Optimizing Recycling

Reclaimed Asphalt Pavement (RAP) in Building & Construction

A Collaboration between StopWaste and the Healthy Building Network

with support from the San Francisco Department of the Environment

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This briefing paper and an associated series of research papers on optimizing specific recycled feedstocks can be found at healthybuilding.net/content/research-and-reports.

The Healthy Building Network (HealthyBuilding.net**)** is a nonprofit organization that works to reduce the use of hazardous chemicals in building products as a means of improving human health and the environment. HBN performs independent, foundational research and product evaluations required to provide building products specifiers with unbiased, up-to-date information about chemical hazards, practical product evaluations and comparisons, and recommendations about the healthfulness of widely-used building products.

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About the Optimizing Recycling Series

The Optimizing Recycling Series of reports is a collaboration between the Healthy Building Network (HBN), a non-profit organization whose mission is to protect health in the built environment, and StopWaste, a public agency responsible for reducing the waste stream in Alameda County, CA, with support from the San Francisco Department of the Environment. The reports examine the hazards, supply chains, and economic impacts of recycled feedstock streams found in the building and construction sector.

The recycling industry has made significant strides toward the vision of a closed loop material system, whereby materials produced today become the raw materials for their products in the future. Contamination of feedstocks with chemicals of concern, however, can reduce feedstock value, impede growth of recycling rates and potentially endanger human and ecosystem health.

We describe the framework for our evaluation of reclaimed asphalt pavement and other feedstocks in our collaboration's overview report, Optimizing Recycling: Criteria for Comparing and Improving Recycled Feedstocks in Building Products. It describes how best practices for monitoring and improving the purity of recycled feedstocks in building materials can improve feedstock value, protect human health and dramatically increase recycling rates in North America.

This report on reclaimed asphalt pavement examines ways to optimize recycled content feedstocks commonly used in building materials. The most common conditions of post-consumer feedstocks, as consumed in California, establish the baseline for assessments found in this report.

The views expressed in this evaluation are those of the authors and do not necessarily reflect the position or policy of StopWaste or donors to HBN. The reports are available on Healthy Building Network's website, http://healthybuilding.net/content/optimize-recycling.

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Executive Summary

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OVERALL: Asphalt is a major contributor to greenhouse gas emissions. It is responsible for one-tenth of such emissions from infrastructure projects. Reclaimed asphalt pavement (RAP, also called recycled asphalt pavement) can be used in road surfacing as a nearly one-to-one replacement of similar virgin material. It can reduce associated greenhouse gas emissions by 75 percent. However, during service life the composition of asphalt pavement changes. It can be contaminated by passing traffic and by treatments and paint applied to the surface. Binder wears off. These changes, along with the use of chemical additives to rejuvenate old pavement, can impact human and environmental health and product performance of pavement that incorporates reclaimed asphalt pavement (RAP). Current industry practices do not adequately consider these issues. However, many efforts are underway to increase transparency about what is in asphalt pavement, improve mix designs for recyclability, and develop bio-based, non-toxic additives that aid blending RAP into mixes.

SUITABLE APPLICATIONS: Recycled asphalt pavement (and recycled asphalt shingles) are suitable for use in roads, parking lots and driveways provided they have been tested to ensure they do not contain toxic chemicals above established thresholds of concern.

UNSUITABLE USES: If the composition of RAP is not tested for contaminants, it should not be used in residential areas. Toxic substances like coal tar sealants can contaminate indoor air and other common areas through emissions and dust.

PATHWAYS FOR OPTIMIZATION: Design first-run mixes with the second generation of asphalt — ideally cold-in-place recycling — in mind. Screen for polycyclic aromatic hydrocarbons (PAHs) and contaminants like lead. Disclose additives used in RAP processing, and use non-toxic, bio-based green chemistry additives that can increase the use of RAP in warm and cold mix central plants and, most preferably, cold-in-place recycling operations.

Introduction

Asphalt (also known as asphalt concrete, bitumen, or road tar) is the most common paving material by far, accounting for a 92 percent share of the 2.5 million miles of roads and highways in the United States. Portland cement concrete roads are a distant second.[1] Asphalt is also a major contributor to greenhouse gas emissions, accounting for about 10 percent of all emissions from construction materials.[2] Reclaiming and reusing asphalt has many benefits, including waste prevention, reduction of greenhouse gas emissions, and lower lifecycle impacts compared to virgin asphalt material use.

The standard formula to make asphalt pavement is to blend about five percent asphalt cement and 95 percent aggregates in a hot mix at a central plant, then to deliver the asphalt to a job site where it is installed.[3] Asphalt cement binds the mixture and forms a protective coating over the load-bearing aggregates.[4]

Reclaimed asphalt pavement (RAP, also called recycled asphalt pavement) is the standard term for removed and/or reprocessed pavement materials.[5] By weight, asphalt pavement is the most recycled material in the United States.[6] In 2014, more than 71.9 million tons of RAP "were used in new pavements in the United States," per the National Asphalt Pavement Association (NAPA).[7]

At low percentages, the RAP acts primarily to displace aggregate in the mix, but at greater percentages it can replace some of the binder. Most often, pavement is reclaimed during road rehabilitation projects that replace the top one or two inches of asphalt with a new surface layer. The milled reclaimed asphalt pavement is trucked to a central hot mix asphalt (HMA) plant for blending into mixes with other aggregates and virgin asphalt binder to make new pavement.[8] Other processes for incorporating RAP into new pavement are gaining market shares, such as warm mix asphalt (WMA) and cold-in-place, both of which can significantly reduce asphalt production's life cycle and human health impacts. Cold-in-place recycling can reduce carbon dioxide (CO_2) emissions by as much as 95 percent per lane mile (see Table 1- Energy Use and Emissions per lane mile on page 12) and save a lot of money — as much as 40 percent compared to conventional techniques.[9]

This report explores the condition of reclaimed asphalt pavement materials as delivered for reuse in new pavement, and the barriers to and opportunities for increasing its reuse as an alternative to virgin asphalt production. This report follows the established format of our Optimizing Recycling series. It evaluates reclaimed asphalt pavement against a set of four criteria. The criteria gauge:

- Impacts on human health and the environment;
- Supply chain controls and transparency;
- The availability of "green jobs;" and
- Opportunities to expand use of the feedstock.

Each criterion is judged on a three-part scale with green indicating "very good," yellow indicating "room for improvement," and red indicating "significant concerns." The review is focused on California's Bay Area wherever possible, and on California more generally. The analysis of health and environmental impacts and supply chain controls is broadly applicable throughout the United States.

Behind the Ratings

FEEDSTOCK HEALTH AND ENVIRONMENTAL HAZARDS

During service life, the composition of asphalt pavement changes. Some asphalt wears off into the surrounding environment. Sealers or preventative maintenance mixtures add new substances to the pavement, as do oils and fluids leaked from passing traffic.[10]

"In the US the qualities of RAP are generally assumed to be identical to that of virgin raw materials and thus no additional testing of Hot Mix Asphalt (HMA) mixtures that contain RAP is required," notes Greenroads International, a non-profit organization that rates and registers sustainable transportation projects. However, Greenroads says, "in both gradation and asphalt quality RAP is different than virgin aggregate and asphalt."[11]

These differences translate into varying impacts on workers and the environment, into which there has been little research. "For bound applications such as hot-in-place and cold-in-place recycling, research into the difference in emissions to that of virgin materials have not been conducted," notes the Recycled Materials Resource Center.[12] Physical differences between reclaimed and virgin pavement also impact how subsequent blends perform over time.

In this section, we explore potential health and environmental impacts. These impacts have many variables including the types of aggregate and binder used in the original mix, sealers and other maintenance additives used during service, pollutants deposited onto pavement, the agents used to rejuvenate RAP, and the temperatures at which RAP is mixed into new pavement.

Common Components of Asphalt Pavement

Asphalt pavement, also known as asphalt concrete, is formed from a mixture of coarse and fine aggregates (typically about 95 percent, combined) and asphalt binder (about five percent). Asphalt coats the aggregate and solidifies as it cools.

Asphalt Binder

Asphalt, or bitumen, is a mixture of long chained hydrocarbons, which are residues from crude oil after lighter fractions (like gasoline) are refined away.[13] Petroleum refining in the United States has enough capacity to produce up to 48 million tons of asphalt per year.[14] Road paving consumes an estimated 35 million tons per year of asphalt, [15] which is about 87 percent of the asphalt generated in the US. Another 11 percent goes into roofing shingles and built-up roofing.[16]

Asphalt binder contains varying proportions of polycyclic aromatic hydrocarbons (PAHs), other chemicals, and heavy metals. Variations run batch to batch, depending upon the source of the crude oil, which is a globally traded resource.[17] PAH concentrations in paving asphalt are typically in the 1.9-66 parts per million range.[18] (For comparison, the US Environmental Protection Agency [EPA] limits PAH in drinking water to 0.2 parts per *billion*.[19]) Most PAHs in asphalt are persistent and bioaccumulative toxicants, carcinogens, and suspected endocrine disruptors.[20]

Much is unknown about the composition of asphalt, despite widespread occupational exposures to PAHs and other substances of concern. OSHA estimates that "over a half-million workers are exposed to fumes from asphalt… Health effects from exposure to asphalt fumes include headache, skin rash, sensitization, fatigue, reduced appetite, throat and eye irritation, cough, and skin cancer." [21] Numerous studies suggest a correlation between asphalt and tar and lung cancer.[22] However, OSHA has not established occupational exposure limits for asphalt fumes from mixing and paving operations.[23] The International Agency for Research on Cancer (IARC, an agency of the World Health Organization) classifies straight-run asphalt used in the paving industry as a Category 2B carcinogen, meaning that occupational exposure to these substances and their emissions may cause cancer. It notes that the "variable physicochemical properties of individual constituents of bitumen mean that the composition and physical form of the emissions from heated bitumens are dependent on the temperature to which the bitumen is heated." This variability challenges efforts to study and assess airborne exposures.[24]

Crumb Rubber Modifiers

Crumb rubber — ground up used tires — is an increasingly common modifier for asphalt binder. In the Bay Area, the

Metropolitan Transportation Commission recently found that rubberized asphalt was more durable than traditional hot mix asphalt.[25] At least 25 Bay Area cities have taken advantage of CalTrans' Rubberized Tire Grant Program, which encourages the diversion of tires from landfills into pavement.[26]

About 2,000 tires can be mixed into a lane mile of asphalt. About 12 million tires are incorporated in asphalt pavement each year, the EPA says, which is enough to feed 6,000 miles of rubberized asphalt.[27]

Concentrations of PAHs in tire crumb can reach as high as 1 percent (that is, 10,000 parts per million) by weight.[28] CalRecycle warns, "Exposure to carcinogenic polycyclic aromatic hydrocarbons (PAH) has been identified for the crumb rubber workers."[29] The addition of crumb rubber to asphalt blends therefore increases the PAH levels in asphalt mixes. When heated in hot asphalt mixes, recycled tires may release volatile organic compounds and particulates.[30]

Tires can also pick up lead content during their use, from fallen wheel balancing weights and from lead oxide pigments used in highway paint striping.[31]

The Healthy Building Network examined the issue of crumb rubber in its 2013 report, *Avoiding Contaminants in Tire-Derived Flooring*. HBN noted that processors rarely screen tire crumb for toxic ingredients. The report recommended specific procedures that at least one manufacturer has since implemented. "Ecore, a major manufacturer of tire-derived flooring, says it has 'adopted and implemented the recommendations from the HBN study,'" reported BuildingGreen in 2016.[32]

Standard Aggregates

The nation's roadways – both asphalt pavement and concrete – consume a tremendous amount of rock. In 2015 alone, over 1.2 billion tons of crushed rock, sand, and gravel were consumed in road construction and maintenance. [33] These natural aggregates are used in road construction, from base to blacktop.[34]

Recycled Aggregates

Recycled materials like RAP can replace substantial amounts of newly mined aggregates (coarse materials such as gravel, sand, and crushed stone) in asphalt pavement. In California, the primary recycled aggregates are RAP, recycled asphalt shingles (RAS), and blast furnace slag.

Recycled Asphalt Shingles

Pavement is a down-cycled fate for most wastes, but asphalt shingles have found no alternative, higher-value use. Each year, roofing replacement and installation generates up to 12 million tons of asphalt shingle scrap.[35] Asphalt shingle scraps are mechanically processed before they are delivered to central asphalt mixing plants. Road construction consumes more than 10 percent of recycled asphalt shingles (RAS). The National Asphalt Pavement Association (NAPA) estimates that the amount of RAS in asphalt pavement and road base, nationwide, peaked at 2.5 million tons in 2010, and dropped to 1.7 million tons in 2014.[36]

The US EPA estimates that an asphalt pavement mixture containing 20 percent RAP and seven percent RAS will reduce life cycle greenhouse gas (GHG) emissions by over 28 percent compared to virgin asphalt. The agency reports, "The greatest GHG emission reductions come from the largest percentage inclusion of both reclaimed asphalt pavement and recycled shingles."[37]

On the other hand, asphalt shingles can introduce some challenges. Shingles on average are six times more heavily saturated with asphalt cement (and its associated PAHs) than pavement.[38]

Asbestos is another potential concern in recycled asphalt shingle scrap. In 2007, about 1.5 percent of 27,000 asphalt shingle samples collected across the country contained over one percent asbestos, mainly from related materials, such as mastic coatings.[39]

The federal government still allows the use of asbestos in roofing.[40] In 2011, an estimated 660 metric tons of asbestos were used in roofing products in the US;[41] by 2015, however, the amount of asbestos used in roofing fell to less than 35 tons.[42] Common asbestos-containing roofing products include base flashing, felt and tar or "Black Jack," a common term for the asbestos-bearing mastic that contaminates shingles.[43]

Blast Furnace Slag

Blast furnace slag from iron and steel mills — specifically, air-cooled blast furnace slag (ACBFS) — is widely used in hot mix asphalt.[44] Asphalt concrete consumes around one million tons of blast furnace slag per year.[45]

Crystalline silica, an occupational carcinogen if inhaled in dust form, is present in ACBFS at up to 2.5 percent by weight.[46] This is a potential issue for workers in pavement milling operations who may be exposed to dust.[47]

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Processing Asphalt Shingles

Preventive Maintenance Treatments

Without maintenance, pavement wears down from many factors, including poor quality mixes, traffic abrasion, chemical reactivity, aging of the binder, and moisture.[48] It can wear down at rates as high as a ½-inch per year, mainly from the loss of mastic, or binder.[49] Surface treatments are applied to retard deterioration of pavement. They also become part of RAP.

Fog Seals

Most commonly, the industry uses fog seals to protect pavement. Typically, this is an emulsified asphalt spray. Emulsified asphalt fog seals are comprised of asphalt cement, broken down to micron-size particles, which are mixed with water and charged to keep the asphalt particles apart.[50] Charging agents may be cationic (positive-charge, based on amines) or anionic (negative-charge, based on fatty acids). Caltrans mostly uses cationic emulsified asphalt, based on amines.[51] These positively charged drops of asphalt attach to the negatively charged surfaces and break apart, water evaporates, and the surface is sealed.[52] Types of cationic emulsified asphalt vary considerably by application. Slow set emulsifiers use quaternary ammonium compounds (quats), which, according the National Institutes of Health, can cause the onset of asthma disease. Quats are also harmful to aquatic ecosystems and persist in the environment.[53] Rapid set emulsifiers are based on fatty diamine; in quickset, amidoamines; and, in microsurfacing, immidazolines, according to Caltrans. Some emulsified asphalt fog seals are modified by synthetic rubbers such as styrene-butadiene rubber. Many applications contain solvents (including the carcinogen, Stoddard solvent) and hydrochloric acid (a developmental and respiratory toxicant).[54]

Levels of PAHs in emulsified asphalt fog seals are comparable to those in asphalt binder, and far lower than those found in coal tar sealers.

Coal tar sealers are used in parking lots, residential driveways, playgrounds, airports, and recreational trails.[55] These types of sealers are rarely used in roads and highways.[56]


© USGS
Spraying Parking Lot with Coal Tar Sealer

The US Geological Survey (USGS) has raised grave concerns about PAH exposures to people living near parking lots or driveways sealed with coal tar.[57] Coal tar use in residential driveways appears to be ending, with just one retail line remaining on retail shelves in 2016.[58]

Coal tar sealers are still legal in California, even though two states (Minnesota and Washington), five counties, and many cities have banned their sale. The city of Austin banned the sealers after officials took thousands of samples of sealing products, pavement scrapings, and run-off and sediment adjacent to roads. They found that coal tar sealers contained seven percent PAH by weight, one hundred times more than the asphalt sealers. They also determined that run-off from pavement sealed with coal tar contained six times more PAH than run-off from asphalt sealed pavement, and sixty-five times more PAH than run-off from unsealed lots.[59]

Alternatives to coal tars include acrylic polymer sealers and gilsonite. Not much research has been conducted on these sealers' potential impacts on RAP's performance or on emissions during mixing. Gilsonite, a resinous hydrocarbon ore mined in Utah, "can double the service life of solid asphalt pavement," according a Texas study.[60]

Other preventative maintenance treatments provide longer term benefits than fog seals, which typically protect pavement for about one year. For example, chip seal (in which a sprayed bitumen emulsion is covered by a layer of fine aggregate) can provide up to six years of protection. The longest lasting treatments are hot-in-place asphalt overlays, which can extend pavement life by five to ten years but require more energy to produce.[61]

Green Codes Do No Allow Coal Tar Sealers

The International Green Construction Code, a model green code developed by the International Code Council, does not allow the use of coal tar sealants in places where they will be conveyed to soil, surface waters, or groundwaters.

Source: The 2015 International Green Construction Code, www.iccsafe.org

Contaminants from Service

Contamination during service life adds a variety of potentially toxic substances to RAP content. Over time, the pavement can become coated with road marker paint that often contains lead or chromium pigments. Cars spew out PAHs from exhaust that deposit onto the pavement. Engines and transmissions and gas tanks leak oils and fluids. Tires shed tread, and even lead weights. All of these toxic contaminants can become part of reclaimed asphalt pavement.[62]

A Swedish study found that leachates from field-tested asphalt contained "several times" more semi-volatile organic compounds (SVOCs) than those tested in a laboratory. The "dominant" SVOCs were naphthalene, butylated hydroxytoluene (BHT) and dibutyl phthalate (DBP), which the researchers said could come from "car exhausts, rubber tires and the asphalt material itself."[63]

In 1998, Dr. Tim Townsend of the University of Florida found evidence of lead leaching from asphalt pavement. "Lead was observed at the greatest concentrations in the oldest RAP samples," he reported. "This indicated that the lead was not a result of the aggregate or asphalt cement, but rather a result of vehicle traffic and emissions."[64]

More recently, students at Worcester Polytechnic Institute compared runoff from RAP and virgin asphalt, and found that that the recycled pavement had "higher concentrations of petroleum hydrocarbons and greater complexity than virgin asphalt." The most complex sample came from a high traffic road. The most polluted sample "had concentrations of hydrocarbons far beyond federal regulations," most significantly benzo[a]pyrene, which they linked to vehicle exhaust, fuels, and oil.[65]

Rejuvenating Additives

Binders in asphalt degrade and stiffen over time, causing brittleness and a loss of flexibility. To revitalize the binders in reclaimed pavement and shingles, processors add a rejuvenating agent, also called a recycling agent. An asphalt pavement recycler says that "without this key ingredient you will end up with a dry patch material that just won't bond."[66]

Asphalt paving producers select rejuvenating agents based on their compatibility with aged binders in the pavement debris. These typically have high aromatic content from hydrocarbons, mainly "soft asphalts" found in typical asphalt binders.[67] These compounds are distilled from petroleum refineries and can include asphalt flux oil, naphthenic (aromatic) oils, paraffinic oil, lube stock, and lubricating and extender oils.[68] Some recycled oil, like waste engine oil, is also marketed as rejuvenating agents.[69]

The long-term performances of these agents are not well understood. The National Center for Sustainable Transportation (NCST) says more testing "is required to evaluate the long-term behavior of mixes produced with rejuvenating agents to determine whether the benefits are limited to production and early life, or whether they extend through the design life of the layer." [70]

In the past, RAP was reprocessed using "cutbacks" – asphalt emulsions mixed with highly volatile solvents, which were expensive and harmful to workers and the environment.[71]

In recent years, efforts have been made to find new rejuvenating agents that cost less, are less toxic, and perform better than soft asphalts.[72] Bio-based, non-petroleum, agents are entering the market, including products based on:

- Waste vegetable oils;[73]
- Byproducts of the paper industry;[74]
- Algae;[75]
- Binders derived from corn stover, the non-food portion of corn;[76] and
- Swine manure.[77]

"It is expected that there will be more bio-based products like this available in the market in the near future," reported *Asphalt Pavement Magazine* in 2015.[78] However, the Federal Highway Administration says little is known about these products. "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 (Departments of Transportation)," says the agency. "No Life Cycle Analysis 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."[79]

The precise composition of these commercial additives is often unknown, which confounds efforts to assess their potential hazards. "Many rejuvenators are proprietary, making it difficult to offer a good generic description," according to *Pavement Interactive*.[80] For example, the Warner Babcock Institute is marketing an "environmental friendly" asphalt rejuvenator sold under the name "Delta S" through a private venture. Its safety data sheet lists five ingredients, all labeled "Trade Secret."[81]

Influence of Mixing Methods

Potential environmental and health impacts from toxic constituents of RAP depend upon the conditions in which pavement is reprocessed. In general, impacts decline as temperatures of asphalt mixes also decrease.

Standard Practice (Hot Mix Asphalt)

RAP typically is crushed and sized as part of a continuous milling operation on the site where asphalt is being reclaimed. Following the crushing, RAP is then trucked to a central asphalt plant, where processors combine RAP with virgin binder, aggregates, and rejuvenating agents. Central plant recycling can be hot, cold, or somewhere in between, but most of the time, RAP runs on hot mixes. RAP can also be processed in-place, through cold processes such as full-depth reclamation.

Hot central plant recycling is the most polluting and resource intensive asphalt mixing process. The typical hot melt operation runs between 150°C (the point at which bitumen becomes liquid) and 165°C.[82] As temperatures rise, so do energy demands, as well as carbon dioxide and other emissions. Driers in hot mix asphalt plants release CO_2, PAHs, and products of incomplete combustion into the air. When RAP is added, operations run even hotter. "Virgin aggregate is 'superheated' well above the normal mixing temperature so the excess heat can be transferred to the RAP during mixing," reports NAPA.[83]

Warm Mix Asphalt

In part to address concerns about pollution and energy demands from hot mix plants, pavers are embracing "warm mix" asphalt (WMA) technologies. WMA requires much lower temperatures, around 130 to 140°C[84] and consumes 10 percent to 30 percent less energy than hot mixes.[85]

"Compared to hot mix asphalt, WMA has many advantages, such as less energy consumption and less pollution during mixing and paving process, better construction environment, and higher percentage usage of recycled materials," says the UC-Davis Pavement Research Center.

"Nevertheless there are also some disadvantages for WMA, for instance, the uncertainty of its long-term performance and higher risk of water damage, which may necessitate more frequent maintenance and therefore heavier environmental burdens," they warn. "Furthermore, the environmental impacts of upstream supply chain that are used during the asphalt mix production process, for example, various additives, have seldom been taken into account." [86]

Two different processes create *foamed asphalt*. In the *foamed water* process, a small amount water is converted to steam at atmospheric pressure and expands to 1,600 times its volume. Foam is produced when asphalt binder encapsulates the steam. The asphalt binder's volume, in turn, increases ten to thirty times. Alternatively, a small dose of *synthetic zeolites* (0.1 to 0.3 percent by weight) produces foamed asphalt, and reduces mixing temperatures by up to 20°C, ten degrees more than foamed water processes.[87] Zeolites are manufactured from crystalline silica and alumina, and contain between 10 percent and 15 percent crystalline silica, which is an occupational carcinogen in dust form.[88]

By either method, foamed asphalt is preferable to, and more common than, the use of chemical additives to facilitate warm mix processing of asphalt. In terms of potential hazards, the foamed water process introduces none. Synthetic zeolites in dust form can release carcinogenic silica and might be an occupational hazard during subsequent milling operations. The use of chemical additives may introduce the most significant potential health hazards in mixing operations, but industry trade secrecy obfuscates attempts to understand them.

Case Study: City of Eugene, Oregon

The city of Eugene, Oregon is an early adopter of warm-mix asphalt for municipal projects. Since 2008, Eugene has successfully installed warm mix asphalt in roads throughout their city. They have found that WMA saves 15 percent energy compared to conventional paving, and results in lower emissions for workers and lower complaints about odors in the neighborhoods where it is used. Warm mixes are also easier to compact than conventional HMA pavement. Compaction helps to extend the longevity of pavement. By 2014, the City of Eugene specified the placement of approximately 361,000 tons of WMAC, reducing greenhouse gas emissions by approximately 8,700 metric tons of carbon dioxide equivalents. The use of WMAC in Eugene is now the standard practice for all City paving projects. Eugene also pioneered the use of recycled asphalt pavement (RAP) in the 1980s, and is increasing the proportion of RAP in city roads. Nearly a dozen streets used 35 percent RAP in 2014 and 2015, and the city planned to install pavement containing 40 percent RAP in 2016.[94]

A case study on the city of Eugene's sustainable paving initiatives, as well as sample specifications and resources for local governments interested in WMAC and RAP, can be found at the EPA's West Coast Climate & Materials Management Forum website: https://westcoastclimateforum.com/cfpt/asphalt/.

Chemical additives can be used in conventional asphalt plants and allow operators to switch between hot and warm mixes. These chemical additives are typically mixes of fatty amine derivatives,[89] often reacted with tetraethylenepentamine, a respiratory, eye and skin irritant derived from ethylene dichloride, which in turn is derived from chlorine.[90] They are added at doses of around 0.2 percent to 0.5 percent by weight of the binder and can lower mix production temperatures by as much as 40°C.[91] The precise hazards introduced by these additives are often difficult to discern given widespread industry claims of "trade secrecy" of these formulations. In December 2016, for example, a chemical company in Corpus Christi released a fatty amine derived asphalt emulsion into the city's water supply and refused to publicly disclose the pollutant's chemical composition.[92]

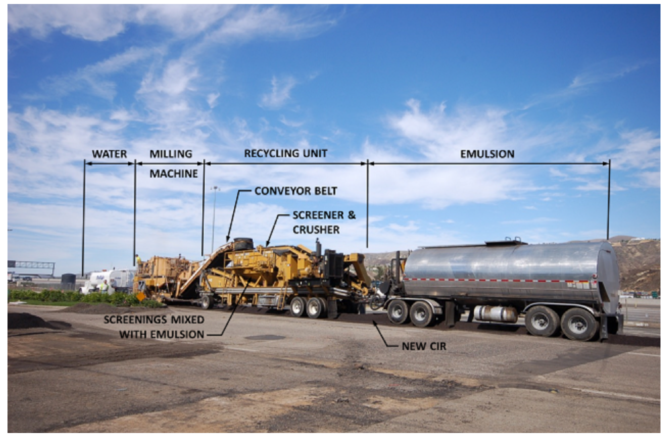
In California, about eight percent of asphalt mixes are warm. An estimated 88 percent of these warm mix asphalt operations use foaming processes; another 11 percent use chemical additives.[93]

Cold-In-Place and Cold Central Plant Recycling

Cold (ambient temperature) recycling processes can occur on the site where asphalt is being reclaimed in Cold-In-Place Recycling (CIR) pavement rehabilitation projects, or off-site in central mixing plants.[95] Both methods, CIR most of all, save significant amounts of energy compared to HMA or WMA. Surface milling asphalt for RAP, and recycling the millings on-site can reduce carbon dioxide emissions by as much as 95% (see Table 1 - Energy Use and Emisssions per lane mile on page 12).

However, ambient temperature recycling often uses more chemical additives than warmer process, although foamed techniques can avoid these toxic inputs.

CIR recycling is just how it sounds: instead of importing asphalt mixes from a central plant, machines plane and pulverize the top two to eight inches of existing pavement, mix the material with additives, and reuse it on-site as a base layer.[96] In some cases, after the base layer of CIR asphalt cement is compacted, a layer of HMA or chip seal may be added.[97]



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Cold-in-Place Recycling

The Metropolitan Transportation Commission found that if all candidate streets in the region used CIR instead of HMA, the savings would be 725,000 metric tons of greenhouse gases, the equivalent of annual emissions from 143,096 cars.[98] Several Bay Area cities are experimenting with CIR. "On average, each lane mile paved with CIR instead of conventional hot-mix asphalt reduces CO2 emissions by 131,000 pounds… at a cost 20 to 40 percent below that of conventional techniques," it estimates.[99]

However, when CIR relies upon chemical additives, it can significantly increase pollution. The use of "cutback asphalt" — asphalt dissolved in petroleum distillates — has been in decline due to environmental regulations.[100] In California, cutbacks are no longer used on top of pavement but are still used mainly to coat (prime) aggregate base materials before they are surfaced by asphalt.[101] Cutback asphalt use can amplify VOC emissions from paving operations. The Center for Biological Diversity says "the use of just 2 percent cutback would triple emissions."[102] In addition to emissions from their initial use in mixes, chemical additives can increase VOC emissions during future recycling if the asphalt is later reclaimed and processed in warm or hot mixes. "If cutback or emulsions are used to make cold mix asphalt, VOC emissions [from blending RAP in HMA plants] can be significant," reads an Australian government report. "When cold mix bitumen is heated, organic fumes and VOCs may be emitted as visible emissions if the asphalt is cut with lighter ends or other additives needed for a specification; however, these emissions are not normally seen when heating bitumen, as the boiling point of bitumen is much higher."[103]

While chemical inputs increase emissions from cold recycling processes, foaming techniques like those employed in warm mixes can be used instead. Foamed processes can even be integrated into the pulverization, mixing and paving train that creates CIR pavement. An expansion chamber is added to the train, in which water is injected into hot bitumen. The foamed asphalt binder is then dispersed and mixed in with RAP materials and virgin aggregate. This process, called Cold In-place Recycled Expanded Asphalt Mix technology, may be the least polluting of all.[104]

The influence of these various recycling techniques on future mixes are not often considered when designing mixes using RAP that has already been recycled, suggests the NCST. Aged binders and additives in RAP can influence the performance of subsequent generations of pavement. When reclaimed asphalt has been used in small quantities as an aggregate replacement, the NCST says, the "properties of the aged RAP binder were not taken into account in new mix designs. This generally did not result in any problems as long as the percentage of RAP was kept below approximately 15 percent, as was common in many states including California until recently."[105]

The US Department of Transportation (DOT) recently noted that "pavement with recycled mixtures may deteriorate faster in the field than pavements with less (or without any) RAP. The possible substandard performance of recycled mixtures will necessitate more maintenance and rehabilitation activities, thereby offsetting the economic and environmental benefits of using RAP."[106] The US DOT traces many of these issues to the "initial quality of pavement products." Increasing this quality "can increase initial costs but may decrease life-cycle costs," including energy and emissions.[107]

Due to the wide array of potentially toxic inputs in RAP, and a generally poor understanding of potential releases from blending them into new pavement, it scores a "Red - Significant Concerns" for Health and Environmental Hazards.

TABLE 1. **Energy Use and Emissions per lane mile**

	Energy (MJ/lane mile)	Carbon Dioxide (kg/lane mile)
Conventional Hot Mix Asphalt		
Aggregate production	46,683	8,336
Asphalt production	343,980	15,514
Production of Hot Mix Asphalt	386,100	30,888
Laying of Hot Mix Asphalt	12,636	843
TOTAL – HMA Process	**789,399 MJ/lane mile**	**55,581 kg CO2/lane mile**
Cold-in-place Recycling (CIR)		
Surface milling of asphalt for RAP	16,848	1,123
In-situ Cold Recycling Stabilization	21,060	1,587
TOTAL – CIR Process	**41,796 MJ/lane mile**	**2,987 kg CO_2/lane mile**

Source: Data extrapolated from Table 1. Energy Use and GHG Emissions for Pavement Construction Materials (Chappat and Bilal, 2003) in Compendium of Papers from the First International Conference on Pavement Preservation.[108] According to Scruggs Company,[109] one lane mile of asphalt (1 mile of road, 24 feet wide, two inches deep, weighs 1,548 short tons, or 1,404 metric tons). This calculation assumes a standard mix of 95% aggregate, 5% binder, and does not include emissions from use of chemical additives, hot mix chip seals or other finishes.

SUPPLY CHAIN QUALITY CONTROL AND TRANSPARENCY

Standard supply chain quality controls are described in a Best Practices Guide published by the National Asphalt Pavement Association (NAPA), a trade association of the asphalt pavement industry. This guide, however, does not address best practices from an environmental and human health perspective. The Greenroads rating system, which rates road construction on a point-based system not unlike the LEED rating system for buildings, addresses these issues more extensively. The wide variety of binders, additives, and aggregates leads to "general non-uniformity of recycled materials," says Greenroads International, which leads to significant quality control concerns.

"Best Practices"

In 2015, NAPA released a "Best Practices" guide for managing RAP and RAS. It provides guidance on creating consistent quality feedstocks with what it considers to be best practices in inventory management, milling pavement layers, processing and crushing RAP, and incorporating RAP into mixes.

"A common misconception exists that RAP stockpiles are highly variable and, thus, using higher RAP contents in new asphalt mixes will lead to more variability in the mixtures. However, well-managed RAP stockpiles have a more consistent gradation than virgin aggregates," NAPA asserts. The association's main consideration is "consistent gradation." To confirm RAP's binder content and physical properties, the association recommends a minimum of one set of tests per 1,000 tons of RAP.[110] At typical proportions in pavement, 1,000 tons of RAP would cover 3.2 miles of roadway.[111]

> The United States is not a party to the Basel Convention and does not regulate pavement sealed with coal tar as hazardous waste. Screening incoming loads of RAP for PAHs is not a common practice in most of the United States, although Minnesota and Washington prohibit recycling pavement containing coal tar.[124]

NAPA does not recommend testing for chemicals of concern, such as PAHs or asbestos,[112] either in RAP or RAS.[113] Instead, NAPA describes asphalt pavement as "inert." The trade association claims, "No materials are leached from the pavement itself (because it is waterproof)."[114] The industry relies upon leaching studies from 2002 and earlier to assert "asphalt pavement's inert quality."[115]

However, recent studies expose weaknesses in the research upon which NAPA bases its claim. A student of one of those studies' authors found PAHs migrating from asphalt pavement, contradicting his advisor's prior work. "The absence of sufficient scientific data on these PAHs has prevented scientist, engineers, and policy-makers from making sound decisions concerning reuse of waste," wrote Edmund Mawuli Azah in a 2011 doctoral dissertation.[116]

Numerous other reports describe low level PAH releases from asphalt pavement from the time it is installed to when it is reclaimed. Researchers also have identified heavy metals, including lead and mercury, leaching from pavement. Suspected sources of these metals include the aggregate used in pavement, and contaminants from passing traffic.[117]

PAH levels in RAP can be significantly higher than in virgin pavement. One quarter of asphalt debris samples tested in

Belgium contained PAHs in the thousands of parts per million range (0.1% or higher by weight). Two samples contained over 0.8% PAHs.[118]

Using RAP in hot mix asphalt production can result in higher PAH releases than virgin asphalt. In a 2013 study of French HMA plant emissions, researchers found that as RAP content increased, more PAH pollution resulted. Total PAHs nearly doubled when recycled content increased from 0% to 20% of the hot mix.[119]

A recent Caltrans study performed by the UC Davis Pavement Research Center also found that adding RAP to mixes increased PAH emissions. It examined emissions of various PAHs for four types of mixes, two warm, one hot mix without RAP and one hot mix with 15% RAP. In the mix with RAP, tests found air concentrations of nearly 100 µg/m3 phenanthrene and over 60 µg/m3 anthracene.[120] These concentrations, combined, approach California OSHA's permissible exposure limit of 200 µg/m3 (8-hour TWA (ST) STEL (C) Ceiling) for coal tar pitch volatiles (which includes phenanthrene and anthracene).[121]

Regulators outside the US have restricted RAP from commerce if it contains too many PAHs, particularly if it contains coal tar sealer. The European Union and other parties to the Basel Convention (a global treaty regulating hazardous waste) classify RAP that contains coal tar as a hazardous waste. Any RAP containing over 50 parts per million of the representative PAH, benzo(a)pyrene must be managed as hazardous waste.[122] In response, outside the US, the asphalt industry has developed rapid screening methods to detect PAHs in RAP.[123]

The United States is not a party to the Basel Convention and does not regulate pavement sealed with coal tar as hazardous waste. Screening incoming loads of RAP for PAHs is not a common practice in most of the United States, although Minnesota and Washington prohibit recycling pavement containing coal tar.[124]

Nowhere in the world do there appear to be regulations or industry standards governing heavy metal content in RAP, or ambient air emissions from asphalt pavement, whether new or reclaimed. California has no restrictions on PAHs or other toxic contents in RAP.[125]

Supply Chain Transparancy

Knowing the origin and composition of RAP is essential to understand its hazards and physical qualities, and, perhaps most significantly, its utility as a binder for new pavement.

© US DOT

Stockpile of unprocessed RAP millings

In what it says is a response to the new era of product transparency, NAPA is developing an Environmental Product Declaration (EPD) program that "will allow decision makers to make informed comparisons among asphalt mixtures and ingredients with the goal of improving the environmental impact of pavements."[126] However, EPDs are life cycle assessment tools, not content transparency reports, and environmental and/or human toxicity are not necessarily addressed in EPDs.

As a first step in developing an EPD, NAPA drafted product category rules for asphalt mixtures.[127] These draft rules point toward the development of rather generic data. For example, "no differentiation is made between a 'hot' asphalt and 'warm' asphalt mixture; instead, for each asphalt mixture, the plant production temperature will be declared in the EPD."[128]

The National Center for Sustainable Transportation says the highly variable compositions of reclaimed asphalt and shingles means that there is no "representative binder" present in these recycled materials; they also note the high variability even of virgin asphalt. For this reason, the composition of both virgin and reclaimed binders "must be well understood to ensure optimal performance of asphalt mixes containing high quantities of reclaimed asphalt."[129]

The construction industry is making headway towards better understanding of lifecycle impacts and health effects of building materials like asphalt. The US Green Building Council's LEED Rating System, for example, now includes credit for selecting products that have disclosed environmental impacts and hazards, and gives preference for selecting preferable materials based on environmental and toxicity concerns.[130]

Furthermore, the Greenroads rating system recognizes the importance of transparency. Its latest version includes credits for EPDs and Health Product Declarations (HPDs). "The move in the building industry is definitely toward more transparency in upstream production for supplies used in buildings. Greenroads is incorporating EPDs and HPDs as voluntary credits to follow suit," they explain.[131]

Disclosing and understanding the composition of RAP, and implementing screening protocols to identify and remove pavement contaminated by substances of concern, are essential steps toward minimizing the health impacts of reclaimed asphalt pavement, and maximizing its use. Platforms like HPDs[132] , Portico[133], and the International Living Future Institute's *Declare* program[134], provide opportunities for achieving this depth of understanding.

While product labeling and building rating systems show promising ways forward, transparency in this industry will not occur over night. Given the current lack of precision in understanding what is in RAP, and the industry's lack of human health concern in its "Best Practices" document and LCA analyses, we rate the current state of supply chain control and transparency as red (significant concerns).

GREEN JOBS & OTHER LOCAL IMPACTS

Virtually all reclaimed asphalt pavement is used in hot mix operations, typically near the roadways from which it was milled, sometimes (in the case of cold-in-place reclamation) right where it lies. There are about 4,000 hot mix asphalt plants in the country.[135] NAPA president Mike Acott says, "Some 300,000 workers are involved [directly and indirectly] in the production and placement of asphalt pavements. Because the asphalt industry is America's number one recycler, almost all these workers can be described as having green jobs." [136]

The US Bureau of Labor Statistics also considers asphalt paving to be a green industry due to its recycling activity.[137] The US Department of Labor estimates that there were 4,800 people working in the paving industry in 2014 in California – 57,700 nationwide.[138]

While there are concerns about some of the content of RAP in use today, occupational conditions for asphalt plant and paving workers are improving. Warm mix and even cold mix asphalt production incorporating RAP is increasing, which can benefit occupational health (over the use of hot mix asphalt). "There would be additional worker exposure reductions if emissions could be controlled at the source through reduction of mix temperature," NAPA acknowledges. "(L)ower temperatures would result in cooler working conditions, reduced overall emissions, a reduction in energy consumption, and other sustainability benefits… Warm-mix asphalt has the potential to virtually eliminate fume surrounding paving workers."[139]

Many of today's jobs are not as green today as they will become, when supply chain transparency and controls on incoming recycled materials improve, mixing temperatures lower, recycled content increases, and projects meet the highest standards of ratings systems like Greenroads. This leads us to rate this feedstock "yellow – room for improvement" against our Green Jobs criterion.

TABLE 2. **Greenroads Projects in California**

Project Name	Project Location
2010 STP Resurfacing and Rehabilitation Project - Monterey Road	San Jose, CA, United States
Bristol Street Widening Phase II	Santa Ana, CA, United States
Hacienda Avenue Green Street Improvement	Campbell, CA, United States
Presidio Parkway Phase I - Pilot Project	San Francisco, CA, United States
Presidio Parkway Phase I - Ruckman Bridge	San Francisco, CA, United States
Presidio Parkway Phase I - Southbound Battery Tunnel	San Francisco, CA, United States
Presidio Parkway Phase I - Southbound Doyle Drive to Battery Tunnel	San Francisco, CA, United States
Presidio Parkway Phase II - Pilot Project	Pilot Project - San Francisco, CA, United States
Tesoro Extension	Mission Viejo, CA, United States
West Anaheim Street	Long Beach, CA, United States

ROOM TO GROW

The share of RAP incorporated in California's pavement is not particularly impressive (just above 10%). With careful mix designs and more quality control, asphalt mixes could incorporate a lot more recycled content than current practice, and thereby displace virgin asphalt.

Underutilized Resource

The US EPA estimates place the recovery rate for asphalt paving debris at between 80 percent and 85 percent, with the balance going to landfills.[140] NAPA asserts a higher figure: "More than 99 percent of asphalt pavement reclaimed from roads and parking lots was reclaimed for use in new pavements instead of going into landfills."[141] However, about 20 percent of asphalt pavement debris is never classified as RAP and goes directly to landfills.[142]

A statewide waste characterization study for California in 2008 estimated that 129,834 tons of asphalt paving were disposed, not recycled.[143] By comparison, in 2009, NAPA estimated that 900,000 tons of RAP were used in pavement mixes and another 400,000 tons were used as aggregate.[144] This suggests that around 90 percent of the asphalt paving debris is recycled into new roads in California.

By any measure these are impressive numbers, but much more RAP could be incorporated into new asphalt pavement. Despite asphalt pavement's high recycling rates, there is a chronically low percentage of RAP in new pavement. Between 2009 and 2014, according to NAPA estimates, California annually produced 21.1 million tons of hot mix and warm mix asphalt, about 10 percent (2.3 million) of which was comprised of RAP.[145] In other words: *roughly ten times more new asphalt pavement was created than reclaimed*.

This disproportional use of new asphalt draws from several factors. During milling operations, typically, a thin surface layer is removed leaving behind useable base layers. Replacement surface layers, along with brand new roads and parking lots, typically use low proportions of RAP. The system is not designed to maximize the recovery of RAP in milling operations, nor to minimize virgin materials in pavement that replaces it.

Most RAP is taken into central plants for recycling is used as aggregate in base layers. HMA plants use it mainly because it is free, not because it is an intentional part of the design. "Asphalt plants do not typically buy RAP – infrequently, they do – and therefore are not creating a demand for it. Typically, RAP arrives at a plant from milling and maintenance operations without a payment for receiving or depositing the material," says NAPA.[146]

RAP is more commonly mixed into subsurface layers of pavement, rather than in the thin surface layer from which RAP is milled. New (virgin) asphalt overlays are often heavier than the milled pavement they replace, which have worn down over time. In short, the amount of RAP that is produced (mainly by milling a thin layer of pavement from existing roads) does not come close to meeting the pavement industry's overall demand for asphalt, from the base layer to the top.

California Lagging

California's average RAP content in HMA/WMA (10.7 percent) lags many states and countries. Neighboring Oregon incorporates around 26 percent RAP. Some states, like Michigan have achieved rates of more than 30 percent.[147] In the city of Eugene, Oregon, mixes with 40% RAP are now standard practice (see case study on page 10.) In Japan, some districts average 51 percent RAP content in pavement; the national average is 47 percent.[148]

Among the asphalt industry's primary challenges to increasing the use of RAP in new pavement has been the State of California's transportation department specification limits. In 2012 California passed legislation that allowed the state transportation department to develop specifications for the use of RAP of up to 40 percent in HMA by 2014. Previously, RAP was limited to 25 percent by the state.[149] In a 2016 report to the Legislature, Caltrans expressed its concern about this higher rate. At mix concentrations under 15 percent, RAP doesn't displace virgin asphalt's binding function, but as rates increase beyond that, blending occurs with virgin binders. These interactions remain poorly understood.[150] Caltrans argues that they need more information about the amount and type of recycled binder contributed by the RAP. It is working with the asphalt industry "to develop specifications that will allow the use of a sustainable amount of RAP and RAS in HMA without negatively affecting product performance."[151]

The complex variety of asphalt mixes frustrates efforts to incorporate higher percentages into new pavement. As percentages of RAP get higher, "they tend to affect overall mixture behavior, which necessitates special testing," notes Greenroads International. "As a result, most agencies set limits for the amount of RAP allowed but require no special mix design if you use RAP. This issue leads to a limit or maximum fraction of recycled materials that is allowed in a construction material." RAP content limits are meant to "prevent a substantial undesirable change in material properties from that of a material made entirely from virgin raw materials."[152]

The US DOT laments the missed opportunities of using RAP in HMA. "Less than half of State transportation departments use more than 20 percent RAP; however, based on State transportation department specifications, it is possible for States to use up to 30 percent RAP in the intermediate and surface layers of pavements. Currently, it is unknown why over half the country uses less than 20 percent RAP in HMA." A prior survey of state transportation department cited the variability of RAP, the lack of RAP availability, and past experiences (such as reports of premature cracking) as the most common reasons.[153]

California also consumes very little RAS, although amounts have been increasing, from none in 2009 to 19,500 tons in 2013, per NAPA estimates.[154] With additional sorting infrastructure in place in California, the use of RAS could be expanded. Currently, RAS sources that are contaminated with paper and other tear-off wastes are not clean enough to be recycled back into asphalt products, and often end up as Alternative Daily Cover on landfills in California.[155]

Quality Control Boosts Rates of Use

In Japan, asphalt pavement contains about 50 percent RAP thanks to a series of quality controls that ensure greater consistency. The industry has reduced the number of mix formulations on the road. It boosted RAP supplies by using rubble from pavement demolition projects, and by taking deeper millings (two to four inches) than is typical in the US (one to two inches). It also tracks millings and rubble "from the project site through processing and recycling back into new asphalt pavements," observed a delegation from NAPA. The industry tests incoming RAP to ensure a minimum asphalt content of 3.8 percent, and can thereby provide the dual functionalities of binder and aggregate in new asphalt mixtures.[156]

The approach in Japan reinforces the essential requirement for growing the amount of RAP (and reducing the amount of virgin asphalt) in pavement: quality control. However, Japan's asphalt pavement industry also depends upon heavy doses of rejuvenators to make high RAP asphalt mixtures work. Depending on the composition of these recycling agents, and the mixing temperatures of different processes, this dependence may increase potential occupational hazards and pollution.[157]

Given the long-term pressures on virgin asphalt supply, the bountiful in-place availability of material, trends toward increased usage, and improved quality control, we evaluate RAP's Room to Grow as "Green – Very Good."

Conclusions

Current practices skim the surface of what is possible in asphalt pavement reclamation. California trails many states and countries in using RAP in asphalt pavement. Because of the impressive amount of asphalt already in place throughout California's streets, on roofs, and highways, recycling large amounts of asphalt should be a preferred strategy for the state.

Increasing RAP content in paving projects reduces the need for virgin aggregate and binder. It could eliminate the need for energy-intensive central plant mixing. It can even close the asphalt material loop on-site during rehabilitation projects.

The asphalt paving industry, with an interest in minimizing costs, is beginning to cash in on RAP's economic benefits (the raw materials are free; new asphalt binder and aggregate are not). However, NAPA has not taken any interest in testing for potentially toxic substances in RAP, such as coal tar sealers, asbestos, and lead.

As we have seen with most other feedstocks examined in the Optimizing Recycling series, the value and use of recycled materials increase and healthier jobs are created when the industry improves its standard practices. In the case of asphalt pavement, these improvements are readily at hand. Tools for improvement include the adoption of screening protocols that identify and reject substances of concern, the development of cleaner technologies (like warm mixing), and the potential availability of bio-based, non-toxic rejuvenating agents.

Disclosing and understanding the composition of asphalt materials, as well as implementing screening protocols to identify and remove substances of concern, are essential first steps in the optimization of reclaimed asphalt pavement.

The general trends here are positive. Several factors are converging to clean up the asphalt production cycle and to encourage greater proportions of recycled materials in pavement. These include:

- Rating systems like LEED and Greenroads;
- Industry momentum towards greater product and mix design transparency;
- Higher allowances for RAP in transportation department specifications; and
- Lessons from pilot programs and broader successes in other states and countries to incorporate high proportions of recycled asphalt in pavement.

These forces are nudging this industry in the right direction. Recycled asphalt appears to be on the cusp of a transformation in transparency, materials selection, and mix design.

Recommendations

The transformation of asphalt pavement can be accomplished through commitments to build infrastructure such as cold-in-place milling equipment, to utilize recycled feedstocks, and to develop and standardize mix designs that maximize the use of RAS and RAP and do not compromise performance.

At its best, asphalt recycling would take place on the site of pavement rehabilitation and reconstruction projects, at ambient temperatures. The initial mix on the road would be designed with cold-in-place recycling without the use of harmful chemical additives, so that almost all content of the new pavement could come from the old. Ingredients in the old pavement would be fully identified. RAP would be tested to ensure that, after use, the asphalt still contains no PAHs or other substances in concentrations above thresholds of concern. Rejuvenators would be perfected to ensure performance and minimize emissions at ambient temperature. Any other additives to the cold-in-place mix, such as bio-based rejuvenating agents, would be certified organic, GMO-free, and achieve Greenscreen Benchmark 3 or higher (meaning they contain no chemicals with high human or ecotoxicity).[158] Emerging bio-based binders, potentially replacing virgin asphalt, would also meet these criteria. Asphalt pavers would fully disclose results of testing for toxic substances, and the identities of additives used in the RAP mix, to ensure that the RAP-laden mix may be readily recycled in place the next time it is milled.

There is much that the asphalt and green chemistry industries, governments, and consumers can do to optimize reclaimed asphalt pavement.

Recommendations for the Asphalt Pavement Industry:

- Never use coal tar sealers or cutback asphalt.
- Screen all inputs for toxic substances and ensure they are not introduced into any operation to which people or the environment are exposed.
- Test recycled content for substances of concern, such as coal tar, other sources of PAHs, lead, asbestos, and especially PAHs. Consider the pathways by which these substances may be released into the air, in mixing plants, from pavement in use, and from subsequent milling and reclamation efforts.
- Draw from established efforts to screen and prevent these substances from being passed along the supply chain. The Global Automotive Declarable Substances List (GADSL), for example, prohibits products that contain more than 0.1% anthracene (a common PAH), 0.1% lead, or any asbestos.
- Absent testing and a fully disclosed chain of custody, assume coal tar sealer or other high hazard substances are present in RAP. Avoid using any mixes containing untested RAP in residential areas, where it can be tracked indoors and pollute indoor air.[159]
- Accelerate the transition from hot mix asphalt to warm mix and especially cold-in-place processes that produce fewer emissions.
- Embrace green chemistry and transparency in selecting rejuvenating agents that facilitate these processes.
- In all mix designs, seek asphalt binders with the lowest possible levels of PAHs, preferably bio-based chemicals that are certified organic, GMO-free, and achieve Greenscreen Benchmark 3 or higher.
- Demand full content disclosure from upstream asphalt, additive, and aggregate manufacturers.
- Establish environmental and human health criteria along with performance criteria for asphalt pavement projects.

For Additive Manufacturers:

- Rejuvenating agents hold the key to optimizing RAP. Fully disclose the contents of asphalt pavement additives, as

this knowledge will facilitate recycling the next generation of asphalt.
- Ensure that the additives are bio-based chemicals that are certified organic, GMO-free, and achieve Greenscreen Benchmark 3 or higher.

For Consumers:

- Do not buy coal-tar sealers or recycled products that contain contaminants of high concern.
- Prefer RAP and RAS over virgin materials wherever possible.
- Encourage local building codes that prohibit the use of coal tar sealants on any pavement.

For Transportation Agencies:

- Streamline and adjust asphalt blending formulas to encourage increased use of RAP.
- Support the provision of testing equipment for chemicals of concern in state-funded transportation projects.
- Invest in testing equipment that allows use of higher proportions of RAP.
- Invest in milling equipment that supports cold-in-place recycling without using toxic chemicals.
- Support R&D of mixes containing bio-based rejuvenators that maximize performance and minimize pollution.
- Establish environmental and human health criteria along with performance criteria for asphalt pavement projects.
- Adopt policies that support full disclosure or ingredients; discourage use of additives that are Greenscreen Benchmark 2 or lower and encourage the use of bio-based and organic bio-based ingredients.

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