Towards Sustainable Pavement Systems: Webinar Series

Webinar #4:

Maintenance, Preservation, and End-of-Life

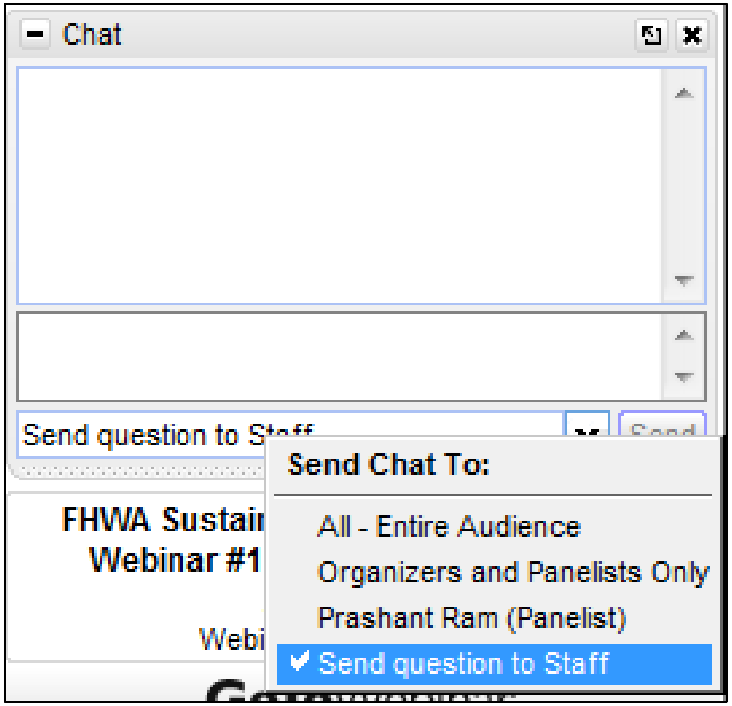
August 20, 2015

Webinar Series

- Sponsored by Federal Highway Administration
- "Towards Sustainable Pavement Systems: A Reference Document"
  - http://www.fhwa.dot.gov/pavement/sustainability/
- Total of 5 webinars from April to September
- Webinars recorded for posting on FHWA website

Housekeeping

- Formal Presentations:
  - 1 hour 40 min
- Questions:
  - 20 minutes
  - Use chat box to submit
  - Use dropdown menu to "send questions to staff"



- Professional Development Hours (PDHs) Certificates
  - 2 hours per webinar

Today’s Webinar

- Topic: Maintenance, Preservation, and End-of-Life
- Speakers:
  - Gina Ahlstrom, FHWA
  - Tom Van Dam, NCE
  - Imad L. Al-Qadi, University of Illinois
  - Hasan Ozer, University of Illinois
  - Mark Snyder, Engineering Consultant
- Moderators:
  - Kurt Smith, Applied Pavement Technology, Inc.
  - Tom Van Dam, NCE

FHWA Sustainable Pavements Program

Background and Overview

Gina Ahlstrom

US DOT is Committed to Advancing Sustainability

- DOT will incorporate sustainability principles into our policies, operations, investments and research through innovative initiatives and actions such as:
  - Infrastructure investments and other grant programs,
  - Innovative financial tools and credit programs,
  - Rule- and policy- making,
  - Research, technology development and application,
  - Public information, and
  - Enforcement and monitoring.

Policy Statement

Signed Secretary Anthony R. Foxx, June 2014

U.S. Department of Transportation
Federal Highway Administration

FHWA
Sustainable Pavements Program

- Support the US DOT goals for sustainability
- Increase the body of knowledge regarding sustainability of asphalt and concrete materials throughout the pavement life cycle
- Increase the use of sustainable technologies and practices in pavement design, construction, preservation, and maintenance

“Towards Sustainable Pavements: A Reference Document”

- Guidelines for the design, construction, preservation and maintenance of sustainable pavements using asphalt and concrete materials
- Educate practitioners on how sustainability concepts can be incorporated into pavements
- Encourage adoption of sustainable practices

A Collaborative Effort

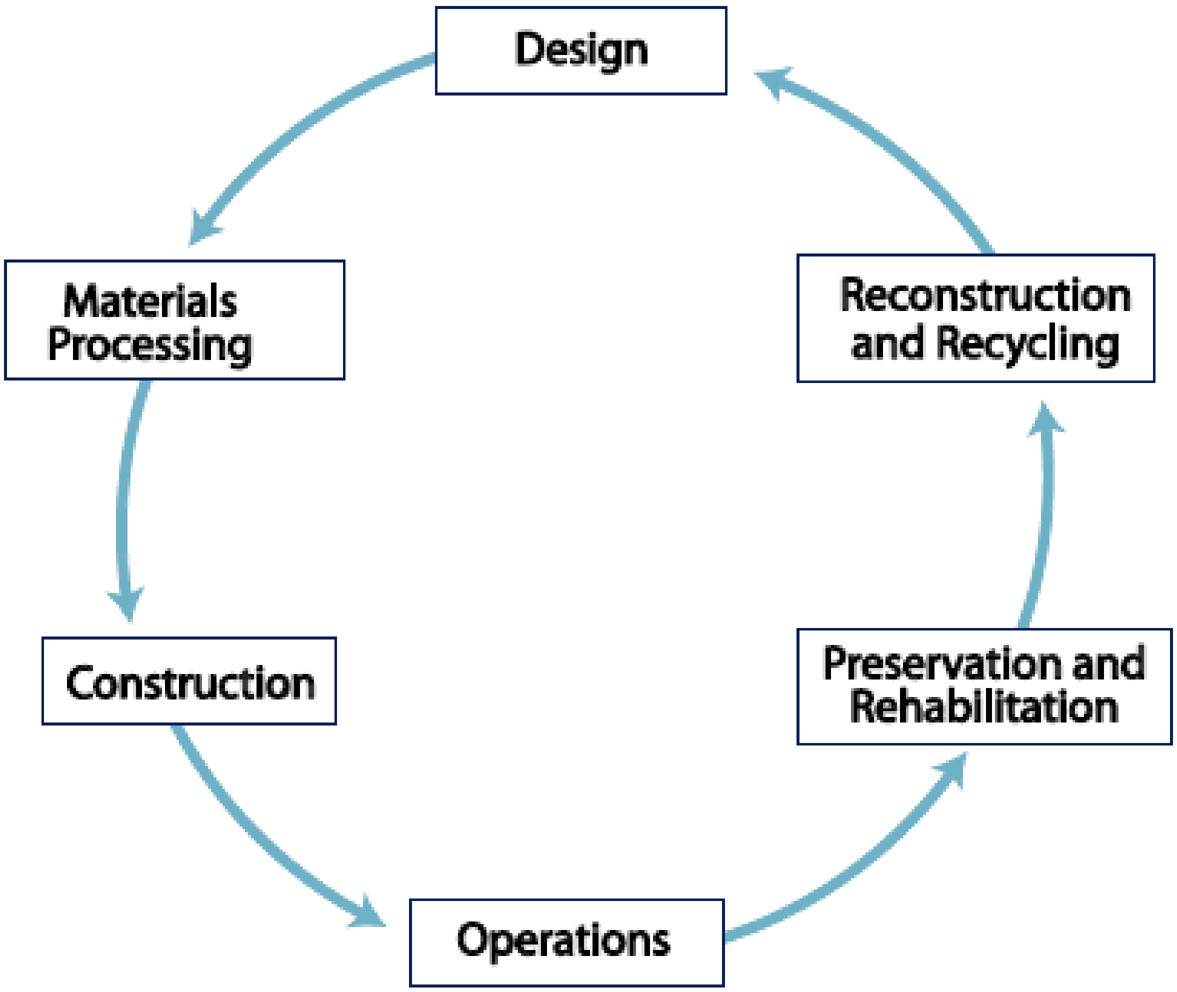
- Comprehensive review of current literature
- Extensive review by representative from key stakeholders groups:
  - State Departments of Transportation
  - Other Public Agencies
  - Asphalt and Concrete Industries
  - Academia

- **Pavement Preservation and Sustainability**
- **Pavement Maintenance and Preservation Techniques**

Tom Van Dam

Triple Bottom Line

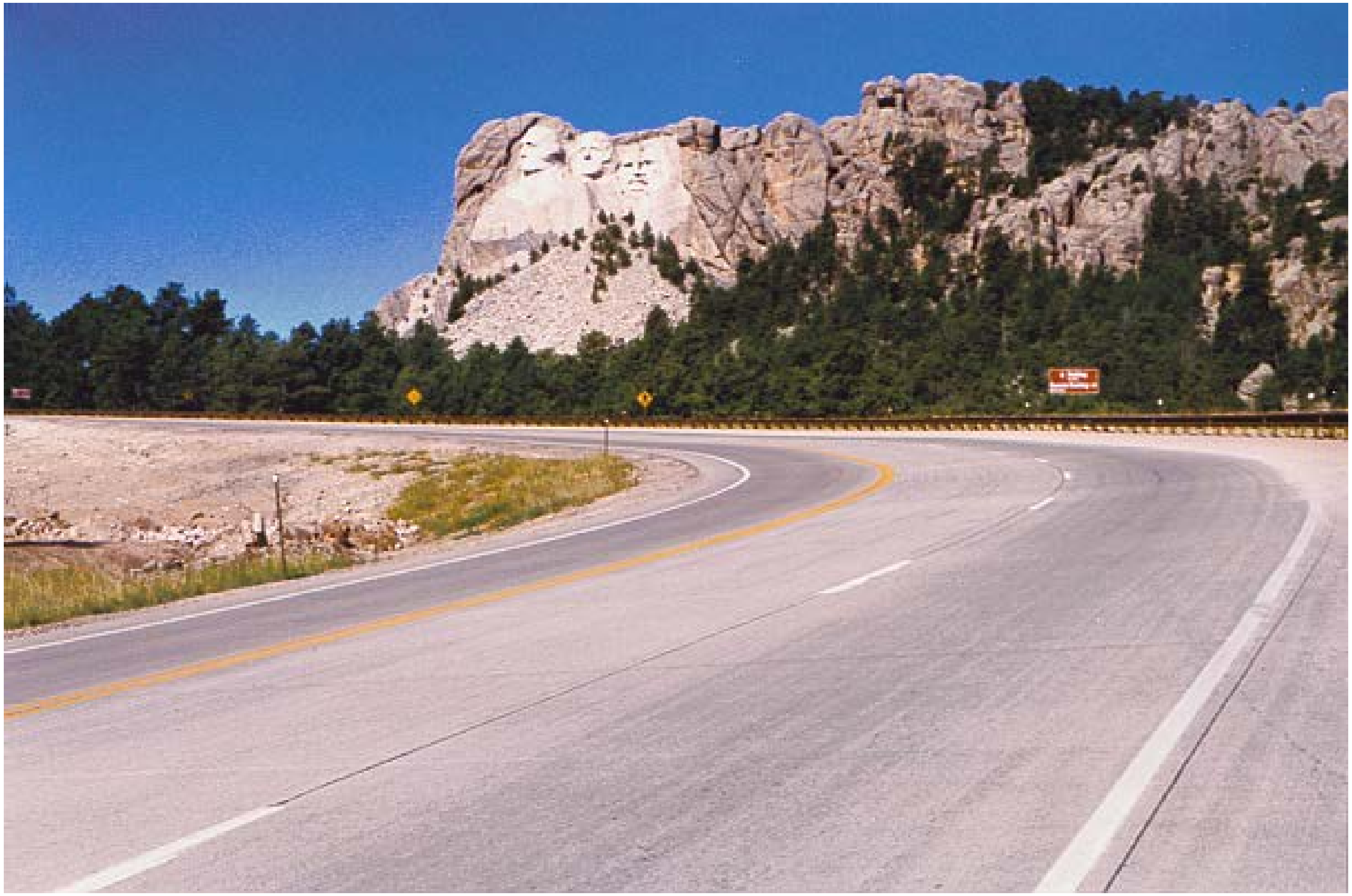
Consider the Life-Cycle



Pavement Preservation and Sustainability

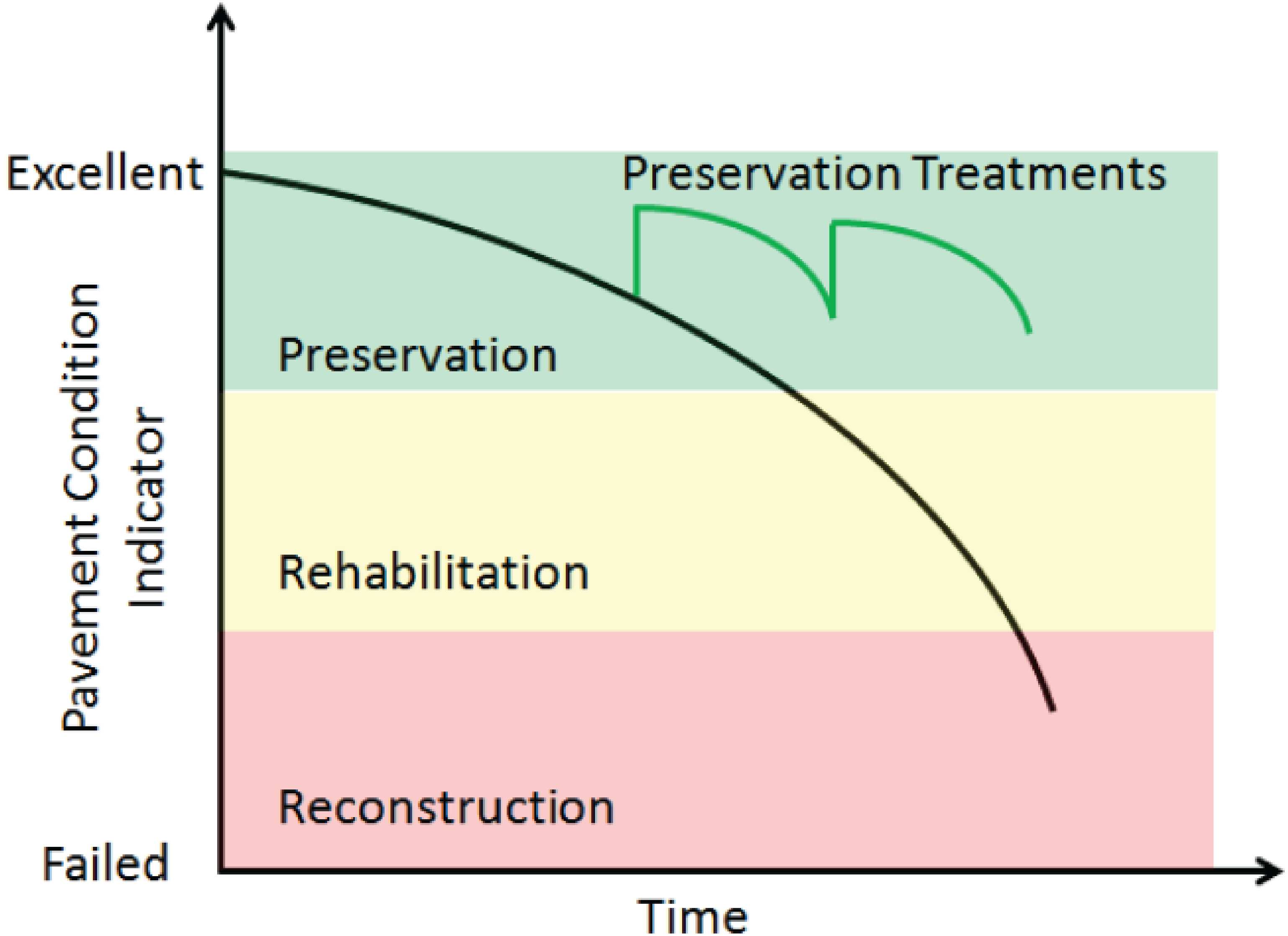
- The visibility of pavement preservation continues to rise
  - Budgets continue to be very tight
  - Consideration of the pavement life cycle
  - Integrating preservation with design
    - NCHRP Project 1-48
    - Very common in P3 design-build-operate
    - Tollways are very cognizant of this link

Preservation Philosophy



Keep good roads in good condition!

Impact of Pavement Preservation



Pavement Preservation

- An inherently sustainable activity
  - Good design and construction, then maintain
  - Typically low-cost, low-environmental-impact activities
  - Conserves energy and virgin materials

Pavement Preservation

- Restores and maintains functionality
  - Improved safety (skid, markings)
  - Reduced noise
  - Improved fuel efficiency
  - Enhanced aesthetics
- Many little things result in big improvement over the life cycle

Preservation Considerations

- Cost effectiveness of pavement preservation has been investigated and broadly accepted
- Must consider the impact of a preservation treatment on traffic and the community
- Level of improvement and longevity are closely linked to construction quality
- There is currently a lack of life cycle inventory data for many preservation activities
  - More of a concern for proprietary treatments

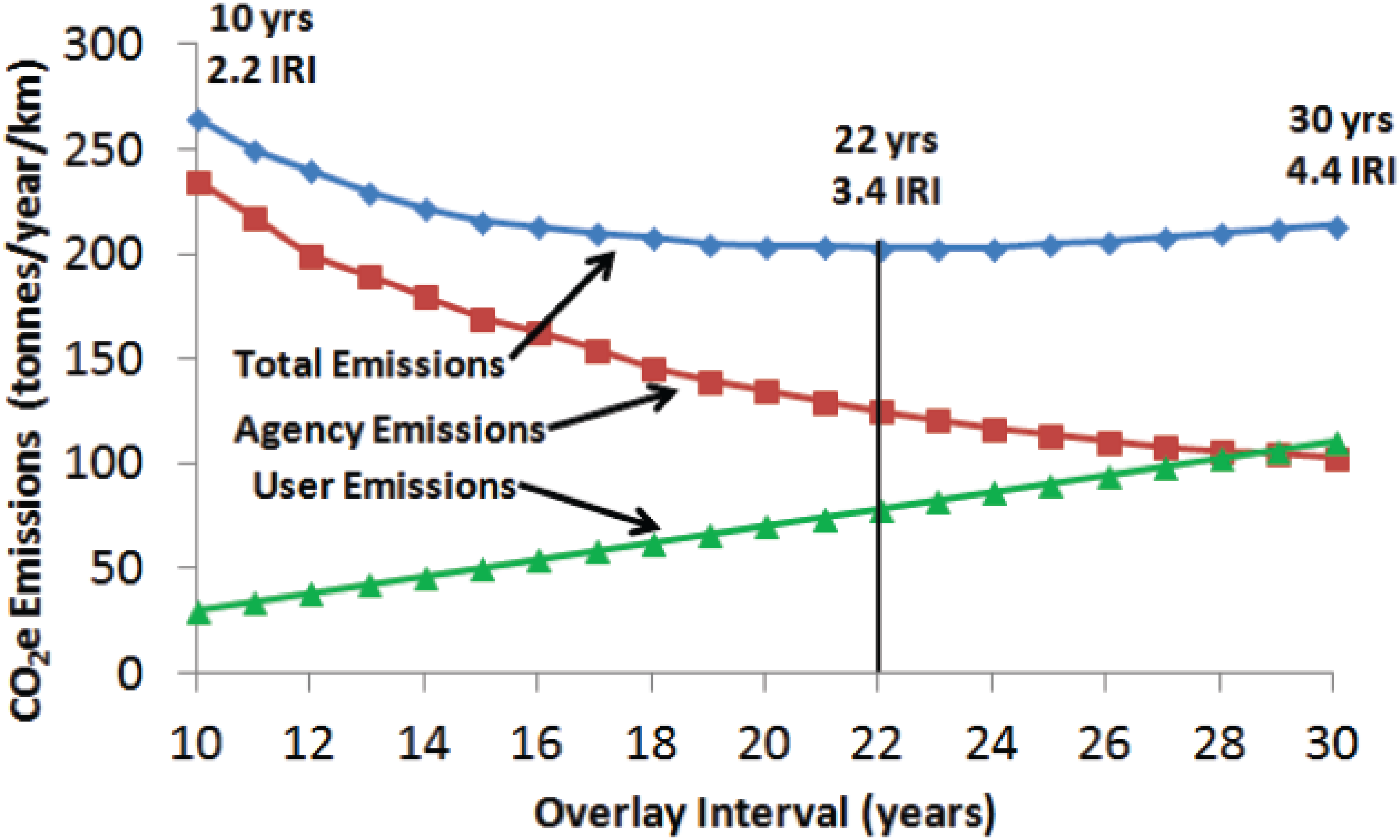
Low Volume Roads

- Reduced impacts due to vehicle operations thus agency impacts dominate decision-making
  - Minimize treatment application and the amount of material used for each treatment
  - Optimize treatment selection and timing to avoid major structural damage

High Volume Roads

- Impacts from the Use Phase (more on this during the next webinar) become more important
  - Impacts of preservation activities become minor in comparison
  - Vehicle operations can become dominant
- This creates a more complex problem as agency and user impacts and costs must both be considered

The Balance



Lidicker et al. 2013 with permission of ASCE

Agency Costs Versus User Costs

- Agencies are typically focused on minimizing there own life cycle costs
  - Works well for low volume roads as this strategy also aligns with improvement is broader sustainability goals
- For higher volume pavements, agencies need to better consider the broader sustainability impact of their choices
  - Keeping smooth pavements smooth, safe pavements safe, and quiet pavements quiet

Preservation Techniques

- There are a plethora of techniques available for pavement preservation
  - Multiple resources and continuing education classes are available
- Consider pavement type, type and extent of distress, climate, cost, expected life, and functional requirements
  - Other factors are also important including MOT, traffic loading, and contractor and material availability

Specific Sustainability Impact

- Generally believed to be inherently sustainable but quantification is just emerging
- Details of treatment type, including materials, construction intensity, and placement frequency are important
- Functional improvement, particularly with regards to smoothness, is very important

Pavement Maintenance and Preservation Techniques

Asphalt	Concrete
Crack Filling/Sealing	Joint/Crack Sealing
Asphalt Patching	Slab Stabilization/Slab Jacking
Fog Seals/Rejuvenators	Diamond Grinding/Grooving
Chip Seals	Partial-Depth Repairs
Slurry Seals	Full-Depth Repairs
Microsurfacing	Dowel Bar Retrofit
Ultra-thin and Thin Asphalt Overlays	Slot/Cross Stitching
Hot In-Place Recycling	Retrofitted Edge Drains
Cold In-Place Recycling	Ultra-thin Bonded Wearing Course
Ultra-thin Bonded Wearing Course	Bonded Concrete Overlays
Bonded Concrete Overlays	

Common Treatments for Asphalt-Surfaced Pavements

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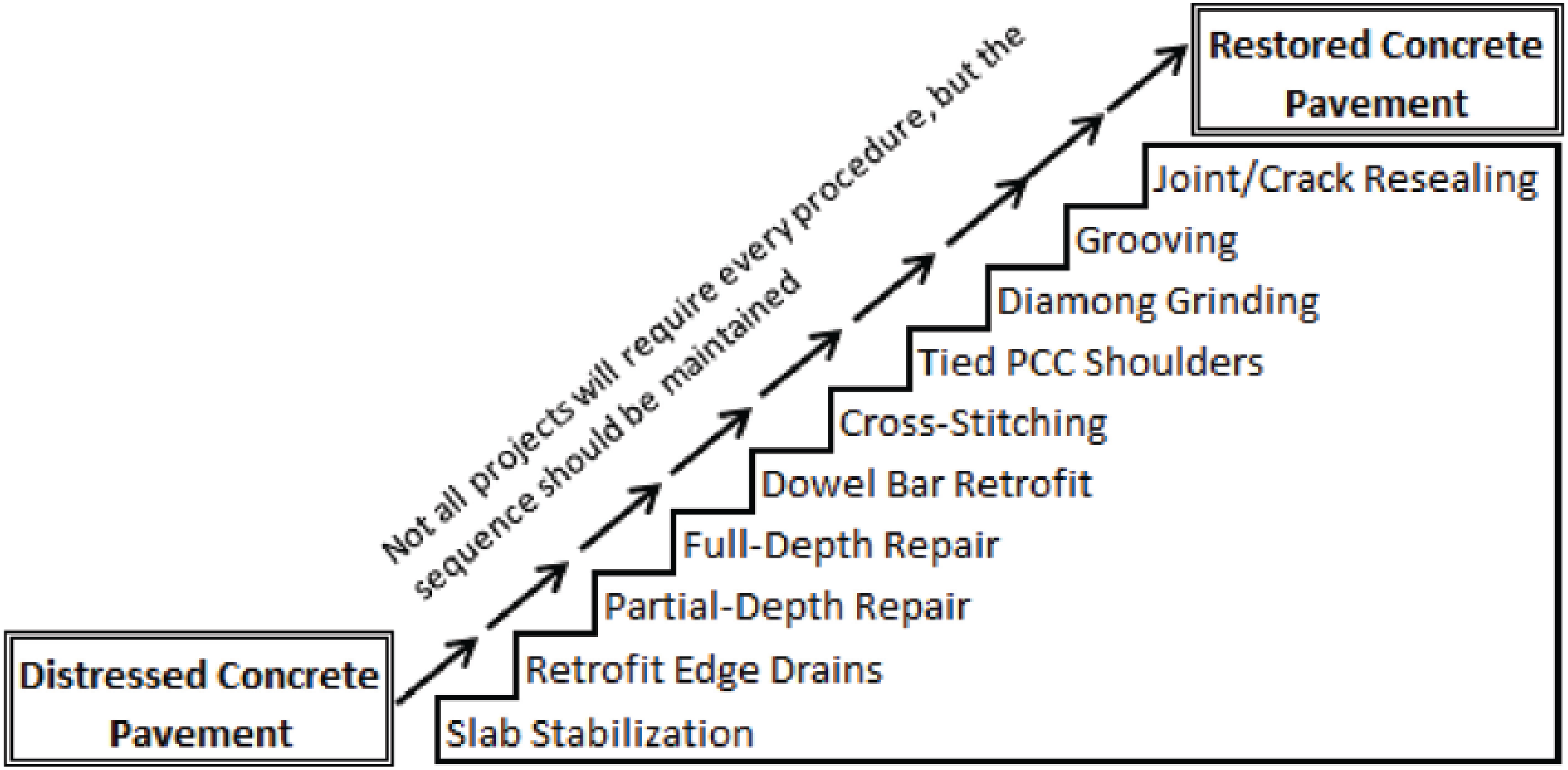
Common Treatments for Asphalt-Surfaced Pavements

Some Comparisons (Annual)

Treatment	Details	Energy Use (MJ/m^2)	GHG (kg/m^2)
HMA Overlay	5.0 cm thick	7.7 to 15.4	0.7 to 1.3
Heavy Chip Seal	2.0 L/m^2 emulsion with 21 kg/m^2	1.5 to 3.0	0.08 to 0.10
Slurry Seal/Microsurfacing	14% Type II emulsion with 13 kg/m^2 aggregate	1.3 to 3.3	0.06 to 0.10
Fog Seal	0.5 L/m^2 50/50 diluted emulsion	0.8	0.04

From Chehovits and Galehouse 2010

Common Treatments for Concrete-Surfaced Pavements



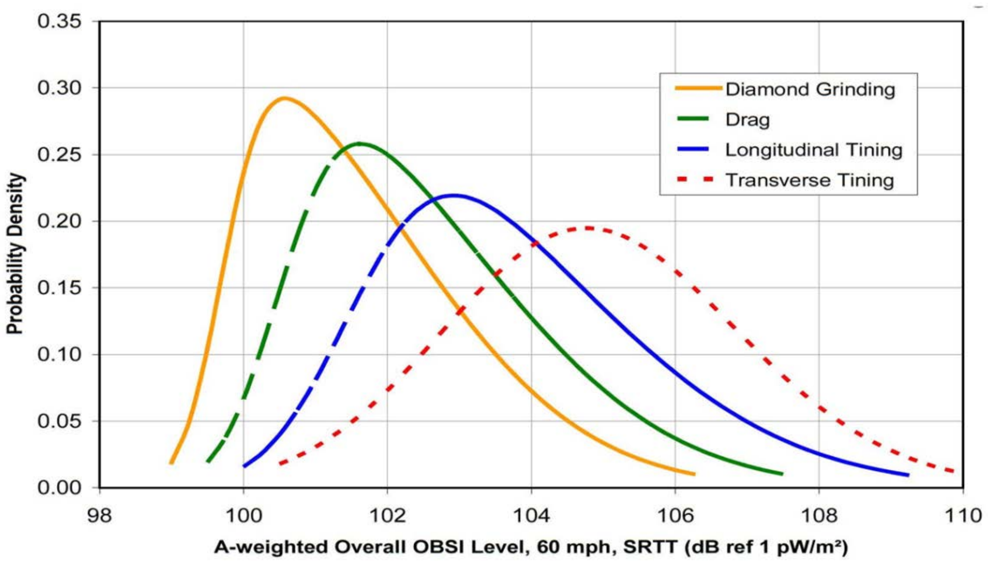
Common Treatments for Concrete-Surfaced Pavements

Common Treatments for Concrete-Surfaced Pavements

Steps for Treatment of Concrete-Surfaced Pavements

Benefits of Diamond Grinding

- Significant reduction in roughness
- Improved skid resistance
- Reduced noise level



From Rasmussen 2012

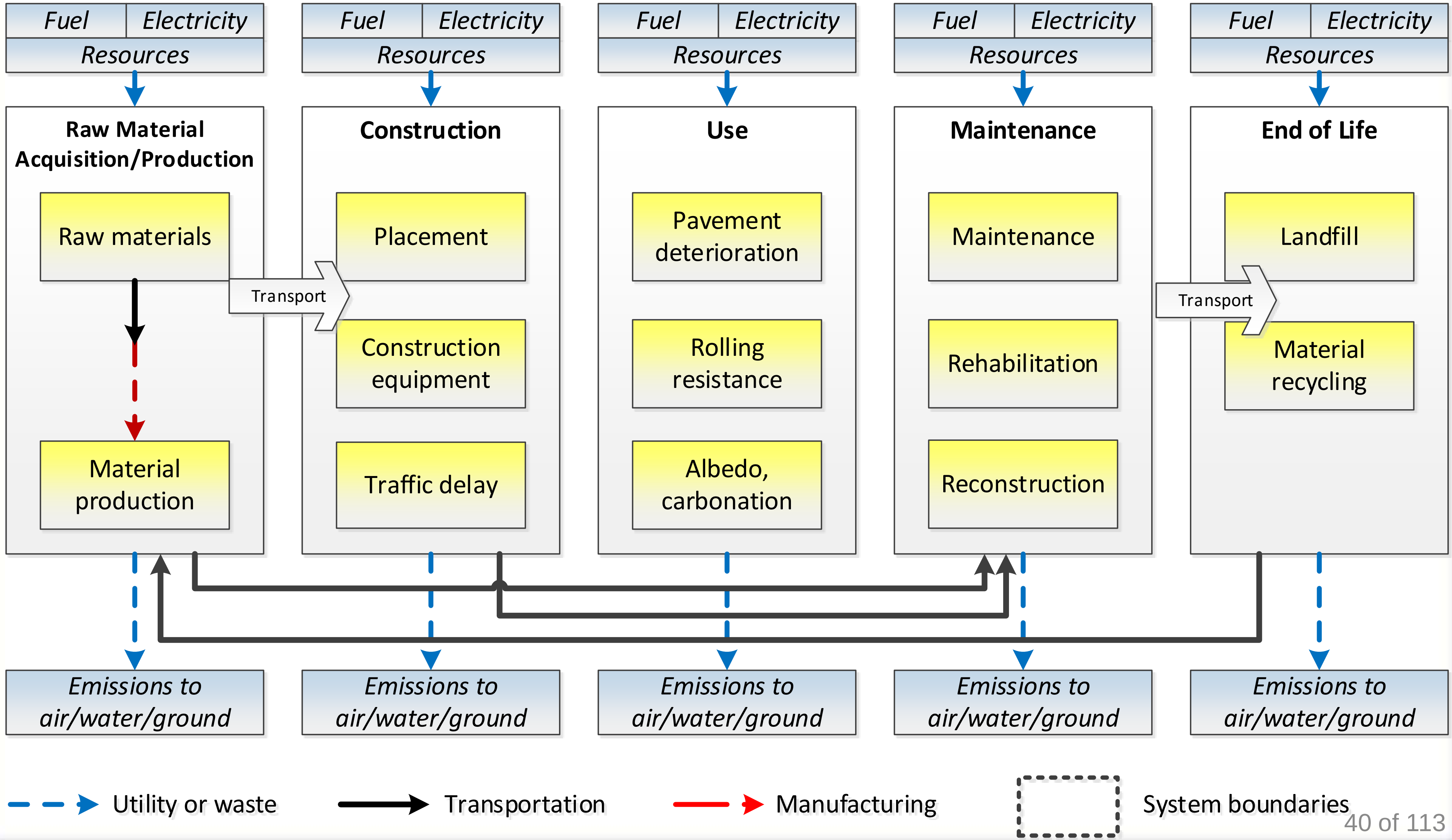
Concluding Remarks

- Preservation is inherently sustainable
  - Keep good pavements in good condition, smooth pavements smooth, quiet pavements quiet, and safe pavements safe
- Multiple treatment options exists
  - Sustainability impacts on low volume roadways often correlated with agency costs
  - Sustainability impacts on high volume roadways heavily influenced by user costs (functional attributes of the pavement)

- **End-of-Life Considerations**

Imad Al-Qadi

EOL in Pavement Life-Cycle



Pavement End-of-Life (EOL)

- Pavement end-of-life (EOL) is defined as the "*final disposition and subsequent reuse, processing, or recycling of any portion of a pavement system that has reached the end of its useful life*."
  - On-site and off-site recycling operations
  - Reuse of pavement layers and materials
  - Landfilling operations

EOL Options

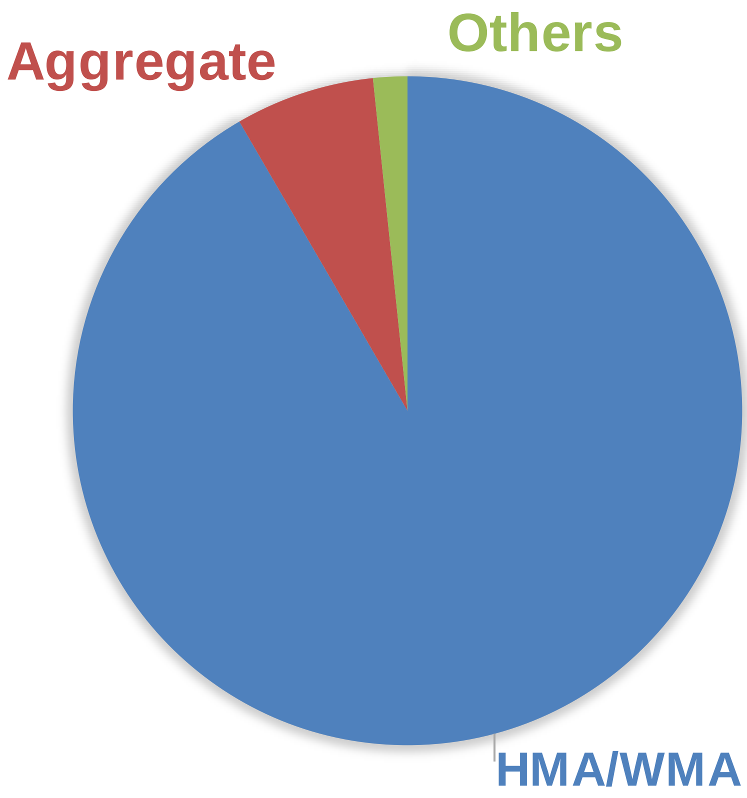
Asphalt Pavement	Description
Central plant recycling (hot or cold)	Remove AC pavement to a central plan for further processing to replace virgin materials in subsequent applications
Full-depth reclamation	On-site recycling of AC layers for new pavement applications
Landfilling	Mill, remove, and transport to a landfilling site
Concrete Pavements	**Description**
Recycling	Concrete pavement is removed and crushed off-site or on-site (rubblization)
Reuse	Pavement remains in place and used as part of supporting structure (overlays on concrete)
Landfilling	Break, remove, and transport to a landfilling site

Ultimate EOL Goal for Pavements

- An ideal goal would be to use recycled materials to produce a long-lived, well-performing pavement, and then at the end of its life recycle back those materials again into a new pavement, effectively achieving a zero waste highway construction stream.

Asphalt Pavement Recycling Statistics

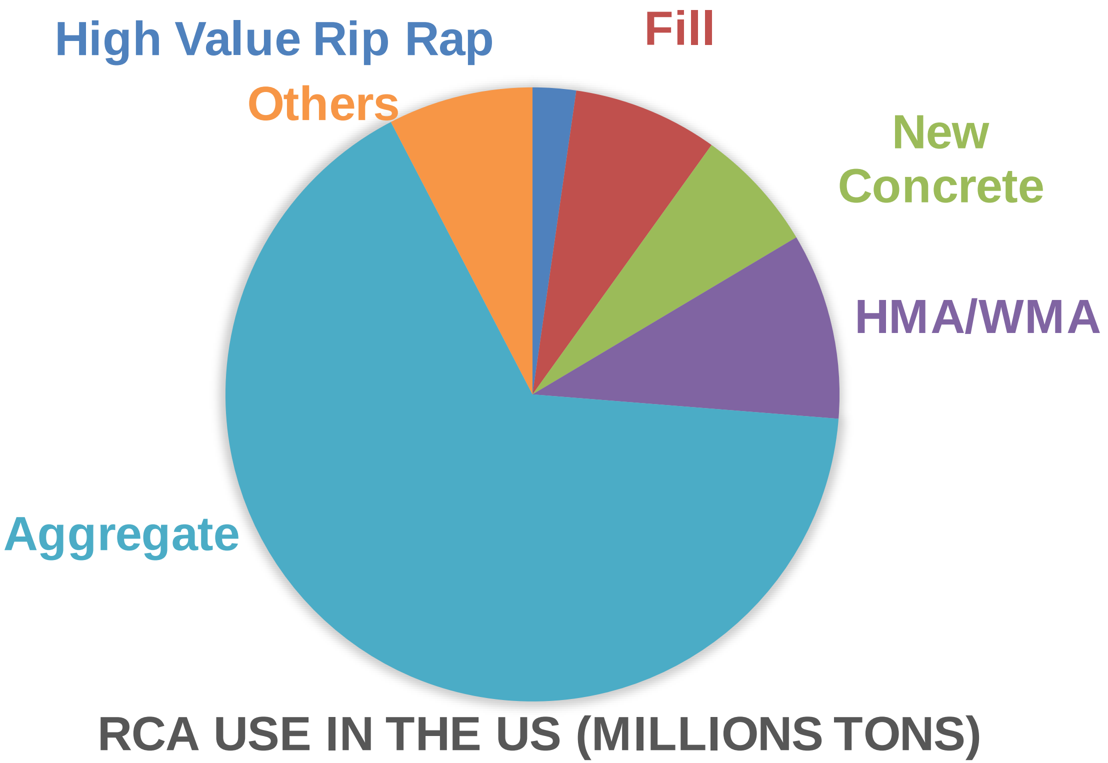
- Pavements are among the most commonly recycled materials
- Less than 1% of RAP is sent to landfills
- Total RAP used in pavements are 68.3 million tons



Data from Hansen and Copeland (2013)

Concrete Pavement Recycling Statistics

- The total amount of recycled concrete used in the U.S. is estimated at 140 million tons in various application



Data from CDRA (2014)

EOL Impacts on Pavement LCA

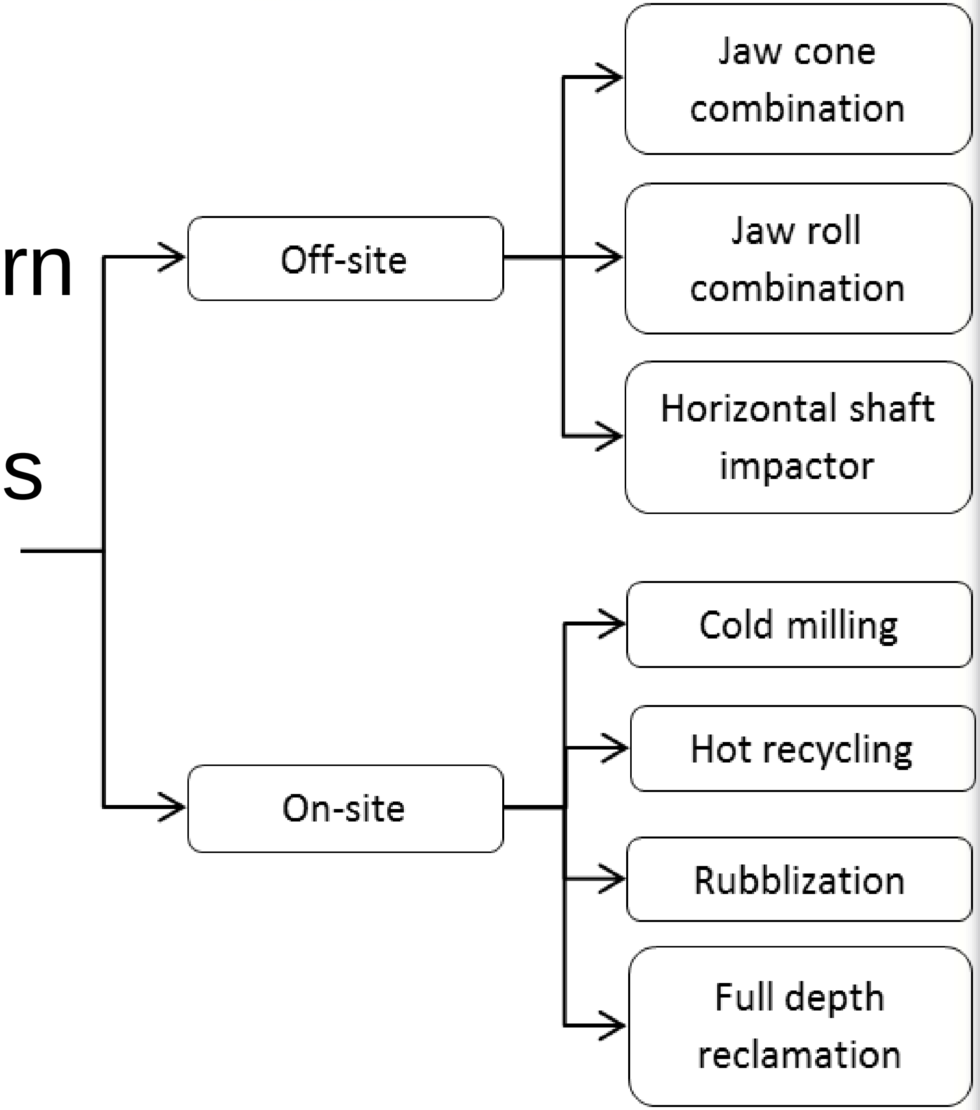
- Major contributing EOL unit processes are landfill related, recycling operations, and transportation
- Hazardous wastes in construction and demolition waste landfills comprise a small percentage therefore landfilled pavement debris can be considered inert (non-hazardous)
  - Therefore, long-term environmental impacts of landfill resulting from pavement recycled materials is insignificant
  - Landfilling processes (transportation, stockpiling, tipping, etc.) should be included
- Recycling processes include removal, transportation, crushing/screening, and stockpiling

Economic and Environmental Considerations

- Economic and environmental analyses are needed to fully quantify the effects of various EOL options
- The following factors should be considered in selecting an EOL option:
  - Available technology
  - Disposal costs
  - Transportation
  - Application
  - Quality

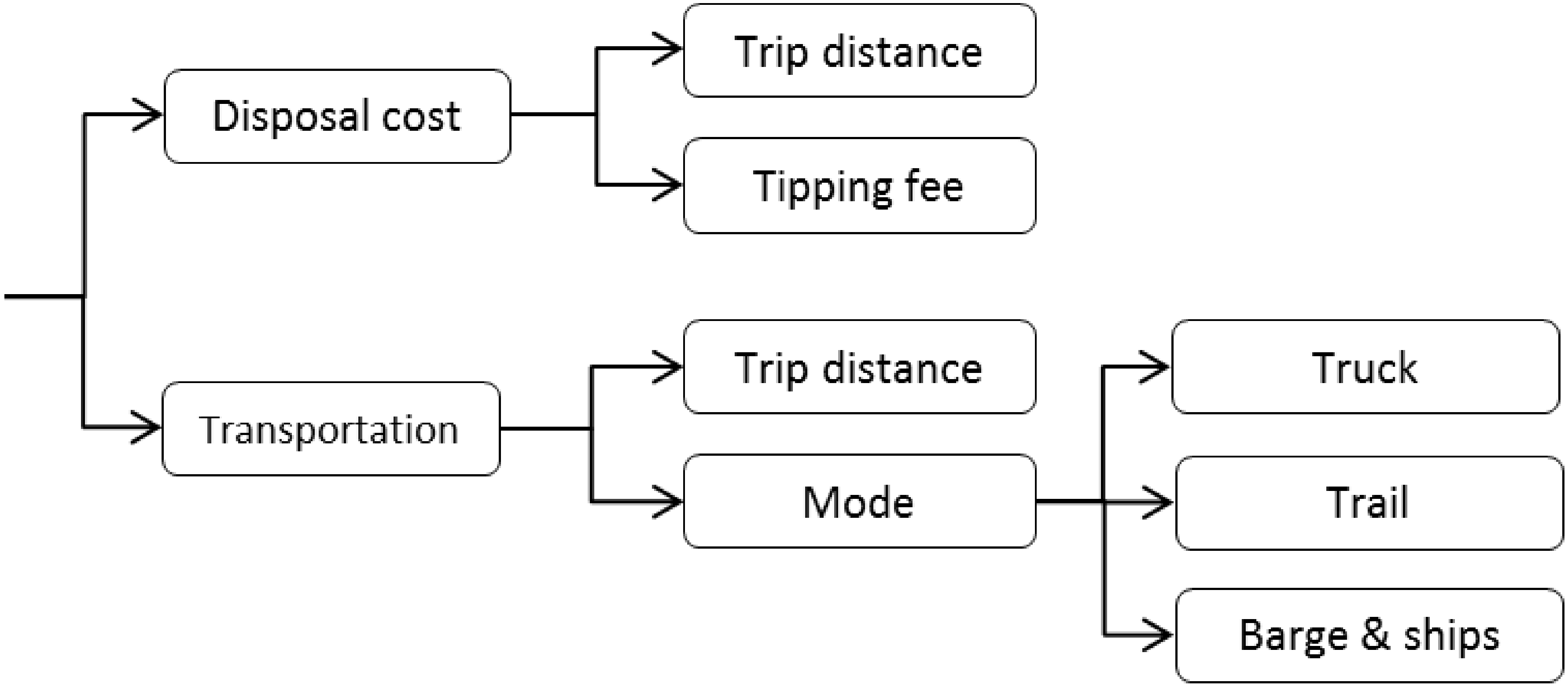
Available Technology

- Availability of central plants for processing and storage can govern economic and environmental burdens
- Available technology can govern final selection:
  - Crushing process
  - Availability of on-site recycling technology



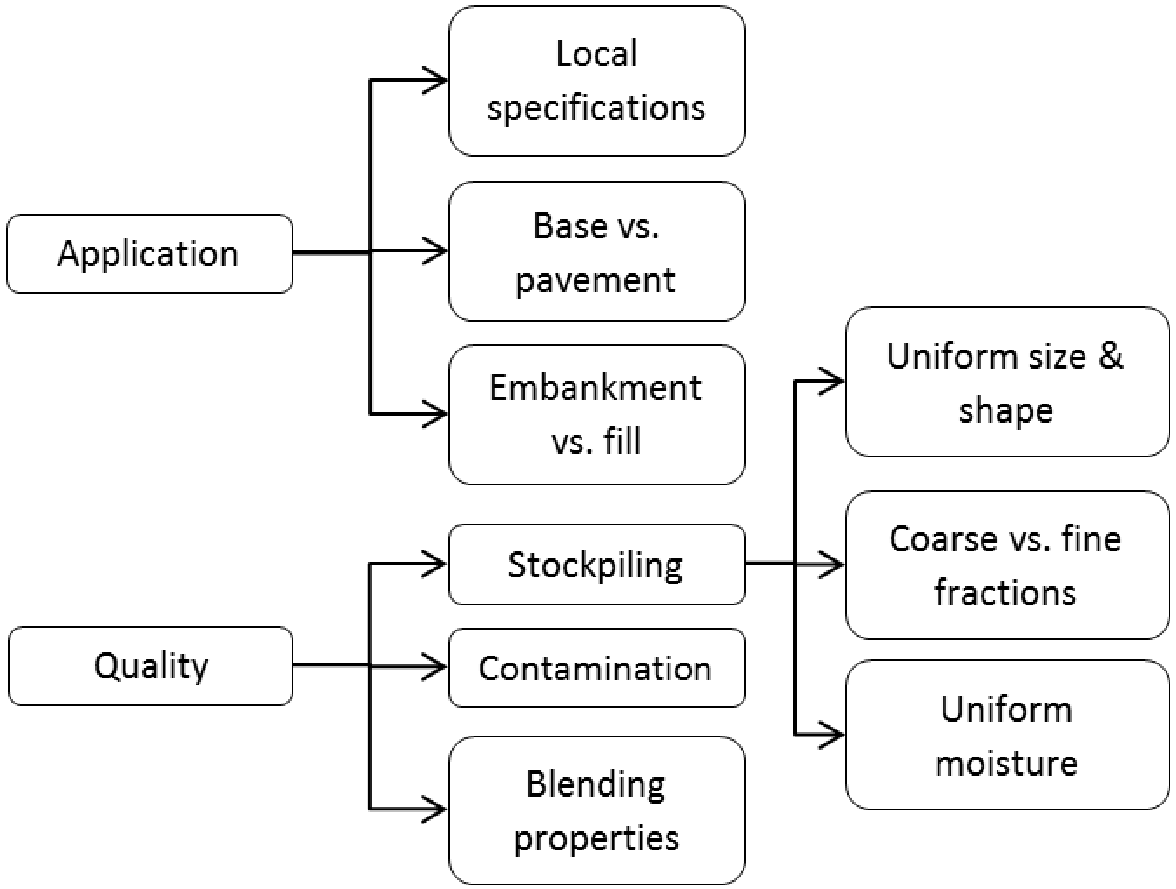
Disposal Costs and Transportation

- Disposal costs at a landfill include demolition, transportation, and tipping fees



Application and Quality

- Availability of EOU options of recycled materials determine the demand/supply balance; hence costs



A Strategy for Optimizing the Use of Recycling Options

- Assessment considering all environmental and cost determinants are needed
- Apply all four concepts of sustainability assessment
  - Functional performance (equal or better performance)
  - Life-cycle cost (economic benefits or tradeoffs)
  - Life-cycle assessment (environmental)
  - Sustainability rating

Critical Questions

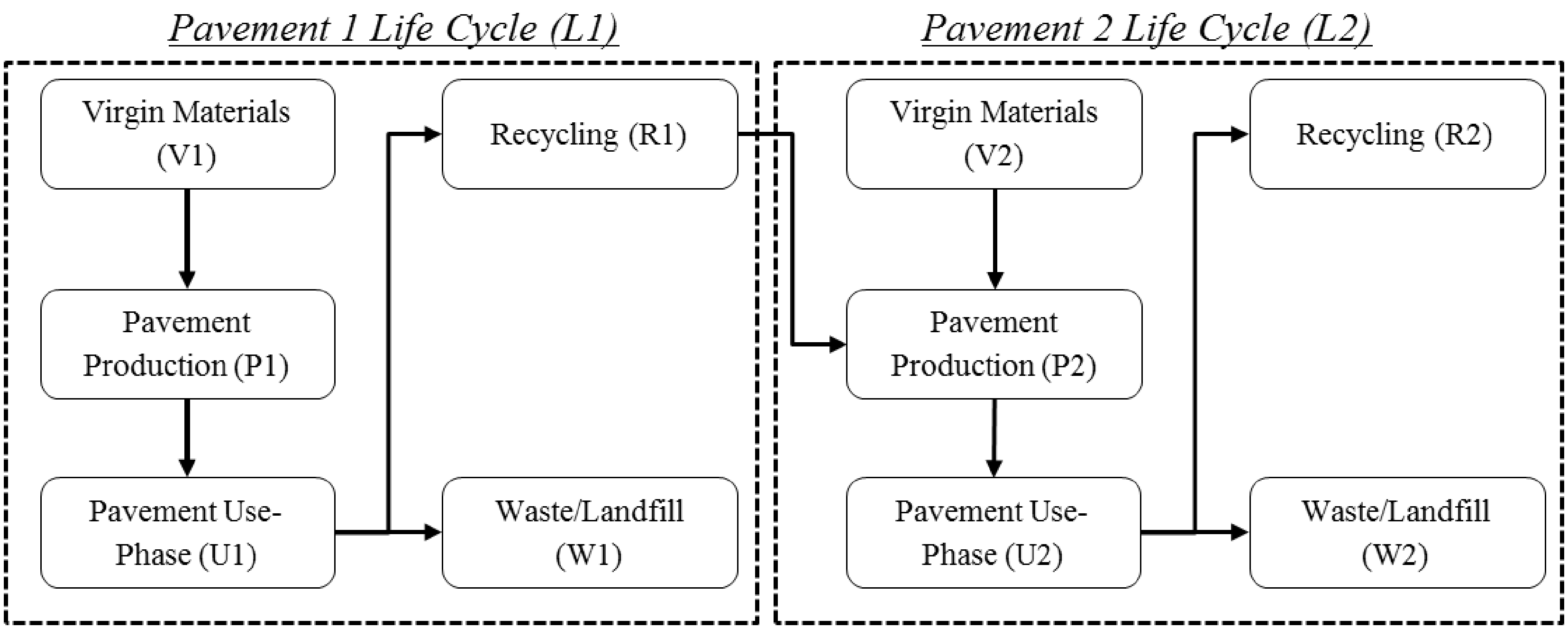
- When the material is recycled, a system boundary is crossed from one pavement life cycle to another.
  - How much environmental "credit or burden" should be given to recycled materials (i.e., what is the environmental impact of recycled materials)?
  - Who is going to bear the burden or enjoy the benefits? (Initial producer [upstream] or last producer [downstream] or user of the recycled content)

Sharing the Burden and Credits

- LCA handles such critical questions using allocation rules
- Allocation is defined by ISO 14044 as partitioning the input or output flows of a process or a product system between one or more product systems
  - Using set of rules for recycled pavement materials that define whether upstream or downstream producer should receive recycling credits

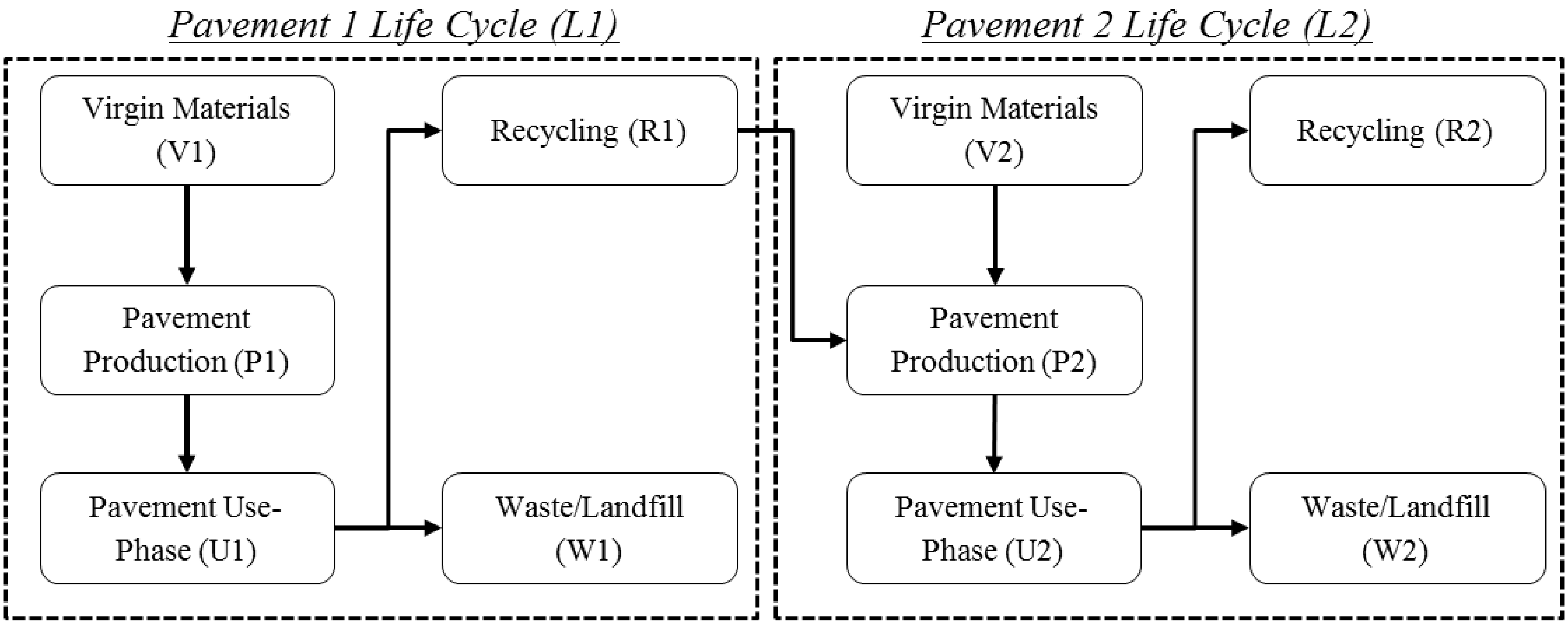
Allocation Rules for Pavements

- Cut-off method allocates the full benefits of recycling to the product using recycled material (all benefits are given to downstream)
  - Pavement 2 (downstream) is responsible for the impacts of R1 and no credit for pavement producing recyclable material (upstream manufacturer)



Allocation Rules for Pavements

- Substitution method allocates the full benefits of recycling to the product producing recyclable material
  - Pavement 1 (upstream) is responsible for recycling operations and receives credit for producing recyclable products
- Alternatively, distribute credits and burden 50/50



Common Practices

- When to use cut-off method
  - Long-lived products where future recycling is uncertain
  - The product may change its properties and deteriorate during its use

  Most EPDs and LCA applications for pavements use this approach

- When to use substitution method
  - Time period of product is short and future recycling is certain
  - Inherent properties with use and recycling do not change

LCA Recommendations

- Provide incentives for practices reduce environmental impact.
- Control process to avoid double counting of credits or omission of important items.
- Provide fairness between industries by reflecting facts or good estimates.
- Be transparent so that all parties can understand how allocation is applied and how it influences the results.

EOL Calculation Procedures

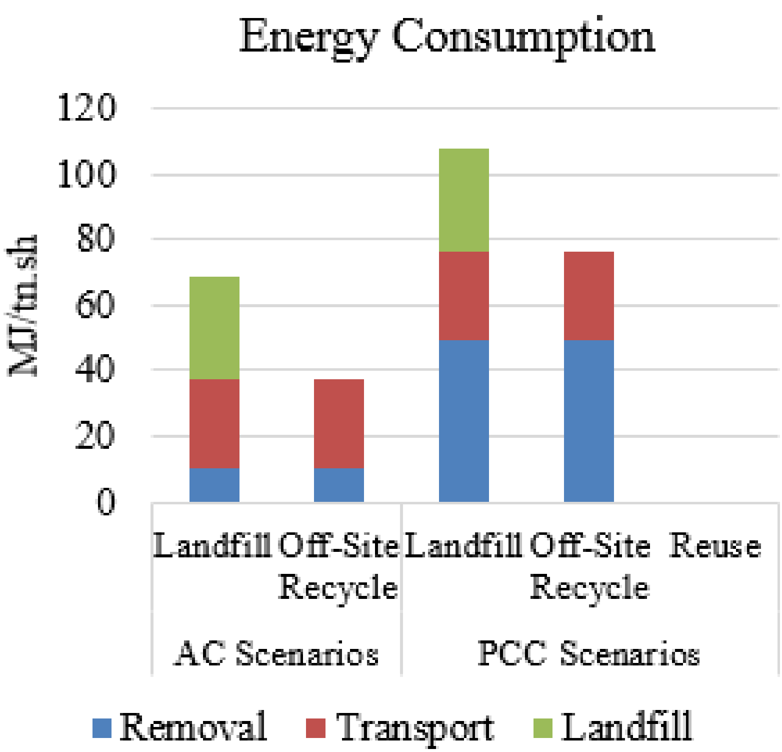
- Collect the information below as applicable:

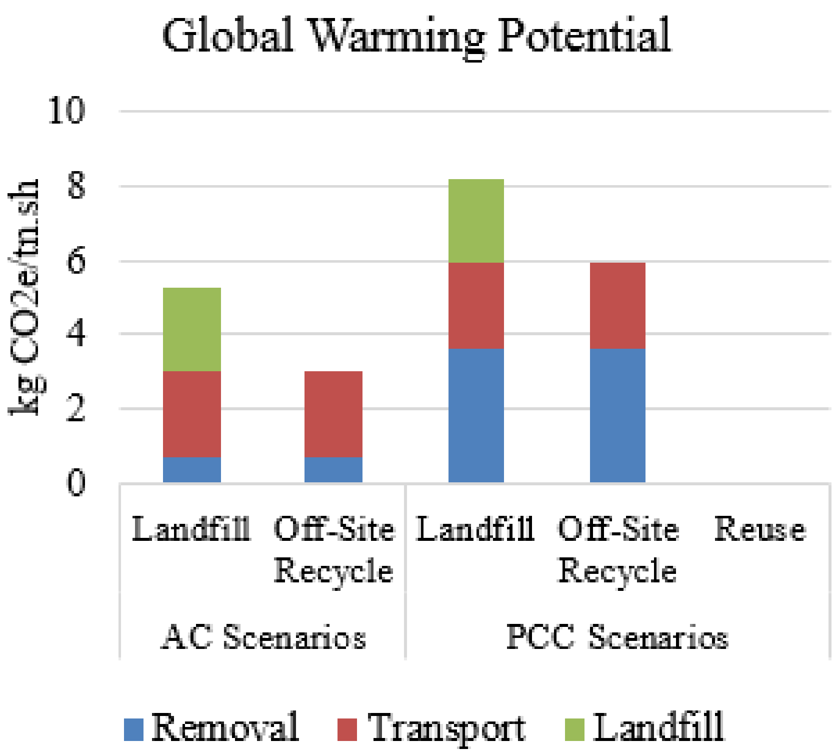
Scenarios	Unit (expressed per functional unit)	Processes Included
Landfill	kg collected separately	Demolition and transportation to landfilling facility
Recycled on-site	kg recycled back to the same project	On-site recycling processes (milling, crushing, screening)
Recycled off-site	kg recycled off-site	Demolition and transportation to the central recycling facility
Reuse	kg reused	Removal and transportation to the central collection facility (i.e., guard rails) or concrete slabs remaining in-place (minimal processing)

- Calculate environmental impact for each process following LCA procedures

Example: EOL Impacts

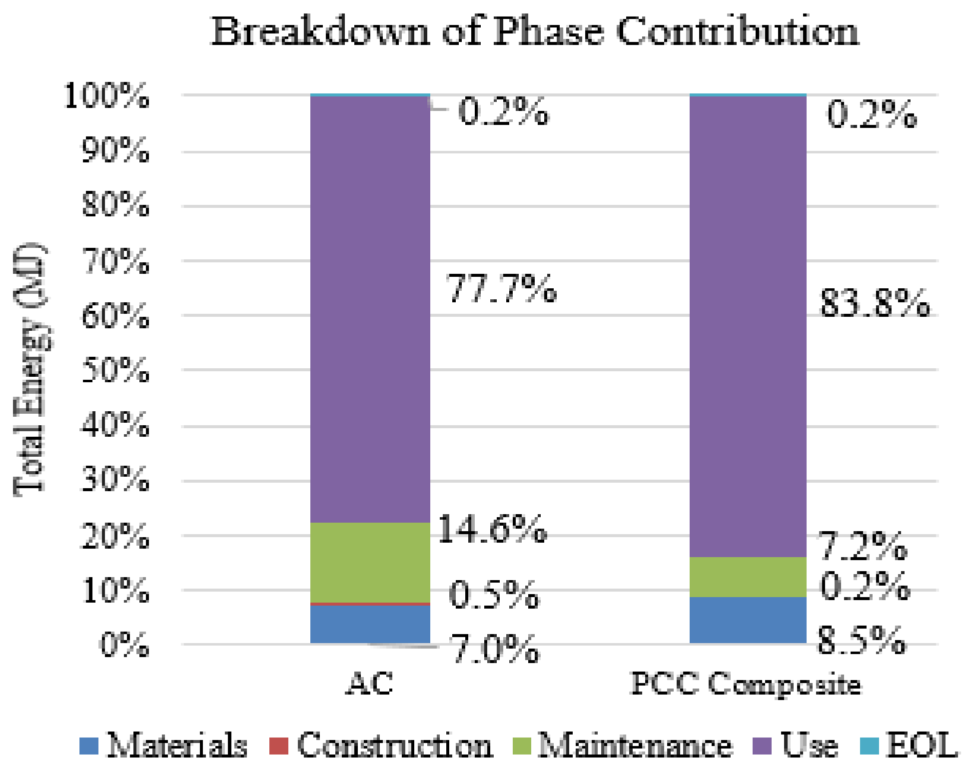
- For a 5% landfill scenario with 95% recycled or reused, impact of EOL processes:





Example: EOL in Pavement LCA

- Compared to other life-cycle stages, the EOL phase has small contribution (0.2 to 1.0%)
- For a typical EOL application:



- **End-of-Life Options for Asphalt Pavements**

Hasan Ozer

Central Plant Recycling

- Hot central plant recycling to produce RAP for various layers in asphalt pavements
- Cold central plant recycling (CCPR) combines RAP with softening aging to produce mixtures for primarily base or subbase courses (not very common)

RAP Processing

Removal of existing pavement & transportation

Crushing/Screening

Coarser RAP

Finer RAP

Sustainability Considerations for Central Plant Recycling

- Improve pavement performance by:
  - Fractionating RAP reduce moisture in RAP stockpiles
  - Improving plant technology to handle higher percentages of RAP
  - Using softening agents or modifiers if performance is experimentally promising
- Use RAP when economically and environmentally advantageous
  - Perform a complete life-cycle sustainability evaluation

Virgin vs. RAP

- The following questions need to be answered:
  - Can equivalent or better performance achieved?
  - What is the transportation distance?
  - Does RAP undermine future recyclability?
  - Can target volumetrics be achieved in the plant and field?
  - Are there any specifications limiting its use?

Environmental Impact of Hauling

Average transportation intensity of a hauling truck is 150 ton-miles/gallon of diesel (1 gallon to transport 150 ton for 1 mile)

1 gallon diesel contains 128,000 btu of energy

853 btu/ton-miles (853 btu required to move 1 ton for 1 mile)

Average virgin aggregate production energy requirement (~100,000 btu/ton)

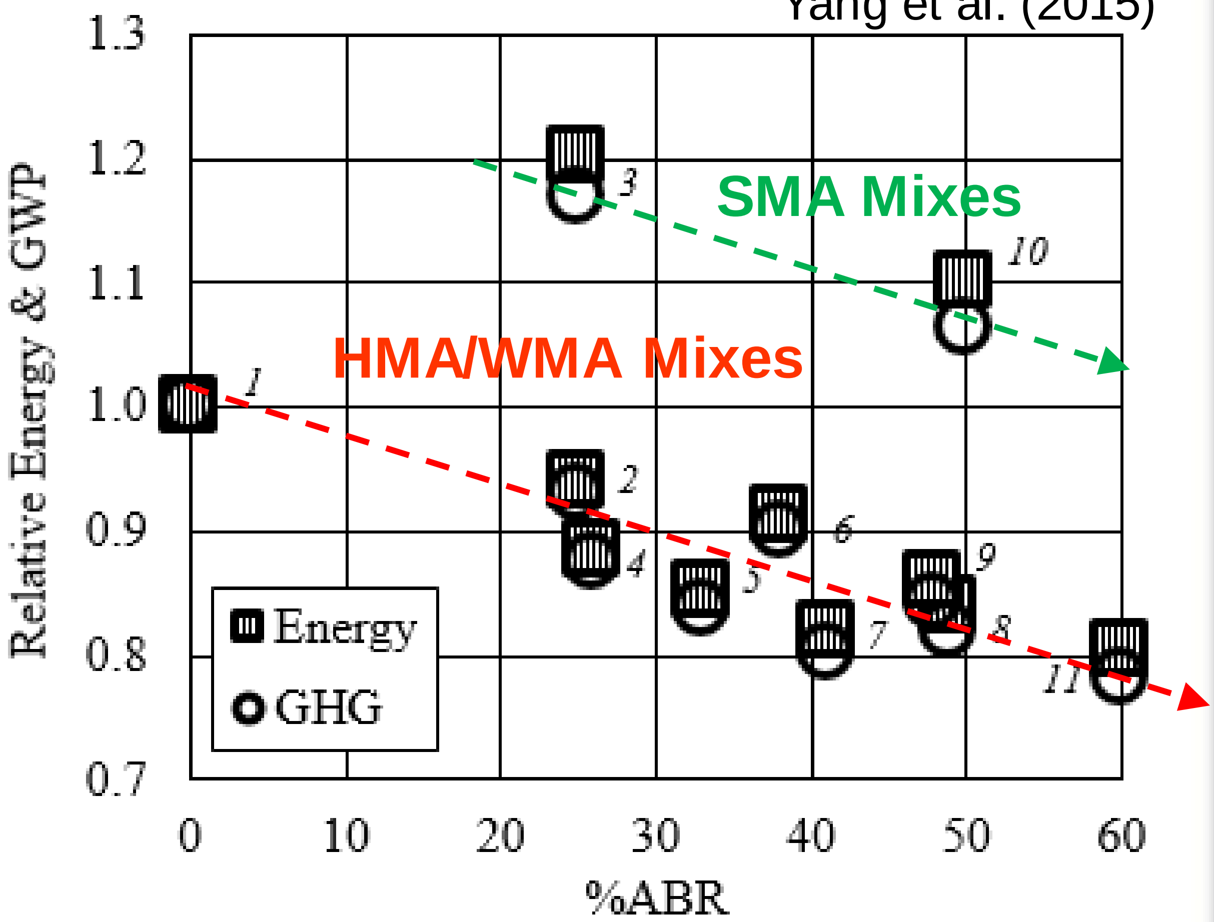
What is the equivalent distance to aggregate production energy?

Answer: 117 miles

RAP and Environment

- Clear reduction in energy and GWP when using recycled materials for replacing virgin binder with recycled binder
- SMAs have generally higher energy and GWP

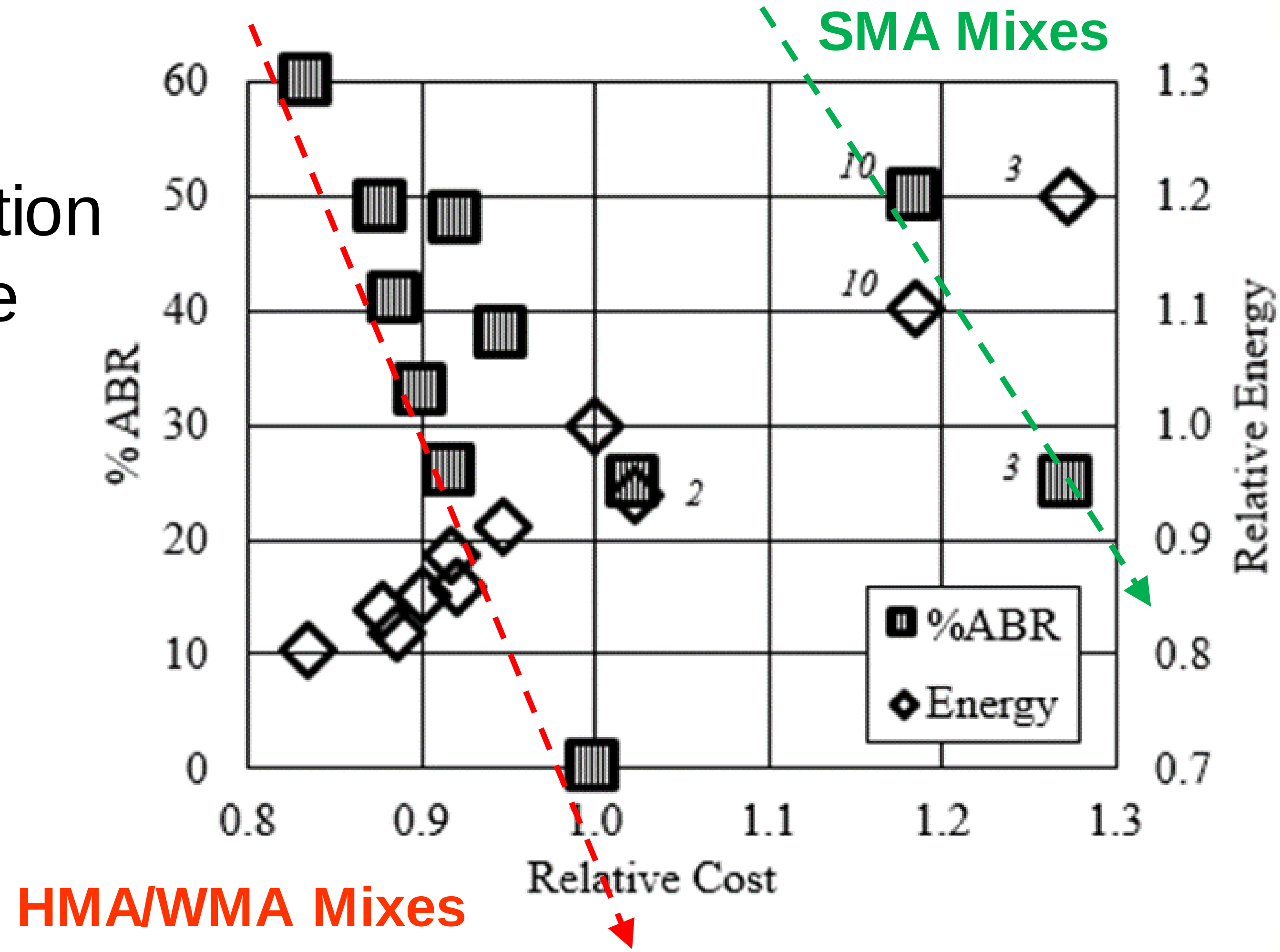
Yang et al. (2015)



Common mixtures used in Illinois having various combinations of RAP and RAS that result in different asphalt binder replacement (ABR) levels

RAP and Economy

- Decreasing initial production costs with the increase of recycled materials



Yang et al. (2015)

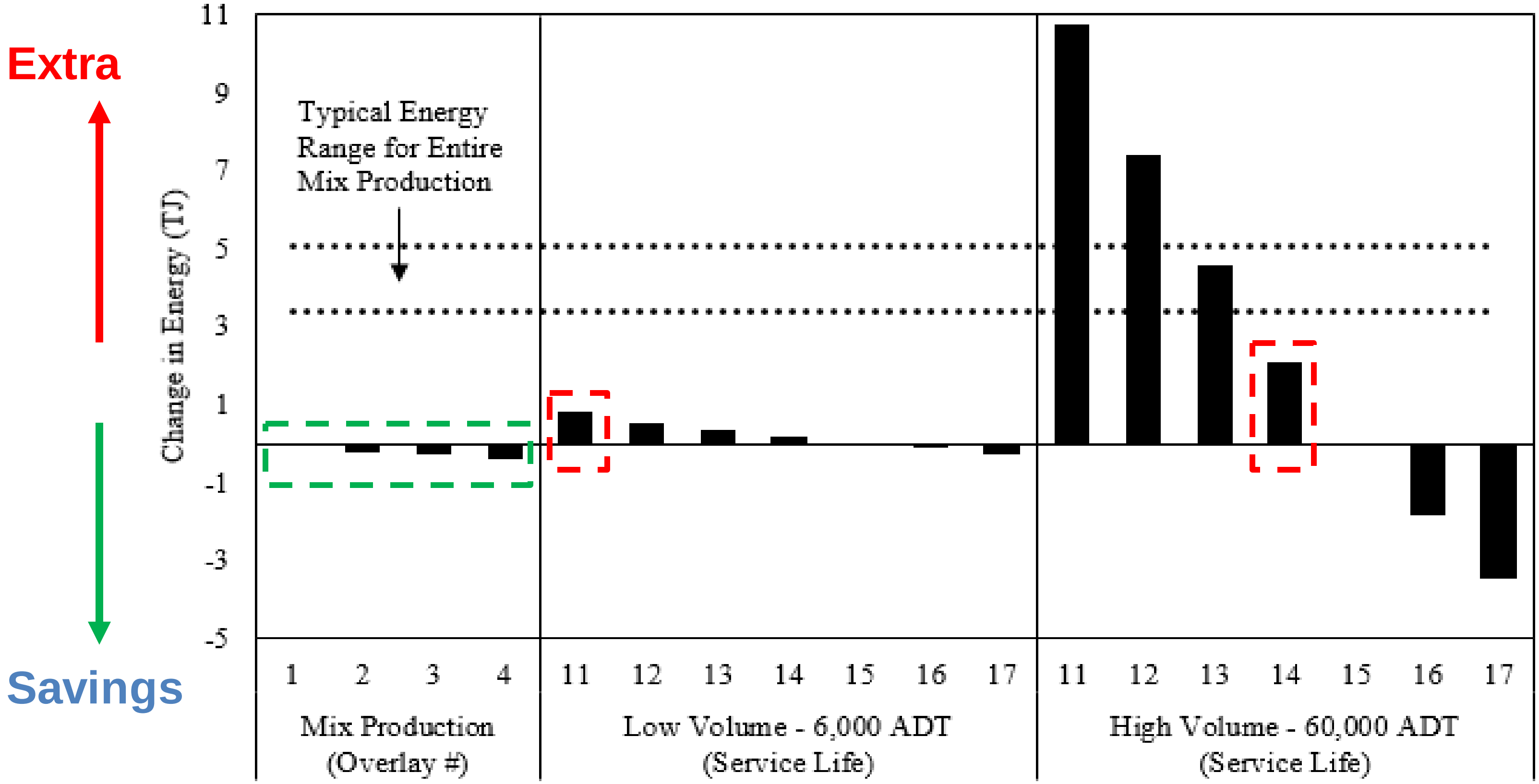
RAP in Complete Life-Cycle

- Material acquisition and production phase
  - (↑) Replacing virgin binder and aggregates
  - (↓) Potential increase in plant energy consumption
- Construction
  - (↔) If same workability is achieved
- Maintenance/Rehabilitation
  - (↓) In case of performance reduction, more frequent interference may result
- Use-phase
  - (↓) In case of performance reduction, additional vehicle fuel consumption

RAP in Complete Life-Cycle

Initial benefits for low volume roads can be offset by 3-4 year reduction in service life

Initial benefits for high volume roads can be offset by less than 1 year reduction in service life



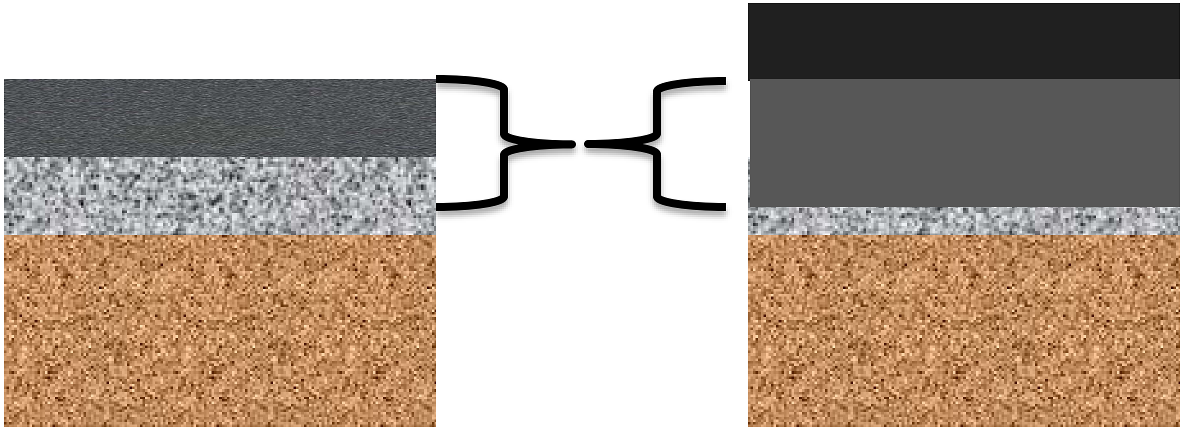
RAP in Complete Life-Cycle

- Full life-cycle analysis is required to evaluate upfront benefits with potential future tradeoffs
- Excessive use of recycled materials may result in accelerating pavement deterioration
  - Savings occurring during production can be neutralized by reduction in IRI or additional maintenance/rehab activities that require more energy consumption during the use-phase

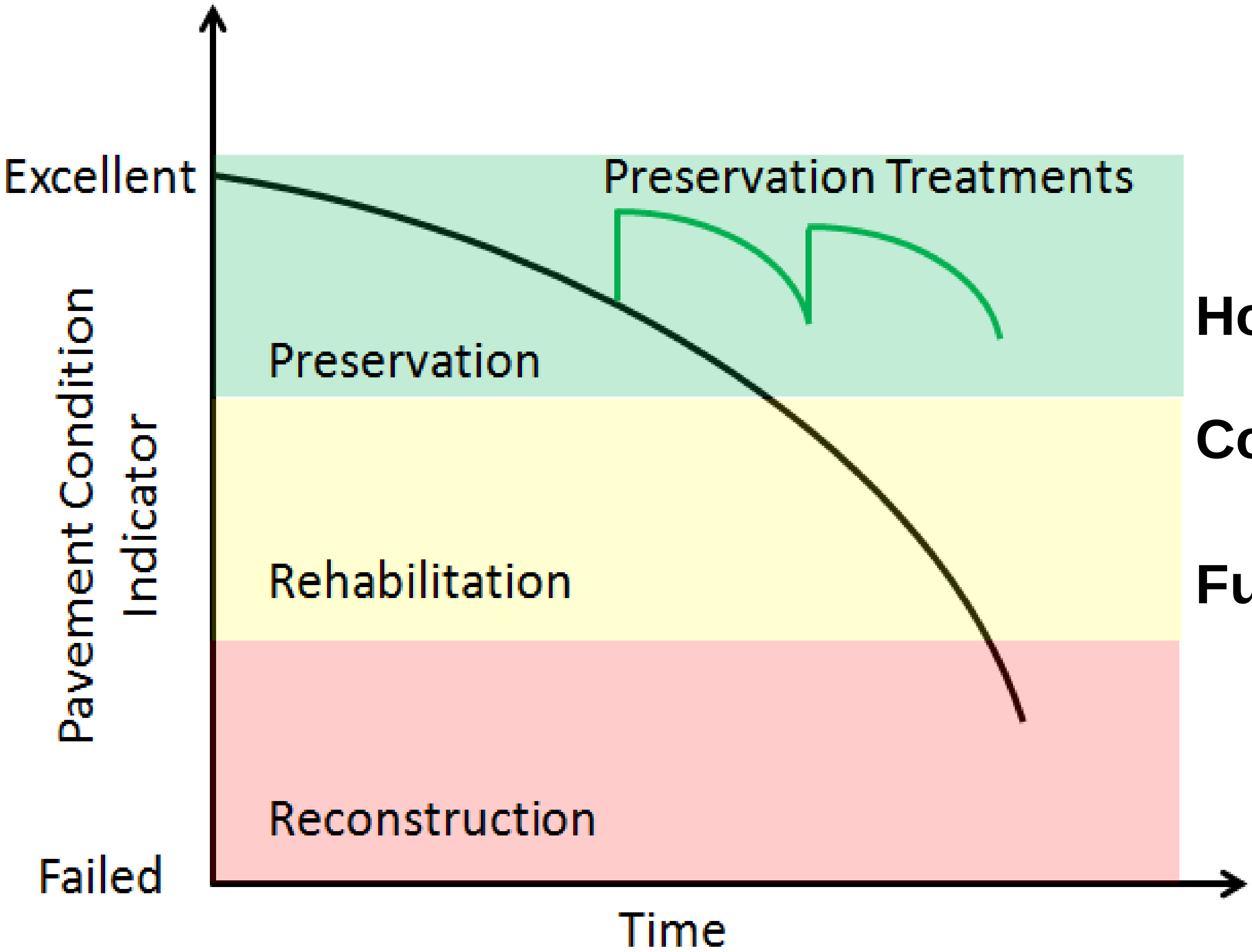
Full-Depth Reclamation (FDR)

- Existing asphalt pavement and a predetermined portion of the underlying materials (base and subbase) are uniformly pulverized and blended to provide a homogeneous material

Depth of recycling can be 6 to 12 in



Other In-Place Recycling Methods



Hot in-place

Cold in-place

Full depth reclamation

FDR Candidates

- Pavements with severe longitudinal and transverse cracking.
- Pavements with poor ride quality.
- Pavements with permanent deformation problems.
- Pavements with raveling and potholes.
- Inadequate structural capacity.

FDR Processes (1)

- Pulverization is the first stage where existing HMA and part of the granular layers are transformed into uniform granular material

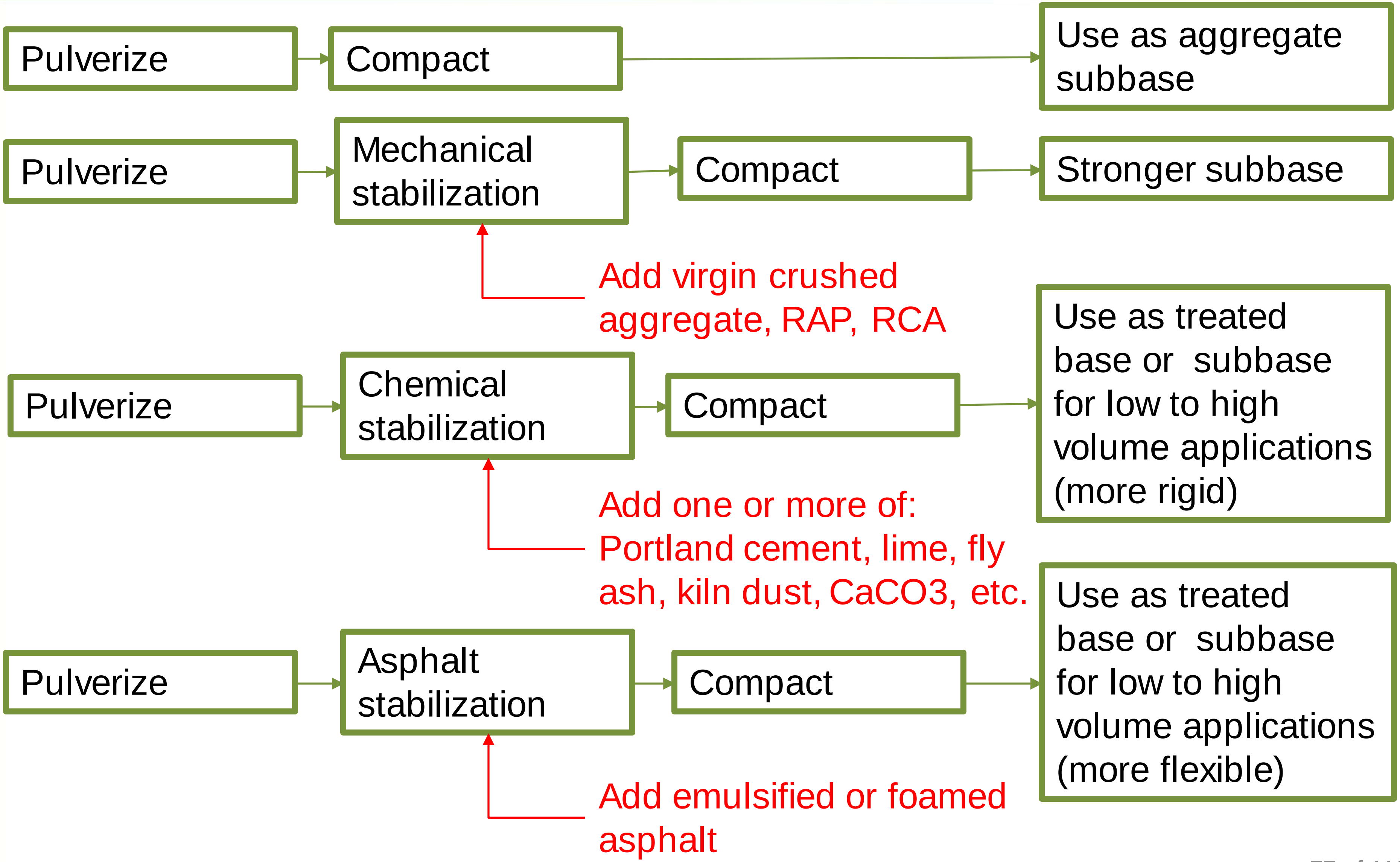
Courtesy of Marshall Thompson

FDR Processes (2)

- Stabilization (mechanical, asphalt, or chemical) and compaction followed by a surfacing

Courtesy of Marshall Thompson

FDR Pavement Alternatives



Critical Steps to Achieve Best Performance

- *Project selection* – finding the right pavement for FDR treatment
- *Mixture design* – Tailor mix designs for each project and analyze existing materials
- *Selection of additives* – Use best working additives for in-situ conditions and target structural requirements
- *Achieve uniform gradation* – resizing the pulverized materials and add virgin as needed
- *Compaction* – Should always be included in the QC/QA

Sustainability Considerations for FDR Applications

- FDR performance depends on:
  - Project selection (in-situ materials, timing, existing condition, weather, traffic)
  - Quality and uniformity of existing materials
  - Mix design and selected additives
  - Surfacing type selection
  - Construction quality (this is a specialized operation and requires specialized contractors)
- Curing and traffic opening time
- Availability of virgin materials for an alternative reconstruction

- **End-of-Life Options for Concrete Pavements**

Mark Snyder

EOL Considerations for Concrete Pavements

- Recycling
  - Breaking, removing and processing concrete to produce RCA, a granular substitute for natural aggregate
  - Extensive use in Europe since 1940s, and in the U.S. since the 1970s (first U.S. application in 1940s on Route 66!)

- Reuse
  - Applications where material is used in current form, often in current placement with minimal (if any) processing
  - Examples: asphalt overlays, unbonded concrete overlays
- Land Filling and Disposal

Each of these activities has economic, environmental and societal impacts that should be considered.

Disposal / Land Fill

- Removal and hauling of paving material to land fill where it serves no purpose.
- Disposal costs vary widely
  - Includes demolition, transportation (varies with haul distance), and tipping fees (which vary regionally … up to $70.53/ton reported in 2007)
  - Opportunity cost or lost of value of RCA should be considered (varies with source concrete and availability of local natural aggregate)
- *Bottom lines:*
  - *Economic and environmental costs of disposal are high*
  - *Disposal as an EOL option is not often preferred over recycling and reuse*

Concrete Reuse

- "[M]aterial is used in its current form, often in its current placement … with minimal (if any) processing."
- Most common: base or subbase for overlay or new pavement
- Rubblization in prep for HMA overlay counts
  - Process is one of several options (e.g., use of various interlayers) for preventing reflection cracking of overlay
- Suitability for reuse may be limited by distress type, severity and extent
  - Pavements with large amounts of joint deterioration or "soft spots" may be better candidates for recycling or may require rubblization (or disposal, in extreme cases)

Considerations for Concrete Reuse

- Evaluation of Existing Pavement Structure
  - Uniformity of support? Need for repairs?
  - Significant structural or drainage issues?
  - Quality, strength and durability of foundation
- Geometric and Safety Considerations
  - Increase in pavement elevation, adjustment of appurtenant structures and features, slopes, etc.

Environmental and Economic Impact of Concrete Reuse

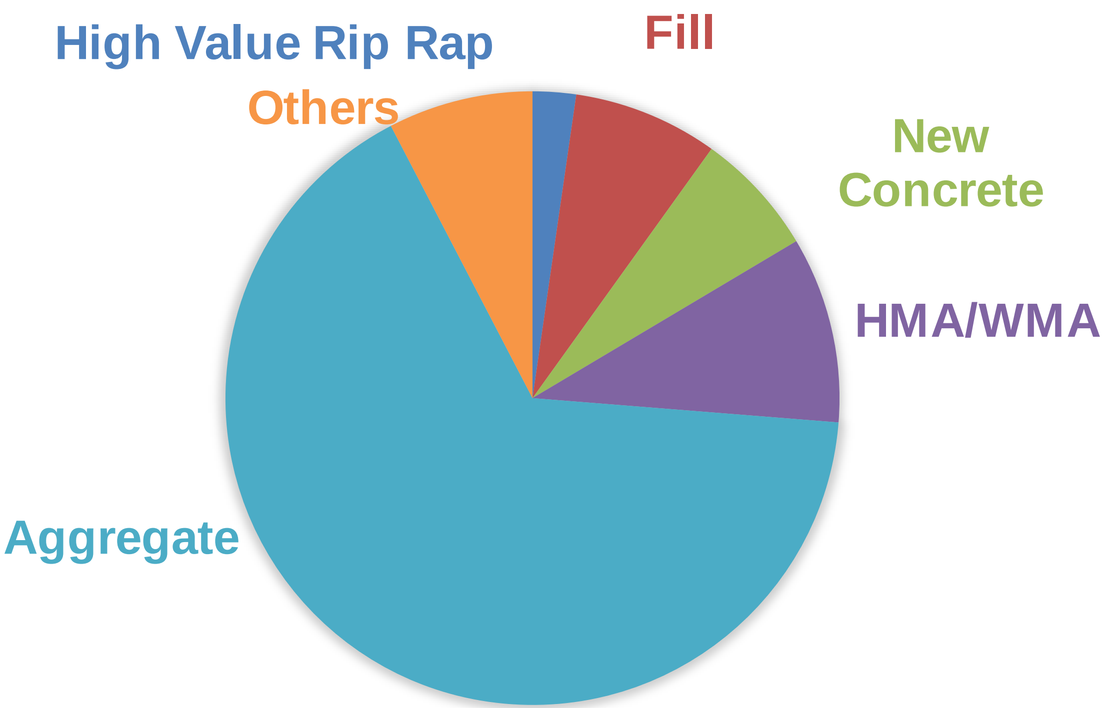
- Potential Benefits – generally the highest of all PCCP EOL options
  - Material savings, conservation of resources
    - Materials and energy required to produce and haul new materials
    - Reductions in energy and costs associated with disposal
  - Short construction duration, reduced impacts to local users
- Benefits can be partially (or wholly) offset by shorter performance life or more frequent maintenance.
  - Example: foundation and drainage deficiencies
  - Use LCA, LCCA and pavement performance analyses to determine suitability for reuse.

RCA Applications

- Many potential applications
  - PCC pavement (single- and two-lift)
  - HMA pavement
  - Subbase (unbound or stabilized, drained or undrained)
  - Fill/embankment material
  - “Rip-rap”
  - More …
- Specific applications limited by quality of source concrete
  - Materials-related distress (AAR, freeze-thaw)
  - Pavement vs. Building demolition

Concrete Pavement Recycling Statistics

- The total amount of recycled concrete used in the U.S. is estimated at 140 million tons in various application



RCA USE IN THE US (MILLIONS TONS)

Data from CDRA (2014)

Economics of Concrete Recycling

- Aggregate Cost Data (USGS 2005, Kuennan 2007)
  - RCA: $6.93/ton avg (range: $3.41 - $9.00/ton)
  - Virgin: $6.52/ton avg (range: $3.54 - $10.01/ton)
- A ton of RCA goes 5 – 20% farther (volumetrically) than a ton of virgin aggregate
- Single project savings of $5M or more have been reported (CMRA 2008)

Benefits of RCA: Environmental Sustainability

- Conservation of aggregate and other resources
- Reduces unnecessary consumption of landfill space
- Potential reductions in greenhouse gas emissions
  - Mining/extraction activities, reduced haul distances, slab disposal (associated fuel consumption)
- Captures atmospheric CO_2

Caveat:

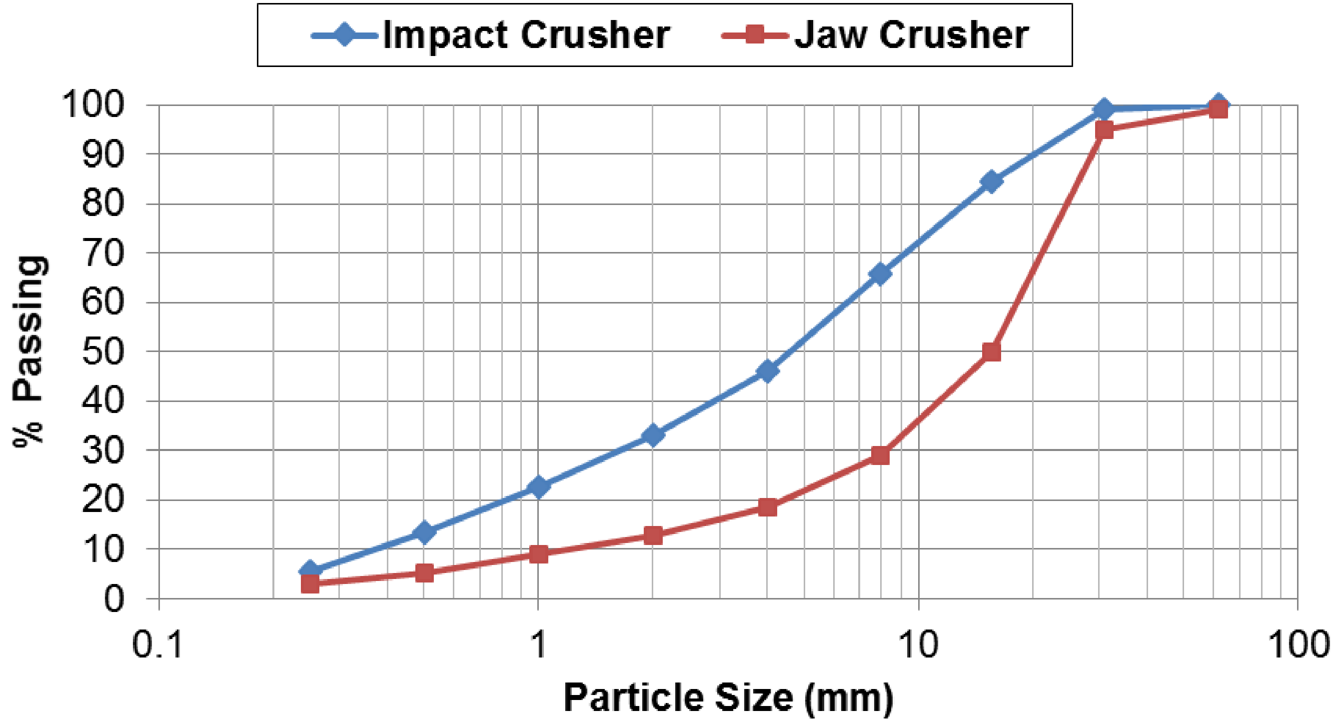
Actual benefits can only be evaluated when impacts over complete life cycle are evaluated

Considerations for Concrete Recycling

- RCA from D-cracked concrete?
- RCA from ASR affected concrete?

Considerations for Concrete Recycling

- Production processes impact product quality and reclamation efficiency



- Maximize reclamation? Minimize mortar?

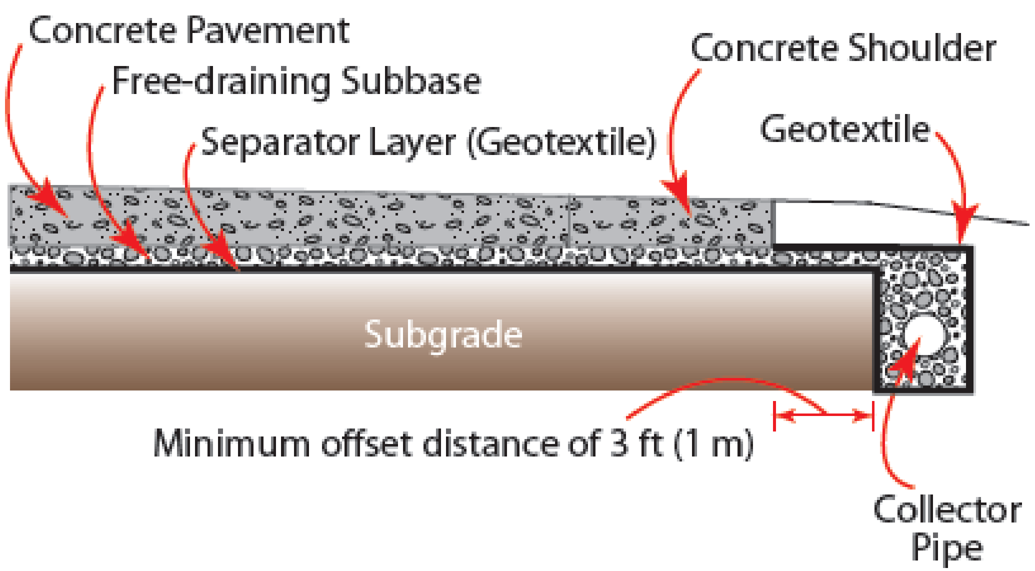
Considerations for Concrete Recycling

- Stockpile runoff and drainage effluent

Photos courtesy of PennDOT

Preventing Drainage Structure Clogging

- Minimize use of RCA fines.
- Crush to eliminate reclaimed mortar
- Blend RCA and virgin materials
- Use largest practical RCA particle sizes.
- Wash RCA to reduce ISR deposits.
- Use high-permittivity fabric
- Wrap trench, not pipe
- Consider daylighted subbase



Source: ACPA 2009

Drainage Effluent and Stockpile Runoff

- Initially highly alkaline (pH > 10) due to dissolution of calcium hydroxide
  - May see small areas of vegetation kill near drain outlets
  - Typically mitigated within several feet of discharge point due to neutralization (acid rain), dilution, soil buffering, combination with atmospheric CO_2 (tufa formation).
- Runoff pH typically decreases rapidly after a few rainfall events as $Ca(OH)_2$ is depleted.

Considerations for Concrete Recycling

- Effects of material properties on design and construction
  - Effects of unbound RCA on pavement design
    - Increased stiffness may impact panel length, thickness
  - Effects of RCA on PCC mixture design
  - Effects of RCA on hardened PCC properties and PCCP design inputs
    - Structural properties, CTE, shrinkage, durability, abrasion resistance, etc.

Recommendations: RCA in Mixture Design

- AASHTO MP16-07
- Quality Requirements and Properties
  - Generally the same as for PCC with virgin aggregate
  - Exception: sulfate soundness (unreliable for RCA)
- Materials-Related Distress
  - Alkali-silica reactivity
    - Lithium
    - Class F fly ash and/or slag cement
    - Limit RCA fines
    - Reduce water access (joint sealing, drains, etc.)
  - D-cracking
    - Reduce coarse aggregate top size
    - Reduce moisture exposure
  - Test effectiveness of all treatments before construction!

Recommendations: RCA in PCC Mixture Proportioning

- Consider Specific Gravity and Absorption Capacity
- Consider higher strength variability
- To maintain workability, add 5 – 15% water

OR

- Use admixtures (chemical and/or mineral)
- Verify air content requirements (adjust for air in reclaimed mortar)
- Trial mixtures are essential

Fresh (Plastic) Properties

Property	Coarse RCA	Coarse and Fine RCA
Workability	Similar to slightly lower	Slightly to significantly lower
Finishability	Similar to more difficult	More difficult
Water bleeding	Slightly less	Less
Water demand	Greater	Much greater
Air content	Slightly higher	Slightly higher

Source: ACPA 2009

Design Recommendations for RCA Concrete Pavements

Design Element	Design Recommendations
Pavement Type	JPCP (15-ft panels); JRCP/CRCP with larger or blended aggregate and possibly added reinforcement.
Slab Thickness	Same as conventional if RCA PCC mix is designed for strength.
Joint Spacing	May be reduced to minimize potential for JPCP cracking, reduce JRCP crack width.
Load Transfer	Same criteria for dowels as conventional.
Joint Sealant Reservoir Design	Consider potential for higher joint movements (due to higher shrinkage, thermal sensitivity) with RCA concrete.
Subbase Type	Same as conventional, except consider free-draining subbase for RCA PCC produced from D-cracked or ASR concrete.
Reinforcement	Higher amounts may be required to resist higher shrinkage, thermal stresses.
Shoulder Type	Same as conventional.

Source: ACPA 2009

Hardened Properties

Property	Coarse RCA	Coarse and Fine RCA
Compressive strength	0% to 24% less	15% to 40% less
Tensile strength	0% to 10% less	10% to 20% less
Strength variation	Slightly greater	Slightly greater
Modulus of elasticity	10% to 33% less	25% to 40% less
CTE	0% to 30% greater	0% to 30% greater
Drying shrinkage	20% to 50% greater	70% to 100% greater
Creep	30% to 60% greater	30% to 60% greater
Permeability	0% to 500% greater	0% to 500% greater
Specific gravity	0% to 10% lower	5% to 15% lower

Source: ACPA 2009

Approaches for Improving Sustainability of Concrete Pavement Recycling

Recycling Objective	Approach to Improvement	Economic Impact	Environmental Impact	Societal Impact
Increase Use of Recycled Materials	Testing and Characterization	Initial research $	Reduced emissions and waste through better material use	Preserve natural resources, reduce need for land fill
	Adjust RCA Production Processes	Initial $	Reduced fuel consumption and waste.	Preserve natural resources, reduce need for land fill
	Customize prep of source concrete	Increased production cost? Offset by increased production rates?	Reduce material waste	Preserve natural resources, reduce need for land fill
Reduce Life Cycle Emissions	Sequester CO_2 Using RCA	None	Potential to reduce CO_2 from cement manufacture	Reduced impact on climate change
Reduce Use of Virgin Materials and Transportation	On-site recycling	Reduced fuel, labor costs. Increased site set up costs.	Reduced GHG due to reduce haul	Reduced haul traffic, congestion

Strategies for Improving Concrete Pavement EOL Sustainability

- Optimize Use of Recycled Materials Through Testing and Characterization
- Adjustment of RCA Production Operations
  - Customize Preparation and Breaking of Source Concrete
  - Customize Crushing and Sizing Operations
- Sequestration of CO_2
- On-Site vs Off-Site Processing

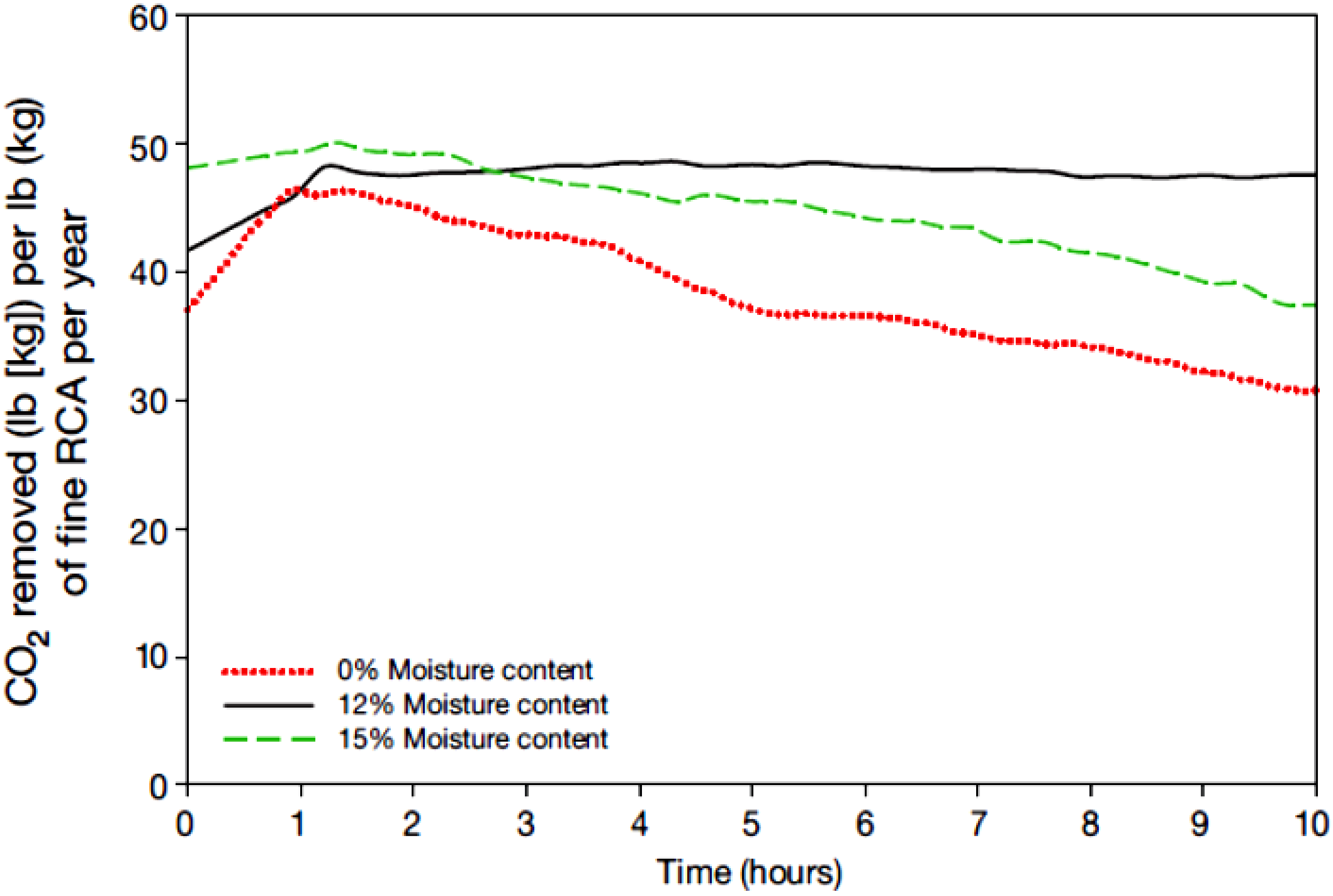
Recommended RCA Subbase Quality Tests and Threshold Values

(Saeed and Hammond, 2008)

- Micro-Deval Test (% loss)
  - <5 to <45%
  - Limits on loss increase with traffic, moisture and freezing climate
- Tube Suction Test (dielectric constant)
  - ≤7 to ≤20%
  - Limits on decrease with increasing traffic, moisture and freezing climate
- Static Triax Test (max deviator stress), Repeated Load Test (failure deviator stress) and Stiffness Test (resilient modulus)
  - Required minimums increase with increasing traffic, moisture and freezing climate

Preparing and Breaking Source Concrete

Carbon Sequestration by RCA



Source: Gardner, Leipold and Peyranere (2006)

On-site vs. Off-site Processing

On-site processing:

- Environmental: Reduced fuel consumption and emissions
- Societal: Reduced haul truck traffic congestion and delays
- Economic: Potential for cost savings (partially offset by cost of setting up portable crusher)

In-place recycling:

- Used when RCA will be used as a foundation layer
- Potentially eliminates haul trucks and waste material

Future Directions/Emerging Technologies

- Increased Recycling/Reduced Disposal
  - Concrete pavement is 100% recyclable, but significantly less than 100% of concrete debris is being recycled
    - 60 – 70% of all concrete debris (likely higher for pavement sources)
    - Goal: zero waste
- Improved Utilization of RCA Products
  - "Best" sustainable practice generally means use in highest-grade application
  - 2000 USGS report: 15% of RCA used in new PCC or HMA mixtures; 78% in base and land fill
  - Improved utilization through guidance, training

Concrete Recycling Guidance

- AASHTO M319: *Reclaimed Concrete Aggregate for Unbound Soil-Aggregate Base Course*
- AASHTO MP16: *Reclaimed Concrete Aggregate for Use as Coarse Aggregate in Hydraulic Cement Concrete*
- ACI 555R: *Removal and Reuse of Hardened Concrete* (2001)
- ACPA EB 043P: *Recycling Concrete Pavements* (2009)
- FHWA *Formal Policy on the Use of Recycled Materials* (2002)
- FHWA T5040.37: *Use of Recycled Concrete Pavement as Aggregate in Hydraulic Cement Concrete Pavement* (2007)

Economic and Environmental Considerations for EOL Options

Recycle and reuse are generally accepted as one of the most effective ways to improve pavements sustainability, but… analyses must be done to quantify effects for various EOL options!

Example:

Impact of transportation costs on recycling vs. cost of new material delivered to site

End-of-Life Considerations

- Growing importance of incorporating RCWMs in new and rehabbed pavements
  - Depletion of quality aggregate sources
- Ideal goal: zero-waste highway construction stream!

Zero-Waste (Closed-Loop) for Pavement Systems

- In closed-loop or zero-waste concepts, a significant portion of energy and materials will be provided from recycled or reused materials

Lehman (2011)

Potential Advantages of Zero-Waste Systems

- Avoids waste being generated in the first place.
- Creates closed-loop economies with additional employment opportunities in recycling industries.
- Transforms industries toward a better use of resources, cleaner production processes, and, importantly, extends the initial producer's responsibility.
- Delivers economic benefits through more efficient use of resources.
- Conserves landfill space and reduces the need for new landfill spaces.

Thank You!

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