

## CHAPTER 5. CONSTRUCTION CONSIDERATIONS TO IMPROVE PAVEMENT SUSTAINABILITY

### Introduction

Pavement construction practices have changed significantly over the last several decades, utilizing new technologies that have significantly improved pavement quality and construction efficiency while decreasing environmental impacts. These construction practices, in concert with an appropriate pavement structural design (chapter 4) that uses appropriate materials (chapter 3), can provide significant improvements to the overall sustainability of a pavement system. Critical areas of pavement construction that can have a significant effect on the overall sustainability of a paving project include:

- Fuel consumption (during material transport from the site and between the plant and the site and the construction operations themselves).
- Exhaust and particulate emissions.
- Traffic delays, congestion, and noise emissions generated during construction.
- Constructed characteristics of the pavement surface, which impacts surface friction (safety), noise, and possibly fuel efficiency during the use phase.
- Pavement performance and overall life (as a result of construction quality).

This chapter summarizes various approaches for improving the sustainability of pavement construction. It first begins with a discussion of general sustainability issues that are common to all types of pavement construction (such as energy consumption and effects on localized or surrounding areas), and includes a summary of specific strategies that can be used to address those issues. This is followed by separate sections that are devoted to strategies and approaches that can be used to improve the sustainability of both asphalt and concrete pavement construction. Note that material production (discussed under chapter 3) includes plant mixing, and thus construction starts “at the gate” with respect to asphalt and concrete mixtures.

### Sustainability of Pavement Construction Operations: General Issues

The following are the general pavement construction factors that impact pavement system sustainability over the life cycle:

- Construction-related energy consumption.
- Effect on the surrounding area (including particulate and gas emissions, noise, effects on residents and businesses, and effects on wetlands and streams).
- Economics of construction practices, including user costs (due to construction-related traffic delays or normal operations).

An introduction to these factors is presented next, followed by a section on potential strategies for addressing them.

### Construction-Related Energy Consumption and Emissions

In general, pavement construction is an energy-intensive process that involves excavation, earthwork movement, material processing and placement, and compaction/consolidation of the

paving layers. Pavement construction equipment includes excavators and haul equipment, crushers, asphalt and concrete mixing plants (discussed as part of materials in chapter 3), graders, pavers, rollers, and more. The associated energy consumption of equipment is a function of the equipment/vehicle operation energy efficiency, which in turn is a function of the operation of that equipment within ideal power bands and minimization of idle time and engine speed during idle time. External factors (independent of equipment efficiency) that influence construction fuel consumption include site operations (e.g., haul distances, construction staging, and the need for multi-pass operations) and specific site-related conditions (e.g., quality and maintenance of haul road surfaces). Other factors that can affect energy consumption include fuel types (including the use of alternative fuels such as biodiesel and compressed natural gas) and the type of power source for stationary construction equipment (i.e., generator driven vs. grid powered).

The use of RAP and RCA in the base or subbase offers a strong potential for sustainable construction, particularly when the source materials are available and processed on site. In addition to offering the potential for reductions in construction-related fuel consumption and emissions, recycling (particularly on-site recycling) reduces the costs, fuel consumption, emissions, and land use associated with excavating, processing, and hauling virgin materials, as well as the economic and environmental costs of disposing of the old materials. Actual savings of fuel, emissions, and costs vary widely for a particular recycling project, depending on such things as the abundance of suitable local virgin aggregate sources, haul distances, crushing costs, and the potential for use of the recycled material in a higher type application (e.g., in new asphalt or concrete surface layers), which depends upon the quality of the source material. There may even be savings in surface material costs if the increased stiffness of a recycled base (due, for example, to the rough-textured, angular nature and secondary cementing action of RCA) provides additional structural capacity to allow a reduction in surface layer thickness. Additional guidance on the cost and energy savings and structural benefits associated with recycling asphalt and concrete pavements is available from ARRA (2001) and ACPA (2009), respectively.

Construction emissions are those generated from the operation of the various construction-related equipment due to direct construction activities, and also include the emissions that result from indirect construction activities (including vehicles using a roadway that experience construction-related delays). The emissions emanate from equipment powered by fossil fuels (using diesel, gasoline, or coal to heat or run equipment) and from electricity obtained from the grid used as part of the construction. Waste disposal should also be considered in order to account for a comprehensive measure of sustainability.

Emission categories for mobile sources used during construction activities usually include the following exhaust pollutants:

- Hydrocarbons (HC) or non-methane hydrocarbons (NMHC).
- Nitrogen oxides (NO<sub>x</sub>).
- Carbon monoxide (CO).
- Carbon dioxide (CO<sub>2</sub>).
- Sulfur oxides (SO<sub>x</sub>).
- Volatile organic compound (VOC) (replaced all HCs by EPA [2005]).
- Particulate matter (PM).

There have been numerous studies estimating the contribution of roadway construction projects to the overall life-cycle energy consumption and emissions of a pavement system. As described in chapter 2, pavement construction activities are estimated to be responsible for 70 percent of the highway and street construction expenditures (USDOT 2010). Total GHG emissions due to all highway and street construction is estimated to be around 117 million tons (106 million mt), which is approximately 7 percent of the U.S. transportation total. Currently, a national effort is underway to develop a guidebook for selecting and implementing sustainable highway construction practices (under NCHRP Project 10-91, *Guidebook for Selecting and Implementing Sustainable Highway Construction Practices*).

With respect to the total life cycle of a pavement system, the construction stage constitutes approximately 5 percent of the total pavement production cycle, including plant production, transportation, and construction activities. In an overall roadway life cycle, which commonly may be 40 to 50 years, the total energy consumed can be 18 to 20 times that for pavement production, which includes plant production, transportation, and construction (Muench 2010). The total energy and associated emissions during the life cycle of a pavement include pavement production, use phase related to the operation of roadway (e.g., fuel consumption by vehicles, lighting, traffic signals, urban heat island), maintenance, and end-of-life strategies. A detailed discussion of the pavement life cycle is presented in chapter 2.

The EPA (2009) has introduced the concept of *emission intensity* to provide a means for comparing the relative emissions of GHGs between various industries or economic sectors while taking into account their economic output. Emission intensity is typically calculated as the ratio of the GHG emissions produced per dollar of gross domestic product (GDP). Within the construction sector, the highway construction subsector had the highest emission intensity at 0.54 tons (0.49 mt) of CO<sub>2e</sub> emissions per thousand dollars of GDP (in 2002 dollars), with total annual emissions of 19.5 million tons (17.6 million mt) CO<sub>2e</sub>.

### Impact of Construction on Surrounding Areas

#### *Emissions from Equipment Exhaust*

The use of heavy equipment for earth moving and construction operations generates engine combustion emissions that may have significant impact on local air quality in surrounding areas, as well as on climate change. Heavy duty construction equipment is usually diesel powered, which yields NO<sub>x</sub>, GHG, and diesel PM as significant emissions. The particulate fraction of diesel exhaust emissions is reported as a toxic air contaminant posing chronic and carcinogenic public health risks (AEP 2012).

The EPA regulates the emissions from all mobile sources including on-road and non-road vehicles and engines. Non-road vehicles and engines include a category called compression-ignition (CI) engines covering equipment used in various construction activities. The EPA has established stringent standards for carbon monoxide, volatile organic carbon, nitrogen oxides, and particulate matter that a vehicle and engine may emit, and manufacturers, refineries, and mixing plants are responsible for meeting those standards. A tiered approach was put forward by EPA depending on the vehicle's engine rated power and age. Figure 5-1 illustrates the limits proposed by EPA (EPA 2013a), and it is noted that the band of restrictions will become much tighter after 2015.

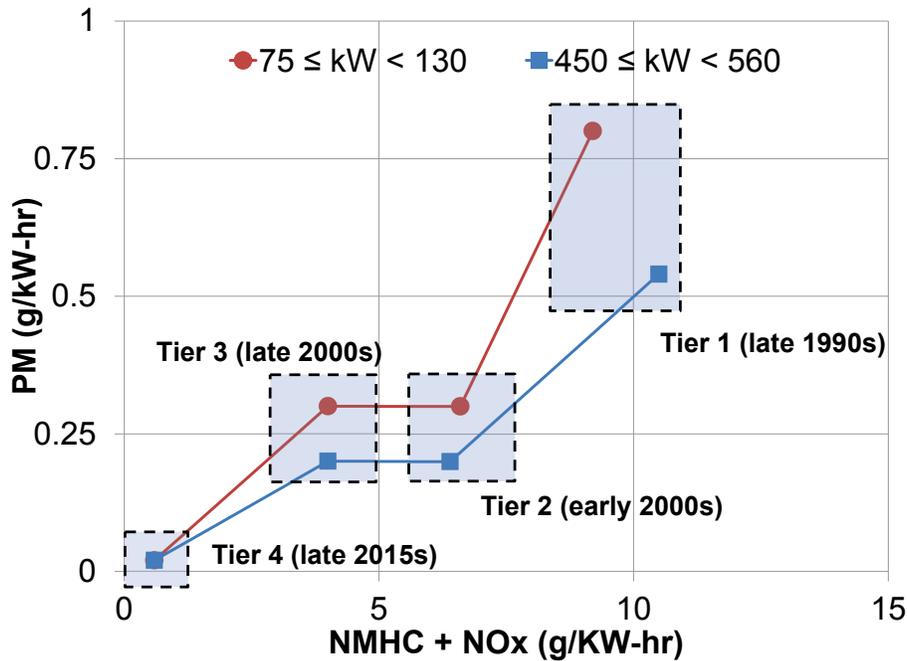


Figure 5-1. EPA non-road diesel engine limits for construction vehicles with two different ranges of rated power illustrating tightening of the emission limits (adapted from EPA 2013a).

Construction emissions can be calculated for all projects that are expected to exceed a certain threshold defined by the construction significance criteria (AEP 2012). Emissions can be calculated using the available databases, EPA sources, or commercial software using the construction activities and productivity of the equipment and use. For those projects exceeding the significance criteria, short- and long-term mitigation strategies can be applied, as described later in this chapter. An example of the construction emissions thresholds proposed by the California Environmental Quality Act (CEQA) is given in table 5-1.

Table 5-1. Thresholds of significance for construction operations (SLO county APCD 2012).

Pollutant	Daily Threshold	Quarterly Tier 1 Threshold	Quarterly Tier 2 Threshold
VOC + NO <sub>x</sub> (combined)	137 lbs	2.5 tons	6.3 tons
Diesel PM	7 lbs	0.13 tons	0.32 tons
Fugitive PM (PM <sub>10</sub> ), Dust		2.5 tons	
GHG	*	*	*

1 lb = 0.45 kg; 1 ton = 0.91 metric ton

\* GHG emissions need to be combined with other life-cycle emissions and amortized over the life of the project.

In order to estimate GHG emissions, the information related to equipment productivity is needed. Hourly equipment emission rates can be calculated using the following formula (Tang, Cass, and Mukherjee 2013):

$$\text{Hourly Equipment GHG Emission Rate} = O_t * L_f * HP * C_f * \varepsilon \quad (\text{Equation 5-1})$$

where:

$O_t$  = Operating time factor (usually taken as 45 min per hr)

$L_f$  = Average load factor corresponding to actual operating horsepower

HP = Average horsepower

$C_f$  = Fuel consumption rate (Gal/(HP\*hr))

$\varepsilon$  = Emission rate (i.e., 22 lbs CO<sub>2</sub>/Gal (2.6 kg/l) for burning conventional diesel)

### ***Airborne Particulates from Construction Operations***

In addition to the generation of particulates and pollutants from vehicle exhaust, pavement construction activities commonly generate dust, fine soil, and other airborne particulates from normal operations, particularly when construction takes place in dry or windy conditions. This is sometimes referred to as fugitive dust, and is primarily particulate matter that is less than ten microns in size (PM<sub>10</sub>) (AEP 2012). There are a number of sources of fugitive dust, including the following:

- Haul vehicle traffic on dry, unstabilized surfaces (including haul roads, pavement foundation layers).
- Wind erosion of exposed unstabilized materials.
- Stockpiling, hauling, and placement of unstabilized materials.
- Tracking and subsequent breakdown of soils and construction materials on local roads near site and plant entrances.

The distribution of particulates can vary constantly with wind speed and patterns, precipitation events, and other factors. However, it can be controlled and mitigated through good construction practices.

### ***Noise Generated from Construction Operations***

Pavement construction generates noise from the excavation, movement, processing, and placement of large volumes of material using large, powerful machinery. The resulting noise from exhaust stacks, plant site operations, earthwork construction, material hauling, and so on can be irritating at best, and potentially hazardous to the health of workers or area residents in the worst cases. High noise levels contribute to many health problems, including hearing loss, sleep disturbance, interference with communication, and physical health issues typically associated with stress (e.g., cardio-vascular problems) (Hygge 1998; Berglund and Lindvall 1995). Similar to airborne particulates, construction noise problems can be affected by wind patterns and other weather conditions.

### ***Construction Impacts on Local Traffic, Residences, and Business Operations***

In addition to pollution, particulate, and noise concerns, construction activities can also impact local residents, businesses, and visitors by temporarily preventing or restricting access to residential and commercial buildings, creating congestion and contributing to significant travel delays, and generally making an area undesirable to visit. Congestion-related impacts can spread well beyond the immediate limits of the construction area, depending upon local traffic patterns and route capacities

and the availability of alternate modes of transportation. Significant and prolonged access problems to commercial areas may cause financial hardship to business owners and, in some cases, may result in business failures, having financial impacts on both the business owners and the community in general.

Public safety, both on the road and in areas adjacent to the construction site, is also a concern, particularly in high business zones and residential areas. The use of private property for construction activities (whether through rental, purchase, or condemnation) is another social impact of construction activities.

### *Construction Near Streams, Wetlands, and Environmentally Sensitive Areas*

The potential for soil erosion in construction zones is increased by the removal of vegetation during earthwork and grading operations, allowing for more rapid concentration of precipitation and subsequent higher flow rates and increased potential for erosion. In addition, surface water runoff from construction zones can carry potentially hazardous materials into local waterways.

The failure to control erosion and surface runoff during construction can cause both on-site and off-site impacts (NRCS 2000). On-site impacts include the loss of topsoil resulting in elimination of the soil's natural ability to provide nutrients to plants. Off-site impacts are related to the erosion from construction sites resulting in water quality problems through excess nutrients transported via eroded soil and excess sediment. Excess nutrients impact water quality through eutrophication, a process in which excess nitrogen and phosphorus transported into surface waters causes unwanted biological growth, raising the level of lake or river beds which can eventually convert the area to dry land (Lawrence, Jackson, and Jackson 1998). Transported sediments can also be detrimental to aquatic life by interfering with photosynthesis, respiration, growth, reproduction, and oxygen exchange in waterways (Waters 1995; Newcombe and MacDonald 1991; Illinois Tollway 2013).

### Economics of Construction Practices, Including User Costs

The adopted or specified construction practices for any given pavement construction project have direct bearing on both the initial construction costs and the long-term life-cycle costs of the project. Changes in construction practices to enhance the sustainability of the project (such as noise and pollution reduction procedures, controlling erosion and stormwater runoff, and providing better local access) are expected to incur increased costs, which must be considered and weighed against expected benefits over the life cycle of the pavement to determine its effective impact. Changes that incur unacceptable economic expense may not be easily adopted in spite of potential environmental or societal benefits.

In addition, construction work often results in reductions in roadway capacity and throughput due to geometric restrictions, reduced speed limits, temporary closures, detours, and other congestion-inducing activities. Significant costs are associated with construction-related traffic delays and congestion, including lost time and decreased productivity for users, wasted fuel, and economic loss due to the inefficient movement of goods and services. Highway construction work zones account for nearly 24 percent of nonrecurring congestion in the U.S. (other sources include vehicle crashes and breakdowns, and weather conditions), which translates to 482 million vehicle hours of delay per year (USDOT 2006). Highway construction work zones are estimated to be responsible for 10 percent of all highway congestion in the U.S., which translates to an annual fuel loss of \$700 million (Antonucci et al. 2005).

According to recent congestion reports, while the magnitude of these emissions varies widely, Chan (2007) has reported an increase in emissions related to traffic delay as traffic volume increases, but generally less than the emissions associated with material production. In another study, Häkkinen and Mäkelä (1996) reported that fuel consumption and corresponding emissions due to the disruption of normal traffic flow by construction and maintenance activities are in the range of 1 percent of the total life-cycle emissions of asphalt and concrete pavements. These numbers may vary depending on the type of the pavement and sequence of construction activities and the assumptions of use-phase traffic related emissions.

In order to calculate emissions from traffic delays during construction and maintenance activities, the modeling effort must consider the stop and go nature of traffic flow as it approaches, passes through, and leaves the construction zone. For example, consider a typical vehicle traveling at 55 mi/hr (89 km/hr) that stops as it approaches a construction zone and remains stopped for 10 minutes; it then proceeds through the construction zone at a constant speed of 45 mi/hr (73 km/hr) and at the end of the construction zone accelerates to once again reach the posted speed limit (Mukherjee, Stawowy, and Cass 2013). This travel schedule can be modeled in various available programs to calculate emission factors for the given traffic and project construction data. The final outcomes of this analysis are the emissions and fuel usage from traffic delays triggered by highway construction activities. The EPA's Motor Vehicle Emission Simulator (MOVES) software is one program that can be used to calculate emissions due to construction and maintenance activities (see <http://www.epa.gov/otaq/models/moves/>).

Different road closure strategies and their impacts on the pavement construction energy consumption and GHG emissions were calculated by Kang et al. (2014). Three hypothetical scenarios were generated for a reconstruction project on the I-90 highway corridor around the Chicago area. The Kentucky Highway User Costs Program (KYUCP) model, developed by the University of Kentucky, was used to estimate driving schedules due to road closure scenarios. The emissions associated with changing driving schedules were predicted using EPA's MOVES software. The following scenarios for work zone closures and construction schedules were considered in the traffic and emissions simulations for a 7.6 mi (12.2 km) work zone:

- The first case assumed that the 7.6 mi (12.2 km) work zone was divided equally into four 1.9 mi (3 km) work zones. For the construction of each 1.9 mi (3 km) work zone, a nighttime closure strategy was assumed between 9 p.m. and 5 a.m. in order to minimize additional emissions from traffic delay by avoiding the time period when peak traffic volumes would be experienced.
- The second case assumed that the 7.6 mi (12.2 km) work zone was divided in half. For the construction of each of the two 3.8 mi (6.1 km) work zones, a 16-hour closure between 10 p.m. and 2 p.m. (following day) was assumed to avoid the time period when peak traffic volumes would be experienced.
- The third case was based on the construction of the entire 7.6 mi (12.2 km) in a single stage. A 32-hour closure was assumed for this scenario from 9 p.m. to 5 a.m. (2 days later).

The simulation results for energy consumption and CO<sub>2</sub>e emissions are provided in figure 5-2. Total emission and energy during construction activities were compared in the figure to the baseline case assuming traffic flow at the posted speed limits. The additional emissions and energy from work zone traffic delay increased slightly as the length of the work zone doubled from 1.9 mi (3 km) to 3.8 mi (6.1 km) because no traffic queue was developed during the nighttime closure. The emissions and energy consumption drastically increased in the third case when the entire 7.6-mi (12.2-km) work zone was assumed to be closed for 32 hours. Total energy and emissions were converted to the functional unit of LCA to evaluate the impact of traffic delay on pavement construction and material acquisition phase. Global warming potential due to traffic delay was reported to be 1.3 percent (best case scenario) to 2.7 percent (worst case scenario) of the total GWP including material and construction phases.

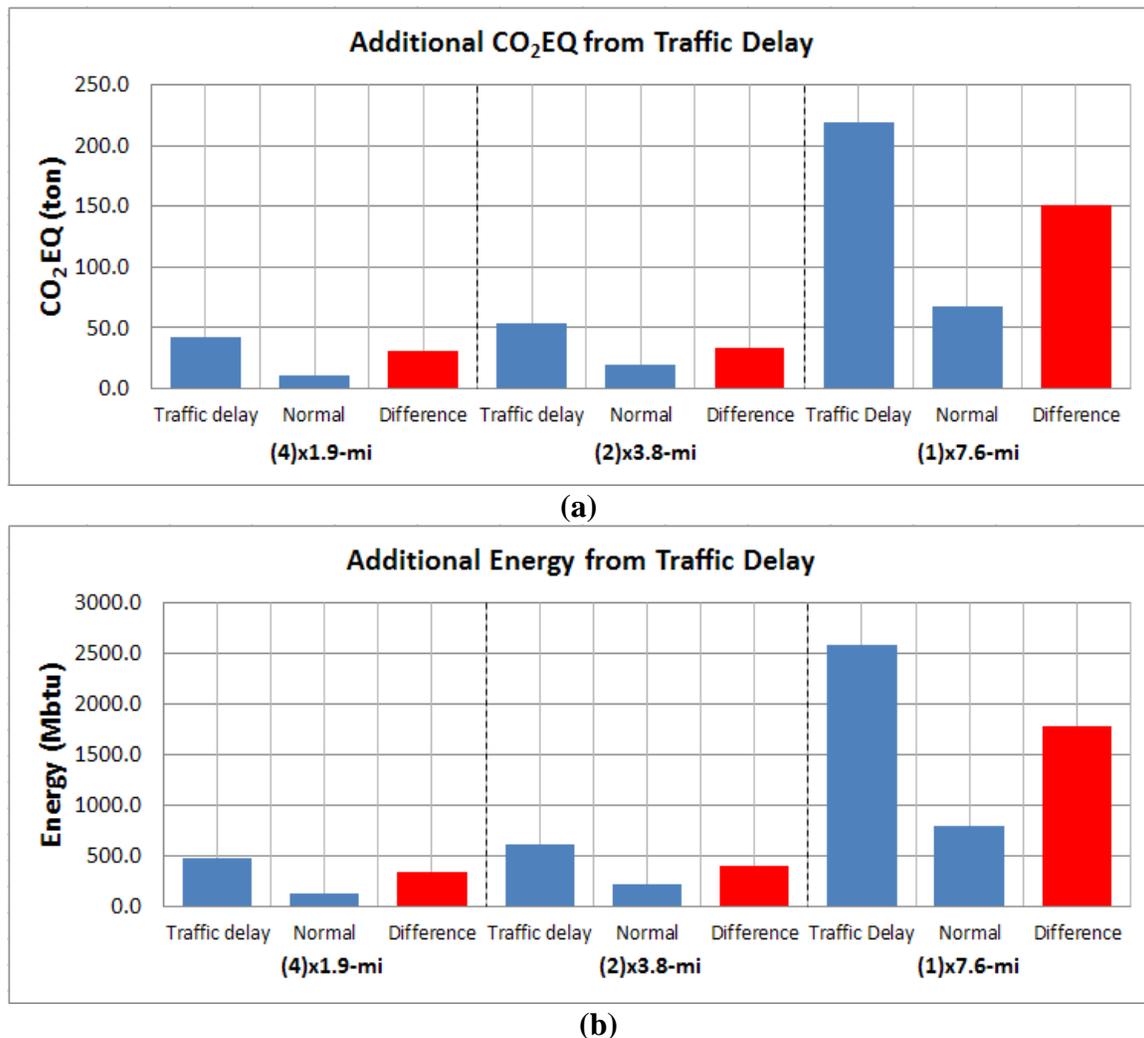


Figure 5-2. Impact of construction-related traffic delay: (a) addition emissions, (b) additional energy consumption for normal traffic and traffic delay scenarios for work zone lengths of 1.9 mi (four 8-hr nighttime closures avoiding morning and evening peak hours), 3.8 mi (two 16-hr night and daytime closures avoiding evening peak hours), and 7.6 mi (32-hr closure). (Traffic delay case indicates the case in which traffic delay due to work zone construction is developed; normal case indicates the traffic when all lanes are open with no work zone construction activity) (Kang et al. 2014).

## Quality and Performance of Constructed Pavement System

Even with the most durable materials and the most effective pavement designs, the overall pavement performance expectations will go unrealized if poor construction practices or inadequate quality assurance are performed. The quality of constructed roads becomes even more critical as transportation agencies need to maintain the facilities with limited resources. Performance specifications have been recently accepted as a way to improve the quality of construction and also to encourage contractors to develop innovative solutions that save time, minimize traffic delays, and enhance durability. SHRP 2 project R07 was charged to develop such performance specifications (Scott et al. 2014). The implementation of performance specifications are discussed in the context of various contract delivery methods including design-build, design-bid-build, and other innovative contracting variations. The findings of the study support the use of performance specifications.

Providing an effective working platform to facilitate construction activities is critical in ensuring adequate pavement performance. The load bearing capacity of native subgrade soil is generally improved through soil stabilization. Several techniques can be used to stabilize subgrade soils depending on site-specific characteristics and the predominant soil type; these include pulverization and homogenization using existing materials (without additives); stabilization using a single additive such as lime, cement, or asphalt binder (or less commonly, fly ash or other mineral fillers); and stabilization using multiple additives such as lime-fly ash (LF) or lime-cement-fly ash (LCF) combinations. These materials and technologies were introduced in chapters 3 and 4.

One of the primary factors that control the sustainability of a pavement system through the use phase of its life cycle is the durability and longevity of the pavement. Pavements that deteriorate quickly and require frequent repairs and rehabilitation result in greater agency and user costs, greater environmental impacts (i.e., fuel consumption and emissions), and undesired levels of service to the users.

The overall quality of the pavement must be reflected in both its structural and functional characteristics. For example, even a strong and durable pavement that has poor ride quality will result in relatively higher levels of user fuel consumption (and resulting vehicle emissions), lower levels of service, and may even increase average vehicle maintenance costs and damage to transported goods (or increases in required packaging costs). Specific issues and strategies for improving the quality of construction for asphalt and concrete pavements will be discussed later in this chapter.

### **Strategies to Improve Sustainability of General Pavement Construction Operations**

Table 5-2 summarizes several different strategies for improving the sustainability of construction operations that are applicable to all highway construction projects, regardless of pavement type. These strategies revolve around four major objectives (reduce fuel consumption and emissions, reduce noise, accelerate construction, and control runoff, erosion, and sedimentation), and the economic and environmental impact and trade-offs associated with each strategy are described. Additional discussion on these strategies is provided in the following sections.

Table 5-2. Approaches for improving general sustainability of pavement construction operations.

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
<b>Reduce Fuel Consumption and Emission</b>	Minimize haul distances	Reduced fuel costs	Reduced GHG emissions and air pollutants	
	Select appropriate equipment type and size for the job	Reduced fuel costs but may require capital investment	Reduced GHG emissions and air pollutants	
	Idling reduction	Reduced fuel costs; may require some capital investment to minimize idling	Reduced GHG emissions and air pollutants	Improved air quality
	Use alternative fuels	Varies	Reduced emission	Improved air quality
	Retrofit construction equipment, use hybrid equipment, or both.	Will increase costs due to initial capital investment	Reduced GHG emissions and air pollutants	Improved air quality and may decrease construction related noise
<b>Reduce Noise</b>	Construction time restrictions	It may lead to reduction in construction productivity	May increase emissions if construction is prolonged	Less noise and may affect air quality
	Equipment maintenance or modification	Increased capital investment	No environmental impact	Less noise
<b>Accelerate Construction</b>	Effective traffic control and lane closure strategies	Reduced fuel costs for users and agency	May reduce traffic delays and associated emissions	Less traffic disturbance
	Establish performance goals and measures for work zones	Reduced fuel costs for users and agency costs	May reduce traffic delays and associated emissions	Less traffic disturbance
	Use project management software for construction sequencing and managing traffic delays	Reduced fuel costs for users and agency; extra effort for agency/contractor	May reduce traffic delays and associated emissions	Less traffic disturbance
	Implement intelligent transportation warning systems	Increased agency costs	May reduce traffic delays and associated emissions	Less traffic disturbance and improve work zone safety
<b>Control Erosion, Water Runoff, and Sedimentation</b>	Use perimeter control barriers (fences, straw bales, etc.)	May result in increased project costs	Reduced sedimentation, prevent degradation of water quality	No direct impact on society
	Minimize the extent of disturbed areas	May result in increased project costs	Reduce disturbed areas	May reduce impact on surrounding residential areas
	Apply erosion control matting or blankets	May result in increased project costs	Reduced sedimentation	May reduce impact on surrounding residential areas
	Store/stockpile away from watercourse	No significant economic impact	May reduce potential water pollution	May reduce potential impact on area water

## Strategies to Reduce Construction-Related Energy Consumption and Emissions

### *Opportunities to Reduce Energy Consumption and Emissions*

There are a number of opportunities in the pavement construction process where energy and GHG emissions can be reduced. These opportunities can be grouped into three major categories:

1. Fuel use (moderate to major effect).
2. Electricity conservation (moderate to major effect).
3. Selection of construction materials (no to minor effect).

This section focuses on activities that contractors can control or influence to reduce energy and GHG emissions. Often, steps taken to reduce these parameters can provide a number of auxiliary benefits, such as increased equipment life and improved working conditions.

### *Fuel Use*

According to the estimates reported by EPA (2009), nearly three-quarters of the GHG emissions in various industrial processes are due to fossil fuel combustion. This is true for pavement construction, where fuel type and its efficient use can play a major role in the reduction of GHG emissions. Table 5-3 presents the emission factors for commonly used fossil fuels, that is, the emissions generated (in terms of lbs of CO<sub>2</sub>) per gallon of fuel used. It also shows the potential reduction in GHG emissions for two assumed levels of increased fuel efficiency resulting in either a 3 percent or a 10 percent reduction in fuel consumption for highway construction activities. Clearly, even a modest reduction in fuel usage can have a significant effect on GHG emissions.

Table 5-3. GHG emissions reduction scenarios from fossil fuel use (EPA 2009).

<b>Fuel Type</b>	<b>Emissions, lbs CO<sub>2</sub> per unit material<sup>1</sup></b>	<b>Estimated GHG<sup>2</sup> Reduction Using 3% less fuel</b>	<b>Estimated GHG<sup>2</sup> Reduction Using 10% less fuel</b>
Diesel	22.37 lbs CO <sub>2</sub> /gallon	600 million lbs CO <sub>2</sub>	2000 million lbs CO <sub>2</sub>
Gasoline	19.54 lbs CO <sub>2</sub> /gallon	186 million lbs CO <sub>2</sub>	621 million lbs CO <sub>2</sub>
Natural Gas	11.7 lbs CO <sub>2</sub> /1,000 ft <sup>3</sup>	106 million lbs CO <sub>2</sub>	353 million lbs CO <sub>2</sub>

<sup>1</sup> Emission factors are taken from EPA (2009).

<sup>2</sup> GHG reduction is calculated using the data provided in EPA (2009) and percentage of highway construction sector (13.4 percent) in total GHG of entire construction sector. The reduction in GHG is derived from the total construction sector emissions reported in EPA (2009). For example, using 3 percent less fuel may reduce CO<sub>2</sub> emissions by 4,455 million lbs (2,022 million kg) as an estimate of sector-wide emissions, with highway construction responsible for approximately 13.4 percent of total emissions. Therefore, such reduction in fuel use may contribute to an emission reduction of 600 million lbs (272 million kg).

The EPA (2007) recommends several low-cost strategies to reduce construction equipment emissions, including improved operating strategies, fuel strategies, and equipment strategies. Additional details on these strategies are provided below.

### *Operation Strategies for Fuel Reduction*

Equipment idle control, engine preventive maintenance, and operator training are some of the primary strategies for reducing fuel consumption and resultant emissions. For example, a typical

Class 8 diesel engine at high idle may consume 1.2 gal (4.5 L) of fuel per hour, a value that translates to the release of 26.1 lbs (11.8 kg) of CO<sub>2</sub> emissions per hour (EPA 2009). At low idle, the fuel consumption can be cut by one-half to 0.6 gal (2.3 L) of fuel per hour. For many contractors, fuel reduction simply involves changing work practices or investing in low-cost equipment. A summary of some of the recommended strategies for reducing fuel consumption, along with anticipated costs and benefits, is presented in table 5-4 (EPA 2007). In addition, carefully selecting material sites and plant locations for a specific job, as well as maintaining a stable haul road, can contribute to reduced fuel consumption.

Table 5-4. Operational strategies to reduce emissions incurred due to construction activities (EPA 2007).

<b>Operation Strategy</b>	<b>Costs</b>	<b>Benefits</b>
Equipment idle reduction and control	Low administrative costs for training and tracking of idling Upfront investment if on-board idle reduction equipment <sup>1</sup> is used (cost varying \$500-\$9000) <sup>2</sup>	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Longer engine life and reduced maintenance costs
Engine preventive maintenance	Low administrative costs for tracking equipment maintenance needs	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Longer engine life and reduced maintenance costs
Equipment operator training	Upfront investment for training programs	Reduced PM, NOx, CO, and HC emissions Significant fuel savings Improved operator efficiency
Construct choose and maintain stable haul roads	Upfront investment may be required to construct and maintain haul roads	Smooth haul roads improve fuel consumption Longer engine life and reduced maintenance costs
Select proper size and type of equipment depending on the production rate and road conditions	No investment is required	Reduction fuel consumption Longer engine life and reduced maintenance costs
Minimize haul distances by optimizing the plant and materials storage site location	No investment is required	Reduction fuel consumption

<sup>1</sup> Idle reduction technologies recommended by EPA's SmartWay Technology Program can be found at the following web address: <http://www.epa.gov/smartway/>

<sup>2</sup> The benefits of idling can be calculated using the worksheets developed by Argonne National Laboratory for heavy-duty and light-duty vehicles (Argonne 2011).

### ***Fuel Use Strategies***

Ultra low sulfur diesel (ULSD), biodiesel fuels, and compressed natural gas (CNG) are examples of alternative fuels that are being used in construction equipment to help reduce emissions. ULSD is a diesel fuel that has gone through additional processing to remove sulfur, and hence is a cleaner-burning fuel that can be used in any diesel engine. For example, regular non-road diesel has a sulfur content of 3,000 to 5,000 parts per million (ppm), whereas ULSD has a sulfur content of 15 ppm or less. Biodiesel is a renewable fuel made from domestically grown crops such as soybeans, cottonseed, peanuts, and canola. Biodiesel is usually available at the pumps blended with conventional petroleum diesel (e.g., B5, 5 percent biodiesel; B20, 20 percent biodiesel). CNG is made by compressing natural gas (which is mainly composed of methane, CH<sub>4</sub>) to less than 1 percent of its volume and storing it in special containers under high pressure (up to 3,600 lb/in<sup>2</sup> [25 MPa]). Table 5-5 summarizes some of the alternative fuel strategies with associated benefits and trade-offs.

Table 5-5. Alternative fuel use strategies to reduce emissions (EPA 2007).

<b>Operation Strategy</b>	<b>Costs</b>	<b>Benefits</b>
Ultra-low sulfur diesel (ULSD)	Higher price at the pump Lower energy content	Reduce PM and SO <sub>x</sub> emissions Reduce engine wear Increase oil change interval
Biodiesel (B5 and B20)	Higher price at the pump Increase NO <sub>x</sub> emissions Power loss and decreased fuel economy Degradation and wear in engine hoses or gaskets	Reduce PM, CO, and HC emissions Improve lubricity and reduce engine wear
Compressed natural gas (CNG)	Retrofit from gasoline and diesel vehicles is required Limited vehicle availability	Lower price at the pump Reduction in PM and greenhouse gas emissions

### ***Equipment Optimization Strategies***

Modifying and retrofitting existing construction equipment is another way to reduce emissions during construction activities. The initial investment required for this strategy is relatively high compared to the aforementioned strategies. Major equipment modification approaches include repowering or upgrading older diesel engines and using grid electricity or hybrid equipment (EPA 2007).

Diesel retrofitted devices can be installed on new or existing equipment as a post-treatment pollution control to reduce PM, NO<sub>x</sub>, HC, and CO. Diesel oxidation catalysts, diesel particulate filters, selective catalytic reductions, and exhaust gas recirculation are some of the retrofit technologies available in the market (EPA 2013b).

Switching to dual-fuel generators or grid electricity, when it is available, can provide modest emissions benefits. On average, an approximate reduction of 15 percent can be achieved using grid electricity over the use of diesel generators, although this can be much higher depending on the source of the grid electricity.

Other equipment optimization strategies may include selecting haul equipment (type, size, and quantity) based on production rates, haul route conditions, and maneuverability requirements; matching plant production, hauling needs, and paving operations; and avoiding extended time of heavy equipment idling.

### Strategies to Reduce Impact of Construction on Surrounding Area

#### *Air Quality Assurance Practices during Construction (Other than Vehicle Emissions)*

There are a number of practices that can be adopted to improve air quality issues associated with pavement construction, other than those that result from vehicle emissions. Some of these strategies include water sprinkling and other dust control techniques, regular maintenance of dust collectors at concrete and asphalt plants, and consideration of the proximity of residential and light commercial areas in the selection of plant and materials storage locations.

#### *Construction Noise Control*

Among the potential activities that could be considered to help control pavement construction noise are selecting plant and material storage locations away from residential and light commercial areas, limiting and mitigating excessive noise from haul vehicles (e.g., loud exhaust, banging tailgates), employing noise-reducing equipment modifications, and applying time-of-day construction restrictions.

#### *Effective Traffic Control, Lane Closures, and Work Zone Safety*

Establishing work zones imparts restrictions on the highway driving space, and can result in traffic congestion with a number of detrimental impacts, including lost time, increased fuel consumption and air pollution, inefficient movement of goods, decreased productivity, and potentially compromised roadway safety. The contribution of emissions from construction-related traffic delays to total life-cycle emissions varies with construction schedule and duration, roadway capacity, and traffic volume and control. A wide range of emissions and additional fuel consumption has been associated with traffic delays (Chan 2007). Based on several construction and reconstruction projects studied in Michigan, the contribution of traffic delays to overall pavement service life emissions was comparable to

### **Transportation GHG Analysis Tools**

A number of tools are available for use in analyzing GHG emissions on construction projects.

**State Inventory Tool (SIT):** *This tool from the EPA consists of eleven modules for applying top-down approach to calculate GHG emissions and provides an aggregated total for each sector (industrial, commercial, residential, and transportation) at the state level. Emissions for specific construction activities are not included.*

**NONROAD:** *This tool from the EPA helps to estimate emission factors from all non-road vehicles (except locomotives, aircrafts, and commercial marines). This tool can differentiate equipment type and other characteristics and can be used to calculate emissions from specific construction activities.*

**MOVES:** *This is a comprehensive tool from the EPA for all on-road vehicles providing detailed reports on vehicle emissions. Vehicle operation characteristics, fuel type, geographic location, vehicle miles traveled, and other factors that may contribute to emissions are considered. However, since non-road vehicles are not considered, this model cannot be used alone to estimate construction related emissions.*

**PE-2:** *This is a web-based pavement LCA tool applying a project based approach. The focus of the tool is estimating emissions associated with highway transportation projects over their life cycle, including production, construction, maintenance, and use phase.*

**GreenDOT:** *This is an Excel-based greenhouse calculator from the operations, construction, and maintenance activities of state DOTs. It was developed under NCHRP Project 25-25 Task 58.*

production stage emissions for high-volume roads; however, projects with Average Annual Daily Traffic (AADT) less than 20,000 vehicles per day (vpd) did not show a significant contribution to pavement total emissions and fuel use (Chan 2007).

An FHWA study reported on the analysis of 3,110 work zones on the National Highway System, covering thirteen states (Wunderlich and Hardesty 2003). Analysis of the collected data shows that the work zone closures resulted in a loss of 60 million vehicles of capacity per day. Among the work zones examined, 58 percent of them had lane closures primarily during the daylight hours, 33 percent had closures primarily during the nighttime hours, and 9 percent had continuous, 24-hour closures. The average work zone had lane closures for 11 hours a day and occupied 6.8 mi (10.9 km) of roadway for an average of 125 days (Wunderlich and Hardesty 2003).

Several strategies can be considered to reduce the impact of work zone delays, including the following (FHWA 2007):

- Implementing effective road and lane closure strategies – Effective traffic control strategies should reduce the period of time that work zones are active. This minimizes traffic delays and resultant emissions while keeping the motorists and construction workers safe. Some of the specific work zone strategies include using narrower lanes or shoulders, applying weekend lane or road closures, and charging lane rental, where contractors are charged for closing down lanes with an incentive to accelerate the time of construction.
- Establishing performance goals and measures for work zones – Highway agencies can set goals to help manage their work zones, and could target such items as reducing work zone delays, reducing queue length, and minimizing GHG emissions. This strategy has been implemented by some DOTs and by some European countries, including Germany and the Netherlands. For example, in the Netherlands the target work zone delay is 6 percent of all traffic delays. This number in the U.S. has been reported as 10 percent, based on national averages (Cambridge Systematics 2005).
- Incorporating lane/road closure analysis strategies during project planning – Different project management software programs can be incorporated into the planning and design phase to predict the impact of various lane or road closure strategies on traffic delays and emissions, and can also be used during construction to obtain feedback and monitor progress. This type of analysis in the planning stage can help sequence the schedule of activities while optimizing the process to reduce the impact on the users and the environment. Examples of the tools that can be used for this purpose include QuickZone, CA4PRS, and Dynasmart-P. CA4PRS is available free of charge to all highway agencies and is available at: <http://www.fhwa.dot.gov/research/deployment/ca4prs.cfm>.
- Implementation of intelligent transportation systems (ITS) – ITS technologies measure, analyze, and regulate traffic speed and volume and can help reduce traffic congestion in work zones by advising drivers of downstream traffic conditions. Components of an ITS may include dynamic message signs, a highway advisory radio, a citizen band radio channel, portable signs, a portable trailer, variable work zone speed limits, speed warning systems, and web cameras (Antonucci et al. 2005). Providing alternate routes or modes to drivers can also significantly reduce traffic demand in the work zone (Lee, Choi, and Lim 2008). A case study in Michigan that adopted ITS technology and a dynamic lane merge (DLM) system (which encourages motorists to merge lanes well before reaching

the work zone) found that the DLM can increase safety while reducing the delay in lane closure area in work zone (Paniati 2004). Monitoring and optimizing the entrance and exit of operation equipment to the construction site is also an important activity to reduce delays in the work zone.

### *Erosion/Stormwater Runoff and Sedimentation Control*

Generally, highway construction projects that involve earthwork removal require a plan for erosion and sedimentation control. Temporary erosion and sedimentation control plans or stormwater pollution prevention plans may be needed for the highway project that includes earthwork removal. In addition to conventional approaches, a number of innovative methods are being used in this regard, such as harvesting the existing vegetation mat and then reinstating it after the earthwork has been completed, and performing only a partial cleaning of the bottom of the ditch so that the upper part of the vegetation remains in place. However, even on project sites where recommended practices or innovative procedures are employed, sediment can continue to be discharged at concentrations dangerous to aquatic life. For example, in one construction project, it was reported that suspended solid concentrations increased by 500 percent on the downstream side of the construction site (City of Toronto 2006). Hence, effective best management practices to prevent erosion and to reduce the risk of costly sedimentation control measures and environmental damage are part of sustainable pavement construction.

The unique characteristics of each pavement construction project challenges contractors to meet the governing regulatory agency requirements (conservation authorities, municipal, provincial, and federal). Therefore, it is critical to have an environmental assessment to determine the extent of environmental constraints to ensure implementing sustainable construction practices. The control plan should include a multi-barrier approach to control erosion during construction and sediment transport from the construction site. In addition, timely consideration of environmental constraints is critical to reduce delays and undesired environmental implications. The suggested plan for erosion control may include the following (City of Toronto 2006):

- Minimize the extent of disturbed areas by construction sequencing, preserving and protecting natural cover, and immediately stabilizing disturbed areas.
- Establish erosion control protocols for the site considering topography, site conditions, and infiltration rates; these protocols may include vegetation (e.g., mechanical seeding, terraseeding, hydroseeding, sodding, tree and shrub planting), erosion control matting or blankets, and scarification of disturbed surfaces.
- Apply sediment transport control measures when vegetation practices could not be implemented. This includes perimeter controls, settling controls, and filtration controls.
- Limit duration of soil exposure and phase construction when possible.
- Minimize slope length and gradient.
- Store/stockpile away from watercourse (e.g., greater than 40 ft [12.2 m]).
- Ensure inspection and maintenance of the implemented sediment and erosion control practices.
- Perform revegetation of plant and construction sites as soon as is practical.

### *Construction Sequencing and Planning*

Knowledge-based construction and scheduling analysis tools can be used to estimate optimum rehabilitation schedules, balance pavement design requirements, and develop effective traffic management plans. With a strong need to maintain traffic while rehabilitating or reconstructing a deteriorated pavement, accelerating the overall construction process becomes the key to reducing problems with congestion, safety, and user delays, particularly in heavily traveled urban areas. The CA4PRS software, mentioned earlier, is one tool that can help planners and engineers select economical rehabilitation strategies while minimizing disruption to drivers and the surrounding community (Lee, Harvey, and Samadian 2005). Several demonstration projects illustrated that the tool was beneficial in increasing productivity and reducing work zone related traffic delays. For example, the concept of a 55-hour, extended weekend closure was first validated on the I-10 Pomona project in California, achieving a 40 percent increase in production when compared to traditional nighttime closures (Lee, Harvey, and Thomas 2005). Other construction planning tools available include QuickZone and Dynasmart-P.

### *Construction Materials Storage and Waste Management*

Management of construction materials and waste can be critical in controlling stormwater pollution. Best practice management plans should be prepared for dealing with contaminated soils; vegetative waste and excess paving materials; materials removed from ditches, drains, and culverts; waste piles; and other material that can affect stormwater quality (ICF 2006). In addition, plans for hazardous waste management should be developed during construction when applicable, and may include critical recommendations such as:

- Groundwater resources should be protected from leaching by placing an impervious material on areas where toxic liquids are to be stored.
- During rain events, stockpiles of cold-mix asphalt should be covered.
- During rain events, stockpiles of soil should be covered or protected with a temporary sediment barrier.
- During rain events, stockpiles of hydraulic cement concrete and asphalt concrete rubbles should be covered or protected with a temporary sediment barrier.
- Aggregate segregation during storage and handling should be avoided.

#### **Software Tools to Support Construction Practices**

**CA4PRS** is a software tool supporting the analysis of project alternatives for different pavement design, construction logistics, and traffic operation options and is designed to help highway agencies and contractors develop construction schedules to minimize traffic delay and reduce agency costs.

**QuickZone** is a software tool for traffic analysis that compares traffic impacts for work zone mitigation strategies and estimates traffic delays and cost.

**Dynasmart-P** is a dynamic traffic assignment analysis tool used in decision making for regional work zone management. It models the evolution of traffic flows resulting from travel decisions of the individual travelers. It can be used to evaluate traffic management strategies for highway construction projects, and can also help assess the impacts of ITS technologies.

### Evaluation of Sustainable Contracting Alternatives for Environmental Considerations

The level of emissions associated with construction operations is considerable and thus effective mitigation strategies are needed. For example, contract specifications may require contractors to use construction equipment certified by EPA, or may require that diesel retrofit devices be installed to reduce emissions. Some examples of such contract specifications used in public projects include the Central Artery project by Massachusetts Highway Department, the Dan Ryan Expressway construction by Illinois Department of Transportation, and in every recent contract by the New York Metropolitan Transportation Agency (Ahn 2012). The primary intent of these specifications is mainly to reduce critical air pollutants rather than GHG emissions. There are currently only a few agencies (e.g., Metropolitan Transportation Commission in San Francisco area and the Capital District Transportation Committee in Albany) attempting to quantify GHG emissions associated with construction and maintenance activities (ICF 2008).

Innovative and alternative contracting and bidding methods may also be considered as a means of reducing the environmental burden of construction activities; otherwise, contractors may not voluntarily take the necessary steps to reduce GHG emissions or critical air pollutants. As one example, in 1994, the New York State DOT introduced “A+B” bidding (also referred to as cost plus time bidding) to encourage contractors to more actively manage their work schedules and adopt innovative and aggressive scheduling and construction management processes to accelerate construction completion. The “A” in the term refers to the cost associated with the amount of work to be completed, while the “B” refers to the calendar days proposed by the bidder to complete work multiplied by a daily user costs. The success of the A+B bidding method laid the groundwork to introduce environmental costs in the bidding process; for example, Ahn (2012) proposed “A+C” and “A+B+C” bidding methods, in which “C” refers to an environmental component. Environmental costs are defined based on the concept of the eco-costs (Vogtländer, Brezet, and Hendriks 2001; Ahn 2012). However, emission estimates, eco-cost of emissions, fossil fuel use, and eco-cost of natural material depletion need to be known to calculate the “C” component, and thus bidders are required to use LCA to estimate emission and energy consumption values.

### **Strategies for Improving Sustainability of Asphalt Pavement Construction Practices**

Asphalt pavement construction generally entails the preparation and compaction of the subgrade, granular or treated subbase and base layers, and asphalt mixture layers, as described below:

- The construction activities for unbound and treated layers (subgrade and subbase/base layers) may include excavation, leveling, hauling of excavated or borrow materials, and layer compaction to design density levels. Locally available crushed aggregates are usually used for layer construction.
- Construction of asphalt mixture layers usually involves asphalt mixture preparation, transportation, material placement, and compaction. Asphalt mixture preparation involves the mixing of multiple aggregate stockpiles at predetermined ratios, heating the combined aggregate, and mixing it with hot asphalt binder at a specific temperature, as described in chapter 3. The resulting asphalt mixture is transported directly to the project site or stored for later transport. The asphalt mixture is placed utilizing a paver and then compacted at predetermined temperature using appropriate rollers of defined types and with specified loading magnitude and frequency. A schematic of the overall asphalt pavement construction process is presented in figure 5-3.



Figure 5-3. Generalized asphalt pavement construction processes and associated fuel factors (fuel factor source: Skolnik, Brooks, and Oman 2013).

Major equipment used in asphalt pavement construction and their contribution to energy use and emissions should also be noted. Approximate levels of energy use and GHG emissions associated with the construction and equipment used in various asphalt pavement construction activities are presented in table 5-6.

Table 5-6. Energy efficiency and CO<sub>2</sub> emissions for common equipment used in asphalt pavement construction (compiled from Santero and Horvath [2009a]; Skolnik, Brooks, and Oman [2013]).

<b>Construction Activity</b>	<b>Equipment</b>	<b>Horsepower Range</b>	<b>Fuel Consumption Range (gal/hr)</b>	<b>CO<sub>2</sub> Emissions Range (lb/hr)</b>
<b>Asphalt Paving</b>	Paver	125-225	35-50	90-136
	Pneumatic Roller	100-135	6-12	45-136
	Vibratory Roller	100-135	4-6	226-1130
<b>Milling</b>	Milling Machine	400-875	2-6	113-339
<b>Excavation and Placing</b>	Excavator	100-320	10-50	136-226
	Vibratory soil compactor	100-180	5-15	271-361
	Bulldozer	250-500	6-10	90-136

1 gal = 3.8 l; 1 lb = 0.45 kg

General approaches to improving pavement sustainability with regard to the construction of asphalt pavements are summarized in table 5-7. It is recommended that a comprehensive LCA be used to verify the precise environmental benefits or trade-offs that may result from employing any of these specific strategies. The following sections describe these strategies in more detail.

### **Placement and Laydown**

Every year 500 million tons (453 million mt) of new asphalt pavement material is produced in the U.S. at approximately 4000 asphalt mixing plants (NAPA 2013). Because of the widespread use of asphalt mixtures, even small changes in asphalt pavement technology can lead to significant savings in fuel and energy consumption and reductions in GHG emissions. In addition, opportunities exist to reduce exposure to asphalt fumes and other potential hazards associated with asphalt mixture production and placement. Table 5-8 presents some of the best practices that can be implemented at the plant and paving site to reduce fumes, emissions, and odors.

Asphalt pavement system layers must be placed in accordance with prevailing standards and specifications. The effective placement and compaction of bound and unbound subbase and base layers ensures the needed foundation for the surface layers, while the placement and compaction of asphalt concrete layers are elements critical to long-term performance. The proper placement and compaction of asphalt concrete layers prevents the development of segregation and longitudinal joint deterioration, ensures that the proper grade and cross slope of the pavement are met, and achieves the specified density and smoothness requirements. Recommended practices for asphalt concrete placement and compaction are summarized below.

### ***Segregation Control***

Asphalt concrete may undergo aggregate or temperature segregation, which can occur during any stage of production, transportation, or placement due to improper mixing or handling. Hence, addressing segregation usually involves troubleshooting different stages of production and placement. At the asphalt plant, production must be monitored carefully to avoid segregation (checking aggregate stockpiles, storage silos, and loading of the hauling trucks). In the production stage, modifying the mixture design, correcting improper material transfer from the stockpiles to the bins and from the bins to mixers, and improving handling and movement of mixtures in the storage are some of the key items to be considered. During the paving operation, paver hopper and auger are the two key areas that need to be monitored to prevent segregation. The use of a material transfer vehicle (MTV), a transfer vehicle positioned between the truck and the paver, helps minimize segregation since it serves to remix the asphalt and makes the temperature of the asphalt more uniform.

### ***Proper Construction of Longitudinal Joints***

Improperly constructed longitudinal joints in asphalt concrete surface layers result in an overall reduction of pavement service life and ride quality due to potential density variations. Joint failures can be due to a combination of low density, segregation, and lack of adhesion between two adjacent lanes. Minimum density requirements at the longitudinal joints are usually specified, being no more than 2 percent less than the mat density and with no density measurement being less than 90 percent of the theoretical maximum density, although some agencies accept densities as low as 88 percent (Buncher 2012). A notched wedge joint is recommended when the lift thickness is between 1.5 and 3 inches (38 and 76 mm). Joint adhesives (overbanding with sealants) or tacking the existing face of joint with emulsion or asphalt binder can also be considered. Recommended practices must be followed to avoid mixture segregation.

Table 5-7. Approaches for improving sustainability of asphalt pavement construction operations.

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
<b>Achieve Target Density Requirements</b>	Increase thickness to nominal maximum aggregate size ratio	Potentially reduce costs since it can reduce number of lifts constructed	Reduce environmental impact through less hauling trips Increased pavement life due to better compaction Better resistance to top-down cracking	Longer life and less frequent interventions
	Use warm-mix technologies	Potentially increase costs due to additives and capital investment	Reduce environmental impact by lowering compaction temperature	Reduce construction related air pollution and potential for irritation for sensitive workers
	Follow laydown temperature requirements	No change in cost	Accelerate construction due to achieving required mat thickness and density at a faster rate	Less exposure to traffic delays
	Select proper equipment for placement and compaction equipped with smart technology	Need capital investment and increased agency costs but has long-term benefits to contractors and agencies	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention
<b>Prevent Segregation</b>	Use thermal cameras to avoid erratic mat temperatures and temperature related segregation	May increase contract costs due to capital investment	Reduce environmental impact through good quality materials and longer life pavements	No direct impact
	Use of material transfer vehicles	May increase contract costs	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention
	Proper handling of materials during transportation, placement, compaction	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Longer pavement life Less intervention
<b>Construct Effective Longitudinal Joints</b>	Avoid segregation during transportation and placement	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Improve ride quality Longer pavement life Less intervention
	Use of adhesives or sealants overbanding the joint	May increase contract costs	Reduce environmental impact through good quality materials and longer life pavements	Improve ride quality Longer pavement life Less intervention
	Proper compaction to achieve joint density	No cost associated with this approach	Reduce environmental impact through good quality materials and longer life pavements	Improved ride quality Longer pavement life Less intervention
<b>Achieve Target Smoothness Requirements</b>	Proper placement and compaction techniques	No cost associated with this approach	Reduce environmental impact through reduced fuel consumption	Improve ride quality Longer pavement life Less intervention

Table 5-7. Approaches for improving sustainability of asphalt pavement construction operations (continued).

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
Use Innovative Contracting Alternatives	Implement multi-parameter bidding systems (i.e., A+B+C)	May increase contract budgets due to consideration of time to complete projects and environmental damage	Reduce environmental impact since lowest bidder will win and accelerate construction	Less exposure to traffic delays
	Incentivize equipment retrofits	No additional agency costs if federal grants or tax reduction incentives are in place	Reduce air pollutants and greenhouse gas	Reduce impact on local air quality

Table 5-8. Best practices to control fumes, emissions, and odors from asphalt mixture plant and paving operations.

Location	Best Practices <sup>1</sup>
Plant	Select plant mixing temperature by consulting asphalt supplier
Plant	Read the material data safety sheet for all materials
Plant	Regularly calibrate thermocouples
Plant	Collect continuous data on aggregate moisture and fuel/energy usage
Plant	Have stack gases tested to check limits
Plant	Keep a record of fuel usage over time
Plant	Do not use diesel fuel and kerosene as release agents
Paving Site	Keep paving temperatures as low as possible (blue smoke indicates overheating) consistent with achieving adequate compaction of the mat
Paving Site	Check paver ventilations systems regularly
Paving Site	Ensure that tail pipe and ventilation stacks exhaust above the height of the paver operator
Paving Site	Consider increasing mat thickness prior to an increase in plant temperature

<sup>1</sup> Compiled from APEC (2000) and NYSDOT (2003).

### Meeting In-Place Density Requirement

The two main objectives of compaction are achieving prescribed layer densities and meeting smoothness requirements. Most minimum density requirements are in the range of 92 to 93 percent of the theoretical maximum density. A strong correlation between service life and in-place density of asphalt concrete layers is reported in the literature (Puangchit et al. 1983; Christensen 2006; Buncher 2012). For example, figure 5-4 shows the estimated impact on pavement life by improving the density of the asphalt concrete (expressed in terms of a reduction of the air voids from 8 to 5 percent) and thus reducing bottom-up fatigue cracking. An optimized mixture density reduces rutting and cracking potential (Harvey et al. 2004).

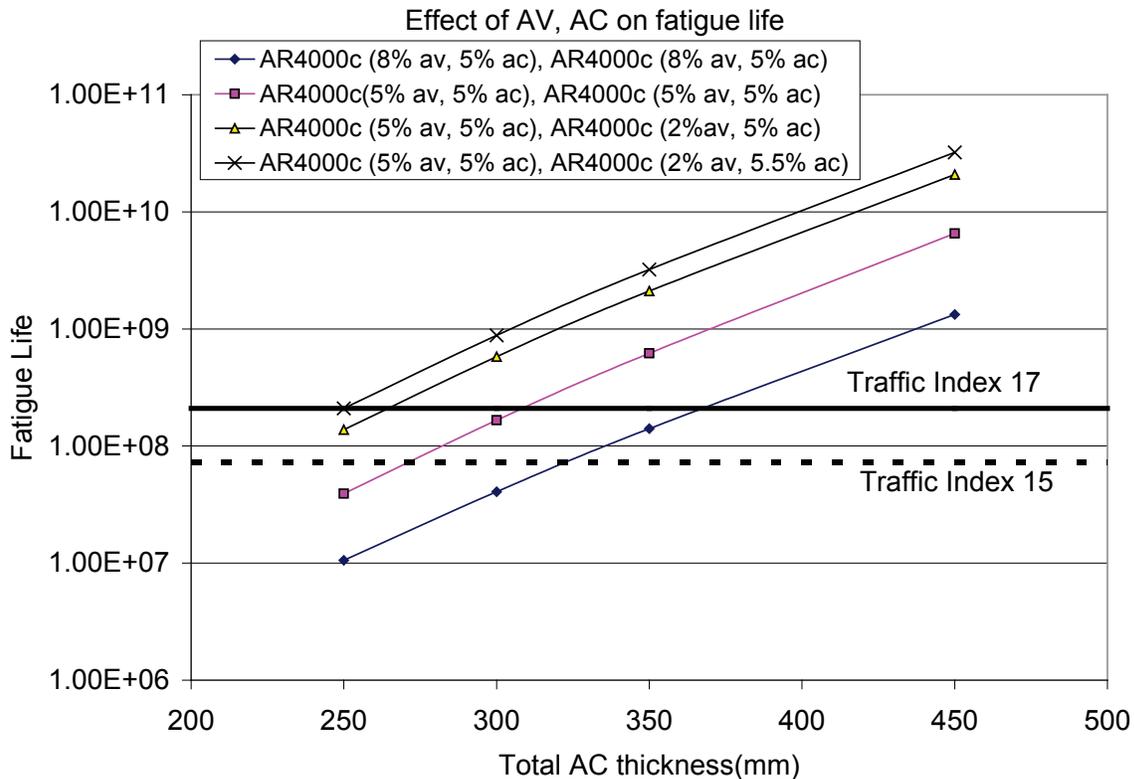


Figure 5-4. Effect of compaction on predicted bottom-up fatigue life for two-layer beam specimens in mixture using a AR4000c binder (binder type used in several western highway agencies prior to Superpave) and at different air void and binder content levels (after Harvey et al. 2004).

Improved compaction requires no additional materials, and usually requires no new equipment, but does demand strong attention to details, effective temperature monitoring and control, and management of the factors controlling the compaction process. 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 an FDR material), increasing the density of a material by compaction will improve both the rutting and cracking resistance. Overall, the factors affecting asphalt concrete compaction can be categorized into five classes:

1. Mixture properties (aggregate, binder, and mixture design) – The pavement construction stage has little to no influence on the selection of mixture properties. Selecting the materials and design of pavements with proper materials is discussed in chapters 3 and 4.
2. Environmental conditions – Most highway agencies follow standard specifications that address air and surface temperature requirements, seasonal limitations, and weather requirements. In general, asphalt concrete shall not be produced and placed in rainy weather and when ambient temperatures are less than 35 to 60 °F (2 to 16 °C) (based on the mixture type).
3. Laydown temperatures – The temperature of the mixture is one of the main factors affecting compaction. The lower and upper temperature limits at which compaction is effective is approximately in a range of 185 to 350 °F (85 to 176 °C) (NCDOT 2012). At

the time of placement, the temperature can be considered uniform in the mat; however, the mixture quickly starts cooling down and at a higher rate on the surface resulting in a temperature gradient through the mat. The rate of cooling is a function of the mixture type, design, base temperature, air temperature, and layer thickness. The allowable time recommended for compaction as a function of these variables is summarized in table 5-9.

Table 5-9. Typical minimum requirements for laydown temperatures as a function of base temperature and lift thicknesses (NCDOT 2012).

Lift thickness	½ in	¾ in	1 in	1-½ in	2 in	+3 in
Base Temperature	Mixture Temp (°F)					
20-32	NA	NA	NA	NA	NA	285
32-40	NA	NA	NA	305	295	280
40-50	NA	NA	310	300	285	275
50-60	NA	310	300	295	280	270
60-70	310	300	290	285	275	265
70-80	300	290	285	280	270	265
80-90	290	280	275	270	265	260
+90	280	275	270	265	260	255
Rolling Time (min)	4	6	8	12	15	15

°C = 5/9 (°F – 32); 1 in = 25.4 mm

4. Lift thickness – Lift thicknesses are commonly selected based on the nominal maximum aggregate size (NMAS) in the mixture and the mixture type (leveling or surface course). The thickness may vary from 0.38 to 3 inches (9.5 to 76 mm) from smaller to larger aggregate size, respectively. The rule of thumb for the ratio of lift thickness to NMAS is at least 3:1 for fine-graded mixtures and 4:1 for coarse-graded mixtures (Brown et al. 2004). Fine graded and coarse graded refer to the ratio between the coarse aggregate in a mixture (create voids) and the fine aggregate (fill voids) relative to the control sieve for a particular mixture. The lift thickness is one of the factors governing in-place density as it influences the cooling rate and provides space for aggregate movements. As the lift thickness increases, the lift can retain the heat for longer time periods thereby increasing the compaction time and allowing desirable density levels to be more easily achieved (Brown et al. 2004). The lift thickness has an impact on the environment as well, since it influences compaction productivity due to cooling time.
5. Compaction equipment and procedures – Compaction is done using several types of compactors including vibratory, static steel, static pneumatic rubber, and oscillatory rollers. The compactor type and applied loading amplitude and frequency are selected based on the layer characteristics. In recent years, rollers are equipped with intelligent compaction systems to ensure the pavement material is appropriately compacted. Additional details on intelligent compactors are provided later in this chapter.

### *Achieving Smoothness*

There are numerous benefits of achieving specified initial pavement smoothness. Some of these benefits are reduction in dynamic loads on pavements, enhanced rideability over a longer period of time, reduced fuel consumption, and reduced vehicle wear and tear in the use phase. In addition, studies have shown that pavements constructed smoother initially stay smoother longer, all other things considered equal (Smith et al. 1997).

Most highway agencies have adopted smoothness specifications, along with incentive and disincentive provisions, to encourage the construction of smooth pavements. At the same time, recent years have seen a number of agencies move to the use of lightweight inertial profilers to assess initial smoothness, although a few agencies still use profilographs. During placement and compaction of asphalt concrete layers, pavement smoothness can be adversely affected by lack of uniformity in paving operations, variations in mixture temperature, variations in paver speed, segregation, and improper rolling. Critical items to help ensure that high levels of initial smoothness are achieved include (NCDOT 2012):

1. Maintain continuous operation of the paving train and minimize paver stops.
2. Correct irregularities in lower courses by adding or removing materials.
3. Leave adequate amount of material in the paver hopper between loads to prevent rough texture due to end of the load segregation.

### Construction Quality Assurance

Quality assurance (QA) activities performed during pavement construction are necessary to ensure that the material and workmanship meet the project specifications. This includes proper placement and compaction of all pavement layers and ensuring that specified smoothness criteria are met. Pavements constructed in accordance with specifications and meeting all quality standards are likely to achieve their design life and exhibit lower maintenance costs and corresponding lower use phase and maintenance-related environmental burdens.

Effective specifications and adherence to rigorous construction inspection procedures play a significant role in achieving the expected quality of pavements. QA plans have been implemented by contractors and agencies to improve the quality of materials and processes used in the construction of highway projects and to reduce life-cycle costs. The QA plan often covers all phases of asphalt concrete construction, including production, placement, and compaction. In many highway agencies, asphalt concrete acceptance and payments are based on contractor's fulfillment of inspection, sampling and testing, resident engineer's inspection, and statistical evaluation of specified quality characteristics (Caltrans 2009). Important pavement quality characteristics during asphalt concrete placement may include subgrade density, ambient and mixture temperature, layer thicknesses, joint construction, segregation, in-place density, and smoothness.

Many highway agencies are using percent within limits (PWL) statistical methods as part of their acceptance criteria. The PWL method is used to assess the "quality" of the constructed pavement by estimating the percentage of the quality characteristic population that falls within the specification limit; the results can be used to determine pay factors (incentives or disincentives) based on the anticipated effects of the quality characteristic on pavement performance (Hand and Epps 2006).

Some of the common quality characteristics used to determine PWL (and pay factors) for asphalt pavements are in-place density or air voids and initial smoothness. This framework is designed with an assumption that there is a relationship between these quality characteristics and the long-term performance of the pavement. There is clearly a need for developing advanced methods and procedures for performing real-time monitoring and measurement of some of these key quality characteristics, and some advancements are being made in the use of ground penetrating radar (GPR), intelligent compaction (IC) technology, and infrared thermography (IRT) for this purpose.

The quality assurance of as-constructed pavement smoothness is performed by profile testing. Smoothness is one of the most critical pay items in most asphalt pavement contracts, and pavements that do not meet specification requirements can be subjected to expensive corrective actions and significant price adjustments. There is a strong correlation between in-service pavement smoothness and fuel consumption by vehicles using the pavement, as discussed in chapter 6.

### Improving Sustainability through the Use of Innovative and Emerging Technologies

Traditionally, various field and laboratory tests using field-extracted cores have been used for asphalt pavement density measurements. However, these conventional methods have several shortcomings. For example, in situ field tests (such as nuclear density gauge measurements) provide data from only a limited number of test locations. Similarly, extracted cores provide data from only a few locations on the pavement, in addition to being a destructive test (Al-Qadi et al. 2010; Leng 2011; Leng, Al-Qadi, and Lahouar 2011; Leng et al. 2012; Shangguan, Al-Qadi, and Leng 2012; Shangguan et al. 2013).

The application of nondestructive testing (NDT) methods, such as GPR and IRT, can overcome some of the shortcomings of the conventional QA methods. For example, figure 5-5 shows continuous density measurements of an asphalt pavement using the GPR technique. This method is rapid, provides greater coverage area, allows real-time monitoring of compaction efforts, provides near real-time density data, and, when calibrated for the specific aggregate used, provides greater accuracy than nuclear gauges (Leng 2011).

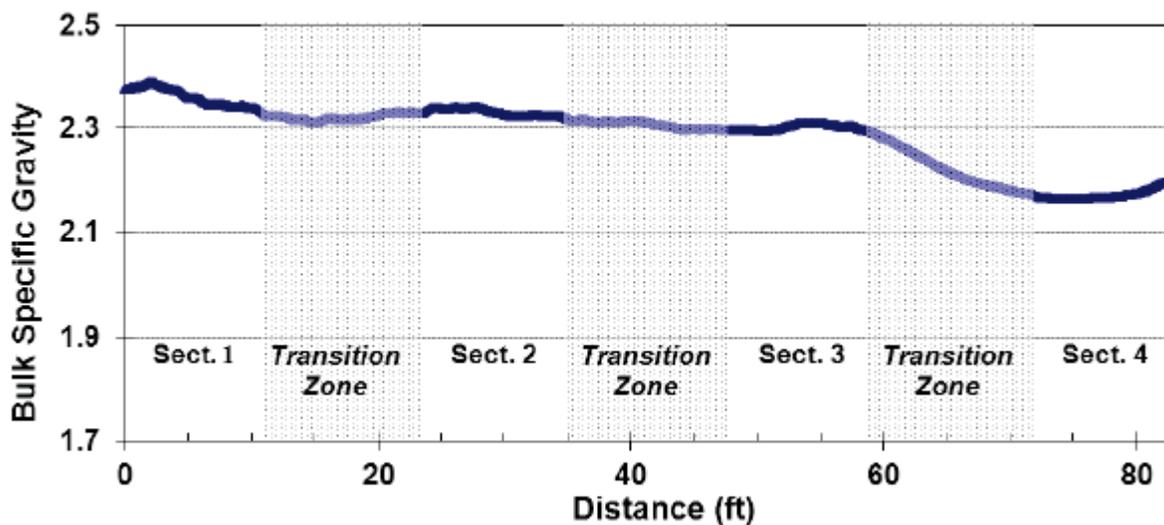


Figure 5-5. Bulk specific gravity profile of one test lane (Leng 2011).

Infrared thermographic scanning carried out immediately behind the paver screed can be used to monitor asphalt concrete materials and pavement surface temperatures. When temperature differentials exist in an asphalt pavement, the degree of compaction varies due to the viscoelastic material response to loading. The ability to detect and address thermal segregation during construction reduces potential pavement irregularities and, hence, improves the rideability and durability of asphalt pavements (Mahoney et al. 2003).

Another innovative construction QA method that can be used to optimize the compaction and desired density of unbound materials is intelligent compaction. The IC system uses a double-drum vibratory roller equipped with a measurement/control system. Unlike conventional asphalt pavement compaction equipment, IC rollers are equipped with technology such as a GPS-based system, color-coded display, and a temperature measurement system that can help monitor pavement construction data in real time, including the number of roller passes, roller speeds, and asphalt pavement surface temperatures, and can store these data for later evaluation (Horan et al. 2012).

It is noted that the application of IC for asphalt materials is limited to compaction process monitoring at this time. Measurements are affected by the material temperature and the stiffness of the supporting layers.

During the asphalt paving process, the use of spray pavers and MTVs can also be beneficial. A spray paver includes the functions of both a conventional paver and tack coat distributor (see figure 5-6). Thus, a tack coat can be placed immediately before the asphalt concrete layer is placed. This approach saves time, reduces the use of a distributor vehicle, and prevents contamination from the passage of paver treads over the tack coat thereby enhancing bond potential. And, as previously described, the use of an MTV is also expected to improve pavement sustainability by reducing potential segregation and temperature variation and maintain material consistency and uniformity.

### **Intelligent Compaction**

*Since 2008, the FHWA has been leading a national effort to advance the implementation of intelligent compaction (IC) technology to improve compaction of materials that include granular and cohesive soils, stabilized bases, and asphalt pavements. One of the emphasis areas in its Every Day Counts (EDC) initiative, the FHWA defines IC as a process that includes vibratory rollers equipped with a measurement and control system that can automatically control compaction parameters in response to materials stiffness measured during the compaction process. The roller must be equipped with GPS measurements and a documentation system that allows for continuous measurements of the roller location and the corresponding stiffness-related output. Through this process, improvements in the quality and uniformity of constructed pavements are achieved, resulting in better performing, longer lasting pavements. Moreover, IC efficiencies also produce significant time, cost, and fuel savings.*

*Additional information on IC is found at <http://www.intelligentcompaction.com/>.*



Figure 5-6. Spray paver on the left and material transfer device on the right used in the overlay construction in Illinois (Al-Qadi et al. 2012).

### Strategies for Improving the Sustainability of Concrete Pavement Construction Practices

Concrete pavement construction generally consists of the following activities:

- Preparation of the subgrade (including any required excavation, hauling, borrow, leveling, and compaction of multiple lifts of material).
- Hauling, placement, trimming, and compaction of subbase and base layers, which may also include curing.
- Proportioning and mixing of the concrete materials (see chapter 3).
- Hauling and placing of the concrete materials.
- Finishing, texturing, and curing of the concrete pavement.

This general process is depicted in figure 5-7. Throughout every stage of this construction process, there are numerous opportunities for improving the environmental, economic, and societal impacts (i.e., the sustainability of the process).

Long service life is one of the primary drivers of pavement sustainability. The ability to achieve that long service life is strongly impacted by the quality of construction. In fact, the potential gains in sustainability afforded by the optimization of structural design, the use of highly durable or recycled materials, and the improved efficiencies in the production of cement and other materials can be completely negated by poor construction quality and improper construction techniques. The following subsections describe the various impacts of construction quality on pavement service life and sustainability and provide strategies and techniques for improving the same.

Previous portions of this chapter describe many of the strategies that can be considered for pavement construction processes in general, and those are not repeated here. Furthermore, chapter 3 describes techniques for improving the sustainability of the production of concrete materials, including the production of cement and the operation of concrete batch plants, and those topics are generally not repeated here other than to discuss how they impact the sustainability of concrete pavement construction operations.

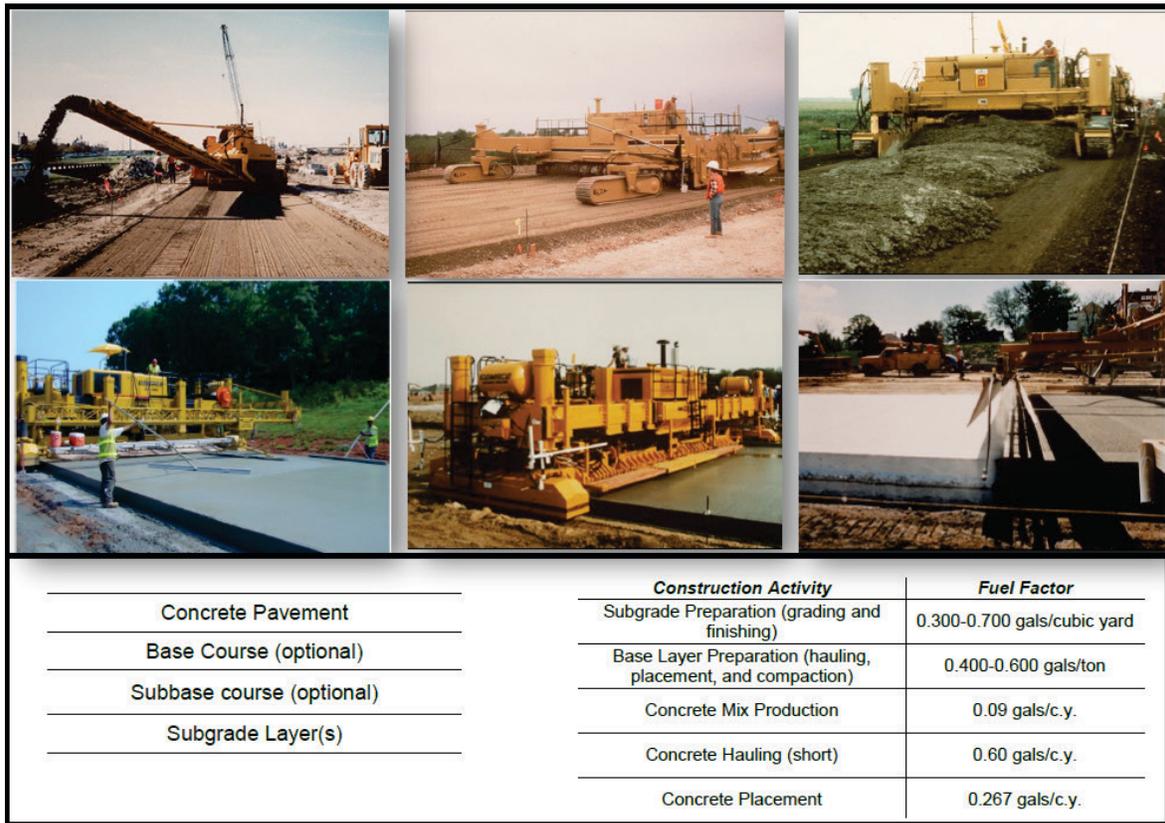


Figure 5-7. Generalized concrete pavement construction processes and associated fuel factors (fuel factor source: Skolnik, Brooks, and Oman 2013).

General approaches to improving the sustainability of concrete pavement construction operations, along with a qualitative assessment of the interactions and trade-offs between their economic, environmental and societal impacts, are summarized in table 5-10. A comprehensive LCA must be considered to provide quantitative estimates of the benefits and impacts that result from any proposed sustainability-improving action.

**Site Prep Work**

***Preparation of Support Layers***

The accurate grading and uniform compaction of foundation layers are essential for ensuring the economy and long-term performance of all pavement types. These are accomplished by 1) providing a solid and accurate paving platform that allows the construction of the pavement surface (usually the highest quality and most expensive material in the structure) to the proper grade and cross slope without using unnecessary material; and 2) providing uniform as-designed support to ensure long-term ride quality and resistance to distress. The latter item is particularly true and important for concrete pavements because the rigidity of the pavement surface resists deformation due to movement in the underlying layers. Studies have also shown that, all things being equal, improvements in initial ride quality translate directly into longer pavement service life (when structural or material durability problems are not present) (Smith et al. 1997). Care must also be taken that any required interlayer materials are properly installed to ensure isolation of the surface (i.e., over cement-treated or lean-concrete base layers, where required).

Table 5-10. General approaches for improving the sustainability of concrete pavement construction.

Objectives	Sustainability Improving Approach	Economic Impact	Environmental Impact	Societal Impact
<b>Protect Water Resources</b>	Concrete wash water collection and reuse	Increased cost for collection and removal, but reduced costs of remediation and clearing drains.	Positive impact by eliminating localized vegetation kills and pH impact on local surface waters.	Negligible to slightly positive impact.
<b>Reduce Use of Virgin Materials</b>	On-Site Recycling	Reduced haul costs, reduced material costs.	Reduced fuel consumption, reduced GHGs, reduced consumption of resources.	Negligible to slightly positive impact.
	Two-Lift Paving	Negligible to slightly higher construction costs.	More energy consumed in construction, improved use of local and recycled materials, potential reductions in use-phase fuel consumption and GHGs.	Negligible to slightly positive impact.
<b>Improve Initial Ride Quality (Minimize Use-Phase Fuel Consumption and Emissions)</b>	Two-Lift Paving	Negligible to slightly higher construction costs.	More energy consumed in construction, improved use of local and recycled materials, potential reductions in use-phase fuel consumption and GHGs.	Positive impact of improved ride quality, reduced use-phase costs for vehicles.
	Real-Time Profile Measurement	Capital cost of equipment.	Potential reductions in use-phase fuel consumption and GHGs.	Positive impact of improved ride quality, reduced use-phase costs for vehicles.
<b>Increase Pavement Service Life</b>	Improved Construction QA (including Dowel Alignment Measures)	Additional testing costs.	Potential for longer life cycle.	Potential for extended time between maintenance activities, longer life cycle, and lower user costs.
	Good Curing Materials and Practices	Negligible to modest increase in construction costs.		
<b>Balance Surface Friction and Tire-Pavement Noise</b>	Selection and Design of Surface Texture	Negligible to modest increase in construction costs (depending upon surface texture selected).	Potential to reduce tire-pavement noise inside and outside of vehicles.	Potential for improvements in friction, safety.
<b>Minimize Construction Fuel Use and Emissions</b>	On-Site Recycling (Foundation Layers)	Reduced haul costs, reduced material costs.	Reduced fuel consumption, reduced GHGs, reduced consumption of resources.	Negligible to slightly positive impact.
	Match Construction Equipment and Production Capacities	Cost savings	Reduced fuel consumption and GHGs, less wasted material.	Minor impact.
	Single-Lift Construction	Cost savings over multi-lift construction processes	Lower fuel consumption and GHG emissions.	Negligible to favorable impact, depending upon time savings.
	Use Roller-Compacted Concrete	Significant construction cost savings (mainly due to materials)	Lower fuel consumption and GHG emissions in construction	Minimal impact for low-speed pavements; generally inadequate ride quality (without overlay or diamond grinding) for high-speed roadways
	Use Early Entry Saws	Reduced cost	Reduced construction fuel consumption and GHG emissions.	Negligible.

### *Installation of Dowels, Tie Bars and Slab Reinforcement*

Dowels, tie bars, and slab reinforcement are essential structural elements of concrete pavement systems. As with any structure, these elements can only perform their intended functions properly if they are installed at the correct locations, at the proper elevations, and in the correct alignment or orientation. For example, reinforcing steel that is placed too close to the pavement surface may cause surface distresses that require costly and disruptive repair activities. Dowels, an essential element for the performance of heavy-duty concrete pavements, may be misaligned or mislocated in one or more of five different ways (three translational modes, two rotational modes), each of which has a different potential impact on pavement performance. Mislocated tie bars may cause surface spalls, may fail to hold joints tightly together and in alignment, or may improperly interfere with the function of other joints.

Ensuring the proper location and alignment of dowels, tiebars, and slab reinforcing can require maintenance and calibration of insertion equipment, proper location of baskets and support systems, proper anchoring of basket and support systems (to prevent shifting and overturning during paving), and adequate joint marking and sawing practices (to ensure that joints are sawed over properly located dowels and tie bars). The specification and use of corrosion resistant (or corrosion proof) dowels, tiebars, and reinforcing is a design issue, but is worth mentioning again as an important component in the context of the construction of long-life, durable concrete pavement systems.

After the concrete has been placed, the measurement of in situ dowel alignment can be performed nondestructively using one of several relatively new devices. The MIT-SCAN2-BT, which uses magnetic tomography to determine dowel alignment, was first introduced to the market in 2001, and is probably the most widely adopted dowel alignment measurement device in the U.S. Additional information on this device can be found at the websites of the manufacturer<sup>1</sup> and the FHWA.<sup>2</sup> GPR-based devices for measuring dowel alignment include the GSSI StructureScan™ Mini HR<sup>3</sup> and the Hilti PS 1000.<sup>4</sup> An additional device, the MIRA Tomographer, uses ultrasonic tomography to measure dowel alignment. More information on this device can be found at the manufacturer's website.<sup>5</sup> Overall guidance concerning dowel alignment tolerances is available in several recent publications (Snyder 2011; ACPA 2013).

### Proportioning Concrete Mixtures – Impacts on Sustainable Construction Practices

Strategies for developing and producing durable, economical, and sustainable concrete mixtures are covered in chapter 3. However, one key point worth repeating is concrete mixture proportioning, largely because of its impact on concrete pavement constructability and paving operations, as well as its effect on pavement longevity.

Mixture proportions must be developed to achieve the proper balance of economy, strength, durability, and workability (defined as the property of fresh concrete that determines the ease with which it can be mixed, transported, placed, consolidated, and finished to a homogenous condition). Improvements in any two or three of these criteria are generally achieved at the expense of the others. For example, reductions in the water-cementitious materials ratio

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<sup>1</sup> <http://www.mit-dresden.de/en/produkte/duebelmessgeraet/kurzbeschreibung1.html>

<sup>2</sup> <http://www.fhwa.dot.gov/pavement/concrete/mitreport/mits03.cfm>

<sup>3</sup> <http://www.geophysical.com/>

<sup>4</sup> [http://www.hilti.com/holcom/page/module/product/prca\\_rangedetail.jsf?&nodeId=-450121&selProdOid=1107542](http://www.hilti.com/holcom/page/module/product/prca_rangedetail.jsf?&nodeId=-450121&selProdOid=1107542)

<sup>5</sup> <http://www.germann.org/Brochures/Catalog-NDT-2010.pdf>

generally increase both strength and durability, but may adversely affect concrete workability and finishing characteristics if other mixture adjustments are not made as well (e.g., changes in aggregate gradation or the use of chemical or mineral admixtures). A mixture with poor workability and finishing characteristics may require additional energy for mixing, placing, strike off, vibration, screeding, and finishing. Furthermore, paving production rates may be lower and construction-related energy and labor costs may also increase.

### Concrete Hauling and Placement

The best concrete hauling, placement, and finishing operations cannot add to the quality and longevity of a concrete pavement; they can only serve to achieve the potential intended by the design and materials engineers. Substandard operations can, however, negatively affect concrete pavement and material properties, thereby adversely affecting long-term pavement performance and sustainability.

One way in which the sustainability of the pavement *construction process* can be improved is by maximizing the efficiency of the overall operation. This requires that the most efficient equipment be selected for the critical operation (typically, the paving operation) and that the production capacities of other operations be matched to that efficiency. For example, the type and size of equipment to be used for hauling operations must be selected with consideration of the project haul routes and maneuverability requirements, and the number of units must be chosen to allow continuous operation of the paver at its most efficient speed. Table 5-11 presents typical ranges of fuel consumption and emissions for concrete mixing, paving, and texturing activities and illustrates the potential impact of “right-sizing” equipment to minimize fuel consumption and emissions. It should be noted that the ranges presented also reflect potential variations in operational efficiencies, which are affected by the stiffness, workability, and finishing characteristics of the paving mixtures.

Table 5-11. Energy efficiency and CO<sub>2</sub> emissions for typical equipment used for concrete pavement construction (compiled from Santero and Horvath 2009a and Skolnik, Brooks, and Oman 2013).

<b>Construction Activity</b>	<b>Equipment</b>	<b>Horsepower Range</b>	<b>Fuel Consumption Range (gal/hr)</b>	<b>CO<sub>2</sub> Emissions Range (lb/hr)</b>
Concrete mixing in truck	Mixing truck	--	6-10	136-226
Concrete Paving	Slipform paver	100-250	5-13	113-294
	Texture/curing machine	70	5	113
	Concrete saw	10-40	0.5-1	11-23

Competing sustainability measures involving economics (initial and life-cycle costs) and environmental impacts (fuel consumption and emissions) must be weighed and balanced in considering the construction of single-lift pavement surfaces versus multi-lift pavement structures (including two-lift concrete paving [discussed at the end of this chapter], typical asphalt pavement construction, composite pavement construction, and even “staged construction”). Single-lift construction offers clear benefits in terms of reducing the number of

paving passes (and rolling and compacting passes for asphalt and RCC pavements), and may even result in the operation of fewer pieces of construction equipment for a given project (e.g., two paving machines and two batch plants are often employed for two-lift concrete paving versus one of each for single-lift paving). In addition, the placement of a single lift of paving may expedite project completion. However, the construction of multi-layer pavement structures, whether concrete or asphalt, generally results in better initial pavement smoothness, which can extend pavement maintenance cycle times and service life. Multi-layer paving also facilitates the use of different types of materials in the various paving layers (e.g., in two-lift concrete pavement, recycled concrete aggregate in the lower lift and hard, angular rock in the top lift).

Skolnik, Brooks, and Oman (2013) recently compiled updated typical fuel usage factors for many aspects of pavement construction; these values can be used to compare the relative fuel consumptions associated with single-lift versus multi-lift construction activities. This information can then be weighed against the other benefits and costs of each construction technique while keeping in mind the overall sustainability goals and objectives of the agency.

There are many aspects of concrete pavement construction for which QA is essential in order to achieve the full potential longevity (and, therefore, sustainability) of concrete pavements. These include (but are not limited to): stringline setup and maintenance, plant certification, proper equipment setup and hauling (including haul time restrictions in normal and hot weather), proper placement of the concrete (to minimize segregation and maintain a constant load ahead of the paver), control of water use at the job site, proper materials quality assurance (e.g., monitoring mixture consistency through air, slump and unit weight testing, as well as thickness control and strength or maturity testing), proper concrete consolidation of concrete without overvibration (through the use of vibratory frequency monitors and their adjustment with variations in the concrete mixture), and proper selection and use of curing materials, among others. Best practices for all of these aspects of concrete paving are described in detail in several key references (ACPA 2008; ACPA 2010).

All hauling, paving, and finishing equipment must be maintained in a way that prevents the buildup of hardened concrete. This is particularly true for haul trucks, where old concrete material can become a “contaminant” and cause finishing or performance problems in future loads.

Haul trucks and other equipment must be washed out frequently, but concrete wash water is toxic to fish and aquatic life and can contaminate drinking water supplies. In addition, washout sediment can clog pavement drain systems. Therefore, concrete wash water must be prevented from entering waterways, drainage systems, and groundwater. Best management practices include the return of all concrete waste and wash water with each concrete truck for disposal at the concrete batch plant. If this is not possible, an on-site, concrete washout area should be established to collect washout water.

There are several options for on-site, concrete washout water collection, including prefabricated containers (for which some supply companies offer maintenance and disposal services) and self-installed, above-ground or below-ground containers (which may be less reliable and more prone to leaks than the prefabricated containers) (Ecology 2012). Any on-site containers should be placed 50 ft (15.3 m) or more from drains, ditches, and surface waters, and must be properly sized. Ecology (2012) provides good guidance on the design of on-site, washout water-collection facilities.

Technologies for using increasing amounts of “grey water” (from washing concrete production equipment and trucks) are rapidly becoming more common and accepted. Chapter 3 presents a schematic illustration for recycling concrete wash water into batch plant mixture water and also summarizes typical limits on chlorides, solids, and other potentially harmful contaminants in recycled water.

### Finishing, Texturing, Jointing, and Curing

Finishing, texturing, jointing, and curing have the potential to impact pavement service life (which affects maintenance activities and life-cycle costs) and initial smoothness (which impacts fuel efficiency and vehicle wear and tear in the use phase). The following subsections briefly describe sustainable practices these aspects of concrete pavement construction.

#### *Finishing*

If good mixture proportioning, hauling, and placement practices are followed and if the paving equipment is properly set up and well maintained, very little hand finishing is needed. Hand finishing should be used sparingly and only as necessary to correct significant pavement surface flaws and profile defects. Overfinishing and the use of water added to the surface as a finishing aid must be avoided because loss of surface durability may result. ACPA (2010) provides additional details concerning best practices for concrete pavement finishing.

#### *Texturing*

Concrete pavement surface texture must be constructed to provide both adequate surface friction (sustainability through safety and reduced crash rates, particularly in wet weather) while also minimizing the generation of noise through tire-pavement interaction. There are many concrete pavement surface texture options, including transversely oriented textures (e.g., transverse tining, brooming and grooving), longitudinal textures (e.g., longitudinal tining, brooming, grooving, turf drag and

### **Concrete Pavement Surface Texture**

*A number of different concrete pavement surface textures are used by highway agencies, as shown below. The FHWA provides guidance on the selection and creation of each of these textures and allows for the use of other textures “if research indicates long-term safety performance is achieved.” (FHWA 2005).*



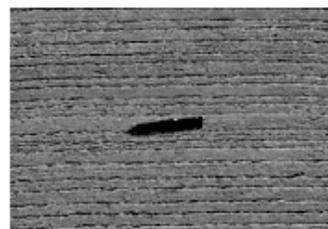
*Turf Drag*



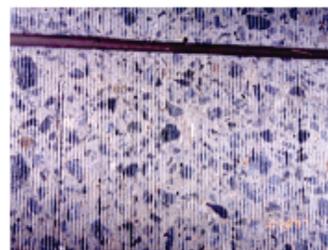
*Long. Tining*



*Exposed Agg*



*Trans. Tining*



*Diamond Grind*

*Photos courtesy of ACPA.*

diamond grinding), and textures with no particular orientation (e.g., porous concrete, and exposed aggregate finishes). Details concerning the tire-pavement noise and friction characteristics of each of these surface types throughout the use phase of the pavement life cycle are presented in chapter 6.

The success of some of these types of texture require specific mixture design characteristics (e.g., the inclusion of siliceous fine aggregate for microtexture, specifically graded and shaped coarse aggregate particles for exposed aggregate finishes, and low water-cementitious ratios for durable turf drag finishes) and construction techniques to achieve proper texture depth and pattern spacing.

### Jointing Considerations

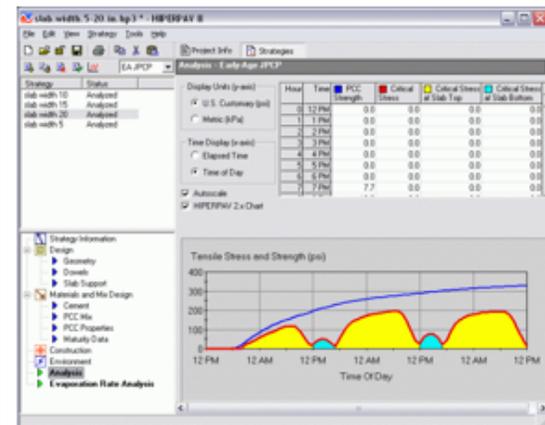
All concrete pavement contraction joints must be sawed in a timely manner to prevent the development of uncontrolled cracking. Successful joint cutting requires that the contractor accurately determines the window of sawing opportunity: too early and the concrete will ravel and be damaged by the sawing operation, too late and the pavement may crack randomly and not at the planned joint locations. Contractor experience can play a major role in the timing of joint saw cuts, but tools such as the HIPERPAV program (which considers factors such as mixture components, proportions, and temperature in the context of ambient environmental conditions) can also be used to determine appropriate sawing times. HIPERPAV can be downloaded free of charge at <http://www.hiperpav.com/>.

Early entry saws, which can be used to make a shallower joint sawcut at an earlier age, typically require less operational energy and can be used to improve the sustainability of the joint sawing operation (although extra care must be taken to avoid damaging the young concrete with the early sawing operation).

It is very important that the joint locations be accurately established prior to sawing and that the saw operators take care to cut the joints precisely. Failure to do so may result in an effective longitudinal translation of any dowel load transfer devices, even if the basket placements or insertion processes were accurate. Significant longitudinal translations can result in poor joint

### High PERFORMANCE concrete PAVing Software (HIPERPAV)

HIPERPAV® is software that can be used to analyze the early-age behavior of jointed concrete pavements, continuously reinforced concrete pavements, and bonded concrete overlays. Developed under FHWA funding, the program considers concrete mixture design materials and proportions, pavement geometry, environmental conditions, and additional inputs to determine the development of stresses caused by temperature and moisture gradients (i.e., curling and warping).



The program then compares these stresses with the predicted strength development for the specified mixture and provides users with a graphical indication of when cracks can be expected to develop (i.e., when stresses exceed strength) if they aren't controlled by joint sawing.

HIPERPAV can also perform an analysis of potential evaporation rates for the specified mixture and environmental conditions (ambient temperature, relative humidity and wind speed), which is useful in ensuring timely application of curing techniques to prevent shrinkage cracking.

behavior and premature failures. ACPA (2010) provides guidance on joint sawing operations and ACPA (2013) provides guidance on limitations for dowel longitudinal translation (and, therefore, accuracy of joint saw cutting).

### *Curing*

Good curing practices are essential to the control of early-age pavement temperatures and the prevention of moisture loss, which can result in decreased concrete strength, shrinkage cracking, slab warp and curl (and their associated stresses), loss of concrete durability, and other problems that can reduce concrete pavement performance life and, therefore, sustainability. The use of effective curing materials (applied at the proper time and (for liquid curing compounds) at the proper rates of application is essential. Research suggests that there is a wide range of effectiveness in moisture retention among commonly accepted curing techniques (Whiting and Snyder 2003; Vandenbossche 1999).

### Improving Sustainability through the Use of Innovative and Emerging Technologies

#### *Two-Lift Concrete Paving*

Two-lift concrete paving involves the placement of the concrete in two layers (wet-on-wet) rather than the single-lift paving that is typically used. Two-lift paving can provide improved ride characteristics, facilitate the effective use of local, recycled, or marginal quality aggregates (in the lower layer), increase the use of SCMs (in the lower lift), and reduce overall material costs without sacrificing pavement quality and service life (Fick 2010). Environmental impacts are expected to be less because of the use of SCMs and RCWMs, and construction costs may also be reduced, although this will be project specific.

Two-lift concrete pavements have been constructed in the United States since 1891, when the first U.S. concrete pavement was constructed in Bellefontaine, Ohio as a “two-course” pavement. Two-lift construction was widely used to facilitate the placement of mesh reinforcing in jointed reinforced concrete pavement (JRCP) designs that were widely used in the 1960s and 1970s, but fell from common practice when short-panel, unreinforced slab construction became the norm. Only a handful of two-lift concrete pavements were constructed in the U.S. in the 1980s and 1990s, but two-lift paving technology was identified as a high-priority implementation technology as a result of the May 2006 FHWA SCAN tour of European concrete pavements. The strong potential for improved sustainability in this type of construction has been demonstrated in several countries, including

#### **Two-Lift Paving**

##### *Kansas Demonstration:*

*In October 2008, the Kansas DOT (KDOT) constructed a two-lift paving demonstration project on I-70 in Saline County, Kansas. Dense, wear-resistant rhyolite aggregate was imported for the top lift, while a more porous local limestone was used for the lower course. A Class F fly ash-gypsum combination was substituted for 20 percent of the cement in the top lift to reduce permeability and assist in mitigating any possible ASR. In addition, cement-treated recycled concrete aggregate from the original pavement was used as a base layer. Several different surface textures were used in various sections to evaluate their effects on tire-pavement noise.*

##### *Missouri Demonstration:*

*In September 2010, a portion of Route 141 in St. Louis County was reconstructed with an innovative section of two-lift concrete paving that was highlighted by the use of photocatalytic cement in the top lift, along with pervious concrete pavement in the shoulders.*

*Open Houses were held for both of these demonstration projects, and the presentations and other reports and handout materials from the open houses are available through the National Concrete Pavement Technology Center at:*

*<http://www.cptechcenter.org/research/research-initiatives/two-lift/>*

*<http://www.cptechcenter.org/events/archive/2lift-StL-page.cfm>*

Austria, where 100 percent of the old concrete pavement is recycled into a bound subbase and the lower lift of a two-lift concrete pavement (Hall et al. 2007).

Between 2008 and 2010, two major two-lift PCCP demonstration projects were constructed in the U.S. (in Kansas and Missouri – see sidebar for additional information) in order to demonstrate the technology and assess the potential economic and environmental benefits of two-lift concrete paving. Moving from demonstration to routine practice, the Illinois Tollway made two-lift concrete paving (using reclaimed asphalt pavement and crushed concrete in the lower lift) a major component of the 2012-2016 reconstruction and widening program of more than 180 lane miles of Interstate 90 between Elgin and Rockford.

### *Roller Compacted Concrete (RCC) Paving*

RCC is a no-slump concrete mixture that is initially compacted using the paver screeds and tamping bars of a traditional asphalt paving machine or high-density paver, followed by the use of heavy vibratory and rubber-tired rollers—much like conventional hot-mixed asphalt concrete.

RCC consists of the same basic ingredients as conventional concrete, but has different mixture proportions, and has similar strength properties. The most significant difference between RCC mixtures and conventional concrete pavement mixtures is that RCC has a higher percentage of fine aggregates, a lower cement content, and a very low water-cementitious material ratio (hence the very low slump). Load transfer dowels are not used with stiff, dense RCC mixtures, and transverse joints are either not sawed or are sawed at greater-than-usual spacing (due to the reduced shrinkage potential of the mixtures) mainly for aesthetics. Load transfer across transverse cracks and joints is provided mainly by aggregate interlock.

The initial compaction of the RCC allows for almost immediate use of the pavement by light vehicles (support is provided through particle-to-particle contact), with cement hydration providing excellent, long-term strength and durability (without the use of air-entraining admixtures). The resulting ride quality is generally adequate for lower-speed traffic, but diamond grinding and overlays are often used to provide an improved surface profile for higher speed traffic.

RCC offers the superior load-carrying capacity and longevity of concrete pavements while having reduced material costs (due to lower cement contents and fewer admixture requirements), reduced construction costs (due to the use of lower-cost paving equipment and often no sawing of contraction joints), and lower local impact to traffic because of the ability to allow limited traffic access within just a few hours of placement.

A comprehensive review of the design and construction of roller-compacted concrete pavements is available from the Portland Cement Association (Harrington et al. 2010).

### *Real-Time Smoothness Measurements*

The measurement of concrete pavement profiles (useful in computing indicators of pavement ride quality and smoothness, like IRI and various forms of the Profile Index [PI]) has historically (and necessarily) been performed after the pavement has hardened and can be subjected to foot or light vehicle traffic. Two major disadvantages of this approach to profile measurement are: 1) pavement texturing and joint forming operations can affect profile measurements (usually adversely), and 2) corrective measures (to address existing profile problems and to prevent problems with further paving) are limited.

Non-contact surface profilers are now available to provide real-time measures of pavement profile directly behind the paving machine, thereby eliminating the effects of measuring texture and pavement joints while allowing for construction process corrections that will prevent continuing and recurring profile problems (Rasmussen et al. 2013). The data collected can still be used to produce IRI or PI values, and are also useful in establishing baseline profiles for pavement curing or curling/warping studies. Some real-time profile measurement devices can also be used for prepaving checks of stringline setup and subgrade/subbase profile (to maximize paving yields).

Real-time profile measurement of concrete pavements offers potential sustainability advantages in improving initial pavement smoothness, which should produce corresponding increases in vehicle mileage in the use phase and may also result in deferment of ride-related maintenance and rehabilitation actions, as well as extended overall pavement service life.

Available real-time profiling equipment comes in different options for mounting directly on the paver, on a work bridge, or on a separate piece of specially designed and dedicated profile measurement equipment. More information on two of the available systems can be found at <http://www.gomaco.com/Resources/gsi.html> (for the Gomaco Smoothness Indicator [GSI] system) and at <http://www.amesengineering.com/RealTimeProfiler.html> (for the Ames Engineering SmoothPave RTP [Real-Time Profiler]).

### Concluding Remarks

Pavement construction activities offer many opportunities to adopt practices that improve the sustainability of the pavement system. Obvious and highly visible example practices include the use of on-site recycling to produce pavement foundation layers and the protection of groundwater and local fauna by collecting and removing (for recycling) concrete waste water. Less obvious are the impacts that good construction practices can have on fuel consumption and user vehicle expenses and agency repair costs during the use phase.

The potential impacts of the construction phase (i.e., construction equipment and activities) on overall life cycle assessment for a given roadway may be relatively small, particularly when compared to the impact of the materials phase and the use phase (Santero and Horvath 2009b). For example, Zapata and Gambatese (2005) indicate that the “placement phase” consumes only about 3 percent of the total energy in the pavement life cycle. However, the construction phase is a phase over which engineers and contractors have a great deal of influence. Therefore, it is important to be cognizant of the many ways that construction phase activities can influence overall pavement sustainability. This chapter provides a good perspective of the many opportunities for improving (or maintaining) pavement sustainability during the construction phase of the overall pavement life cycle.

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