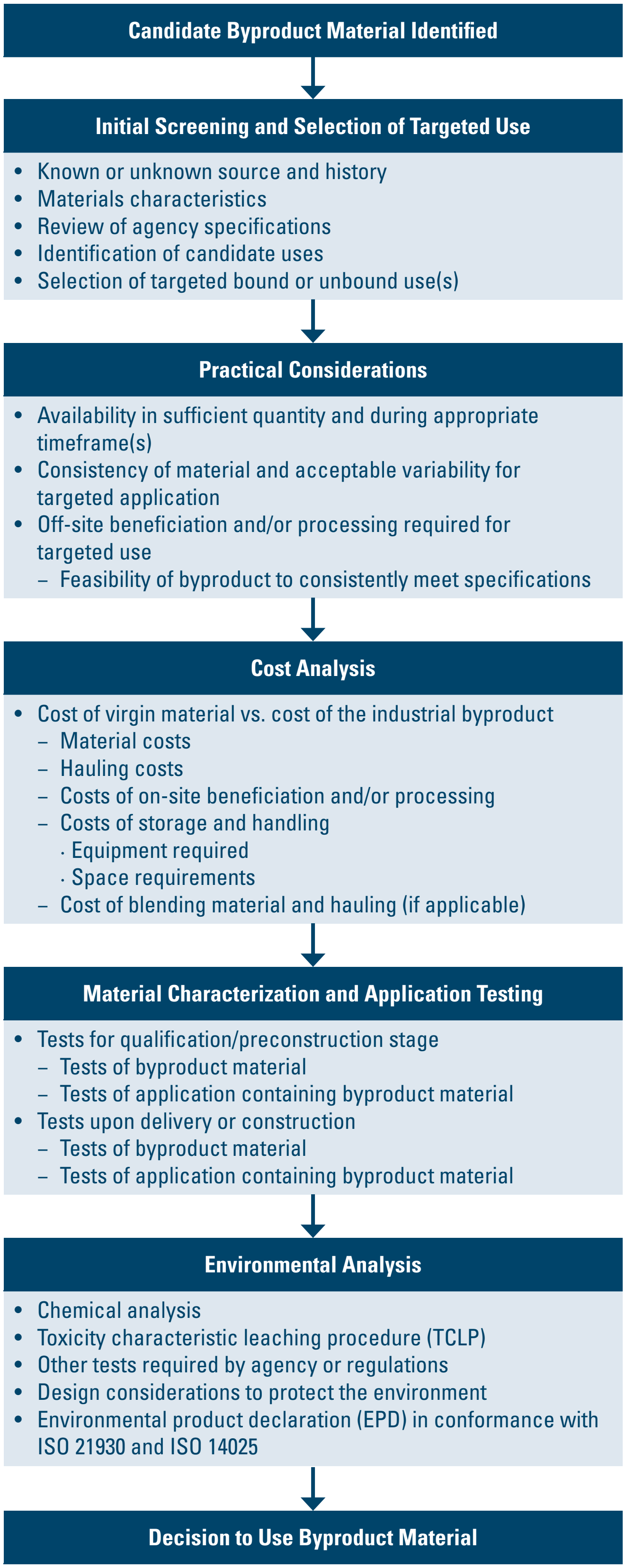
The use of foundry sand in flowable fill reduces the workability of the mixture and increases admixture demand. With increasing replacement rates of foundry sand for natural sand, the compressive strength of the hardened flowable fill may decrease while the permeability increases. Studies have shown that an increase in foundry sand content increases the material's resistance to chloride penetration, but the material has also been shown to be more susceptible to sulfate attack (Goulias et al. 2016).

Cement- and lime-stabilized foundry sand or natural aggregate blends have been used in stabilized base applications. Prolonged curing times have been shown to provide strength improvements over control mixtures (Goulias et al. 2016).

In concrete mixtures, foundry sands have been studied for use as a fine aggregate replacement. Studies have shown mixed performance regarding the impact of foundry sand on concrete compressive strength (Elinwa and Kabir 2019, Bhardwaj and Kumar 2017) and permeability (Bhardwaj and Kumar 2017). An increase in drying shrinkage and an increased susceptibility to carbonation have also been observed (Goulias et al. 2016). At this time, the use of foundry sand in concrete applications is not suggested.

Evaluation for Use

Careful evaluation of any industrial waste material is suggested prior to its use in a concrete paving project. Whenever possible, this evaluation should occur early in the project planning and scoping phases to capture the material's potential beneficial use and to mitigate risk. ASTM C1709, Standard Guide for Evaluation of Alternative Supplementary Cementitious Materials (ASCM) for Use in Concrete, provides information for evaluating a material (in this case, an industrial waste) for use as an ASCM in a given concrete paving project. This framework is illustrated in Figure 3.



Candidate Byproduct Material Identified

Initial Screening and Selection of Targeted Use

- Known or unknown source and history
- Materials characteristics
- Review of agency specifications
- Identification of candidate uses
- Selection of targeted bound or unbound use(s)

Practical Considerations

- Availability in sufficient quantity and during appropriate timeframe(s)
- Consistency of material and acceptable variability for targeted application
- Off-site beneficiation and/or processing required for targeted use
  - Feasibility of byproduct to consistently meet specifications

Cost Analysis

- Cost of virgin material vs. cost of the industrial byproduct
  - Material costs
  - Hauling costs
  - Costs of on-site beneficiation and/or processing
  - Costs of storage and handling
    - Equipment required
    - Space requirements
  - Cost of blending material and hauling (if applicable)

Material Characterization and Application Testing

- Tests for qualification/preconstruction stage
  - Tests of byproduct material
  - Tests of application containing byproduct material
- Tests upon delivery or construction
  - Tests of byproduct material
  - Tests of application containing byproduct material

Environmental Analysis

- Chemical analysis
- Toxicity characteristic leaching procedure (TCLP)
- Other tests required by agency or regulations
- Design considerations to protect the environment
- Environmental product declaration (EPD) in conformance with ISO 21930 and ISO 14025

Decision to Use Byproduct Material

Recreated from Tara Cavalline, University of North Carolina at Charlotte

Figure 3. General framework for evaluation of an industrial waste for use in a concrete pavement project

ASTM C1709 suggests an initial screening of the material prior to the identification of potential uses and selection of the final use(s). The initial screening of the waste product should include information on the source, history, and material characteristics. Relevant agency specifications should also be reviewed. Practical issues to be considered include the availability of the waste product in a sufficient quantity during the appropriate timeframe(s), the consistency of the material and the variability of the desired characteristics, and the need for beneficiation. If the waste product shows promise for use, further analysis to explore economic, performance, and environmental considerations is necessary. Additional discussion of this framework is presented in the following sections.

Feasibility Analysis (Initial Screening, Practical Considerations, and Cost Analysis)

The feasibility of using a waste product for a given project is determined through the initial screening, assessment of practical considerations, and cost analysis. These considerations involved in determining feasibility, discussed subsequently, can generally be grouped into availability, consistency, and cost.

The availability of an industrial waste is often based on the location of the project and its proximity to a source for the waste, such as an industrial process or a C&D waste recycling facility. The ability to use a waste product in a specific concrete paving application can also be a function of project staging, scheduling, and duration. An adequate supply of the waste material should also be available to meet the needs of the project (or selected portions of the project). Guidance on project scoping and staging for RCA, including estimating the availability of waste for use in different applications at specific project schedule points, is provided in Snyder et al. (2018) and in a webinar by Fick (2017).

The consistency of the material, or its uniformity, is one measure of the quality of a material and reflects the processing and handling techniques used in its production. Approaches to evaluating the consistency of a material are described subsequently in this document.

Although reuse of waste products typically provides environmental and economic benefits, cost factors can drive the decision to recycle and beneficially use a waste material, particularly if the decision is primarily led by the contractor. For example, if the waste product is used as an aggregate, the cost savings can be calculated as the difference in cost between using the waste product and using virgin material. If a material contributes to cement hydration or pozzolanic reactions or improves the paste-aggregate bond through surface texture or other means, it may reduce the need for conventional binders such as portland cement or fly ash, resulting in additional cost savings. Some factors to consider when computing a cost comparison between virgin and waste materials are shown in Table 6.

Use of the waste product in lower grade applications (such as unbound bases or fill) rather than higher grade applications (such as bound bases or new concrete) may reduce the costs associated with production and testing because the contractor often has more flexibility in establishing operations to produce materials that meet project specifications for lower grade applications. Use of the waste product in densely graded applications, such as shoulders or fill, can also allow for a greater amount of the material to be beneficially used (Snyder et al. 2018).

Table 6. Factors influencing costs of using industrial wastes and virgin materials

Cost of the Virgin Material	Cost of the Industrial Waste Material
• Material costs (either virgin aggregate or binder) • Transportation to site • Placement and compaction methods needed (for unbound uses) • Handling, storage, and stockpile management (for bound uses)	• Processing needed to achieve suitability for use (e.g., drying, grinding, blending) • Transportation to site • Storage and handling equipment needed (e.g., extra silos, engineering controls for safety, personal protective equipment) • Placement and compaction methods needed (for unbound uses)

The use of waste product material should be considered early in the project bidding or delivery phases. Early consideration allows time for practical issues associated with availability to be identified and addressed, characterization and assessment of the material for the targeted use to be performed, and a cost comparison to be conducted. If waste products are evaluated for use during the project bidding phase, cost savings can be passed on to the agency in the form of lower bid prices.

Performance Analysis

For an industrial waste to be beneficially used in concrete paving projects, the following should be understood:

- The characteristics of both the material and the application
- The potential variability of the material's characteristics
- The material's suitability for the application

Issues with the source material that could affect pavement performance, such as excessive contamination or the potential to induce materials-related distress (such as ASR or sulfate attack in concrete), should be identified in advance.

For concrete construction applications subject to ACI 318/318R, Building Code Requirements for Structural Concrete and Commentary on Building Code Requirements for Structural Concrete, Holland and Hover (2020) proposed a data sheet for alternative cementitious materials that could help suppliers of these materials provide the information that users need to adequately evaluate the products for use and that agencies and other stakeholders need to evaluate their suitability for particular applications. The data sheet would provide a series of questions and commonly requested information, including a general description of the material, considerations related to concrete production, typical contractor concerns, the material's structural performance and compliance with ACI 318, the material's durability performance, sustainability considerations, and architectural concerns. Since it is intended for structural applications, the data sheet would provide more thorough information than that needed for materials used in unbound applications.

An issue that can arise is how to demonstrate that the performance of waste products is equivalent to that of conventional materials for different uses. A development that may help resolve this issue is that many agencies are moving toward performance-based specifications for concrete and other construction materials. Ongoing research to support performance-based specifications for SCMs and other materials should provide additional tools and information to support the increased acceptance and use of waste product materials (CP Tech Center 2022, NCHRP 2022, FHWA 2022).

Existing test methods characterize and qualify waste product materials as aggregates and SCMs, with some notable exceptions. For example, ASTM C1709 provides technical information for evaluating alternative SCMs in concrete that fall outside the scope of ASTM C618, ASTM C989, ASTM C1240, and ASTM C1866. The standard specifically suggests field performance testing.

Appropriate tests to consider for characterizing waste materials will vary with the desired use in various aggregate and ASCM applications, such as bound and unbound bases, fills, and concrete mixtures.

Materials to Be Used as ASCMs

For materials used as ASCMs, ASTM C1709 states that the performance of the evaluated ASCM should be compared to that of an existing SCM, such as a material falling within the scope of ASTM C618, ASTM C989, or ASTM C1240. A five-stage program is suggested:

- Stage I. Characterization of the material
- Stage II. Determination of suitable fineness
- Stage III. Testing to specifications such as ASTM C618, ASTM C989, ASTM C1240, or ASTM C1866
- Stage IV. Concrete performance tests
- Stage V. Field trials and long-term performance and durability assessment

Stage I includes a chemical analysis to determine the quantity of the major, minor, and trace element constituents using methods such as x-ray fluorescence, atomic absorption spectroscopy, and inductively coupled plasma spectroscopy. If this analysis indicates the presence of compounds potentially harmful to the hydration of cement or to the properties of concrete, tests to evaluate the "availability" of the compounds to participate in hydration reactions should be performed.

In Stage II, particle size distribution, fineness, and specific surface area are determined. Mortar tests per ASTM C109/109M are suggested, with the test program modified to support comparison between mortars containing the ASCM at the typical proposed replacement level and mortars produced with a control portland cement.

In Stage III, testing is performed to assess the chemical, physical, and uniformity characteristics of the ASCM against the appropriate standard of the SCM to which it is being compared.

If the ASCM is to be used in concrete, a series of mixtures should be created in Stage IV to evaluate the performance of the ASCM in fresh and hardened concrete, with the mixtures proportioned in a manner that reflects the intended use of the material. The test program should also include commonly used admixtures, at least one commercially available SCM conforming to an applicable standard, and a control mixture. Mixtures containing a range of potential ASCM contents that bracket the intended level of use should be prepared using total cementitious contents varying from 337 to 674 lb/yd^3 (200 to 400 kg/m^3). If the ASCM is to be used as an SCM in base or fill, tests to evaluate the performance characteristics required for the specific use should be performed in Stage IV.

If the ASCM demonstrates acceptable performance in the previous stages, field trials to assess its long-term performance and durability are performed in Stage V. ASTM C1709 also suggests that sampling and testing be performed to determine that the uniformity of the ASCM in production meets the standard applicable to the existing SCM to which it is being compared (ASTM C618, ASTM C989, or ASTM C1240). Sampling and testing frequencies should be greater than those outlined in the relevant standard during the first six months of production of the ASCM.

During delivery and construction, tests on both the ASCM and the material produced using the ASCM should be performed. Variability in the ASCM should be determined at a suitable frequency. For a given use, variability in the performance of the material produced using the ASCM should be correlated with the uniformity of the ASCM. The agency should set appropriate limits on the uniformity of the ASCM based on these results.

Materials to Be Used as Aggregates

If a material is to be used as an aggregate in base or fill, the generally accepted best practice is that the general specifications of AASHTO M 147 should be met. The physical characteristics of the material should be determined, including gradation (AASHTO T 27/M 43), particle shape (ASTM D4791), unit weight (AASHTO T 19), deleterious components (ASTM D2419), and soundness (AASHTO T 103, or the hydraulic fracture test). The presence of contaminants should be limited during production and processing and determined via AASHTO M 319. The user should also consider determining the chemical composition of the material via x-ray fluorescence and x-ray diffraction.

If a material is to be used as an aggregate in drained, unbound base applications, carbonates that may form tufa should be identified. Tests of the system containing the material as an aggregate should also be performed. For coarser materials, these tests may include the Micro-Deval test for abrasion loss, the Tube Suction Test for dielectric constant, and tests for the resilient modulus (AASHTO T 307) and shear strength (static and repeated triaxial loading at optimal moisture content and saturated conditions). For finer materials that act more like soils, appropriate tests may include consolidation (ASTM D2435), vertical free swell (ASTM D4546), and liquid and plastic limit (ASTM D4318).

If a material is to be used as an aggregate in concrete, the requirements of ASTM C33 should be met, including those associated with deleterious substances. The physical characteristics of the material should be determined, including gradation (AASHTO T 27/M 43), unit weight (AASHTO T 19), abrasion resistance (AASHTO T 96), and soundness (AASHTO T 103, or the hydraulic fracture test). The presence of contaminants should be limited during production and processing and determined via AASHTO M 319. The user should also consider determining the chemical composition of the material via x-ray fluorescence and x-ray diffraction. Tests on the system containing the material should also be performed, including those to assess the potential for alkali-aggregate reactivity per AASHTO R 80 and the susceptibility of the material to D-cracking per ASTM C666 (if the material has not been tested using AASHTO T 103 or the hydraulic fracture test).

During delivery and construction, tests for particle size, uniformity, and the presence of contaminants should continue to be performed on the material. Tests of the system produced using the material (concrete, bound fill, unbound fill) should also be performed. For base and fill applications, these should include tests for optimum moisture content and maximum dry density (AASHTO T 134) and compacted density (AASHTO T 310, AASHTO T 191, ASTM D2167). For concrete, these should include tests for workability, air content and air system parameters, and strength.

The variability of the material in the field should be determined at a suitable frequency. For a given use, variability in the performance of the system produced using the material should be correlated with the uniformity of the material. The agency should set appropriate limits on the uniformity of the material based on these results.

Environmental Analysis

Many industrial wastes contain small amounts of heavy metals or contaminants from the source material (such as fly ash in the source concrete for RCA) or from the coal or municipal solid waste that was combusted or incinerated. The potential environmental impacts of a waste material should be understood prior to its use. Appropriate agency regulations, specifications, and permitting requirements should be reviewed, and environmental considerations should be identified and addressed. Information on the content of heavy metals or other potentially harmful components in the material should be provided by the supplier, along with test data regarding the performance of the material in leaching tests using the LEAF procedure (EPA 2022) or other appropriate methods. Steps should be taken by the agency, by the designer, and during production to ensure that the recycled materials will not cause environmental issues during handling and construction or while in service.

Environmental considerations can and should be incorporated into both the design and construction operations. Some waste products, such as recycled aggregates, can produce high-pH runoff from stockpiles and while in service in unbound applications (Snyder et al. 2018). In unbound applications, water flowing through RCA can result in highly alkaline runoff or effluent with pH values as high as 12. The high pH of effluent from RCA can occur early and then diminish over time as calcium hydroxide near the surfaces of the RCA particles is consumed. This effluent is typically not an environmental concern, given that it is often rapidly diluted over distance with other rainfall runoff, or the pH is neutralized by soils or other landscape components.

Contractors should be aware of the potential for high-pH runoff; consider the sensitivity of local soils, receiving waters, and vegetation; and use mitigation measures such as traditional stormwater best management practices (BMPs) for stockpiles or setbacks of drains from receiving waters (Cavalline 2018). Monitoring of effluent can be performed by qualified laboratories and personnel, if needed.

Leachate and runoff can also include small amounts of pollutant materials, such as heavy metals. Although the levels of these pollutants in runoff may be greater than those acceptable in drinking water, runoff or leachate can be readily diluted, mitigated, or captured in nearby environmental systems (such as bioswales) and using other typical stormwater BMPs (Snyder et al. 2018).

Acceptable levels of pollutant materials vary by agency, receiving water, and other factors, and the appropriate regulations should be consulted.

Stormwater BMPs to address the potential environmental impacts of runoff from industrial wastes should be implemented for stockpiles and potentially for drains beneath pavements. These BMPs can be incorporated into a stormwater pollution prevention plan. Practices to protect water and air quality, as well as to reduce noise and other local impacts, are presented in Snyder et al. (2018). Although the information in this resource focuses on RCA production and use, much of it is also applicable to the use of the industrial wastes discussed in this technical summary.

Approaches and Considerations for Approval of Waste Products

The approaches, considerations, and processes used by agencies for the approval of materials that can be used in paving projects vary widely due to environmental and climate factors, performance history, available resources, and other factors (Kasana et al. 2020). State agencies may maintain a list of materials that are prequalified for use and provide a method that stakeholders can follow to apply for approval or certification of new products and alternative materials. Designated agency personnel perform tasks such as discussing approval processes with interested parties, visiting plants and production facilities, receiving and evaluating test data and other supporting information and disseminating it to other personnel for review, coordinating in-house testing and evaluation, and preparing or overseeing the documentation necessary to support approval.

State agencies may maintain a website where the process for seeking approval of a new material is presented along with the appropriate forms, specifications, and testing requirements. To approve a new product for use, most agencies require laboratory testing. The burden of testing is typically placed on the material producer or supplier, and some State agencies require that materials be tested at approved testing laboratories. Laboratory tests recommended for evaluating the use of waste materials as aggregates and ASCMs in bound and unbound applications are presented previously in this document, with typical values summarized in Table 2.

Some agencies recommend or require field trials to demonstrate the constructability and performance of a new material or product. When scoping trial projects, considerations often include the type and location of the element to be constructed, the extent of the application, the type and quantity of traffic that the trial project is expected to experience, and the duration of the trial. A plan for monitoring, testing, and inspection should be developed to include provisions for both construction and in-service evaluation. Case studies describing field trials with RCA are presented in Snyder et al. (2018), with field trials for other materials presented in other publications.

Conclusions

Several types of beneficial use applications exist for industrial wastes, including use in unbound fills and base materials, in stabilized bases, and in new concrete applications. These beneficial use applications have the potential to conserve landfill space and natural resources and reduce costs. After an application for a material is identified and practical considerations indicate that the material could be used for that application, the economic feasibility, technical performance, and environmental impacts of the material's beneficial use should be analyzed using the approaches and considerations described in this document. The economic benefits associated with use of a waste product can be further quantified using a life-cycle cost analysis (LCCA) (FHWA 2024), and the environmental impacts and benefits associated with use of a waste product can be evaluated using a life-cycle assessment (LCA) (Harvey et al. 2016).

The performance of several of the waste materials discussed in this technical summary, including RCA, coal ash, and GGP, has been demonstrated through research and field trials in concrete paving applications, and standards and guide documents exist (or are in development) to support their use. The performance of other materials, including foundry sand and MSWI ash, is not entirely understood, and standards to support their use do not currently exist. Regardless of the waste material used, tests should be performed on the material itself and on the application product (e.g., base, fill, or concrete material) during the qualification/preconstruction phase and upon delivery or during construction.

Agencies use a variety of approaches to evaluate and approve new products for use in paving projects. If agencies promote beneficial use options for waste products and provide clear practices for handling and treating these products and determining allowable applications, contractors and agencies can capitalize on potential cost savings at the time of bidding and have confidence in the measures and methods needed for the beneficial use of industrial wastes.

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