CHAPTER 3. MATERIALS CONSIDERATIONS TO IMPROVE PAVEMENT SUSTAINABILITY

Introduction

This chapter reviews materials used for paving applications, and how these materials affect the overall sustainability of the pavement system. Included in this review are aggregates, asphalt materials, cementitious materials, and other materials that are commonly used in pavement construction. Recycled materials are introduced, with more detailed information provided in chapter 8. Some construction quality considerations are also introduced, but these are discussed in more detail in chapter 5.

The impacts of material acquisition, processing, and transportation are discussed and presented in the context of how they influence pavement life. The scope of this chapter is from the extraction of materials to the point where materials begin final transportation to the construction site, either from the final processing plant (e.g., the stockpile for aggregates being used for base or subbase construction) or from the exit gate of the mixing plant (in the case of asphalt or hydraulic cement concrete production). In the latter case, it includes the mixture design and proportioning, as well as the plant operations to the point where the material is placed in trucks for transportation to the pavement grade. The disposition of the materials once they leave the plant is considered in chapter 5.

Materials and Consideration of the Life Cycle

Pavement materials should be assessed from a life-cycle perspective to determine the role they play in contributing to the sustainability of a pavement system. A life-cycle perspective allows decision makers to examine potential economic, environmental, and social impacts that may occur throughout the life cycle, and also to evaluate potential trade-offs. Some typical questions that arise with regards to pavement materials and overall decision making include:

- What are the sustainability goals of the organization specifying the materials, and are they compatible such that a clear set of criteria can be used when making materials decisions?
- For a selected life-cycle time period, what is the total life-cycle impact resulting from using a paving material only once versus using it multiple times?
- If a recycled, co-product, or waste material (RCWM) is used in a pavement construction project:
  - Does the RCWM result in equivalent structural or durability behavior as the material being replaced such that performance is not compromised? Does sufficient knowledge regarding performance exist that this question can be answered with confidence?
  - Does the RCWM have to be processed or transported long distances such that the impact on sustainability of the processing or transportation is greater than the benefits to sustainability of using it?
  - Does the inclusion of the RCWM make the resulting material difficult to recycle in the future?

Recycled, Co-Product, or Waste Materials – What's the Difference?

– Recycled materials are obtained from an old pavement and are included in materials to be used in the new pavement. Common recycled materials include reclaimed asphalt pavement or recycled concrete pavement. Depending on the regional market, these materials would be "waste" if not recycled, ending up in a landfill. Allocation of environmental impact between the manufacture of the original material and its reuse in the new material is based on the processing needed to make this material suitable for use in the new pavement. The demolition of the existing pavement and its transportation to a processing plant is allocated to the old pavement.

– Co-products are derived as part of another process—often industrial but possibly agricultural—that brings value to the overall process. For pavement applications, some of the most common co-products result from the production of pig iron for steel making, including slag cement and air-cooled iron blast furnace slag aggregate. Allocation for co-products is based on some agreed upon approach, but most often is based on economic worth of the various co-products.

– Wastes are materials that normally would be sent to a landfill, for which the cost of transport and processing is the only source of economic value. If the material has value beyond this, it is no longer considered a waste, but instead a co-product. Recycled asphalt shingles is an example of one such waste material as long as the economics stay consistent with the above definition. The classification of fly ash is more complex, as in some regional markets it would fit the definition of waste whereas in other markets it is clearly a co-product because it has economic value beyond the cost of transport and disposal.

- Does the constructability of a particular material increase the variability of performance in the field and, if so, does it increase the risk that it must be replaced more frequently?
- Does specifying a longer lasting material offset the impact of longer transportation distances or higher production-related impacts?
- Are specifications that limit the use of lower impact materials effective in reducing the risk of poor performance, or do they prevent the opportunity to improve the overall sustainability of a pavement project?
- Is the pavement designed to make the best use of lower impact materials without compromising performance?
- Can the impacts of transporting materials be reduced by improving logistics and through greater permitting of local materials? Can transportation impacts also be reduced by targeting the use of higher grade materials in the wearing course and lower quality local materials in the other layers?

These are just a few of the questions that transportation professionals often face when making material choices to improve the overall sustainability of a pavement over the life cycle. Others will be apparent in the discussions presented in this chapter.

Chapter Overview

The primary materials used in pavement applications include aggregates, asphalt materials and mixtures, hydraulic cement materials, and other assorted materials (e.g., steel, fibers). Each of these materials is addressed in this chapter as a separate section, with parallel sections introducing the material, describing the issues associated with its use, outlining strategies for improving its sustainability, and describing future directions and emerging technologies. Again, the focus is on aspects of the material processing and production, and includes consideration of RCWM materials.

Aggregate Materials

Introduction

Aggregates make up the largest share of the mass and volume in a pavement structure, whether used without a binding material (e.g., unbound subbase or base material), or as part of an asphalt or hydraulic cementitious bound layer. Although aggregates are relatively low cost and have a low environmental impact per unit mass relative to other materials that are used in pavements, they can have a significant impact on pavement sustainability because they are consumed in such large quantities. The U.S. Geological Survey (USGS 2013a) terminologies for different sources of aggregates used in pavements are *crushed stone* and *construction sands and gravels*. The majority of crushed stone and construction sands and gravels produced in the U.S. are used for roads. Crushed stone is defined as aggregate taken from hard rock quarries (often by blasting) and then processed through crushing to desired sizes. Groundwater may need to be pumped off depending on the depth of the quarry and the level of the water table, which can affect water tables in the surrounding areas. The biodiversity of a quarry site can be improved from pre-quarry to after-quarry use when proper remediation or restoration efforts are put in place.

Major Issues:

- ✓ *Environmental and social implications of aggregate acquisition and transportation.*
- ✓ *Special concerns regarding aggregate processing.*
- ✓ *Implications of aggregate durability.*
- ✓ *The utilization and performance of RCWMs as aggregates.*

Construction sands and gravels are predominantly mined from alluvial sources, usually by scraping or bucketing directly from the deposits. Some alluvial sources are in existing waterways, such as rivers and lakes, in which case removal of the sand and gravel can affect water quality and change stream flow patterns (speed, volume, and connectedness of channels). This, in turn, can affect aquatic habitat and can also change scour and the sediment-carrying capacity of streams. Other alluvial sources are from historical flood plains that do not currently hold water. In either case, large quantities of material are permanently removed, leaving deep pits across large areas of land that require remediation either to restore stream flow characteristics or to make dry land pits suitable for other purposes. Sands and gravels are often, but not always, processed through crushing to obtain the desired sizes and surface textures for road base and for mixing with asphalt or hydraulic cement.

Aggregates from both sources (hard rock quarries and alluvial deposits) must also be transported within the site and mechanically sorted by particle size by sieving, both of which are processes that consume energy. Aggregates are categorized by particle size as being coarse or fine. Typically, coarse aggregates are those retained on the No. 4 (4.26 mm) sieve, and fine aggregates are those that pass that same sieve. For unbound bases and subbases, material passing the No. 200 (0.075 mm) sieve is often referred to as *fines* whereas in asphalt mixture production those materials are most commonly referred to as *dust* or as *filler*. For concrete production, it is desirable to eliminate aggregates smaller than sand size from the gradation. This often requires washing the aggregates, which can consume significant quantities of water and affect water quality.

Aggregate Usage and Economics

In the U.S. in 2012, approximately 1,324 million tons (1,200 million mt) of crushed stone worth approximately $12 billion was produced by 1,550 companies operating 4,000 quarries, 91 underground mines, and 210 sales/distribution yards in all 50 states. Of the total crushed stone produced in 2012, about 69 percent was limestone and dolomite, 14 percent granite, 7 percent traprock, 5 percent miscellaneous stone, and 4 percent sandstone and quartzite (USGS 2013a). Limestone is also used in the manufacture of most hydraulic cements including portland cement as well as being used as the aggregate in concrete and asphalt mixtures and for base and subbase layers. Granite and traprock (such as basalt) are used extensively as aggregate in both concrete and asphalt mixtures. Of the portion of total crushed stone production reported by use in 2012, 82 percent was used as a construction material, mostly for road construction and maintenance and 10 percent, for cement manufacturing (USGS 2013a).

In the U.S., approximately 927 million tons (840 million mt) of construction sand and gravel worth $6.4 billion was produced in 2012 by an estimated 4,000 companies from about 6,400 operations in 50 states (USGS 2013a). It is estimated that about 43 percent of construction sand and gravel was used as concrete aggregates, 26 percent for road base and coverings and road stabilization; 12 percent as construction fill; and 12 percent as asphalt concrete aggregates and in other asphalt-aggregate products (USGS 2013a).

As shown in figure 3-1, aggregates account for 80 to 85 percent by volume of typical asphalt concrete and 62 to 68 percent by volume of hydraulic cement concrete (Tayabji, Smith, and Van Dam 2010).

About 42 percent of the aggregates consumed by weight in the U.S. have been processed through crushing (Moray et al. 2006). These are mainly used in highway applications. As shown in figure 3-2, crushed aggregates, whether from crushed stone (hard rock mining) or construction sand and gravel (alluvial mining), are more angular than aggregates obtained from natural sand and gravel deposits. Crushed faces on aggregates are required for use in unbound aggregate base courses and asphalt mixtures as they interlock and provide stability to the layer under loading. They are also used for higher strength concrete mixtures as the increased roughened surface area provides enhanced bonding of the hydrated cement paste to the aggregate. In concrete mixtures, uncrushed rounded sand and gravel often provides better mixture workability, and is acceptable for use in concrete provided that the required strength and other specified property requirements are met.

In general, processing to achieve crushed aggregates consumes more energy and releases more GHGs during extraction and production than unprocessed sand and gravel aggregates. This is because manufacturing crushed stone requires drilling, blasting, and crushing, while production of unprocessed sands and gravels does not. Energy consumption and the release of GHGs for construction sands and gravels that are processed through crushing falls between that for crushed stone and unprocessed construction sands and gravels.

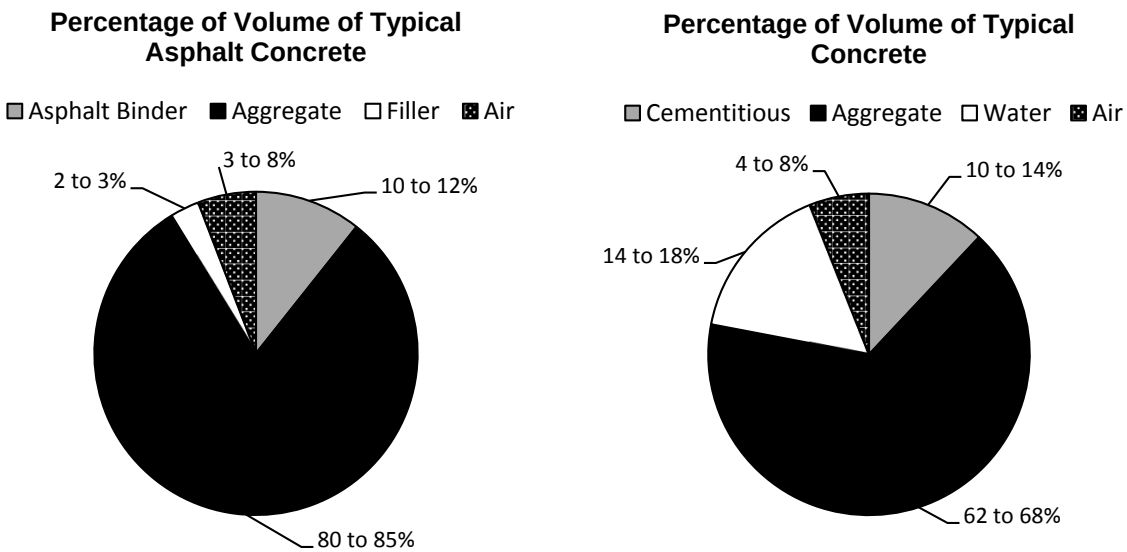

Figure 3-1. Typical volumes of aggregate in dense-graded asphalt concrete and in dense-graded hydraulic cement concrete (asphalt concrete: summary of mixture designs by authors; concrete: Tayabji, Smith, and Van Dam 2010). (Note: Aggregate for dense-graded asphalt concrete includes all sizes, whereas aggregate for concrete typically excludes sizes smaller than sand.)

Figure 3-2. Coarse aggregates: rounded gravel (left) and crushed stone (right) (Kosmatka and Wilson 2011).

Another group of aggregates that are used in highway construction are manufactured aggregates. Manufactured aggregates are those that are created specifically to possess a unique property (such as expanded shale and clay to create lightweight aggregates), or are a co-product of another process (such as crusher fines, foundry sands, or slag aggregates). Manufactured lightweight aggregates are rarely used in pavements, but are occasionally used in bridge structures. An emerging application of lightweight aggregates is to provide a source of internal moisture for curing concrete (ACI 2013). In that application, part of the natural sand is replaced with fine saturated lightweight aggregate (SLWA) to enhance strength gain and minimize early-age cracking of concrete (Bentz and Snyder 1999; Henkensiefken et al. 2009).

From a sustainability perspective, it is convenient to combine manufactured aggregates with recycled materials into the RCWMs category that was defined earlier. Thus, the following aggregates are classified as RCWMs:

- Reclaimed asphalt pavement (RAP) – RAP is most often produced when existing asphalt concrete layers are cold milled from an existing asphalt pavement as part of a rehabilitation or maintenance overlay, and the removed materials stockpiled for use in a new asphalt pavement, base, or subbase. While the predominant use is in new asphalt pavement, RAP is commonly used in aggregate bases, and coarse fractionated RAP is being used as aggregate in new concrete. More details on the use of RAP are provided later in this chapter and in chapter 8.
- Recycled concrete aggregate (RCA) – RCA is created when concrete is purposefully crushed to create aggregates for use in subbase, base, or paving (asphalt or concrete) applications. RCA often contains previously unhydrated cement that produces increased stiffness in bases/subbases when mixed with compaction water, creating a material with superior properties compared with virgin aggregates (Chai, Monismith, and Harvey 2009). When used as base or subbase, both the coarse and fine RCA are often used. In new concrete, it is most common to use only the coarse fraction of the RCA as the fines significantly increase water demand and also have a disproportionately high concentration of chlorides if recycled from pavements subjected to chemical deicing. RCA is discussed in greater detail in chapter 8.
- Recycled asphalt shingles (RAS) – Although predominately used as a source of reclaimed binder, RAS also provides fine aggregate for use in new asphalt concrete mixtures. RAS is discussed in detail later in this chapter.
- Air-cooled blast furnace slag (ACBFS) – ACBFS is an industrial co-product from iron blast furnaces in which pig iron is extracted from iron ore and the remaining molten material (slag) is directed into pits where it is allowed to cool in air. Once cooled, this material is crushed and can be used as aggregate for subbase and base applications, in asphalt concrete, and in concrete. Two recent publications provide more details on the use of ACBFS as an aggregate material in concrete (Morian, Van Dam, and Perera 2012; Smith, Morian, and Van Dam 2012).
- Steel furnace slag (SFS) – SFS is a co-product of the manufacturing of steel. The properties of the SFS, and thus the suitability for it to be used in pavement applications, are largely controlled by the method of processing. While most SFS can readily be used in asphalt pavements, some SFS is not considered suitable for use in concrete as it may lead to undesirable expansion and deterioration. Further, the expansion potential of some SFS has resulted in damaging expansion of unbound base or subbase material. As a result, SFS must be tested and its properties understood prior to use in a pavement structure to ensure that damaging expansion will not occur (Chesner, Collins, and MacKay 1998).
- Foundry sand – Waste foundry sand is generated by the ferrous and nonferrous metal casting industries. It can be used as a partial replacement of fine aggregate in concrete, in asphalt concrete mixtures, and as engineered fill material. As a waste material generated through an industrial process, the impact on mixture performance must be fully studied, as must the potential for leaching of heavy metals.

Regardless of the aggregate grouping, the extraction (e.g., mining, dredging, milling), processing (crushing and sieving), and transport of aggregates consumes energy and generates emissions from the fuel consumed by equipment and vehicles, and often from the electrical grid. Furthermore, fugitive dust is produced and water resources are utilized and impacted. Figure 3-3 summarizes the environmental burdens of mining and processing crushed aggregates and natural aggregates from a number of cited sources. Energy consumption and GHG emissions (in terms of Global Warming Potential [GWP]) included in the figure are calculated based on the lower heating values of consumed fuels and the electrical grid mix of the specified region (CA – Canada; SE – Sweden; CH – Switzerland; FI – Finland, US – United States) as identified by different life cycle inventories (Ecoinvent 2011; Stripple 1998; Häkkinen and Mäkelä 1996; Athena 2006; Marceau, Nisbet, and VanGeem 2007). An examination of each inventory data source indicates that the production of crushed stone consumes more primary energy (meaning the total energy burden including the production of energy resources) than the production of gravels and sands. That energy use will increase as the amount of crushing of the alluvial gravels and sands is increased to meet tighter material specifications for crushed faces on the aggregate, which improves the performance of asphalt materials and aggregate base materials.

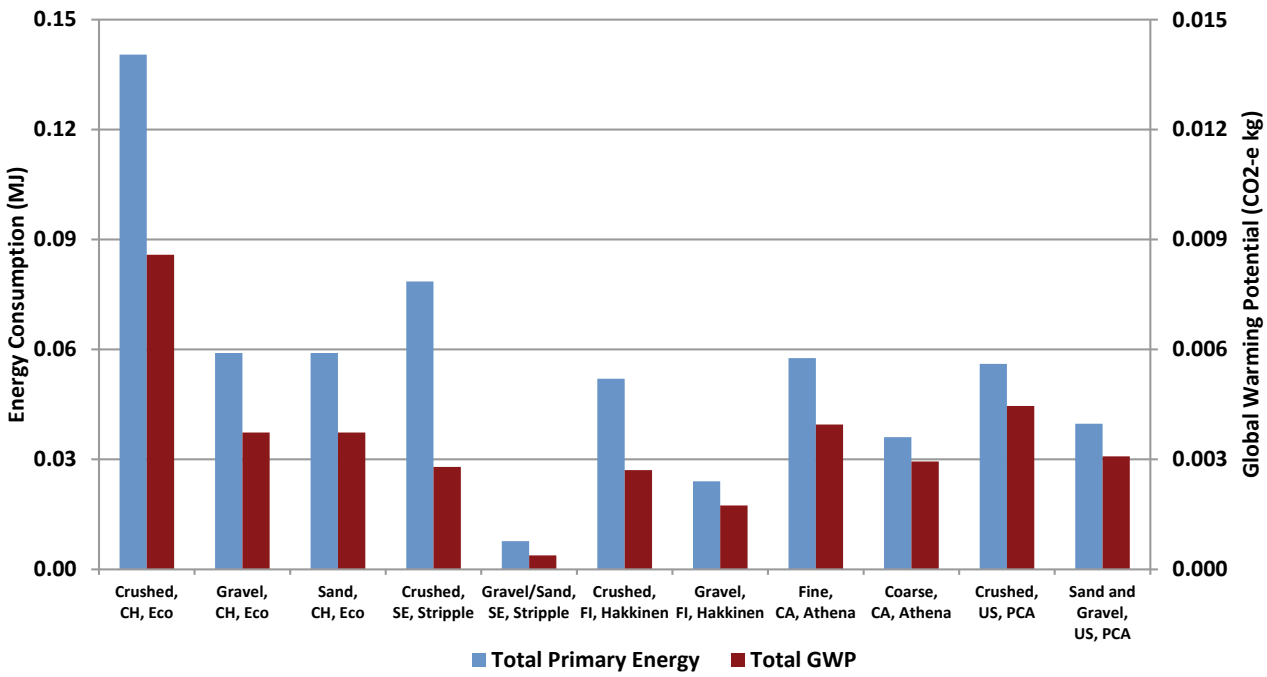

Figure 3-3. Primary energy and global warming potential from aggregate production per kg, at quarry (adapted from Wang et al. 2012). (Notes: 1. Energy consumption shown here excludes the production of capital goods such as construction of dams, power plants and transmission lines; 2. CO_2e per MJ is different for each case, depending on the electrical power production mix and fuels consumed).

The environmental burden of energy consumption depends largely on the source of the energy (e.g., coal, oil, gas, hydro, nuclear, renewables). Energy consumed in the production of aggregates includes transportation within the quarry and processing plant using earth moving equipment and trucks that are primarily powered by petroleum products, and conveyors powered by electricity. Another major component is the crushing and sorting equipment, which are

typically powered by electricity. Electricity is usually drawn from the regional grid although in some cases the electricity may be produced on site through fossil fuel powered generators. As fuels that power electrical grids vary considerably by region and country, energy intensity, environmental emissions, and water use will vary as well. The regional electricity grid can affect the life-cycle impacts of aggregate production, or any other product, and must be considered when calculating or interpreting life-cycle impacts or comparing sources of materials.

Accounting for water consumption for electricity generation is an important topic and not always a straightforward issue. Energy produced in power plants by thermoelectric systems evaporate water during the cooling of the condenser water and hydroelectric plants evaporate water off the surface of the reservoirs (Torcellini, Long, and Judkoff 2003). There are differences in modeling storage water for hydroelectric facilities, turbine, and cooling water; a specific example is the net water consumption at hydroelectric facilities. This consumption is primarily related to the evaporation rate from the associated reservoir. This rate, which is a function of surface area, local climate, and other factors, is a challenging value to ascertain. Not only is the science complex and evolving, but is also highly variable between locations. These complexities are apparent when comparing different life-cycle inventory (LCI) datasets for hydropower (e.g., Ecoinvent, GaBi).

Another major source of environmental burden associated with aggregate is transportation. Aggregate must be transported from the source to the job site for unbound bases and subbases, and transported to the mixing plant for asphalt bound materials and hydraulic cement concrete (if the plant is not located at the quarry) and then to the project site. Transport-related impacts primarily involve the burning of petroleum-based fuels in trucks or other transport vehicles. The energy use and GHG emissions from transport can be larger than those from mining and processing, especially if trucks are used instead of more fuel efficient transportation modes such as rail or barges. Table 3-1 shows the relative fuel efficiency for the three primary modes of aggregate transport: truck, rail and barge. The values shown in the table are gross estimates that provide a first order comparison; actual fuel use will vary based on the specific mode technology used, load magnitude, percent of empty back haul, and topography.

Table 3-1. Summary of estimated national average freight movement fuel efficiency[1] (diesel) of freight transportation modes (2009 data) (Kruse, Protopapas, and Olson 2012).

Mode	Ton-Miles/Gallon
Trucks[2]	150
Rail	478
Inland towing	616

Notes:

1. This is gross fuel use, not life-cycle fuel use.
2. Truck load assumed to be 25 tons (22.6 mt) on a 40 ton (36.28 mt) gross vehicle weight truck, loaded one way.

Other environmental issues arising from aggregate mining, processing, and transportation include dust pollution, groundwater use, noise, pavement damage and traffic safety issues on roads leading to and from the source, and quality of life issues for residents and plant/wildlife subjected to those impacts. For these reasons, it can be a long and difficult process to obtain permits for aggregate quarries and pits, sometimes taking 10 years or more.

Because of these challenges, new aggregate quarries in some areas are located further away from the urbanized areas where aggregates are most often needed, increasing the environmental burden of aggregate transport to the main locations of consumption. In some areas, suburban sprawl has occurred on prime aggregate sources making it even more difficult to get permits, or the encroaching development results in reduced operating hours and other restrictions on existing quarry operations. For example, the California Geological Society (CGS 2012) has documented the anticipated scarcity of aggregate supplies in California over the next 50 years. Some urban areas that have river, lake, or sea access (such as Detroit, the San Francisco Bay Area, Chicago, Los Angeles) overcome this problem by importing aggregate to urban processing plants using low-impact marine transportation, sometimes from foreign countries over very long distances.

Strategies for Improving Sustainability

Some general approaches to improving pavement sustainability with regard to aggregate production, and the trade-offs that should be considered are summarized in table 3-2. A brief discussion of some of the major strategies to address these issues is summarized next.

Strategy: Reduce the Amount of Virgin Aggregate Used

There are two approaches that can be utilized to achieve Strategy No.1. The first is to increase the volume of recycled material used as aggregate. Pavement recycling is discussed in detail in chapter 8, but it is noted again here that a wide variety of RCWMs (e.g., RAP and RCA) can be effectively used as aggregate in pavements. The use of these materials often requires additional knowledge and care in processing, handling, and proportioning of the aggregate to ensure performance. Although it is attractive to introduce RCWMs into a paving project as a "sustainable" aggregate solution, this may lead to reduced sustainability if done without consideration of the effects that those materials have on the performance of the pavement. Thus, the use of a given RCWM for a given application must be carefully considered to achieve a balance between the following:

- Availability – Is the RCWM locally available compared to the natural aggregate being replaced? In many cases suitable RCWMs are readily available and are less expensive or similarly priced. But in those cases where a local source of the RCWM is not available, it may require long distance transportation that may result in increased cost and environmental damage. Thus, local availability must be considered before requiring the use of a certain percentage of RCWMs.

Table 3-2. Approaches for improving aggregate production for pavement sustainability.

Aggregate Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce the Amount of Virgin Aggregate Used	Use more aggregates derived from RCWM sources.	Can potentially reduce cost, and preserve scarce or difficult to permit virgin sources. May increase cost depending upon availability, transportation, or processing required; reduce ability to recycle in the future; durability; special pollution problems (pH, toxicity, contaminants).	Dependent on characteristics of RCWM, considering transportation, processing, ability to recycle multiple times, special pollution problems.	Preserves virgin sources. Can reduce need for new sources and associated impacts. Reduces need for new landfills. Potential for negative impacts depending upon transportation, processing requirements.
	Use more durable aggregate, maximizing pavement life.	May increase initial cost, decrease life cycle cost.	Dependent upon transportation distance if not locally available.	Primarily dependent upon transportation.
Reduce the Impact of Virgin Aggregate Acquisition and Processing	Review environmental impact and remediation plans of different aggregate sources when permitting (handled via the NEPA guidelines or equivalent environmental impact review [EIR] and permit process in many states).	Dependent upon requirements imposed by permit. Most permit processes do not consider impacts of locating quarries outside of the jurisdictional area and importing the aggregate (transfer of impacts).	More sustainable features for quarry may come from permitting process.	More sustainable features for quarry may come from permitting process.
	Implement processing and mining operations using less or lower impact energy sources and less water.	Will often result in initial cost increase due to changeover and life cycle cost decrease due to greater energy efficiency.	Will generally reduce environmental impact.	Will often reduce societal impact.
Reduce the Impact of Aggregate Transportation	Use locally available materials or those using a low impact mode for transportation (next item).	Will often reduce initial cost, may increase life cycle cost if there are significant differences in durability.	Will often reduce environmental impact.	May increase impact for those near local source production and transportation locations.
	Minimize transportation impact by maximizing use of marine/barge and rail transport and minimizing truck transport.	Will often reduce cost.	Will usually reduce environmental impact.	Will usually reduce societal impact, focusing it on marine and rail routes reducing noise, safety issues compared with road transport.
	Facilitate permitting of aggregate sources and processing sites near major use areas.	Will generally reduce cost due to reduced transportation cost.	Will usually reduce environmental burden due to reduction in truck transportation.	Will increase impact on those living near mining or processing sites.

- Experience – Is the local contracting community experienced in using RCWMs in the application and volumes that are being considered? It is well known that many RCWMs act differently during construction than natural aggregates, depending on the use and application. For example, if coarse aggregate RCA is to be used as a replacement for natural coarse aggregate in concrete, the RCA stockpile must be kept wet during mixture batching (ACPA 2009). This is not a common practice in some locales and omission of this important step can lead to mixing problems and performance issues. Similarly, RAP can be added to asphalt concrete mixtures at much higher levels than most current practices allow, but additional care must be taken throughout the entire mixture design and construction process to minimize durability and workability difficulties, such as processing to reduce variability within the stockpile, and screening into separate size graded or "fractionated" stockpiles. Providing additional information, training, and support to the contracting community may be required to develop local expertise on the use of RCWMs for different applications.
- Performance – Although the potential exists for the volume of RCWMs in a given application to be increased, there is also an increased risk that pavement performance will suffer if care is not taken to understand the impacts of increased RCWM aggregate volume on mixture performance. For example, in recent years as technology and understanding have improved, the maximum amount of RAP used in asphalt concrete mixtures has increased well beyond what had traditionally been specified. Yet there is a point beyond which increased RAP volume may have a negative impact on the long-term performance of the pavement, perhaps stiffening the mixture and adding a source of variability that can be difficult to manage. A good understanding of the material and the use of mechanistic-empirical design and appropriate laboratory testing and specifications is needed to design pavement structures without increasing risk. In addition, the use and application must also be considered, as "too much" RAP may create a mixture that is too stiff and brittle for a thin overlay surface mix, yet the same percentage of RAP might be much less than can be used for thick structural layers located below the surface where the increased stiffness is needed to reduce bottom-up tensile stresses (see chapter 4 for more information).

Illinois Tollway's Experience with RCWMs

The Illinois Tollway System is comprised of four toll roads including the Tri-State (I-94/I-294/I-80), Jane Addams Memorial (I-90/I-39), Reagan Memorial (I-88), and Veterans Memorial (I-355), collectively routes carrying more than 1.4 million vehicles per day and connecting Northern Illinois, Wisconsin, and Indiana. The Tollway has been enhancing the transportation infrastructure of Chicago Metropolitan area through major programs such as Congestion Relief (2004-2016) and Move Illinois (2012-2026). The major objectives of these programs are to enhance regional mobility, save drivers' time and money, and create jobs while adopting materials and construction sustainability plans. The Tollway requires 100 percent recycling of concrete and asphalt pavements to be reused in new pavements. The levels of asphalt binder replacement (ABR) in asphalt mixtures are typically 40-60 percent. High levels of ABR are achieved by Tollway contractors due to good construction practices such as RAP fractionation, inclusion of RAS, and utilization of the fine portion of fractionated RAP. WMA has been used in all large volume asphalt paving and overlay applications including warm mix stone matrix asphalt (WMSMA). The Tollway has recently implemented two-lift or composite concrete pavements. Large volumes of two-lift concrete, as high as 3,000,000 yd^2, are expected to be used on I-90 reconstruction over the next 4 years starting from 2014, which will allow for high levels of RCWM use in the non-exposed lower lift.

Improvements in understanding and technology continue to push the limit on RAP replacement levels, but additional research is required to provide better design and construction information for wide-scale adoption of elevated RCWM replacement levels.

The increased use of RCWMs as aggregate for bases and subbases and in asphalt concrete and concrete mixtures offers a significant opportunity to increase the overall sustainability of pavements. The key to effectively implementing this approach is increased understanding and improved technology. Understanding is needed to appreciate how the inclusion of higher volumes of RCWMs will impact constructability and long-term performance. Improvements in technology will help address current limitations as well as provide better understanding of how these materials perform.

A second approach that can be employed to reduce the amount of aggregate used over the life cycle is to improve aggregate durability. Durability is not an intrinsic material property of the aggregate, but instead reflects the ability of the material to maintain its integrity when exposed to service conditions. Aggregates can degrade due to physical processes (e.g., wetting and drying, freezing and thawing) or chemical processes (e.g., alkali-silica reactivity [ASR] in cementitious materials) or may just interact poorly with the binding agent (e.g., moisture susceptibility in asphalt mixtures). Premature pavement failure due to durability issues can have significant environmental, economic, and social costs.

A suite of laboratory tests are used to assess the durability of aggregates for various applications. Some common tests include:

- AASHTO T 104/ASTM C88, *Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate* – This test is a surrogate for general aggregate soundness.
- AASHTO T 161/ASTM C666, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing* – This test assesses the aggregates' resistance to freezing and thawing.
- AASHTO T 303/ASTM C1260, *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method)* – This test, along with ASTM C1293, *Standard Test Method for Determination of Length Change of Concrete Due to Alkali-Silica Reaction*, assesses the aggregates resistance to ASR.
- ASTM D4792, *Standard Test Method for Potential Expansion of Aggregates from Hydration Reactions* - This test is used as a measurement of durability for steel slag.
- AASHTO T 283/ASTM D4867, *Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures* – This test method evaluates an asphalt mixture's susceptibility to moisture damage.

There are many other tests for various applications. Some are used exclusively by a local or statewide transportation agency whereas others are documented in national standards. The key is recognizing that the durability of the aggregate has a big impact on the future performance of the pavement and that adequate testing of aggregates is needed in order to avoid unanticipated failures.

In addition, there are standard practice documents to help guide pavement practitioners through the process of selecting durable aggregates. For example, AASHTP PP 65-11, *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction*, can be used to guide a practitioner through the recommended testing sequence and to develop a reasonable ASR mitigation strategy for a given pavement project.

As high-quality, durable aggregates become increasingly scarce, it is important to require only that level of durability that is needed for the specific application. Requiring "premium" aggregates for every application is not prudent, but instead is wasteful and contributes to the scarcity of those durable aggregates that are needed for the most severe environment, contributing to associated high economic and environmental costs. With the use of appropriate specifications, pavement durability can be ensured in a cost effective and more sustainable manner.

Strategy: Reduce Impact of Virgin Aggregate Acquisition and Processing

The first step in reducing the impact of virgin aggregate acquisition is to review environmental impact and remediation plans of different aggregate sources when issuing permits. This is typically conducted under NEPA guidelines or equivalent environmental impact review (EIR) and permit process conducted in many states. Most permit processes do not consider the potential for increasing the environmental impacts of locating quarries outside of the jurisdictional area caused by the need to transport aggregate over longer distances. A permitting process that establishes a broader analysis has the potential to reduce the likelihood of unintended consequences of transferring impact and therefore may improve the overall sustainability of aggregate acquisition.

Aggregates must uniformly possess the size and properties needed to ensure performance within the pavement structure. Uniformity is controlled by the parent material, the extraction operation, transportation, and handling during construction. Other attributes of the aggregate can impact the required processing energy and emissions, including the type of equipment used and aggregate hardness. In particular, the type and size of the crusher has a large impact on the size and shape of the aggregate particles. Efforts must be exerted to optimize the crushing operations to create aggregates possessing the size and shape needed for the application while minimizing waste by avoiding the production of an inordinate amount of fines (known as crusher fines). Many aggregate sources require washing to be suitable for use in some applications and thus issues of water use, reuse, and quality must be addressed. Noise and dust from aggregate processing also have environmental and social impacts.

Strategy No: Reduce Impact of Aggregate Transportation

High-quality aggregates often must be transported over long distances to meet localized demands. In some cases, these aggregates are being imported hundreds and even thousands of miles from other states and even from other countries (e.g., Mexico and Canada on the west coast, Bermuda on the east coast, Central America in the Gulf region). This can have a significant economic and environmental impact, especially if the major mode of transportation is by truck. Additionally, as previously mentioned, the expansion of existing aggregate pits and quarries and the development of new ones are becoming increasingly difficult, particularly in environmentally sensitive areas or in the vicinity of human habitation. Priorities for protecting local habitats and local communities must be weighed against the disruption of habitat and

communities elsewhere, along with increased environmental impacts associated with long-distance transport.

Approaches to reduce the impact of aggregate transportation include increased use of locally available materials. This includes both natural sources of aggregates as well as the use of locally available RCWMs including RCA, RAP, and ACBFS. A key element of this approach is to ensure that the aggregate meets the durability requirements specifically for the application. For example, aggregates used in lower layers of a pavement—whether an asphalt mixture (e.g., base and binder layers) or concrete (the lower lift in a two-lift concrete pavement)—do not need to possess the same resistance to wear and polishing as those used in the surface layer. This consideration can be used to reduce the need to import wear resistant aggregates from greater distances at a higher cost.

Another approach is to minimize transportation impact by maximizing the use of marine/barge and rail transport and minimizing truck transport. As indicated previously in table 3-1, truck transport is significantly less efficient compared to marine/barge and rail transport. Facilities have been established in a number of urban centers that have marine access to specifically handle and stockpile aggregates, thus supplying the urban market. Further, continued growth in rail facilities will result in increased efficiency and reduced cost and environmental burden.

The final approach listed is to facilitate permitting of new aggregate sources and processing sites near major use areas. This approach will result in lowering the impact of aggregate transport, with the trade-off of potentially operating aggregate sources within more populated areas thus increasing negative social impact. The use of advanced aggregate acquisition and processing strategies can minimize this impact, but cannot completely alleviate it.

Issues/Future Directions/Emerging Technologies

Issues, future directions, and emerging technologies for enhanced sustainability of aggregates in transportation include:

- Increased shipping of aggregates by truck from long distances increases emissions, energy use, and noise, whereas local quarrying of aggregates has implications for land use, noise, dust, and other factors. As local aggregate sources are exhausted and the development of new sources stymied by community opposition, pressure will be exerted to use aggregates with less desirable characteristics. This could affect the long-term performance of pavements.
- Increasing pressure to use higher volumes of RCWMs will likely renew pressure to make complete use of <u>all</u> materials from a construction site (e.g., current practice often is to waste crushed concrete fines, but their use may be highly encouraged in the future). Further, pressure to use non-conventional RCWMs (such as steel slag aggregate or recycled glass, for example) may also increase. If done without sufficient research, the increased use of RCWMs may compromise pavement performance unless it is accommodated in the design stage and utilizes effective construction practices.
- As readily available sources of aggregates of the highest quality become exhausted, the use of “marginal” aggregates will increase. In many cases, these aggregates can be used without negatively affecting pavement life. Yet if such aggregates are used inappropriately, premature pavement failures will likely occur.

- Specialty aggregates are at times needed to fulfill a specific need driven by a sustainability goal. For example, highly durable aggregates will be needed on an exposed aggregate surface, or a light-colored aggregate may be specified to increase surface reflectivity to reduce lighting requirements. In addition, other aggregates might be sought to improve the quality of the pavement material such as saturated, lightweight fine aggregate added to cementitious mixtures to enhance curing.

Asphalt Materials and Mixtures

This section reviews the manufacture and transportation of asphalt materials. It summarizes generic asphalt mixture types and provides a brief overview of their uses, design, and plant operations. Sources of environmental impact are identified in the exploration, extraction, and transport of petroleum, the refining of petroleum into asphalt binder, the modification of the binder, the transport of all materials to the plant, and the combining of the materials at the plant where asphalt mixtures are made. Discussions of mixture design, proportioning, and plant operations are also included, while specific construction considerations are presented in chapter 5 (except as it is affected by materials selection and mixture proportions).

Long-term binder availability and sources of cost variability are also discussed in this section. Introduction of recent innovations that are changing the face of the asphalt paving industry are presented, including WMA and high binder replacement mixtures using RAP and RAS.

Asphalt Materials Usage and Economics

The U.S. used approximately 130 million barrels (23 million tons [21 million mt]) of asphalt binder and road oil in 2011, worth $7.7 billion, according to the US Energy Information Administration. In the recent peak years of 1999 and 2005, nearly 200 million barrels were consumed (EIA 2011). According to the Asphalt Institute, approximately 83 percent of asphalt binder used in the U.S. in 2011 was used for paving purposes (Grass 2012). In the U.S., more than 92 percent of all paved roads and highways are surfaced with asphalt products. The U.S. has about 4,000 plants producing asphalt mixtures with total production of about 452 million tons (410 million mt) in 2007 (NAPA/EAPA 2012) and about 396 million tons (359 million mt) in 2010 (Hansen and Newcomb 2011). The value of asphalt paving mixtures produced in the U.S. was estimated at $11.5 billion in 2007 (U.S. Census Bureau 2007a).

Introduction

Asphalt materials, are sticky, black, highly viscous liquids or semisolids that consist of the heavier and more polar molecules that are present in many crude petroleum sources (AI 2007). Asphalt materials may be found in natural deposits where geological conditions have left primarily asphalt-type material mixed with fine dust material, such as Trinidad Lake (Trinidad, West Indies) and La Brea (Los Angeles), or distributed in rock formations, such as in west Texas. Some forms of these natural asphalt material deposits may be used directly in pavement construction and maintenance.

However, the vast majority of asphalt material used for pavement comes from petroleum refineries that produce gasoline, kerosene, diesel, and lubricating oils, among other products. Petroleum residues from the distillation of crude oils are the starting materials for asphalt material production. Of the multitude of crude oils commercially available, only a limited number are considered suitable for producing asphalt materials of the required quality in commercial quantities. In general, heavy (specific gravity >0.9) crude oils are used to produce asphalt materials of the required quality. These types of crude oil tend to contain high sulfur contents (>1 percent by mass). Asphalt residues, as a fraction of suitable crude oils, typically range between 20 to 50 percent by mass, and a smaller percentage by volume because of the

heavier specific gravity of asphalt materials compared to other materials made from crude oil (Asphalt Institute and Eurobitume 2011).

Asphalt material is typically produced by removing the lighter hydrocarbon molecules through a combination of vacuum and heat, or by mixing with a solvent such as propane. The source of crude oil can have a significant effect on the energy and environmental impact of a specific asphalt material as the processes needed to extract, process, transport, and refine it to produce asphalt material and other products will vary with the source.

Major Issues:

- ✓ *Continued increase in price of petroleum, and thus asphalt, which is a finite resource.*
- ✓ *Appropriate use of polymer, rubber, and other types of binder modifiers.*
- ✓ *Depletion of high-quality aggregates needed for some type of mixtures.*
- ✓ *Specialization of mixtures for safety, noise, and structural considerations and their environmental and cost implications.*
- ✓ *Use of RAP and other RCWMs including asphalt shingles, recycled tire rubber, and sulfur.*
- ✓ *Environmental, social, and cost implications of mixture design and durability.*
- ✓ *Future binder availability and alternatives.*

Confusion sometimes arises in the terminology used to describe asphalt paving products. In North America, *asphalt* is taken to be the material refined from petroleum that is then combined with other materials to create products having a variety of names (e.g., asphalt concrete, hot-mix asphalt, warm-mix asphalt). In other countries, the petroleum-derived product is referred to as *bitumen*, and the term *asphalt* refers specifically to certain types of mixtures of bitumen and aggregate. Additionally, the word *tar* is sometimes incorrectly used as a colloquialism to refer to asphalt. Actually, *tar* is a specific material made from destructive heating of organic materials in a process called pyrolysis, and when produced from pyrolysis of coal or petroleum the resulting tar may have negative environmental impacts associated with its use (Mahler and Metre 2011; EPA 2008). Tar mixtures were used for a small portion of the paving done in the United States up until the 1970s and in other countries (NAPA/ EAPA 2012). Tar was attractive as a paving material because it is not soluble in petroleum-derived fuels or lubricants and thus will not degrade in parking or service areas where it may be exposed to fuel or lubricant leaks or spills. As a result, it is still sometimes used as a surface sealant for asphalt parking lots and driveways, even though there are environmental and human health concerns associated with its use because of the carcinogenic nature of coal-derived tars.

Asphalt Binders

In a complex refinery, a broad range of petroleum products is produced, with asphalt material being a minor product compared to the more valuable transport fuels (Bernard, Blomberg, and Southern 2012). Plant design and operations vary for each refinery based on the markets for each product, the characteristics of the crude sources, and prevailing environmental and other regulations. Different processes, such as vacuum/steam or solvent deasphalting, can be used to break the hydrocarbons in crude oil into different products, with each having different environmental and energy impacts. Crude sources can have different composition depending on their location and to a lesser extent on the method of retrieval; this determines which crudes can be recovered economically (e.g., primary, secondary or tertiary recovery from wells, surface deposits, oil sands, hydraulic fracturing), but can also vary with time, depending on market prices for products and the availability and cost of different types of crudes. “Light” and “sweet” crudes, meaning respectively those with less asphalt material and less sulfur, command higher

prices because they produce more transport fuels and are generally less costly to refine. In assessing the contribution of refinery operations to the energy and emission of asphalt production, storage of asphalt should also be considered, since asphalt must often be kept at a constant high temperature by heating to pump it through the refinery, in and out of storage tanks, and while in truck or rail transport. This is particularly important in cold climates. Blending of different grades of asphalt to meet specifications, and the production, milling, and blending of polymers, rubber, and other asphalt modifiers also consume energy and produce emissions.

Not all petroleum refineries produce asphalt. Since 1980, the refining industry's emphasis has shifted from growth of operable crude oil distillation capacity to investment in downstream (secondary) processing units, thereby increasing the overall level of refinery complexity (Lidderdale, Masterson and Dazzo 1995). Secondary processing units, such as use of delayed cokers, catalytic crackers, and hydrocrackers, are used to break the portion of the oil that would otherwise be used for asphalt to improve the yields of lighter products. As of January 2013, 56 of 131 oil refineries in the U.S. produced asphalt (EIA 2013).

Asphalt Paving Materials

Asphalt is produced in different forms for use in pavements, which mostly have to do with how the viscosity of the asphalt is reduced (i.e., made more flowable) for construction so that it can coat aggregates or be sprayed onto the surface before reverting to a more viscous or semisolid state prior to opening to traffic. A schematic illustrating the production of asphalt cement is shown in figure 3-4.

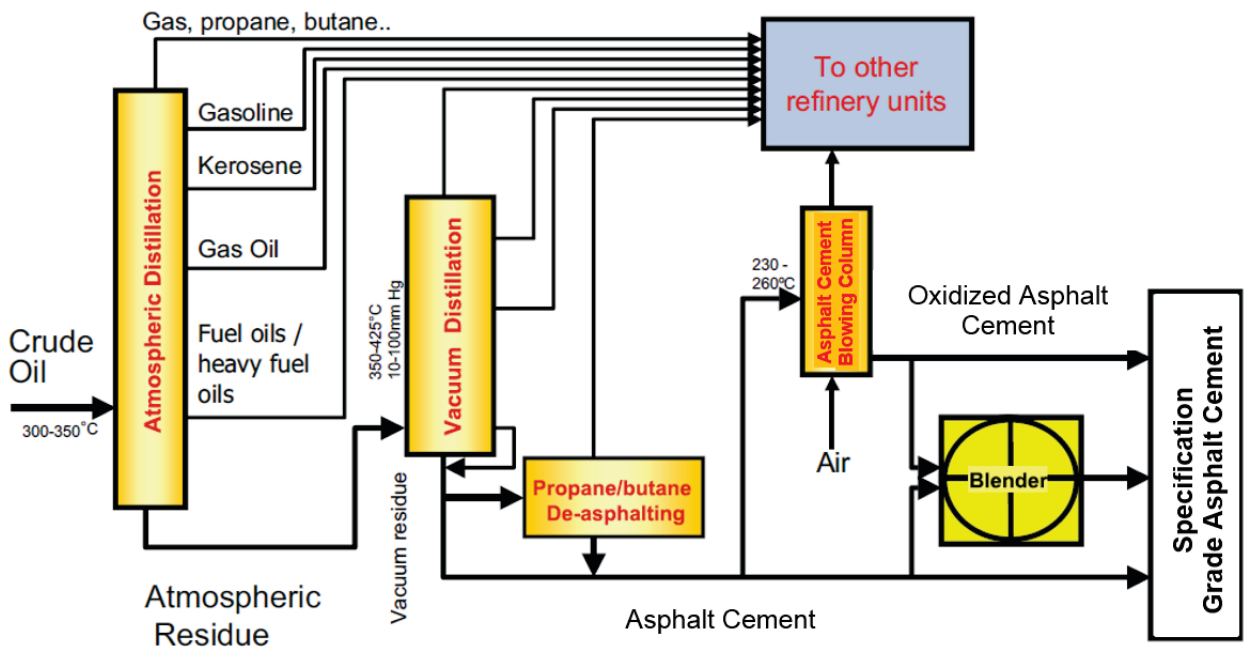

Figure 3-4. Schematics illustrating straight-run distillation of asphalt within a complex refinery (Asphalt Institute and Eurobitume 2011).

The following defines some basic terminology as applies to asphalt paving materials (note that most asphalt and asphalt-aggregate materials have a number of nearly synonymous terms and nomenclatures, varying by specifying agency and sometimes changing over time) (AI 2007):

- *Asphalt cement*, also referred to as *neat asphalt*, *asphalt, or asphalt binder*, is the portion of the crude oil that is used directly in paving. In this form, it is made flowable by heating and then reverts to a semisolid state as it cools. *Asphalt cement* is used as the binder in *hot-mix asphalt*, *warm-mix asphalt*, *open-graded asphalt, stone mastic asphalt*, *chip seals* and as a *tack coat*. It is the asphalt material used to produce *asphalt emulsion, polymer-modified asphalt, rubberized asphalt*, and *asphalt cutback*.
- *Asphalt emulsion* is made by shearing asphalt into microscopic droplets (0.5 to 10 microns) which are mixed with water (typically in ratios between 40:60 and 60:40 asphalt:water) and an emulsifying agent (very small percentages) that keeps the drops in suspension in the water. The asphalt reverts to the semisolid state when the emulsifying agent is neutralized or "breaks," allowing the particles to join together, which is followed by evaporation of the water. Asphalt emulsions are used extensively for surface treatments such as *fog seals* (emulsion and other hydrocarbons), *sand seals* (emulsion and fine aggregate), *microsurfacings* (emulsion, water, fine aggregate, mineral filler, other additives) and *slurry seals* (emulsion, fine aggregate and cement*). Polymer-modified asphalt* and *rubberized asphalt emulsions* are also used for these and other applications. Asphalt emulsion can be mixed with aggregate at an asphalt mixing plant to create *cold-mix asphalt* or in situ for *cold in-place recycling* (CIR).
- *Asphalt cutback* is made when asphalt cement is dissolved in a petroleum-based solvent. Solvents include gasoline or naphtha (rapid curing cutback), kerosene (medium curing cutback) or low-volatility oils (slow curing cutback). These materials are liquid at ambient temperatures with the asphalt cement being reconstituted as the solvent volatilizes after the cutback is spray applied or mixed with aggregates. The modern use of asphalt cutbacks has been curtailed as they produce significant volatile organic carbon (VOC) air emissions, but they are still used in some locales, especially during cooler temperatures or in wetter climates when asphalt emulsions become ineffective. Asphalt cutback can be mixed with aggregate at an asphalt mixing plant to create *cold-mix asphalt* or in situ for *CIR*.
- *Hot-mix asphalt* is produced when heated asphalt cement is mixed with heated, dense-graded aggregates in a plant to achieve a mixture at temperatures of approximately 275 °F to 329 °F (135 °C to 165 °C). HMA is often used as the main structural layer as well as the surface layer in many kinds of asphalt, composite, and semi-rigid pavements.
- *Warm-mix asphalt* represents a broad range of technologies used with asphalt concrete that allow the mixture to stay workable and compactable at lower temperatures. WMA can be used to reduce the mixing temperature and facilitates paving in cooler weather, and also allows longer transportation distances. Utilization of WMA technology can reduce compaction temperatures by approximately 25 to 80 °F (14 to 25 °C) (PAPA 2011). The amount of reduction depends on the WMA technology used and the characteristics of the mix, plant, climate, lift thicknesses, and hauling distance.
- *Open-graded asphalt* is made when asphalt cement is mixed in a plant with the aggregate gradation missing portions of the smaller-sized particles. Open-graded asphalt placed as a thin surface course on top of a traditional asphalt concrete improves surface friction and reduces tire-pavement noise. Open-graded asphalt can also be used to create a permeable base if used below an impervious surface layer or it can be used as the full depth of the paved surface as part of a pervious pavement system.

- *Stone mastic asphalt* (SMA) is created when asphalt cement is mixed with gap-graded aggregates. SMAs are used almost exclusively as surface courses as they are highly resistance to pavement deformation (rutting) in the wheelpaths and top-down cracking.
- A *tack coat* is an asphalt cement, asphalt emulsion, or asphalt cutback sprayed onto a paved surface to assist in bonding asphalt concrete layers together during construction.
- A *prime coat* is used to waterproof and bind together aggregate base surfaces. Sometimes prime coats are made with asphalt emulsions having up to 30 percent slow curing solvent to keep the asphalt liquid longer. Slow curing cutbacks are also used as *prime coats*.
- *Chip seals* are created when an asphalt cement, asphalt emulsion, or asphalt cutback is sprayed onto a granular base or onto an existing pavement surface and followed with the application and embedment of single-size aggregate "chips." *Rubberized asphalt* is also used for *chip seals*.
- *Crumb rubber modifier* (CRM) is created by grinding recycled tire rubber after stripping out steel reinforcement. CRM can be mixed with asphalt cement, natural rubber, and other ingredients to produce *rubberized asphalt* (ASTM specifies that rubberized asphalt has a minimum 15 percent recycled rubber by mass; AASHTO does not currently have a specification but is working on developing one [RAF 2013]). Rubberized asphalt is used in different types of asphalt-aggregate mixtures for structural and surface layers, and for chip seals. CRM is also used with polymers in *terminal blend rubberized asphalt*, although with no required minimum CRM content and more finely ground particles (Hicks, Cheng, and Duffy 2010).
- *Polymer-modified asphalt* (PMA) is created when, asphalt cement is mixed with a number of different polymers to produce a binder with the properties needed for different applications, most typically with enhanced high temperature performance characteristics.

Co-Product Treatment for Asphalt Materials

Asphalt is one of many co-products produced in oil refineries. Because of the importance of refinery products on the environment and economy, many of these products have been studied using LCA. Each study has had to select a co-product treatment approach. Nearly all rely on allocation, although some have combined subdivision methods with allocation by distinguishing processes within the refinery that can be attributed to particular products while relying on allocation by energy or mass to partition oil extraction and transport impacts and other processes that cannot be reasonably partitioned. Since different refinery products have different fuel contents, weights, or economic values, the method of allocation can have a significant effect on the calculated impact. Different allocations can be applied to different steps in the asphalt production. The extraction and transport of the crude to the refinery is similar for all the products obtained from the crude. At the refinery level, depending on the refinery setup, some processes may be common to some products while other processes are unique to a single product.

Most LCA studies use mass allocation. To help understand the impact, sensitivity analyses are often performed in LCA using alternative allocation methods. Wang, Lee, and Molburg (2004) suggest that the different approaches for allocation for different refinery products can lead to differences in assigned environmental impacts of up to 25 percent. A more recent LCI considering a typical set of crude sources in Northern European refineries has been prepared by Eurobitume for conventional asphalt binders. A hybrid approach using allocation based on mass for parts of the process and economic value for other parts was used to determine the environmental impacts for the cradle-to-gate inventory (Eurobitume 2012; Bernard, Blomberg, and Southern 2012).

Polymer-modified asphalt are used in different types of asphalt-aggregate mixtures for structural and surface layers, and for chip seals. As mentioned, CRM is also used with polymers in *terminal blend rubberized asphalt* (Hicks, Cheng, and Duffy 2010).

- *Cold-mix asphalt* used as a storable patching material most often uses cutback asphalt and/or asphalt emulsion mixed with aggregate and/or RAP.
- *Cold in-place recycling and full-depth reclamation* produce materials that involve mixing RAP that is created in-place with various materials, including asphalt emulsion, foamed asphalt, cement, lime, and other cementitious materials. These treatments are discussed in more detail in chapters 7 and 8.

Mixture Design of Asphalt Concrete

Mixture design for asphalt concrete generally requires the following steps:

- Identification of the function of the pavement layer (e.g., surface drainage layer, surface layer, structural layer, fatigue resistant bottom layer, subsurface drainage layer, base for concrete or asphalt pavement), and selection of appropriate mixture type (e.g., dense-graded asphalt concrete, SMA, open-graded asphalt concrete, rich-bottom asphalt concrete). A decision on whether to use a WMA technology is often also made at this juncture. Open-graded asphalt mixtures used for thin permeable layers on pavement for high-speed traffic are also used as the surface layers for fully permeable asphalt pavements (NAPA 2008).
- Identification of the asphalt material to be used appropriate to the mixture type (conventional, polymer-modified, rubberized, terminal blend rubberized) and the selection of the grade of asphalt. Most paving asphalt used in the U.S. is specified in terms of its Performance Grade (PG), which considers workability, the high-temperature properties important for rutting, and the low-temperature properties important for low-temperature cracking as the binder ages.
- Identification of the aggregate sources having specified properties for the application and testing of volumetric properties to determine the aggregate gradation.
- Selection of the final binder content based on relationships between the binder content and other mixture proportions. These include the risks of too much binder, such as rutting and shoving, which are predominately an issue in the first few years of service before the asphalt stiffens as it ages. Also considered are the risks of too little binder, which include early cracking, raveling, water damage, and inadequate compaction, all of which have additional negative impacts that affect the long-term performance of the mixture.
- Consideration of the amount of RAP or RAS included in the mixture, as these affect the properties of the blended asphalt binder (composed of virgin and recycled binder), the aggregate characteristics and gradation, and the volumetric proportions associated with performance.
- On some projects where the risks warrant additional cost and time, advanced materials characterization is performed on the draft final mixture design to help determine whether it meets the requirements for the project (called *performance-related testing*). The properties measured in many of these tests, such as the complex modulus, can also be

used as inputs to mechanistic-empirical pavement design methods, which are discussed in more detail in chapter 4.

Two strategies for reducing the environmental impacts of asphalt mixtures are to:

1. Increase their performance and therefore increase the time between future maintenance and rehabilitation treatments.
2. Decrease the negative impact of materials in the mixture by reducing the amount of virgin asphalt binder and aggregate through the use of recycled materials such as RAP, RAS, and recycled tire rubber, by minimizing or eliminating those additives that may increase the impact of material production (polymers, virgin rubber, or chemical WMA additives[1], for example), and by changing specifications to permit increased use of locally available but lower quality aggregates. Inherent in the use of these approaches is that overall pavement performance is not reduced or compromised.

These two strategies may contradict each other, with one calling for enhanced durability and the other for the use of potentially less durable materials, and therefore must be balanced. Solutions that are able to achieve both longer life and a reduction in the amount of virgin materials offer the most promise for improving sustainability.

One type of distress that can substantially shorten the life of asphalt pavements is moisture damage, which is amplified when water is able to penetrate the asphalt pavement matrix. Certain types of aggregates carry a much greater risk of moisture damage than others. Lime and liquid anti-strip chemicals are two additives that can reduce the susceptibility of mixtures to moisture damage. Lime is typically added at about 1 percent by weight of mixture (~37.3 lb/yd^3 [22 kg/m^3]), whereas liquid anti-strip agents are typically added at about 1 percent by weight of asphalt cement (~0.24 gal/yd^3 [1.2 l/m^3]). Each additive has its own particular economic and environmental impacts. Lime, for example, has a relatively high GHG emissions footprint as its production requires calcination of calcium carbonate, which uses heat to liberate fossil carbon dioxide, leaving calcium oxide. Liquid anti-strip additives are made from a variety of chemicals, each of which has its own impact on the environmental impact of the mixture.

Mixture Design of Other Asphalt Road Materials

The design of materials for full-depth reclamation (FDR, as well as other forms of in-place recycling), chip seals, and other road materials containing asphalt follow a similar process as that described for asphalt concrete above: identification of the function of the material; review of alternative aggregates, asphalt binder, and other materials to be included in the mixture; selection of final materials based on the existing structure, climate, traffic, and applicable specifications; and optimization of the proportions. For example, chip seals will include consideration of aggregate size, shape, gradation and mechanical durability, determination of whether to use sprayed asphalt or an emulsion and whether it will include polymers or rubber, and selection of the final application rates for the asphalt and aggregate. For full-depth reclamation, the mixture design will include characterization of the in-place materials, selection of stabilization materials

[1] Note that there are a number of WMA technologies that have very different environmental impacts. Those based on chemical additives often have a greater benefit in maintaining compactability at lower temperatures than those based on mechanical water foaming, but chemical additives may also have a higher environmental impact during their production. However, most chemical WMA additives are used in very small amounts, typically 1 percent by weight of asphalt cement (~0.24 gal/yd^3 [1.2 l/m^3]), and thus the overall environmental impact is thought to be small.

Full-Depth Reclamation with Foamed Asphalt

The process of full-depth reclamation (FDR) involves the pulverization of the existing asphalt surface and the recyclable (unbound or chemically stabilized aggregate) underlying materials, to a maximum depth of 12 to 18 in (305 to 457 mm) depending on available compaction equipment and subgrade support, while simultaneously mixing it with a binding material, or less frequently compacting it without stabilization as aggregate base. Binding materials can include a combination of foamed asphalt, cement filler, and water, cement and water, emulsified asphalt, or other cementitious materials. The mixture is graded, compacted, and overlaid after recycling. One type of full-depth reclamation is with foamed asphalt (FDR-FA), which is created when cold water, along with compressed air, is injected into hot asphalt in a specially designed chamber. The water becomes steam when it undergoes the sudden increase in temperature, which becomes trapped in tiny asphalt binder bubbles. This results in a thin-film, high-volume asphalt foam with reduced viscosity and increased coating potential. The foaming state is temporary, and within a few minutes the asphalt binder will assume its original properties. Foamed asphalt has been used effectively as a stabilizing agent in full-depth reclamation (source: http://www.pavementinteractive.org/). FDR-FA has sustainability benefits for lower volume roads (AADT <20,000) including (Caltrans 2012; Fu 2010):

- *Reduced life-cycle costs due to longer service life.*
- *Lower environmental impact due to reduced use of virgin aggregates and reduced landfill usage.*
- *Increased structural capacity.*
- *Reduced use-phase costs through expedited construction and simplified staging.*

Caltrans (2012) and Jones, Harvey, and Halles (2008) provide further details on this topic.

(as appropriate), such as cement, foamed asphalt (typically with a small amount of cement as well) or asphalt emulsion (conventional and fast curing), and final proportions to achieve desired properties that can be tested in the laboratory. FDR is most commonly used on low- to medium-volume routes, but has been used on some high-volume routes such as I-80 in California (over a cement-treated base) and I-81 in Virginia.

The same approach should be used when designing these materials, attempting to find the balance between specifying the use of higher quality materials (which often have higher initial cost and environmental impact) and the use of lower quality, lower cost materials (with a lower environmental impact but potential performance reductions). Thus, the entire life cycle must be considered, not only from an economic perspective but also from an environmental perspective. The ideal solution will be a function of the materials, traffic, climate, and construction processes.

Mechanistic-empirical (ME) design procedures can be used to calculate the anticipated effects of material choices on pavement performance, given detailed material properties, pavement structure information, traffic loadings, and climatic factors. It can therefore be used to investigate the trade-offs due to changes in material that affect the material properties and to see how those changes affect the structural capacity of the pavement over time. If LCA is combined with ME design, together they can be used to calculate the net environmental impact of changing materials properties and performance over the life cycle. Chapter 4 includes more discussion on the use of ME design, and how materials properties are considered in the structural design of pavements.

Warm-Mix Asphalt Technologies

Almost without exception, increasing the density and decreasing the variability of asphalt materials will improve performance. WMA is a relatively new technology being used to increase overall

density and lower variability of density, and offering the possibility of lower production temperatures and less initial environmental impact of materials production and construction.

As discussed in chapter 5, increased asphalt concrete density is a result of good specifications and the effective quality assurance (QA) practices regarding compaction that are well known in the industry. This requires attention from both the owner and the contractor. Improved compaction requires no additional materials, and usually requires no additional equipment usage, but rather careful attention to details and effective management of the factors controlling success. Unlike changing mixture design parameters (e.g., changing the binder content in an asphalt concrete material, using a softer binder to improve reflection cracking resistance in an asphalt concrete material, or increasing the cement content of a FDR material), increasing the density of a material by compaction will improve both the rutting and cracking resistance. Further discussion of compaction and other construction operations is included in chapter 5.

As previously described, WMA technologies are used with asphalt concrete to allow the mixture to stay workable/compactable at lower temperatures. WMA may be used for a number of reasons, including reducing mixing temperature, facilitating paving in cooler weather, or allowing longer transportation distances (or combinations of all three).

Most asphalt mixing plants in the U.S. have shifted from diesel or other fuel oil and are now fueled by natural gas, which is primarily used for heating aggregate and asphalt for mixing, and secondarily for drying aggregate (EPA 2000; Cleaver 2011; Carbon Trust 2010). In recent years, a number of asphalt mixing plants have begun burning recycled motor oil as a fuel for mixing and drying, which disposes of this otherwise hazardous material in a safe manner while at the same time offsetting the use of other fossil fuels (EPA 2012). WMA can be used to significantly reduce mixing temperatures, with the amount of reduction depending on the WMA technology used and the characteristics of the mixture, plant, climate, lift thicknesses, and hauling distance (D'Angelo et al. 2008). WMA technologies will reduce the environmental impact of asphalt mixture preparation and paving if they are used to reduce mixing temperature, thus decreasing the fuel consumed to heat the asphalt mixture. The total environmental impact of the use of WMA will depend on the technology used as technologies that use waxes or polymers have associated environmental impact of the additive itself that must be considered, but are also generally more effective than mechanical foaming WMA technologies. Keeping aggregate and RAP sources dry also helps to reduce the energy needed to dry aggregates (Cleaver 2011; Carbon Trust 2010).

The estimated total amount of WMA in the U.S. has grown rapidly over the past several years as shown in figure 3-5. This increase in use reflects the key advantages of using WMA: reducing the fuel used to heat the mixture at the plant, improved mixture compactability, and increased flexibility during the construction phase allowing longer haul distances and extending the paving temperature range.

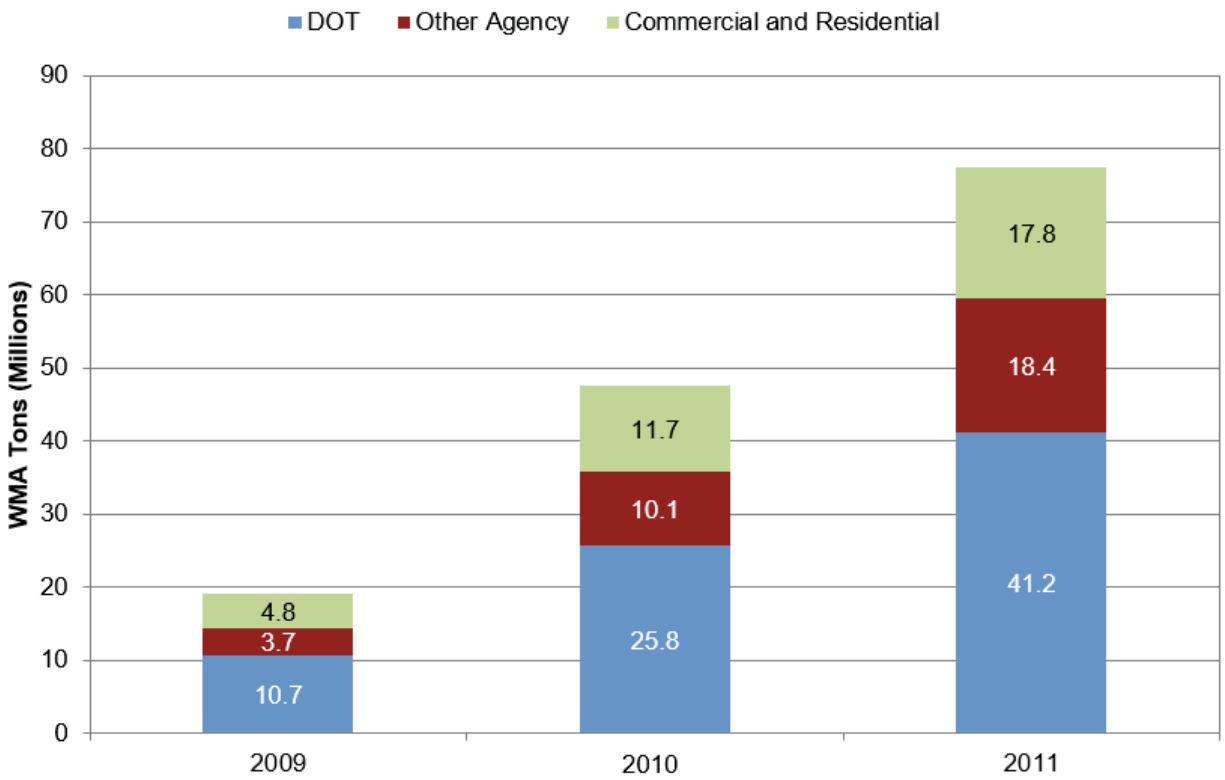

Figure 3-5. Estimated tons of WMA usage by industry sector 2009-2011 (Hansen and Copeland 2013).

WMA technologies are generally grouped into three families: chemical admixtures, chemical foaming agents, and mechanical foaming, the latter of which is most commonly used in the U.S. (Hansen and Newcomb 2011). Chemical admixtures can further be divided into those that change the melting point of asphalt and those that change the coating characteristic of the asphalt. Chemical foaming agents add a chemical that does not change volume as it releases water into the mix. Mechanical foaming of the asphalt cement is accomplished either before the cement is added to the aggregate in a special foaming chamber or after by introducing moisture in the fine aggregates. All of these technologies allow the aggregate particles to orient themselves at lower than normal temperatures while being compacted. The reduction in mixing temperature at the plant depends on the WMA technology used, the materials, the haul distance, and the weather. Current research suggests that WMA does not significantly affect the long-term performance of the pavement, provided all other aspects of mixing and compaction are done appropriately. If asphalt mixing plants are adjusted to use WMA technologies by reducing mixing temperatures, then WMA can potentially reduce energy use. Because good asphalt compaction has such a significant effect on performance, it is possible that the major benefit of WMA is as a compaction aid resulting in increased pavement longevity with longer times between maintenance and rehabilitation activities.

Research regarding environmental benefits for different situations is ongoing. LCIs of WMA chemicals, which would permit consideration of the environmental impacts of their production in an LCA, have not been published to date. Mechanical foaming only uses relatively small amounts of water and involves the initial installation of foaming equipment, which should have minimal environmental impact.

Over the years, there have been a number of studies looking at air emissions and exposure of construction workers to asphalt concrete materials (see, for example, NAPA/EAPA 2012). While WMA technologies are used to reduce the mixing and compaction temperatures of asphalt mixtures, they can also reduce the emissions associated with the hot material that sometimes cause short-term worker irritation during mixing and laydown (there are very few emissions released after initial compaction) (Farshidi et al. 2011). This is especially helpful for rubberized mixtures that otherwise can sometimes generate enough fumes that workers require respirators when paving (Farshidi et al. 2011). Worker exposure and leachate into water are issues to consider when adding any material other than conventionally refined asphalt and aggregate to asphalt concrete.

Although it is far more difficult to document, and less conspicuous than introducing a new material, increasing the density and decreasing the variability of asphalt concrete offers opportunities for significant improvements in performance and consequent environmental benefits. The benefits include less use of currently used materials, which may be amplified in high-traffic situations. Implementation of good QA practices requires investments in human capital and organization, which may pose a particular challenge for smaller contractors and local governments where specialized pavement expertise for effective QA is less available. Moreover, the benefits that come from these investments may be difficult to communicate.

Highest Use for Recycled Materials: Core Concepts

Recycling of used materials can be a good strategy to reduce the need for new materials. Examples are the use of RAP in new asphalt pavement or RCA in new concrete pavement. But it extends beyond aggregates. Depending on the material, secondary uses can include the use as fuel (for example rubber tires), feedstock (for example RAS to displace asphalt binder), or material resource (for example RAP or RCA). In addition to that, the material can be used in the original function (aggregate in asphalt mixture), or in a different function (aggregate in the base). When considering sustainability, the question comes up: what is the highest use for recycled material?

The first step to realize is that defining the highest use is a project-based (or at most a regional) decision. The second step is to make sure that whatever use is intended, it has to perform from a technical perspective. If adjustments need to be made, for example to a mix design, then those adjustments need to be taken into account when making this decision. The next step is to look at other relevant sustainability parameters through an LCCA approach, an LCA approach, and a rating systems approach. The highest use can be synergetic between these three systems, but sometimes it is not. This is what is referred to as trade-offs. Another consideration in defining the highest use is the starting point at which whatever decision is made, and that it should always be made with a life cycle perspective. Not setting appropriate systems boundaries and leaving out life-cycle phases can lead to missing important trade-offs. The implementation approach is presented in a sidebar discussion in chapter 8.

Recycling and Asphalt Road Materials

RAP is an important source of aggregate and asphalt binder for asphalt paving projects. RAP can be used as a replacement for virgin aggregate base, which does not take full advantage of the potential contribution of the asphalt coating the aggregate as a binder. In general, recycled materials should be used for the "highest use," which would be first as replacement for virgin asphalt and aggregate in new asphalt concrete, followed by use in recycled cold-mix materials, followed by use as aggregate base or aggregate in concrete. The asphalt binder in asphalt concrete carries much of the total environmental impact of the mixture because of the impact of petroleum acquisition and refining. Use of RAP in asphalt concrete replaces not only virgin aggregate, but the RAP binder is reused

as binder, at least in part, thereby reducing the amount of virgin binder needed in the new asphalt concrete. Thus, RAP use in new asphalt concrete reduces the need for virgin asphalt and aggregate, both non-renewable and finite materials, making asphalt concrete the highest use (i.e., its use displaces consumption of high impact and non-renewable materials) for this material.

The amount of RAP used in asphalt mixtures was 66.7 million tons (60.5 million mt) in 2011, a 19 percent increase over 2009 (56 million tons [50.1 million mt]) and about a 7 percent increase over 2010 (62.1 million tons [56.3 million mt]). Assuming 5 percent liquid asphalt in RAP, this represents approximately 3.6 million tons (3.3 million mt), of virgin asphalt binder conserved, or about 12 percent of the total binder used in 2011 (Hansen and Copeland 2013).

Looking at U.S. data from 2011 (see figure 3-6), approximately 87 million tons (79 million mt) of RAP that was milled from existing pavements was run through asphalt mixing plants that year, with approximately 74 million tons (67 million mt) of the 81 million tons (73 million mt) of RAP (92 percent) recycled into new asphalt concrete materials. For the years 2009 through 2011, RAP that was not recycled into asphalt concrete was used for aggregate base (less than 10 percent annually) and cold mix (less than 3 percent annually). Less than 0.1 percent landfilled (Hansen and Copeland 2013). These figures do not consider asphalt pavement recycled in place.

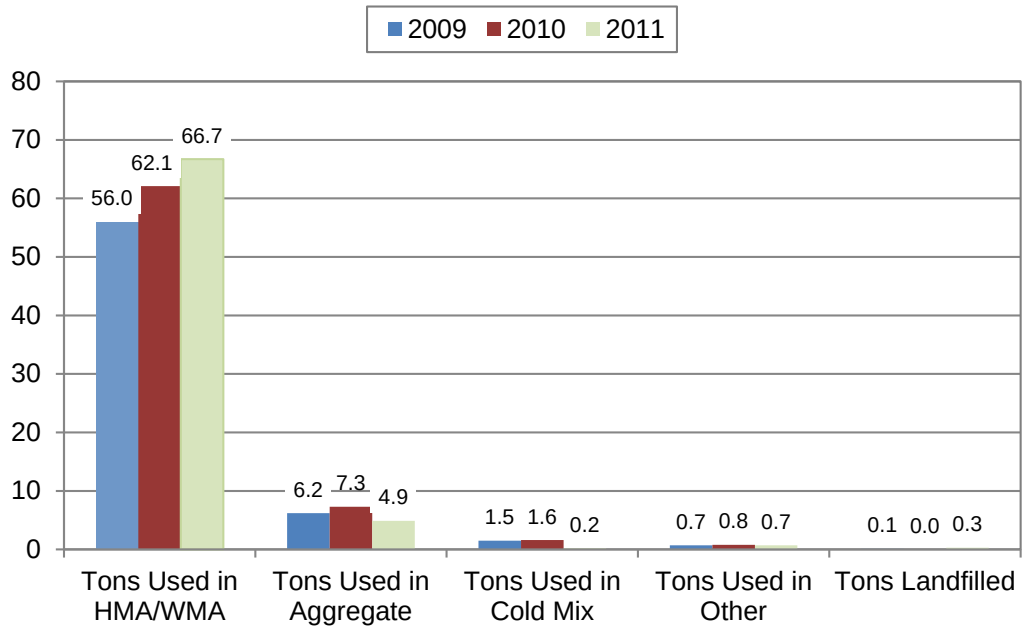

Figure 3-6. RAP use in the U.S., 2009 through 2011 (adapted from Hansen and Copeland 2013).

The characteristics and quality of the aggregate and asphalt in the RAP are dependent on the quality of the original materials, any additional patching or other maintenance materials recovered during milling, and any additional processing that occurs during and after milling and reuse. The effects of moisture-sensitive aggregate, rubber, polymers, or other ingredients in the milled material have not been the subject of intensive research. The variability of the characteristics and quality are dependent on the variability in the milled material, and the amount of crushing, sizing, and reblending that is done to homogenize the material at the plant.

The asphalt binder in RAP, called the residual binder, is generally stiffer and more brittle than virgin asphalt because it has been oxidized through previous heating in the mixer and its atmospheric exposure during service. The latter is particularly true for RAP recovered from older pavements, for RAP in hotter climates, and for RAP obtained from layers near the surface where some of the lighter molecules may have volatilized. The aged residual asphalt binder will stiffen the new mixture, generally improving rutting resistance but potentially increasing the tendency for top-down cracking when used in surface mixtures unless it is well managed through specifications. The stiffer, aged residual binder in RAP can help reduce bending and tensile strains that contribute to bottom-up cracking when used in thicker layers below the surface.

The degree to which the residual binder on the RAP particles blends with virgin asphalt has an important effect on the properties of the new mixture and its performance. The amount of blending is dependent on the properties of the new asphalt, how long and at what temperatures the RAP is heated during its processing, the mixing time, and whether softening agents are added. For example, there is very little blending in cold-mix recycling technologies. The amount of blending that actually occurs in asphalt concrete, its effect on the mixture properties, and how much of the asphalt in the RAP can be considered as replacement of virgin asphalt is a subject of research at this time.

The ability to control particle size and avoid segregation during mixing with virgin materials in an asphalt plant is largely dependent on whether the RAP is sized, or fractionated, and binned into different consistent size gradations (Bonaquist 2011; Christensen and Bonaquist 2006). Controlling particle size is more difficult during in-place mixing processes.

RAP has been used for up to 50 percent replacement of virgin materials in dense-graded asphalt concrete. However, where mixture performance is most critical, such as in asphalt surface layers, the level of replacement is often lower. Many agencies place limits on how much RAP can be used for different applications, depending on their assessment of risk. In general, replacement at up to 15 percent is considered to have minimal effects on properties. Most state highway agencies allow up to 15 or 30 percent replacement for structural layers, and some also allow those amounts for surface layers. The average RAP content in asphalt concrete mixtures in the U.S. in 2009/10 was about 13 percent for state DOT mixtures, 15 percent for other agency mixtures, and 18 percent for commercial and residential paving mixtures (Hansen and Newcomb 2011). Since most asphalt used in asphalt concrete is specified in terms of its PG grade (which accounts for the binder's contribution to rutting, thermal cracking, and fatigue cracking), the method of estimating these properties for the blended (or partially blended) residual and virgin binder is critical.

Increasing the amount of virgin binder replaced through mobilization of the residual binder as part of the new blended binder greatly reduces the environmental impact of the mixture. These benefits are offset somewhat by the additional energy needed to heat the virgin aggregate in the blended mixture to higher than normal temperatures for mixing, because the RAP cannot be heated to normal mixing temperatures without burning the residual asphalt. Instead, for RAP contents up to about 35 percent, the virgin aggregate must be heated to temperatures of 420 °F to 500 °F (215 °C to 260 °C) compared to 275 °F to 330 °F (135 °C to 165 °C) for a mixture made entirely with virgin materials (Kandhal and Mallick 1997; AI 2013). For higher RAP contents it is necessary to ensure that the RAP is dry (stockpiles should be covered) to avoid heat loss in removing water from RAP. Transportation of RAP for use in locations where it is not readily available must also be considered when evaluating energy and environmental impacts because long haul distances by truck have significant cost and environmental impacts.

Use of CRM in Asphalt Binders

The inclusion of CRM from recycled tires in asphalt binders, primarily as rubberized asphalt, has been the subject of extensive research starting in the 1980s. It is used extensively by a few states, primarily in gap-graded and open-graded asphalt concrete and rubberized chip seals. Rubberized asphalt includes at least 15 percent recycled tire rubber. Accelerated pavement testing has demonstrated that a rubber-modified asphalt mix on top of a dense-graded mix can delay or arrest further propagation of bottom up cracks through the rubber modified mix to the surface (Gibson et al. 2012; Jones, Harvey, and Monismith 2008). Field studies in California indicate that rubberized open-graded asphalt mixtures have superior performance to open-graded mixtures with conventional binders in terms of raveling, cracking, and noise (Rezaie, Harvey, and Lu 2012). These mixtures have higher binder contents and are mixed at temperatures that are approximately 18 to 36 °F (10 to 20 °C) higher than conventional binders, both of which increase their environmental impact per unit volume (Bearden and Le 2011). The net effect with the thickness reduction and performance can be calculated through an LCA. An LCA that considered GHG and energy use in one case study demonstrated that full thickness of asphalt concrete and half thickness of gap-graded rubberized asphalt concrete in a thin overlay with similar expected performance had nearly the same materials production impacts, but the half thickness rubberized mix had a lower construction phase impact due to the reduced mass of material that had to be transported to the site (Wang et al. 2012). Similar calculations can be made for terminal blended rubberized asphalt, which is used in some asphalt concrete mixtures and in chip seals. The future effects of increasing quantities of rubberized asphalt in RAP stockpiles on mixture design and performance have not yet been investigated by researchers. Methods need to be developed to determine how much rubberized material exists in a given RAP stockpile as well as understanding of how this material will affect the properties of the new asphalt mixture.

As is discussed in more detail in chapter 7, most in-place recycling is done "cold" or "warm." CIR consists of milling the top 3 inches (76 mm) of the existing pavement, mixing with asphalt emulsion or cutback and asphalt cement, placement and compaction of the mix, followed by a thin asphalt overlay or surface treatment. It is used in lieu of milling and replacement with asphalt concrete. CIR reduces the thickness of the asphalt concrete overlay needed (or may eliminate it altogether) to obtain the desired life.

Full-depth reclamation, which is discussed in detail in chapter 8, is used for badly cracked asphalt pavement where overlays and surface treatments will not provide much additional life. It consists of pulverizing all of the existing asphalt and part of the aggregate or treated base and subbase beneath it up to depths of approximately 18 inches (457 mm), compaction, and then the placement of an asphalt overlay. FDR can use the pulverized material as an untreated aggregate base, or more commonly, a stabilizer (e.g., small amounts of cement, asphalt emulsion with some cement, or foamed asphalt with some cement) is introduced during the pulverization process. The stabilized FDR eliminates reflection cracking, reducing the thickness of the asphalt overlay needed, and can potentially provide a long life stabilized base with no need for new aggregate (see chapter 8 for more details on FDR).

Hot in-place recycling (HIR) is sometimes performed on existing asphalt pavements, where about 2 inches (51 mm) of the existing pavement is heated, milled, mixed with virgin materials, placed and compacted, all in one pass of an equipment train. Chapter 7 provides more information on HIR.

RAS, obtained from the roofing industry, is another source of recycled asphalt for asphalt concrete. On average, RAS contains about 20 percent asphalt binder by mass compared with about 5 percent for RAP, along with aggregates, mineral filler, and fibers. Approximately 1.3 million tons (1.2 million mt) of RAS were used in asphalt concrete in 2011 (Hansen and

Newcomb 2011), with RAS usage in 2011 replacing about 0.42 million tons (0.38 million mt) of asphalt. To create RAS, shingles are shredded and sorted for use. If shingles were obtained postconsumer (i.e., as part of a roof tear off and replacement), additional sorting is necessary to remove nails and other impurities. Typical use is limited to about 5 percent by mass of the total mixture because of potential for variability, the higher stiffness of roofing asphalt compared to asphalt used for pavements, and the degree to which RAS blends with virgin and residual RAP asphalt. A number of high profile projects have been constructed with mixtures containing both RAS and RAP, including an overlay of Michigan Avenue in Chicago (Illinois Interchange 2012). RAS/RAP mixtures are also being used by the Illinois Tollway to lower costs and reduce the environmental impacts of pavement materials. The EPA (2013a) recently performed a limited LCI and LCA on the use of RAS, evaluating only GHG emissions, and concluded that there are environmental benefits to the use of recycled asphalt shingles in asphalt production for use in road construction, and that the addition of RAS to pavement mixtures containing RAP helps further increase environmental reductions relative to the baseline of using virgin asphalt.

Various polymers are used to improve the viscoelastic properties of asphalt binders, improving the rutting and cracking performance of pavements. Polymer addition is typically 3 percent by weight of asphalt cement (about 0.70 gal/yd^3 [3.5 l/m^3]). Polymers used to modify asphalt are primarily derived from petroleum, and there are a number of different polymers each used for specific purposes. The use of polymer-modified asphalt can improve the performance of pavements, but the manufacturing of these polymers can also increase the environmental impact of the asphalt binder in the mixture, a fact that must be considered when evaluating environmental impacts.

Polyphosphoric acid (PPA) is a polymer of orthophosphoric acid (H_3PO_4). Experience has shown that PPA increases the high temperature stiffness of an asphalt binder to reduce rutting with only minor effects on the intermediate and low temperature properties, and it is typically used as an alternative to polymers for this purpose. Some highway agencies have no restrictions on the use of PPA as an asphalt modifier, while others have restrictions on its use. Work by the FHWA has clearly demonstrated that the increase in binder stiffness from the addition of PPA is crude-source dependent, with anywhere from 0.5 to over 3 percent needed to increase the high temperature binder grade (FHWA 2012a). Other laboratory testing has indicated that there may be some interactions with hydrated lime and an increased potential for moisture damage when more than 1 to 1.5 percent by mass of binder is used. LCI data are available for PPA to evaluate its environmental impact when included in asphalt materials (FHWA 2012a).

In addition to tire rubber (see CRM sidebar), other RCWMs have been recycled into asphalt concrete mixtures, including glass as a replacement for aggregate, slag from metallurgical processing, foundry sands, and recovered sulfur as an asphalt binder modifier. Before utilizing these or other RCWMs, a thorough review of the available information on the RCWM in question should be performed, and an LCI should be used to evaluate potential environmental impacts over the life cycle (this should include an assessment of leachate and volatilization potential as well as worker health and safety). Furthermore, the impact of RCWM use on pavement performance must be considered. One particular issue that should be considered is whether the inclusion of the RCWM places any constraints on the future recycling of the mixture. Even if an RCWM is used in a mixture, aggregate and asphalt will still be the primary materials, and the influence of the additional materials on their repeated recyclability may not be considered in the literature and can only be considered in an LCI if the information is available.

Assessment and Minimization of Environmental Impacts of Asphalt Road Materials

As previously indicated, different asphalt materials and mixtures have different environmental impacts. With regards to binders, the crude source, refining, transport, and the type of binder (asphalt cement, cutbacks, emulsions) all influence the environmental impacts (energy, GHG, air pollution, and so on). The amounts and methods of inclusion of rubber, polymers, PPA, solvents, emulsifying agents, and other binder modify agents will also change the impacts, generally increasing the impact in the materials production stage of the life cycle on a per mass basis.

The type of mixture (e.g., HMA or WMA, dense graded or open graded) and how it is placed (e.g., with a paver or applied as a surface treatment) also affect its environmental impact. Additionally, the type and amount of RCWM that is used, whether RAP, CRM, RAS, or any number of other materials, will likely influence the environmental impact either adversely or positively. An overriding concern is how the performance of the pavement is influenced by changes in the mixture, because a reduction in pavement performance can counteract any environmental benefit that was gained during the materials selection and construction phases. Thus, the overall pavement life cycle must be considered in order to help resolve some of the complexity in the decision-making process.

Other Asphalt Road Material Considerations

Where local or area urban heat islands are an issue (see chapter 6 for details), the solar reflectivity, heat capacity, heat conductivity, and permeability of the pavement may play a role. Ongoing research is being conducted to determine the importance of these characteristics and this phenomenon in different contexts. New asphalt concrete typically has low solar reflectivity, or albedo, on the order of about 5 percent, which means 95 percent of the incident solar radiation is absorbed. However, it tends to become more reflective over time as the asphalt oxidizes and as traffic or other abrasive actions wear the asphalt film off of the surface aggregates, at which point the reflectivity becomes more a function of the color of the aggregate.

Slurry seals are expected to exhibit reflectivity levels similar to the asphalt binder used, although there are little data available. The reflectivity of chip seals is largely dependent on the reflectivity of the aggregate used for the chips. Chips that are precoated with asphalt will have reflectivity similar to that of asphalt concrete materials, with the same type of increase in reflectivity occurring over time. Fog seals and other treatments that place fresh asphalt on the surface will tend to reduce reflectivity for a short period of time. The aggregate mineralogy, and the permeability of the pavement material, will affect the heat capacity and thermal conductivity that can have a significant effect on pavement temperatures, although less so than reflectivity (Li et al. 2013; Stempihar et al. 2012).

Treatments are available for asphalt concrete that can make it more reflective to solar radiation (Tran et al. 2009). Information regarding the environmental impacts of producing those treatments, and their potential effects on performance and future recycling, is not available in the literature. However, if the temperatures in the upper 4 inches (102 mm) of asphalt concrete layers is reduced, the risk of rutting is also reduced, particularly where heavy trucks move at slow speeds in hot climates. Light colored chip seals or other surface treatments that can reduce pavement temperature may help reduce that risk (Pomerantz, Akbari, and Harvey 2000).

Photocatalytic coatings primarily based on titanium dioxide have been developed for asphalt pavements to react with chemicals in the ambient air contributing to air pollution (Dylla et al. 2013; Brovelli and Crispino 2013).

Most pavement materials, including rubberized and polymer-modified asphalt mixtures, have been found to produce no leaching of pollutants into water that exceeds regulatory requirements, even when used with open-graded mixtures and after simulated aging (Kayhanian et al. 2009). Open-graded asphalt materials can potentially be used on pavement surfaces to trap pollutants from vehicles and airborne deposition that might otherwise be carried off the roadway into receiving waters or stormwater systems by rainfall.

Substitutes for Petroleum Asphalt

Petroleum typically contains between 0 and 3 percent sulfur, with the sulfur being removed during processing of "sour" crudes, resulting in an abundance of sulfur. The last decade has also seen a rise in the available sulfur on the market due to the increased use of acid gas wells to produce liquefied natural gas (LNG); sulfur levels can be as high as 35 percent (weight of material) taken from these natural gas wells. Because of this abundance of elemental sulfur, there has been considerable interest in using sulfur as a binder extender. Work on this was first performed in the late 1970s and early 1980s, but interest dropped due to cost and technical/safety reasons (FHWA 2012b). More recently, a new technology, known as Sulfur Extended Asphalt Modifier (SEAM) and recently renamed Shell Thiopave®, has been developed that is intended to function as both a binder extender and an asphalt mixture modifier (Tayabji, Smith, and Van Dam 2010). However, even though Thiopave pellets contain some additives designed to reduce odor and fumes during mixing, temperature control of the mixture and good ventilation practices are still required. Asphalt concrete mixtures produced with Thiopave must be mixed above a temperature of 248 °F (120 °C) for the sulfur pellets to melt and be dispersed throughout the asphalt mixture, but the temperature must remain below 293 °F (145 °C) to avoid the potential for emission generation that can be harmful to both workers and equipment. Furthermore, the location of Thiopave mixtures must be tracked in the field so that it can be properly handled and engineered if it is recycled as RAP into new asphalt concrete materials because of possible worker safety and equipment damage issues.

Research work is underway in the U.S. and other countries evaluating the replacement of petroleum-based asphalt with "bio-binders," which are made from biomass such as tree, plant, and animal waste (TRB 2012). Bio-binders exhibit similar properties to asphalt, such as the ability to flow when heated so they can coat aggregate or be sprayed, and the ability to withstand large strains without cracking. Examples include binders derived from corn stover, the non-food portion of corn (Metwally 2010), swine waste (Fini et al. 2011), algae (TRB 2012), and vegetable oil. One issue is the desire not to use biomass that would otherwise be useful as human or animal food.

Land-produced plant biomass is typically 80 percent cellulose and 20 percent lignin, and lignin can be a source of polymers for use in asphalt. Cellulose is a dense polymer chain of sugar molecules, and lignin is composed primarily of phenolic compounds in a hard, polymer-like structure. Three different types of processes are being evaluated to convert cellulose containing biomass to liquid fuels (King and King 2009):

- Fermentation, in which enzymes convert the biomass to energy, leaving lignins that would need to be further modified to function as paving binder.
- Fast pyrolysis, in which biomass is heated to very high temperatures in the absence of oxygen, breaking down the cellulose and lignin into smaller molecules that might then be processed into liquid fuels and possibly asphalt.
- Gasification, in which biomass is converted to combustible gases using newly developed processes similar to coal gasification technology.

Currently, there are some bio-binder products available on the market, although none have replaced a significant amount of paving asphalt in pavements built for state DOTs. No LCA publication was found in the literature on any of these bio-binders that considers the net life-cycle effects of the materials production, construction, use, and end-of-life phases.

Strategies for Improving Sustainability

Some general approaches to improve sustainability with regard to asphalt materials (and the trade-offs that should be considered) are summarized in table 3-3. It is noted that very little quantitative analysis of the net effects of these possible sustainability-improving practices has been evaluated using LCA procedures that would consider the materials production, construction, use, and end-of-life phases. A brief discussion of the identified strategies is provided below, and it is noted that many of these strategies reduce life-cycle costs as well as environmental impacts while enhancing overall social good.

Strategy: Reduce Amount of Virgin Asphalt Binder and Virgin Aggregate in Asphalt Concrete by Plant Recycling

The extraction and production of virgin asphalt binder from petroleum, a finite resource, is one of the major sources of environmental impact for asphalt concrete. The technology for performing mixture designs with increased percentages of reclaimed asphalt materials, such as RAP and RAS, and the use of binders modified with CRM from waste tires, is rapidly improving as is the design technology for using these mixtures in a manner that does not compromise the performance of the pavement.

Strategy: Reduce Energy Needed and Emissions from Mixing Asphalt Concrete

Use of warm-mix technology can potentially reduce the energy needed to produce asphalt concrete, and can also reduce the emissions. However, this does depend on the type of WMA technology employed and how it is used. The environmental impact of producing alternative WMA technologies has not been clearly established. Changing the fuel used in production (e.g., from diesel to natural gas) will reduce emissions, but with the potential for slight additional cost. The use of newer, more efficient asphalt mixing plants will reduce energy consumption and emissions, allow a greater percent incorporation of RAP and RAS, and many newer plants are equipped with WMA foaming technologies. This will result in overall cost and emission reductions, although requiring additional capital investment.

Table 3-3. Approaches for improving pavement sustainability with regard to asphalt materials production.

Asphalt Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce Virgin Binder Content in Asphalt Concrete	Use greater quantities of RAP if same or better performance can be realized.	Reduces cost of asphalt concrete if RAP available.	Dependent on performance, energy costs of mixing, transportation.	Extends life of petroleum resources. Reduced need for landfill.
	Use rubberized asphalt for asphalt concrete.	Some increase in initial cost, impact of mixture design higher, potential payback in less material for thin overlays, increased life.	Reduces impacts by decreasing amount of materials needed over time horizon.	Reduced exposure of public to accidents in work zones.
	Use RAS as partial replacement for asphalt binder if same or better performance can be realized.	Reduces cost of asphalt concrete if RAS available.		Extends life of petroleum resources. Reduced need for landfill.
	Use bio-binders.	Impacts and trade-offs unknown.	Impacts and trade-offs unknown.	Impacts and trade-offs unknown.
	Use sulfur-modified asphalt.	Not well quantified.	Potential difficulty in future recycling.	Risks for worker health.
Reduce Virgin Aggregate Content in Asphalt Concrete	Use greater quantities of RAP if the same or better performance can be realized.	Reduced cost of asphalt concrete if RAP available.	Dependent on performance, energy costs of mixing, transportation.	Extends life of aggregate resources. Reduced need for landfill.
Reduce Energy Consumed and Emissions Generated to Produce Asphalt Concrete	Use WMA to reduce mixing temperatures.	Zero to small increase in cost.	Reduced energy and GHG to make asphalt concrete. Impact of producing WMA additives needs to be considered.	Reduced worker exposure to fumes.
	Change fuel used for heating to reduce emissions, such as natural gas.	May increase cost.	Reduced emissions to make asphalt concrete.	Reduced worker exposure to fumes.
Reduce Energy Consumed and Emissions Generated to Produce Asphalt Concrete	Employ new, more efficient plant designs to reduce energy consumption and increase the percent RAP and RAS used	Increased capital cost to upgrade existing facilities. Reduced operating cost due to decreased energy consumption as well as increased use of RAP and RAS.	Reduce emissions to make asphalt concrete through reduced fuel consumption and higher percentage use of RAP and RAS	More efficient utilization of recovered materials such as RAP and RAS
Extend Lives of Asphalt Concrete Materials	Increase compaction specifications, no trade-offs.	Some increase in initial cost for extra contractor effort and inspection, large payback in increased life.	Reduces impacts by decreasing amount of materials needed over time horizon.	Reduced exposure of public to accidents in work zones.
	Use WMA to obtain better compaction.	Zero to small increase in cost, payback in increased life.	Reduces impacts by decreasing amount of materials needed over pavement life cycle. WMA additives needs to be considered.	Reduced exposure of public to accidents in work zones
	Improved mixture designs.	Some cost for new equipment, training, payback from longer lives.	Reduces impacts by decreasing amount of materials needed over life cycle.	Reduced exposure of public to accidents in work zones.
	Use polymers.	Some increase in initial cost, impact of polymer production, potential payback in increased life.	Reduces impacts by decreasing amount of materials needed over life cycle. Impact of producing polymer additives needs to be considered.	Reduced exposure of public to accidents in work zones. Increased exposure of workers to fumes.
	Use rubberized asphalt.	Some increase in initial cost, impact of mixture design higher, potential payback in less material for thin overlays, increased life.	Reduces impacts by decreasing amount of materials needed over time horizon.	Reduced exposure of public to accidents in work zones. Increased exposure of workers to fumes.

Table 3-3. Approaches for improving pavement sustainability with regard to asphalt materials production (continued).

Asphalt Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Extend Lives of Asphalt Concrete Materials	Use lime or liquid anti-strip to decrease risk of early failure due to moisture damage.	Slight increase in initial cost, payback from extended life where warranted.	Initial impact from manufacture of materials, potential payback if life would otherwise be shortened.	Increased worker exposure to lime or chemicals.
Reduce Materials Transportation Impacts	Use more locally available materials.	Lower initial cost. Potential for greater life cycle cost if perform is compromised. May have shorter lives if performance-related properties are poorer.	Reduces impacts of transportation of materials, particularly important if trucks would be used. May have shorter lives if performance-related properties are poorer.	Reduced exposure of public to trucking.
Extend Lives of Seal Coats	Use rubber or polymer binders.	Some increase in initial cost, impact of binder production higher, potential payback from increased life.	Increased impact due to production of polymers. Potential payback from improved life.	Polymers made from finite petroleum resources.
Reduce Need for Virgin Materials and Transportation	Use in-place recycling (full-depth reclamation, partial-depth recycling). May have high construction variability.	Can potentially reduce initial cost by reducing transportation of virgin materials and permitting thinner overlays, and may extend life where appropriately selected and designed. May have high construction variability.	Can reduce use of virgin materials depending on life. Can reduce transportation of materials. Energy savings dependent on technology and life. May have high construction variability.	Fewer heavy trucks on the road hauling materials.
Increase Pavement Albedo where Warranted (See Chapter 6)	Use lighter colored aggregates, place light colored chip seals, other reflective surface treatments.	Cost may be greater if reflective treatment not otherwise needed. Can potentially reduce risk of rutting of asphalt concrete. More materials used if additional coating applied that is not otherwise needed.	Needs to be evaluated on a case by case basis (see Chapter 6). If warranted, specific impacts that are positively impacted must be noted. Unintended consequences should also be examined.	Needs to be evaluated on a case by case basis (see Chapter 6). If warranted, specific impacts that are positively impacted must be noted. Unintended consequences should also be examined.

Strategy: Extend Life of Asphalt Concrete Materials

All things being equal, extending the life of asphalt concrete and seal coats reduces environmental impacts over the pavement life cycle. Effective mixture design and a high degree of construction compaction are strategies that are known to extend life, typically with few trade-offs. Dense-graded asphalt concrete can usually be compacted to 2 percent air voids without risk of rutting, and good compaction can be made easier to achieve with the aid of warm-mix technology. Rubber and polymers can be used in mixture designs for specific applications to increase life, but these may potentially carry some additional environmental impact from a materials production standpoint. They also typically have additional initial cost, which can be offset if they permit a reduction in pavement thickness. They may also negatively affect the ability to fully utilize RAP containing the additives in future asphalt concrete. As such, these materials should be used where they provide significant increases in performance. Reducing the risk of moisture damage in asphalt concrete through additives can also increase life, although the net environmental impacts of the additives have not been investigated through an LCA.

Strategy: Reduce Need for Virgin Materials and Transportation through In-Place Recycling

Recycling and reclamation can result in substantial cost savings and environmental impact reductions over the use of new materials when the technology (partial-depth recycling, full-depth reclamation) is properly selected, designed, and constructed. The cost and impact reductions can come from less use of new materials and reduced haulage. The life of the material must be considered when selecting strategies, since improvements in manufacture and construction can be offset by reduced life. Recycled materials have proven to be at least equal to new materials in quality, when properly engineered. FDR can be used to improve pavement cross-sectional geometrics and in some cases the traffic disruption is lessened compared to other rehabilitation techniques. Kandhal and Mallick (1997) provide additional information on recycling.

Strategy: Develop Alternatives to Petroleum-Based Binders

Work is under way to develop alternative binders, particularly bio-binders that have reduced environmental impacts compared to those derived from petroleum. However, the environmental impacts of these materials have not yet been evaluated using LCA, nor have their long-term performance capabilities been demonstrated.

Future Directions/Emerging Technologies

A number of strategies for reducing impacts from asphalt binders, modifiers, additives, and aggregate have been presented. Some future directions and emerging technologies that should be monitored and implemented, when and where beneficial, are:

- A reduction in material quantities through improvements in mixture design, construction practices, and, in some cases, new materials such as WMA or, where traffic, climate and existing condition warrant, inclusion of polymers, rubber, and other modifiers.
- Greater use of RCWMs, including RAP, RAS, and others, to reduce the mining, extraction, manufacture, and transport of non-renewable virgin materials, provided that performance is not compromised. For individual projects, this requires analysis of whether suitable RCWMs are locally available because long transportation distances may reduce the energy and environmental benefits of using RCWMs.
- Greater use of locally available pavement materials provided that those benefits are not offset by reduced performance. For asphalt materials, locally available aggregates are the primary consideration.
- Development of alternatives, namely bio-based alternatives, to nonrenewable feedstocks such as petroleum. The environmental, economic, and societal impacts of producing these alternatives will need to be evaluated to determine their overall feasibility.

Hydraulic Cement Materials

This section reviews the manufacture of HCC mixtures, including material acquisition, processing, transportation, and processing at a concrete plant. As aggregates were discussed at the beginning of this chapter, the focus of this section is on cementitious binders and additives, and how these combined with aggregates can be used to improve the sustainability of pavements. Economic and environmental impacts occur throughout all life-cycle phases, with this section focused on those directly related to the materials including cementitious materials, mixture design, proportioning, and mixing. Topics include energy consumption, emissions, calcination,

resource consumption, and water use. Recent innovations are discussed including mixtures with high contents of supplementary cementitious materials (SCMs), portland limestone and other blended cements, high-efficiency cement manufacturing plants, and concrete plant operations. Materials transport from the plant and construction are discussed separately in chapter 5.

Major Issues:

- ✓ *The relatively high non-renewable energy consumption and GHG emissions inherent in the portland cement manufacturing.*
- ✓ *The non-renewable energy consumption and GHG emissions associated with the production of traditional paving concrete.*
- ✓ *Water use associated with concrete production.*
- ✓ *Increasing the use of RCWMs as aggregates without compromising performance.*
- ✓ *Ensuring concrete durability.*

Introduction

In its simplest form, HCC is a mixture of coarse and fine aggregate bound together with "glue" that is created when water is mixed with hydraulic cement. Air is present in the mixture, either being entrapped or purposefully entrained as microscopic air bubbles. Figure 3-7 presents the components and their typical volumetric distribution in dense-graded HCC.

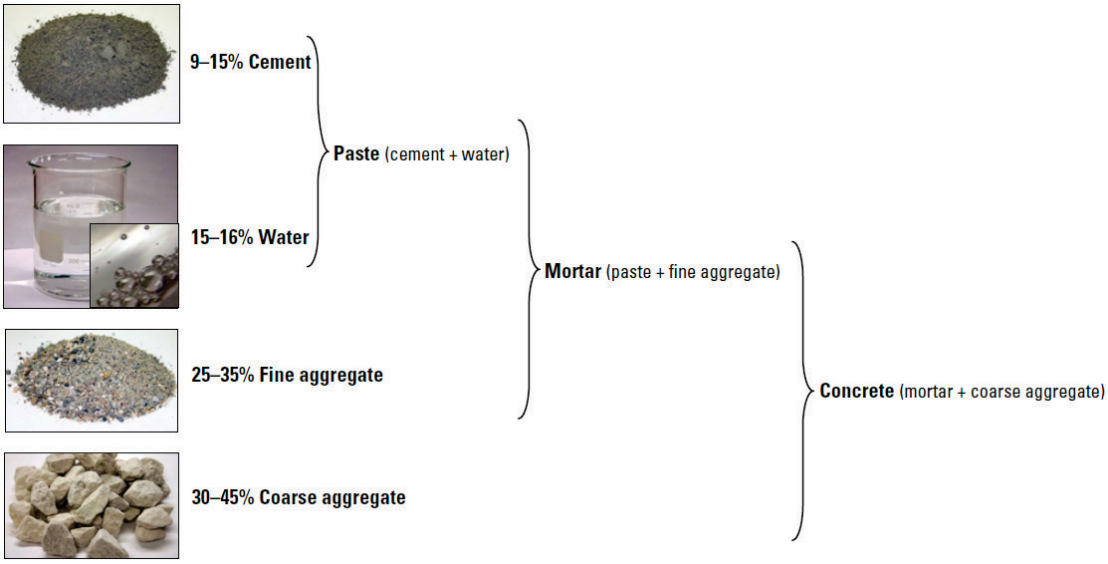

Figure 3-7. Typical volumetric distribution of hydraulic paste (cement, water, air) and aggregates in paving concrete (Taylor et al. 2006).

The hydraulic cement used today is most commonly a blend of portland cement (AASHTO M 85/ASTM C150), SCMs, and ground limestone. Furthermore, chemical admixtures are almost always employed to modify the behavior of the fresh and hardened HCC, making it easier to place, enhancing its strength, and making it more durable. In addition, the aggregates are often graded to possess a more optimized size distribution to create a mixture with a reduced cementitious content, improved workability, and enhanced long-term performance.

Portland Cement

Following water, HCC is humankind's most commonly used material, with roughly 1 yd^3 (0.76 m^3) of it produced annually for every person on the planet. As such, the economic, environmental, and societal impacts of HCC are huge. Furthermore, the cost and environmental impact of HCC is largely dependent on the cement (much of this section will generally refer to portland cement instead of hydraulic cement since it is by far the mostly commonly used type). This is illustrated in table 3-4, which shows that the production of portland cement consumes 74 percent of the energy and produces 81 percent of the GHG emissions associated with the cement and concrete industry in the U.S. (Choate 2003).

Table 3-4. Annual energy and CO_2 emissions associated with U.S. cement manufacturing and concrete production (Choate 2003).

	On-site Energy 10^6 kJoules	**On-site Energy %**	**CO_2 Emissions 10^6 tonne**	**CO_2 Emissions %**
Raw Materials – Quarrying and Crushing				
Cement Materials	3,817	0.7%	0.36	0.3%
Concrete Materials	14,287	2.6%	1.28	1.2%
Cement Manufacturing				
Raw Grinding	8,346	1.5%	1.50	1.4%
Kiln: fuels	410,464	74.0%	38.47	36.8%
Reactions			48.35	46.3%
Finish Milling	24,057	4.3%	4.32	4.1%
Concrete Production				
Blending, Mixing	31,444	5.7%	5.65	5.4%
Transportation	61,933	11.2%	4.53	4.3%
Total	**554,409**	**100%**	**104.50**	**100%**

Source: Energy and Emission Reduction Opportunities from the Cement Industry, U.S. Department of Energy.

Portland cement is manufactured by pyroprocessing raw materials, dominated by limestone, in a rotary cement kiln at high temperatures (2460 to 2640 ºF [1348 to 1448 ºC]). This alters the mineralogy of the raw materials, creating small, dark nodules referred to as cement "clinker" composed of reactive cementitious phases (Kosmatka and Wilson 2011). Although the consumption of fuel (which will differ regionally, consisting of pulverized coal, natural gas, used tires, waste industrial oils and solvents, and, in some cases, biomass) is responsible for a portion of the GHG emissions, over half of the GHG emissions in clinker production are released due to the decomposition of limestone ($CaCO_3$) into lime (CaO) and carbon dioxide (CO_2) (EPA 2013b; Van Dam et al. 2012).

Hydraulic Cement Materials Usage and Economics

The U.S. used approximately 79 million tons (72 million mt) of hydraulic cement in 2011, worth about $6.5 billion, according to the U.S. Geological Survey (USGS 2013b). In the recent peak year of 2005, approximately 111 million tons (122 million mt) of cement were consumed (USGS 2013b). Calcium sulfoaluminate and other non-portland hydraulic cements used are included in these figures, but only account for about 0.03 percent of cement used. According to the USGS, approximately 5 percent of cement used in the U.S. in 2011 was used for road paving purposes (USGS 2013b). In the U.S., about 8 percent of all paved roads and highways are surfaced with concrete. The U.S. has about 5,500 ready mixed concrete plants in 2011 (U.S. Census Bureau 2013), many of which produce concrete for paving. The value of ready mixed concrete produced in the U.S. was estimated at $34.7 billion in 2007 (U.S. Census Bureau 2007b), which suggests that the value of concrete used for road paving was about $1.7 billion based on 5 percent of cement used.

Even though cement kiln efficiency has improved markedly over the last two decades—significantly reducing the energy needed for pyroprocessing and the associated emissions—the calcination reaction is an unavoidable occurrence in creating portland cement and thus the CO_2 liberated from this reaction cannot be eliminated. Approximately 0.8 to 1.0 tons (0.7 to 0.9 mt) of CO_2 are produced per ton of cement manufactured in the U.S. (Van Dam et al. 2012). Furthermore, cement production is responsible for approximately 31.6 Tg CO_2e, or just under 0.5 percent of the U.S. total GHG emissions of 6,702 Tg CO_2e in 2011 (EPA 2013b). This is a dramatic reduction in GHG emissions from the peak that occurred in 2005 when 45.2 Tg CO_2e were associated with cement production, largely due to the economic downturn and resultant reduction in demand for cement that began in 2008.

As previously described, portland cement clinker is manufactured through pyroprocessing in large rotary kilns. Older technology is referred to as "wet process" in which the raw materials were ground wet, and then stored, proportioned, and fed into the kiln as a slurry. Modern cement kiln technology has reduced the energy needed to evaporate the water used in grinding through dry-process grinding and material handling. A schematic of a modern dry-process plant is shown in figure 3-8. This figure shows a general process design, but in truth every plant is unique, with modern plants incorporating new technologies to increase efficiency and reduce waste/emissions. A modern cement plant can take over a decade to permit and build at a cost of over $1 billion, and is much more efficient than plants that were prevalent two decades ago. Prior to the economic downturn in 2008, the U.S. cement industry continued to use a number of the wet-process plants, but today these are no longer operational. The following discussion focuses on the production of cement and enhancements that have occurred over time.

The first step in manufacturing cement is to mine and process the raw materials necessary. The single largest need is for calcium, which is predominately obtained from limestone (calcium carbonate). As a result, cement plants are often located near an abundant source of limestone. Silica and alumina are most often provided by natural materials such as clay or shale, although to create the desired proportions of calcium, silica, alumina, and iron, other materials are often blended in including fly ash or iron blast-furnace slag. This basic process has not changed much over the decades, although more efficient mining equipment and crushers have been employed.

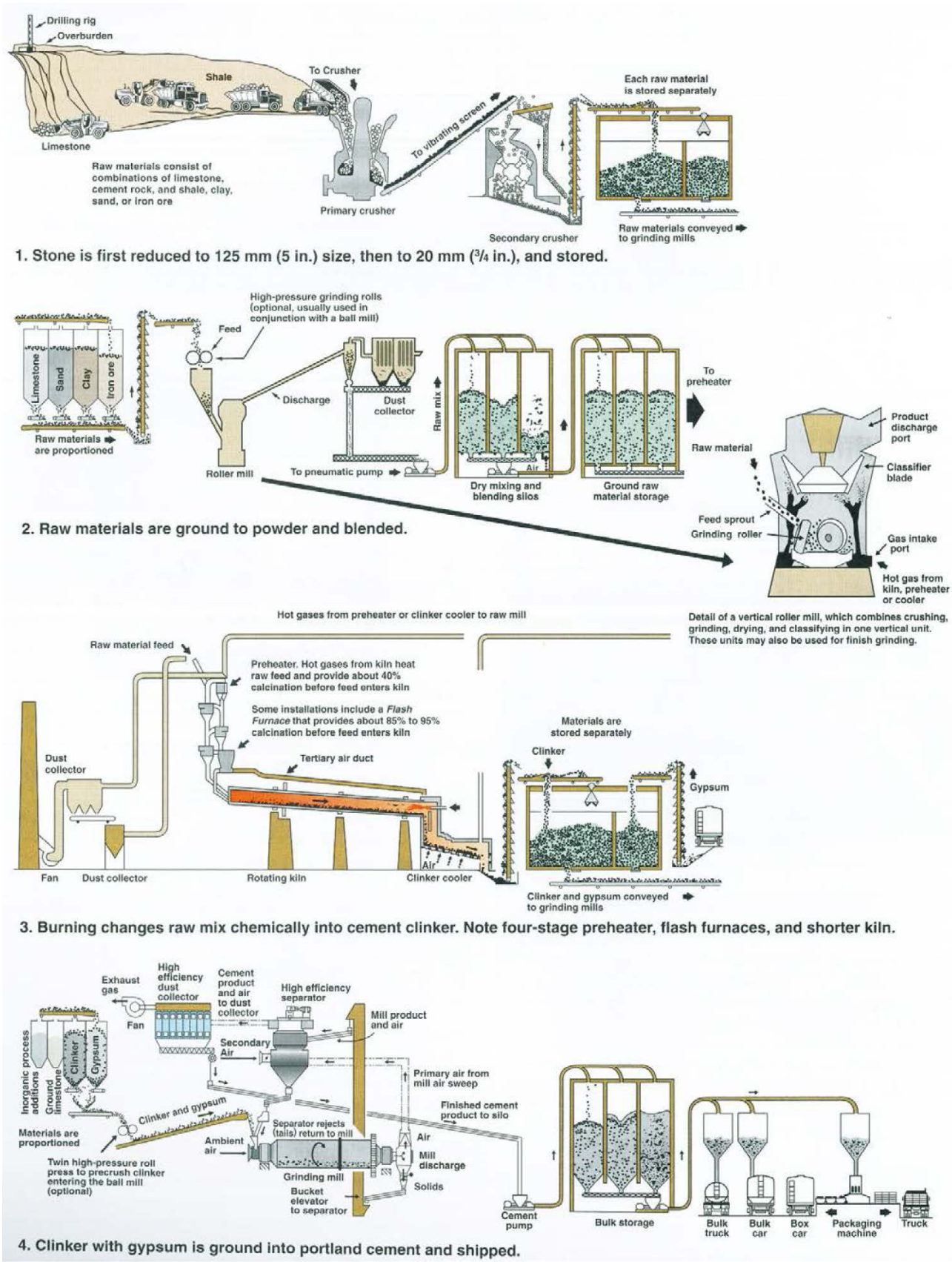

Figure 3-8. Steps in the modern dry-process manufacture of portland cement (Kosmatka and Wilson 2011).

As illustrated in figure 3-8, these mined raw materials are sized (crushed if needed) and stored, then finely ground prior to burning in a rotary kiln. Improvements in technology at this stage have resulted in significant increases in processing efficiency over the last few decades, with the biggest change occurring by moving from wet processing to dry processing. As the name implies, in wet processing water is used in a grinding mill to create slurry that is then fed into the rotary kiln. This requires a very long kiln, as the first stage in the burning process is to dry the slurried kiln feed, a process that is very energy (and therefore emissions) intensive. In older dry process facilities, grinding mills and air separators are used to create powder that is then fed into a shorter kiln. Although grinding energy is increased, the net energy savings relative to wet process technology is significant. In modern cement plants, as illustrated in figure 3-8, the older grinding mills and air separators are replaced with much more efficient roller mills that combine crushing, grinding, drying, and classifying into a single vertical unit.

Additional efficiencies have been incorporated into the burning process, most focusing on recirculating hot exhaust gases and using them to dry, heat, and initiate the calcination of raw materials before they enter the kiln. As shown in figure 3-8, hot gases from the kiln already begin the drying process in the vertical roller mills. The raw materials in a modern plant are then fed through a series of vertical heat exchange devices known as preheater cyclones and precalciner vessels. The most modern cement plants will have flash furnaces installed at which point 85 to 95 percent of the calcination occurs before the raw feed even enters the kiln (Kosmatka and Wilson 2011). Such cement plants have very short kilns, further improving efficiency.

In the kiln, the raw materials are heated until “clinkering” occurs in which the primary cement phases are formed. Upon cooling, the greyish black pellets that emerge are called clinker. As shown in figure 3-8, the cooled clinker is combined with calcium sulfate (gypsum), which is added to control the time of setting, and is then ground in a grinding mill. Many improvements in efficiency have occurred during this step as well, including the use of more efficient grinding mills, high efficiency separators, and high efficiency dust collection. After grinding, the grey powder is now “portland” cement, which will be stored for shipping in bulk or bagged form.

Today, portland cement sold in the U.S. under AASHTO M 85 almost always contains ingredients beyond ground clinker and gypsum. For one, the specification allows up to 5 percent limestone to be interground with the clinker, although the practical limit is somewhere around 3.5 percent in order to meet other specification requirements. Furthermore, up to 5 percent inorganic processing additions may also be added, the most common being slag cement. And finally, 1 percent organic processing addition may also be added. As these additions have a lower environmental impact (e.g., lower GHG emissions, embodied energy) than portland cement, the addition of each has the potential to lower the energy consumed and emissions generated to manufacture a unit mass of portland cement.

Innovations at cement plants continue to improve efficiency and thus lower energy consumption and emissions. Some plants rely on renewable energy to provide their electrical needs, including electricity produced by wind and solar. Additionally, coal is increasingly being replaced as a fuel, with some plants switching to natural gas or a combination of biomass fuel and waste fuels, such as worn-out tires, solvents, and waste oil (Kosmatka and Wilson 2011). Many plants also use highly efficient modes of transportation, shipping cement in bulk either by rail or barge. The main driver for most of these changes is economics, but regulatory changes and the need to be more “sustainable” has motivated the cement manufacturing industry to minimize waste and reduce emissions, with the overall effect being an increase in efficiency.

Nevertheless, increasing levels of efficiency do not reduce the CO_2 released in the calcination process, which as shown in table 3-4 is roughly 46 percent of all CO_2 released in the production of concrete (Choate 2003). As mentioned earlier, this CO_2 cannot be reduced through improved efficiency or renewable fuels. The only solution for reducing calcination CO_2 is to reduce the amount of portland cement clinker consumed over the life cycle of the pavement. A recent LCI on the manufacturing of portland cement in the U.S. is available (Marceau, Nisbet, and VanGeem 2007).

Supplementary Cementitious Materials

SCMs are materials that when blended with portland cement contribute to the properties of concrete through hydraulic or pozzolanic activity, or both (Kosmatka and Wilson 2011). Hydraulic activity occurs when the material chemically reacts with water, forming cementitious hydration products. Pozzolanic activity occurs in the presence of water when reactive siliceous or aluminosiliceous material reacts with calcium hydroxide (a reaction product from the hydration of portland cement) forming calcium silicate hydrate and other cementitious compounds. Calcium silicate hydrate is a more desirable hydration product than calcium hydroxide and the pozzolanic reaction is considered to have a positive impact on the long-term properties of the hardened concrete.

SCMs can be mixed into the cement by the cement manufacturer and sold as blended cement under AASHTO M 240 or added at the concrete plant by the concrete producer. SCMs that are commonly used in paving concrete include fly ash (specified under AASHTO M 295) and slag cement (specified under AASHTO M 302). Far less commonly used SCMs are natural pozzolans (also specified under AASHTO M 295) and possibly small amounts of silica fume (specified under AASHTO M 307).

Alternative Fuels for Cement Kilns

As part of their effort to reduce their GHG footprint, the cement industry continues to seek alternative fuels to burn in cement kilns as an alternative to the use of fossil fuels such as coal, petroleum coke (produced when asphalt is processed to make lighter products), and natural gas. The most common alternative fuel is derived from waste tires, which pound for pound have more fuel value than coal, and can also result in lower emissions (PCA 2011). Other waste-derived alternative fuels include paper, packaging, plastics, saw dust, and solvents that, because of the extremely high temperatures that exist in a cement kiln (well above 3000 °F [1650 °C]), burn quickly and with extreme efficiency (PCA 2011). This perspective is echoed by the Cement Kiln Recycling Coalition (CKRC 2013), which states that alternative fuels for cement kilns can be produced from paint solvents, discarded paints and coatings, inks and ink solvents, various resins and organic sludges, petroleum refining by-products, as well as scrap tires and many other materials. In 2010, over 68 percent of U.S. and Canadian cement plants reported using one or more waste fuels, providing 13 percent of the energy demand at cement plants (PCA 2011).

The sustainability benefits of using these types of alternative fuels are great as materials that would otherwise need to be treated as hazardous waste are handled and used in a safe and beneficial manner. This reduces the need for landfills for hazardous waste as well as the amount of fossil fuel consumed in cement production, thus conserving fossil fuel and reducing GHG emissions. In addition to waste-derived alternative fuels, considerable interest exists to utilize biofuels in cement production. In one investigation, the main biofuel used was sorghum, which was complemented by maize (varieties of corn that don't go to seed), perl millet, switchgrass and oat hulls (Norris 2011). The investigation showed enough promise that it was thought that biofuels could be used to completely replace coal by 2020. In another investigation, a cement plant has employed a novel approach to use the carbon dioxide-rich exhaust gases from the cement kiln to accelerate the growth of algae, which in turn is dewatered and burned as fuel in the kiln (Tree Hugger 2013).

Table 3-5 summarizes properties of these common SCMs, noting that calcined clay, shale, and metakaolin are classified as natural pozzolans. Tables 3-6 and 3-7 summarize how each SCM impacts the behavior of fresh and hardened concrete, respectively. Brief descriptions of some of the primary SCMs are provided in the following sections.

Table 3-5. Chemical composition and select properties of common SCMs (Taylor et al. 2006; Kosmatka, Kerkoff, and Panarese 2002).

Component	Type I Cement	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume	Metakaolin
Silica (SiO_2),%	22.00	52.00	35.00	35.00	90.00	53.00
Alumina (AI_2O_2),%	5.00	23.00	18.00	12.00	0.40	43.00
Iron oxide (Fe_2O_2)%	3.50	11.00	6.00	1.00	0.40	0.50
Calcium oxide (CaO),%	65.00	5.00	21.00	40.00	1.60	0.10
Sulfate (SO_4),%	1.00	0.80	4.10	9.00	0.40	0.10
Sodium oxide (Na_2O),%	0.20	1.00	5.80	0.30	0.50	0.05
Potassium oxide (K_2O),%	1.00	2.00	0.70	0.40	2.20	0.40
Total eq. alkali (as Na_20),%	0.77	2.20	6.30	0.60	1.90	0.30
Loss on ignition,%	0.20	2.80	0.50	1.00	3.00	0.70
Blaine fineness, m^2/kg	350.00	420.00	420.00	400.00	20,000.00	19,000.00
Relative density	3.15	2.38	2.65	2.94	2.40	2.50

Table 3-6. Effects of SCMs on the properties of fresh concrete (Taylor et al. 2006).

Property	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume	Calcined Shale	Calcined Clay	Metakaolin
Water Requirements	↓↓	↓↓	↓	↑↑	↔	↔	↑
Workability	↑	↑	↑	↓↓	↑	↑	↓
Bleeding and segregation	↓	↓	↕	↓↓	↔	↔	↓
Air Content	↓↓	↓	↓	↓↓	↔	↔	↓
Heat of Hydration	↓	↕	↓	↔	↓	↓	↓
Setting Time	↑	↕	↑	↔	↑	↑	↔
Finishability	↑	↑	↑	↔	↑	↑	↑
Pumpability	↑	↑	↑	↑	↑	↑	↑
Plastic Shrinkage Cracking	↔	↔	↔	↑	↔	↔	↔

Table 3-7. Effects of SCMs on the properties of hardened concrete (Taylor et al. 2006).

Property	Class F Fly Ash	Class C Fly Ash	Slag Cement	Silica Fume	Calcined Shale	Calcined Clay	Metakaolin
Early strength	↓	↔	↓		↓	↓	
Long-term strength	↑	↑	↑	↑↑	↑	↑	↑↑
Permeability	↓	↓	↓	↓↓	↓	↓	↓↓
Chloride ingress	↓	↓	↓	↓↓	↓	↓	↓↓
ASR	↓↓	↕	↓↓	↓	↓	↓	↓
Sulfate resistance	↑↑	↕	↑↑	↑	↑	↑	↑
Freezing and thawing	↔	↔	↔	↔	↔	↔	↔
Abrasion resistance	↔	↔	↔	↔	↔	↔	↔
Drying shrinkage	↔	↔	↔	↔	↔	↔	↔

Sources: Thomas and Wilson (2002); Kosmatka, Kerkoff, and Panarese (2002)

Key:
- ↓ reduced
- ↓↓ significantly reduced
- ↑ increased
- ↑↑ significantly increased
- ↔ no significant change
- ↕ effect varies

Fly ash is collected from the flue gases of coal-fired power plants. As pulverized coal is combusted, mineral impurities are carried away in the flue gases, solidifying into spherical glassy particles as they cool. These are collected by electrostatic precipitators or bag filters as particles roughly the same size as cement. In 2011, approximately 59 million tons (54 million mt) of fly ash were produced in the U.S., of which 38 percent was beneficially used with 13 million tons (12 million mt) used in concrete/concrete products or in blended cement/raw feed for clinker (ACAA 2013a). As shown in figure 3-9, this is a decrease in both peak fly ash production (which was approximately 78 million tons [71 million mt] in 2002) and utilization rate (approximately 45 percent in 2006) (ACAA 2013b). The main reason for the decrease in fly ash production and utilization was the economic slowdown in the U.S. beginning in 2006. Other pressures exist that may reduce fly ash availability in the future, including increased reliance on natural gas instead of coal for electrical production as well as increasing environmental pressures to reduce emissions from power plants.

Fly ash varies in composition and mineralogy as a result of the source of coal, how it is burned, and how the ash cools. Under AASHTO M 295, it is classified as either a Class C fly ash or a Class F fly ash. A summary of how the different fly ashes behave in concrete, based on tables 3-6 and 3-7, is as follows:

- As seen in table 3-5, in general, Class C fly ash has higher calcium oxide content than Class F fly ash and thus has both hydraulic cementitious and pozzolanic characteristics; Class F fly ash, on the other hand, has less calcium oxide and is therefore more pozzolanic.

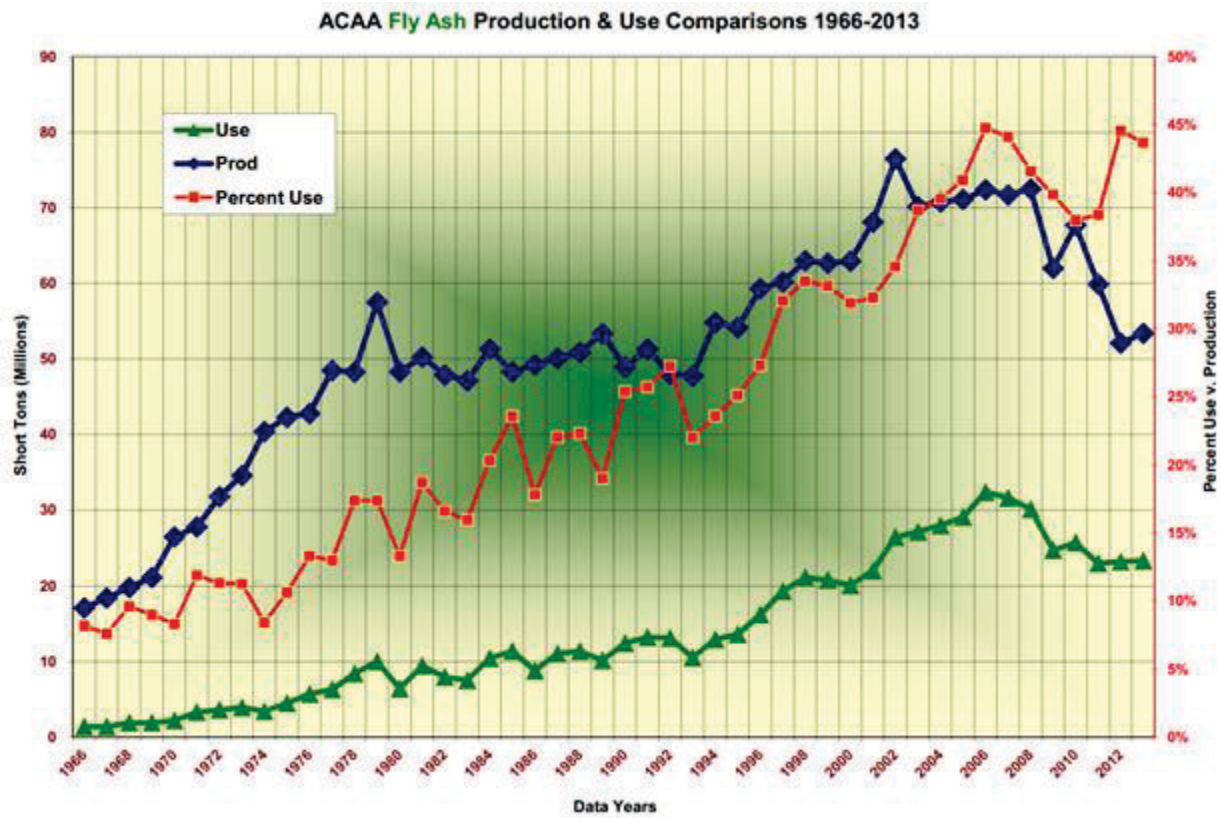

Figure 3-9. U.S. fly ash production, use (U.S. short tons), and utilization rate from 1966 to 2013 (ACAA 2013b). (Note: 1 short ton = 0.907 metric ton)

- Class C fly ash is typically dosed at 15 to 40 percent by mass of the total cementitious materials used whereas Class F fly ash is typically dosed at 15 to 25 percent for pavement applications (Taylor et al. 2006).
- The spherical nature of the fly ash particles improves the workability and cohesiveness of concrete paving mixtures while reducing water demand. Furthermore, the lower density of fly ash versus portland cement means that for a given mass there is more volume in the paste. This improves cohesiveness and workability and also reduces bleeding.
- The presence of fly ash can negatively impact the ability to entrain air in the concrete, primarily due to carbon impurities that may be present. The limits on loss on ignition is an attempt to control the amount of carbon. A newly released NCHRP study provides methods to evaluate a given fly ash's impact on air entrainment (Sutter, Hooton, and Schlorholtz 2013).
- Class C fly ash may affect early setting and the heat of hydration whereas Class F fly ash almost always delays setting while reducing the heat of hydration. In concrete made with Class F fly ash, the delay in setting and early strength gain increase with increasing dosage and may impact the constructability of the pavement, especially in cooler weather.
- Early strength gain is rarely affected by Class C fly ash but almost always slowed when Class F fly ash is used. On the other hand, all fly ash tends to improve long-term strength and reduce permeability (which increases durability).

- The pozzolanic reaction helps mitigate ASR and sulfate attack. Thus, in general, concrete made with Class F fly ash will have improved chemical durability over concrete made with pure portland cement or Class C fly ash. In some cases and in some dosages, concrete containing Class C fly ash can actually have poorer durability than would be incurred in concrete made with a pure portland cement.

As an industrial co-product or waste material, the composition, reactivity, and properties of fly ash are highly variable. This variability can be extreme for fly ashes from different sources, but is also true for fly ash produced at the same electrical plant because coal sources, burning techniques, and environmental technologies are changing rapidly. As a result, rigorous testing of fly ash must be conducted on a frequent basis to ensure its continued suitability for use in concrete. NCHRP Report 749 provides guidance on the testing of fly ash for highway structures (Sutter, Hooton, and Schlorholtz 2013).

Slag cement is an industrial co-product from iron blast furnaces in which pig iron is extracted from iron ore. The remaining molten material (slag) is directed into a granulator that quenches the material using water to form glassy, sand-like particles. These are then ground to similar size, or slightly finer, than portland cement. Although the chemical composition is identical to that of air-cooled blast furnace slag, the rapid cooling through quenching does not allow chemically stable crystalline minerals to form. Instead, the amorphous oxides of calcium, aluminum, magnesium, and iron (the typical composition is shown in table 3-5) are reactive, either slowly in the presence of water alone or more vigorously when activated in water in the presence of sodium hydroxide or calcium hydroxide. The latter is the condition present in the pore solution of hydrating portland cement, and thus the two react in a complementary manner.

Co-Product Treatment for SCMs

There is debate on how to allocate environmental impacts for high value SCMs, such as fly ash and slag cement. In the past these materials were considered wastes from industrial processes (coal-powered electricity generating fly ash, and steel production generating blast furnace slag). The current practice in the U.S. is to consider fly ash a waste material diverted from a landfill for beneficial use, meaning that none of the environmental impact associated with electricity generation is typically assigned to the fly ash. As long as the cost of transport and processing of the fly ash is the only source of economic value, a waste classification is appropriate. However, once the fly ash has value beyond this, it should no longer be considered waste, but instead a co-product. Already in some markets fly ashes are in high demand and economically valuable, meaning they are no longer waste flows. In these cases, it is appropriate to allocate some of the environmental burden associated with coal-fired power plants to fly ash. The most common means to accomplish this is through economic worth of the co-products. LCAs in some regions (e.g., Europe) show that the economic worth of fly ash compared to electricity generation is small and hence the assigned environmental impacts are also small. The same practices can be applied to slag cement as a co-product in steel production. It is noted that different allocation methods can lead to differences in assigned environmental impacts. There are also other motivations for industries to seek classification as waste or co-product. For example, in Europe fly ash producers often do not want classification as "waste" because that requires a much more difficult regulatory environment for handling, storing, and transporting the material. Chen et al. (2010) considered different allocation methods for slag cement and fly ash used in Europe, arguing that demand for these products outpaced production and thus their designation as a waste may not be appropriate. Allocation based on economic value as compared to allocation by mass leads to significantly lower environmental flows attributable to both SCMs, and seems to better reflect the purpose of the industries that produce the SCMs – production of steel or electricity.

As shown in figure 3-10, slag cement use dropped with the economic downturn beginning in 2007. The Slag Cement Association (SCA) reported an 11 percent drop in 2009, although there was an even greater drop in the use of portland cement suggesting that slag cement was gaining popularity even as portland cement use fell. Overall trends appear to show some increases in slag production as the economy improves, but a long-term trend of decreased availability due to the closure of a number of U.S. blast furnaces and a lack of construction of new furnaces is expected. As of 2011, there were only four granulators installed at active blast furnaces in the U.S. (USGS 2013a).

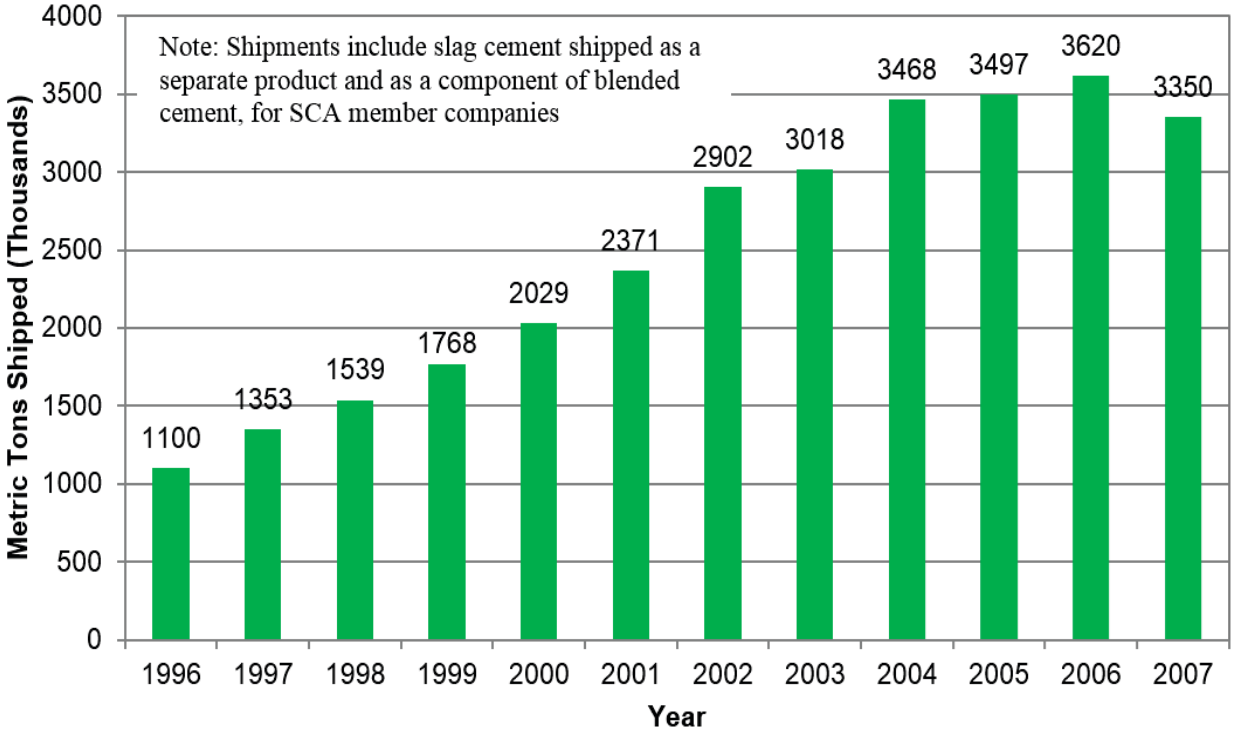

Figure 3-10. U.S. slag cement shipments from 1996 to 2007 (adapted from SCA 2007).

Slag cement is an attractive SCM for a number of reasons. For one, the typical dosage of slag cement is usually in the range of 25 to 35 percent of the total cementitious materials for paving concrete, although it can be used in even higher amounts (ACPA 2003). Furthermore, slag cement creates very light colored concrete that some find aesthetically pleasing and has a high albedo that may help reduce the urban heat island effect where this is important (this is discussed in chapter 6). Some additional commentary on slag cement and paving concrete constructed with it include:

- Although slag cement particles are angular, it has a lower specific gravity than portland cement, meaning that a greater volume of slag cement is used to replace the same mass of portland cement; this results in reduced water demand and improved workability.
- Slag cement can reduce air entraining efficiency so this must be carefully controlled.
- Slag cement can reduce the heat of hydration, which can be effectively used to reduce built-in curl and cracking if the specific concrete heat of hydration is measured. On the other hand, the lower heat of hydration can result in increased setting times, particularly

during cold weather placements. A rule of thumb is that the set time is delayed 30 minutes for every 10 percent slag cement replacement of portland cement (ACPA 2003).

- Early strength gain is generally retarded when slag cement is used, but the long-term strength is increased.
- Permeability and chloride ion ingress are reduced when slag cement is used, and slag cement can be used to effectively mitigate ASR and sulfate attack.

As an industrial co-product material, slag cement will vary from source to source, but variability within a given source is usually very low. Often the properties of the slag cement are altered slightly depending on the fineness of the grind, with more finely ground slag cement being more reactive. An LCI for slag cement has been published (Prusinski, Marceau, VanGeem 2004).

Other SCMs, including silica fume and natural pozzolans, are rarely used in concrete paving. Silica fume, an ultrafine non-crystalline silica co-product of the production of silicon metals and ferrosilicon alloys, is a highly reactive pozzolan often used in high-performance and ultra-high-performance concrete (UHPC). It is difficult to work with and is significantly higher in cost than portland cement and thus its use is often restricted to applications such as bridge decks that demand high strengths and a highly impervious matrix.

Natural pozzolans represent a family of SCMs produced from natural mineral deposits or biomass. Some of these minerals, such as volcanic ash, are similar to what were used in ancient Rome to construct the Pantheon and aqueducts and can be used with only minimal processing, whereas others require calcination through heat treatment. More recently, there have been efforts to derive commercially viable natural pozzolans from biomass such as rice husks, but this effort has not yet been commercially successful in the U.S., primarily because of difficulties in controlling burning processes to produce consistently high quality pozzolans. Abundant supplies of natural pozzolans are available in many parts of the world where volcanic activity is common, including parts of Europe, Central America, and Africa. In the U.S., interest in natural pozzolans is increasing due to some rising uncertainty regarding the supplies of fly ash and slag cement.

Blended Cements

Blended cement is produced and sold by cement manufacturers that intergrind or blend portland cement with fly ash, natural pozzolans, slag cement, limestone, or a combination. The blended cement can be a binary system, made with portland cement and one other material, or a ternary combination of portland cement and two other materials as specified under AASHTO M 240, *Standard Specification for Blended Hydraulic Cements*. These materials are classified as follows:

- Type IP(X) – The “P” indicates that this is portland-pozzolan cement in which “X” denotes the targeted percentage of pozzolan expressed as a whole number by mass of the final blended cement. Thus, a Type IP(20) is a blended portland-pozzolan cement that contains 20 percent pozzolan. The range of X allowed is up to 40 percent by mass of the blended cement.
- Type IS(X) – The “S” indicates that this is portland-slag cement in which “X” denotes the targeted percentage of slag cement expressed as a whole number by mass of the final blended cement. Thus, a Type IS(35) is blended portland-slag cement that contains 35 percent slag cement. The range of X allowed is up to 95 percent by mass of the blended cement.

- Type IL(X) – The "L" indicates that this is portland-limestone cement in which "X" denotes the targeted percentage of limestone expressed as a whole number by mass of the final blended cement. The limestone can constitute up to 15 percent by mass of the blended cement.
- Type IT(AX)(BY) – The "T" indicates that this is ternary blended cement in which the "A" refers to the type of pozzolan, slag, or limestone (either "P" for pozzolan, "S" for slag cement, or "L" for limestone) that is present in the larger amount by mass and the "B" refers to the additional material, either "P" for pozzolan, "S" for slag cement, or "L" for limestone that is present in the lesser amount. The "X" and "Y" refer to targeted percentage of mass for constituent "A" and "B" respectively. For example, a material designated as Type IT(S25)(P15) contains 60 percent portland cement, 25 percent slag cement, and 15 percent pozzolan. Two different pozzolans can also be blended together to create a Type IT(PX)(PY).

Typical portland cement replacement rates for blended cements are 10 to 12 percent for Type IL, 15 to 25 percent for Type IP, and 30 to 50 percent for Type IS (based on Van Dam and Smith 2011). The composition of a Type IT can vary significantly depending on the characteristics of the specific SCMs.

In addition to the above designations, blended cements can be further labeled with the following suffixes:

- "A" to indicate air-entrained material.
- "MS" or "HS" to indicate moderate or high sulfate resistance.
- "MH" or "LH" to indicate moderate or low heat of hydration.
- "R" to indicate resistance to alkali-silica reactivity (note this was added in 2014).

The most recent addition to AASHTO M 240 is the Type IL portland-limestone cements that were added in 2012. This followed the allowance of intergrinding portland cement clinker with up to 5 percent limestone that has been allowed in AASHTO M 85 since 2007. Portland-limestone cements have been used in Europe for over 25 years (with the most popular type of cement used in Europe containing up to 20 percent limestone), and Canada approved the use of portland-limestone cements containing up to 15 percent limestone in 2009. In the latter case, the 15 percent limit is in place to ensure the portland-limestone cement performs similarly to conventional portland cement and blended cements. At that replacement level, it is estimated that the use of a portland-limestone cement reduces CO_2 emissions by up to 10 percent compared to conventional portland cement (CAC 2009).

Although it is more common in the U.S. for the concrete supplier to blend portland cement with SCMs at the concrete plant, when the pozzolan, slag cement, or limestone are interground or blended by the cement supplier under AASHTO M 240 there is a greater level of quality assurance over the final product with less potential for unforeseen interactions and incompatibilities (Taylor et al. 2006). In addition, the use of AASHTO M 240 blended cements helps to avoid the potential for proportioning mistakes that can occur in the field. One drawback, however, is the use of a blended cement limits the concrete supplier's ability to adjust the SCM content in response to changing conditions (e.g., cooler weather).

Although all of these blended cements have been extensively evaluated in the laboratory, and early performance has also been assessed, continued monitoring and assessment of their long-term performance and characteristics for consideration in pavement design is needed.

Aggregates in Hydraulic Cement Concrete

Aggregates have been discussed earlier in this chapter, including the environmental impacts of mining and processing them for use in pavements. This section addresses attributes of aggregates as they have a direct impact on the sustainability of hydraulic cement paving concrete. These attributes include aggregate grading, durability, and the use of RCWMs.

Aggregate coefficient of thermal expansion (CTE) is an important property that is defined as the change in unit length per degree of temperature change. Since coarse aggregate makes up the bulk of the volume of concrete, the CTE of the coarse aggregate is the most influential factor in the CTE of the concrete. Aggregates with very high CTE require special consideration when used in concrete paving mixtures, particularly in climates with large diurnal and seasonal temperature changes. High CTE in concrete results in greater curling of the concrete under a thermal gradient, when the top and bottom of the slab are at different temperatures. This results in the development of higher tensile stresses that increase the potential for cracking in both jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP), and provides an increased potential for faulting and roughness in jointed designs that must be handled in the pavement structural design and construction specifications. AASHTO T 336 is the recommended test method for CTE of the concrete mixture (FHWA 2011). Greater discussion of the effects of concrete CTE is included in chapter 4.

Aggregate grading is an important step in establishing concrete mixture proportions as it has a profound effect on the amount of cementitious material needed to obtain the desired fresh and hardened properties for paving concrete. There are multiple approaches used to establish mixture proportions to achieve the proper balance of workability, strength, volumetric stability, and durability in the most cost effective and environmentally benign manner possible. Trade-offs often exist when attempting to optimize any one or two of these criteria at the expense of another. For example, reductions in the water-cementitious materials ratio (*w/cm*) generally decreases paste permeability and increases paste density, thereby increasing both strength and durability; however, workability will likely suffer if other adjustments are not made at the same time (e.g., changes in aggregate gradation or particle shape or the inclusion of chemical or mineral admixtures).

A properly proportioned concrete paving mixture will often have an "optimized" aggregate grading (sometimes referred to as a well-graded mixture), in which multiple aggregate particle sizes are represented. This allows for a reduction in cementitious material content (making good use of fly ash, slag cement, and limestone replacement of portland cement) while achieving the required fresh (workability, finishability, and so on) and hardened (strength and durability) properties. Aggregate grading optimization has many different forms and there is not a single method that must be followed to achieve it. Pioneering work by Shilstone (1990), modified by others, provides good guidance but other approaches exist that work equally well. At its core, aggregate optimization is an empirical exercise that not only is affected by the aggregate particle sizes, but also the particle shape, texture, and specific gravities. When done correctly, aggregate grading optimization maximizes the aggregate volume through careful consideration of the particle size distribution. Today it is common to find highly workable, strong, and durable concrete paving mixtures with total cementitious materials contents of 540 lbs/yd^3 (320 kg/m^3) or less, resulting in both economic and environmental savings compared to previous practices.

Aggregate durability has been discussed earlier in this chapter, but its importance to the overall durability of concrete and on the longevity of the pavement cannot be overemphasized. Fundamentally, durability reflects the ability of a material to maintain its integrity in the environment it serves, and a concrete pavement that fails prematurely due to poor durability is not considered sustainable. It is therefore critical that aggregates used in concrete meet all the requirements of AASHTO M 6, *Standard Specification for Fine Aggregate for Portland Cement Concrete* and M 80, *Standard Specification for Coarse Aggregate for Portland Cement Concrete*. In addition, the aggregate should meet the following durability requirements:

- Freeze-thaw durability – Certain coarse aggregates are susceptible to damage if subjected to cyclic freezing and thawing in a saturated state. Aggregates are most often tested for freeze-thaw durability using ASTM C666.
- ASR – ASR has affected countless pavements throughout the U.S. resulting in early loss of service life. The FHWA maintains a web-based ASR reference center (http://www.fhwa.dot.gov/pavement/concrete/asr.cfm) to provide the latest information on ASR to the pavement community and AASHTO recently published a provisional protocol PP65-11, *Standard Practice for Determining the Reactivity of Concrete Aggregates and Selecting Appropriate Measures for Preventing Deleterious Expansion in New Concrete Construction* that should be used to screen aggregates to be used in paving concrete. The use of SCMs such as Class F fly ash or slag cement are the most common mitigation strategies employed if susceptible aggregates are to be used.

As discussed previously under the aggregates section of this chapter, the use of RCWMs continues to increase for economic and environmental reasons. Specific issues regarding the use of RCWMs as aggregate in paving concrete are as follows:

- Recycled concrete aggregate – Specific caution needs to be exercised when using RCA as aggregate in new concrete. For one, it is most common to use only the coarse fraction of the RCA because the fine fraction has high water demand that affects workability and may have high chloride contents if deicers have been used. Furthermore, it is critical that the aggregate stockpile is watered prior to batching. There are several recent publications that provide excellent guidance on the use of RCA as aggregate in paving concrete (ACPA 2009; Van Dam et al. 2011).
- Reclaimed asphalt pavement – RAP is a commonly recycled material produced when an existing asphalt concrete pavement is cold milled as part of a pavement rehabilitation or reconstruction. The preferred higher use of RAP is in new asphalt concrete as it makes maximum use of the binder as well as the aggregate. In some markets, such as the Chicago area, there is a large surplus of coarse "fractionated" (material retained on larger sized sieves) RAP and it is being used as aggregate in new paving concrete by some entities such as the Illinois Tollway Authority. In these instances, care should be exercised to ensure the presence of the RAP will not negatively impact the fresh and hardened properties of the concrete.
- Air-cooled blast furnace slag – ACBFS continues to be used as a coarse aggregate in paving concrete. However, there are pavement design, concrete mixture, and construction considerations that must be followed in order for the material to be used most effectively in this application (Morian, Van Dam, and Perera 2012; Smith, Morian, and Van Dam 2012).

Water Sources

Water is used in the concrete production process not only in the preparation of the concrete mixtures, but also in the cleaning of trucks and equipment. Decisions regarding concrete mixing water must consider three criteria (Van Dam et al. 2012):

1. Quality (e.g., the water must be free of organic materials that may adversely affect strength and durability of the concrete);
2. Impact on the environment (e.g., depletion of local water resources, such as wells, streams and ponds, or energy required for potable water distribution systems and the infrastructure required for delivery of that water); and
3. Economic factors.

Technologies for using increasing amounts of "grey water" (that obtained from washing concrete production equipment and trucks) are rapidly becoming more common and accepted. Figure 3-11 presents a schematic for recycling concrete wash water into concrete mixture water, while table 3-8 presents typical limits on chlorides, solids, and other potentially harmful contaminants in recycled water. Table 3-9 shows some of the impacts the use of recycled water can have on concrete properties, with the primary concern being high solids content.

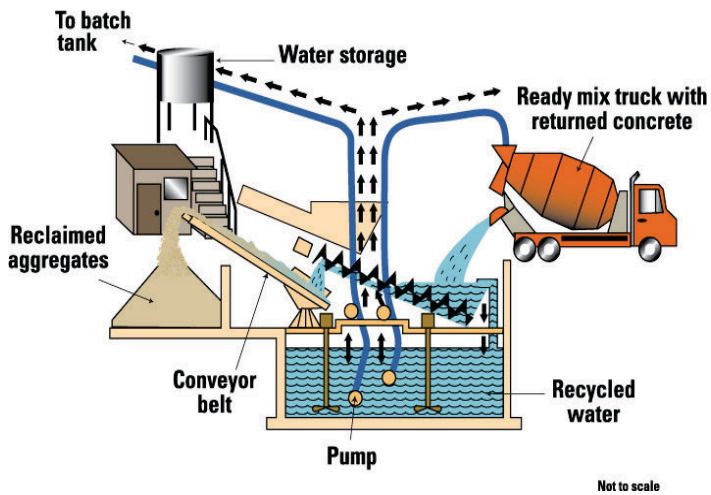

Figure 3-11. Schematic of mixer truck washout water recycling for concrete batch plant mix water (Taylor et al. 2006).

Table 3-8. Harmful contaminants, tests methods and limits for grey water to be used in concrete mixtures (Taylor et al. 2006).

Maximum Conc. In Combined Water	Limits, ppm	Test Method
Chloride as Cl^- Prestressed Other Reinforced Concrete	 500 1000	ASTM C 114
Sulfate as SO_4	3000	ASTM C 114
Alkalis as (Na_2O +0.658 K_2O)	600	ASTM C 114
Total Solids by Mass	50,000	ASTM C 1603

Table 3-9. Effect of recycled water on concrete properties (Taylor et al. 2006).

Recycled Water with	Water Demand	Setting Time	Compressive Strength	Permeability	Freeze-thaw Resistance
Solid contents within ASTM C94 limits ($\leq$ 8.9 kg/m^3 or $\leq$15 lb/yd^3)	↔	↔	↔	↔	↔
High solid contents (> 8.9 kg/m^3 or >15 lb/yd^3)	↑	↓	↓**	↑**	↔
High solid contents and treated with hydration stabilizing admixture	↔	↔	↔	no data	no data

Source: After Lobo and Mullings (2003)
* Compared to reference concrete with tap water.
** Strength and permeability effects were related to increased mixing water content.
Key: ↓ decreased
↑ increased
↔ no trend

Chemical Admixtures

Chemical admixtures are added during batching to modify the fresh or hardened properties of concrete. These modifications can enhance sustainability by improving the workability of the concrete, reducing water demand, and improving durability. Modern paving concrete makes extensive use of chemical admixtures with the most common admixtures listed in table 3-10. An excellent description of the various chemical admixtures can be found in Kosmatka and Wilson (2011). A summary of the three most common classes of chemical admixtures used in pavements follows.

Table 3-10. Common chemical admixtures used in paving concrete (Taylor et al. 2006).

Class	Function
Air-entraining admixture (AEA)	To stabilize microscopic bubbles in concrete, which can provide freeze-thaw resistance and improve resistance to deicer salt scaling.
Water-reducing admixture (WRA)	To reduce the water demand by 5 to 10 percent, while maintaining slump characteristics.
Mid-range water reducing admixture (MRWRA)	To reduce the water demand by 6 to 12 percent, while maintaining slump and avoiding retardation.
High-range water reducing admixture (HRWRA)	To reduce the water demand by 12 to 30 percent, while maintaining slump.
Retarder	To decrease the rate of hydration of cement.
Accelerator	To increase the rate of hydration of cement.

Air entraining admixtures (AEAs), specified in accordance with AASHTO M 154, are used almost universally in modern paving concrete to enhance the freeze-thaw durability of the hydrated paste, but they also improve the workability of the concrete and reduce water demand, mixture segregation, and bleeding (Taylor et al. 2006). AEAs form microscopic spherical bubbles that should remain stable as the concrete hardens. It is essential that the bubbles are uniformly spaced and sufficiently close to protect the paste from damage during freezing and thawing. Figure 3-12 shows the air voids in a polished concrete sample viewed through a stereomicroscope.

Traditionally, AEAs were predominately based on salts of wood resins (Vinsol® resin) but modern AEAs are often derived from varied natural and synthetic sources. Because the chemistry of the AEA and interactions with other mixture constituents can impact its effectiveness, it is important to test the concrete during laboratory mixture proportioning through construction using the job mix formula (Taylor et al. 2006).

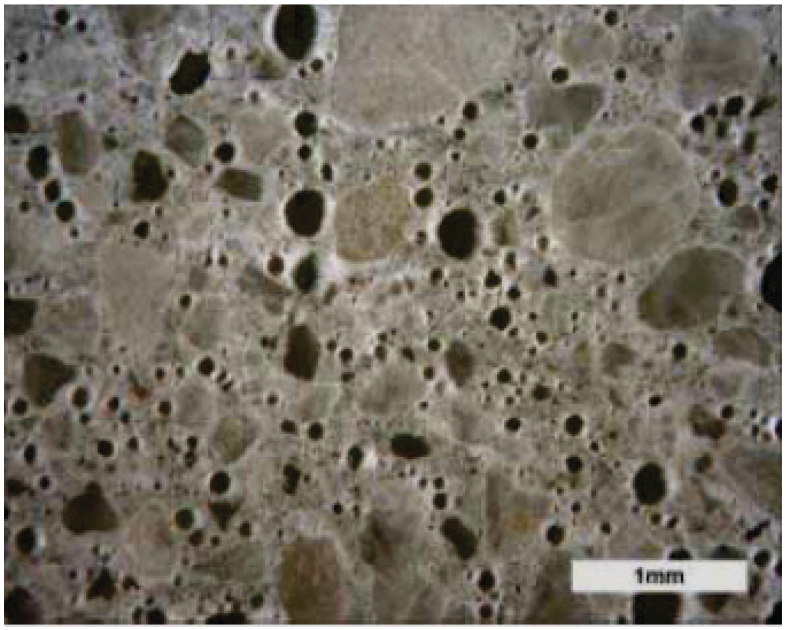

Figure 3-12. Polished slab of concrete viewed through stereomicroscope. Dark circles are entrained air voids distributed throughout the grey hydrated cement paste.

For the most part, testing of fresh concrete measures only the total air content in the concrete, but ideally what is desired is an indication of the size and distribution of those air voids in the concrete. The air-void analyzer (AVA) showed early promise in measuring the air-void system parameters in fresh concrete but it has not been found to be as effective when used with stiff, low slump paving concrete. Currently, the only way to ensure that the air-void system parameters meet the criteria for resistance to freeze-thaw damage is to cut and polish the hardened concrete and examine it with a stereomicroscope in accordance with ASTM C457. Automated methods based on digital image analysis are in use and being refined to make this process less onerous.

Water-reducing admixtures are divided into two classes, according to ASTM C494: water-reducing admixtures (WRA) and high-range water-reducing admixtures (HRWRA), although it is common to also include a mid-range water-reducing admixture (MRWRA) as previously listed in table 3-10. These admixtures function at the surface of the cement grains, causing grains to disperse and minimizing cement particle agglomeration. This makes the available water much more effective, and therefore reduces water demand.

For paving, it was very common in the past to use standard WRAs (based primarily on lignosulfonate chemistry) but this practice is slowly giving way to the increasing use of MRWRA based on the newer polycarboxylate chemistry. This chemistry is highly advantageous as it maintains its effectiveness for longer periods of time, but polycarboxylates are also known to entrain air and thus must be formulated for the application and tested for compatibility with the AEA to ensure that the entrained air-void system has the desired properties.

From a sustainability perspective, water-reducing admixtures have revolutionized concrete technology including concrete paving. A WRA will permit up to 12 percent water reduction while maintaining the desired level of workability (slump, cohesiveness, compactability, finishability). This allows for the mixing water to be reduced while holding the cementitious content constant, thus reducing the *w/cm*. All things equal, lowering the *w/cm* reduces the volume of pores in the hardened concrete, which in turn results in higher strength and lower permeability. Thus, water-reducing admixtures are considered an essential constituent in improving the sustainability of paving concrete as they increase concrete longevity, reduce water use, and allow for a reduction in cementitious materials.

Set-Modifying Admixtures are used to either accelerate (accelerators) or retard (retarders) the set time and early strength gain of concrete. Cement hydration is a chemical reaction that is sensitive to many factors, some of which are inherent in the mixture and others external to it. Externally, the biggest factor affecting set time is temperature, with cold temperatures slowing down the hydration process. To address this, accelerators are sometimes used during cold weather placements to “kick-start” the reactions so that the heat of hydration can be engaged to support continued reaction. This is especially true for high SCM mixtures that often have a lower heat of hydration. Accelerators are also often used in accelerated construction in which the pavement needs to be opened to traffic as soon as possible.

At the other extreme, higher temperatures may accelerate the hydration process, and the use of retarders may then be needed during hot weather conditions in an attempt to delay hydration. In addition, a long hauling distance may require that the concrete set be retarded to accommodate the time of transport.

In the long term, accelerated mixtures rarely achieve the same strength or as low a permeability as mixtures that were retarded. Thus, the need for early strength in some applications needs to be balanced against the potential for lower long-term strength and reduced durability over the life cycle.

Alternatively, proprietary non-portland cement-based systems are available that can achieve high-early strength and reportedly long-term performance, but these materials are more costly than portland cement-based systems and are often more difficult to work with. This restricts their use primarily to maintenance and rehabilitation applications. The environmental impacts of non-portland cements depend on the raw materials and processes used to produce them. For example, the GHG emissions from calcium sulfoaluminate (CSA) cement production can be

significantly lower than for portland cement. This is true even though the mining of the primary raw ingredient in CSA, bauxite, produces more GHG than does the raw materials extraction for portland cement, because the bauxite does not undergo calcination (Quillen 2007). Other emissions may be higher for CSA than portland cement.

The **environmental impact of admixtures** must consider the impacts incurred in the production and transportation of the admixture to the concrete plant site. In general, the amount of admixture used is quite small, usually on the order of less than 0.25 gal of liquid admixture per yd^3 (1.23 l per m^3) of concrete. As a result, it is common for the environmental impact of chemical admixtures to not be included in an LCA as the impact of such small dosages of these admixtures was found to be insignificant in previous LCA studies. However, there are some types of admixtures that are rarely used in paving concrete, such as HRWRA, that when added at a much higher dose may contribute significantly to the environmental impact of the concrete mixture. For example, at least one study on concrete bridge decks has shown that admixtures can contribute a non-negligible fraction of material production energy and emissions when heavily dosed (Keoleian et al. 2005).

Mixture Proportioning and Plant Production

For slipform paving concrete, the general approach to mixture design is to economically create relatively stiff concrete mixtures (slumps typically in a range of 0.5 to 1.5 inches [13 to 38 mm]) with good cohesiveness and finishability. The specified air content will vary with the type of exposure the pavement will have to freeze-thaw cycling and deicers, but generally will lie in a specified range between 5.0 and 7.5 percent. The concrete strength is often assessed based on flexural strength, most often measured in third-point loading in accordance with AASHTO T 97, and exhibiting typical values between 600 and 800 lb/in^2 (4.2 and 5.5 MPa) at 28 days. There are many other factors that can be considered, any of which contribute to the overall sustainability of the concrete. Detailed information on concrete mixture design and proportioning for pavements can be found in Taylor et al. (2006). Other plant-prepared concrete mixtures that might be used on a pavement project include roller compacted concrete (RCC), cement-stabilized or cement-treated bases, or pervious concrete. Regardless of the mixture type, a similar approach is used for proportioning and production.

Mixture proportions are selected prior to construction to meet the various mixture design objectives, which may include economy, workability, strength, durability, and sustainability. There are many approaches to establishing the required proportions, but all involve working in the laboratory with the anticipated concrete constituents and batching and testing mixtures until the desired mixture design objectives are met in the laboratory. It is then essential that the concrete is tested in the field prior to full-scale production to ensure that the laboratory-derived proportions can be produced under field conditions using the assigned concrete plant and will yield the desired fresh and hardened properties.

Batching is the process of measuring quantities of concrete mixture ingredients, based on the proportions developed previously, and then introducing them into the mixer. Central batching of the mixture must be executed under tight control because the consistency of the mixture from batch-to-batch and day-to-day significantly affects the workability and finishability of the fresh concrete as well as the hardened concrete properties (strength and durability). Batch-to-batch consistency is absolutely essential to creating a good performing concrete pavement as non-uniform concrete can lead to variable quality that can adversely affect initial ride quality, surface texture, and ultimately performance and life.

Once the concrete is batched into the mixer, it must be thoroughly mixed to a uniform consistency. Not only must the mixing process thoroughly combine the cementitious materials, aggregates, and water, it is also an essential step in creating the entrained air-void system that protects the concrete paste against freeze-thaw damage. Properly mixed concrete should have essentially the same fresh and hardened properties throughout the entire batch, allowing for variability in the testing itself. This can be evaluated using AASHTO M 157.

Most concrete used in paving projects will be produced by a stationary central mixer, whether a permanent plant or a portable plant erected on site. There are many different types of stationary concrete mixers, with a tilt rotating drum mixer being the most common for paving concrete although non-tilting type, reversing drum, or horizontal shaft mixers are also used. Quality concrete can only be produced in a well-maintained plant, and thus worn, damaged, or coated blades must be replaced, repaired, or corrected. For a given concrete plant, the three most important factors are:

- Batch Size – Mixers should not be loaded above their rated mixing capacities.
- Sequencing – Mixture constituents must be added in a given sequence that must not vary batch to batch. In general, some of the water is added first, followed by coarse aggregate, sand, and then the cementitious materials. Approximately 10 percent of the water is held back to be added after all other materials are in the mixer. Admixtures in particular must be added in the same sequence each time.
- Mixing Time – The time of mixing is critical as inadequate mixing will result in non-uniformity and over mixing can negatively impact the entrained air-void system. Many specifications require a minimum mixing time of 1 minute plus 15 seconds for every cubic yard of concrete unless performance testing is conducted that demonstrates uniformity in a shorter period of time.

Once concrete is mixed in a stationary mixer, it is deposited in non-agitating trucks or into truck mixers that operate at "agitating speed" of 2 to 6 rpm to maintain homogeneity (Kosmatka and Wilson 2011). Truck mixers can also be used to finish the mixing process that was begun in the stationary mixer (referred to as shrink-mixed concrete).

In some cases, typically for smaller projects, when high-early-strength materials are being used in maintenance or rehabilitation, or when exceptionally long transit times exist, concrete constituent materials are batched dry and mixed in truck mixers. Typically 70 to 100 revolutions of the drum or blades at mixing speed (12 to 18 rpm) are used to produce the uniformity required, after which the speed is reduce to 2 to 6 rpm (agitating speed) to maintain homogeneity in transit and during delivery (Kosmatka and Wilson 2011). Overmixing can have negative effects on the fresh and hardened concrete properties and thus AASHTO M 157 limits the number of drum revolutions to 300 after water is added to the dry constituents.

There are also specialized mobile volumetric mixers that batch concrete by volume and continuously mix it using an auger system (Kosmatka and Wilson 2011). These types of mixers are typically used for small batches or with rapid-setting proprietary materials during concrete pavement maintenance and rehabilitation.

Factors that impact the quality assurance of mixture production include material handling and stockpiling operations (especially the use of techniques that prevent aggregate segregation and

ensure consistent aggregate moisture conditions), the calibration and accuracy of batch scales and weigh hoppers, and ensuring adequate mixing time. It is particularly important that aggregate moisture contents be measured frequently and that mixture proportions are adjusted accordingly. In addition, mixer uniformity testing should be performed in accordance with ASTM C94 for each concrete plant/mixture combination to determine the minimum mixing time required to achieve uniform concrete. Taylor et al. (2006) and Kosmatka and Wilson (2011) provide excellent guidance on the required concrete plant operations necessary to produce consistent concrete for a paving operation.

Durability

A number of properties of the hardened concrete influence durability, including permeability, strength, air-void system characteristics, resistance to external chemical attack, and the physical and chemical stability of the aggregates. ACI 201.2R (ACI 2008) provides an excellent summary of physical and chemical mechanisms that can impact the durability of concrete and describes strategies to improve durability.

Sustainability dictates that the concrete used in paving be durable in the environment in which it serves. Concrete has a reputation as a long-lasting paving material, and there are many examples of concrete pavements remaining in service for 40 years or more (Tayabji and Lim 2006). As a result, it has become common practice for some highway agencies to design high-traffic-volume concrete pavements for services lives of 40 to 50 years. But for this practice to be sustainable, the concrete must possess the durability to withstand the environmental loading it will be subjected to over many decades of service. During laboratory mixture proportioning, testing must be conducted confirming that the proposed concrete mixture meets or exceeds the design requirements, and rigorous testing must be conducted during production to make sure that concrete as produced possesses the attributes to create a long-lasting concrete pavement.

The concrete design, proportioning, and production process must create a concrete paving mixture that economically meets all design strength, durability, and sustainability requirements over the pavement life cycle. Concrete with a low cementitious materials content (540 lbs/yd^3 [320 kg/m^3]), a high replacement of portland cement with high-quality SCMs (30 percent or greater), durable aggregates, a properly entrained air-void system, and a relatively low *w/cm* (based on mass, 0.40 to 0.45 is considered good for most applications) will have a relatively low GHG emissions footprint at production and is expected to have good long-term physical properties to provide excellent economic, environmental, and societal performance. However, there is no one "recipe" that will create "sustainable" paving concrete. Instead, the concrete technologist/producer needs to work within project constraints and the available materials to balance a number of discrete and competing variables to enhance sustainability moving forward.

Strategies for Improving Sustainability

Some general strategies for addressing the major issues described above are summarized in table 3-11, with greater elaboration provided below. Although some quantitative analysis of the net impacts of these practices to improve sustainability have been evaluated using LCA (particularly as relating to the use of SCMs to replace portland cement in concrete), more work needs to be done to consider the full materials production phase.

Table 3-11. Approaches for improving pavement sustainability with regard to concrete materials production.

Concrete Materials Objective	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Reduce Non-Renewable Energy Consumption and GHG Emissions in Cement Manufacturing	Improved cement plant efficiency through better energy harvesting and improved grinding	High capital cost but lower cost of manufacturing	Reduced energy consumption and GHG emissions	Less fuel consumed and emissions generated
	Utilization of renewable energy including wind and solar	High capital cost but lower cost of manufacturing	Reduced non-renewable energy consumption and GHG emissions	Less non-renewable fuel consumed and GHG generated
	Utilization of more efficient fossil fuels	Lowers manufacturing costs	Reduces emissions per unit of energy used	Cleaner burning fuel
	Utilization of waste fuels	Lowers manufacturing costs	Beneficial use of waste material	Reduces materials in landfills
	Utilization of biofuels	Reduces cost to cost neutral	Reduces GHG emissions	Reduces dependency on fossil fuels
	Minimize clinker content in portland cement through allowable limestone additions and inorganic processing additions	Reduces cost to cost neutral	Reduces GHG emissions and consumption on fuel	Reduces dependency on fossil fuels and lowers emissions
	Increase production of blended cements containing limestone or SCMs	Reduces cost	Significant reduction in energy consumption and GHG emissions. Redirects RCWMs from landfill	Reduces dependency on fossil fuels and less material sent to landfill
Reduce Energy Consumption and Emission in Concrete Production	Increase concrete mixing plant efficiency and reduce emissions	Increased capital cost but decrease production costs	Reduced emissions	Reduced local emissions including noise and particulate
	Utilization of renewable energy	Cost neutral to increase cost	Reduced emissions	Reduced emissions
	Use electrical energy from the grid	Depends on proximity to grid – should save cost	Reduced emission, better emission controls	Reduced local emissions
	Use less cement in concrete mixtures without compromising performance	Reduce cost of concrete	Reduced emissions and energy	Longer lasting pavements – less delays
	Use more blended cements without compromising performance	No impact on cost	Reduced emissions and energy	Longer lasting pavements – less delays
	Increase addition rate of SCMs at concrete plant without compromising performance	Reduce cost of concrete	Reduced emissions and energy	Longer lasting pavements – less delays
Reduce Water Use in HCC Production	Recycle washout water	Cost neutral to slightly added cost	Use less water resources	Improved water quality
	Recycle water used to process aggregates	Cost neutral to slightly added cost	Use less water resources	Improved water quality
Increase Use of RCWMS and Marginal Materials as Aggregate in Concrete	Change specifications to allow greater amounts of RCWMs to be used in concrete without compromising performance	Reduced cost	Less landfill material, less transportation	
	Use RCWMs and marginal aggregates in lower-lift of two-lift pavement	Cost neutral to slightly added initial cost; potential for reduced life cycle costs	Less landfill material, less transportation	
Improve the Durability of Concrete	Lower *w/cm* through admixture use	Cost neutral to slightly added cost	Longer lasting pavements	Less delays over life cycle
	Utilize an effective QA program throughout material production phase	Slightly added initial cost – save cost on litigations	Longer lasting pavements	Less delays over life cycle

Strategy: Reduce Non-Renewable Energy Consumption and GHG Emissions in Cement Manufacturing

There are two major approaches to implementing this strategy: reduce consumption of non-renewable energy in the manufacturing process and reduce the clinker content of the cement that is shipped. Regarding the first approach, the main obstacle to implementation is the need to invest capital to improve existing cement plants or construct new ones. Retrofitting new technology on older plants is not always possible and it can take over a decade and $1 billion to permit and construct a new cement plant. Yet innovations can result in significant improvement to existing plants, including increasing the use of renewable energy (e.g., wind, solar) to generate electricity and switching to alternative fuels in the kiln (such as natural gas, waste fuels such as used tires and solvents, and increased use of biofuels). Nevertheless, the "low hanging fruit" regarding improvements to existing facilities have already been picked and future enhancements will take greater investment. The capital to invest in such improvements will remain tight until the world market for cement improves.

The second approach to this strategy is to focus on diluting the clinker content of the cement that is shipped from the plant. The largest contributor to GHG emissions is tied to calcination of calcium carbonate, an inherent process essential to the manufacturing of portland cement. From a cement manufacturer's perspective, major reductions in GHG emissions can only occur by reducing the clinker content in the cement sold, both by increasing the percent of limestone and inorganic processing aids in AASHTO M 85 portland cement and through increased production of AASHTO M 240 blended cements containing limestone or SCMs (i.e., Type IL, Type IP, Type IS, and Type IT). As manufactured products, the quality assurance on blended cements is higher than what occurs when SCMs are added to the concrete mixture at the plant. However, the trade-off is reduced flexibility during concrete production that may require capital investment by the concrete producer to add one or more additional cement silos. Furthermore, stable sources of high quality SCMs are uncertain, which may result in shortages in the future.

Strategy: Reduce Energy Consumption and Emissions in Concrete Production

The concrete production process is complex, but efficiencies can be realized at almost every step. To help evaluate the overall efficiency of concrete production, the National Ready Mix Concrete Association (NRMCA) offers a Sustainable Concrete Plant Certification[2] that provides a quantitative, performance-based metric for concrete suppliers to demonstrate excellence in sustainable development. This certification includes reduced energy consumption, particulate and GHG emissions, water use, and groundwater and surface water contamination.

The efficiencies of concrete plants continue to improve, resulting in economic, environmental, and societal savings. The utilization of renewable energy, whether produced on site or purchased off the grid, will result in reduced consumption of energy produced by fossil fuels and a reduction in emissions. If electricity is not produced on site using renewable means (e.g., wind, solar), the concrete plant should draw from the electrical power grid if at all possible because this is more efficient than producing power with on-site generators. On-site production of power is the least attractive alternative as it is not only inefficient, but can have major local impacts regarding emissions and noise generation.

Although the strategies cited to reduce energy consumption in concrete production also reduce GHG emissions, additional strategies can be employed to further reduce GHG emissions

[2] http://www.nrmca.org/sustainability/Certification/PlantCertification.asp

associated with the production of concrete. These are centered on using less portland cement clinker per cubic yard of concrete, which can be accomplished through the following means:

- Use an optimized aggregate gradation. This is commonly the most effective way to reduce the required total cementitious materials content, but often requires one or more additional aggregate bins be added to a concrete plant that was originally set up to handle only coarse and fine aggregate. The concrete properly produced with an optimized gradation will have good uniformity, resist segregation, be readily consolidated and finished, and have excellent strength, shrinkage, and permeability characteristics.
- Use blended cements. Blended cements provide a means to significantly reduce GHG emissions by reducing the content of GHG-intensive portland cement used in the mixture. However, the use of blended cements will require concrete suppliers to have at least three cement silos: one for portland cement, one for blended cement, and one for an SCM. In this scenario, many suppliers would have to add an additional silo that would represent a significant capital investment.
- Increase the addition rate of SCMs at the concrete plant. SCMs added at the concrete plant can be used in lieu of blended cement or can be used in addition to a blended cement in a complementary fashion. There is a practical limitation to how much total replacement of portland cement with SCMs can be used, and depends on the required early strength, type of SCM, and ambient climatic conditions, among other factors. The importance of good mixture proportioning and testing, as well as good quality assurance during production, cannot be overemphasized; otherwise, pavement performance may be compromised.

Strategy: Reduce Water Use in HCC Production

Water is used in the production of concrete to support the chemical reactions that cause cement to harden and gain strength. A typical concrete made with 564 lbs of cement per yd^3 (335 kg of cement per m^3) of concrete and a *w/cm* of 0.50 will require 282 lbs of water per yd^3 (167 kg of water per m^3) of concrete. Through good mixture proportioning and the use of water-reducing admixtures, the cement content could easily be reduced to 520 lbs/yd^3 (308 kg/ m^3) and the *w/cm* could be reduced to 0.42, saving 64 lbs of water per yd^3 (38 kg of water per m^3) of concrete. Not only is water saved, but the GHG emissions are also reduced through the reduced quantities of cement.

Water consumption can also be reduced by recycling water used to process aggregates, including the water used for aggregate washing and for maintaining aggregate moisture, and in washing out trucks and equipment as illustrated previously in figure 3-11. This requires capital investment and space to establish an area to recycle water.

Strategy: Increase Use of RCWMs and Marginal Materials as Aggregate in Concrete

Of all the various strategies, this one requires the greatest care during mixture proportioning and production to ensure pavement performance is not compromised. RCA and ACBFS have both been successfully used as coarse aggregates in concrete pavement, yet both have also resulted in some notable failures. One problem is that concrete made with RCWM coarse aggregates often exhibits hardened properties that differ from concrete made with virgin aggregates and these differences may not be accounted for in the structural design of the pavement. Another potential issue is that RCA and ACBFS coarse aggregate must be kept wet when stockpiled prior to

batching due to their high absorptivity. If batched dry, they will absorb a significant amount of the mixing water, which not only negatively affects workability but can also lead to early cracking. Guidance on using RCWMs as aggregates in paving concrete is available from several sources (e.g., ACPA 2009; Van Dam et al. 2011; Smith, Morian, and Van Dam 2012).

The use of "marginal" aggregates is something that is becoming a necessity as sources of good quality aggregates become exhausted. Many factors can make an aggregate marginal, including issues with cleanliness, freeze-thaw durability, wear resistance, or susceptibility to ASR, among other items. The key to the effective utilization of marginal aggregates is to understand what properties of the aggregate are in question and then implementing strategies to address those limitations, primarily through consideration of these properties in design. For example, if it is a matter of cleanliness, washing the aggregates may be all that is needed. If freeze-thaw durability is an issue and it is related to the size of the aggregate (larger sized aggregate particles are more susceptible to freeze-thaw damage, all other things equal), then the aggregate can be crushed more thoroughly to a smaller size and then blended with a larger-sized stone that possesses the required freeze-thaw durability. Aggregates that are susceptible to ASR can be used if an effective mitigation strategy is employed, such as the use of an appropriate SCM. Wear resistance can be addressed by using susceptible aggregates in lower depths within the concrete slab through the use of two-lift construction. In fact, two-lift construction is a very effective design that can be used to accommodate increasing levels of RCWMs in the lower lift and thus reduce the overall environmental impact of the pavement.

Overall, the success in using marginal aggregates depends on having the knowledge to mitigate the weakness in the aggregate and then employing the appropriate mitigation strategy is employed during production.

Strategy: Improve the Durability of Concrete

There are many examples around the U.S. where concrete roads built in the early 1900s are still in service today, and other examples of concrete roads that carried traffic for 30 to 40 years with little need of maintenance. At the same time, there are also many examples of concrete roads that have suffered serious damage within a decade of construction due to durability issues such as freeze-thaw damage or ASR. For example, a current issue in several Midwestern States is joint deterioration that is the result of freeze-thaw damage, apparently amplified by the use of liquid brine deicing agents (Taylor 2011). Since durability is not an intrinsic property of concrete, but instead reflects the concrete's ability to resist the environment in which it serves, there is no way to directly measure it. ACI 201.2R (ACI 2008) provides a good description of mechanisms that can affect concrete durability and how durability can be enhanced. In general, depending on the environment, durable concrete possesses the following characteristics:

- A relatively low *w/cm*, typically in a range of 0.40 to 0.45. This will reduce the permeability and increase the strength of the hardened concrete.
- A high quality SCM in sufficient quantity to reduce permeability and increase long-term strength. An SCM can also be used to mitigate ASR and sulfate attack, but its ability to do so must be verified through testing.
- An effective air-void system comprised of closely spaced, spherical microscopic air bubbles. These are essential to relieve pressure generated as the water freezes in the concrete pores, and are particularly critical in freeze-thaw environments where deicing chemicals are used.

- Aggregates that are both physically and chemical stable, and will not degrade or crack under service conditions. If ASR susceptible aggregates must be used, mitigation strategies in accordance with AASHTO PP 65-11 should be employed to minimize the risk of damage.

Additional features may be needed to ensure durability for a given situation. It is essential that an effective QA program be rigorously adhered to throughout concrete production and construction.

Future Issues/Emerging Technologies

There are a number of issues and emerging technologies that have the potential to affect the production and use of concrete materials in the near future. These include:

- The EPA released an amended air toxics rule for portland cement manufacturing that significantly restricts emissions (especially of mercury which comes from both the burning of coal and calcination of the calcium carbonate) by U.S. cement plants by September 2015[3]. The impact of this new rule is uncertain, but it is clear that it will result in lowering the environmental impact of cement production. Switching to alternative fuel sources can address some of the issues related to mercury released during coal combustion, but mercury released during calcination of the calcium carbonate will result in increased capital cost for some cement plants to install mercury capture equipment and the likely closing of others where it is not economically viable.
- If fly ash becomes scarce, the market share of slag cement would be expected to increase. As U.S. slag production is expected to remain relatively constant, the long-term growth in the supply of slag cement is likely to hinge on imports, either of ground or unground material (USGS 2013b). The environmental impact of

Portland Limestone Cements (PLC)

One way to reduce the environmental footprint of cementitious binders is through the use of AASHTO M240 (ASTM C595) Type IL portland-limestone cements, which allows up to 15 percent limestone to be interground with portland cement clinker. The 15 percent limit is in place to ensure the PLC performs similarly to conventional portland cement and blended cements. At this replacement level, it is estimated that the use of portland-limestone cement reduces CO_2 emissions by up to 10 percent compared to conventional portland cement (CAC 2009).

Although the major motivation to use Type IL cement is to reduce CO_2 emissions, there are other advantages. Limestone is softer than clinker and thus when the two are interground the limestone particles are finer than the clinker particles resulting in improved particle packing. The fine limestone particles act as dispersed nucleation sites for the formation of hydration products that result in a dense microstructure as hydration proceeds. And finally, the limestone reacts with the aluminate phases present in portland cement and many SCMs to create carboaluminate phases (Matschei, Lothenbach, and Glasser 2007). Further advantages can be achieved when an SCM (e.g., fly ash, slag cement) is combined with a Type IL cement. Thus, in an AASHTO M240 Type IT blended ternary cement, cement manufacturers can optimize the chemical and physical properties of the portland cement, limestone, and the SCM to achieve equivalent or even improved performance to that obtained using conventional portland cement. Several North American field studies have demonstrated that Type IL cements can be used similarly to AASHTO M85 and other M240 cements in the construction of concrete pavements (Thomas et al. 2010; Van Dam, Smartz, and Laker 2010). It is cautioned that long-term pavement performance data are not yet available for concrete pavements made with Type IL cements.

[3] http://www.epa.gov/airquality/cement/pdfs/20121220_port_cement_fin_fs.pdf

importation will be closely linked to the mode of transportation, with transport by barge/ship having significantly lower impact than by truck (see table 3-1).

- One innovation is the high-volume SCM/portland limestone cement mixtures that are becoming more common. As state highway agencies accept this technology, it has the potential to significantly lower the GHG emissions associated with paving concrete.
- Photocatalytic cement is another innovation that potentially offers an opportunity to create a highly reflective surface that remains clean while treating air pollution through a photocatalytic reaction involving nanoparticles of titanium dioxide (TiO2). The reactions result in a chemical reduction of nitrous oxides (NOx), which prevents the formation of ozone and associated smog. In addition to this pollution-reducing quality, these cements are often very lightly colored and have very high albedo (reflectance) properties, which can result in a lowering of pavement and near surface temperatures (see chapter 6) while providing an aesthetically pleasing appearance due to their self-cleaning properties. The environmental benefits of photocatalytic cements have been documented in laboratories and on paving projects throughout Europe (Guerrini et al. 2012; Beeldens 2012), where more than 2.4 million yd2 (2 million m^2) of photocatalytic surfaces have been constructed, with horizontal surface applications like pavements (including both paving block and single-lift concrete pavement) comprising about half of that total. Reductions in NO_x have been reported to be as high as 60 percent, depending upon local environmental conditions and the technique for dispersing the TiO_2 in the concrete (Beeldens 2012). Pavement uses of photocatalytic cements in the U.S. have included paving blocks, porous concrete, and slurry-infiltrated asphalt pavement (Guerrini et al. 2012). One acclaimed project is the reconstruction of Cermak Road in Chicago, where pervious pavers with a photocatalytic surface have been employed (Oberman 2013). An effort to implement this technology featuring its use in the top layer of a two-lift concrete pavement project constructed on Route 141 near St. Louis, Missouri in 2010 was not as successful as hoped, demonstrating the need for continued research on this technology to determine the best avenue for implementation.
- Low carbon and carbon sequestering cementitious systems are emerging including geopolymers (Van Dam 2010) and alkali-activated fly ash (Hicks, Cheng, and Duffy 2010). Work continues on a number of other cementitious systems that have the potential to actually sequester carbon dioxide as they harden, lowering the carbon footprint of concrete mixtures. However, at the current time none of these systems is currently viewed as economically viable for large-scale adoption.

Other Concrete Mixtures

The preceding discussion focused almost exclusively on paving grade concrete, which is most often placed with a slipform paver or in fixed-form construction. Other types of plant-mixed concrete used in pavement applications include:

- Roller-compacted concrete (RCC) – RCC consists of the same basic ingredients as conventional paving grade concrete and obtains the same basic strength properties, but is a much stiffer mixture that is placed and compacted similar to asphalt concrete. The biggest difference is in the mixture proportions, in which RCC has a higher percentage of fine aggregate allowing tight packing and consolidation. For pavements, RCC has traditionally been used for industrial and heavy-duty parking and storage applications, but

lately it is seeing more use for streets and highway shoulders. Detailed information on RCC for pavement applications is available from Harrington et al. (2010).

- Lean concrete and cement-treated base (CTB) course – There are multiple variations of cement-stabilized and cement-treated base courses consisting of aggregate, cement (also made with SCMs), and water. They can be made in a concrete plant or mixed on grade. A lean concrete base is, as the name implies, similar to a traditional concrete but has less total cementitious materials content (typically between 200 and 350 lbs/yd^3 [99 and 174 kg/m^3]) and develops 28-day compressive strengths between 750 and 1500 lbf/in^2 (5.2 and 10.3 MPa). If still less cementitious materials are used, the material is referred to as cement-treated, which typically achieves a 28-day compressive strength of just around 750 lbf/in^2 (5.2 MPa) (Smith and Hall 2001). CTBs can be made to be permeable, allowing infiltrating water to flow through the base to the drainage system.
- Pervious concrete – Pervious concrete pavements have a high degree of porosity allowing precipitation to flow through the voids in the concrete surface, helping to recharge groundwater while reducing stormwater runoff. Pervious concrete mixtures are carefully controlled, containing little to no sand that results in the inherent porosity (15 to 25 percent) needed to allow moisture flow through the material. Some pervious concrete mixtures being used have much smaller maximum aggregates sizes, but have similar permeability to that of "traditional" pervious concrete mixtures. Pervious concrete is most often used in parking areas, shoulders, or for low-volume roads. Information on pervious concrete can be found in a recent FHWA Tech Brief (Smith and Krstulovich 2012).

Other Materials

This section briefly reviews the manufacture of other common materials used in pavements, including steel, soil stabilizers and geosynthetic materials. Sources of environmental impact are identified in the acquisition, manufacturing, and transport of these materials to the site. Topics include energy and emissions generated.

Steel

Most concrete pavements constructed today are either JPCP or CRCP. JPCP is the most common type, and are built without steel reinforcement in the central portions of the slab, but may contain embedded steel in the form of smooth, round dowel bars at the transverse joints or deformed tie bars at the longitudinal joints. CRCP designs are constructed by several highway agencies, often in high-volume urban corridors. These designs contain a significant amount of continuous longitudinal steel, perhaps up to 100 to 120 tons (90.7 to 108.8 mt) per lane-mile (Tayabji, Smith, and Van Dam 2010).

Traditional steel manufacturing is a high environmental impact activity, involving the extraction of iron ore, limestone, and coal; making of coke; smelting the ore to create pig iron in a blast furnace; and then making steel through alloying with carbon and other elements in a steel furnace. Improvements in technology have increased the efficiency of the process, but there are still unavoidable impacts from the production system, which requires high temperatures and thus combustion of fuels, and the release of additional CO_2 emissions as the limestone undergoes calcination during the reduction of iron ore to pig iron. Secondary (recycled) steel production in electric arc furnaces has fewer environmental impacts; this is important because structural steel

is estimated to have a recycled content of greater than 90 percent, and much of the reinforcing steel used in the U.S. is recycled (AISC 2013).

Reinforcing Fibers

It is becoming more common for fibers to be used in concrete in certain pavement applications (most notably thin overlays) to overcome the quasi-brittle nature of concrete and its relative weakness in tension/flexure. Common fibers are composed of various materials including organic matter (i.e., cellulose), polymers (i.e., polypropylene, polyester, nylon), glass, and steel. The ability to modify the behavior of concrete is heavily influenced by the fiber material, shape, and volume fraction. In general, low-strength, low-modulus fibers such as polypropylene microfibers added in low volume show some ability to reduce plastic shrinkage cracking in concrete but little ability to affect the mechanical properties of hardened concrete. On the other hand, the use of high-strength, high-modulus fibers at relatively high volumes significantly increases the modulus of rupture, fracture toughness, and impact resistance of the hardened concrete.

The addition of fibers to concrete changes its workability, and as the fiber stiffness, length, thickness, and volume fraction increase, so do difficulties in placing and finishing. The trade-off is to find a fiber type (material and size) and volume that provides the desired enhancement to the concrete's mechanical properties without compromising workability beyond the point where the pavement cannot be placed and finished. Today, synthetic macrofibers (1.5 to 2 inches [38 to 51 mm] long with an aspect ratio of 75) are filling this niche for pavement applications, typically being composed of high-strength, high-modulus polymers and dosed at a rate between 3 to 7.5 lbs/yd^3 (1.8 to 4.5 kg/m^3).

The sustainability benefits derived from fiber reinforcement can be ascertained by considering the environmental impact of fiber production and balancing it with anticipated improvements in pavement performance or reductions in slab thickness. As with many additives, the mass of fibers added to concrete is relatively small (around 0.1 percent by mass) and thus the impact is likely below the cutoff for consideration in an LCA. Nevertheless, this should be demonstrated by considering the manufacturing process for the particular fiber under consideration and the anticipated dosage.

Interlocking Concrete Pavers

Interlocking concrete pavers are precast concrete manufactured in central plants. They can be used to create both impermeable and permeable pavements, typically where vehicles are traveling at lower speeds. Permeable pavers have laying patterns that create gaps between them that are filled with permeable aggregate that allows water to pass through the surface (Smith 2011). Concrete grid pavements consist of larger units with surface openings typically filled with soil and grass (ICPI 2013). Interlocking concrete pavers can be manufactured with two layers of concrete where the top layer is made with photocatalytic cement. Pavers are often used in urban areas for traffic calming and aesthetics, and their easy removal and reinstatement provides ready utility access. Pavers have also been used extensively in port areas carrying extremely heavy wheel loads.

Sustainability issues for the production of pavers are similar to those for other concrete materials, since they share many of the same mixture ingredients and processes. But they provide aesthetic appeal, are readily repairable, can be used to create permeable surfaces, and can be highly reflective, all features that give them strong applicability to urban markets.

Geosynthetics

Geosynthetic materials take many forms that are used for a number of pavement applications, primarily with asphalt-surfaced structures. These include:

- Non-woven geotextiles or geosynthetic fabrics are used to reduce infiltration of fine and plastic soils particles from the subgrade into non-plastic base and subbase layers. This is particularly critical when the base or subbase layer is being used as a drainage layer, in which case the drainage pipes/trenches are often also wrapped in the fabric.
- Woven geotextiles and polymeric geogrids are used as reinforcement to improve the stiffness and shear strength of granular soils layers by providing confinement and bridging support near the bottom of the granular layer, particularly when placed over soft subgrades.
- A number of geosynthetic products, often different types paired in layers, have been used to retard the propagation of reflection cracking; applications include asphalt layers placed over existing cracked asphalt layers, asphalt layers placed over existing jointed concrete pavement, or asphalt layers placed over cement- or lime-stabilized soils or base layers that may have the possibility of shrinkage cracking.

Geosynthetics are primarily made of polymers derived from petroleum or fiberglass. Each has their own inherent environmental impacts that have not been assessed in the current literature, but can be roughly quantified by considering the mass of the materials. The additional environmental impacts of using geosynthetics should be considered relative to their contributions to extended pavement life.

The potential constraints on the future recycling of pavements that incorporate geosynthetic systems should also be considered. These constraints occur if the materials make it difficult for recycling machinery to operate (such as milling and pulverization equipment) or if the materials will interfere with mixing and other construction processes.

Soil Modifiers/Stabilizers

There are various materials that can be used to modify or stabilize soils to improve their behavior during and after pavement construction. These include some previously discussed materials such as:

- Portland cement – Portland cement can be used to stabilize both fine-grained plastic, non-plastic, and granular materials (see http://www.cement.org/pavements/pv_sc.asp). Depending on the application, the dose of portland cement can be relatively small (to improve the mechanical properties of a problem soil) to relatively high (for binding aggregates together to form a solid base). The environmental impact of portland cement stabilization largely rests with the amount of cement that is used in the application.

- Fly ash – Fly ash is a commonly used soil stabilizer. It can be used alone if the fly ash is "self-cementing," which is characteristic of many Class C fly ashes. Class F fly ashes are also used for soil stabilization if combined with a source of reactive calcium such as lime, cement kiln dust (CKD), lime kiln dust (LKD), or cement. When using fly ash for soil stabilization, care must be exercised to avoid swelling resulting from the expansion of sulfate minerals. Additional information on the use of fly ash for soil stabilization can be found at: http://www.fhwa.dot.gov/pavement/recycling/fach07.cfm

- Asphalt stabilizers – Asphalt can be used as a stabilizer of non-plastic granular materials. The most common asphalt stabilizers are emulsions or foamed asphalt, which are often used as part of a full-depth reclamation. Additional information on asphalt stabilizers is found at: http://ict.illinois.edu/publications/report%20files/FHWA-ICT-09-036.pdf

In addition to the materials listed above, lime is one of the most common soil modifiers/ stabilizers used in pavement construction (NLA 2013). Lime reduces the plasticity of highly plastic soils, making them more compactable and significantly reducing differential soil expansion under wetting and drying cycles, which can be critical to the functionality of the pavement. Where siliceous components are part of the soil chemistry, lime provides calcium and thus can also lead to pozzolanic reactions creating soil cementing in addition to soil modification. In soils that do not have a reactive form of silica present, lime can be combined with fly ash to achieve soil stabilization. More information on lime for stabilization can be found at: (http://www.lime.org/index/). Similar to lime, CKD and LKD can be used to treat plastic soils if they possess sufficient free lime to chemically react with siliceous components in the soil; they also have the added advantage of being waste products that have the potential for beneficial use.

Care must be taken in applying soil stabilizers that chemically react with the soil (e.g., portland cement, lime, fly ash, CKD, or LKD) to be certain that they will gain expected strength with a particular soil, and not produce undesirable unintended effects such as high levels of expansion due to unwanted chemical reactions. This is particularly true if lime stabilizers are being used and if sulfates are present in the soil (or if fly ash, CKD, or LKD are used that contain sulfates). It is therefore necessary to conduct a thorough laboratory investigation with the proposed stabilizing agent and actual soils from the project prior to using them in a full-scale field application.

The environmental impacts of portland cement, fly ash, and asphalt have already been discussed previously. Lime is produced by calcining limestone, and thus considerable CO_2 is liberated in the conversion of calcium carbonate to calcium oxide (quick lime) as well as from the burning of fuel. This must be considered when evaluating the benefits of stabilization through the use of lime. CKD and LKD are waste products, and therefore allocation is based on transporting the materials from the source (cement or lime kiln) to the project site. If the local market for CKD or LKD becomes such that they obtain economic value beyond the cost of transportation and disposal, they then need to be treated as a co-product.

Soil stabilization has the potential to substantially reduce the thickness of the pavement structure and to increase the life, both of which can reduce environmental impact. Moreover, they can be used to provide an effective working platform, greatly expediting the construction process and making it more efficient. Consideration of alternative pavement structures including those with soil stabilization should consider the life cycle to obtain an understanding of the trade-offs between materials production impacts and life increases or pavement structure reductions.

Major Issues

- Fibers may improve the mechanical properties of concrete such that the thickness of the pavement structure may be reduced or its life extended, but those benefits must be balanced with the increased difficulty in handling fresh concrete and increased environmental impacts and increased costs of using the fibers.

- Geosynthetics represents a broad range of products, most based on polymers derived from petroleum and fiberglass that can be used to reinforce soil, aggregates, and even asphalt surfaces. Again, the benefits of extended life should be considered in terms of their environmental impacts and costs.
- A number of different soil modifiers are available to improve a range of soil conditions. As with the other items, the benefits of reduced structural thicknesses or extended life must be balanced with the increased environmental impacts and costs.

Strategies for Improving Sustainability

- Fibers are being used as reinforcement to improve the mechanical properties of concrete used in thin bonded overlays. They can potentially reduce the thicknesses of the concrete slab by making the concrete more ductile and less susceptible to cracking.
  - Some fibers may be used to extend joint spacing without increasing the risk of cracking.
  - Some fibers can be used to reduce the risk of plastic shrinkage cracking.
  - Macrofibers of sufficient volume can reduce the amount of cracking and severity of cracking that does occur.
- Geosynthetics are often used to stabilize areas where conventional techniques fail, contributing to the pavement structure while expediting construction. They can potentially reduce the thicknesses needed for other pavement materials.
  - Geosynthetics can reinforce soil and unstabilized subbase and base materials.
  - Geosynthetics can be used to reinforce asphalt pavements.
  - Geosynthetics can be used to minimize or control the development of reflection cracking.
- Soil modifiers are typically based either on cementitious systems or asphalt and thus suffer many of the issues previously described.
  - Some soil stabilizers, such as lime, have a high carbon footprint due to calcination of the limestone.
  - Others stabilizers, such as fly ash, CKD, and LKD, are RCWMs and thus may have a low carbon footprint if locally available and if acceptable performance can be achieved.
- Potential issues and trade-offs.
  - There are various fibers on the market and it requires knowledge to select the proper fiber for a given application. At the high-volume fractions needed to modify the hardened properties of concrete, fibers will negatively impact mixture workability and potentially affect the environmental impact of the concrete.
  - Geosynthetics must be carefully designed and placed to be certain that they provide sufficient desired benefits (e.g., reflection crack control, longer life) for their cost (Koerner 2005).
  - Some soil modifiers/stabilizers derived from RCWMs can have chemistries that result in soil heaving, resulting in poor pavement performance.

  - Other modifiers, such as lime, are made by calcining limestone and thus have a high carbon footprint. Lime can also negatively interact with some soil types resulting in heaving.

Concluding Remarks

This chapter reviews the range of materials that can be used for paving applications, primarily including aggregates, asphalt materials, and cementitious materials. The way that each of these materials affects the overall sustainability of the pavement system is described, along with strategies that can be used to improve that sustainability. The scope of the chapter is from the extraction of materials to the point where materials begin final transportation to the construction site.

Some of the major issues regarding aggregate production and use are:

- Environmental and social implications of aggregate acquisition and transportation.
- Special concerns regarding aggregate processing.
- Implications of aggregate durability.
- The utilization and performance of RCWMs as aggregates.

Some of the major issues regarding asphalt materials used for pavement are:

- Continued increases in the price of petroleum, and thus asphalt, which is a finite resource.
- Appropriate use of polymer, rubber, and other types of binder modifiers.
- Depletion of high-quality aggregates needed for some type of mixtures.
- Specialization of mixtures for safety, noise, and structural considerations and their environmental and cost implications.
- Use of RAP and other RCWMs including asphalt shingles, recycled tire rubber, and sulfur.
- Environmental, social, and cost implications of mixture design and durability.
- Future binder availability and alternatives.
- Ensuring asphalt material durability.

A summary of some of the major issues confronting the acquisition and production of concrete materials used for paving are as follows:

- The relatively high non-renewable energy consumption and GHG emissions inherent in the portland cement manufacturing.
- The relatively high GHG emissions associated with the production of traditional portland cement, and its impact on portland cement concrete mixtures with high cement contents.
- Water use associated with concrete production.
- Reducing the amount of cement used in concrete mixtures through improved gradations and increased use of SCMs.
- Increasing the use of RCWMs as aggregates without compromising performance.
- Ensuring concrete durability.

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