ADVANCING CONCRETE PAVEMENT TECHNOLOGY SOLUTIONS

Use of Construction Byproducts in Concrete Paving Mixtures

Technical Summary | December 2024

National Concrete Pavement Technology Center

CP Tech Center

Iowa State University
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16. Abstract

Construction byproducts are produced during concrete pavement construction and rehabilitation. They include recycled asphalt pavement (RAP), recycled concrete aggregate (RCA), and slurries from activities such as diamond grinding and hydrodemolition. Operations to produce natural aggregates and RCA at both on-site and off-site facilities result in two other byproducts: quarry fines and RCA fines.

Although many construction byproducts are disposed of in landfills, research and field studies have shown they can be beneficially reused in several bound and unbound applications, sometimes on the same project from which they are produced. Reuse of construction byproducts in concrete paving projects provides economic and environmental benefits, improving the sustainability of the highway system. The complexities of disposal, whether real or perceived, where the byproducts are produced can make reuse of the byproducts desirable for agencies.

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Executive Summary

Construction byproducts are produced during concrete pavement construction and rehabilitation. They include recycled asphalt pavement (RAP), recycled concrete aggregate (RCA), and slurries from activities such as diamond grinding and hydrodemolition. Operations to produce natural aggregates and RCA at both on-site and off-site facilities result in two other byproducts: quarry fines and RCA fines.

Although many construction byproducts are disposed of in landfills, research and field studies have shown they can be beneficially reused in several bound and unbound applications, sometimes on the same project from which they are produced. Reuse of construction byproducts in concrete paving projects provides economic and environmental benefits, improving the sustainability of the highway system. Table 1 lists estimates for the annual national production and reuse of these construction byproducts. The complexities of disposal, whether real or perceived, where the byproducts are produced can make reuse of the byproducts desirable for agencies.

This document presents an overview of the production and beneficial reuse of construction byproducts in concrete paving projects. It describes each byproduct and its characteristics and provides information on the handling and processing that may be involved for reuse.

This document provides suggestions and highlights best practices on how to evaluate construction byproducts for reuse in bound and unbound applications, along with a description of the potential impacts of reusing each byproduct in specific applications. A suggested protocol for characterizing and assessing byproducts for reuse is presented, with suggestions on qualification/preconstruction- and construction-phase testing for the byproduct materials and for applications using these byproduct materials, including bound or unbound bases, fills, and concrete mixtures.

Finally, this summary describes design and construction considerations, including ways to protect the environment.

Table 1. National production and reuse of construction byproducts (annual, unless otherwise noted)

Construction Byproduct	Production	Beneficial Reuse	Disposal
RAP	107 million tons (EPA 2020)	102.1 million tons (EPA 2020)	4.9 million tons (EPA 2020)
RCA	405.2 million tons (EPA 2020) (a)	334.0 million tons (EPA 2020)	71.2 million tons (EPA 2020)
Quarry fines	484 million tons (Willett 2021a and 2021b) (b)	N/A	N/A
RCA fines	101.3 million tons (c)	N/A	N/A
Solids recovered from diamond grinding	0.284 million tons (d) (IGGA 2021 and Dufalla et al. 2015)	0.10 million tons (d) (IGGA 2021 and Dufalla et al. 2015)	0.184 million tons (d) (IGGA 2021 and Dufalla et al. 2015
Solids recovered from diamond grooving	0.006 million tons (e) (IGGA 2021 and Dufalla et al. 2015)	0.002 million tons (e) (IGGA 2021 and Dufalla et al. 2015)	0.004 million tons (e) (IGGA 2021 and Dufalla et al. 2015)
Hydrodemolition materials	36 million ft² of deck area hydrodemolished per State since practice began (Simmons et al. 2020) (f)	N/A	N/A

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

(a) 2018 data include 24.2 million tons of construction waste and 381.0 million tons of demolition waste.

(b) Metric tons in 2020 computed assuming quarry fines are 20% of crushed stone, sand, and gravel production.

(c) Calculated using EPA 2018 RCA production data assuming RCA fines are 25% of production.

(d) Calculated using International Grooving and Grinding Association (IGGA) estimate from 2020 of 20,000,000 yd² of grinding per year. Assuming a 12 ft lane width, this equates to 2,841 lane miles/year. Grinding produces approximately 100 tons of concrete fines per lane mile (Dufalla et al. 2015). IGGA estimates 30% to 40% of grinding solids are beneficially reused with the remainder for disposal. A 35% beneficial reuse rate was assumed for the estimates shown.

(e) Calculated using IGGA estimate (2020) of 2,000,000 yd² of grooving per year. Assuming a 12 ft lane width, this equates to 284 lane miles/year. Grinding produces approximately 21 tons of concrete fines per lane mile (Dufalla et al. 2015). IGGA estimates 30% to 40% of grooving solids are beneficially reused with the remainder for disposal. A 35% beneficial reuse rate was assumed for the estimates shown.

(f) Average of seven States reporting on the amount of bridge deck concrete removed by hydrodemolition (Simmons et al. 2020).

Introduction

Constructing, rehabilitating, and reconstructing the highway infrastructure are resource-intensive activities. Use of virgin materials impacts the environment, consumes limited resources, and results in the expenditure of limited funds. These activities and others, such as demolition of existing infrastructure and production of new materials, produce byproducts that many times are hauled away and disposed of in a landfill.

Many construction byproducts have characteristics that make them suitable for beneficial reuse applications in lieu of disposal. Construction byproducts can be used as replacements for virgin materials in paving projects in both bound (new concrete or stabilized base) and unbound (base and fill) applications.

The reuse of construction byproducts in concrete paving projects has become more attractive due to the potential environmental, economic, and societal benefits. In some areas, sources of virgin material are becoming scarce, and stakeholders are experiencing limited availability of some construction materials. Reuse of materials can save landfill space, reduce the need for additional virgin material, and conserve energy and fuel associated with production and hauling.

If byproducts are reused on site or locally sourced, State departments of transportation (DOTs) can save the time and the money associated with hauling materials (Snyder et al. 2018, Tutumluer 2013). Emissions from production and hauling of virgin materials, as well as emissions from hauling of disposed materials, are reduced (Snyder et al. 2018). The number of haul vehicles on local roadways can also be lowered, reducing impacts to the community and helping to preserve roadway conditions.

Cited barriers to reuse of construction byproducts in concrete paving applications include the following (Cackler 2018):

- Potential variability of byproduct materials
- Availability of an adequate supply of byproducts to support beneficial reuse
- Performance of the byproduct (or of the application using the byproduct) once in service
- Environmental concerns

Many of these barriers can be overcome through the following:

- Projects are planned, staged, and scheduled considering byproduct reuse.
- Byproducts are characterized and tests are performed to ensure the material's composition and uniformity are known.
- The appropriate beneficial reuse application is selected.
- The performance of the byproduct or the system containing the byproduct are understood.

Environmental concerns can generally be mitigated by use of conventional best management practices (BMPs) (Snyder et al. 2018).

Types of Construction Byproducts Reused In Concrete Paving Projects

Each of the following sections presents an overview of a type of construction byproduct that can be used in concrete paving projects, along with a description of the process used. Each section includes suggestions for handling and additional processing of each type of byproduct, as well as the physical and chemical characteristics for each type.

Tables 2, 3, and 4 summarize characteristics of the construction byproducts commonly considered for reuse in concrete paving projects (Collins and Ciesielski 1994, Edil et al. 2012, Melton and Kistler 2013). Table 2 provides the typical properties of as-produced RAP and RCA (including both fine and coarse aggregates), along with those of natural aggregates.

Table 3 summarizes the characteristics of RCA fines and quarry fines (typically material smaller than ¼ in. or passing the No. 4 sieve).

Table 4 lists the typical characteristics of slurries from diamond grinding/grooving and from hydrodemolition.

Table 2. Typical properties of natural aggregate, RAP, and RCA

Property	Natural Aggregate*	RAP	RCA*
Shape and texture	Well-rounded and smooth (gravel) to angular and rough (crushed rock)	Rounded to angular, smooth to rough surface	Angular with rough surface
Absorption capacity (%)	0.8–3.7	1.78–2.79 (coarse) (Mukhopadhyay and Shi 2019)	3.7–8.7
Specific gravity	2.4–2.9	2.1–2.7 (coarse), 1.8–2.5 (fine)	2.1–2.4
LA abrasion test mass loss (%)	15–30	27–29 (grading of sample not provided) (Settari et al. 2015)	20–45
Sodium sulfate soundness test mass loss (%)	7–21	Not found in the literature	18–59
Magnesium sulfate soundness test mass loss (%)	4–7		1–9
Chloride content (lb/yd^3)	0–2		1–12
Sample grain size distributions	—	(FHWA 1997, Debbarma et al. 2020)	—

** Data for natural aggregate and RCA are for as-produced material, including both fine and coarse material.*

Sources: After Snyder et al. 1994, Chesner et al. 2008

Table 3. Typical characteristics of RCA fines and quarry fines

Property	Quarry Fines*	RCA Fines**
Plastic limit (PL)	9–34	Nonplastic (Lim et al. 2003)
Liquid limit (LL)	6–62	< 40 (Lim et al. 2003)
Plasticity index (PI)	5–16	Nonplastic (Lim et al. 2003)
Soils classification	AASHTO A-2-4, A-4, A-6	Silty sand (Lim et al. 2003)
Specific gravity	2.65 (Puppala et al. 2008)	2.10–2.38 (Lim et al. 2003)
Fineness modulus	2.86–4.05	—
Sample grain size distributions	(Tutumluer et al. 2015, Puppala et al. 2012)	(Lim et al. 2003)
Passing No. 200 sieve (%)	7–15	1–26 (Lim et al. 2003)
Sample chemical compositions	(Satvati et al. 2020, Tutumluer et al. 2015)	(Lim et al. 2003)

** Quarry fines in the studies by Puppala (2008, 2012) and Tutumluer et al. (2015) were materials finer than 5 mm.*

*** RCA fines in the study by Lim et al. (2003) were materials passing the No. 4 sieve and were obtained from a variety of Texas sources.*

Table 4. Typical characteristics of diamond grinding/grooving slurry and hydrodemolition slurry

Property	Diamond Grinding and Grooving Slurry	Hydrodemolition Slurry
pH value	10–12.5	11–12.5
Particle sizes 0.2 to 2.0 mm (%)	15–35	Varies by pressure used and source concrete quality; typically larger sizes than grinding and grooving slurry
Particle sizes 0.02 to 0.2 mm (%)	20–30	
Particle sizes 0.002 to 0.02 mm (%)	45–60	
Sample grain size distributions	(DeSutter et al. 2011a)	
Sample chemical compositions	(IGGA 2011, Townsend et al. 2016)	(Line et al. 2017)

Sources: Townsend et al. 2016, Winkler 2014, Line et al. 2017

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Figure 1. Reclaimed asphalt pavement

Reclaimed Asphalt Pavement (RAP)

RAP is produced from crushed or milled asphalt pavement. Particles are comprised of asphalt cement, additives within the asphalt cement, and aggregate (Figure 1).

More than 100 million tons of RAP are produced each year in the United States (EPA 2020), and roughly 90 percent (89.2 million tons in 2019) is reused in new asphalt pavements to reduce the amount of virgin asphalt binder used (Williams et al. 2020). In concrete paving projects, RAP can be used in bound or unbound applications as a partial replacement for virgin aggregate (Roesler 2013).

The characteristics of RAP vary by source. Characterization of RAP for use in new hot- or warm-mixed asphalt includes tests to determine the content of foreign matter, the type of binder, the binder content, binder properties, aggregate grading, maximum particle size, and the presence of tar in the reclaimed asphalt (European Committee for Standardization 2005).

The mechanical properties of RAP particles vary with the properties and relative proportions of the component asphalt and aggregate. For example, RAP particles comprised primarily of original aggregate typically have good strength and are resistant to deformation. Particles containing agglomerations of fine aggregate and asphalt cement tend to be brittle or malleable, depending on the degree of oxidation and aging of the RAP (Hoppe et al. 2015).

Selected properties of RAP are compared to properties of natural aggregate in Table 1. Due to the techniques used to produce RAP, its gradation tends to be finer than that of its original aggregate constituents, and it tends to be crushed and screened (or fractionated) to sizes of ¼ to ½ in. and smaller (Griffiths and Krstulovich 2002). This results in the typical gradation of RAP falling somewhere between that of a conventional fine aggregate and coarse aggregate (Huang et al. 2005).

The presence of the asphalt binder in RAP, typically between 2 and 7 percent by weight (Roesler 2013, Chesner et al. 2008), causes it to have a lower specific gravity than natural aggregates (Singh et al. 2018) and results in hydrophobic behavior, which improves the ability of RAP to drain water compared to that of other natural and recycled aggregates (Edil et al. 2012).

Recycled Concrete Aggregate (RCA)

RCA is produced by crushing existing concrete—after removal of steel and other undesirable materials—into new aggregate. Refer to Cavalline et al. (2022) for more information on this topic. RCA can be produced on site using either stationary or mobile crushing equipment (Figure 2) or can be produced off site by hauling the broken concrete to a stationary crushing operation.

Concrete paving projects produce high-quality RCA that is most often used in unbound bases and fill but can also be used in bound applications such as new concrete or stabilized bases (Cackler 2018). For example, in a project completed in 2019, concrete pavement and structures owned by a transportation agency provided 86,000 tons of RCA for use as an unbound base and fill (Cavalline et al. 2022).

RCA particles are comprised of the original aggregate and adhered mortar from the source concrete. The volume and quality of the residual mortar fraction of RCA significantly affect the physical properties and durability performance of the RCA. The mortar fraction causes the RCA to be more absorptive than virgin aggregates, influencing water demand and workability in both unbound and bound applications.

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Figure 2. Mobile on-grade production of RCA

The amount of residual mortar contained in the RCA is influenced by the crushing process (i.e., the types, sizes, and sequencing of the crusher used), the size fraction produced, and the quantity of fines generated. For example, jaw crushers typically produce RCA with a greater percentage of adhered mortar than cone crushers or impact crushers, and fine RCA likely contains a greater percentage of mortar than coarse RCA (Snyder et al. 2018).

As shown in Table 2, the relatively porous mortar fraction causes RCA to have lower specific gravity than that of the component virgin aggregate. It also contributes to typically lower resistance to abrasion by the RCA.

RCA sulfate soundness test results can be unreliable in predicting freeze-thaw durability because the test sulfates attack the cement paste. Therefore, these tests should be waived for RCA. If freeze-thaw performance is a concern, testing should be performed using other methods (such as AASHTO T 161, which is not a Federal requirement).

Quarry Fines

In 2020, approximately 1.46 billion metric tons of crushed stone and 0.96 billion metric tons of construction sand and gravel were produced in the United States (Willett 2021a and 2021b). Quarry operations, including blasting, crushing, and other processing steps, produce fine byproduct materials called quarry fines.

British Standard European Norm (BS EN) specifications describe quarry fines as the fraction of aggregate passing the 0.063 mm (No. 230) sieve, or finer than 63 microns. However, it is common for quarries to produce mixtures of fine, medium, and coarse materials that are excluded from other sellable products including particle sizes up to ¼ in., and quarry fines are typically stockpiled at aggregate production facilities across the country (see Figure 3) (Mitchell 2009).

The composition of quarry fines can vary based on the source minerology of the parent rock, the crushing process, and the local market for quarry products (Mitchell 2009). The quantity of quarry fines produced can range from 10 to 15 percent for some igneous and metamorphic rocks to 25 percent for limestone/dolomite to 35 percent for sandstone/gritstone as far as the total aggregate produced from the process (Petavratzi and Wilson 2007, Stroup-Gardiner and Wattenberg-Komas 2013, Mitchell 2009). Again, for the purposes of this technical summary, this quarry byproduct material with particle sizes up to ¼ in. is referred to as quarry fines and is assumed to be 20 percent of total production.

Characteristics of quarry fines can depend on the stage of aggregate production in which the fines are produced, as well as the type of crusher used. Impact crushers typically produce 25 to 30 percent more fines than jaw crushers and cone crushers (Mitchell 2009). The quantity of fines produced typically increases from the primary crusher to the tertiary crusher, and fines are typically classified as screening fines, baghouse fines, and pond fines. Screening fine sizes range from the No. 4 sieve to smaller sizes, while baghouse fines are typically smaller than the No. 200 sieve size. Typically, 90 to 95 percent of pond fines are smaller than the No. 100 sieve, with 80 percent or more finer than the No. 200 sieve (Tutumluer et al. 2015).

Possible applications for quarry fines include incorporation into aggregate subgrades, embankment or fill materials, cement- or fly ash-treated subbases and bases, and blends in hot-mix asphalt (HMA) mixtures (Tutumluer et al. 2015).

RCA Fines

The crushing and grading operations used to produce RCA also produce non-product fines and dust (Figure 4) in addition to the quarry fines described in the preceding section.

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Figure 3. Quarry fines with material smaller than ¼ in. (left) and stockpile of quarry fines (right)

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Figure 4. Crushing, grading, and stockpiling of RCA and non-product fines

Most of these fines become separated from the produced RCA and are collected and stockpiled (or disposed of) during the operations, although some may cling to the produced RCA unless they are removed by washing, air-blowing, or other processes (Snyder et al. 2018). Note that RCA fines, generally material with particle sizes up to ¼ in., refers to a *byproduct* of RCA production. RCA fines should not be confused with fine RCA, which refers to an RCA *product* meeting specifications for fine aggregate.

Like quarry fines, the quantity of RCA fines produced varies with the characteristics of the source concrete and with the crushing process. As previously mentioned, the size and type of crusher used to produce RCA has been shown to influence the quantity of fines produced. Jaw crushers typically produce the least quantity of fines, while impact crushers produce the greatest quantity of fines.

The type of natural aggregate contained in the RCA has also been shown to affect the quantity of fines produced. For example, crushing concrete containing granite typically results in the production of fewer fines than crushing concrete containing limestone (Snyder 1999). As shown in Table 3, RCA fines typically include a large quantity of material passing the No. 200 sieve and can include clay and other soils incorporated during the demolition and removal process (Lim et al. 2003).

Possible applications for use of RCA fines include unbound bases, embankment or fill materials, and (if free from soil contamination) treated bases (Snyder et al. 2018).

Diamond Grinding and Grooving Slurries

Diamond grinding is performed on concrete pavements to improve pavement ride quality and provide a skid-resistant surface macrotexture. Grooving is sometimes performed to reduce the potential for hydroplaning. Both diamond grinding and grooving rely on a constant stream of water to cool the saw blades that texture the pavement surface and to trap the removed concrete surface particles in slurry form to avoid creating silica-bearing construction dust.

The slurry is collected during the grinding process and is often temporarily stored in holding tanks or tanker trucks. In some cases, slurry can be directly applied to vegetated slopes (often in rural areas, dependent on local and State regulations and permits) (Tymvios et al. 2019).

Tara Cavalline, University of North Carolina at Charlotte, used with permission

Figure 5. Settling pond for diamond grinding slurry

In urban areas or where disposal on land is not feasible, the slurry is typically placed in settling tanks or basins to allow separation of the solids and wastewater components using gravity or flocculants (see Figure 5).

The pH of the wastewater can be lowered using carbon dioxide or other chemical addition.

The characteristics of diamond grinding and grooving slurry vary with the characteristics of the source concrete, the diamond grinding process, and the processing approach utilized to separate and treat solid and wastewater components. Solids included in diamond grinding and grooving slurry range from silt-sized particles (about 0.002 mm) to sand-sized particles (2 mm) (Townsend et al. 2016).

Solid residuals recovered from diamond grinding and grooving slurry (often called concrete grinding residuals [CGR]) can be disposed of in a landfill or can be beneficially reused in fill or other construction applications, such as unbound or stabilized bases (IGGA 2013, Tymvios et al. 2019). For example, residuals from concrete grinding and grooving have been found to effectively improve soil engineering properties, especially for finer soils (Tymvios et al. 2019).

In one study, concrete grinding residuals were found to increase soil strength and California bearing ratio (CBR) values, optimum moisture content, pH, electrical conductivity, alkalinity, and cation exchange capacity. The maximum dry unit weight, plasticity index, and swelling potential of CGR-stabilized soil were found to decrease, although the study was limited to a single type of CGR and two types of soils (Yang et al. 2019).

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Figure 6. Hydrodemolition resulting in concrete slurry prior to removal from bridge deck

Hydrodemolition Materials

Hydrodemolition includes removal of concrete material from structures using high-pressure water jets. The residual material includes wastewater, chips and chunks of concrete, sand, and concrete slurry (Figure 6), which are vacuumed from the surface and collected in a separate holding tank (Winkler 2014).

Hydrodemolition produces larger residual solids and a greater volume of liquid waste than diamond grinding and grooving. Like residuals from grinding and grooving, hydrodemolition materials are placed into tanks to allow separation of solids and treatment of wastewater.

Solid residuals can either be disposed of in a landfill or can be beneficially reused in fill or other construction applications such as unbound or stabilized bases (Tymvios et al. 2019).

Other Materials

Other construction byproducts can also be beneficially reused. Materials that can be reused in new concrete paving applications include base materials reclaimed from existing pavements, such as cement-treated bases, asphalt-treated bases, stabilized subgrades, and unbound aggregates. These materials can be used in structural fills and embankments, in full-depth reclamation, in new road base and subbase layers (both stabilized and unstabilized), and in lower-grade uses, such as haul roads and erosion control (Melton and Kessler 2013).

Reclaimed water from hydrodemolition and diamond grinding and grooving can be recycled and can also be applied to haul roads or land on or adjacent to the site in some instances (Tymvios et al. 2019). Wash water from equipment and concrete trucks can be reused in a variety of applications—from wetting haul roads to use in concrete mixtures (Su et al. 2002, Dufalla et al. 2015). Returned and reclaimed concrete can be crushed into RCA and used in bound and unbound applications or utilized as material for temporary roads (Obla et al. 2007, ACPA 2009).

The References section includes sources of additional information on these materials, which are not the focus of this document.

Applications for Use and Design Considerations

Applications for reuse of byproduct materials in concrete paving applications can be generally classified into unbound and bound uses, as shown in Tables 5 and 6.

Table 5. Unbound applications for use of construction byproducts

Application	Potential Byproducts
Land application	• Diamond grinding slurry • Diamond grooving slurry
Soil stabilization and working platforms to bridge unsuitable soils	• Quarry fines • RCA fines • Diamond grinding/grooving residual solids
Capping layer on pavement base	• Quarry fines • RCA fines • Diamond grinding/grooving residual solids
Fill material	• RAP • RCA • RCA fines • Quarry fines • Diamond grinding/grooving residual solids • Hydrodemolition residual solids
Base material	• RAP • RCA • RCA fines • Quarry fines
Shoulders	• RAP • RCA • RCA fines • Quarry fines

Table 6. Bound applications for use of construction byproducts

Applications	Potential Byproducts
New concrete • Single-lift pavement • Two-lift pavement • Asphalt shoulders	• RAP • RCA • Quarry fines (limited to low percentage by weight) • RCA fines (limited to low percentage by weight)
Treated base layers • Cement-treated base layers • Asphalt-treated base layers	• RAP • RCA • RCA fines • Quarry fines • Diamond grinding slurry • Diamond grooving slurry

In both bound and unbound applications, byproducts are used in place of virgin aggregates. In some applications, byproducts with binding capability can help stabilize soils and other bound bases.

Unbound Applications

Applying to Land

The composition of diamond grinding and grooving slurry makes it suitable for use as a soil amendment in some areas. Some States allow diamond grinding and grooving slurry to be applied to land alongside roadways in approved locations and on other private or public lands. Land application of slurry can be approved in rural settings, but not near sensitive waterways.

When land application of slurries can be performed alongside the grinding or grooving operation, the need for handling or treatment of the slurry and hauling and disposal of the liquids and solids is eliminated. However, some States restrict or prohibit applying slurries to land, often due to environmental concerns, and may require permitting (Tymvios et al. 2019).

Solid residuals contain the materials originally used in the concrete, including sulfates, chlorides, hydrocarbons, metals, and—potentially—other contaminants from being in service. Research has shown that, despite the presence of these materials in limited amounts, residuals from diamond grinding/grooving and hydrodemolition do not need to be treated as hazardous waste (IGGA 1990, DeSutter et al. 2011b, Line and Smyth 2014, Townsend et al. 2016). The International Grinding and Grooving Association (IGGA) has published BMPs for handling slurry (IGGA 2013), and the International Concrete Repair Institute (ICRI) has published similar suggestions for handling of hydrodemolition residuals (Winkler 2014).

Soil Stabilization and Working Platforms to Bridge Unsuitable Soils

The chemical composition of some quarry fines, RCA fines, and residual solids from diamond grinding or grooving can make these byproducts suitable for use as stabilizing agents for some soils. Studies have shown that these materials can improve the shear strength, compressive strength, and deformation properties of soils, and particularly those with high clay content (Kianimehr et al. 2019). Fines with higher alumina content and plasticity indices (PIs) typically exhibit higher binding characteristics when used in soil stabilization (Satvati et al. 2020).

Along with the chemical composition of the byproduct material, differences in particle shape and gradation affect the binding properties. Therefore, tests to determine the strength, modulus, and deformation characteristics of soils stabilized with these materials are suggested.

The quantity of quarry fines needed to stabilize soil depends on the soil type and desired CBR (Kalcheff and Machemehl 1980). Field studies in Iowa showed that quarry fines can be used to stabilize granular roadways (Satvati et al. 2020), and in Illinois quarry fines were successfully used with large-sized aggregates to construct working platforms for airfield pavement construction (Qamhia et al. 2017).

Fill Material

Most construction byproducts (including RAP and RCA fines from producing RCA and virgin aggregates and solid residuals from grinding, grooving, and hydrodemolition) can be used as fill material alongside roadways and beneath pavements (Cosentino et al. 2003, Snyder et al. 2018, Kumar and Hudson 1992, Tymvios et al. 2019). To be used in fill applications, byproduct materials need to exhibit adequate properties to support adequate compaction, as well as satisfactory strength and bearing capacity in service. These byproducts may need to be blended with other materials to improve properties or to meet agency specifications (Cosentino et al. 2003, Snyder et al. 2018, Mwumvaneza et al. 2015).

Suggestions for using RAP and RAP-soil mixtures as fill are presented in Cosentino et al. (2003), while possible uses for RCA in fill applications are presented in Snyder et al. (2018).

Concern exists regarding the use of some byproducts in fill applications due to the presence of heavy metals and other potentially harmful substances. Heavy metals can leach from the material when exposed to water. Studies have shown that concentrations of heavy metals from RAP are below Environmental Protection Agency (EPA) standards and that RAP does not pose an environmental concern as an unbound highway material (Cosentino et al. 2003). Many projects utilizing RCA have been in service for years with no reported water quality or drainage issues (Cackler 2018). Strategies for mitigating water quality concerns associated with the use of RCA are presented in Snyder et al. (2018). A publication by Tymvios et al. (2019) presents a state of the practice on disposal or reuse applications for residuals from grinding, grooving, and hydrodemolition and includes references and links to State transportation department specifications for the use of these byproducts in fill and other applications.

Using construction byproducts as fill material beneath the pavement or shoulders is a beneficial reuse with lower risk than other applications (within the pavement structure) that bear traffic loads. Broader byproduct gradations can be used in fill material applications, which results in more complete use and less waste of these byproducts. From a sustainability standpoint, reuse in higher-grade applications is often desirable (Van Dam et al. 2015). However, reuse in a fill application is typically more desirable than landfilling a byproduct as a waste material.

Base Material

Both RAP and RCA have been used as the primary aggregate in unbound base layers. RCA fines and quarry fines have also been used in unbound base layers as a component of the base (together with virgin or recycled aggregates) or as a cap layer for other densely graded base materials. Use of byproduct materials in unbound bases includes characterization of the material's properties as well as those of a blended application, if used. Characteristics of materials affecting unbound base layer performance include the following (Tutumluer 2013):

- Mineralogy
- Particle size distribution (gradation), fines content, and types of fines (plastic or nonplastic)
- Particle shape, surface texture, and angularity
- Durability (soundness, abrasion resistance)

Unbound layer performance is also affected by the degree of compaction and moisture content (Tutumluer 2013). For RCA, secondary cementing effects may also affect unbound base behavior and performance.

RAP has been successfully used in unbound base materials for several decades (Collins and Ciesielski 1994). Bases containing 100 percent RAP have exhibited higher stiffness and resilient modulus values but lower shear strengths than bases comprised of virgin aggregates (Bennert et al. 2000). Bases containing RAP can also be associated with large permanent deformations, possibly attributable to the breakdown of the asphalt binder under load (Bennert et al. 2000) and oxidation of the asphalt binder (Roberts et al. 1996). The shear strength of bases has been shown to decrease with increases in RAP content (Locander 2009), and bases containing RAP have also been associated with lower bearing capacities than conventional bases with only virgin aggregates (Locander 2009, Ayan 2011).

RAP can be blended with other aggregates to reduce its negative effects on base mechanical properties and behavior, such as creep (Cosentino et al. 2012). Many States limit RAP content to 50 percent in unbound base and subbase layers (Hoppe et al. 2015). A study of State transportation departments found that 16 agencies allowed RAP to be used at a 100 percent rate of substitution for virgin aggregate in unbound pavement layers, while five agencies limited the substitution rate to 50 percent or less by weight (Saeed 2007, 2008). In Germany and France, up to 30 percent RAP by weight is allowed in unbound layers (Hoppe et al. 2015).

Performance of RAP in unbound applications has been characterized by some State agencies as satisfactory to excellent (Collins and Ciesielski 1994), and a Virginia DOT study found that an approximately 30 percent savings in material costs could be obtained if a 50:50 RAP blend was used in base and subbase applications (Hoppe et al. 2015).

The most common reuse application for RCA produced from concrete pavement slabs is for base layers (Cackler 2018). This is because on-site production and processing equipment can produce significant cost savings while providing a base that meets or exceeds the performance of bases constructed with virgin aggregates (FHWA 2004). The improved performance of RCA in densely graded bases (typically increased stiffness) is attributed to secondary hydration of exposed cement particles in the RCA, as well as the improved stability offered by angular, rough-textured RCA particles. Other advantages to using RCA in unbound bases (rather than in higher-grade-type applications) is the relative insensitivity of base performance to larger amounts of contaminant material, allowing the contractor flexibility in production and construction (Snyder et al. 2018).

Design of unbound RCA base layers should be performed using the same tools and approaches used for unbound base layers with virgin aggregates and should result in similar layer thicknesses. The re-cementation of RCA particles (and particularly fines) can lead to improved performance (Snyder et al. 2018). However, stiffening of an unbound RCA base over time may cause it to perform more like a stabilized base. As such, slightly higher curling and warping stresses may result in jointed concrete pavement slabs. Greater levels of slab restraint can also occur in jointed and continuously reinforced concrete pavement (CRCP) slabs. The American Concrete Pavement Association's (ACPA's) Engineering Bulletin EB204 provides additional information on the impacts of the greater base stiffness of RCA bases on concrete pavement behavior and performance. EB204 also provides design approaches that can be used to account for the additional base thickness (ACPA 2007). Use of EB204 is not a Federal requirement.

Concrete pavement design thicknesses may be reduced slightly due to the increased support of an RCA base. However, these reductions are offset by the need for additional pavement thickness (or shorter panel lengths) to counteract increased curling and warping stresses. In CRCP, additional reinforcing steel might be needed to counteract higher stresses due to increased slab restraint. However, the literature generally does not suggest that agencies are significantly changing their pavement designs to accommodate the greater stiffness of unbound RCA bases. It has been said that there are "no particular concrete pavement design implications associated with the use of RCA in unbound base layers for concrete pavements" (Snyder et al. 2018).

When RCA is used in free-draining base layers, in drainpipe backfill, or in densely graded base layers that carry water to drain systems, the byproduct's potential to contribute to clogging of drainage system components should be considered. RCA can produce leachates such as calcium carbonate precipitate or calcareous tufa, which can clog drainpipes. To reduce the potential for issues with tufa formation and other deposits, the following strategies can be used (Snyder et al. 2018):

- Limit the fines content or avoid the use of fine RCA.
- Wash the RCA.
- Blend the RCA with virgin aggregate.
- Use high-permittivity filter fabrics.
- Use effective drainage design features.

ACPA (2007, 2008) suggests the section shown in Figure 7 for a drained RCA base, including geotextile fabric wrapped around the RCA base and drain trench.

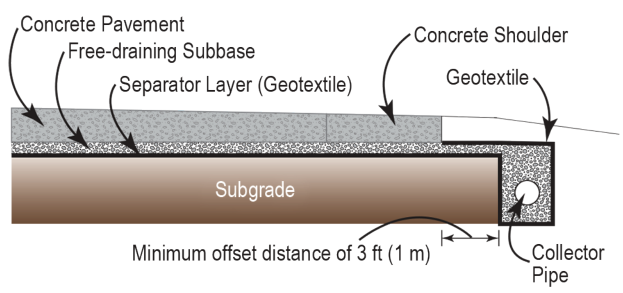

Figure 7. Typical drainage system for use of free-draining RCA base

Alternatively, daylighted base designs or stabilized bases (encapsulating the RCA particles in the binder) can be used to mitigate precipitate-related drainage problems (Snyder et al. 2018).

Research has shown that RCA fines can be used in unbound bases. However, the large amount of material passing the No. 200 sieve (from both RCA processing and potentially soils incorporated during the slab removal process) can result in greater water demand to reach optimum moisture content for compaction (Lim et al. 2003).

Although the use of quarry fines as unbound base material has been investigated, researchers have found these materials (when used alone) to exhibit low strength and low modulus values, performing similarly to sandy material with very few fines (Puppala et al. 2008). Improvement using stabilizers (discussed later under Bound Applications) or blending quarry fines with other materials has provided suitable performance while beneficially using this byproduct (Tutumluer et al. 2015).

Regardless of the types of byproducts used, the fines content of an unbound granular base has an impact on the base's hydraulic conductivity and should be considered (Bouchedid and Humphrey 2005, Dennis et al. 2006). In a study of granular aggregate bases comprised of coarse and fine quarried materials, an increase in fines content was found to increase the resilient modulus of the material (Hatipoglu et al. 2020). Some distresses that could be attributed to frost or moisture heave have been reported in Michigan and Minnesota. However, the use of more open gradations for greater permeability or limiting the amount of fines have been shown to mitigate these issues (Snyder et al. 2018).

Shoulders

RAP and RCA have been used in unbound shoulder applications. Agencies often require material used in shoulders to meet the qualifications and construction considerations that apply to the use of virgin material in unbound base applications (Snyder et al. 2018). Blending byproducts with virgin materials can be required by agency specifications or may be performed to achieve the desired performance. Deleterious materials should be limited to specified amounts, and the byproduct gradation should be selected to provide suitable stability in service.

RCA has successfully been used as an unbound shoulder material in several States, and grading specifications reported by nine States are provided in Snyder et al. (2018). RAP has been used in shoulder applications in at least two States, although the relatively lower bearing capacity and potential for long-term, load-related deformation has led some States to prohibit this use. In Florida, for example, some instances of excessive settlement of RAP layers used beneath shoulders were reported when large trucks were parked overnight. (Hoppe et al. 2015).

RCA fines and quarry fines are often allowed in unbound shoulder applications to some extent (Snyder et al. 2018). For example, Iowa DOT specifications for granular surfacing and granular shoulder aggregate allow up to 6 percent of the aggregate material to be finer than the No. 200 sieve, with up to 30 and 50 percent recycled material (RCA, RAP, or a composite of the two materials) allowed for use in new granular shoulders and existing granular shoulders, respectively. (Iowa DOT 2021).

The design of shoulders incorporating construction byproducts should be performed similar to the design of shoulders using other materials.

Bound Applications

Many of the construction byproducts discussed in this document have been used in bound applications, including treated base layers and new concrete, for concrete paving projects.

Treated Base Layers

In treated base layers, byproducts can be used as replacements for virgin aggregates. One advantage to using byproducts in bound applications is that potentially harmful components are mostly encapsulated by the binder. Therefore, components do not leach out of the material, eliminating the potential for environmental issues and effectively eliminating the potential for tufa to clog drainage components (Snyder et al. 2018).

RCA has been used successfully in lean concrete bases, cement-stabilized bases, asphalt concrete, and asphalt-stabilized base layers (Snyder et al. 2018). When used in treated bases, the physical and mechanical characteristics of the RCA should be determined and considered in the design of the treated base materials and in construction. RCA used in lean concrete bases and cement-treated bases should meet agency specifications for conventional aggregate (Snyder et al. 2018). Lean concrete bases containing RCA could be designed using published suggestions on the design of RCA concrete mixtures (Snyder et al. 2018, Cavalline et al. 2022). RCA's increased absorption is a consideration in mixture design and placement of lean concrete bases containing RCA.

Asphalt and asphalt-stabilized bases have been successfully constructed using RCA at replacement rates up to 75 percent (Snyder et al. 2018). Although asphalt mixtures using RCA may use additional asphalt binder to achieve the desired base properties, the U.S. Geological Survey (USGS) reported in 2004 that roughly 10 percent of RCA was being used in asphalt concrete applications (Van Dam et al. 2015).

Although RAP has been studied in cement-treated, cement-fly ash-treated, and self-cementing fly ash-treated bases, findings on the performance of these materials have been mixed. Typically, the CBR and unconfined compressive strength of stabilized RAP bases decrease with increases in RAP content and increase with increases in the stabilizer content (Thakur and Han 2015). Some self-cementing fly ash mixtures have exhibited excessive volume changes in wetting-drying tests (Hoppe et al. 2015). However, laboratory studies of cement-treated bases using RAP and quarry fines exhibited satisfactory strength and stiffness properties (LaHucik et al. 2016).

When used alone, quarry fines typically exhibit poor performance in unbound bases. However, when stabilized with cement or fly ash, the performance of quarry fine bases has been shown to significantly improve (Puppala et al. 2008, 2012). In one study, quarry fine bases stabilized with Class C fly ash exhibited unconfined compressive strengths 10 to 30 times greater than those of unstabilized quarry fine bases (Tutumluer et al. 2015).

Recent work performed for the Illinois DOT (IDOT) has explored the mechanical properties, durability performance, and field performance of quarry fine-recycled aggregate blends (both RAP and RCA) stabilized with cement and Class C fly ash in base layers. Accelerated pavement testing (APT), falling weight deflectometer (FWD) testing, and other methods showed satisfactory results, including lower surface deflection measurements using FWD testing, higher layer strength profiles using dynamic cone penetrometer (DCP) testing, and improved rutting performance when the base layer was topped with HMA (Qamhia et al. 2018, 2019a).

Qamhia et al. (2019b) studied the freeze-thaw and wet-dry durability of quarry byproduct materials using the procedure outlined in AASHTO T 136 and AASHTO T 135, respectively, in stabilized bases containing RAP and RCA. The study found mixed results, depending on the composition of the stabilized base, the parent rock type or the source of quarry fines, and the tests performed (Qamhia et al. 2019b). Cement-stabilized applications of quarry fines typically outperformed fly ash-stabilized materials.

All samples subjected to the wet-dry durability testing (AASHTO T 135) performed well and correlated with field performance. However, the research suggested that the AASHTO T 136 freeze-thaw durability test could be too aggressive for these materials, with combinations that showed adequate field performance performing poorly in the laboratory tests (Qamhia et al. 2019b).

Test sections where quarry fines were combined with RAP and RCA showed the best performance and were determined to have the greatest potential for implementation. For future use, the researchers suggested that mixture designs be tested for durability and unconfined compressive strength (Qamhia et al. 2019b).

In other recent work for IDOT, quarry fines were combined with primary crusher-run rock from quarries to create aggregate subgrade improvement layers (Qamhia et al. 2018). To construct the test sections, the layers were constructed in two 10.5 in. lifts, with primary crusher rock placed first. Quarry fines were then spread on top of the primary crusher rock and shaken into the voids using a vibratory roller (see Figure 8).

Pilot studies showed promising performance for this use of quarry waste in pavement foundation layers (Qamhia et al. 2021).

Qamhia et al. 2021, Illinois Center for Transportation, used with permission

Figure 8. Compaction of quarry byproduct aggregates into aggregate subgrade improvement layer (top) and compacted quarry byproduct aggregate layer (bottom)

Limestone quarry fines have been used in base layer field studies in Iowa with screenings stabilized using cement kiln dust (CKD), Class C fly ash, and a combination of both CKD and fly ash (Rupnow et al. 2010). Although the CKD-stabilized bases did not pass freeze-thaw and wet-dry durability tests, adding Class C fly ash to the CKD-stabilized bases significantly improved the performance of these blends. Use of CKD and Class C fly ash increased the unconfined compressive strength of the mixtures, and the test section withstood daily quarry truck traffic (Rupnow et al. 2010).

New Concrete

Other concrete applications that can potentially benefit from construction byproduct reuse include single-lift pavements, two-lift pavements, and shoulders.

RCA has been successfully used in many concrete pavements as a complete or partial replacement for virgin aggregates. With some exceptions, most of these pavements have been in service for many years and have exhibited satisfactory durability performance (Snyder et al. 2018). The basic approach to designing, batching, and placing an RCA concrete mixture does not differ from that used for conventional concrete.

When using RCA in new concrete, the aggregate properties should be determined and considered in the concrete mixture design. The quantity and characteristics of the reclaimed mortar fraction in RCA affects both the fresh and hardened properties of the concrete, and trial batches/tests should be used to understand how the mixture should perform. Existing concrete pavements have been shown to be excellent sources of RCA for new concrete because the component materials have previously met agency specifications and the RCA product is often uniform (Snyder et al. 2018).

In concrete, the higher absorption of RCA results in greater water demand and can cause issues with workability. Results of strength and durability performance tests for concrete produced with RCA are typically lower than those of similar mixtures produced with conventional aggregates but are still generally acceptable. However, approaches such as prewetting the RCA prior to mixing can help with water demand, and using conventional mixture design and proportioning strategies have been shown to resolve other issues (Cavalline et al. 2022). For example, using a lower water-to-cement ratio paired with a water-reducing admixture has been shown to offset issues with workability, mechanical properties, and durability performance.

It is typically appropriate to limit RCA fines in new concrete to achieve the desired performance. However, RCA fines can be used in concrete mixtures, and suggestions for doing so are provided in Dufalla et al. (2015). Information on constructability considerations, pavement design considerations (hardened properties), and mixture design using RCA are presented in Snyder et al. (2018) and Cavalline et al. (2022).

Several studies have explored the potential use of RAP in new concrete pavement. When used in concrete, the asphalt contained on the RAP particles creates a weak interface with the new mortar, resulting in cracks propagating along the aggregates but not through them (Huang et al. 2005). This interface has been shown to help dissipate energy and improves the strain capacity of the concrete when measured using splitting tensile tests (Huang et al. 2005). However, the compressive strength, flexural strength, splitting tensile strength, and modulus of elasticity of the concrete decreases with increasing percentages of RAP (Tia et al. 2012). Still, RAP mixtures have been shown to provide enough strength and other mechanical properties for concrete paving applications (Hossiney et al. 2010).

From a durability perspective, inclusion of RAP in low-permeability concrete mixtures has not adversely affected the permeability (Brand et al. 2012) and has resulted in comparable to slightly reduced freeze-thaw durability (Berry et al. 2013). The coefficient of thermal expansion of concrete produced with RAP can be 10 to 40 percent higher than that of concrete made with natural aggregate (Hossiney et al. 2010). RAP has also shown promise for use in lean concrete base mixtures, showing improved fatigue performance in one study (Li et al. 1998).

Studies for IDOT indicated that the use of up to 50 percent RAP may be able to meet the State's paving application requirements (Brand et al. 2012). Further, the studies showed that despite a reduction in slab or beam strengths, RAP concrete slabs can have similar loading capacities to those obtained using virgin aggregate concrete.

Gillen et al. (2013) found that slab thicknesses for concrete containing RAP do not need to be increased. The Illinois Tollway constructed several two-lift concrete sections with RAP in the lower-lift concrete, and performance has been satisfactory (Gillen et al. 2012, Gillen 2013).

Quarry fines have been used as a partial replacement for sand in concrete. In one study, compressive strengths of the concrete increased when fines content up to 30 percent were used, then decreased as fines content increased above 30 percent. Researchers attributed the increase in strength to pozzolanic reaction and a filler (densification) effect (Lohani et al 2012).

Naik et al. (2005) found that quarry fines could be used in self-consolidating concrete (SCC), allowing lower dosages of a high-range water-reducing admixture and viscosity-modifying admixture without reducing the strength of the SCC. Quarry fines have also been successfully used in controlled low-strength materials (CLSMs) using Class C fly ash and synthetic gypsum (Halmen and Shah 2015) and in ready-mixed flowable fill as a partial or full replacement for natural sand (Kumar and Hudson 1992, Wood and Marek 1995).

Evaluation for Use

Considerations for the selection and use of byproducts can be grouped into availability, consistency, and cost.

Byproduct availability is project-specific (for site-produced byproducts) or based on the project's proximity to a byproduct producer (such as a quarry or a construction and demolition waste recycling facility). Availability of a byproduct for use can also be a function of project staging, scheduling, and duration.

Byproducts may be produced during one phase of the project but needed during another phase. That means the material's handling and storage should be considered. The quantity of byproducts produced during different construction activities should also be compared to the immediate need or handling or storage capacity. For example, when RCA is produced on site and used as unbound base, more RCA is sometimes produced from an existing pavement than can be used in a new base layer alone. One strategy to maximize RCA use is to extend RCA bases for the full width of the roadway (including shoulders) (Snyder et al. 2018).

Material consistency is a function of the quality of the source material and the processing and handling techniques used. Characterization of byproduct materials to help evaluate the consistency of the materials and their suitability for use is described in the next section of this document.

Economic factors can affect the decision to recycle, particularly if the decision is driven by the contractor. If used as an aggregate, the cost savings can be calculated as the difference in cost between using the byproduct and the cost of using virgin material. If the materials show binding capacity, byproducts may reduce the need for conventional binders such as portland cement, fly ash, or asphalt. Some factors to consider when computing a cost comparison between virgin and conventional materials are shown in Table 7.

Note that in the case of byproducts produced from existing concrete or asphalt pavement, the cost of breaking and removing the existing pavement is pertinent for both the use of virgin material and the use of RAP or RCA. Therefore, this cost can be omitted from the comparison. Additionally, for unbound uses, the cost to place and compact the recycled material can be similar to the cost to place and compact virgin materials and can also be omitted from the comparison.

If a byproduct is used in lower-grade applications (such as unbound base or fill) rather than higher-grade applications (such as bound bases or new concrete), the costs associated with production and testing may be lower. Costs may be lower because the contractor may have more flexibility in establishing operations resulting in materials that meet project specifications. Use of byproducts in densely graded applications, such as shoulders or fill, can also allow for a greater amount of the material produced to be beneficially reused (Snyder et al. 2018).

Environmental impacts and public perception can also influence the decision to beneficially reuse construction byproducts.

Byproduct material use consideration should take place early in the project bidding or delivery phases. Early consideration allows time for practical issues associated with availability to be identified and addressed, appropriate characterization and assessment for the use to be performed, and a cost comparison to be conducted. If byproducts 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.

Characterization and Assessment for Use

Byproduct characteristics need to be suitable for the appropriate reuse application. Therefore, the potential variability of these characteristics should be anticipated and accounted for in design and construction. Issues with the source material, including excessive contamination or materials-related distress (such as alkali-silica reaction [ASR] or sulfate attack in concrete), that could affect performance should be identified and considered.

Table 7. Factors to consider when comparing costs of using construction byproducts and virgin materials

Cost of the Virgin Material	Cost of the Construction Byproduct
• Material costs (either virgin aggregate or binder) • Cost to haul to site • Cost to place and compact (for unbound uses) • Cost to handle/store/manage (for bound uses) • Cost to haul away existing or unsuitable materials • Cost of existing or unsuitable material disposal	• Cost to take material to a crushing facility (if produced on site) • Cost of hauling material to the site (if produced off site) • Cost of blending material and hauling (if applicable) • Cost of crushing and screening material produced on site (if applicable) • Cost of placement and compaction of material (for unbound uses)

Figure 9 presents a flowchart of possible testing options to characterize byproduct materials and applications using the byproduct materials in bound and unbound bases, fills, and concrete mixtures.

Possible Characterization Tests for Use of Byproduct as Aggregate or supplementary cementitious material (SCM)

		Byproduct to be used as **Aggregate**		Byproduct to be used as **SCM**	
		Tests to Support Use of Byproduct as Aggregate in **Base** or **Fill**	Tests to Support Use of Byproduct as Aggregate in **Concrete**	Tests to Support Use of Byproduct as SCM in **Base** or **Fill**	Tests to Support Use of Byproduct as SCM in **Concrete**
Suggested Tests for Qualification/Preconstruction Stage	Tests of Byproduct Material	❑ General specifications (AASHTO M 147) ❑ Gradation (AASHTO T 27 / M 43) ❑ Contaminants (visual or per AASHTO M 319) ❑ Particle shape (ASTM D4791) ❑ Unit weight (AASHTO T 19) ❑ Deleterious components (ASTM D2419) ❑ Soundness (AASHTO T 103 / hydraulic fracture test) ❑ Consider determining chemical composition via XRF or XRD. For use in bases that are both unbound and drained, carbonates that may form tufa should be identified. ❑ Micro-Deval Test (percent loss) ❑ Tube Suction Test (dielectric constant) For finer materials that may act more like soils than aggregates: ❑ Consolidation (ASTM D2435) ❑ Vertical free swell (ASTM D4546) ❑ Liquid and plastic limit (ASTM D4318)	❑ Requirements of ASTM C33 should be met, particularly those associated with deleterious substances. ❑ Gradation (AASHTO T 27 / M 43) ❑ Contaminants (visual or per AASHTO M 319) ❑ Unit weight (AASHTO T 19) ❑ Abrasion resistance (AASHTO T 96) ❑ Soundness (AASHTO T 103 / hydraulic fracture test) ❑ Consider determining chemical composition via XRF or XRD. Sulfate and aluminate components should be identified. ❑ Assess the potential for alkali-aggregate reactivity using AASHTO R 80	❑ Guidance provided in ASTM C109 should be followed. At a minimum, the suitability of the material for the intended application should be assessed using the following: ❑ Chemical composition via XRF or XRD. For use in unbound and drained bases, carbonates that may form tufa should be identified. ❑ Contaminants (visual and/or XRF) ❑ Particle size and fineness (ASTM C311 and C430) ❑ Strength activity index	❑ Guidance provided in ASTM C109 should be followed. At a minimum, the suitability of the material for the intended application should be assessed using the following: ❑ Chemical composition via XRF or XRD. For use in concrete, sulfate and aluminate components should be identified. ❑ Contaminants (visual and/or XRF) ❑ Particle size and fineness (ASTM C311 and C430) ❑ Strength activity index ❑ Setting time (ASTM C191) ❑ Temperature development (ASTM C1702 or calorimetry)
	Tests of Application Containing Byproduct Material	❑ Resilient modulus (AASHTO T 307) ❑ Shear strength (static triaxial and repeated triaxial loading, at optimal moisture content and saturated conditions)	❑ Assess the potential for alkali-aggregate reactivity using AASHTO R 80 ❑ Assess the susceptibility of the material to D-cracking using ASTM C666 (only if byproduct material was not previously assessed using AASHTO T 103 or the hydraulic fracture test).	❑ Compressive strength (ASTM C593 and/or D1632) ❑ Freeze-thaw durability (ASTM C593 and/or D560) ❑ Maximum dry density and optimum moisture content (ASTM D698 or D1557) ❑ Compacted density (ASTM D1556 and/or D3877) ❑ Volumetric stability (ASTM D3877) ❑ Resilient modulus (AASHTO T 307)	❑ Strength development (AASHTO T 22 / T 97) ❑ Unrestrained volume change (AASHTO T 160 or T 334) or restrained volume change (AASHTO T 363)
Suggested Tests Upon Delivery or Construction	Tests of Byproduct Material	❑ Gradation (AASHTO T 27) ❑ Contaminants (visual or per AASHTO M 319) ❑ Uniformity should be evaluated. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity. ❑ Optimum moisture and maximum dry density (AASHTO T 134)	❑ Gradation (AASHTO T 27) ❑ Contaminants (visual or per AASHTO M 319) ❑ Uniformity should be evaluated. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity.	❑ Contaminants (visual or per AASHTO M 319) ❑ Uniformity should be evaluated. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity.	❑ Contaminants (visual or per AASHTO M 319) ❑ Uniformity should be evaluated. The agency should determine the sampling frequency and allowable variability that provides confidence in the uniformity.
	Tests of Application Containing Byproduct Material	❑ Compacted density (AASHTO T 310, AASHTO T 191, ASTM D2167)	❑ Workability (AASHTO T 119 / TP 129 / TP 137) ❑ Air content (AASHTO T 152 or T 196) ❑ SAM number (AASHTO TP 118) ❑ Strength (AASHTO T 22 / T 97)	❑ Optimum moisture and maximum dry density (AASHTO T 134) ❑ Compacted density (AASHTO T 310, AASHTO T 191, ASTM D2167)	❑ Workability (AASHTO T 119 / TP 129 / TP 137) ❑ Air content (AASHTO T 152 or T 196) ❑ SAM number (AASHTO TP 118) ❑ Strength (AASHTO T 22 / T 97)

Recreated from Tara Cavalline, University of North Carolina at Charlotte, used with permission

Figure 9. Possible tests to characterize byproduct materials and applications, including fills, bases, and concrete, using byproduct materials

Environmental Impacts

The potential environmental impacts of reusing construction byproducts should be considered during both the qualification/preconstruction stage and the construction stage. During qualification/preconstruction, the appropriate agency regulations, specifications, and permitting should be reviewed, and environmental considerations should be identified and addressed.

Many construction byproducts contain small amounts of heavy metals and contaminant materials. These components come from the source material (such as fly ash included in the source concrete for RCA and binders used in asphalt pavement) or from the parent rock (in the case of quarry fines, RAP, and RCA). These byproduct components should be considered, particularly related to water quality on and near the site.

Potential environmental impacts from RAP include the pH of runoff water and leachate as well as contaminants, including polycyclic aromatic hydrocarbons (PAHs) and metals such as aluminum, cadmium, chromium, lead, silver, and selenium (Hoppe et al. 2015).

Notably, though, field evaluation tests of RAP bases by Cosentino et al. (2003) found that all levels of metals in the leachate were below the limits of EPA drinking water standards. Research using both the toxicity characteristic leaching procedure (TCLP) and a synthetic precipitation leaching procedure has also shown that RAP material was "unlikely to contribute to groundwater contamination under beneficial reuse conditions" (Townsend and Brantley 1998, Brantley and Townsend 1999).

Similarly, RCA can produce high-pH runoff, both from stockpiles and in unbound applications. Leachate and runoff can also include small amounts of pollutant materials such as heavy metals. Although these levels can be present in runoff in amounts 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).

Construction Considerations

Processing, Handling, and Storage

Processing, handling, and storing construction byproducts can typically be performed using equipment and methods like (or the same as) those used for conventional materials. To maintain the quality and performance of byproducts, contaminants should not be introduced during the processing, handling, and storage operations. Appropriate stockpile management and handling practices should be used to prevent intermixing of materials and introduction of contaminants and materials from beneath the stockpile.

For RCA, limiting stockpiles to a single source of material is generally an appropriate technique for helping to ensure uniform characteristics and performance of the byproduct. However, processes and techniques exist to support blending of RAP from multiple sources to achieve uniform composition (Hoppe et al. 2015). Suggestions for managing the asphalt reclaiming process, processing RAP, stockpile management, and sampling and testing of RAP are presented by West (2015).

The IGGA provides suggestions for handling and disposal or reuse of diamond grinding and grooving slurry (IGGA 2013). These practices include information on deposition and spreading of slurries on vegetated slopes, as well as collection of slurry, placement into settlement ponds or tanks, and pond decanting. The IGGA suggestions (which are voluntary and not Federal requirements) also provide a pH control plan.

Hydrodemolition slurries tend to have larger residual solids but more liquid than slurry produced by grinding or grooving. The ICRI provides BMPs for handling and disposal or reuse of hydrodemolition residuals (Winkler 2014). These suggestions include treatment to remove suspended solids using a settling area or tank, as well as pH adjustment of the liquids. Some agencies rely on contractors to provide plans for handling, treatment, and disposition of hydrodemolition residuals, while others have prescribed practices and specific requirements (Tymvios et al. 2019).

Mitigating Potential Environmental Impacts

In unbound applications, water flowing through RCA can result in highly alkaline runoff or effluent with pH values often in the range of 11 or 12 (Townsend et al. 2016). The high pH of effluent from RCA often occurs early and then diminishes over time as calcium hydroxide near the RCA surfaces are consumed (Snyder et al. 2018). This effluent is typically not an environmental concern given that it is typically 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 BMPs for stockpiles or other strategies, such as setbacks of drains from receiving waters (Cavalline 2018).

BMPs to protect the environment should be implemented or constructed and maintained around stockpiles and potentially at drains beneath pavements. BMPs to address the potential impacts of runoff from construction byproducts can be incorporated into a stormwater pollution prevention plan. Suggestions to protect water and air quality, as well as to reduce noise and other local impacts, are presented in Snyder et al. (2018). Although this information focuses on RCA production and use, much of it could be applied to the production and use of the other construction byproducts.

The wastewater from diamond grinding, grooving, and hydrodemolition is highly alkaline, with a pH value typically ranging from 11 to greater than 12.5. Testing of liquids for pH is often required for either beneficial reuse or disposal options (Tymvios et al. 2019). The pH values of slurries collected in decanting tanks or ponds may need to be adjusted using chemicals such as acids or carbon dioxide (Winkler 2014). Depending on agency regulations, wastewater can be disposed of at municipal wastewater treatment plants or into local sanitary sewer systems with appropriate permits. Some agencies allow wastewater to be discharged onto the ground where it subsequently evaporates or is absorbed. However, wastewater from these operations should not be discharged into or near receiving bodies of water or wetlands (VanOcker and Winkler 2010).

Impacts to the environment and the community, including noise, dust, emissions, and traffic, should also be considered, particularly when byproducts are produced on site. However, the benefits from using a construction byproduct on site typically offset the environmental and community impacts associated with its production. When using a byproduct, fewer natural resources are consumed to produce virgin materials, traffic and emissions from hauling can be reduced, and landfill space is conserved. Practices for mitigating jobsite impacts associated with RCA are presented in Snyder et al (2018) and may be applicable to other construction byproducts.

Compaction of Unbound Bases and Fill

Excessive hauling, movement, and compaction of some byproducts, including RCA, may result in additional fines generated through friction between aggregate particles, fracture of aggregate particles, or both, resulting in reduced stability. Use of compaction equipment with rubber tires (rather than steel contact surfaces) may reduce the degradation and fracture of particles. During production of RCA, care should be taken to ensure that the byproduct does not contain embedded steel fragments that could damage rubber tires. Processing steps that remove embedded steel using mechanical means or magnets can prevent this issue (Snyder et al. 2018).

For unbound bases and fill, byproducts should be placed at a moisture state close to optimal to ensure that adequate compaction is achieved. The Proctor test (AASHTO T 99; not a Federal requirement) could be used to support compaction density control with an in-place density of at least 95 percent of standard Proctor. If it becomes difficult to meet the desired density without adversely crushing or degrading the material during compaction, an option may be to relax the compaction requirement slightly or require a specified number of compaction passes (Snyder et al. 2018).

Alternatively, Appendix X1 of AASHTO M 319 (which is not a Federal requirement) describes an alternative field control method that includes the use of variable acceptance criteria for compaction based on tests performed on designated lots or sublots. Although cementitious byproducts used in shoulders can gain strength over time due to secondary hydration of cement particles after construction, compaction specifications should ensure sufficient stability immediately after construction (Snyder et al. 2018).

Conclusions

Several types of beneficial reuse applications exist for construction byproducts, including use as unbound fills and base materials, as stabilized bases, and in new concrete applications. These reuse applications reduce environmental impacts, conserve landfill space and natural resources, and can save money, particularly when byproducts are reused on site.

Agencies use a variety of specification approaches to direct and oversee the handling, treatment, and disposal of these byproducts. If beneficial reuse options are encouraged by agencies in specifications and/or contract provisions, and clear practices for the handling, treatment, and allowable end uses of construction byproducts are provided, contractors and agencies can capitalize on a variety of benefits, including potential cost savings.

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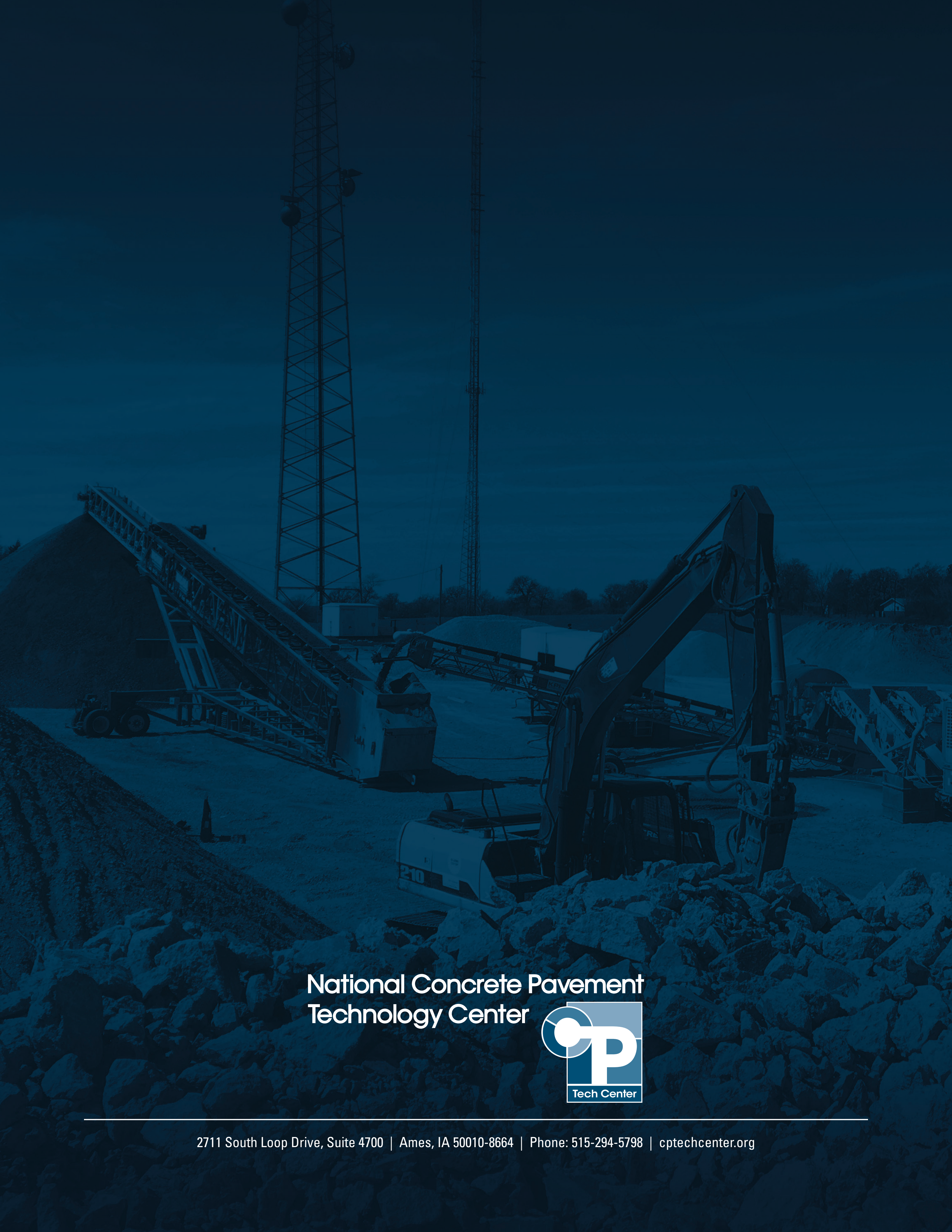

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