Sustainability, Rehabilitation, and Management of Pavements

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Section 1 — Concept of Sustainability

Sustainability is the concept of satisfying the needs of the current demand without compromising potential consumers' ability to meet their own needs, taking into account the three main components: economic, environmental, and social impacts. The significance of each of these factors depends on the goals, demands, characteristics location, materials, and constraints of a given project.

Section 2 — Role of Pavement in Sustainability

Sustainability in pavement refers to a pavement's ability to (Van Dam et al., 2015):

- Attain the engineering requirements in the pavement structures and materials.
- Preserve and improve the surrounding ecosystems.
- Assure an economical use of resources.
- Provide satisfaction to users.

The United States has over 4 million miles of public roads (FHWA, 2013a). Nearly 3 trillion vehicle miles traveled (VMT) over these roadways were logged in 2010, consuming over 169 billion gallons of fuel in the process (FHWA, 2010a). The total highway investment in the United States in 2008 was $182.1 billion (FHWA, 2010a). A variety of vehicles (cars, trucks, buses, bicycles) and users (commuters, commercial motor carriers, suppliers and service providers, local users, leisure travelers) benefit from sustainable pavements. Below are some examples of how pavements can affect sustainability:

- Environmental benefits by saving energy consumption, greenhouse gas emissions, noise, air quality, water treatment, and so on.
- Social benefits by improving safety (fatalities, injury, damage to property), smoothness, vehicle operating costs, access mobility, aesthetics, etc.
- Economic benefits from reducing costs of construction, repair and rehabilitation, operating costs of vehicles, accident costs, etc.

According to AASHTO (2009), the aim of the transport system is no longer merely to move people and goods but to achieve sustainability in economic social and environmental sustainability. Transportation helps and enhances the quality of people’s lives.

Section 3 — Pavement Life Cycle

To better understand the effects of pavements on sustainability, it is useful to divide a pavement's life cycle into several significant phases as shown in Figure 1.

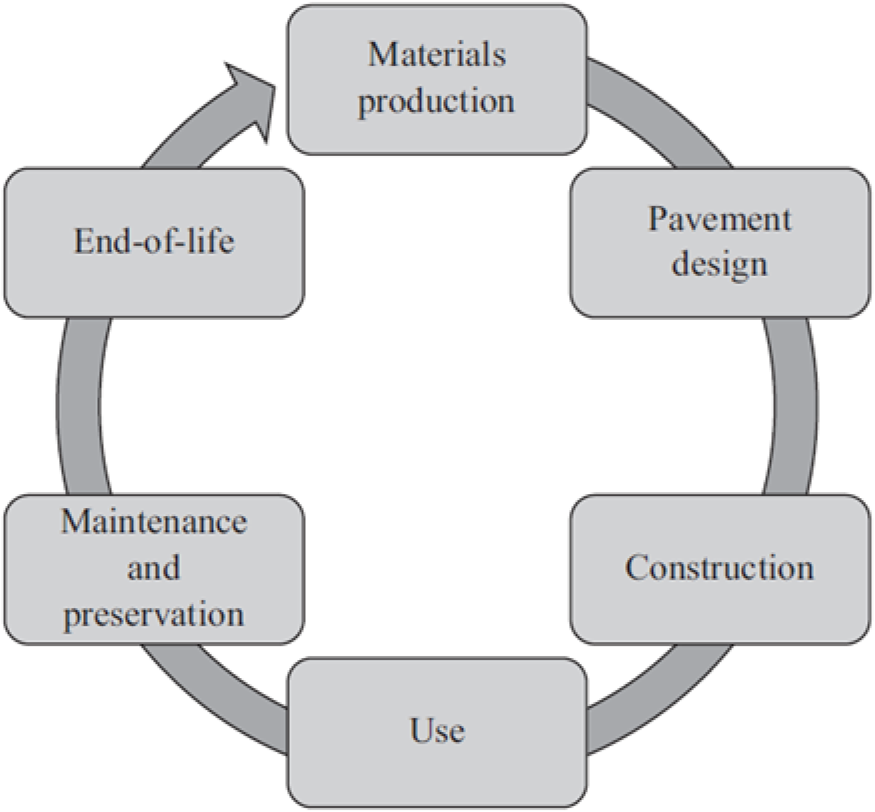

Figure 1 Pavement Life Cycle

Material Production: This applies to all the processes involved in the procurement of pavement products (e.g., mining, crude oil extraction) and processing (e.g., refining, manufacturing, mixing). Materials production affects such sustainability factors as air and water quality, health of the environment, human health and safety, depletion of non-renewable resources, and the life-cycle costs.

Pavement Design: This refers to the process of defining a pavement's structural and functional requirements for specific site conditions (subgrade, climate, existing pavement structure, traffic loadings) and then determining the structural composition of the pavement and accompanying materials. Structural design affects sustainability factors such as performance life, longevity, cost of the life cycle, construction (e.g., constructability, sequencing schedule), and material use.

Construction: Pavement construction refers to initial construction and subsequent maintenance and rehabilitation efforts. Construction activities affect sustainability factors such as air and water quality, human health and safety, durability and traffic disruptions in the working area, as well as project costs and time.

Use: Pavement use refers to many key pavement factors (e.g., roughness, viscoelastic energy dissipation, deflection, macro texture) that can have a significant impact on most sustainability metrics including fuel economy, vehicle operating costs, and related greenhouse gas emissions and energy consumption. Environmental interactions (e.g., stormwater disposal, heat/conductivity, and reflectivity) may also have an impact on other sustainability factors such as human health and safety, the effect of urban heat islands, and global scale radiative forcing.

Maintenance and Preservation: Pavement maintenance and preservation refers to actions that help slow a pavement's rate of deterioration by identifying and addressing specific deficiencies in the pavement that contribute to the overall deterioration. Maintenance and preservation have an impact on sustainability factors such as performance life, reliability, life-cycle costs, construction (e.g., constructability, sequencing scheduling), and material usage. Appendix A addresses different maintenance and preservation techniques.

End-of-Life: Pavement end-of-life refers to recycling any part of a pavement system that has reached the end of its useful life. Considerations of end-of-life affect sustainability factors such as waste generation and disposal quality of air and water, and use of materials. Appendix B addresses different recycling techniques.

Section 4 — Materials Consideration for Sustainability

Aggregates

Aggregates are relatively cheaper and have a low environmental impact compared with other pavement materials. Aggregates, however, constitute the more significant part of the structure of the pavement. Because aggregates are consumed in such large quantities, they can have a significant impact on the sustainability of the pavement. For example, in 2012, the United States produced about 1,324 million tons of crushed stone worth about $12 billion. Of the total crushed stone, 82% were used as construction material, mostly for road construction and maintenance. Approximately 927 million tons of sand and gravel worth about $6.4 billion have been produced for sand and gravel, of which 26% for road base, road covering, and road stabilization and 12% for asphalt concrete aggregates and other asphalt aggregate products (USGS, 2013a). Reducing the use of raw materials and using locally available materials and recycled materials would improve overall sustainability. Some strategies for the adoption of sustainability in pavements for aggregate use are shown in Figure 2.

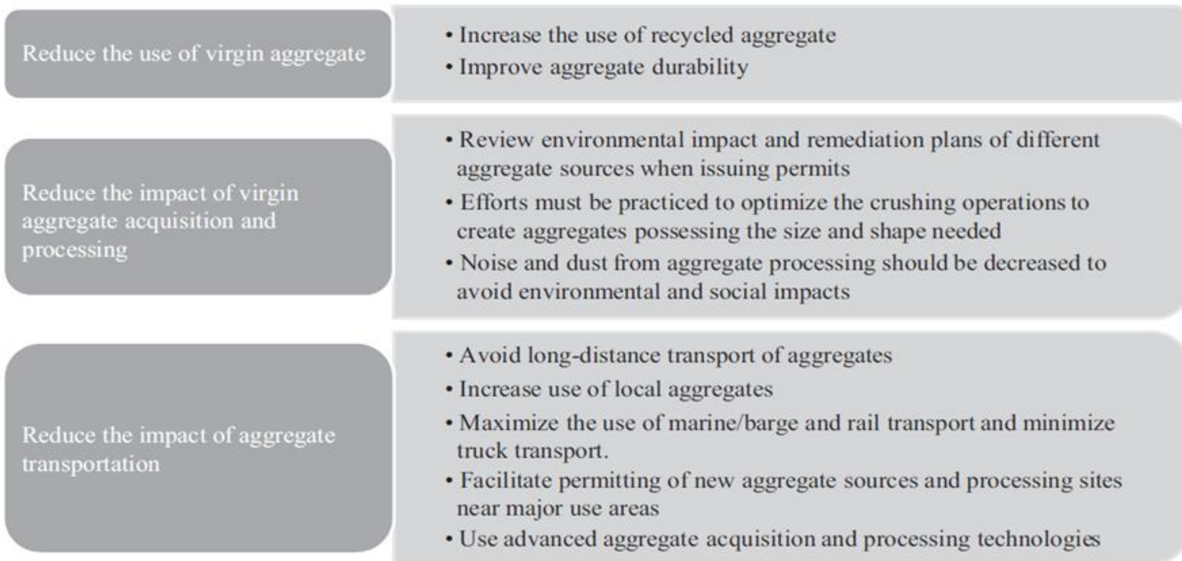

Figure 2 Strategies to Adopt Sustainability in Using Aggregates in Pavements

Asphaltic Materials

Asphalt binder is used to manufacture asphalt mix between 3% and 6% of the total mix. The United States used about 130 million barrels (23 million tons) of asphalt binder and road oil in 2011, worth $7.7 billion (EIA, 2011). The amount of U.S.-produced asphalt paving mixtures was estimated at $11.5 billion in 2007 (United States Census Bureau, 2007a). This data shows the importance of asphalt binder in the sustainability of pavements. In recent years, asphalt technology has greatly improved with the use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS). Also, polymer and rubber are used to improve binder properties. Some other sustainable practices, such as the use of warm-mix and cold-mix asphalt mixtures, are used to reduce energy consumption and greenhouse gas emissions, reduce the impacts of transporting materials, etc. Some strategies for improving the asphalt materials production are listed below:

- Reduce the amount of virgin asphalt binder and virgin aggregate in asphalt concrete by plant recycling.
- Reduce the energy needed and emissions from mixing asphalt concrete.
- Extend the life of asphalt concrete materials.
- Reduce the need for virgin materials and transportation through in-place recycling.

- Develop alternatives to petroleum-based binders.

Concrete Materials

According to the U.S. Geological Survey, the United States used about 111 million tons of hydraulic cement in 2005, worth about $9.1 billion. Approximately 5% of cement is used for road paving purposes in the United States in 2011 (USGS, 2013b). The United States has 5,500 ready-mixed concrete plants in 2011 (United States Census Bureau, 2013). The value of ready-mixed concrete manufactured in the United States in 2007 was estimated at $34.7 billion, indicating that the value of concrete used for road paving was approximately $1.7 billion based on 5% of cement used (United States Census Bureau, 2007b). However, Portland cement production uses huge amounts of energy and produces greenhouse gasses. Reductions can be made in these energy consumption and emission levels by reducing the use of Portland cement in paving mixtures. Several techniques for concrete paving are listed in Table 1.

Strategy	Sustainability improving approach
Reduce non-renewable energy consumption and greenhouse gas emissions in cement manufacturing	Improve cement plant efficiency through better energy harvesting and improved grinding
	Utilize renewable energy including wind and solar
	Utilize more efficient fossil fuels
	Utilize waste fuels
	Utilize biofuels
	Minimize clinker content in portland cement using limestone and inorganic processing
	Increase production of blended cement or supplementary cementitious materials (SCMs)
Reduce energy consumption and emission in concrete production	Increase concrete mixing plant efficiency and reduce emissions
	Utilize renewable energy
	Use electrical energy from the grid
	Use less cement in concrete mixtures without compromising performance
	Use more blended cements without compromising performance
	Increase addition rate of SCMs at concrete plant without compromising performance
Reduce water use in concrete production	Recycle washout water
	Recycle water used to process aggregates
Increase the use of recycled aggregates in concrete	Change specifications to allow more significant amounts of recycled, co-product or waste materials to be used in concrete without compromising performance
	Use RCWMs and marginal aggregates in lower-lift of two-lift pavement
Improve the durability of concrete	Lower water use through admixture use
	Utilize an effective quality assurance program throughout material production

Table 1 Strategies for Improving Pavement Sustainability for Concrete

Other Materials

Steel reinforcing fibers, geosynthetics, etc. are some other materials used in pavement steel production consumes a significant amount of energy and emits greenhouse gasses. It is even worse to make steel from raw materials. Steel production using electric arc furnaces has less impact on the environment as it produces steel from recycled steel. To increase the strength of concrete, fibers are used as reinforcement. This reduces the concrete slab thicknesses and extends the spacing of the joints. Some fibers can reduce plastic cracking and cracking severity. Geosynthetics can reinforce soil and unstabilized subbase and base materials to minimize the thicknesses necessary for other layers of pavement. It can also reduce or monitor reflection cracking development.

Section 5 — Rehabilitation Design for Sustainability

There is a greater opportunity to consider alternate materials, pavement structures, and construction procedures with the introduction of the AASHTOWare pavement ME design approach. AASHTOWare pavement ME design allows to evaluate changing input parameters in a matter of minutes to assess their effects on the final design. After trying various alternative approaches, it is possible to select the most sustainable design. The implementation of the AASHTOWare pavement ME design procedure thus contributes to the overall sustainability of the resulting design. Some other strategies for adopting sustainability in pavement design include optimizing the use of materials and cross sections, and evaluating pavement designs using life-cycle assessment (LCA), life-cycle cost analysis (LCCA), and rating systems to evaluate their environmental and societal impacts to improve them. The complete cycle can be summarized, as shown in Figure 3.

Section 6 — Construction Considerations for Sustainability

Pavement construction affects the sustainability of a pavement construction in different ways:

- Fuel consumption during material transport.
- Exhaust emissions such as carbon monoxide, carbon dioxide, sulfur oxide, nitrogen oxide, etc.
- Traffic delays and noise emissions during construction.

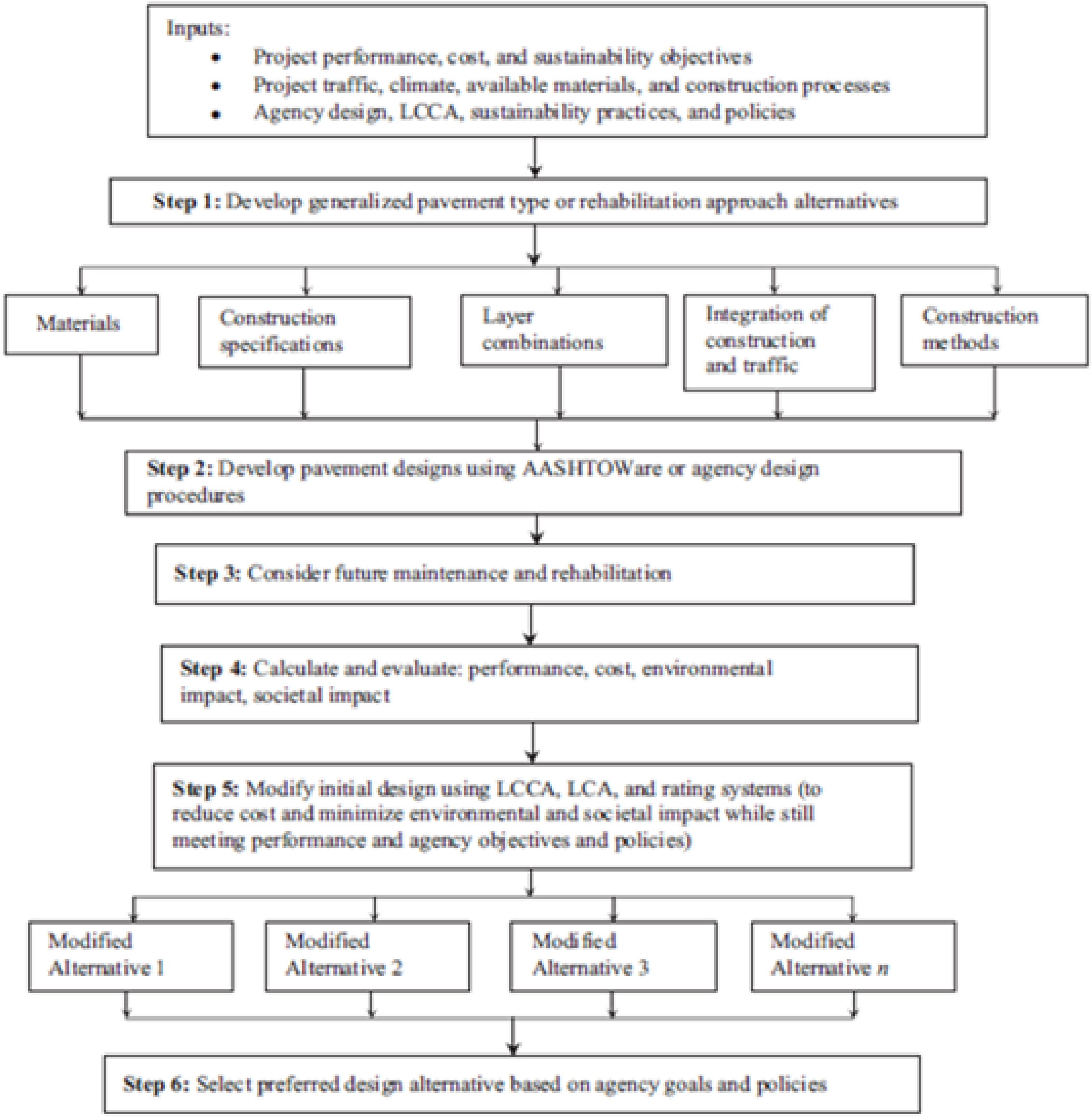

Figure 3 Process for Considering Sustainability in Pavement Design

- Constructed characteristics of the pavement surface such as surface friction, noise, and possibly fuel efficiency during the service time.

- Pavement performance and overall life as a result of construction quality.

The strategies to improve sustainability of general pavement construction operations are listed in Table 2.

Objectives	Sustainability improving approach
Reduce fuel consumption and emission	Minimize haul distances
	Select appropriate equipment type and size for the job
	Reduce idle time
	Use alternative fuels
	Retrofit construction equipment, use hybrid equipment, or both
Reduce noise	Introduce construction time restrictions
	Ensure equipment maintenance or modification
Accelerate construction	Implement effective traffic control and lane closure strategies
	Establish performance goals and measures for work zones
	Use computer software for construction sequencing and managing traffic delays
	Implement intelligent transportation warning systems
Control erosion, water runoff, and sedimentation	Use perimeter control barriers (fences, straw bales, etc.)
	Minimize the extent of disturbed areas
	Apply erosion control matting or blankets
	Store/stockpile away from the watercourse

Table 2 Strategies to Improve Sustainability of Pavement Construction Operations

Section 7 — Maintenance for Sustainability

Pavement maintenance or preservation is all about reducing the agency's life-cycle cost of the pavement. The agency considers only the cost of materials and pavement construction in its life cycle. The use-phase costs (primarily vehicle operating costs) are not taken into account by the agency and are mostly borne by users of pavement. Pavement maintenance or preservation uses gravel, water, cement, and asphalt combinations as construction materials and engines for combustion (e.g., transportation, removal, and application) to place.

Critical factors for selecting appropriate maintenance or preservation treatment include treatment performance history, overall performance requirements, construction constraints, life-cycle cost analysis (LCCA), and life-cycle analysis (LCA).

The sustainability value of any maintenance or preservation treatment is difficult to judge, as there are multiple factors at work. In general, treatments using the least quantity of material to maintain smoothness over the longest period have the greatest positive effect. Understanding the full impact of the life cycle is a crucial element in establishing the advantages and disadvantages of any maintenance or preservation treatment. Some of the commonly used maintenance or preservation treatments are listed below:

- Crack filling/sealing
- Asphalt patching
- Fog seals/rejuvenators
- Chip seals
- Slurry seals
- Microsurfacing
- Ultra-thin and thin asphalt concrete overlays
- Hot in-place recycling (HIR)
- Cold in-place recycling (CIR)
- Ultra-thin bonded wearing course
- Bonded concrete overlays

General approaches for enhancing sustainability include the use of thinner cross sections, the use of local materials, the maintenance of smoothness, and the increased quality of construction, all of which minimize the environmental burden and lead to more efficient treatment prospects for improving sustainability in the following areas:

- Improved maintenance materials that require the use of less content or last longer.
- Improved approaches for optimizing treatment selection and timing.
- Improved construction.

Section 8 — End-of-Life Considerations for Sustainability

Asphalt Pavements

Asphalt pavement recycling can be achieved through a central plant or in-place recycling techniques as follows:

- Central plant recycling (hot and cold)
- Full-depth reclamation
- Landfilling

Central plant recycling is the method of producing hot or cold asphalt mixtures in a central plant by combining virgin aggregates, new asphalt binders, recyclers, and a certain amount of RAP. RAP is milled off from old pavements, transported to plants, screened, and then used. In hot central plant recycling, heat is used to mix RAP, virgin aggregates, and new asphalt binders. Cold central plant recycling combines RAP with an emulsified asphalt/recycling agent and new aggregates, if necessary, without the use of oil. Full-depth reclamation (FDR) is a method in which the full thickness of the current asphalt pavement and the predetermined portion of the underlying materials (base, subbase, and subgrade) are uniformly pulverized and blended to produce a single material. All of these approaches are discussed in detail in Appendix B.

Asphalt and concrete pavements are usually recycled and reused as construction materials (EPA, 2009). According to industry data, less than 1% of RAP was transported to landfills in 2012, with 68.3 million tons of RAP being used in new asphalt concrete mixtures. This represents a 22% increase in the use of RAP in 2012 relative to 2009 (Hansen and Copeland, 2013). The total amount of recycled concrete used in the United States was estimated to be 140 million tons in 2014, including recycled materials from both pavements and other sources (CDRA, 2014). Such recycled materials can be used either in new asphalt or concrete mixtures, or as aggregates in base layers, or in a variety of other applications, such as filling, riprap, and ballast.

Several approaches to enhance the sustainability with respect to end-of-life pavement recycling, along with related environmental benefits, are summarized as follows:

- Improve plant technology such as improved dust control systems.
- Increase the initial quality of pavement materials and construction, which will increase the level of performance and the overall pavement life and reduce the total cost of pavement.

- Use rejuvenators or softening agents to reduce the brittleness of these materials, and reduce cracking.

- Maintain and manage rap stockpiles fractionated and moisture free to meet the design volumetric and extended performance.
- Select the proper type and amount of additives or stabilizers for the expected improvement in performance and service life.

- Implement the structural overlays to protect the recycled layers from direct exposure to weathering and slow down the deterioration rate.

- Improve the construction quality to improve the long-term performance of pavements.

Concrete Pavements

Concrete recycling includes demolishing, removing, and crushing hardened concrete from the old concrete pavement for the production of recycled concrete aggregate (RCA). The U.S. Geological Survey (USGS) reported that the cost of RCA in 2005 ranged from $3.41/ton in New Jersey to more than $8.09/ton in California, Louisiana, and Hawaii at an average cost of $6.93/ton. Virgin aggregates were estimated to cost an average of $6.52/ton, ranging from $3.54/ton in Michigan to more than $10.01/ton in Mississippi and Hawaii (Van Dam et al., 2015). There are three main end-of-life choices for concrete pavement surfaces:

- Recycling

- Reuse

- Landfilling

The use of recycled concrete aggregates instead of new aggregates is inherently sustainable when all other considerations are equal. The following subsections discuss strategies for enhancing the sustainability of concrete recycling by optimizing the production and use of materials, which are also summarized as follows:

- Optimizing the use of recycled materials through testing and characterization helps better understanding of the RCA properties.

- Adjustment of RCA production operations to reduce fuel and wastage.

- Customizing preparation and breaking of source concrete for higher production, reduce waste, reduce fuel, preserve natural sources, etc.

- Customizing crushing and sizing operations to increase production, reduce waste, preserve natural sources, etc.

- Sequestration of carbon dioxide to reduce the impact on climate change.

- On-site processing to reduce fuel, labor, and traffic congestion.

Section 9 — Measuring Pavement Sustainability

Sustainability measurement is the first step toward establishing benchmarks and assessing progress. The reasons for measuring the sustainability can be categorized into three broad categories:

- *Accounting:* To quantify the parameters such as cost saving and energy saving.

- *Decision Support:* To take organizational or project decisions.

- *Process Improvement:* To provide feedback in support of refining and updating the overall methodology

Currently, four general measurement tools, or methods, can be used to quantify sustainability: performance assessment, life-cycle cost analysis, life-cycle assessment, and sustainability rating systems.

Performance Assessment

Performance evaluation measures and assesses the performance of the pavement for its intended function and physical characteristics. Various performance parameters such as conventional distress (roughness, rutting, fatigue cracking, top-down cracking, and thermal cracking), composite condition ratings, and pavement structural capacity can be assessed.

Performance is most often assessed on the basis of current standard practice. For example, if the current standard asphalt pavement surfacing is supposed to last 10 years, the value of alternative surfacing (say, open-grade, stone matrix, or rubber asphalt) is calculated on the basis of how their expected service life corresponds to the standard 10 years (Van Dam et al., 2015). Alternatives are expected to perform in a manner that is equal to or better than the current standard practice or to produce some other economic, social, or environmental benefits.

Life-Cycle Cost Analysis (LCCA)

Life-cycle cost analysis uses an economic analysis to determine the total cost of a project over its life cycle. This offers a cost comparison between two or more similar design solutions with equivalent benefits. The initial cost of the project and all additional projected costs (such as maintenance costs, annual fees, and salvage value) are converted into current costs and added up to produce a net present value (NPV) or a net present cost (NPC). When several alternatives with similar benefits are considered over identical analysis periods, the NPVs or costs may be compared to determine the alternative that is most cost-effective (FHWA, 2013b).

The value of salvage is also included in the LCCA. It is the value of the materials required to be extracted from the pavement structure once it has expired (no remaining service life; the pavement is to be removed and replaced).

The discount rate parameter is used while using LCCA, which represents the combined effect of interest and inflation rates. The choice of discount rate is very important for the calculation of the NPV. Higher discount rates minimize the present value of future costs by more than lower discount rates. A zero discount rate means that future costs are the same as current costs. Negative discount rates increase the present value of future costs over current costs. Positive discount rates lower the present value of future costs below current costs. For example, for a positive discount rate, if $1 needs to be paid after 10 years, the current cost of $1 is more than $1. Nevertheless, if $1 salvage value needs to be obtained after 20 years, the present value (gain) is less than $1. It is the opposite of a negative worth that is not common.

Let's take an example for better understanding. Say there are some initial costs (materials, labor, paving, etc.) for the construction of a pavement. There will be some annual maintenance costs including crack sealing, patching, etc. once it is in operation. The recycled millings will return some interest to us after their end of life. Then the present value can be calculated as follows:

$$\text{Present value (\$)} = \text{Initial cost (\$)} + \text{Annual cost} \times (F_1)\ (\$)\ - \text{Salvage value} \times (F_2)\ (\$)$$

where F_1 and F_2 are two factors to convert annual cost and salvage value, respectively, into present values.

For positive discount rate, $F_1 > 1.0$ and $F_2 < 1.0$.

For negative discount rate, $F_1 < 1.0$ and $F_2 > 1.0$.

For zero discount rate, $F_1 = 1.0$ and $F_2 = 1.0$.

The most popular LCCA tool for pavement applications is the FHWA's RealCost Software, originally developed in 1997 and undergone numerous improvements (FHWA, 2010b). It is available at the FHWA website at www.fhwa.dot.gov/infrastructureasstmgmt/lccasoft.cfm.

Life-Cycle Assessment (LCA)

Life-cycle assessment quantifies the pavement system's life-cycle environmental impacts. From a number of key environmental factors, such as energy use and greenhouse gas emissions, the results are expressed. It is possible to use some other units, but they are not common. The International Organization for Standardization (ISO, 2006) states that LCA is a mechanism that discusses the environmental aspects and potential environmental impacts (e.g., resource usage and environmental consequences of releases) throughout the life cycle of a product from the procurement of raw materials through manufacturing, use, end-of-life treatment recycling, and final disposal (i.e., cradle to disposal). Nevertheless, multiple software programs (e.g., Athena, Gabi, SimaPro, PaLATE) can be used to build LCA models.

More recently, the project emissions estimator (PE-2) method was built to provide a measure of greenhouse gas emissions for pavement construction maintenance and use (Mukherjee et al., 2013). In addition, AASHTO has published a GreenDOT method calculating carbon dioxide emissions from highway agency activities, construction, and maintenance (Gallivan, Ang-Olson, and Papson, 2010).

Sustainability Rating Systems

A rating system for sustainability is basically a list of best practices for sustainability with a specific associated metric commonly expressed in ratings. In a common unit, it quantifies any best practice. In this way, a specific unit (points) can be used to compare the diverse measuring units of sustainability best practices (e.g., stormwater runoff pollutant, pavement design life, amount of recycled materials, energy consumed/saved, pedestrian accessibility, environment connectivity, and art value). A rating system should count all best practices equally in its simplest form (e.g., all worth one point), in which case the rating system is a list of the number of best practices used. Rating systems assess best practices in more complex forms (usually in relation to their impact on sustainability or priority), which can help to choose the most impactful best practices to be used within a limited scope or budget. In the transportation sector, a number of national and international rating systems are currently available.

A number of rating systems relevant to pavements are INVEST, Greenroads®, Envision™, GreenLITES, etc. The FHWA created INVEST as a self-evaluation tool; version 1.0 is available at www.sustainablehighways.org. It is point-based with a focus on state Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs).

Section 10 — Concept of Pavement Rehabilitation Design

After the design and construction of pavement, the pavement is referred to another department (commonly known as Pavement Management System or PMS) of highway agency that monitors the performance of the pavement, performs maintenance works, and performs subsequent operation. The pavement system undergoes deterioration and damage due to application of repeated loads and adverse climate. It thus requires continuous supervision. Based on the pavement's damage level, it may require any one of the following items:

- Routine maintenance
- Preventive maintenance
- Corrective maintenance
- Major/minor rehabilitation

Maintenance activities that are planned and performed on a routine basis to preserve the condition of highway system are defined as routine maintenance. Routine maintenance is also conducted to respond to specific conditions and events that restore the highway system to a desired level of riding comfort. Routine maintenance includes mowing, cleaning roadsides, cleaning ditches, sealing cracks in the pavement, painting pavement markings, and pruning trees.

Preventive maintenance is conducted commonly on good pavements to preserve the system without (or negligible) improving the quality but retards future deterioration, as shown in Figure 4. Applications as seal coats, crack-joint filling, micro-surfacing, etc. are examples of preventive maintenance.

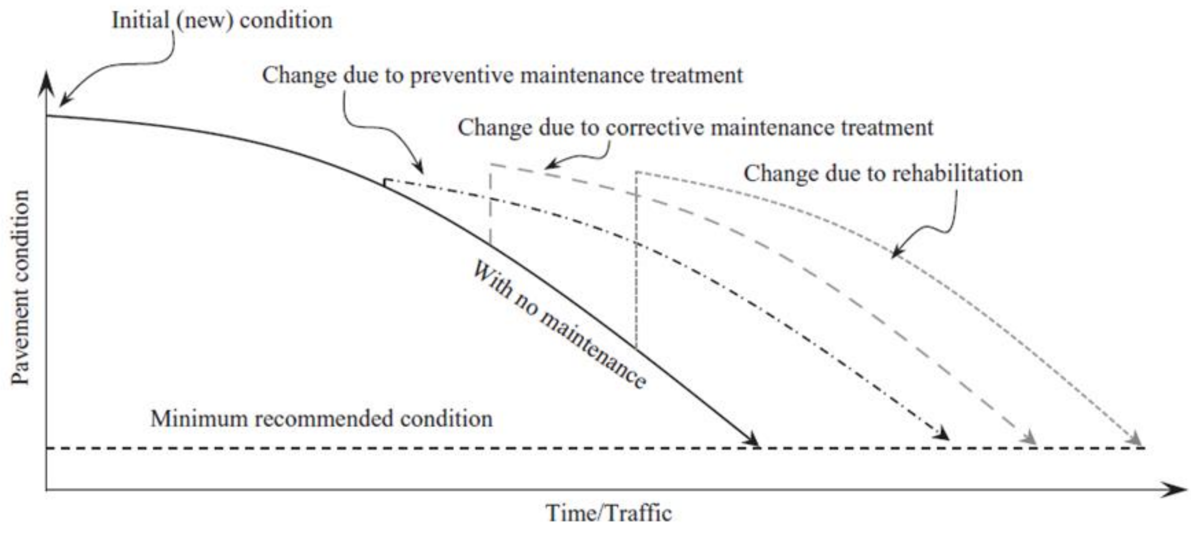

Figure 4 Pavement Condition Deterioration with and without Maintenance

Corrective (or reactive) maintenance is performed in response to a deficiency or deficiencies that negatively impact the operations of the pavements, as shown in Figure 4. Patching potholes may be considered a corrective maintenance as pothole is a deficiency of a pavement.

Major rehabilitation is the extension of service life and/or increasing the load-carrying capacity of an existing pavement. Minor rehabilitation is the functional improvement (riding comfort and safety) of an existing pavement with increasing the structural capacity and life, as shown in Figure 4. Full-depth reclamation, thick overlay, or even reconstruction are examples of major rehabilitation, whereas applying thin overlay or surface recycling is minor rehabilitation.

Maintenance is not a part of pavement or highway design. It is performed by Pavement Management Systems (PMS). However, one component of PMS is rehabilitation design which is contributed by the pavement design group. Therefore, in this text, only the rehabilitation design section is discussed. For more information about PMS, readers are referred to Pavement Management Guide published by the AASHTO, Washington DC (latest edition is the second edition published in 2012). Appendix A also discusses the PMS processes and their activities.

Rehabilitation design requires an evaluation of the existing pavement to provide key information. The AASHTOWare provides detailed and specific guidelines for conducting a pavement evaluation program and taking the results from that program to establish inputs to the AASHTOWare software. It is important to note that the AASHTOWare inputs of existing pavement layers for overlay design are similar to those required for new or reconstructed pavements except that the values may be different due to depreciation or load and climate-caused deterioration of the existing layers and materials with the passage of time.

The most important task in pavement evaluation is to determine the extent of damage and material properties of the in-place layers. This section provides a brief summary of the overall pavement evaluation process, followed by guidelines to obtain inputs to the AASHTOWare for use in rehabilitation design.

The steps of rehabilitation of design include:

- Overall condition assessment
- Fully defining condition assessment
- Analysis of pavement evaluation data
- AASHTOWare software analysis

Overall Condition Assessment

The first step in the pavement rehabilitation design process is to determine the overall condition of the existing pavement. The overall pavement condition could be determined by evaluating the following eight major categories of the existing pavement:

- Structural adequacy (load related)
- Functional adequacy (user related)
- Subsurface drainage adequacy
- Material durability
- Shoulder condition
- Extent of maintenance activities performed in the past
- Variation of pavement condition or performance within a project
- Miscellaneous constraints (e.g., bridge and lateral clearance and traffic control restrictions)

Three types of cases may arise:

- If the pavement has a severe level of distresses, exceeding the threshold value, extensive field, and laboratory testing to characterize the pavement layers becomes less important.
- If the pavement has no structural distress, field and laboratory testing become important to determine the condition of the existing pavement layers. For this case, results from the field [ground penetrating radar (GPR), falling weight deflectometer (FWD), and dynamic cone penetration (DCP) tests] and laboratory tests could be used to determine the condition of the existing layers.
- If the pavement has a marginal level of distress, the results from the visual distress survey may be used to determine the location and frequency of the field tests and cores.

Fully Defining Condition Assessment

The steps for detailed assessment on the condition of the existing pavement for selecting a proper rehabilitation strategy are shown in Figure 5. All steps to complete a detailed assessment of the pavement and individual layers are not always needed.

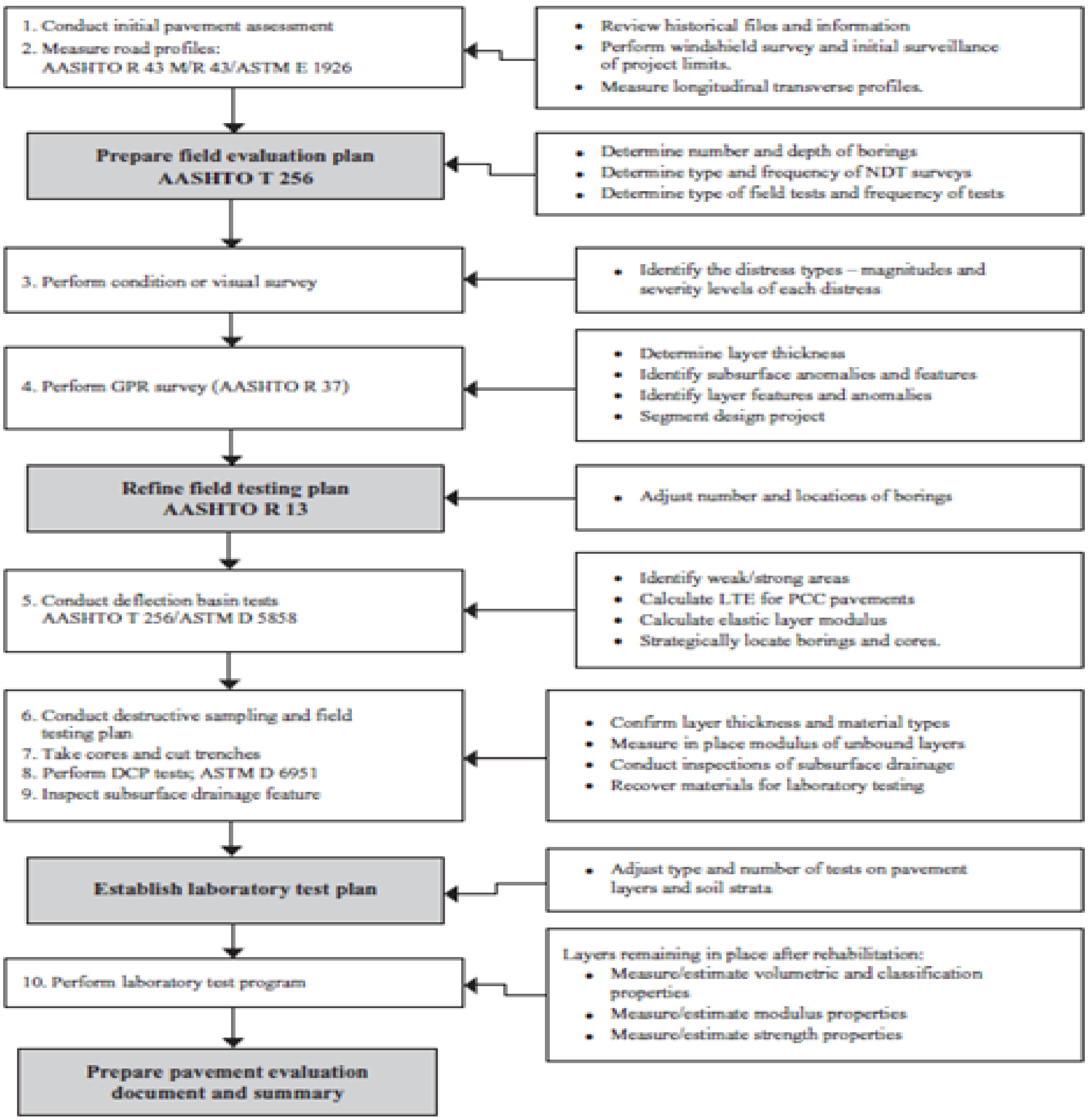

Figure 5 Steps for Assessing the Condition of Existing Pavements for Rehabilitation Design

The fully defining condition assessment starts with the historical data, such as data collected in the overall condition assessment. Then, the field evaluation plan is made. It consists of a detailed condition survey, nondestructive testing, destructive sampling, and testing. Pavement visual surveys are performed to identify the types, magnitudes, and severities of different distresses. The visual survey needs to be performed on the pavement, adjacent shoulders, and any drainage feature along the project site. Automated distress surveys are adequate for rehabilitation design purposes, for most cases. GPR has been used successfully to determine the condition of the existing pavement structure, identify areas with subsurface voids, locate areas with severe stripping in hot-mix asphalt (HMA), and locate interfaces with weak bonds between two HMA layers.

Nondestructive testing could be performed prior to any destructive tests, such as cores and materials excavation, to better select the locations of such tests. The most widely used deflection testing device is the FWD. Destructive tests require the physical removal or damage of the pavement layer to observe the condition of the material. The cores could be used to confirm the layer thicknesses and material types, examine the pavement materials for material durability problems, and collect samples for laboratory tests. Some cores could be drilled through any cracks observed at the surface of the pavement. These cores could be used to determine the depth of cracking and whether the cracks initiated at the surface (top-down) or bottom of the asphalt layer (bottom-up). Knowing the depth and origin of cracking, a proper rehabilitation strategy for the project could be selected.

The dynamic cone penetration test (DCP) or the California bearing ratio test (CBR) can be used to measure the strength of unbound layers and materials in pavement evaluations. It may also be used for estimating soil layer thickness by identifying sudden changes in strength within the pavement structure and foundation. If the existing pavement has subsurface drains that may remain in place, the outlets need to be found and inspected. Mini-camera can also be used to ensure that the edge drains and lateral lines flow freely and do not restrict the removal of water from the pavement structure. The engineer must develop an adequate laboratory test program to estimate the material properties of each layer needed as inputs into the AASHTOWare pavement ME design software.

Analysis of Pavement Evaluation Data

The pavement structural evaluation for determining the condition of the existing pavement layers is based on an analysis of the visual distress surveys, deflection basin, other field tests, and laboratory tests. It is recommended that the highest input level available be used to design high-volume roadways for rehabilitation. Once all data is at hand, the structural adequacy is evaluated as listed in Tables 3 and 4 for rigid pavement and flexible pavement, respectively.

General Overview of Rehabilitation Design Using AASHTOWare

The data obtained in the previous steps are used as inputs to design any rehabilitation option in the AASHTOWare software. The AASHTOWare pavement ME design software can evaluate a wide range of rehabilitation designs for flexible, rigid, and composite pavements.

Load-related distress		Inadequate (Poor)	Marginal (Fair)	Adequate (Good)
JPCP Deteriorated Cracked Slabs (medium- and high-severity transverse and longitudinal cracks and corner breaks), % slabs	Interstate, Freeway	>10	5–10	<5
	Primary	>15	8–15	<8
	Secondary	>20	10–20	<10
JRCP Deteriorated Cracked Slabs (medium- and high-severity transverse cracks and corner breaks), #/lane-mi	Interstate, Freeway	>40	15–40	<15
	Primary	>50	20–50	<20
	Secondary	>60	25–60	<25
JPCP Mean Transverse Joint/ Crack Faulting, in.	Interstate, Freeway	>0.15	0.10–0.15	<0.1
	Primary	>0.20	0.12–0.20	<0.125
	Secondary	>0.30	0.15–0.30	<0.15
CRCP Punchouts (medium and high severity), #/lane-mi.	Interstate, Freeway	>10	5–10	<5
	Primary	>15	8–15	<8
	Secondary	>20	10–20	<10

Table 3 Distress Types and Severity Levels Recommended for Assessing Rigid Pavement Structural Adequacy

Load-related distress		**Inadequate (Poor)**	**Marginal (Fair)**	**Adequate (Good)**
Fatigue Cracking, percent of total lane area	Interstate, Freeway	>20	5–20	<5
	Primary	>45	10–45	<10
	Secondary	>45	10–45	<10
Longitudinal Cracking in Wheel Path, ft/mi	Interstate, Freeway	>1,060	265–1,060	<265
	Primary	>2,650	530–2,650	<530
	Secondary	>2,650	530–2,650	<530
Reflection Cracking, % of total lane area.	Interstate, Freeway	>20	5–20	<5
	Primary	>45	10–45	<10
	Secondary	>45	10–45	<10
Transverse Cracking Length, ft/mi	Interstate, Freeway	>800	500–800	<500
	Primary	>1,000	800–1,000	<800
	Secondary	>1,000	800–1,000	<800
Rutting, mean depth, maximum between both wheel paths, in.	Interstate, Freeway	>0.45	0.25–0.45	<0.25
	Primary	>0.60	0.35–0.60	<0.35
	Secondary	>0.80	0.40–0.80	<0.40
Shoving, percent of wheel path area	Interstate, Freeway	>10	1–10	None
	Primary	>20	10–20	<10
	Secondary	>50	20–45	<20

Table 4 Distress Types and Levels Recommended for Assessing Current Flexible Pavement Structural Adequacy

The AASHTOWare pavement ME design software starts with a trial rehabilitation strategy similar to developing the initial trial design for new pavements. A considerable amount of analysis and engineering judgment is required when determining specific treatments required to design a feasible rehabilitation strategy for a given pavement condition. The AASHTOWare pavement ME design software considers five major strategies, as listed below, which may be applied singly or in combination to obtain the most effective rehabilitation option, listed below:

- Reconstruction without lane additions—considered under new pavement design strategies.
- Reconstruction with lane additions—considered under new pavement design strategies.
- Structural overlay may include removal and replacement of pavement layers.
- Non-structural overlays.
- Restoration without overlays.

The AASHTOWare pavement ME design software provides detailed guidelines on the use and design of rehabilitation strategies depending on the type and condition of the existing pavement and offers specific details on the use of material-specific overlays for existing flexible and rigid pavements. This section provides an overview of strategies for the rehabilitation of existing flexible, rigid, and composite pavements. Figure 6 shows the steps that are suggested for use in determining a preferred rehabilitation strategy.

Rehabilitation Design with HMA Overlays

The AASHTOWare includes specific details for selecting and designing HMA overlays to improve the surface condition or to increase the structural capacity of the following pavements:

- HMA overlays of existing HMA-surfaced pavements, both flexible and semi-rigid.
- HMA overlays of existing Portland cement concrete (PCC) pavements that have received fractured slab treatments: crack and seat, break and seat, and rubblization.
- HMA overlays of existing intact PCC pavements [jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP)], including composite pavements or second overlays of original PCC pavements.

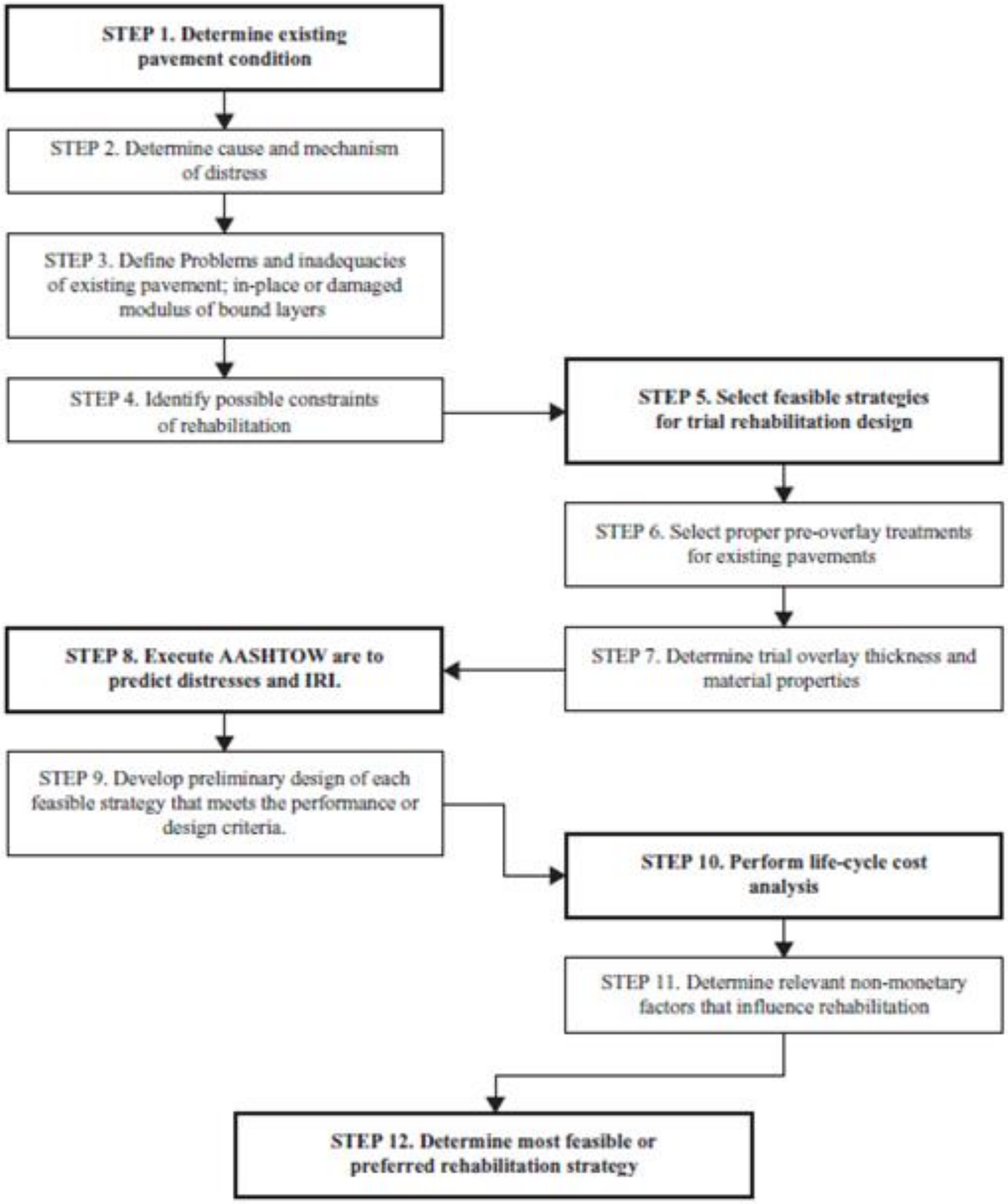

Figure 6 Steps for Determining a Preferred Rehabilitation Strategy

Figure 7 presents a generalized flow chart for pavement rehabilitation with HMA overlays of HMA-surfaced flexible, semi-rigid, or composite pavements, fractured PCC pavements, and intact PCC pavements.

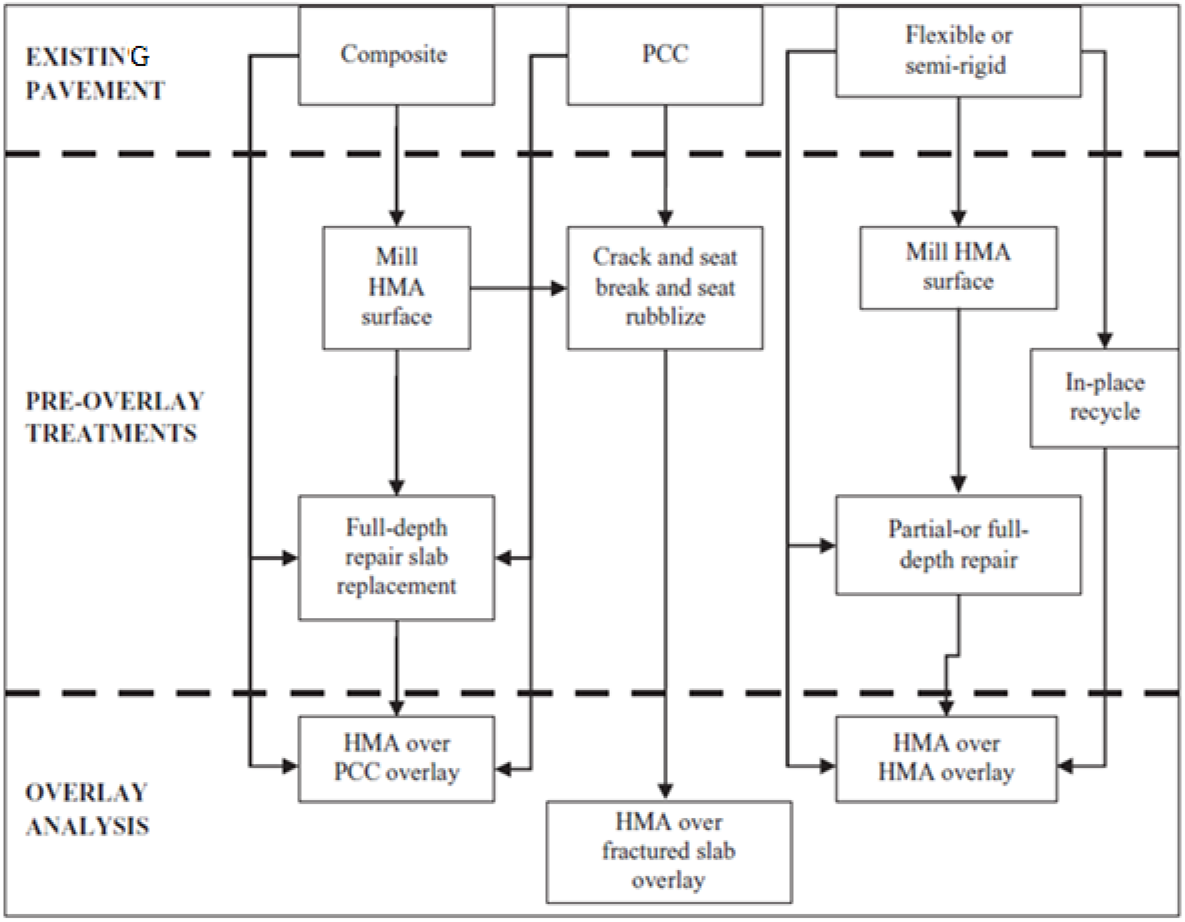

Figure 7 Flow Chart of Rehabilitation Design Options Using HMA Overlays

For existing flexible or semi-rigid pavements, the designer needs to first decide on what, if any, pre-overlay treatment is needed for minimizing the effect of existing pavement distresses on the HMA overlay. Pre-overlay treatments may include the following:

- Do nothing
- A combination of milling full- or partial-depth repairs or in-place recycling.

In either case, the resulting analysis is an HMA overlay of an existing HMA-surfaced pavement. Similarly, the analysis for existing PCC pavements may be either an HMA over PCC analysis or an HMA over fractured slab analysis depending on whether or not crack and seat, break and seat, or rubblization techniques are applied to the existing PCC pavement. Existing composite pavements may result in either an HMA over PCC analysis or an HMA over fractured slab analysis depending on whether or not the existing HMA surface is removed and the underlying PCC pavement is fractured. Determining how much of the distress or damage could be repaired before the HMA overlay is placed requires a careful mix of experience and engineering judgment. Table 5 lists some of the candidate repair or pre-overlay treatments for all types of pavements, while Table 6 lists the major rehabilitation treatments of existing HMA and HMA over PCC pavements. Deciding on the pre-overlay treatment to be used could be based more on experience and historical data, rather than on the distresses and IRI predicted with the AASHTOWare pavement ME design software.

Pavement type	Distress	Preventive treatments	Repair treatments
Flexible and composite	Alligator cracking	Surface/fog seal surface patch	Full-depth repair
	Longitudinal cracking	Crack sealing	Partial-depth repair
	Reflective cracking	Seal cracks Saw and seal cuts above joints	Full-depth repair
	Block cracking	Seal cracks or chip seal	Chip seal
	Depression	None	Leveling course Mill surface
	Rutting	None	Leveling course Mill surface
	Raveling	Rejuvenating seal	Chip seal/surface seal
	Potholes	Crack sealing Surface patch	Full- or partial-depth repair
Rigid	JPCP pumping	Reseal joints Restore joint load transfer Subsurface drainage Edge support (tied PCC should edge beam)	Subseal or mud-jack PCC slabs (effectiveness depends on materials and procedures)
	JPCP joint faulting	Subseal joints Reseal joints Restore load transfer Subsurface drainage Edge support (tied PCC should edge beam)	Grind surface; structural overlay
	JPCP slab cracking	Subseal (loss of support) Restore load transfer Structural overlay	Full- or partial-depth repair
	JPCP joint or crack spalling	Reseal joints	Full- or partial-depth repair
	CRCP punchouts	Polymer or epoxy grouting Subseal (loss of support)	Full-depth repair
	PCC disintegration	None	Full-depth repair Thick overlay

Table 5 Candidate Repair and Preventive Treatments for Different Pavements

The maximum number of overlay layers that may be specified is four. This includes up to three HMA layers, and one unbound or chemically stabilized layer. The total number of layers of the existing pavement and the overlay is limited to 14. For the initial design, however, it is suggested that the total number of layers be limited to no more than eight to reduce the number of required inputs and run time. Depending on the general pavement condition rating, suggested rehabilitation options for level 3 input level are listed in Table 7.

Pavement condition	Distress types	Candidate treatments for developing rehabilitation design strategy											
		Full-depth HMA repair	Partial-depth HMA repair	Cold milling	Hot or cold in-place recycling	Cracking sealing	Chip seal	HMA overlay	HMA overlay of fractured PCC slab	Bonded PCC overlay	Unbonded PCC overlay	Subsurface drainage improvement	Reconstruction (HMA or PCC)
Structural	Alligator cracking	✓			✓		✓	✓	✓	✓	✓		✓
	Longitudinal cracking (low severity)		✓	✓	✓	✓		✓		✓	✓		✓
	Thermal cracking	✓		✓	✓	✓		✓		✓	✓		✓
	Reflection cracking	✓	✓	✓				✓	✓	✓	✓		✓
	Rutting—subsurface			✓	✓			✓		✓	✓		✓
	Shoving—subsurface	✓						✓					✓
Functional	Excessive patching							✓			✓		✓
	Smoothness			✓				✓					
Drainage, Moisture Damage	Raveling		✓	✓				✓					
	Stripping	✓	✓					✓		✓	✓	✓	✓
	Flushing/ bleeding		✓				✓	✓					
Durability	Raveling		✓	✓	✓		✓	✓					
	Flushing/bleeding		✓	✓	✓		✓	✓					
	Shoving—HMA		✓	✓	✓			✓					
	Rutting—HMA			✓	✓			✓					
	Block cracking			✓	✓	✓	✓	✓					
Shoulders	Same as traveled lanes	Same treatments as recommended for the traveled lanes.											

Table 6 Summary of Major Rehabilitation Strategies and Treatments Prior to Overlay Placement for Existing HMA and HMA/PCC Pavements

Rehabilitation Design with PCC Overlays

PCC rehabilitation design process requires nine steps listed below:

- Steps 1–4. Evaluation of the existing pavement:
  - Determine the existing pavement condition.
  - Determine the causes and mechanism of distress.
  - Define the problems and inadequacies of the existing pavement.
  - Identify the possible constraints.

- Step 5. Rehabilitation strategy selection.

Condition	General pavement condition rating		Rehabilitation options to consider
Adequate (has remaining life)	Excellent	No cracking, minor rutting, and/or minor mixture-related distresses (e.g., raveling); little to no surface distortions or roughness	• Surface repairs without overlays (not analyzed with the AASHTOWare) • Pavement preservation strategy (not analyzed with the AASHTOWare) • Non-structural overlay • Overlay designed for future truck traffic levels
	Good	Limited load- and/ or non-load-related cracking, minor to moderate rutting, and/ or moderate mixture-related distresses; some surface distortions and roughness	• Pavement preservation strategy (not analyzed with the AASHTOWare) • Overlays designed for future truck traffic levels, with or without milling and surface repairs
Marginal (may or may not have remaining life)	Fair	Moderate load and/ or non-load-related cracking, moderate rutting, moderate amounts of mixture-related distresses, and/ or some roughness (IRI > 120 in./mi)	• Pre-overlay treatments recommended. • Structural overlay, with or without milling and surface repairs • Replace surface layer prior to overlay • In-place recycling prior to overlay
Inadequate (no remaining life)	Poor	Extensive non-load-related cracking, moderate load-related cracking, high rutting, extensive mixture–related distresses, and/ or elevated levels of roughness (IRI > 170 in./mi).	• Pre-overlay treatment recommended if not reconstructed • Structural overlay, with milling or leveling course, and surface repairs. • Replace existing layers prior to overlay • In-place recycling prior to overlay • Reconstruction
	Very good	Extensive load-related cracking and/or very rough surfaces (IRI > 220 in./mi).	• Pre-overlay treatment recommended if not reconstructed • Structural overlay with milling and surface repairs • Replace existing layers prior to overlay • In-place recycling prior to overlay • Reconstruction

Table 7 Definitions of Surface Condition for Input Level 3 Pavement Condition Ratings and Suggested Rehabilitation Options

- Step 6. Rehabilitation design.
- Step 7. Perform a life-cycle cost analysis (as desired).
- Step 8. Determine the non-monetary factors that influence rehabilitation (as desired).
- Step 9. Determine the preferred rehabilitation strategy (as desired).

Figure 8 presents the design process for major PCC rehabilitation strategies included in the AASHTOWare pavement ME design software.

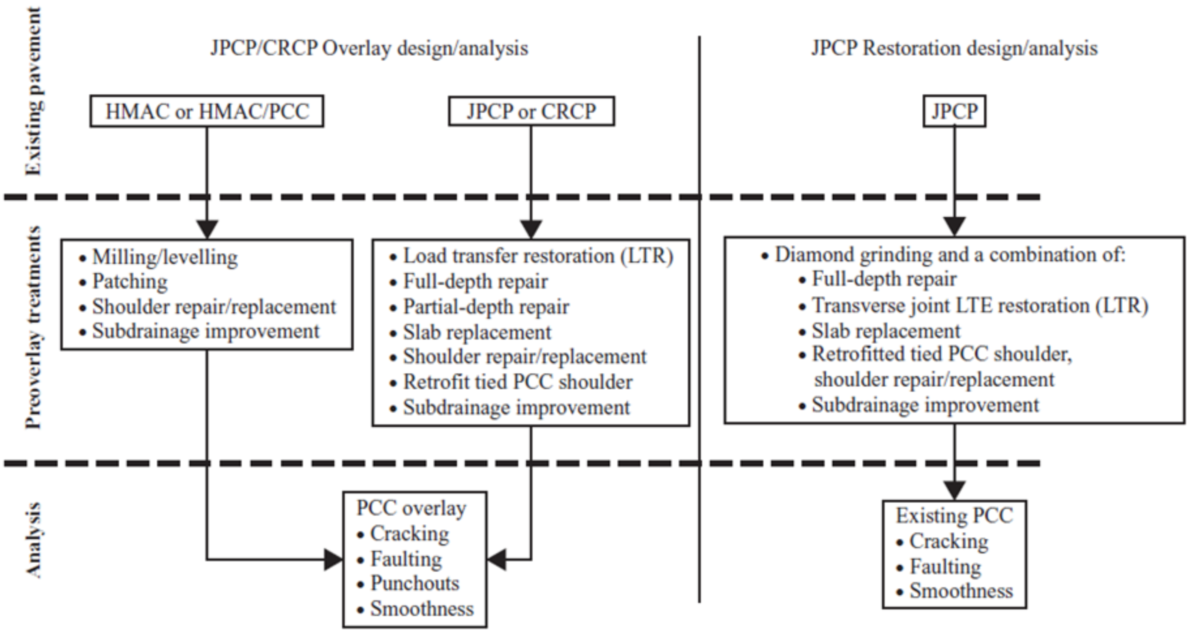

Figure 8 Overall Design Process for Major PCC Rehabilitation Strategies

As with the new pavement design, the first step in rehabilitation design is to select a trial design with defined layers, material types and properties, and relevant design features based on the future level of traffic anticipated. This is followed by the selection of the design performance criteria (used for evaluating the adequacy of the trial design) and the desired level of reliability. Next, the AASHTOWare pavement ME design software is used to process the input data. Data processing includes estimating climate-related aspects such as pavement temperature profile for each analysis period using the ICM and computing long-term PCC flexural strength.

Next, the processed data is used to perform a design analysis by computing pavement structural responses (stress, deflections) required for each distress type incrementally. Computed structural responses are used in transfer functions to estimate distress and smoothness.

The trial rehabilitation design is then evaluated for adequacy using prescribed performance criteria at the given reliability level. Trial designs deemed inadequate are modified and reevaluated until a suitable design is achieved. Design modifications could range from making simple changes to JPCP overlay thickness, varying joint spacing, varying PCC strength, or adopting a new rehabilitation strategy altogether. The design process for rehabilitation design with JPCP overlays or CPR of existing JPCP is very similar to new or reconstructed JPCP design.

Section 11 — References

- AASHTO 2015 Mechanistic-Empirical Pavement Design Guide: A Manual of Practice. Washington, DC: American Association of State and Highway Officials.

Appendix A — Pavement Management System

General

The pavement management system (PMS) encompasses all activities related to the management of the pavement network for different investment decisions for roads, streets, and highways maintenance. PMS consists of a series of tasks or procedures that help pavement managers prepare over a period of time to maintain pavements in a serviceable condition (Mallick and El-Korchi, 2017). PMS is implemented at two different levels:

- Network level for an array of pavements.
- Site-specific level for a particular segment.

In the network level, PMS is utilized to select the most cost-effective strategies from a number of different alternatives for the maintenance of the pavements within a given analysis period considering the entire network. Only one site is analyzed for its optimal solution at a site-specific level, resulting in the maximum benefit-to-cost ratio over the given analysis period. In the PMS, the pavement maintenance activities can be categorized into three types:

- Preventive maintenance
- Corrective maintenance
- Rehabilitation

Preventive maintenance is performed so that the quality of the pavement does not decrease below a desirable level. For example, application of thin overlay to extend the life of the pavement or keep the skid resistance intact. Corrective maintenance is applied to restore the condition of pavement in response to an existing problem such as potholes. Rehabilitation is conducted when the pavement goes under the quality level service or a threshold condition and a major structural improvement of the pavement is required, such as by recycling, placement of a new overlay, or total reconstruction (Nikolaides, 2015). On the other hand, routine maintenance is carried out to ensure serviceability, such as cleaning drains, checking the road signs, and snow removal, which are parts of the PMS. However, this routine maintenance does not require all the steps of the PMS.

Steps in the PMS can be broadly divided into the sequences listed in Figure 9.

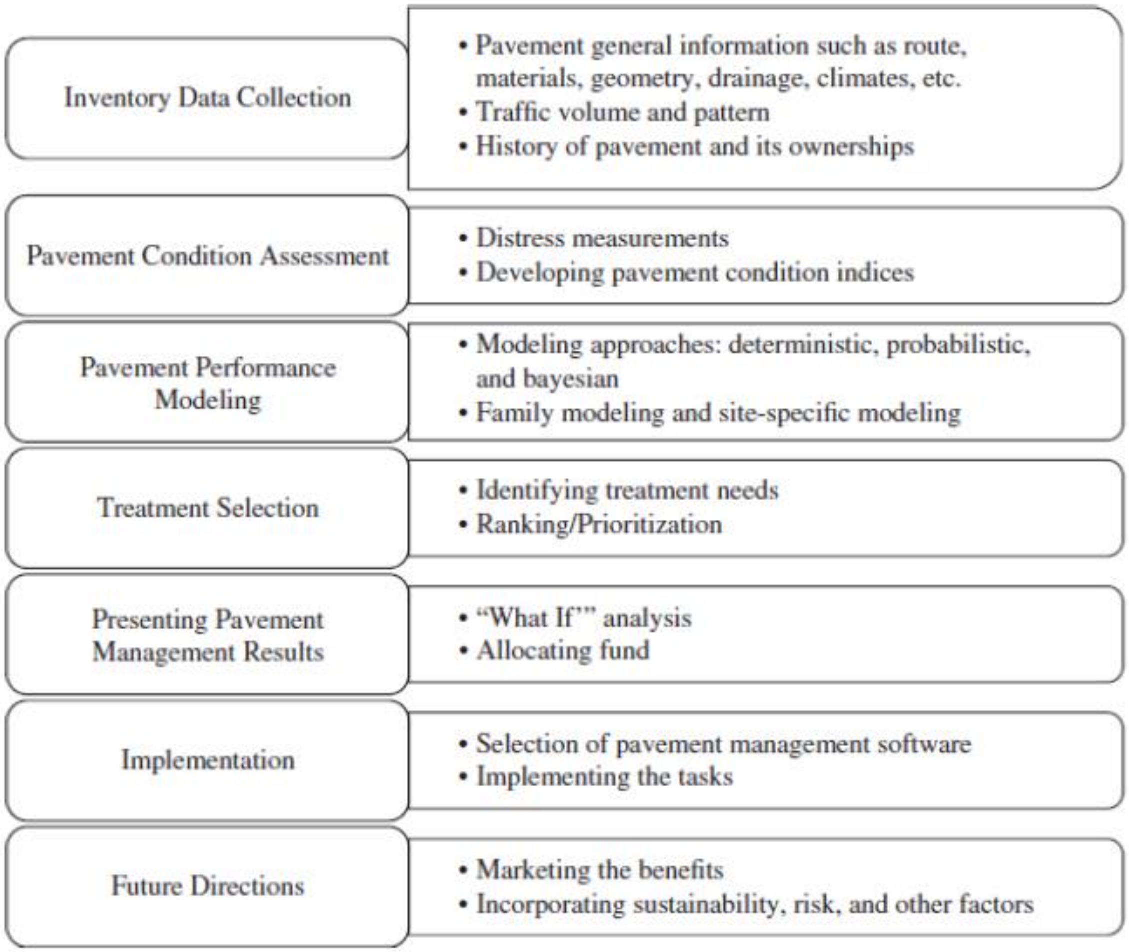

Figure 9 Steps of Pavement Management Systems and its Broad Tasks

Inventory Data Collection

Pavement inventory data collection relevant to the agency's goals is the first and simplest, but very useful, task of the PMS. Some data to be collected are listed below:

- Pavement identity information such as route type, mileposts, functional classification, pavement types, number of lanes, its width, and shoulder information.
- Environment and climate data such as freeze-thaw, precipitation, and temperature.
- Traffic volume, load pattern, traffic distribution, etc.
- History of the pavement such as construction dates, maintenance history, and flooding history.
- Ownership information such as city or state.

- Structural data such as layers, thicknesses, materials, joints characteristics, and subgrade strength.

Pavement Condition Assessment

Pavement condition assessment means the collection of pavement distress and developing pavement condition indices using those distresses.

Distress Measurements

The type of data to be collected is the unique aspects of the agency's network, available resources, demand, etc. Generally, four types of data are collected:

- Pavement distresses such as cracking and rutting.
- Structural capacity such as response due to applied load and load transfer quality.
- Surface characteristics such as smoothness, surface texture, and skid resistance.
- Subsurface characteristics such as voids and drainage quality.

Different methods are used to collect data, such as manual, automated, and combination of manual and automation (semi-actuated). Some methods are destructive such as coring and boring; some are nondestructive such as the falling-weight deflectometer (FWD) testing. The method to be used is dependent on the agency's budget, needs, manpower, and equipment available to the agency.

Pavement Distresses Measurement

The term pavement distress refers to the condition of a pavement surface in terms of its general appearance. A perfect pavement is level and has a continuous and unbroken surface. In contrast, a distressed pavement may be fractured, distorted, or disintegrated. These three basic categories of distress can be further subdivided. For example, fractures can be seen as cracks or as spalling (chipping of the pavement surface). Cracks can be further described as generalized, transverse, longitudinal, alligator, and block. A pavement distortion may be evidenced by ruts or corrugation of the surface. Pavement disintegration can be observed as raveling (loosening of pavement structure), stripping of the pavement from the subbase, and surface polishing. The types of distress data collected for flexible and rigid pavements vary from one state to another. Figure 10 lists the three pavement distress groups, the measure of distress, and the probable causes.

Many highway agencies use some measure of cracking in evaluating the condition of flexible pavements. The most common measures are transverse, longitudinal, and alligator cracks. Distortion is usually measured by determining the extent of rutting and disintegration is

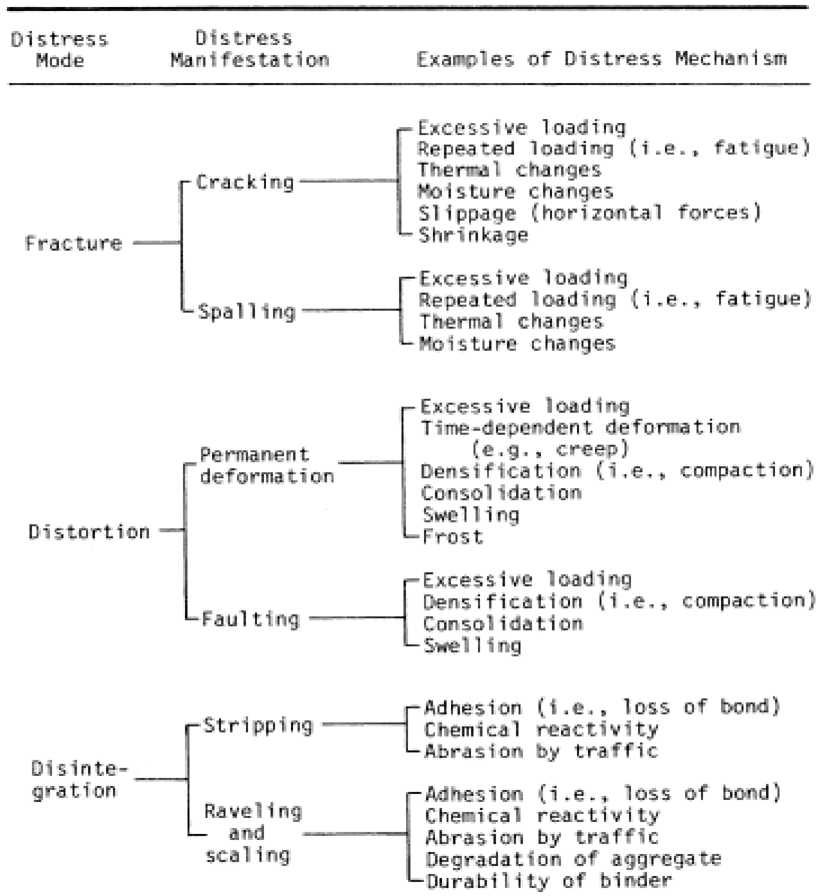

Figure 10 Pavement Distress Groups and their Causes

measured by the amount of raveling. Each state or federal agency has its own procedures for measuring pavement distress. Consequently, there is a wide range of methods used to conduct distress surveys. Typically, the agency has a procedural manual that defines each element of distress to be observed with instructions as to how these are to be rated on a given point scale. The survey forms distinguish between bituminous and Portland cement concrete pavements. For bituminous pavements, the items observed are corrugations, alligator cracking, raveling, rutting, longitudinal cracking, transverse cracking, and patching. For Portland cement concrete, the measures are cracking, raveling, joint spalling, faulting, and patching. Distress data may be obtained by employing trained observers to make subjective judgments about pavement condition based on predetermined factors. Often, photo-graphs are used for making judgments. Some agencies use full sampling, while others randomly select pavement sections. Measurements are usually made on a regular schedule about every one to three years. After the data are recorded, the results are condensed into a single number called a distress (or defect) rating (DR). A perfect pavement is usually given a score of 100; if distress is observed, points are subtracted. The general equation is:

$$DR = 100 - \sum_{i=1}^{n} d_i w_i$$

where

d_i = the number of points assigned to distress type i for a given severity and frequency

n = number of distress types used in the rating method

w_i = relative weight of distress type i

Example 1 Computing Distress Rating of a Pavement Section

A pavement rating method for a certain state uses the following elements in its evaluation procedure: longitudinal or alligator cracking, rutting, bleeding, ravelling, and patching. The weighting factors are 2.4, 1.0, 1.0, 0.9, and 2.3, respectively. Each distress element is characterized by (1) its severity as not severe, severe, or very severe; and (2) its frequency as none, rare, occasional, or frequent. The categories for frequency are based on the percentage of area affected by a particular distress within the area of the section surveyed. For each combination of severity and dis-tress, a rating factor is assigned, d_i, from 0 to 9, as shown in Table 8. A one-mile section of roadway was observed with results shown in Table 9. Calculate the distress rating for the section.

	Severity		
Frequency	*Not Severe (NS)*	*Severe (S)*	*Very Severe (VS)*
None (N)	0	0	0
Rare (R)	1	2	3
Occasional (O)	2	4	6
Frequent (F)	3	6	9

Table 8 Rating Factor di, Related to Severity and Frequency

Distress Characteristic	*Frequency*	*Severity*
Cracking	R	NS
Rutting	O	S
Bleeding	F	VS
Raveling	N	NS
Patching	R	S

Table 9 Observed Distress Characteristics for Road Segment

Solution

Using the data in Table 9 and the rating factors (d_i) in Table 8, each distress is categorized with factors as follows:

Distress Characteristic	*Rating Factor, d_i*	*Weight, w_i*
Cracking	1	2.4
Rutting	4	1.0
Bleeding	9	1.0
Raveling	0	0.9
Patching	2	2.3

Applying the weighting values for each characteristic, the distress rating (DR) for the section is determined using the equation above:

$$\begin{aligned} \text{DR} &= 100 - \sum_{i=1}^{n} d_i w_i \\ &= 100 - (1 \times 2.4 + 4 \times 1 + 9 \times 1 + 0 \times 0.9 + 2 \times 2.3) \\ &= 100 - 20 = 80 \end{aligned}$$

Structural Capacity Measurement

The pavement structural condition means the structural adequacy of the pavement layers. It is evaluated by conducting the nondestructive testing by measuring the surface deflection/deformation under a static or a dynamic load or both. Few devices are used to measure the surface deflection. Nowadays, the most common nondestructive testing device is the Falling Weight Deflectometer (FWD).

The pavement structural condition is very often represented by the pavement condition index (PCI). It is a numerical index to indicate the general condition of a pavement between 0 and 100 with 100 being the best possible condition and 0 being the worst possible condition as shown in Figure 11. The PCI is determined by calculating the weighted average of the conditions for different pavement areas in each segment. The distress types that can be considered when using the PCI include the following:

- *Alligator Cracking:* A series of interconnecting cracks that are caused by fatigue failure of the pavement surface under the repeated traffic loadings.
- *Bleeding**:*** A film of bituminous material on the pavement surface that becomes viscous when warm. It is caused by excessive amounts of bituminous material in the asphalt mix.
- *Block Cracking:* Interconnected cracks that divide the pavement into rectangular pieces.
- *Corrugation:* A series of closely-spaced ridges and valleys occurring at regular intervals.

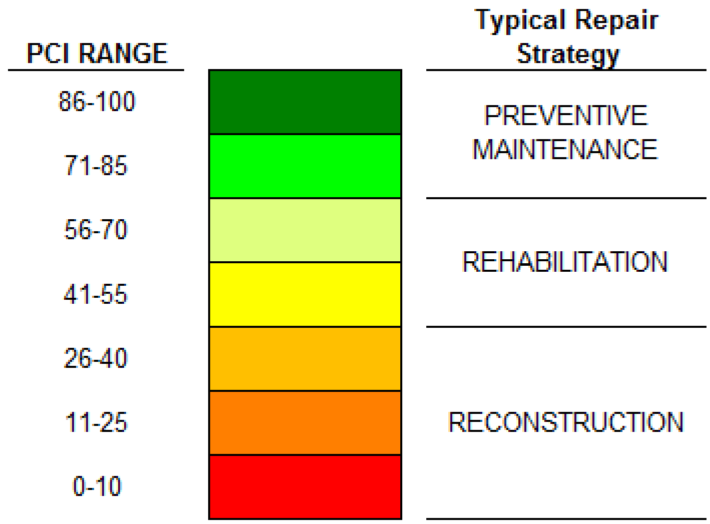

Figure 11 PCI Range with Typical Repair Strategy

- *Depressions:* Localized areas that are below the surrounding surface causing a "bowl-like" shape.

- *Longitudinal and Transverse Cracking:* These may be parallel or orthogonal to the centerline of the pavement.

- *Patching, Utility Cuts, and Potholes:* Patching is the process of filling potholes or excavated areas in the asphalt pavement

- *Rutting:* A surface depression typically along the wheel paths of a road.

- *Raveling:* Wearing of the pavement surface caused by aggregate particles breaking loose and the loss of bituminous material binder.

Surface Characteristics

The surface characteristics represent pavement's riding quality and the driving safety.

Three types of surface characteristics are measured:

- Longitudinal profile and roughness.

- International roughness index (IRI).

- Surface texture and friction.

Longitudinal Profile and Roughness

The unevenness of the pavement's longitudinal profile affecting pavement-vehicle interaction is known as the longitudinal profile and roughness. One indirect way of measuring longitudinal profile and roughness is the present serviceability rating (PSR). PSR is the pavement riding quality based on a panel of observers to ride in a vehicle over the pavement. The scale is 0 to 5, with 5 being excellent and 0 being impassable.

Present serviceability index (PSI) is a substitution of the PSR and is determined based on the measured physical roughness. Again, the scale of 0 to 5 is used with 5 being very good and 0 being very poor. Some of the equipment to measure roughness are listed below:

- Mays Ride Meter
- Bureau of Public Roads Roughometer
- Cox Road Meter

The above-listed equipment does not measure the actual profile of the road, rather it measures the response of the vehicle to surface roughness. The equipment is calibrated to ensure that the response obtained represents true roughness of the pavement. Profilometers can be used to measure the true roughness (profile) and do not need any calibration. Being more sophisticated, profilometers are costly. Examples of profilometers are K. J. Law Profilometers and South Dakota Profilometers.

The PSI can be determined using the following two equations:

$$\mathrm{PSI} = 5.03 - 1.91\log(1+\overline{\mathrm{SV}}) - 0.01(C+P)^{0.5} - 1.38\,\overline{\mathrm{RD}}^{2}\ \text{[for flexible pavement]}$$

$$\mathbf{PSI = 5.41 - 1.80\log(1+\overline{SV}) - 0.09(\mathit{C}+\mathit{P})^{0.5}\ [for\ rigid\ pavement]}$$

where PSI = Present serviceability index

$\overline{\mathrm{SV}}$ = Average slope variance on both wheel paths as obtained by a profilometer (this is an expression of the surface irregularities)

C = Major cracking in linear feet per 1,000 ft^2 area of pavement area

P = Asphalt patching in square feet 1,000 ft^2 area of pavement area

$\overline{\mathrm{RD}}$ = Average rut depth of both wheel paths based on a 4-ft straightedge in inches (this is an expression of the pavement deformation)

International Roughness Index (IRI)

IRI is a standard method of reporting roughness for both flexible and rigid pavements. IRI is calculated using cracking, rutting, and climate factors at the pavement site.

Surface Texture and Friction

Surface texture and friction are two sides of a coin. Surface texture is the roughness of the surface and friction is the consequence of the roughness. The term *skid resistance* is often used to describe these two terms of texture and friction on the surface. Skid resistance is the force developed when a tire (that is prevented from rotating) slides along the pavement surface. Skid resistance is an important pavement evaluation parameter because:

- Inadequate skid resistance will lead to higher incidences of skid-related accidents.
- Most agencies have an obligation to provide users with a roadway that is safe.
- Skid resistance measurements can be used to evaluate various types of materials and construction practices.

The basic formula for friction factor (*f*) is:

$$f = \frac{L}{N}$$

where L = Lateral or frictional force required to cause two surfaces to move tangentially to each other

N = Reaction force perpendicular to the surfaces

The skid number SK can *b*e determined as:

$$\mathrm{SK} = 100f$$

The SK is usually obtained by measuring the forces obtained with a towed trailer riding on a wet pavement equipped with standardized tires. Skid testing in the United States may occur in a number of ways including:

- The locked wheel tester.
- The spin-up tester.
- Surface texture measurement.

The locked wheel tester speeds up at about 40 mph (64 km/h) and water is sprayed ahead of the test tire to create a wetted pavement surface. Then, brake is applied to lock the test tire, the resulting friction force acting between the test tire and the pavement is measured and reported as the skid number (SN). The standard locked-wheel friction tests are AASHTO T 242 and ASTM E 274.

For a spin-up tester, the vehicle speeds up at about 40 mph (64 km/h) and a locked test wheel is lowered to the pavement surface. Due to its contact with the pavement, the test wheel can spin up to normal travel speed. The force can be computed by knowing the test wheel's moment of inertia and its rotational acceleration.

The simplest surface texture measurement is the sand patch test (ASTM E 965). The test is carried out on a dry pavement surface by pouring a known quantity of sand onto the surface and spreading it in a circular pattern with a straightedge. As the sand is spread, it fills the low spots in the pavement surface. When the sand cannot be spread any further, the diameter of the resulting circle is measured. This diameter can then be correlated to an average texture depth, which can be correlated to skid resistance. Laser or advanced image processing equipment are capable of determining surface macro-texture from a vehicle moving at normal travel speeds. One example is the road surface analyzer (ROSAN) that can be used for measuring texture, aggregate segregation, grooves, joints, and faulting.

Figure 12 illustrates typical skid results for various pavement conditions. Skid resistance data are not typically used in developing rehabilitation programs. Rather, they are used to monitor the safety of the highway system and to assist in reducing potential crash locations.

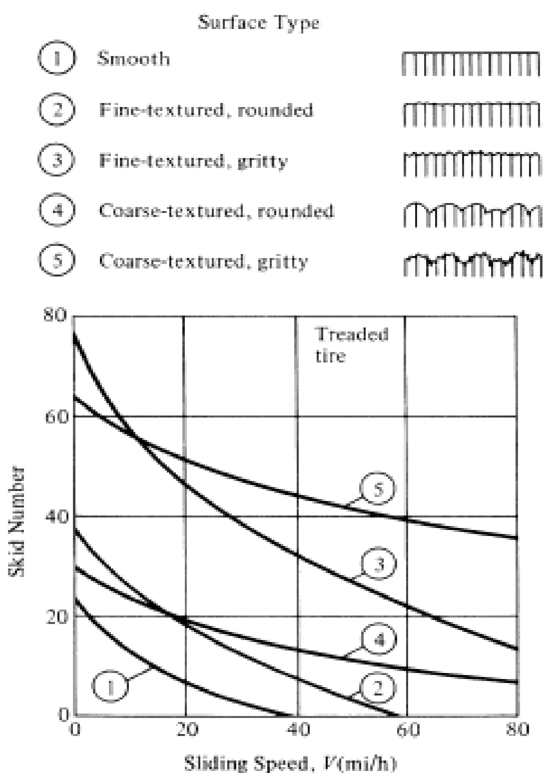

Figure 12 Skid Data for Various Pavements Surface Types

Example 2: Measuring Skid Resistance

A 10,000 lb load is placed on two tires of a locked-wheel trailer. At a speed of 30 mi/h, a force of 5000 lb is required to move the device. Determine the SK and the surface type, assuming that treaded tires were used.

Solution:

$$SK = 100f = (100)\frac{L}{N}$$

$$= 100 \times \frac{5000}{10{,}000} = 50$$

From Figure 12, at 30 mi/h and SK = 50, the surface type is coarse-textured and gritty.

Subsurface Characteristics

The subsurface characteristics such as number of layers, thicknesses, and any voids inside can be measured using the ground penetrating radar (GPR). It transmits a pulse of radar energy into the pavement and measures the time required to receive the reflection back by the receiver. Using the reflection time pattern, the number of layers and their thicknesses can be interpreted. Pavement cores may be required to calibrate or validate the GPR results. Possible voids inside the pavement can also be determined using the GPR.

Developing Pavement Condition Indices

Different pavement condition indices or condition ratings are frequently used in the PMS to report the pavement conditions and select the appropriate treatment strategies.

Two commonly used condition indices and their subdivisions are listed below:

- Composite indices
    - Subjective composite indices
    - Objective composite indices
- Individual indices
    - Roughness index
    - Rutting index
    - Structural/fatigue index
    - Nonstructural cracking index

- Patch index

Pavement Performance Modeling

Pavement performance modeling is conducted to predict future pavement condition, determine the appropriate timing of action, determine the consequences of different strategies, etc.

Performance Modeling Approaches

Modeling or regression analysis is required to predict the distresses for future years—to evaluate the condition after several years. Four types of modeling approaches are used in the PMS:

- Deterministic models
- Probabilistic models
- Bayesian models
- Subjective or expert-based models

Deterministic models predict a single parameter (e.g., cracking, rutting, or condition index) by statistical regression analysis using the historical pavement condition information. Simply, it is the statistical way to determine future pavement condition using the current and past survey data. Probabilistic models predict several parameters (e.g., cracking, rutting, or condition index) using the Markov or Semi-Markov probabilistic approach. Bayesian models use both subjective and objective data to develop probabilistic models without using the historical data. In subjective or expert-based models, an individual or an expert group develops equations to determine the pavement deterioration rate throughout pavement life and future pavement condition is predicted accordingly. The agency may set their own predicting model based on their local experience and resources. Refer to Table 10.

To PCR State

		9 *100 to 90*	*8* *89 to 80*	*7* *79 to 70*	*6* *69 to 60*	*5* *59 to 50*	*4* *49 to 40*	*3* *39 to 30*	*2* *29 to 20*	*1* *19 to 10*	*P*
	9 *100 to 90*	0.90	0.10								1.0
	8 *89 to 80*		0.70	0.30							1.0
	7 *79 to 70*			0.60	0.30	0.10					1.0
From PCR State	*6* *69 to 60*				0.50	0.30	0.15	0.05			1.0
	5 *59 to 50*					0.30	0.40	0.30			1.0
	4 *49 to 40*						0.30	0.70			1.0
	3 *39 to 30*							0.60	0.35	0.05	1.0
	2 *29 to 20*								0.20	0.80	1.0
	1 *19 to 10*									1.0	1.0

Table 10 Probabilities of Pavement Condition Changes

Example 3: Predicting Future Condition Using a Markovian Model

A state DOT district office is responsible for maintaining a network of 1000 mi. The results of the annual survey in a given year showed that the current network condition of these roads are: Group 1: 600 mi with a PCR between 90 and 100, Group 2: 300 mi with a PCR between 80 and 89, and Group 3: 100 mi with a PCR between 70 and 79. Using the probability matrix given in Table 10, determine the condition of the network in year 1 and year 2.

Solution:

Step 1. Determine the current state of each of the three groups.

Group 1: state 9, Group 2: state 8, Group 3: state 7.

Step 2. Determine probabilities of outcomes for each year, in one year. For Group 1, state 9: 90% in state 9, 10% in state 8. For Group 2, state 8: 70% in state 8, 30% in state 7. For Group 3, state 7: 60% in state 7, 30% in state 6, and 10% in state 5.

Step 3. Determine the number of miles involved. Group 1: 0.9 x 600 = 540 mi in state 9, and 0.1 x 600 = 60 mi in state 8.

Group 2: 0.70 x 300 = 210 mi in state 80, 30 x 300 = 90 mi in state 7.

Group 3:0.60 x 100 = 60 mi in state 70, 30 x 100 = 30 mi in state 60 and 10x100 = 10 mi in state 5.

Step 4. Summarize the mileage of highway in each PCR category.

540 = 540 mi will be in state 9 (PCR between 90 & 100)

60 + 210 = 270 mi will be in state 8 (PCR between 80 & 89)

90 + 60 = 150 mi will be in state 7 (PCR between 70 & 79)

30 = 30 mi will be in state 6 (PCR between 60 & 69)

10 = 10 mi will be in state 5 (PCR between 50 & 59)

For year 2, the procedure is the same. Each PCR state is determined, followed by appropriate probabilities. Then calculations are made as shown in step 3 and summarized in step 4. The solution is 486 mi in state 9, 243 mi in state 8, 171 mi in state 7, 60 mi in state 6, 27 mi in state 5, 8.5 mi in state 4, and 4.5 mi in state 3.

Family Modeling

Family-based modeling reduces the number of independent variables and develops pavement performance model for a group of similar pavement sections with similar performance characteristics. The developed single model can be used for any pavement in the family tree.

Site-Specific Modeling

Each pavement is unique and thus two similar pavements are expected to have different performance characteristics. Site-specific model addresses this concept by developing model for a specific pavement site. Sufficient performance data must be collected from that site to develop the site-specific model.

Pavement Rehabilitation Modeling

Condition Assessment

This method is used to develop single-year programs. The agency establishes criteria for the different measures of pavement condition against which comparison of the actual measurements can be made. If the measurement exceeds this limit or “trigger point,” then a deficiency or need exists. Figure 4 illustrates this concept. For example, if a limit of PSI of 2.5 has been set as the minimum acceptable roughness level for a particular class of pavement, then any section with a PSI less than 2.5 will represent a current deficiency. The fixed trigger point thus resolves the timing issue in a simple manner. Whenever the condition index falls below the given trigger point (criteria), it is assumed that rehabilitation is needed. Therefore, by using the trigger criteria, all sections are separated into two groups: “now needs” and “later needs.” In this method, the concern is only with the “now needs.” Having decided upon the sections that need action, the next step is to select a treatment for each of these “now needs.” This could involve simple economic analysis methods such as the net present worth (NPW) or benefit–cost ratio (BCR) based on approximate estimates of the expected life of the different alternatives. After deciding on the treatment, three possible situations may arise: (1) the needs match the budget, (2) the needs exceed the budget, or (3) the needs are less than the budget. Of the three situations, the most common occurs when needs exceed the available funds, and so a ranking of these projects is often needed. The purpose of such ranking is to determine which needs could be deferred to the following year. There are several possible alternatives for ranking. Projects may be ranked by distress, a combination of distress and traffic, the net present worth (NPW), or the benefit-cost ratio (BCR). Sections are then selected until the budget is exhausted. The Rational Factorial Ranking Method (FRM) is an example of a ranking method. It uses a priority index that combines climatic conditions, traffic, roughness, and distress. The priority index is expressed as:

$$Y = 5.4 - (0.0263X_1) - (0.0132X_2) - [0.4\log(X_3)] + (0.749X_4) + (1.66X_5)$$

where

Y = The priority index ranging from 1 to 10, with 1 representing very poor, and 10 representing excellent. Thus a low value indicates a pavement has a high priority for treatment.
X_1 = average rainfall (in./yr)
X_2 = freeze and thaw (cycle/yr)
X_3 = traffic (AADT)
X_4 = present serviceability index
X_5 = distress (a subjective number between −1 and +1)

Example 4: Determining the Order of Priority for Rehabilitation

Three sections of highway have been measured for surface condition with results as shown in Table 11. Also shown are climatic and traffic conditions for each section. Use the Rational Factorial Rating Method to determine the order of priority for rehabilitation.

Section	*Rainfall*	*Freeze/Thaw*	*AADT*	*PSI*	*Distress*
1	10 in./yr	5 cycles/yr	10,000	2.4	+0.5
2	30 in./yr	15 cycles/yr	5,000	3.2	−0.2
3	15 in./yr	0 cycles/yr	20,000	3.0	+0.8

Table 11 Condition, Climatic, and Traffic Data for Highway Sections

Solution:

Using the above equation, and substituting X_1, X_2, X_3, X_4, and X_5 with their appropriate values for each section, Y_1 = 6.099, Y_2 = 4.998, and Y_3 = 6.86. Since low index values indicate poor condition, section 2 should receive the highest priority, followed by section 1, and lastly section 3.

Treatment Selection

Identifying Treatment Needs

Two components must be defined to determine the current or future treatment needs:

- Types of treatments to be considered
- Conditions under which each treatment is considered valuable

For flexible pavements, the following treatment types are commonly considered.

Some are shown in Figure 13:

- Routine maintenance such as crack sealing

- Surface seal coats
- Milling and inlays
- Thin overlays
- Thick overlays
- Mill and overlay
- Reconstruction

Figure 13 Some Primary Preventive Maintenance Activities for HMA Pavements

For rigid pavements, the following treatment types are commonly considered.

Some are shown in Figure 14.

- Slab grinding
- Micro-surfacing
- Full- and partial-depth repairs
- Crack and seal
- Thin-bonded overlays
- Unbonded overlays
- Slab replacement
- Reconstruction


Diamond Grinding


Joint Sealing


Full-Depth Patch

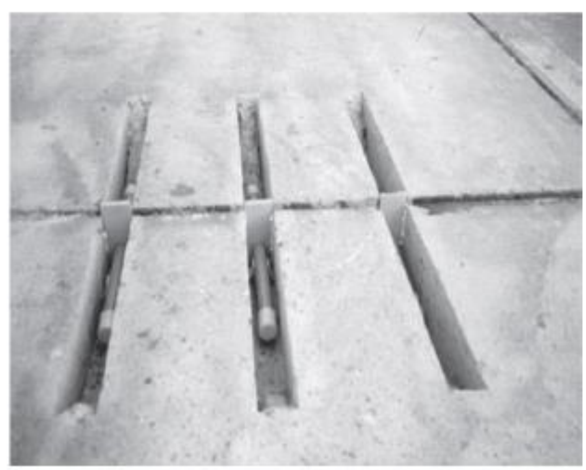
Placement of Dowel Bars

Figure 14 Some Maintenance Works of Concrete Pavements

Sometimes treatment categories are selected instead of selecting the above specific treatment types. Some popular categories are listed below:

- Preventive maintenance
- Surface seal coats
- Minor rehabilitation
- Major rehabilitation
- HMA reconstruction
- PCC reconstruction

Techniques for Treatment Selection

The treatment to be selected must be cost-effective. The following tasks are performed to ensure this objective:

- Ranking
- Multi-Year Prioritization
- Optimization
- Life-Cycle Cost Analysis

Ranking

Ranking is the method of listing candidate pavements based on their condition, initial cost, life-cycle cost, etc. This method does not consider the cost-effectiveness of alternative strategies. The following steps are commonly followed to rank the candidate pavements:

- *Step 1.* Evaluate the pavements with questionable conditions for the current year.
- *Step 2.* Calculate the probable treatment cost.
- *Step 3.* Prioritize the candidate pavements (the worst condition the first).
- *Step 4.* Select one by one pavement from the prioritized list as many as funding allows.
- *Step 5.* Consider the unfunded pavements in the following year.

Multi-Year Prioritization

A better approach over the ranking method is the multi-year prioritization where the current year or more is considered with multiple alternative treatments, resulting in delay or acceleration of treatment and cost-effectiveness. Two types of cost-effectiveness are considered:

- Incremental benefit-cost
- Marginal cost-effectiveness

Incremental benefit-cost approach evaluates if there are any additional benefits such as longer life, riding comfort, and increase in the treatment intervals for incremental increase of investment. Marginal cost-effectiveness considers the cost-effectiveness only, not the benefits.

Optimization

The selection of treatments and their timing of application and the benefits realized from the application of the treatments can be accounted for in the optimization analysis. The optimization can be based on different criteria. For example, either on the concept of minimizing the total cost while keeping all pavements at or above a minimum condition, or on maximizing the total benefit, with the available budget. Every pavement management agency has its own protocol to optimize the benefit and cost.

Life-Cycle Cost Analysis

Life-cycle cost analysis (LCCA) can be used as a decision support tool when selecting treatment selection. LCCA is commonly used while selecting pavement type, determining structure and mix type, construction methods, as well as maintenance and rehabilitation strategy. Typically, LCCA involves the following basic steps:

- Make initial strategy and analysis decisions to establish the parameters under which a LCCA can be carried out.
- Estimate the initial cost and annual costs associated with the owning agency and users for each alternative option.
- Compare alternatives using a common metric such as net present value (NPV) or benefit-cost ratio (B/C).
- Analyze the results and reevaluate alternatives for the most influential costs, factors and assumptions. A sensitivity analysis is often used to do this. Original design strategy alternatives should be reevaluated base on these results analysis in order to improve the cost-effectiveness of each alternative.

The end result of a successful LCCA is not simply the selection of one alternative over the other but the selection of the most cost-effective treatment strategy for a given situation and a greater understanding of the factors that influence cost effectiveness.

Presenting Pavement Management Results

In the next step of the PMS, "what if" or "trade-off" analysis is conducted to determine the impact of different strategies on the cost-effectiveness, performances, etc. This helps decision-makers to assess the overall condition of the network, such as percentage of the network in poor condition, future costs, and targets. Then funds are allocated to ensure that sufficient funding is available for high-priority roadways and distribute the funding logically among regions, districts, or different jurisdictions.

Implementation

Once a decision has been made, the following steps are followed to implement the projects:

- Step 1. Form a steering committee.
- Step 2. Evaluate the goals.
- Step 3. Select the software (such as MicroPAVER).
- Step 4. Collect the field data.
- Step 5. Configure the software accordingly.
- Step 6. Test the software.
- Step 7. Conduct training to the workforce, if required.
- Step 8. Implement the project.
- Step 9. Document the implementation and progress.
- Step 10. Monitor and control the system on a regular basis.

A steering committee is essentially the first step of implementing the project. The roles of each individual must be clearly declared and known to all. The committee should also be aware of the needs and goals of the agency. A software or computer program is selected to execute the project, record the implementation data, and monitor it. A spreadsheet may be good enough for a small project, whereas MicroPAVERTM may be required for large project. The software may be calibrated or tested based on the field data. Once software is finalized, the workforce will be properly trained if there is a new member. Once the work is started, regular monitoring, documentation, and controlling are required to make it a success. Remember that most projects never run as scheduled or planned. Once finished, a proper documentation must be achieved for future reference.

Future Directions

Once the project is over, the job is not over. Once the pavement is in operation, the efficacy of the treatments applied must be monitored, and the results disseminated to the stakeholders concerned for learning and future recommendations. How sustainability can be incorporated or improved must be studied from the project. Any catastrophic event that might take place should be judged as well. All these activities will incur better direction for the future.

Appendix B — Recycling and Rehabilitation of Pavements

General

With the increase in the population of the world, demand has dramatically increased in the roadway network. Nonetheless, the need to provide a safe, efficient, and economic roadway is challenging due to the reduction in the budgetary fund. The construction cost is considered the most at the time of the extension of the roadway. Nonetheless, less attention is given to future maintenance costs. After a few years of service, two simultaneous problems arise on the roadway:

- The roadway requires some maintenance due to wear and tear.
- Traffic volume increases.

The presence of these two issues in the absence of maintenance will result in rapid damage of the roadway. If the available funds are not sufficient to meet the increased maintenance and demand, there will be a significant reduction in the quality and service level for the roadway network. It eventually results in higher overall preventive maintenance and the higher cost of rehabilitation or reconstruction. It ensures that in earlier stages of pavement damage, it is easier to perform maintenance or rehabilitation. The reactive operation becomes more expensive once the level of damage is severe. Research by the World Bank indicates that each $1.00 spent at the first 40% decrease in roadway quality results in savings of $3.00 to $4.00 relative to the investment expected at the 80% decrease in quality (ARRA, 2015).

Rehabilitation or recycling can be described as measures to improve, reinforce, or rescue existing defective pavements so that only routine maintenance can continue service (ITS, 2000). Recycling of pavements will typically offer the following benefits:

- Conservation of natural resources
- Energy saving
- Conservation of environment
- Money saving

Pavement is made up of aggregates, asphalt binder, and a few additives. Aggregate reuse means saving an aggregate source (say, a mountain). Furthermore, recycled aggregates have inherent asphalt binder. The new aggregates require about 4% to 6% of asphalt binder to satisfy the mix design requirements. However, a recycled aggregate pile requires asphalt binder between 1% and 3% by weight of mix (Nikolaides, 2015). Schwartz (2016) reported that cold-in-place recycling (CIR) technology of asphalt pavement (discussed later in this appendix) saves 60% asphalt binder compared to conventional new asphalt mix.

Energy consumption in pavement construction relates to aggregate and asphalt production, transportation, processing, heating, mixing, placing, and compacting. Less new materials mean less energy consumption.

Pollutants such as carbon dioxide (chemically referred to as CO_2) are generated by the use of energy for aggregate and asphalt production, transportation, processing, heating, mixing, placing, and compacting. Recycling of pavement materials saves the emission of this pollutant. For example, the use of asphalt pavement CIR (discussed later in this appendix) is environmentally friendly as it can reduce carbon dioxide emissions by up to 9% compared to traditional HMA mixtures; in the recycling process alone, carbon dioxide emissions are 54% lower (Giani et al., 2015). Schwartz (2016) stated that CIR and cold central plant recycling (CCPR) technologies (discussed later in this appendix) decreased carbon dioxide emissions by 80% and 42%, respectively, compared with conventional HMA applications.

Asphalt Pavement Recycling

General

Since the late 1970's, recycling of asphalt pavement has grown in popularity, mainly due to higher oil prices. Recycling of old pavements had been more costly than placing new hot-mix asphalt (HMA) (Roberts et al., 1996). The invention of milling machines has improved the cost-effectiveness of asphalt recycling compared to new construction (Cross and Jakatimath, 2007). After that, equipment manufacturers and construction industries were interested in developing the methods and techniques of asphalt recycling and since then it has progressed exponentially (ARRA, 2015).

Asphalt Recycling Types

ARRA (2015) divided various asphalt recycling methods into five broad categories:

- Hot recycling (HR)
- Hot in-place recycling (HIR)
- Cold planing (CP)
- Full-depth reclamation (FDR)

- Cold recycling (CR)

Asphalt recycling approaches can be used in some roadway rehabilitation projects in combination with each other. For example, the upper portion of an existing roadway could be removed via CP and the resulting reclaimed asphalt pavement (RAP) could be stored at the asphalt plant. When prepared, the cold planed surface could be overlaid with HMA containing the milled off RAP. Instead, the exposed CP surface could have been HIR, CR, or FDR before the recycled mixture was put to reduce or remove the effects of reflective cracking.

Hot Recycling

Hot recycling (HR) is the world's most widely used method of asphalt recycling. The United States produces more than 100 million tons of RAP. About 15% to 30% of this production is used in hot recycling (ARRA, 2015). Hot recycling is the method of mixing RAP milling with fresh aggregates and a recycled mixture of asphalt binder under heating in a plant. The asphalt binder in the RAP melts first after the RAP has been heated. The new aggregate and binder are then added and thoroughly mixed. It is transported, placed, and compacted once mixed with conventional HMA equipment. Nowadays, this method is the most commonly used practice. Figure 15 shows the entire HR process.

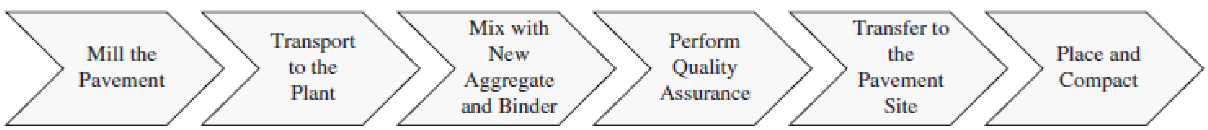

Figure 15 Basic Steps of Hot Recycling

Some of the major advantages of HR include the following:

- Similar performance as pavements constructed with all new materials, thus can be used in all types of pavements.
- Reuse of aggregate and binder, which saves natural aggregates, binder, and energy to produce it.
- No need to dispose of the RAP milling.

Some of the major disadvantages of HR include the following:

- Problems with existing aggregate gradation and/or asphalt binder may reflect in the new layer.
- Too much RAP produces a stiffer mix and thus leads to thermal cracking.
- Transportation cost is involved while carrying to and from the plant.

Hot in-Place Recycling

Hot in-place recycling (HIR) is conducted for less severely damaged pavement compared to the pavement which requires HR. In HIR, all the recycling of the asphalt pavement is completed on site. The deteriorated top ¾ to 3 in. (19 to 75 mm) is heated and softened, milled off, thoroughly mixed inside the truck, and compacted with conventional HMA paving equipment. If required, it is possible to add virgin aggregates, new asphalt binders, recycling agents, and/or new HMA. Generally, virgin aggregates or additional HMA addition are limited to less than 30% by mass of HIR mix due to equipment restrictions. An analysis of the current asphalt pavement properties and subsequent laboratory mix designs will assess the additional levels of the various additives to ensure compliance with the appropriate mix requirements. Figure 16 shows the entire HIR process.

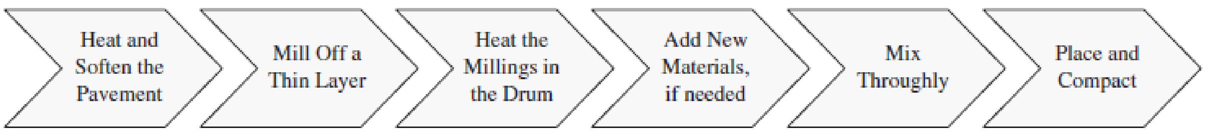

Figure 16 Basic Steps of Hot in-Place Recycling

Based on the process used, three subcategories of HIR are possible:

- Surface recycling
- Remixing
- Repaving

Surface recycling is the HIR process where the deteriorated surface of the pavement is heated, softened, and scarified, and recycling agent is mixed (if required) and the loose recycled mixture is thoroughly mixed with the standard paver screed. No aggregate or binder except the recycling agent is added. The depth of recycling typically varies from ¾ to 1.5 in. (20 to 40 mm). In a subsequent operation, a surface coat such as a chip seal or HMA overlay is usually placed. Figure 17 demonstrates the basic HIR surface recycling process.

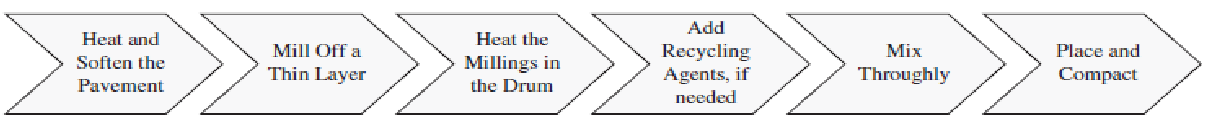

Figure 17 Basic Steps of Hot in-Place Surface Recycling

Remixing is similar to the surface recycling but new materials (aggregate and binder) are added in addition to the recycling agent. More specifically, HIR remixing is the process in which the existing deteriorated asphalt pavement is heated, softened, and scarified and virgin aggregate, new asphalt binder, recycling agent, and/or new HMA are added (as required) and the resultant is thoroughly mixed and then paved. Remixing is typically used when existing pavement properties require significant modifications compared to surface recycling. Treatment depths generally range from 1 to 2 in. (25 and 50 mm) for single-stage remixing. A surface coat such as a chip seal or HMA overlay is usually placed in a subsequent operation similar to surface recycling. Figure 18 shows the basic HIR remixing process.

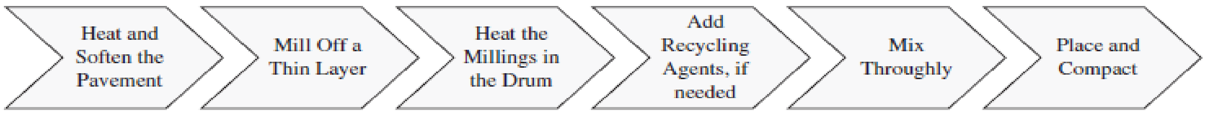

Figure 18 Basic Steps of Hot in-Place Remixing

Remixing is also further classified into two types:

- Single-stage
- Multi-stage

In the single-stage method, the above-described process is performed a single time. The process of heating, softening, and scarifying the existing asphalt pavement is repeated several times in the multi-stage remixing method until the full depth of treatment is reached. The scarified material from each stage is placed in a windrow to allow the underlying layer to be heated and scarified. Once the full asphalt layer is scarified, in addition to the recycling agent, new aggregate and binder may be applied. The entire recycled mixture is then thoroughly mixed, placed on site, and compacted.

Repaving is the method of recycling or remixing the surface with the placement of the new HMA overlay. The surface recycled mix functions as a leveling course in the repaving process, while the new HMA acts as the course of surface or wear. The thick-ness of the pavement can be increased significantly in the course of repaving. Figure 19 shows the entire hot in-place repaving cycle.

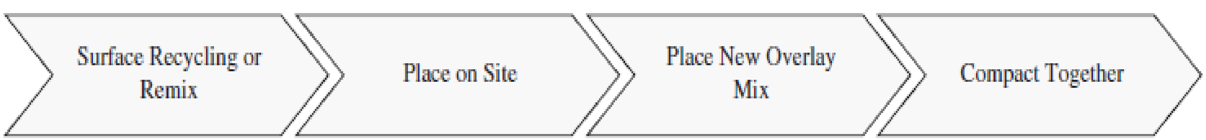

Figure 19 Basic Steps of Hot in-Place Repaving

Repaving is also further classified into two types:

- Single-stage
- Multi-stage

One machine fitted with two screeds is used for single-pass repaving. The first screed places the recycled mixture on top of the recycled mix while the second screed places the new HMA layer. Then the two layers are compacted. In the multi-stage method, the surface recycled mix is positioned by its placing and screeding unit to the correct longitudinal profile and cross-slope. The new HMA overlay material is then immediately placed with a traditional asphalt paver on the hot, uncompacted recycled mix. The two layers are then simultaneously compacted.

Some of the major advantages of HIR include the following:

- Reuse of aggregate and binder, which saves natural aggregates, binder, and energy to produce it.
- No need to dispose of the RAP milling.
- No need to transport the milling; thus, no disposal problems.
- Restores the friction and removes minor distresses such as rutting, potholes, raveling, surface irregularities, and oxidized asphalt binder.
- Structural strength and integrity remain intact or increase.
- In-place construction reduces traffic disruptions compared to HR.
- Cost-saving and less hazardous.

Some of the major disadvantages of HIR include the following:

- Large, specially equipped and costly equipment are required.
- There are not as many options for new materials.
- Quality control is not as good as for HR.
- Only suitable for thin layer treatment.

Cold Planing

Cold planing (CP), also called cold millings, is the removal of the required depth of the existing pavement to restore surface friction, correct corrugation, reduce asphalt bleeding, remove shoves, correct slopes (longitudinal profile and cross-slope), etc. This activity is carried out using specially designed equipment called cold planers or pavement profilers. The textured surface can be opened immediately for normal traffic. The pavement can also be treated or overlaid with one of the other forms of asphalt recycling. This method is very quick, and the public is less disturbed.

The RAP created during the CP operation is removed from the site and, like other RAPs, can be used in different ways. The RAP is then further recycled or could be reused as a base aggregate for roadway construction and widening, ditch linings, pavement repairs, or dust-free gravel road surface, etc. Some of CP's major benefits include the following:

- Removal of deteriorated pavement surfaces.
- Removal of oxidized asphalt.
- Correction of longitudinal profile and cross-slope.
- Removal of some distresses such as rutting, shoving, corrugation, and bleeding.
- Restore drainage.
- Restore friction.

Some of the major disadvantages of CP include the following:

- The resulting pavement surface produces noise while using.
- As the thickness of the surface layer decreases, the capacity of pavement structure may decrease.
- The operation may produce dust, which is a nuisance for the surrounding area.
- CP is difficult to operate for stiffer asphalt.

Full-Depth Reclamation

Full-depth reclamation (FDR) means full depth of asphalt layer, and in some cases, some parts of the underlying base/subbase/subgrade layer are pulverized, blended thoroughly, and compacted in place as a new base layer. The blended material is not heated. Rather, it may be stabilized with a wide range of dry or liquid stabilizing agents or may be even untreated base layer. Some of the commonly used additives are port-land cement, asphalt emulsion, fly ash, foamed asphalt, lime, calcium chloride, magnesium chloride, etc. or a combination of a few. Treatment depths vary between 4 and 12 in. (100 and 300 mm) in common. FDR is conducted to pavements with severe damage in the underlying base/subbase/subgrade layer and/or satisfies the increased traffic demand.

The combined new layer (treated or untreated) consisting of the bound asphalt layer and the underlying unbound layers can be used as it is if the traffic is low. A new granular layer or wearing HMA layer may be applied as desired. The whole FDR process is shown in Figure 20.

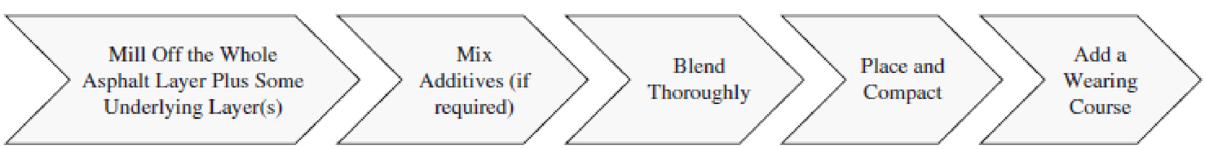

Figure 20 Basic steps of full-depth reclamation (FDR)

Stabilization of the reclaimed pavement can be done by mechanical, chemical, or bituminous means. Mechanical stabilization methods include the addition of the following:

- Virgin aggregate
- Reclaimed asphalt pavement (RAP)
- Crushed Portland cement concrete (PCC)

Chemical stabilization is achieved with the addition of the following:

- Lime
- Portland cement
- Fly ash
- Cement kiln dust
- Calcium/magnesium chloride
- Other proprietary chemical products

Bituminous stabilization can be accomplished with the use of the following:

- Liquid asphalt
- Asphalt emulsion
- Foamed asphalt

For increased stabilization requirements, combinations of all three can also be used.

Some of the major advantages of FDR include the following:

- Reuse of aggregate and binder, which saves natural aggregates, binder, and energy to produce it.
- No need to dispose of the RAP milling.
- No need to transport the milling; thus, no disposal problems.
- Elimination of bumps and dips, rutting, potholes, patches, and cracks.
- Base/subbase/subgrade deficiencies can be corrected by stabilization.
- Significant structural improvement with the addition of stabilizing additive(s).
- Produces thick, bound layers that are homogeneous.

- Permits more flexibility in the choice(s) of wearing surface type and thickness.
- Provides significant structural improvement.
- Improves smoothness and riding quality.

Some of the major disadvantages of FDR include the following:

- Problems with existing aggregate gradation and/or asphalt binder may reflect in the new layer.
- Costly as the full depth is reclaimed.
- Not suitable for areas with drainage problems.
- Soil with high plasticity can result in swelling.
- Not recommended for roads with daily traffic of more than 20,000 vehicles.

Cold Recycling

Cold recycling (CR) is the processing and treatment of existing HMA pavements to recover the pavements without heating asphalt materials. A milling machine extracts the degraded top 2 to 4 in. (50 to 100 mm) of HMA, crushes, and screeds the milled material to achieve a required gradation. The milled material is combined with binding additives such as emulsion, cement, lime, or fly ash. Then the mixture is placed back on the roadway, compacted, and graded to the final elevation. If the volume of traffic is relatively high, a fog seal or thin overlay can be added after compaction of the mixture. Two subcategories within CR are used to further define CR based on the process used:

- Cold in-place recycling (CIR)
- Cold central plant recycling (CCPR)

In the CIR, all operations such as milling, screening, and mixing additives are per-formed on site inside a large truck. After thoroughly mixing, the mixture is placed and compacted. In the CCPR, the milling is transported to a central plant. All the processing of this milling such as screening, gradation, and mixing additives are conducted in the plant. Then the mix is transported to the site, placed, and compacted similar to conventional pavement. Recent studies show that the dynamic modulus of CIR is about half of the conventional mixture at low temperature and is about equal to the conventional mixture at high temperature. Field performance shows that CR and conventional mixtures produce similar performance for low-traffic roadways (Cross and Jakatimath, 2007; Islam et al., 2018; Kim et al., 2010; Schwartz, 2016).

Some of the major advantages of CR include the following:

- Reuse of aggregate and binder, which saves natural aggregates, binder, and energy to produce it.
- No need to dispose of the RAP milling.
- Elimination of bumps and dips, rutting, potholes, patches, and cracks.
- Decrease in carbon dioxide emission.
- Base and subgrade materials are not disturbed.
- Pavement cross-slope and profile can be improved.
- In-place construction reduces traffic disruptions compared to CCPR.

Some of the major disadvantages of CR include the following:

- Problems with existing aggregate gradation and/or asphalt binder may reflect in the new layer.
- Suitable for minor distresses.
- Applicable to low-volume roads.

Compared to CIR, CCPR requires transporting millings to and from the plant but provides better quality control opportunity.

Summary of Rehabilitation Techniques

Various techniques of rehabilitation have been discussed in this appendix. It looks like one technique can be applied to various distresses. In other words, different techniques may be suitable for one form of distress. The decision depends on some factors, including technology availability, skilled labor, traffic volume, etc. Table 12 lists some general recommendations for the preliminary collection of different rehabilitation techniques.

Concrete Pavement Recycling

General

Concrete pavement recycling is a simpler process than flexible pavement recycling. Recycling of concrete pavement includes the demolition and crushing of hardened concrete from an existing pavement to produce recycled concrete aggregate (RCA) (ACPA, 2009). RCA can be used in almost any application instead of new granular materials. The aggregate demand for pavement and building construction continues to rise rap-idly. In the United States, virgin aggregate production increased from 58 million tons in 1900 (or 0.5

Pavement distress mode		CP	HIR	CIR	CCPR	FDR
Surface Defects	Raveling	dark	dark	light	light	
	Potholes		light	light	light	light
	Bleeding	light	light	dark	dark	light
	Skid Resistance	light	light	light	light	
Deformation	Shoulder Drop-Off	light				
	Rutting—Wear	light	dark	dark	dark	
	Rutting—Mix Instability	light	light	light	light	dark
	Rutting—Deep Structural				light	dark
	Corrugation	light	dark	dark	dark	light
	Shoving	light	light	dark	dark	light
Load-Related Cracking	Fatigue—Bottom Up			light	light	dark
	Fatigue—Top Down		light	dark	dark	dark
	Edge		light	light	light	dark
	Slippage		light	dark	dark	
Non-Load-Related Cracking	Block		light	dark	dark	light
	Longitudinal		light	dark	dark	
	Transverse		light	dark	dark	light
	Reflective		light	dark	dark	dark
Combined	Joint Reflection		light	light	light	
	Discontinuity		light	light	dark	dark
Base/Subgrade Deficiencies					light	dark
Rough Ride Quality		dark	dark	dark	dark	

Most Appropriate → *Least Appropriate*

Table 12 Applicability of Recycling Techniques

ton/person) to 2.3 billion tons (2.1 billion metric tons) in 1996 (9.6 tons/per-son) (USGS, 1997). RCA can be a good alternative to meet this high demand. Concrete paving is 100% recyclable (ACPA, 2006). Since the 1940s, concrete recycling has been widely used in Europe and since the 1970s in the United States (NHI, 1998). Concrete recycling is now carried out in at least 41 states for paving applications (FHWA, 2004). Recently, about 140 million tons of annual RCA production in the United States from all sources (both pavements and demolition debris) have been recorded (CDRA, 2018).

Saving natural aggregates, landfill space, energy, and money are some of the advantages of RCA (FHWA, 2002; Hall et al., 2007; Van Dam et al., 2015). Concrete recycling offers 20% to 30% of the cost of pavement with construction materials and supplies and 10% to 15% of total construction costs (Halm, 1980). One case study showed a $5 million savings on a single project, despite cost savings from recycling concrete pavement (CMRA, 2008).

Production of RCA

The basic steps of concrete pavement recycling are listed below and shown in Figure 21.

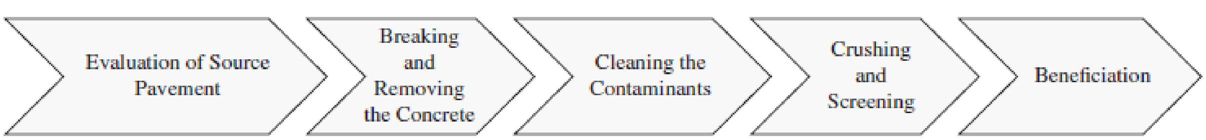

Figure 21 Basic Steps of Concrete Pavement Recycling

- Evaluation of the source concrete

- Breaking and removing the concrete
- Removing any steel mesh, rebar, or dowels
- Crushing and screening the RCA
- Beneficiation or quality control of removing any additional contaminants or improving properties

While producing RCP, effort is made to maximize the production of usable RCA. For example, coarse RCA (material retained on the No. 4 sieve) is typically more valuable and usable than fine RCA (material that passes the No. 4 sieve). Contaminants such as joint sealants, asphalt concrete shoulders, and patching materials, reinforcing steel and dowel bars, and soils and foundation materials should be separated to make the RCA high-quality materials. Any asphalt present in concrete pavement, such as thin layer of asphalt and asphalt repairs, should be separated.

Evaluation of the Source Concrete

In the first step of producing RCA, some basic properties pertaining to the concrete strength and performance such as original aggregate, cement type, and admixture used are evaluated. Based on this information, the proposed use of the RCA is recommended. For example, if the proposed RCA is good-quality material then it could be used for a new structural surface layer of a pavement or other concrete works. On the other hand, inferior RCA may be used for unbound layers of pavement or similar works.

Breaking and Removing the Concrete

The concrete slab is broken into manageable pieces using a heavy scraper or impact breaker and transported to the crushing plant. The first step in the removal process is to loosen the concrete pieces and separate any debonded reinforcing steel. A back hoe or bulldozer with a rhino horn attachment can be used to hook and pull the steel free from the concrete rubble. Some hand work with hydraulic shears may be required to cut the reinforcing steel. Small pieces of embedded steel do not cause problems in the crushing operations and may be removed after crushing.

Removal of any Steel Mesh, Rebar, or Dowels

The separation of steel materials can be conducted in several phases of the entire process, although the earlier the better. After crushing operations, electromagnets are often used to pick steel from the conveyor belts. Manual labor may be used to expedite the steel removal operations. An operation of steel bar removal is shown in Figure 22.

Figure 22 Steel Bar Removal from an Interstate Pavement

Crushing and Screening the RCA

The transported pieces are crushed and screened to produce desirable aggregate gradation. Care is taken to avoid the production of fine aggregates (passing No. 4 sieve):

- Primary crushing
- Secondary crushing

The primary crusher typically reduces the material size down to about 3 to 4 in. (75–100 mm). The crushed material is then screened and material larger than ⅜ in. (9 mm) is fed into a secondary crusher, which breaks the material to the desired maxi-mum coarse RCA size.

Beneficiation

Beneficiation is the treatment or removal of accidental organic material, excessive dust, soil, etc. to improve its physical or chemical properties prior to further processing or use. The produced RCA may be further graded based on size or density to have some desired properties. This is the last step before the usage of RCA and thus can be treated as a QC/QA check

Properties of RCA

Properties of RCA largely depend on the proportion of reclaimed aggregate and mortar, properties of original materials, crushed aggregate gradation, etc. Higher amounts of reclaimed mortar result in higher absorption, lower specific gravity, lower particle strength, and lower resistance to abrasion than would be found in the natural aggregate involved. Typical distributions of few natural aggregates and RCA physical properties are listed in Table 13. It indicates that RCA typically has higher absorption, LA abrasion mass loss, sodium sulfate mass loss, magnesium sulfate soundness mass loss, and chloride content. The actual gravity, however, may be lower than the normal aggregates. In short, RCA's physical properties are different than natural aggregates.

Property	Natural Aggregate	RCA
Absorption capacity (%)	0.8–3.7	3.7–8.7
Specific gravity	2.4–2.9	2.1–2.4
LA abrasion test mass loss (%)	15–30	20–45
Sodium sulfate soundness test mass loss (%)	7–21	18–59
Magnesium sulfate soundness test mass loss (%)	4–7	1–9
Chloride content (lb/yd3)	0–2	1–12

Table 13 Typical Properties of Natural Aggregate and RCA

While using RCA, it should be analyzed as an engineered material with appropriate mixture design or construction adjustments. The RCA materials must satisfy the mix design requirements similar to virgin aggregate for the desired application (e.g., pavement surface layer, unbound base layer, etc.). With proper control, RCA can be utilized to satisfy standard quality and gradation.

Properties of Concrete with RCA

The properties of the RCA-prepared concrete mixture depend on RCA's composition, and gradation. The effect of RCA can be minimized with proper mix design and admixture (ACPA, 2009).

Fresh RCA Concrete Properties

As RCA particles are angular and rough-textured, RCA produces harsh, fresh concrete. If there is too much fine RCA in the mixture, then workability can be a problem. Therefore, to have adequate workability, fine RCA is usually limited to 30% or less replacement of sand to have sufficient workability. A high RCA absorption rate can also cause problems with workability. It is important to use pozzolanic and chemical admixtures to boost workability.

Hardened RCA Concrete Properties

The ranges of concrete properties resulting from the RCA are listed in Table 14. In comparison to the mixture with virgin aggregates, the compressive and tensile strength of the RCA mixture can be up to 40% and 20%, respectively. The elasticity modulus may be 40% lower than the virgin aggregate mixture. On the other hand, thermal expansion and contraction, shrinking, and permeability may increase. The degree of difference depends on the amount of fine RCA.

Property	Coarse RCA Only	Coarse and Fine RCA
Compressive strength	0–24% lower	15–40% lower
Tensile strength	0–10% lower	10–20% lower
Modulus of elasticity	10–33% lower	25–40% lower
Thermal expansion/contraction	0–30% higher	0–30% higher
Drying shrinkage	20–50% higher	70–100% higher
Permeability	0–500% higher	0–500% higher

Table 14 Typical Properties of RCA Concrete Compared to Similar Mixtures with Natural Aggregate

RCA intended for use in concrete paving mixtures must be treated as an engineered material, considering physical and mechanical properties, such as absorption capacity and coefficient of thermal expansion. Consideration of these properties may result in the need to modify the concrete mix design through the use of chemical and/or mineral admixtures, different mix component proportions, and/or aggregate blending. They may also require the consideration of different pavement structural characteristics (i.e., thickness, panel dimensions, reinforcing, etc.).

Since RCA has different physical and mechanical properties than a conventional virgin aggregate, the following considerations should be given while using RCA in pavement design:

- RCA concrete has less strength and elastic modulus. This leads to slightly larger pavement thickness.
- RCA concrete has high shrinkage and thermal expansion/contraction. This leads to more significant joint movements and may require different sealant materials or a small panel span.
- RCA concrete reduces the potential for aggregate interlock. This leads to higher amounts of reinforcing in the mesh-reinforced RCA concrete pavement and continuously reinforced pavement.

Uses of RCA

Since the 1940's in the United States (Epps et al., 1980), RCA has been used widely for roadway concrete layers, shoulders, median barriers, sidewalks, curbs and gutters, building and bridge foundations, and even structural concrete. Since that time, RCA has been used on low-volume roads (e.g., Highway 75 in Iowa) and high-volume roads (e.g., Interstate 10 near Houston, Texas) to create hundreds of concrete pavement construction projects in the United States and around the world (ACPA, 2009). This also included the recycling of pavements that were severely damaged in new concrete pavements due to D-cracking or alkali-silica reactivity

(ASR). RCA is common in some European countries (such as Austria) and is increasingly permitted in the United States (such as the Illinois Tollway Reconstruction I-90) (ACPA, 2009).

Considerations for Mix Design Using RCA

RCA materials to be used in new concrete pavements are expected to be free of potentially harmful contaminants. Study shows that in concrete mixtures, the presence of small amounts of joint sealant, traffic engine oil, and other contaminants on the pavement surface cause problems (FHWA, 2007). When designing mixes, RCA materials must satisfy the same quality requirements as virgin aggregate, although there is usually no need for RCA washing prior to batching. Washing, however, helps to reduce the problems of absorption and workability and to strengthen the bond of cement and aggregate. The mix design of concrete containing RCA can be done using the same com-mon procedures for mixing concrete design with virgin aggregate only. The following are some additional activities suggested for mixing with RCA materials:

- A little higher proportion of cement may be necessary to produce the required strength (FHWA, 2007).
- To confirm similar workability to a conventional PCC mixture, 5% to 15% more water and/or a water-reducing admixture may be required (FHWA, 2007).
- FHWA (2007) recommends a water-to-cementitious material ratio of 0.45 or less.
- To prevent the output of a harsh mix, fine RCA should be limited to 30% of the total fine aggregate. The use of coarse RCA in concrete paving mixtures does not have general limitations.
- RCA substitutions for natural aggregate should be conducted volumetrically because of the lower specific gravity of RCA.