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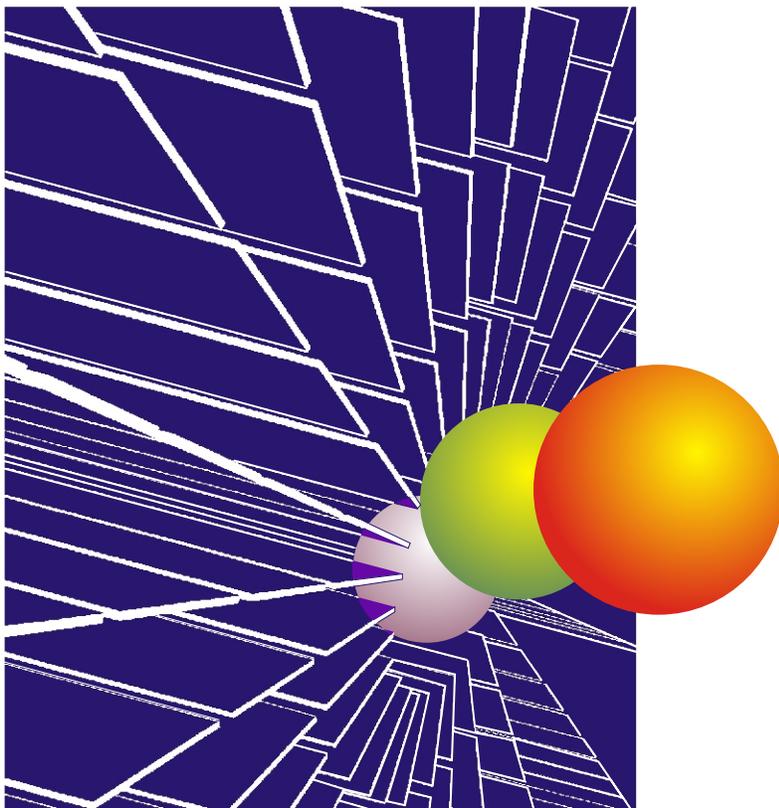
Research, Development and Technology

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# Missouri Guide for Pavement Rehabilitation

RI 00-008



November, 2002

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MISSOURI GUIDE FOR PAVEMENT REHABILITATION

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The opinions and, findings, and conclusions expressed in this publication are those of the principal investigator and the Research, Development, and Technology Business Unit of the Missouri Department of Transportation.

They are not necessarily those of the U.S. Department of Transportation, Federal Highway Administration.  
This report does not constitute a standard, specification, or regulation.

## Executive Summary

An analysis of the performance of Missouri pavements was conducted. Pavement construction and rehabilitation designs were evaluated by functional classification: National Highway System (NHS), remaining arterials, and collectors; and pavement type: Portland cement concrete (PCC), asphalt concrete (AC) overlaid PCC, full-depth AC, and AC overlaid AC. Pavement design and performance information from other states was also closely studied for possible application in Missouri.

This document drew the following conclusions:

### New PCC –

- ❖ PCC pavements on divided NHS routes in Missouri last an average of 25 years before rehabilitation is required
- ❖ Missouri's jointed plain concrete pavement (JPCP) design compares very favorably with other States' long life (40+ years) pavement designs.
- ❖ Continuously reinforced concrete pavement (CRCP) with specific design features has maintenance-free characteristics that, based on performance data from other States, make it an optimum design strategy for the highest volume NHS urban routes.

### PCC rehabilitation –

- ❖ Rubblization of old PCC on NHS and remaining arterial routes can be a viable rehabilitation strategy under the right conditions.
- ❖ Diamond grinding existing PCC pavements with moderate faulting on NHS and remaining arterial routes is an optimum rehabilitation strategy if no subgrade stability problems are evident.
- ❖ AC overlays on PCC on divided NHS routes in Missouri last an average of 10 years before rehabilitation is required. This is congruous with other States' expected performance.
- ❖ Stone matrix asphalt (SMA) overlays on concrete have increased AC overlay lives an average of two years based on extrapolated estimated trends derived from a statistically small percentage of overlays.
- ❖ Superpave AC overlays have demonstrated improvement over conventional AC mixes, but the benefit is not yet quantifiable because of very limited performance data.
- ❖ Unbonded PCC overlays have performed very well in Missouri. Thin AC overlays may be used as short-term strategies before placement of unbonded PCC overlays.

### New full-depth AC –

- ❖ Full-depth Superpave pavements have only recently been implemented in Missouri and very limited data is available, but early performance results have been good.

- ❖ Missouri's AC pavement design has common characteristics with the "perpetual pavement" concept.
- ❖ AC pavements with low stability subgrades require either a thick rock base or subgrade modification.

AC overlay on AC –

- ❖ Thin AC overlays (~ 1 ¼ inch) on AC on NHS and remaining arterial routes last an average of six years before rehabilitation is required. Similar thin AC overlays on AC on collector routes last an average of four to seven years before rehabilitation is required depending on the type of mix.

General –

- ❖ High initial smoothness on NHS and remaining arterial routes, obtained through any practical combination of construction methods, should result in extended pavement service life.
- ❖ Longitudinal drainage pipe systems can easily be modified to allow easier inspection and cleanout, which would ensure a return on the initial investment.
- ❖ General life cycle cost analysis, including present and future construction costs and their associated user costs, indicates that new AC is more cost-effective on lower arterials, while new PCC is more cost-effective on higher-volume arterials.
- ❖ General life cycle cost analysis, including present and future construction costs and their associated user costs, indicates that an AC overlay is more cost-effective on lower arterials, while an unbonded PCC overlay is more cost-effective on higher-volume arterials.

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## **Glossary of Acronyms and Abbreviations**

AADT – average annual daily traffic

AASHTO – American Association of State Highway and Transportation Officials

AC – asphalt concrete

AC/AC – asphalt concrete overlay on asphalt concrete

AC/PCC – asphalt overlay on Portland cement concrete

ACOL – asphalt concrete overlay

ACP – asphalt concrete pavement

ACPA – American Concrete Pavement Association

AI – Asphalt Institute

ARAN – Automated Road Analyzer

ATB – asphalt treated base

CBR – California bearing ratio

CPR – concrete pavement restoration

CTB – cement treated base

CRCP – continuously reinforced concrete pavement

ESAL – equivalent single axle load (18,000 lb)

FHWA – Federal Highway Administration

HMAC – hot mix asphalt concrete

IBV – immediate bearing value (soil stability)

IRI – international roughness index

JPCP – jointed plain concrete pavement

JRCP – jointed reinforced concrete pavement

LRTD – Long Range Transportation Direction (MoDOT’s 20-year planning tool)

LTPP – Long Term Pavement Performance (program)

NAPA – National Asphalt Pavement Association

NHS – National Highway System

PCC – Portland cement concrete

PCCP – Portland cement concrete pavement

PI – plasticity index

PMS – pavement management system

PSR – present serviceability rating

QC/QA – quality control / quality assurance

SMA – stone matrix asphalt

SPS – specific pavement study (part of LTPP program)

Superpave – Superior PERforming asphalt PAVements (mix design)

TMS – Transportation Management System (MoDOT business unit)

VMT – vehicle miles traveled

## Purpose

The purpose of this document was to provide direction for future pavement rehabilitation design decisions. Different treatments were evaluated for potential effectiveness on Missouri roads. Existing Missouri performance data for predominant treatments was analyzed. Performance information for treatments seldom used in Missouri was gathered from other states.

## Proviso

*The conclusions drawn are based on a combination of factual performance data trends and engineering judgment.*

*Past performance, at best, can only provide general indication of future performance when design criteria, material properties, and construction practices change, such as is the case in Missouri. During the past eight years, significant modifications have occurred to rigid and flexible pavements. Missouri has adopted thicker structural layers, drainable bases, JPCP design with short joint spacing and widened driving lanes, Superpave and SMA mix designs, QC/QA specifications for both industries and tightened material specifications. While the data analysis used the best performance information available at MoDOT, it could not reflect the full measure these modifications will have on future performance. Future performance data will provide that enlightenment.*

*Also, where design and performance information was gathered from other state DOTs, consultants, and industry sources, an educated guess was ultimately required by the MoDOT engineering staff to determine how it would apply to Missouri's highway system.*

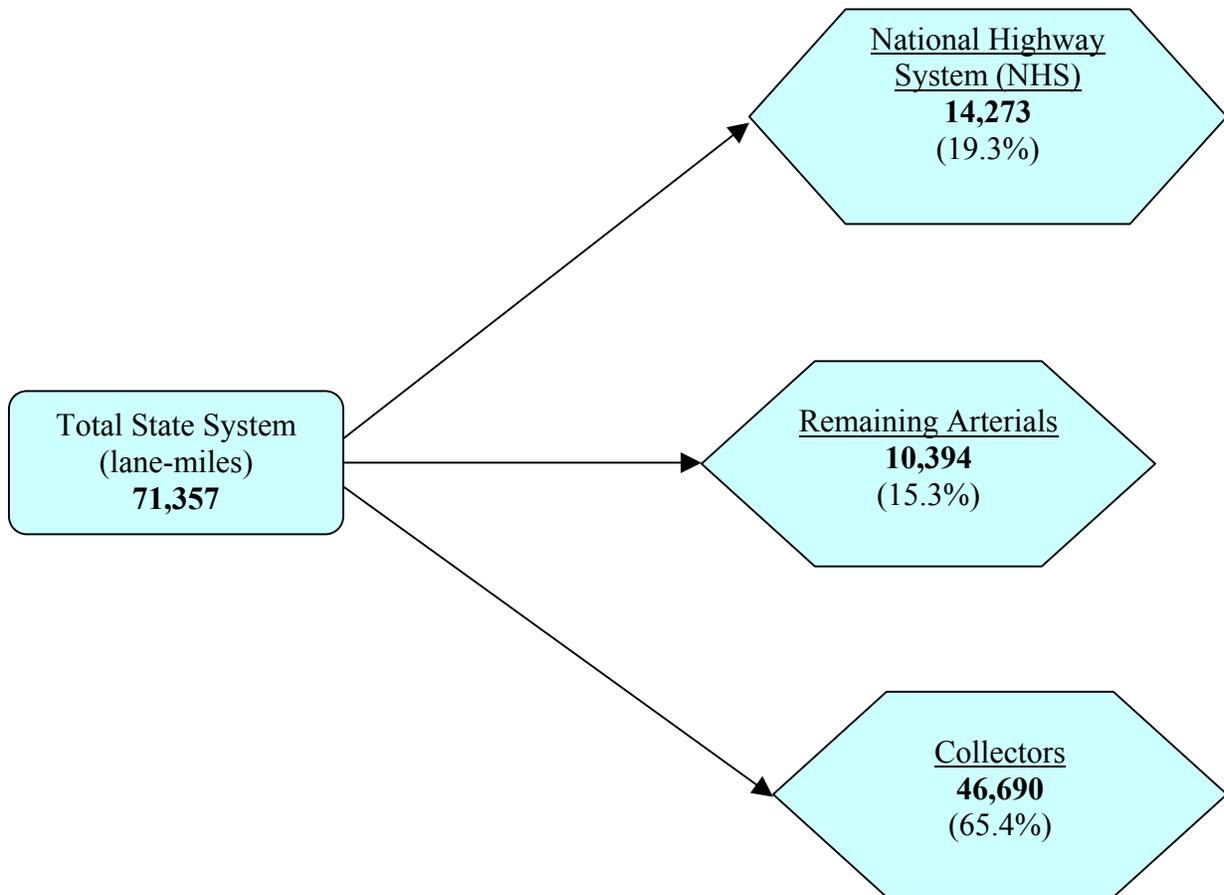
## Missouri Roadway Inventory

### *What makes up the Missouri state highway system?*

The Missouri state highway system consists of over 71,000 lane-miles of pavement. The types of roadway vary from low-volume rural collectors to multi-lane, high-volume urban Interstates. Our level of investment must reflect the strategic importance of each route.

This study divides the Missouri state highway system into the three functional categories addressed in the Missouri Long Range Transportation Direction (LRTD): the National Highway System (NHS), remaining arterials and collectors.

These groups represent different levels of functional importance that require different levels of rehabilitation and maintenance effort.

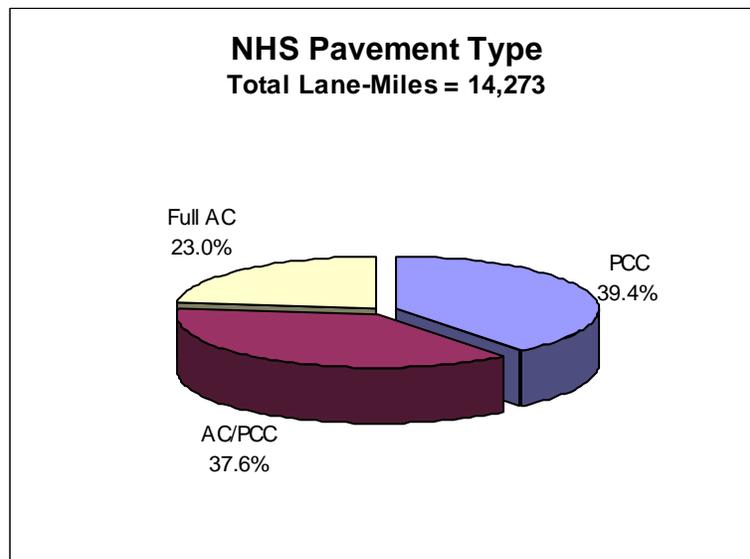


## **National Highway System (NHS)**

The NHS consists of Missouri's highest priority routes. It includes all of the Interstate system, most U.S. routes, and other principal arterials. These roads carry the highest volume per mile and form the backbone of the Missouri highway infrastructure.

NHS routes should be designed to minimize the number of work activities during their performance lives. User costs from delays can be very high, especially in daytime, therefore lane closures must be kept low.

The pie chart below reveals that Missouri's NHS is primarily Portland cement concrete (PCC) or PCC overlaid with asphalt concrete (AC). The percentage of AC/PCC may actually be higher and full-depth AC lower because of uncertainty about the historical records for some full-depth AC pavements. The entire Interstate system was originally paved with PCC, except for a few short stretches on I-44.

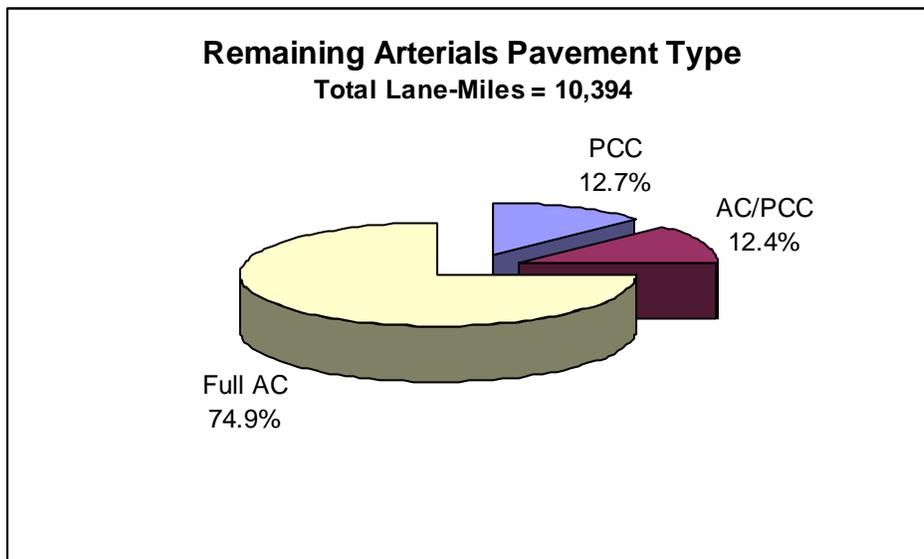


## Remaining Arterials

Remaining arterials include mostly minor arterials and a smaller fraction of principal arterials not on the NHS. Many of these serve as connectors between the NHS and collectors.

Lane closures have a less severe impact to traffic on these lower volume arterials than on the NHS.

The pie chart below reveals that nearly 75 percent of the lane-miles in this category are full-depth AC. The rest is evenly split between bare and overlaid PCC. The percentage of AC/PCC may actually be higher and full-depth AC lower because of uncertainty about the historical records for some full-depth AC pavements.

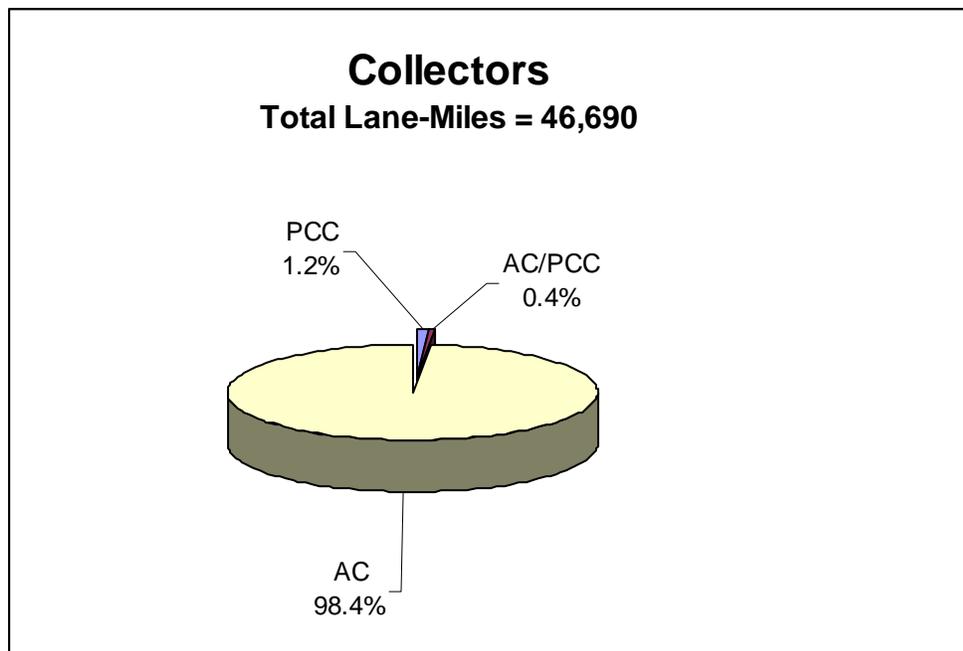


## Collectors

Collectors serve smaller towns and traffic generators that are not on arterial routes. They provide a link to local roads and residential areas. They typically carry low volumes.

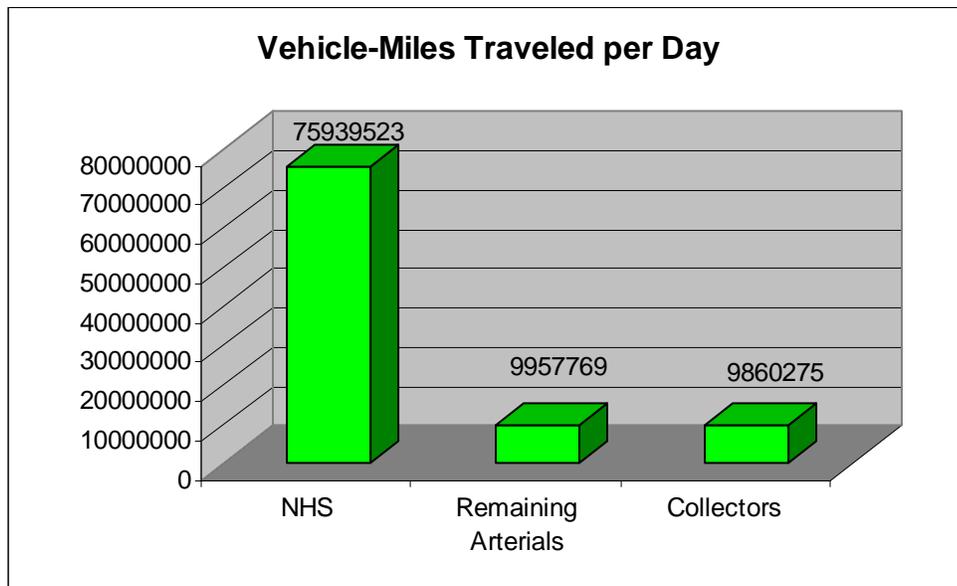
Lane closures have the lowest impact on traffic on collectors. Periodic maintenance treatments are less intrusive than on higher volume routes.

The following pie chart indicates that these routes are predominantly AC.



***How heavily trafficked are these routes?***

The cumulative number of vehicle-miles traveled (VMT) on the NHS is approximately 80 percent of all VMT on the Missouri state system. This equates to carrying 80 percent of the traffic on 20 percent of the lane-miles. The other 20 percent is split nearly even between remaining arterials and collectors; however, remaining arterials have less than 25 percent the lane-miles that collectors have.



***What does the public expect from these routes?***

The Missouri public set the standard for pavement performance at a series of road rallies in the spring of 2000. Their opinions of four different roadway circuits on the state system were correlated to pavement serviceability ratings (PSR)<sup>1</sup>.

The PSR is a scoring index split evenly between roughness and visual distress. Roughness is measured objectively with an Automated Road Analyzer (ARAN), while visual distresses are manually interpreted and recorded from ARAN videotape of the pavement surface.

Public opinion determined that a PSR score  $\geq 32$  was acceptable for the NHS;  $\geq 31$  was acceptable for remaining arterials; and  $\geq 30$  was acceptable for collectors. They were quite certain any roadway  $< 29$ , regardless of functional classification, was unacceptable. A marginal performance range existed between these limits. The threshold of 29 was nearly identical to the breakpoint between fair and poor pavements statistically derived several years ago by the MoDOT pavement management section.

<b><i>NHS PSR</i></b>	
$\geq 32$	ACCEPTABLE
$29 - \leq 32$	MARGINAL
$< 29$	UNACCEPTABLE

<b><i>REMAINING ARTERIALS PSR</i></b>	
$\geq 31$	ACCEPTABLE
$29 - \leq 31$	MARGINAL
$< 29$	UNACCEPTABLE

<b><i>COLLECTORS PSR</i></b>	
$\geq 30$	ACCEPTABLE
$29 - \leq 30$	MARGINAL
$< 29$	UNACCEPTABLE

## PCC Pavements

When we discuss PCC pavements in Missouri we are primarily dealing with NHS routes and remaining arterials. The Interstate system, the core of the NHS, was built almost exclusively with PCC. Most of our U.S. routes were also paved with PCC. Therefore, our PCC pavements have historically conveyed the vast majority of vehicular traffic. We have inherited a large PCC infrastructure that must be maintained at a serviceable level through a combination of appropriate reconstruction, rehabilitation and restoration strategies.

### *What makes our PCC pavements deteriorate?*

PCC pavements are subject to different distress mechanisms, but in Missouri the primary culprits have been:

1. faulting and cracked slabs at joints and cracks,
2. spalling and blowups at joints, and
3. D-cracking
4. loss of load transfer

The first distress mechanism is mainly attributable to a pavement design that, although using the best traffic forecasting tools available at the time, underestimated the amount and severity of actual truck loadings and did not consider drainage. The subgrade under most PCC pavements in Missouri was usually an impermeable soil. Fines from the subgrade would infiltrate into the granular base. All older pavements had no edge drain systems to transport water away. The trapped water, mixed with fines, would eventually get pumped out through transverse joints or working cracks under repeated truck loadings. Loss of fines led to the creation of voided areas under the leave side of slabs, which resulted in faulting, cracking and corner breaks.

The second distress mechanism is not fully understood, but is usually thought to occur through a combination of concrete expansion and incompressible material infiltration into joints that lost their sealant or separated enough to exceed sealant coverage. Material would lodge in the joints during periods of normal to cooler weather. When temperatures would get unusually high, the slabs would try to expand and fail in shear causing spalls, and in more severe cases, blowups. New asphalt overlays also provide enough heat to expand old PCC slabs, as the number of blowups on these types of projects in Missouri can attest.

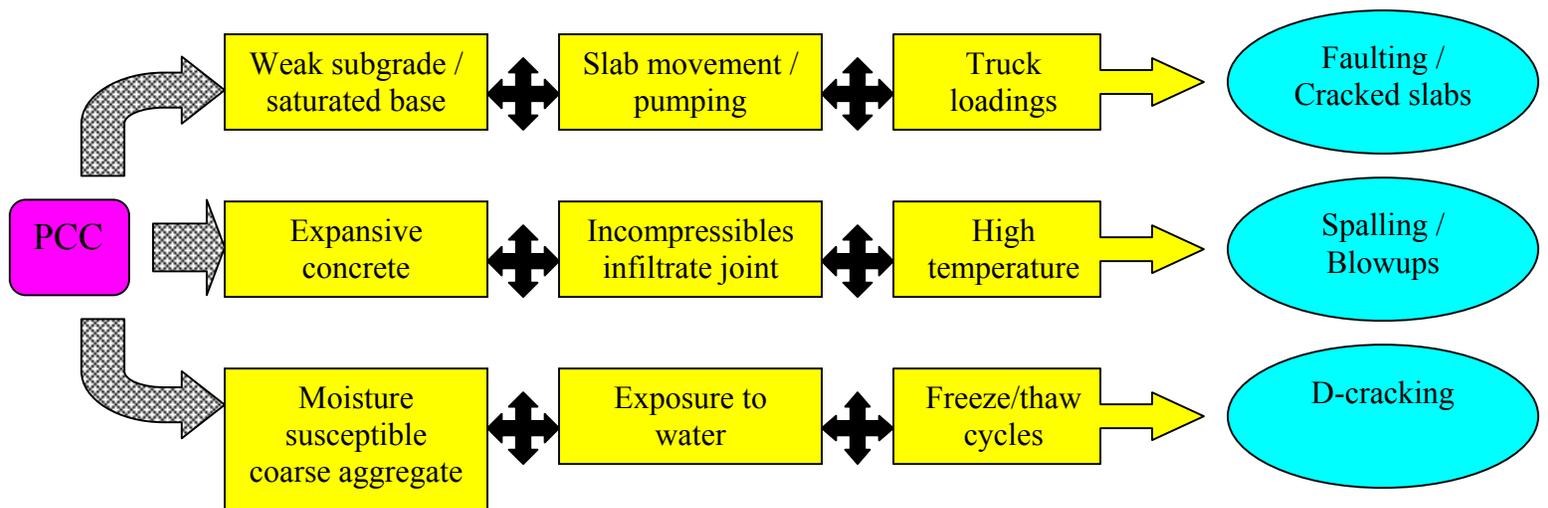
The third distress mechanism is strictly a materials problem. Some coarse aggregate sources, particularly in northwest Missouri, have pore structures that are susceptible to d-cracking. Water would usually permeate this type of aggregate at the joints and under slab edges where the slabs had the greatest exposure. Repeated freeze-thaw cycles would cause the coarse aggregate to fracture from the internal stresses of trapped frozen water. D-cracking can drastically shorten PCC pavement life. Efforts to mitigate d-cracking

through reduced maximum coarse aggregate size appears to be working thus far, based on recent surveys of experimental test sections<sup>2</sup>; however, the trend is not completely clear cut and further surveys are required to validate this idea.

The fourth distress mechanism, loss of load transfer, is derivative of one or more of the other three. It characterizes the overwhelming problem at joints and working cracks.

Outside of deterioration at the slab perimeters and midpanel cracking, PCC pavements have remained structurally intact over long periods of time. Assuming there are no inherent materials-related distresses, such as D-cracking or alkali-silica reactivity (ASR), the interior of a PCCP, designed with adequate thickness for maximum loads, will not fail. In short, PCCP failure seldom occurs from overstressing.

Since all these distresses occurred at joints and cracks the slabs were often repaired with full-depth pavement repairs. However, the same distresses would often recur a short time later and further rehabilitation was needed. Sometimes the repairs themselves led to problems at other joints. Removing an old slab relaxes the compressive forces on adjoining slabs and can reduce their load transfer ability.



The analysis discussed in this report examines the performance of Missouri’s different PCC designs.

***What types of PCC pavements are there and who uses them?***

*There are three basic categories of PCC pavements: jointed reinforced concrete (JRCP), plain jointed concrete (JPCP) and continuously reinforced concrete (CRCP).*

## JRCP

Jointed reinforced concrete pavement (JRCP) has reinforcing steel, in the form of either mesh or tied rebar, across each of its slab areas. The reinforcement is usually placed slightly above mid-depth, but varies from state to state. Joints are formed between slabs. Steel reinforcement does not bridge across the joints. The joints are fitted with dowel bars for load transfer. Typical slab lengths are 60 feet or greater. Thickness varies depending on the structural design capacity.

### *Missouri's experience*

Until 1993 JRCP was the standard design in Missouri. Design thickness ranged from 8 – 11 inches. Joint spacing was 61.5 feet. JRCP performance was often marred by faulting, spalling and general deterioration at joints and sometimes at working third point panel cracks. D-cracking in the northwestern part of the State often accelerated these failures. Outside of these problems, the PCC slabs remained intact for a long time. The biggest concern over this type of design, assuming proper base support, drainage and good quality coarse aggregate are present to keep it structurally sound, is the effect of temperature and moisture-induced slab curvature on ride.



JRCP on NB US 54 in Callaway County

### *Other States' experience*

JRCP used to be the preferred PCC design for most states. A lot of them had problems similar to Missouri's. Virtually all States have replaced JRCP design with JPCP design.

### **JPCP**

Jointed plain concrete pavements (JPCP) have no steel reinforcement. Joints are formed between slabs. The joints are usually fitted with dowel bars for load transfer, but this is not always the case. Typical slab lengths are 15-20 feet. Thickness varies depending on the structural design capacity.

### *Missouri's experience*

Prior to 1994 Missouri had occasionally built some 30-foot JPCPs. These pavements tended to form mid-panel cracks. Since 1994 all PCC pavements in Missouri have been built with the JPCP style. Driving lane slabs are paved 14-feet wide or 2 feet beyond the edge line. Joint spacing is 15 feet, which has virtually eliminated natural mid-panel cracking. Joints are doweled. Slab thickness is 11-14 inches on NHS and other arterial roads, much greater than the older JRCP design. The preferred base type is a 2-foot, daylighted rock base, which provides a stiff platform as well what is currently believed to be a very drainable layer. Performance to date has been excellent.

Recent national research<sup>3</sup> endorses shorter joint spacing, which reduces slab curvature from changing daily temperature gradients and seasonal moisture gradients, and in turn reduces stresses induced by truck loads. Paving 14-feet wide in the driving lane is another research recommendation<sup>4</sup> that Missouri adopted. The extra 2 feet reduces longitudinal edge stresses at the shoulder and provides a better length-to-width aspect ratio. The thicker slab design gives greater structural capacity to meet the needs of heavier axles.



JPCP on SB US 63 in Boone County

### *Other states' experience*

Most states that build significant amounts of PCC have gone to the JPCP design.

### **CRCP**

Continuously reinforced concrete pavement (CRCP) has continuous wire mesh or tied longitudinal rebar across its entire area. The reinforcement is usually placed slightly above slab mid-depth. There are no joints. The slab cracks naturally from shrinkage in 4-5-foot transverse spacing. The cracks are held tight by the steel. The picture below illustrates ideal crack spacings and openings for a CRCP.



Illinois CRCP

A study<sup>5</sup> of over 400 in-service PCC pavements in North America, Europe and Chile revealed that, when comparisons were feasible, CRCPs clearly outperformed JRCPs and had a slight edge on JPCPs. Under similar environmental and construction circumstances, CRCP is naturally smoother than JPCP because of reduction in slab size (less curling) and tight cracks.

#### *Missouri's experience*

Missouri has only one existing CRCP on its system. Four-and-a-half miles of eastbound I-64 in St. Louis County in the Chesterfield bottoms has been performing admirably since 1968. A couple of factors likely aided its performance. It was placed on hydraulic fill (river sand), which has excellent drainage properties. Also, truck traffic had not become very heavy until this past decade. Only recently had the 9-inch pavement begun to show signs of its age. This pavement was overlaid with asphalt in 2001 in connection with the addition of a third lane.

#### *Other states' experience*

Five states use the CRCP design as their primary, heavy-duty pavement type. Two of them, Illinois and Texas, rank in the top six for highway construction programs. They have continued to adjust and improve their CRCPs over the years and are fully satisfied

with the design concept. Oklahoma, South Dakota and Virginia also use CRCP, but are limited to fewer reconstruction projects per year.

Illinois recently developed a 40-year design by tightening aggregate specifications to eliminate d-cracking, providing a 6-inch base of dense-graded AC to prevent punchouts, compacting a thick, granular subbase layer to encourage drainage, and raising the steel content to eight percent to promote tighter crack spacing and crack widths. They expect that the only maintenance work required, if any, will be some diamond grinding to restore smoothness.

Illinois constructed a 10-inch CRCP (w/ 4-inch AC base on 12-inch granular subbase) north of Chicago on the Edens Expressway (I-94) in 1980. In 20 years of service under extremely heavy traffic, the 20-miles of pavement required only nine patches, making it virtually maintenance-free. Illinois also constructed a similar design of 12-inch CRCP (w/ 4-inch AC base on 18-inch granular subbase) in 1992 on the Kennedy Expressway (I-55) in northwest Chicago. This pavement has sustained AADTs in excess of 200,000 every day for ten years and still looks new.

Historically, punchouts have been the major weakness for CRCPs. This was directly related to poor support by the base and subgrade. Short sections of concrete would subside as the base gave way. Eventually, the steel would yield and rupture and then the slab would “punch” through. Illinois, Texas, Oklahoma and Virginia believe they have solved this problem by upgrading the support with a dense-graded AC base layer. Performance to date with this design bears out their belief.

CRCP costs are typically \$4-5 per yard<sup>2</sup> greater than JPCP, but the maintenance-free surface and smoother ride make it a viable option in high-volume, urban areas.

### ***How long do our PCC pavements last?***

Using the Road Rally findings as our barometer for pavement performance, 1995-2000 ARAN data was analyzed to determine PCCP performance. ARAN data is the only statewide measure of pavement performance available.

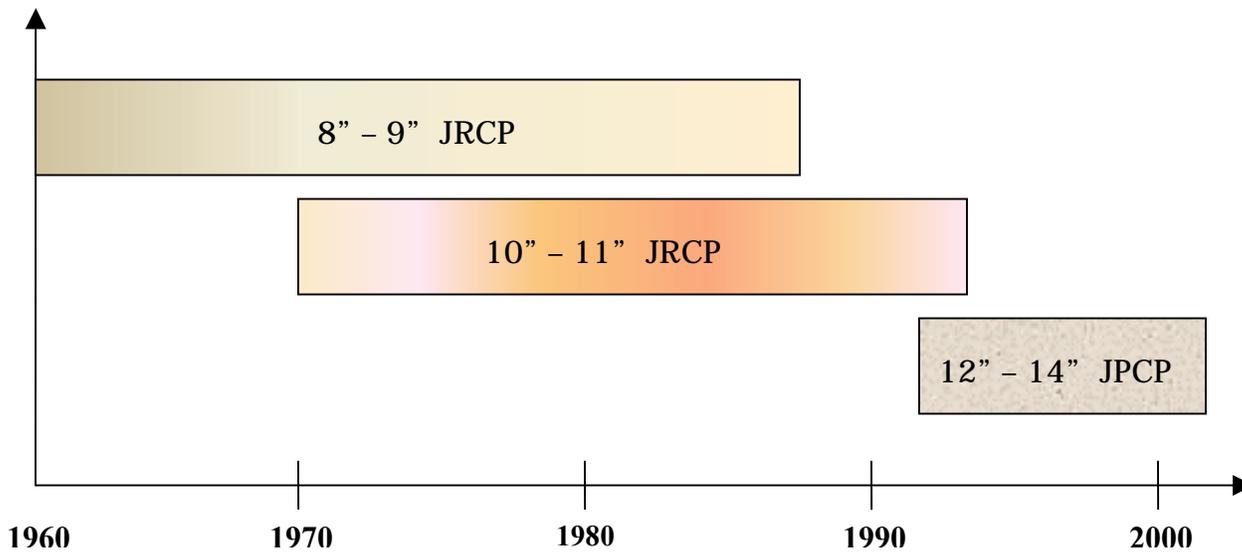
Divided NHS routes were selected for the analysis because they have the greatest strategic importance, carry the most traffic, endure the heaviest loads and require the greatest fiscal investment per lane-mile.

### **Data Sources**

ARAN data was retrieved from the master inventory table in the pavement management system (PMS) database.

## PCCP Variables

The most significant change in PCCP design over time has been thickness. Thickness is an indication of construction era. The 8- 9-inch pavements span back to the 1960s. Fewer were built on what would become NHS routes in the 1980s, because they were deemed structurally too thin for the loads they would carry. The 10 - 11-inch pavements formed the second generation of reinforced routes from the early 1970s through the early 1990s. Finally, 12 – 14 inch PCCPs have been built since 1994 and constitute the current state of structure on the NHS. The newer plain jointed design also constitutes the other major change. Thickness is not broken out as a variable because of data history gaps that exist for each grouping.



Base and subgrade types were not introduced as analysis variables for long term performance, because they were identical in most instances. The fill material was usually fine-grained and poorly draining. Type 3 material was used almost exclusively as a base layer under PCCPs up until the early 1990s. Its dense-graded aggregate with up to 35 percent fines rendered it impermeable. In short, nearly all of the old pavements had drainage problems. Only the 12-14-inch PCCPs had improved drainage systems.

Cumulative equivalent single-axle loads (ESAL) would have been very desirable for this analysis, but were not introduced as variables because insufficient information exists for accurate estimates of truck percentages, weights and ESAL/axle ratios.

Information about D-cracking susceptible aggregate exists on separate project history sheets, but these have never been consolidated into a single list or database that would have made an analysis of the effect of this distress on performance practical.

## Data Accumulation

Each year's performance measurement of each directional pavement section was included in the analysis. Therefore, the cumulative mileages are not composed of unique sections

used only once, but unique sections used up to six times each. In other words, a pavement constructed in 1991 was counted among four-, five-, six-, seven-, eight-, and nine-year-old sections using the unique performance data for each of those six years.

Performance data was averaged for each year of age. Each average was weighted for the length of pavement section.

### **Performance Period**

The performance period used in this analysis was forty years.

### **Performance Indices**

The performance indices used for each year in the analysis were PSR, ride, condition, cracking, and international roughness index (IRI). The ride score used in this analysis is actually IRI correlated to ride on a 1-to-10 basis. Condition scores are an equal combination of cracking, joint condition, spalling, and patching. PSR is equally split between ride and condition.

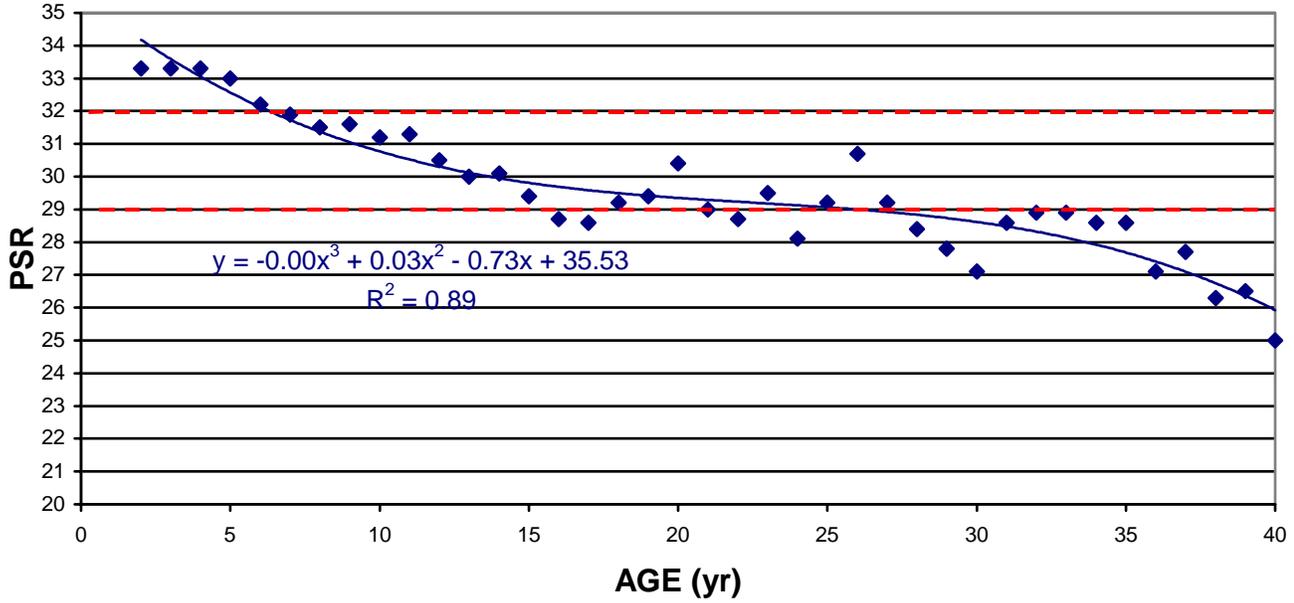
### **Findings**

Average PCCP PSRs deteriorate gradually for the first sixteen to seventeen years and then level off somewhat. A 3<sup>rd</sup> degree polynomial regression approximates the trend well. Maintenance activities such as patching and joint repairs probably account for some of the leveling, however; it would be very difficult without accurate maintenance histories to measure what affect the improvements had on the performance scores. Whatever the case, it can be assumed the conditions were judged not to merit resurfacing. Average time before PCCPs descend to an unacceptable PSR is around 25 years. Ride and condition trends are similar to PSR.

### PSR for PCC on Divided NHS

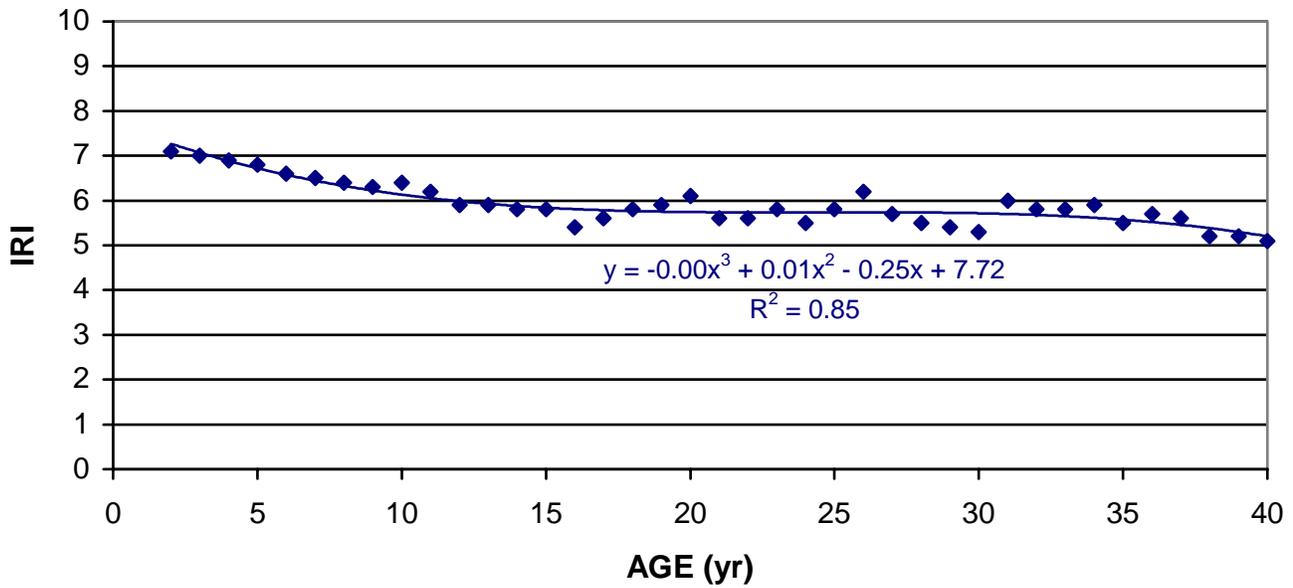
1995-2000 ARAN Data

Cummulative length - 10,234 miles

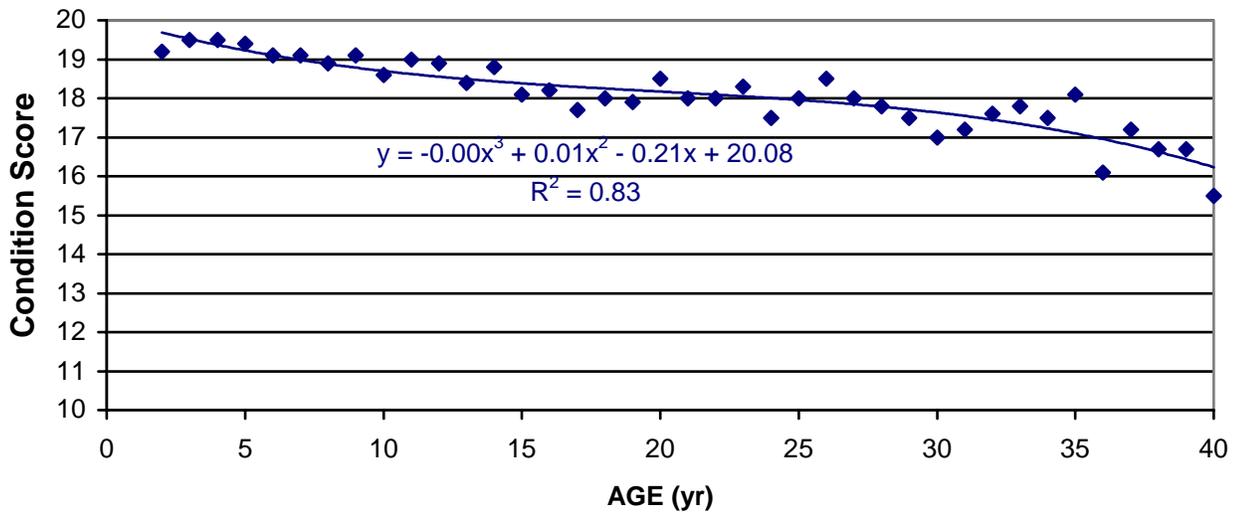


### Ride for PCC on Divided NHS

1995-2000 ARAN Data



## Condition for PCC on Divided NHS 1995-2000 ARAN Data



**PAST AVERAGE  
PERFORMANCE LIFE (at least  
marginal) TILL FIRST MAJOR  
REHABILITATION REQUIRED  
FOR PCC PAVEMENT  
ON NHS  
= 25 YEARS**

***Can initial PCCP smoothness be improved upon?***

Missouri is testing that idea on three projects with contract diamond grinding. All projects incorporated the ‘zero-inch-blanking band’ for profile measurements.

The first is a 4 ½-mile, 12-inch JPCP built on U.S. 60 near Poplar Bluff in 1997. The contractor was paid upfront to diamond grind the finished surface, rather than diamond grind at their own cost to correct deficiencies. In return for this bid item payment, the modified smoothness pay scale raised the level of difficulty for the contractor to earn a bonus.

The result was a superb average profile of 6.3 (in/mile). Even after three years the profile average has barely risen. PSR scores have hovered just above 35 during that time. There was also a companion six-mile JPCP built in the other direction at the same time, differing only in its surface finish with transverse tining and a burlap drag finish. This pavement achieved a 17 (in/mile) longitudinal profile and maintained average PSR scores between 34 and 35.

The second was on an unbonded PCC overlay built in 1998 on I-29 in Atchison County. Contract conditions were the same. Diamond grinding on the entire four-mile surface reduced profile roughness from 25 (in/mile) to 10 (in/mile).

The third project was a six-mile, 8-inch unbonded overlay built in 2000 on I-44 west of Springfield. Contract diamond grinding reduced profile roughness from 24 (in/mile) to 11 (in/mile).

LOCATION	TYPE	PROFILE BEFORE CONTRACT DIAMOND GRINDING (INCHES/MILE)	PROFILE AFTER CONTRACT DIAMOND GRINDING (INCHES/MILE)
US 60 Butler Co.	New 12” JPCP	18	6
I-29 Atchison Co.	5” –11” unbonded overlay	25	10
I-44 Greene Co.	8” unbonded overlay	24	11

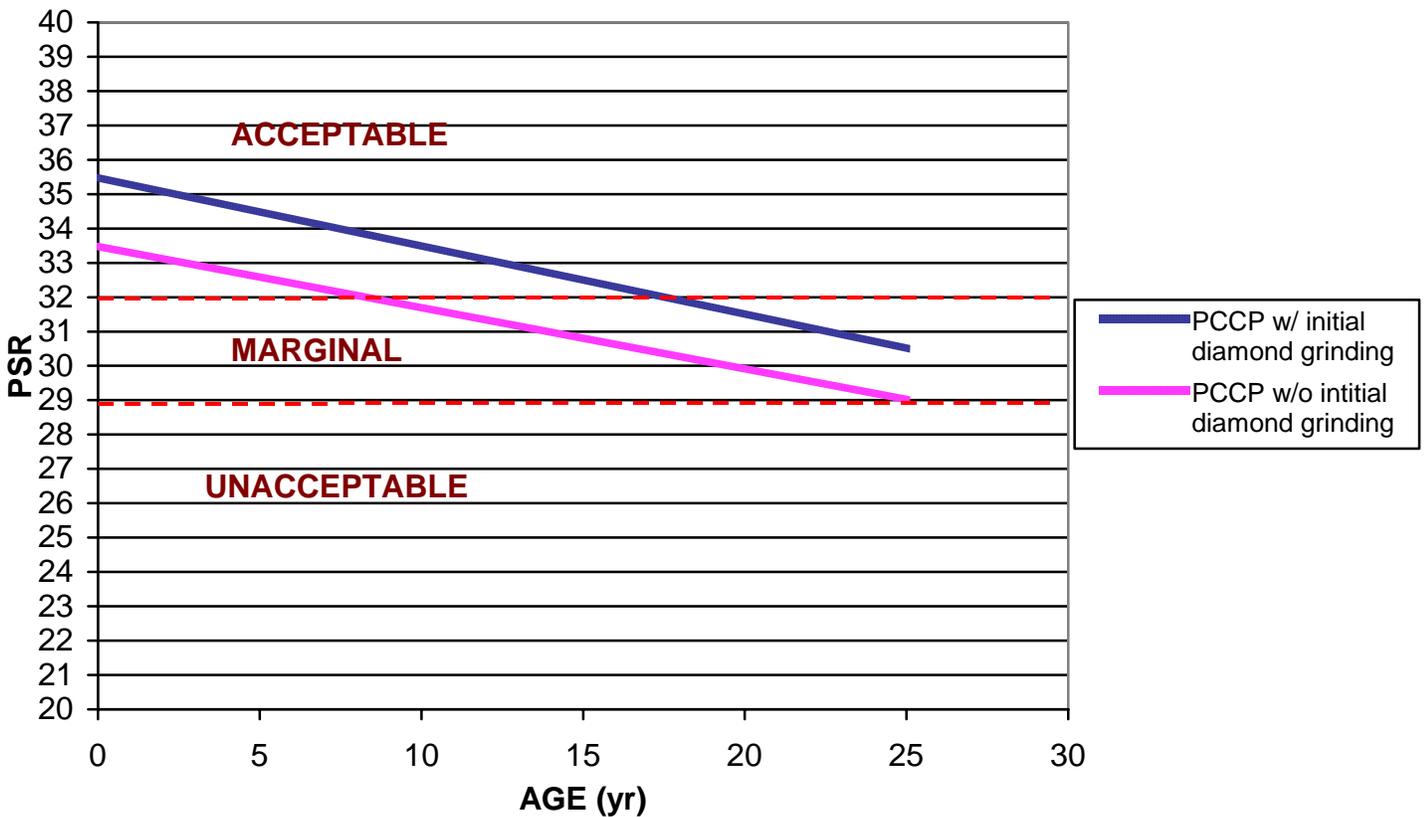
***How would increased smoothness affect future performance life?***

There is growing support for the idea, that for a pair of pavements, if smoothness is improved at construction for one and not the other, and all other factors are held equal,

then overall performance will decrease at similar rates for both and the smoother pavement will maintain a significant edge in PSR for the entire design life. A national study<sup>6</sup> of over 100 projects from around the country partly validated this theory. An important finding was that the average roughness deterioration rate of a non-diamond ground PCCP was approximately 85 percent of a diamond ground pavement, while new AC was 75 percent, AC/PCC was 71 percent and AC/AC was 60 percent.

To illustrate this concept, let's look at two PCCPs that are identical in every way, except that one has had its surface diamond ground while the other has not. Assume the change in Condition scores for each is 1.5 points over a 25-year period, which is consistent with the historical average in the previous Condition chart. Then assume the change in Ride for the non-diamond ground PCCP is approximately 1.5 points, which is consistent with the historical average in the previous Ride chart and that this is 85 percent of the change in Ride for the diamond ground PCCP. Based on the ARAN data for the US 60 diamond grinding project, it can also be assumed the overall initial increase in PSR for a diamond ground PCCP is around 2 points. Therefore, the diamond-ground pavement starting with a PSR of 35.5 would drop to 30.5 after 25 years, while the non-diamond-ground pavement would change from 33.5 to 29.

### Effect of Initial Smoothness on PCCP Performance Life



### ***What else can be done to increase smoothness?***

Other methods can be used to achieve smoother PCCP pavements. Smoothness is a function of subgrade preparation, construction technique and surface finishing.

Many of Missouri's subgrade soils are clays. The California Bearing Ratio (CBR) is an indication of a soil's strength. A CBR below 6 is very poor. Missouri's soils, especially those north of the Missouri River, have CBRs well below 6. A common solution is lime or flyash stabilization. Missouri has had a standard construction specification for stabilization with hydrated lime for years, but it has seldom been used. Lime stabilization significantly reduces a soil's plasticity and increases its stiffness modulus. Illinois and Kansas are border States to Missouri with similar soil conditions. They routinely stabilize the subgrade under most of their new pavements. Thicker stiffer bases are another contributor to overall stability. Contractors also appreciate the improved support for paving equipment.

Construction techniques greatly influence smoothness. Some examples of improvements include using more closely spaced concrete paver stringline stakes and consistently providing the right amount of concrete ahead of the paver. However, it is best not to be too prescriptive in the construction specifications. Rather, an incentive/disincentive clause is probably the best way to entice the contractor into making his own construction technique changes to increase smoothness.

### ***Why else is smoothness important?***

Operational user costs are those costs indirectly incurred by the public during their use of a road. They are associated with the depreciation of vehicles due to surface roughness.

Normal operating costs are computed by estimating the amount of repair, fuel and tire costs generated by degrees of road deterioration. Tire wear and vehicle maintenance<sup>7</sup> increase the most in proportion to the level of roughness of the pavement surface.

If taken at face value, these are by far the greatest life-cycle costs. However, since they represent theoretical soft costs that are not generated directly by roadwork activities, they must be used with caution.

### ***How can deteriorated PCC pavements be rehabilitated?***

Nearly all PCC pavements in Missouri that have deteriorated to terminal levels have been overlaid with asphalt concrete. Since a significant portion of NHS and remaining arterials are AC/PCC pavements, another section of this document is dedicated to discussing their performance. The remainder of the section will discuss other rehabilitation and restoration strategies.

## **Bonded PCC Overlays**

Bonded PCC overlays are typically 3- 5 inches thick. They have to be applied before slab deterioration sets in, although some surface scaling is allowed, because they're supposed to act monolithically with the older concrete by completely attaching itself to it. Joints have to be sawed in very close approximation to existing joints and working cracks. If properly constructed the slab inherits a much greater structural capacity. Without an adequate bond the thin overlay delaminates and quickly begins to fracture and breakup from repeated heavy loadings.

### *Missouri's experience*

Missouri constructed two of these in the early 1990s, one on I-70 in Cooper County and the other on U.S. 67 in Jefferson County. The results have been mixed.

The I-70 project has performed poorly despite its greater-than-traditional-design thickness (5-11.5 inches), although the majority of this may be attributed to the poor consistency of the mix. The high early strength cement in the concrete caused flash setting, even while the concrete was still in the mixing drum. Raw non-hydrated mix and sand lenses were discovered in cores of the hardened concrete. The resulting distresses were uncontrolled transverse and longitudinal cracking, map cracking, and debonding.

The U.S. 67 project contained test sections with bonded overlay thickness ranging from 3-5 inches. There were problems with debonding and excessive transverse and longitudinal cracking on some sections, which appeared to be related to the type of surface preparation. Other portions of the pavement are doing well.



Bonded concrete overlay on NB US 67 in Jefferson County

### *Other states' experience*

Although this method has been around for a while, not many states use it. Iowa has probably built more than anyone else. They have found that, if designed with adequate thickness (at least 4 inches) and constructed properly (locate saw cuts over existing joints), a bonded overlay is a viable alternative to an AC overlay. A nationwide study<sup>8</sup> revealed that bonded overlay performances have been mixed. The usual reason for early distress was the deteriorated condition of the underlying slab causing either debonding or reflective cracking.

### **Unbonded Concrete Overlays**

Unbonded concrete overlays (UBOL) are intentionally separated from the existing PCC pavement by a bond breaker, usually an inch of AC. They become the primary structural layer while the older PCC becomes a stiff base layer. The unbonded overlay may be a JPCP, CRCP, or JRCP design. Their primary advantage over AC overlays is the ability to resist reflective cracking more effectively. UBOLs are not as sensitive to the existing pavement condition as AC overlays and do not require the same level of pre-overlay repair.

There has been some debate over the type and thickness of bond breaker used. ACPA recommends 1-inch, dense-graded AC mix. Most states, including Missouri, have used this design. Illinois and Colorado have preferred thicker designs. The advantages are reduced reflective stresses reaching the unbonded overlay, smoother construction platform (particularly on severely distressed pavements), and perhaps less susceptibility to stripping.

Scheduled properly in a long-range plan, a distressed PCC pavement could be overlaid with AC for an interim period and then partially milled and overlaid with concrete before it becomes too distressed. This eliminates the need to place a bond-breaker layer concrete overlay at the same time.

### *Missouri's experience*

Unbonded PCC/PCC overlays have been built in Missouri since the 1930s on an infrequent basis. Although a dozen or more projects were built before 1990 on the state system, they had all long since been either replaced or overlaid with AC. The designs varied and there was never any attempt to standardize the method. They were usually short sections. Some older ones used gravel for the bond breaker interlayer. A few others were meant to be bonded overlays, but recent coring at two of the sites revealed that the surface preparation was inadequate for bonding. There are five existing conventional UBOLs in Missouri with a couple of others under current construction.

The first is on the southbound lanes of I-55 in Pemiscot County. Over five miles of 9-inch JRCP was placed in 1986 on an AC/PCC pavement. The AC overlay was milled to

varying depths depending on the required elevation. In some locations the remaining AC was 8 inches thick, while in others the old PCC was almost exposed. A recent survey verified the overlay condition was excellent. Transverse cracks are tight and often barely visible.

The second is an 11-inch overlay constructed in 1992 on eastbound I-70 in Callaway County (shown in the photo on the next page). The overlay panels in the through lanes had 61.5-foot joint spacing, while the shoulders were sawed every 30 feet. Most of the project had a 1-inch bond breaker, while the remaining portions required up to 3 inches for leveling purposes. Transverse cracking often emanated from scoring of edges caused by shoulder saw joint overrun. Reflective cracking stresses from the old transverse joints might also have contributed to this. The thicker bond breaker sections yielded a little less cracking. Despite the transverse cracking, which would not be unexpected for long joints in any situation, the overall performance of the project has been good.

The third is the fiber-reinforced overlay with a 1-inch AC bond breaker placed on I-29 in Atchison County in 1998. Eight 2500-foot test sections were constructed. The design variables were fiber reinforcement, thickness and joint spacing. The types of fibers used were steel and polyolefin. The thicknesses were 5-inch (steel and polyolefin), 6-inch (steel and polyolefin), 9-inch (steel, polyolefin and no fibers), and 11-inch (no fibers). The fiber test sections had groups of 15-, 30-, 60- and 200-foot joint spacing, while the two plain test sections only had 15-foot joint spacing. The 5-inch overlays, which were designed to push the limits of minimum structural thickness, have had extensive transverse cracking near the joints, generally lining up with the ends of the dowel bars. Recently, the District One office reconstructed these sections with JPCP. The positive findings from this study have been the reduced transverse cracking of the panels. The thicker sections are cracking at an average between 30-feet' and 60'-feet. This seems to indicate that the fibers are minimizing transverse cracking as they were intended to do. Even the 5-inch reinforced panels showed reduction in transverse panel cracking, if the cracks around the dowel bars were eliminated from consideration.

The fourth is an 11-inch UBOL on I-55 in south St. Louis County. Over two miles of three lanes in the southbound direction and over a mile of three lanes in the northbound direction were paved in 1995. This project remains in excellent condition.

The fifth is the diamond ground 8-inch JPCP, mentioned earlier, with a 1-inch bond breaker on I-44 in Greene County east of Springfield.



Unbonded PCC on I-70 in Callaway County

### *Other states' Experience*

Other states have had enough positive experience with unbonded overlays to designate them as their preferred method of heavy-duty rehabilitation for PCCPs.

Illinois has built 9-12-inch CRCP overlays. They determine the thickness by deducting one inch (structural credit for the existing PCC) from whatever their full-depth CRCP would be for a particular route. The AC bond breaker is 3 inches thick and is usually the existing AC overlay on the old PCC. Their performance has been very good.

Colorado follows a similar pattern to Illinois. Their AC bond breaker is also the old wearing course (~3 inches). They purposely plan to get several years of service out of the AC overlay before it is overlaid with JPCP.

Ohio has constructed 16 UBOLs since 1982. They designed theirs as doweled JRCP with 60-foot joint spacing or undoweled JRCP with 15-foot joint spacing. The bond breaker is 1-inch AC. A couple of the older projects exhibited distresses that they believe were related to the quality of the concrete and the longer joint spacing. Other than these exceptions the Ohio DOT is very pleased with the performance of its unbonded overlays.

Pennsylvania built a substantially long (20 miles) UBOL project on I-80 in 1985. The overlay was 13 inches thick with a 2-inch, paraffin-coated AC bond breaker. Fifteen years later the pavement is structurally perfect.

Iowa built a 5-inch UBOL on I-35 in 1985. It is performing very well. Indiana built a 12-inch UBOL on I-65 in 1994 to compare side-by-side with an AC overlay on crack-and-seat PCC and an AC overlay on break-and-seat PCC. So far, the UBOL is performing well with a slight edge over the others.

A national study<sup>9</sup> concluded, based on an analysis of many in-service pavements around the country, that JPCP unbonded overlays performed best when sufficiently thick ( $\geq 8$  inches), placed on a thick AC interlayer ( $\geq 1$  inch), doweled, and short joint-spaced ( $\sim 15$  feet). The study verified that properly designed and constructed unbonded overlays should provide good performance for 20 years or more.

### **Rubblize / Break and Seat**

Rubblization is the disintegration of an existing PCC pavement. Rubblized pavements are overlaid with either AC or PCC. The process reduces whole slabs to 3-inch to 12-inch chunks. It should not, however, upset the interlocking matrix of pieces. This way the rubblized layer is expected to have about three times the stiffness value of a standard crushed stone base. Care must be taken not to overturn and press large chunks into the subgrade. The rubblized layer then essentially becomes a very stiff granular base layer. The whole point of rubblizing is to eliminate reflecting cracking through the AC overlay.

Breaking and seating a pavement is less destructive than rubblization. This method uses a guillotine-type hammer that is dropped at intermittent points along a concrete surface. After the slab is cracked, a roller goes over it to seat it into the underlying layer, thus eliminating future movement. Once the pavement is completely seated the threat of reflective cracking through the AC overlay is supposedly removed.

#### *Missouri's experience*

Missouri has only four short ( $\sim 500'$ ) rubblized sections, located on I-35 in Harrison County. These were constructed as part of an LTPP SPS-6 site. They consisted of a pair of 7-inch and a pair of 11-inch AC overlays with one 7-inch and one 11-inch section having longitudinal edge drains installed. All the sections have some longitudinal cracking outside of the wheel paths. Some fatigue cracking has developed in the wheel paths of the sections without edge drains. The performance after eight years has been acceptable.

Missouri also had four break-and-seat sections constructed at the same LTPP site. They consisted of a pair of 4-inch and 8-inch AC overlays with one 7-inch and one 11-inch section having longitudinal edge drains installed. All the sections have some longitudinal cracking outside of the wheel paths. Although no fatigue cracking has occurred in the

wheel paths, reflective cracking is showing through. The performance after eight years has been acceptable.

Overall, Missouri has had little experience with rubblization and break-and-seat to draw any final conclusions. Other states have investigated the techniques more fully.

#### *Other states' experience*

The consensus among most other states is that rubblization is more effective than the break-and-seat method<sup>10</sup>. The trouble with the break-and-seat method is that it is extremely difficult to verify that the slabs are properly seated, therefore there is no guarantee that reflective cracking will not develop. A national study<sup>11</sup> of break-and-seat projects revealed that the method merely delayed reflective cracking for 3-5 years. Because of this, the following discussion on state experiences is limited to rubblization.

Michigan has been the national leader for rubblizing pavements. Since 1986 it has built nearly 60 projects. Each project was designed for a 20-year life, however, various early failures have dropped the average life span to fourteen years before rehabilitation was necessary. Researchers at Michigan State University extensively analyzed these projects to determine the common denominators for consistent performance<sup>12</sup>. Their findings revealed that, among other things, visible rubblized pieces over 6 inches must be manually reduced in size, rubblized surface texture must be relatively smooth, exposed steel must be cut, asphalt patches should be removed prior to rubblization, second passes with rubblizers must be avoided, and traffic should not be allowed on the rubblized surface.

Arkansas is in the midst of rubblizing over 200 miles of Interstate that require major rehabilitation. They have even been willing to mill off existing AC overlays before rubblizing the old PCCP. Under their projected traffic loadings Arkansas pavement design engineers believe they will get up to 30 years of acceptable service life from a 13-inch AC overlay on rubblized pavement, with the application of one or two new wearing courses.

Illinois has also carefully studied rubblized pavements<sup>13</sup>. They have constructed ten projects since 1990. Their findings generated a specification chart for selecting the method of rubblization. They also determined a minimum CBR of 5 was required to even attempt rubblization. In general, they concluded that if a long life at a high level of serviceability is desired, reconstruction should be considered, but if a moderately long life at a good level of serviceability is desired, rubblizing with an AC overlay is an excellent option.

Nevada built four rubblized projects in the late 1990s. They expect to get 15 years of service life before replacing the wearing courses.

At least a dozen other states have had experience with rubblization. Most have been satisfied with the results during the limited period of implementation. The only negative

comments have come from states that either underdesigned the overlay thickness or performed the rubblization on a very weak subgrade.

States word their rubblization specifications to allow use of either the multiple head breaker (shown at left below) or the resonant breaker (shown at right below), although pavement engineers in each state may have their own preferences for one or the other.



Multiple-head breaker (left) and Resonant breaker (right)

PCC can also be used to overlay a rubblized pavement. Pennsylvania has practiced putting PCC overlays on rubblized pavement on many miles of I-80, which is a heavily traveled truck route. The results have pleased them and they expect to continue the technique. Of course, a question arises whether placing a PCC overlay on a rubblized layer is very efficient if the primary purpose of rubblization is to stop reflective cracking through AC overlays.

### ***Are there alternatives to adding thickness?***

PCC pavements that are still sound except for some faulting or localized spalling or edge cracking may be restored to an acceptable service level without having to add more structural capacity.

### **Full-depth repairs**

Full-depth repairs are typically necessary for badly deteriorated joints and cracks. The slabs are usually doweled into the existing pavement on either side. The base is also replaced if required. D-cracked pavements must have enough length removed from either side of the joint or crack in order to dowel into sound pavement.

### ***Missouri's experience***

Missouri maintenance forces have performed countless full-depth repairs. Full-depth repairs are usually included in AC overlay contracts. Full-depth repair techniques have

been studied in past Missouri research efforts, but no known estimate of extended pavement service life was ever developed. The photo below shows typical full-depth repairs.



Full-depth repairs

#### *Other states' experience*

Most other states also perform full-depth repairs, but no performance studies were available.

#### **Diamond grinding**

Diamond grinding restores ride on faulted PCCPs. This treatment should not be used on pavements with badly deteriorated joints or cracks. Also, it cannot be used alone if there is inadequate load transfer at joints or cracks.

#### *Missouri's experience*

Three pavements were diamond ground and studied for performance<sup>14</sup>.

Route 171, north of Joplin, which had developed  $\frac{3}{4}$ -inch average faulting, was diamond ground in 1986. Fourteen years later hardly any faulting had returned.

The Long Term Pavement Performance (LTPP) site on I-35 in Harrison County had two diamond ground test sections. The pavement was 18 years old at the time of the restoration. It had some d-cracking at most joints. Faulting was moderate at around  $\frac{1}{4}$ -inch. Performance after diamond grinding was adequate for about four years before full-depth repairs were required.

Ten miles of I-44 west of Springfield in Greene County were diamond ground in 1996. The pavement was badly faulted and had an extremely poor base and subgrade. Significant pumping and slab cracking was evident throughout the project. Faulting returned within a year.

Based on these results it was recommended that diamond grinding in Missouri be limited to pavements with adequate load transfer and support and maximum average faulting around one-half inch. Expected service lives should be five to ten years depending on the type and condition of the pavement.



Diamond grinding on I-44 in Greene County

### *Other states' experience*

A 1999 ERES Consultants study<sup>15</sup> examined the status of 76 diamond grinding projects, spread throughout the country, that were originally part of a 1989 CPR survey. Based on its survival analysis, the study concluded that a state agency can expect, with a high degree of reliability (>90 percent), a minimum life of 8 to 10 years for diamond-ground surfaces.

### **Undersealing**

Undersealing fills in voids and restores support under slabs. This treatment is often used in conjunction with diamond grinding. Undersealing is often used as a contract item prior to an AC overlay. Originally, hot asphalt was the undersealing material of choice. In the 1980s a gradual shift to grout slurry occurred, because of earlier uneven slab jacking and safety concerns with asphalt.

The slurry is injected into a couple of drilled holes on either side of a joint or crack. The joint or crack may or may not be faulted. Load transfer tests are conducted before undersealing to identify voided areas. Care must be taken not to create excessive pressures that crack the slab.

Recently a new proprietary method of undersealing with polyurethane has shown promise. It appears to eliminate some of the problems experienced with grout slurries.

### *Missouri's experience*

Missouri has had extensive experience undersealing, both by maintenance forces and contractors. In fact, Missouri may be one of the few remaining states that uses it routinely. The performance of undersealed slabs has never really been monitored in Missouri, often because they are about to be covered with an AC overlay.



Polyurethane undersealing

### *Other states' experience*

Undersealing was severely curtailed by an FHWA moratorium in the mid-1980s. The FHWA had been alarmed by the frequency of cracked slabs and general worsening of undersealed pavements caused by poor technique. Some states never returned to the treatment because of the skill required and the uncertainty of success. Others, like Wisconsin, decided it was more prudent to wait for PCC slabs to deteriorate to the point where they required full-depth repairs. Nationwide, it has become a dying art.

### **Dowel bar retrofit**

Dowel bar retrofitting restores load transfer across joints and working cracks. The procedure involves sawing out a slot with just enough room to place a dowel bar at adequate depth and backfilling with grout material. It can be performed in joints where there are existing dowel bars, but has usually been done in PCCPs where there never were any.

### *Missouri's experience*

Missouri has placed dowel bars in nearly every jointed pavement it has built, so restoring load transfer in this manner never became an issue. Therefore, we have no experience. However, it may solve load transfer problems at working cracks on our older JRCs, where no dowel bars exist. A couple projects in the Kansas City area were recently let with this in mind. One project will include nearly 10,000 dowel bar retrofits at working cracks.

### *Other states' experience*

The States that have used this technique extensively are the ones with many miles non-doweled jointed pavement. Washington State is a leader in this field. They have been very satisfied with the performance.

### **Edge drain retrofit**

Most pavements built prior to the 1980s had no provision for removing water. Many had 'permeable' granular bases, but no outlet drains to transport water to ditches. Instead, water often became trapped in a bathtub-like basin under the concrete, which led to pumping, loss of support and slab cracking.

In the 1980s AASHTO and the FHWA made a concerted effort to establish design guidelines for installation of longitudinal edge drains and encouraged their use in new pavements. In the early 1990s this effort was expanded to retrofitting existing pavements.

### *Missouri's experience*

Missouri has retrofit longitudinal edge drains on a few projects including several test sections at the LTPP site in Harrison County. It has been difficult to tell if they have had any real impact. Although there is water coming out of the retrofit outlets, it appears to be collecting only local moisture close to the pipes.



Geocomposite edge drain retrofitting

### *Other states' experience*

The FHWA conducted a study<sup>16</sup> of 114 pavements around the country that were diamond ground and retrofit with edge drains. After five years, faulting on doweled JRCs was about 30 percent less for those with edge drains. After 11 years there was no difference, indicating, perhaps, that the drains had clogged.

Arkansas designs its edge drains to work independently of one another. Each 300 feet or so run of longitudinal pipe has its own lateral outlet pipes. The design greatly facilitates flushing out the pipes during maintenance on a periodic basis. Their elbow connections also provide easy access for camera inspections of pipe condition for construction acceptance.

### ***How long will our “new-design” PCC pavements last?***

Any new pavement constructed on high volume routes in Missouri must last a long time with a minimum of lane-closing maintenance and rehabilitation work. Missouri currently designs new pavements for a 35-year life. Data from our new pavement design and other state design policies strongly suggest that we can extend our anticipated performance lives with PCCP.

The following table compares the features of long-term, heavy-duty pavement designs from seven states with Missouri's heavy-duty JPCP design. Missouri's PCCP thicknesses exceed or equal any other state. Our assumption for cumulative rigid ESALs is in the same ballpark as the other states. Missouri's 15-foot joint spacing with a driving lane paved 2 feet over the edge line tied to the shoulder is at least as conservative as any other state with JPCP. Our daylighted two-foot rock base is nearly identical to Minnesota's. Meanwhile, our alternate 4-inch treated permeable base over a 4-inch Type 5 subbase is very similar to Utah and Washington and similar to, although less conservative than, Delaware, New York and Wisconsin. Expectations of other states for

future rehabilitation and maintenance during the pavement design life seldom exceed Missouri's.

In addition to the physical descriptions of layers and dimensions some states also include more stringent material specifications for concrete. Illinois, for instance, has a freeze-thaw expansion limit on coarse aggregate. Minnesota allows a maximum rapid chloride permeability limit of 2500 coulombs. A few states limit the amount of carbonate coarse aggregate. Also, some have experimented with aggregate optimization, similar to the Shilstone design method, for stronger economical mixes.

Therefore, based on the information from other states and the performance trends that we are currently getting from the new JPCP design, it is very reasonable to extend the design life of PCCP in the pavement-type selection process from 35 to 40 years or more. This design life assumption is contingent upon the fulfillment of required material and construction specifications.

<i>State</i>	<i>Delaware</i>	<i>Illinois</i>	<i>Minnesota</i>	<i>New York</i>	<i>Utah</i>	<i>Washington</i>	<i>Wisconsin</i>	<b>Missouri</b>
<b>Design Life</b>	40	40	60+	50	40+	40	50	35
<b>Cumulative Rigid ESALs (millions)</b>	NA	~ 300	100	400	NA	200	200	200
<b>PCC Type</b>	JPCP	CRCP	JPCP	JPCP	JPCP	JPCP	JPCP	JPCP
<b>PCC Thickness</b>	12"	14"	13.5"	13"	12"	13"	13.5"	14"
<b>Joint Spacing</b>	20'	-----	15'	18'	20'	15'	18'	15'
<b>Dowel Bar Type</b>	1 ½" epoxy coated	-----	1 ½" stainless steel clad	1 ½" epoxy coated	1 ¼" epoxy coated	1 ½" epoxy coated	1 ½" epoxy coated	1 ½" epoxy coated
<b>% Steel</b>	-----	0.7	-----	-----	-----	-----	-----	-----
<b>Paved Driving Lane Width</b>	14'	12'	12'	14'	12'	14'	14'	14'
<b>Tied Shoulders</b>	No (AC sh.)	Yes	Yes	Yes	Yes	Yes	Yes	Yes
<b>Base Type</b>	4" ATB w/ edge drains	6" HMAC	2' daylighted clean granular material (< 10% fines)	4" ATB or CTB w/ edge drains	4" LCB or ACB w/ edge drains	4" HMAC w/ geotextile	4" unbound open-graded granular	2' daylighted rock fill or 4" treated perm. w/ edge drains
<b>Subbase Type</b>	6" pugged soil cement	12" crushed stone w/ edge drains	-----	12" granular	6" granular	3-6" granular	6" crushed stone /	4" Type (only with treated perm. base)
<b>Subgrade Modification</b>	some select material replacement	12+" lime modification	-----	-----	-----	-----	18" breaker run	None
<b>Expected Rehab &amp; Maintenance</b>	NA	NA	Diamond grinding @ 25 years	NA	Joint sealing & diamond grinding	Diamond grinding @ 25 years	-----	Diamond grinding @ 25 years

## AC/PCC Pavements

Very few pavements in Missouri were originally designed as composites with asphalt over concrete. AC/PCC pavements have become a predominant pavement type on high-volume roads, however, through the steady and widespread rehabilitation of aging PCCPs. The unique characteristics of these composites merit a separate analysis.

### *What makes our AC/PCC pavements deteriorate?*

AC overlays were put on many old PCC pavements to add structural capacity, provide smoothness and mitigate distresses. These overlays were prone to several distress mechanisms: rutting, raveling, reflective cracking and block cracking.

Rutting in the wheel paths had several causes. Asphalt that was poorly compacted during construction rutted from future densification under truckloads. Truckloads on overcompacted AC at high surface temperatures induced plastic flow and rutting. Also, mixes with high natural sand contents resulted in rutting.

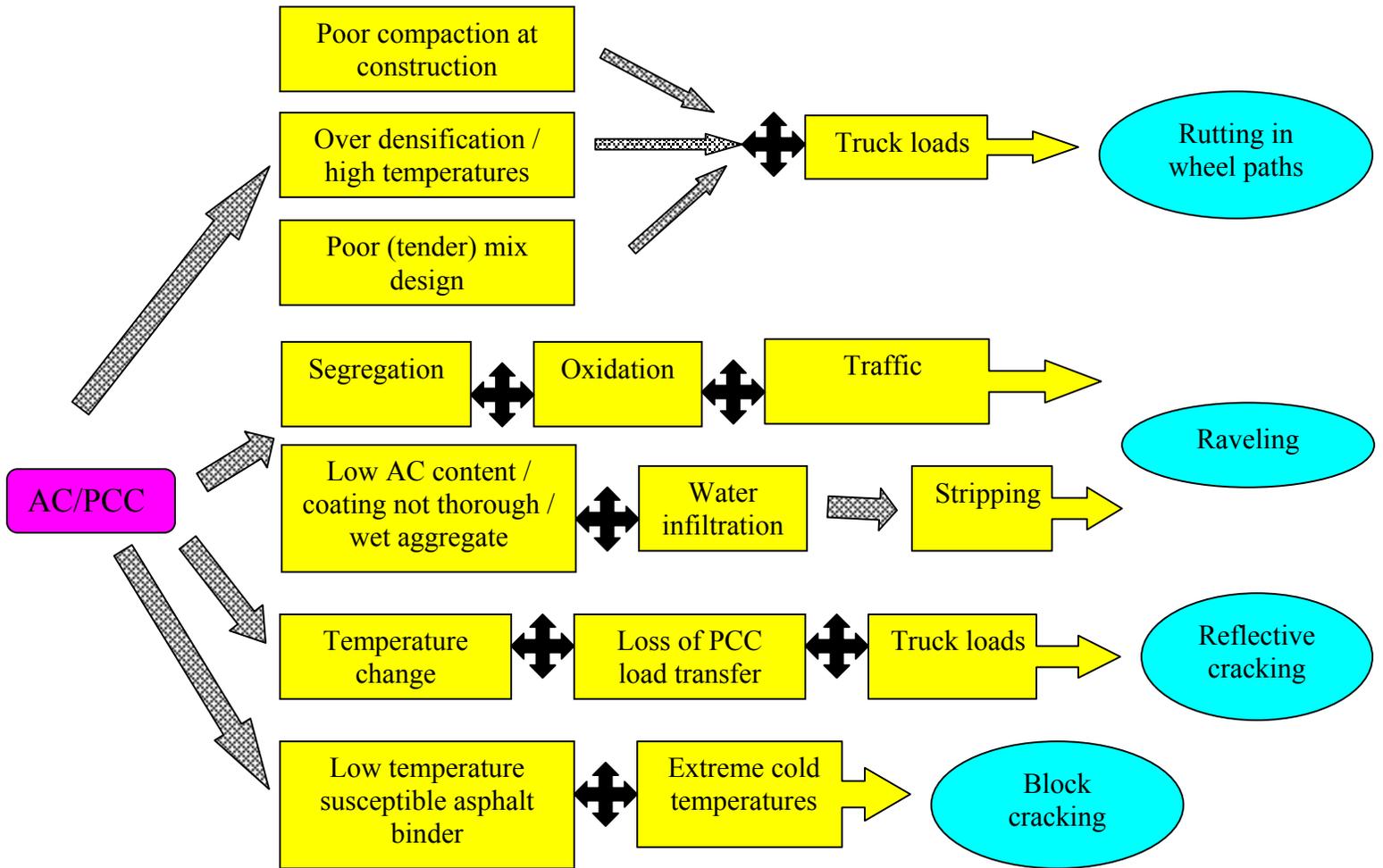
Raveling usually begins in areas that originally had segregation. These areas have less asphalt and are susceptible to the effects of oxidation. The combined brittleness of the oil and shear stresses induced by passing vehicles cause the mix to disintegrate on the surface. It also occurs at longitudinal joints where it is more difficult to get densification. Raveling can be exacerbated by stripping, where aggregate, either not thoroughly coated during mixing or not adequately heated to evaporate excess moisture, debonds from the oil. Left unattended, raveling will eventually develop into large pockets or potholes.

Reflective cracking is theorized to be a product of horizontal and vertical movement in the underlying PCC pavement. It starts when temperature-induced horizontal movement in the PCC slabs cause tensile strains that rupture the AC layer. Left alone the horizontal movement will eventually lead to cracking on the surface, however, the vertical strains induced by a combination of poor load transfer and repeated truck loads cause the rupture to propagate much more quickly. Reflective cracking requires frequent sealing by maintenance crews. If reflective cracks are not attended to they lead to worse distresses such as raveling and even potholes.

Block cracking is an environmental distress, caused by low temperatures that exceed the limit of cold weather ductility for the asphalt binder. It can occur suddenly during a single frigid night. Block cracking should be controlled through cold weather temperature grading for Superpave asphalt binders. It is not nearly as common in AC/PCC pavements as it is in full-depth AC pavements.

Rutting has been reigned in during recent years with the advent of stone matrix asphalt (SMA) wearing courses and Superpave mix design. Reflective cracking, however, still occurs regardless of AC overlay type.

Raveling is yet present because it is usually a product of segregation and poor compaction at longitudinal joints. Segregation is a construction problem that has been tempered somewhat, by practices such as the use of a material transfer device, but has yet to be fully mastered. Longitudinal joint compaction should improve with recently enacted specification requirements.



The analysis discussed in this report examined the effects of multiple overlays, overlay thickness and traffic levels on AC overlay performance.

*How long do our AC/PCC pavements last?*

Fortunately, we have an extensive inventory of AC overlays performance data, since that is our primary rehabilitation method. ARAN data from 1995-2000 was analyzed to determine agreement between the actual performance and the expected performance on which our design is based. Divided NHS routes were selected for analysis for the same reasons as with the PCC analysis.

### **Data Sources**

ARAN data was retrieved from the master inventory table in the pavement management system (PMS) database. Historical information for thickness of original pavement, number and thickness of overlays, base type and thickness and year constructed was retrieved from tables in the Transportation Management System (TMS) database. Performance and historical tables are currently not linked, therefore, NHS route data was manually linked in a spreadsheet for this study.

### **Study Variables**

Variables considered in the analysis were overlay thickness, overlay number, and AADT level. Other variables such as type and thickness of original PCCP, base and subgrade type, ESALs, and existence of d-cracking were not introduced for different reasons.

Original PCCP pavements varied from 7- 9 inches. Structurally speaking, their advanced age and distressed conditions probably blurred what little impact the difference in thickness would have under multiple AC layers. Similarly, the effect of reinforced versus unreinforced PCC was muted.

Subgrade soils and fill material were usually fine-grained and poorly draining. Type 3 base material was used almost exclusively under PCCPs up until the early 1990s. Its dense-graded rock with up to 35 percent fines rendered it impermeable. In short, nearly all of the old pavements had drainage problems.

ESAL measurements would have been very desirable for this analysis, but insufficient information exists for accurate estimates of truck percentages and ESAL/truck ratios.

As previously stated, d-cracking information is available, but not in convenient format for the large number of pavements in the analysis.

### **Data Accumulation**

As with the PCC analysis, annual performance measurement of each directional pavement section was included in the AC/PCC analysis. For each analysis category the performance data was averaged for each year of age. Each average was weighted for the length of pavement section. At the time of analysis only 1995 through 1998 ARAN data was available, therefore up to four years of data were used for each pavement section.

## **Analysis Groupings**

The three primary groupings of analysis for ACOLs were numbers of overlays, thickness and AADTs.

The number of overlays included the first three, which comprise the vast majority of existing overlays.

The thickness ranges were 1- 2 inches, >2 inches - <4 inches, and >=4 inches. They were split this way to provide a somewhat equitable distribution of mileage.

AADTs were split into primary ranges of <10,000, 10,000 – 20,000, and >20,000, also for equitable distribution.

## **Specialized ACOLs**

Stone matrix asphalt (SMA) and Superpave overlays were also evaluated. Year 1999 and 2000 data was collected for individual projects. SMAs were first constructed in Missouri in 1992, therefore they could only provide enough data for an eight-year trend.

Superpave overlays had even less history, since they were first constructed in 1996, and provided only five years worth of data for a handful of projects.

## **Performance Period**

The standard performance period used in this analysis was fifteen years.

## **Performance Indices**

The performance indices calculated for each year in the analysis were ride, cracking, PSR, rutting, condition and international roughness index (IRI). Trend graphs for these indices were created. Condition scores are a combination of cracking, rutting, patching and raveling. The cracking index is doubled in the condition score, while patching and raveling are both halved. PSR is an equal combination of ride and condition.

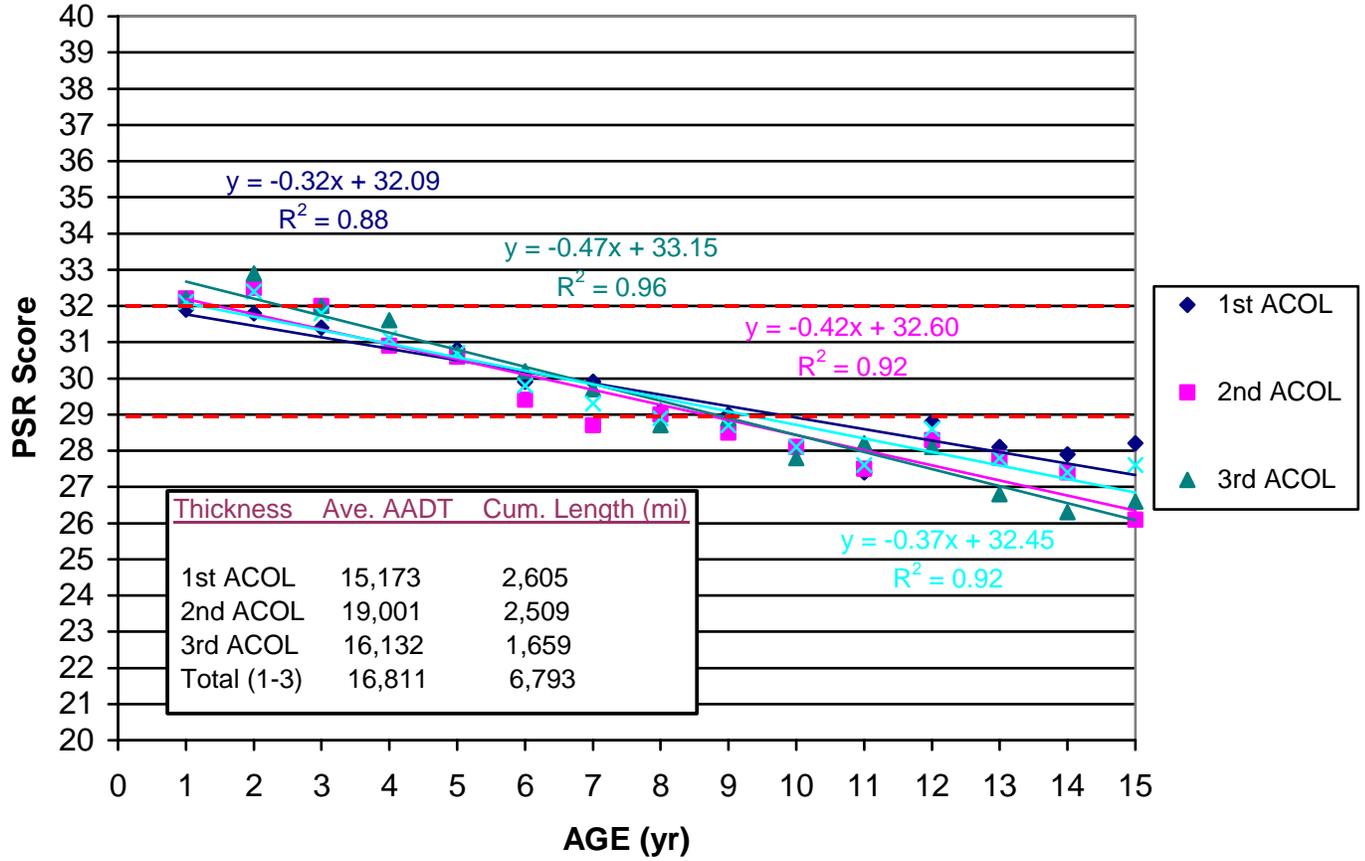
Average AADTs, weighted by section length, were computed for each set of ACOLs.

## **Findings**

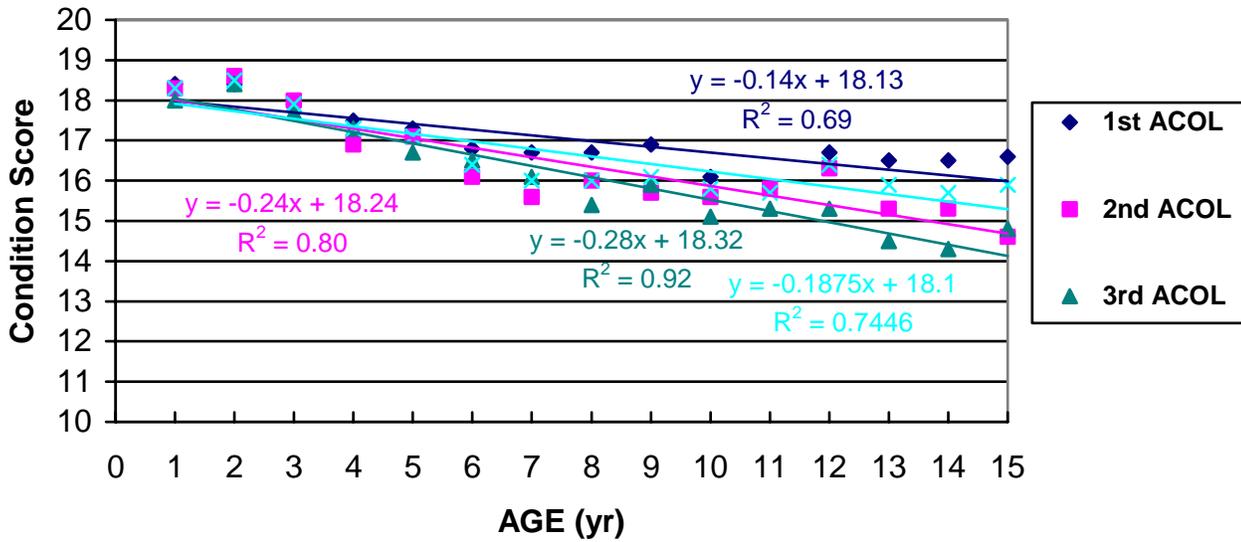
### *AC overlays split by number of overlay*

Deterioration for each ACOL by number follows a linear regression fairly well. Average PSRs reach an unacceptable level between nine and ten years. The only significant difference in performance between overlays occurs in later years when the first, second, and third ACOLs diverge in order of number. This divergence is reflected even more so in the condition graph, while nearly nonexistent in the ride graph.

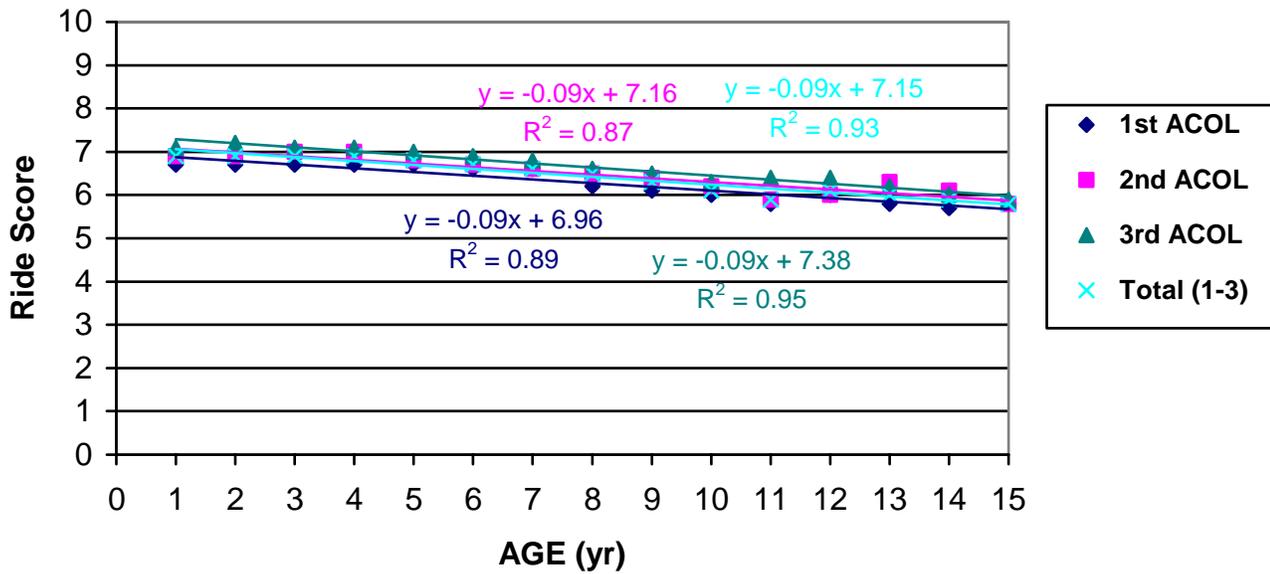
## PSR for ACOL by Number on Divided NHS 1995-1998 ARAN Data



## Condition for ACOL by Number on Divided NHS



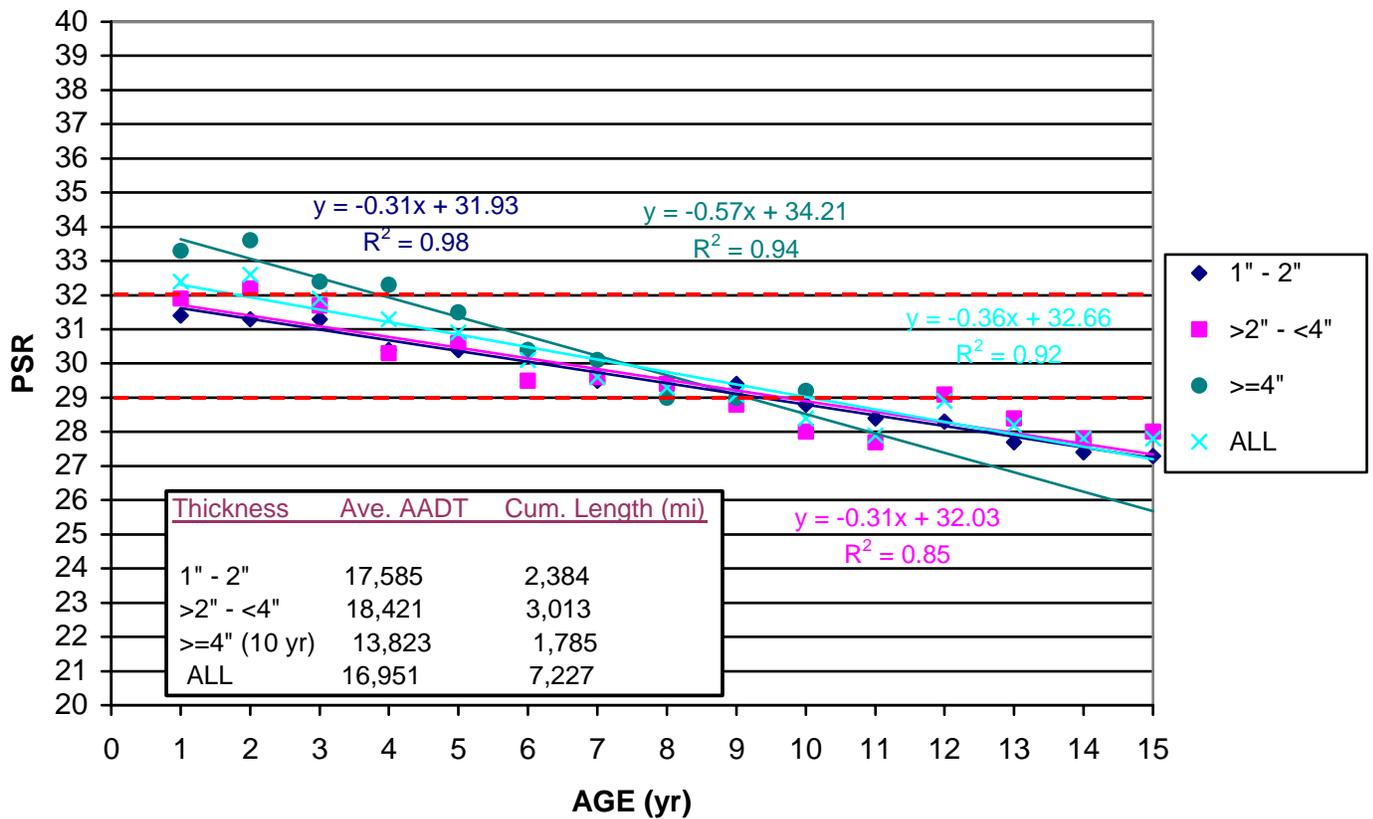
## Ride for ACOL by Number on Divided NHS



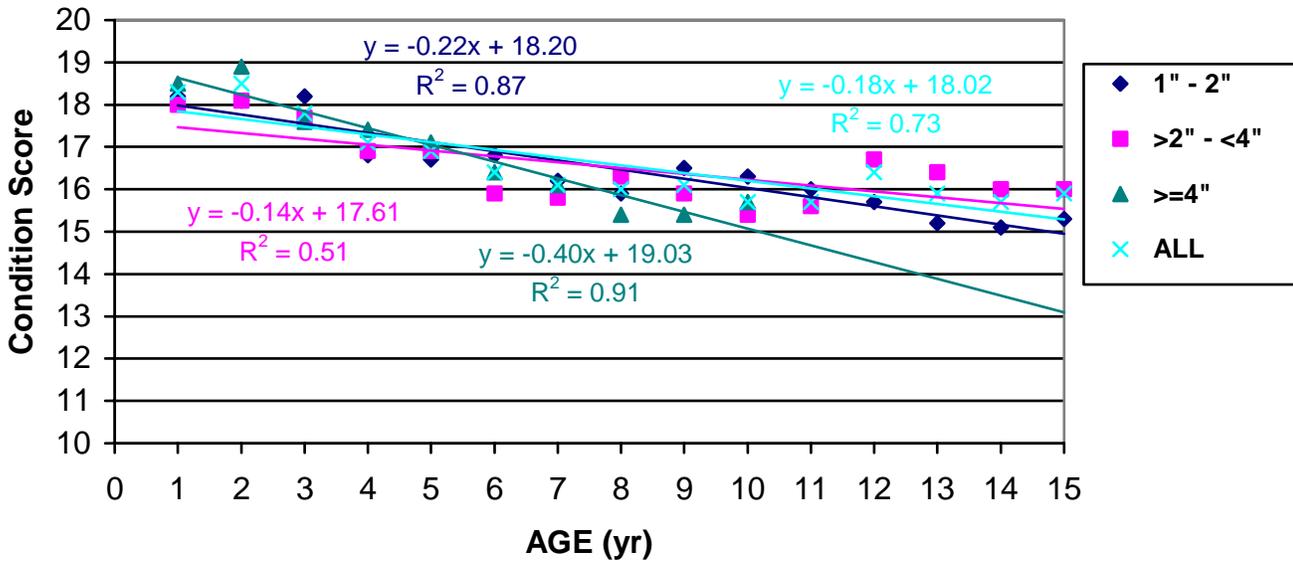
AC overlays split by thickness

Deterioration for each ACOL by thickness follows a linear regression fairly well, although the condition trend for the >2” – <4” range is more erratic. Overlays >= 4” did not have enough mileage beyond ten years to be statistically meaningful and so what data they had were excluded in the analysis (the extension of the >=4” trendlines after 10 years are a spreadsheet limitation and should be ignored). Average PSRs reach an unacceptable level between nine and ten years. Thicker overlays outperform the thinner ones during the first five years, converge with them during years six through eleven.

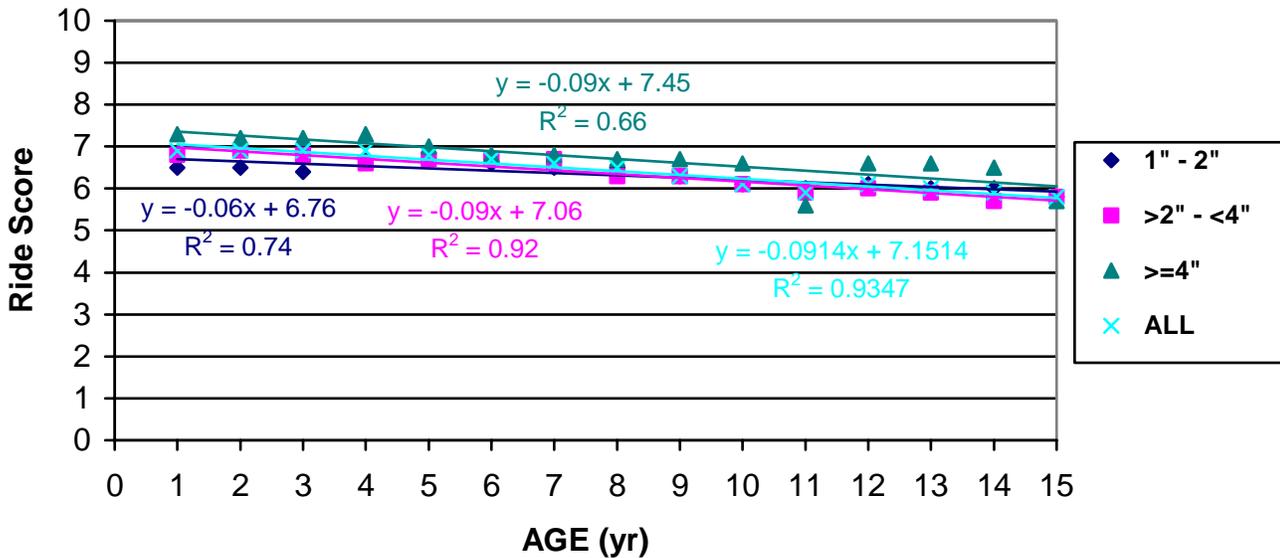
**PSR for All ACOL by Thickness on Divided NHS**  
**1995-1998 ARAN Data**



## Condition for ACOL by Thickness on Divided NHS



## Ride for ACOL by Thickness on Divided NHS

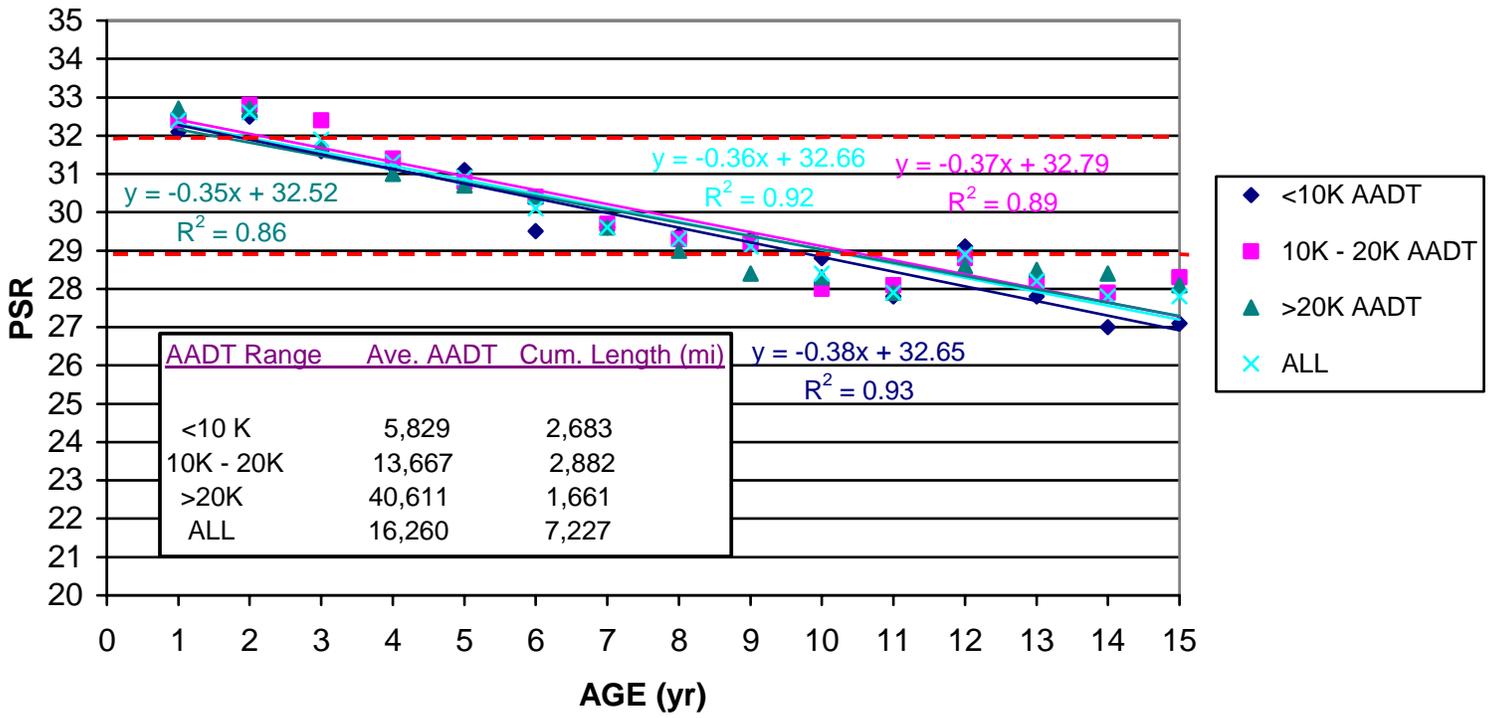


*AC overlays split by AADT range*

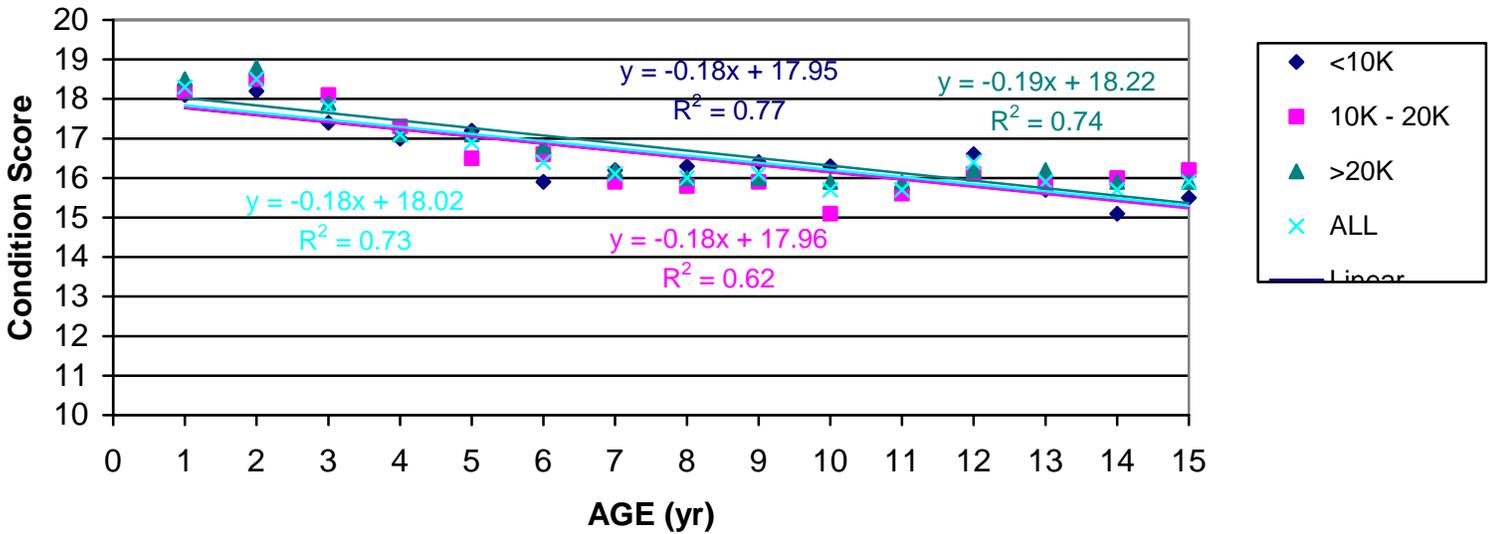
Deterioration for each ACOL by AADT follows a linear regression fairly well. Average PSRs reach an unacceptable level at about ten years. Condition trends for every range are somewhat erratic, owing perhaps to maintenance activities in later years, but ride trends

are more stable. The three AADT ranges do not exhibit any significant differences with each other, outside of the low AADT overlays performing more poorly than the higher volume ones in years fourteen and fifteen.

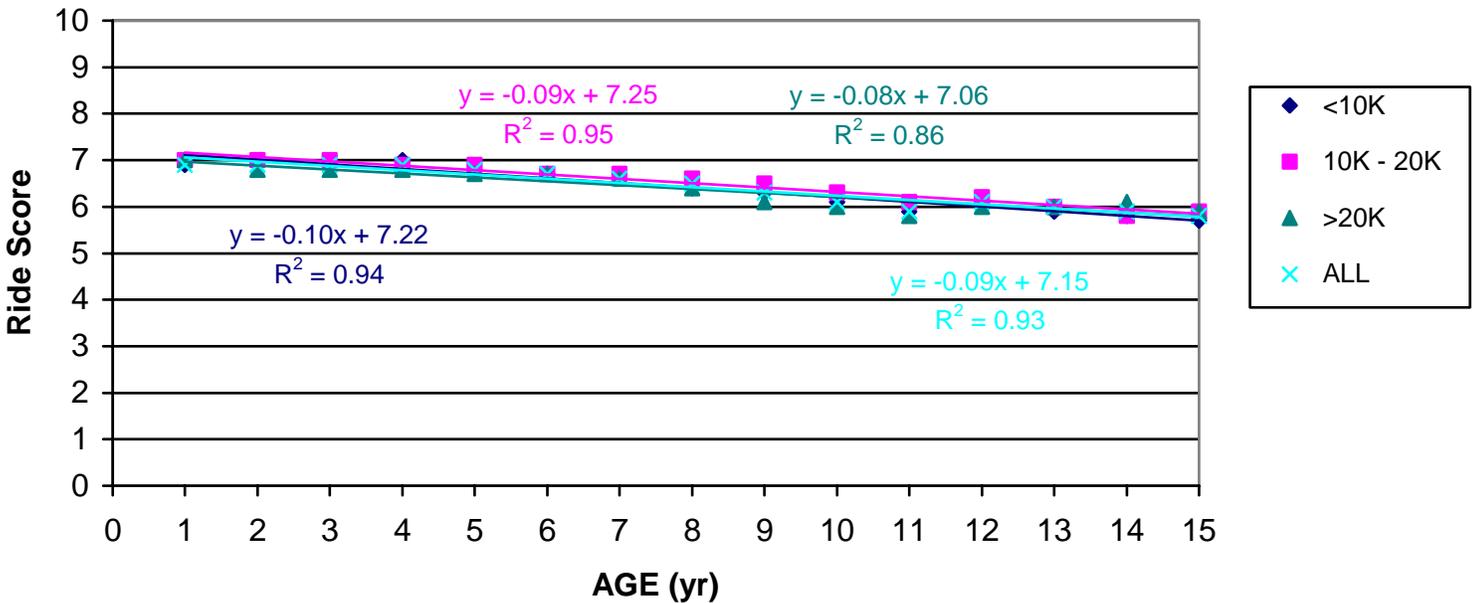
### PSR for ACOL by AADT on Divided NHS 1995-1998 ARAN Data



## Condition for ACOL by AADT on Divided NHS



## Ride for ACOL by AADT on Divided NHS



*AC Overlays in general*

The average service life that ACOLs on divided NHS routes, regardless of number, thickness, or AADT, remain at least marginal ( $PSR \geq 29$ ) is approximately ten years.

Initial overlays sustain better performance for a longer period than later overlays. Thicker ACOLs have not provided significantly longer service lives than thinner ones, although more data for ACOLs  $\geq 4''$  older than ten years is required to make a stronger case. No clear relationship between AADT level and performance is evident.



**PAST AVERAGE  
PERFORMANCE LIFE**  
(at least marginal) FOR  
AC/PCC OVERLAYS ON NHS  
= **10 YEARS**

***How long do other States' AC overlays last?***

A telephone survey was conducted of surrounding states regarding their AC/PCC overlay performance lives on heavy-duty type routes.

STATE	AC Overlay Performance Life (yr)
Arkansas	8 – 12
Colorado	7 – 10
Illinois	10.6 (1 <sup>st</sup> ), 8 – 9 (2 <sup>nd</sup> ), 6 (3 <sup>rd</sup> )
Indiana	10
Kansas	10
Minnesota	8 - 10
Ohio	12
Pennsylvania	10
New York	7 - 10

The information provided confirms that the performance lives derived from the statistical analysis are within the norm.

***What about the performance of SMA and Superpave overlays?***

With the advent of improved asphalt mix designs we should try to judge them to the extent possible given the amount of performance data available.

## **SMA Overlays**

Stone matrix asphalt (SMA) overlays are an alternative to standard hot mix wearing courses. Their stone-to-stone matrix, blend of superior coarse aggregates and fiber additives are designed to withstand rutting and wear. SMAs were first placed in Missouri in 1991. Most SMA wearing courses were placed on I-B binder mixes, which have since been replaced by SP250 (Superpave) mixes.

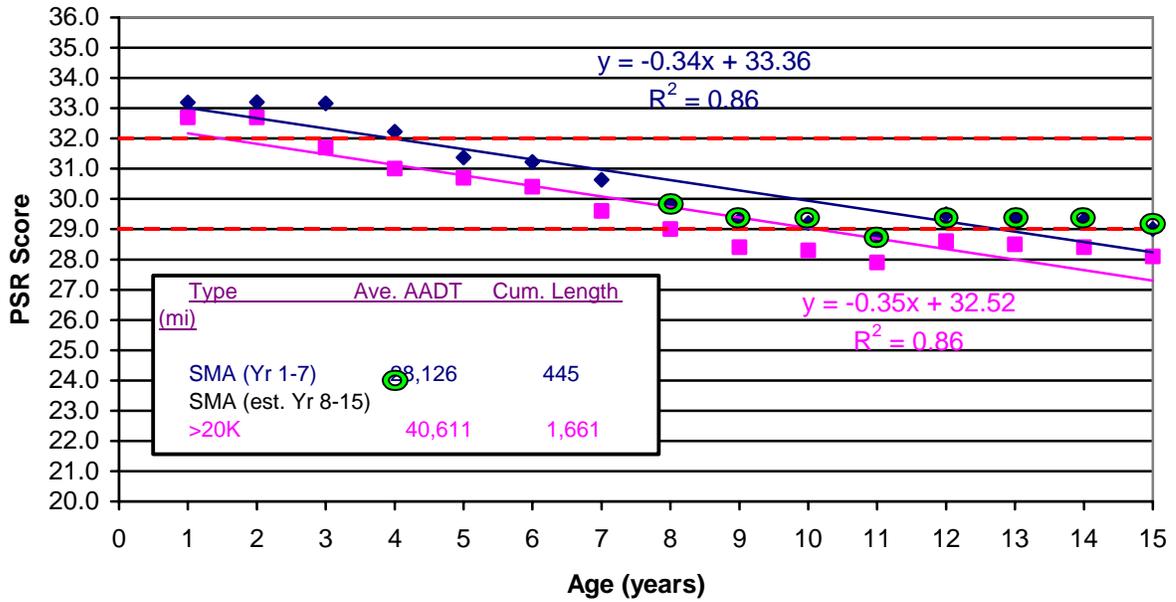


SMA on WB I-70 in Boone County

Eight years of ARAN data have been collected on SMAs, however; only the first seven years have enough data for statistical significance. Since SMAs have mostly been constructed on urban Interstate routes with high traffic volumes, they were compared to the performance trends of all ACOLs with AADTs greater than 20,000.

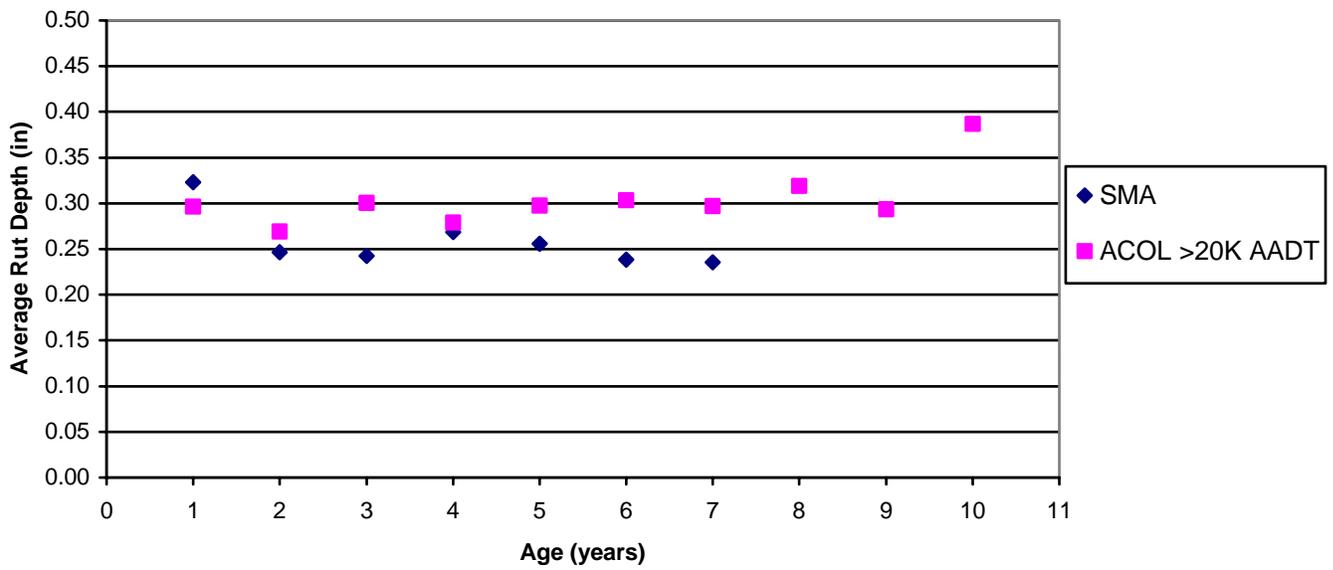
To develop an SMA trendline the average difference in PSR between SMAs and conventional ACOLs for the first seven years (0.9) was added to each of the conventional ACOL data points for years eight through fifteen. It is assumed here that SMAs would maintain their historical edge into the future.

### PSR for Stone Matrix Asphalt vs ACOL (> 20,000 AADT)

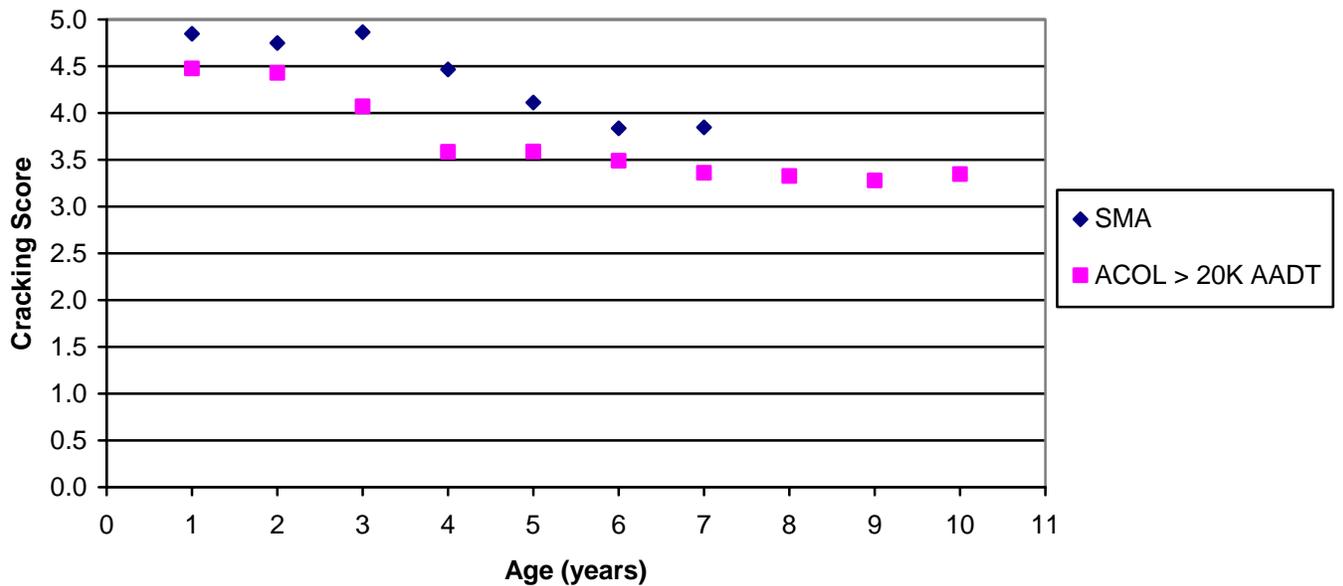


Based on this estimated extrapolation of performance data SMA overlays have roughly two more years of serviceable life than conventional ACOLs. The reasons for this increase seem to be identified in the rutting and cracking graphs below. SMAs appear to slow down the advent of reflective cracking more than conventional ACOLs. Also, their rutting, after initial traffic compaction, saw no increase, whereas conventional ACOL rutting kept growing.

### Rutting for Stone Matrix Asphalt vs All ACOL (> 20,000 AADT)



### Cracking for Stone Matrix Asphalt vs ACOL (> 20,000 AADT)



## SMA ACOs on PCC last two years longer than standard AC overlays\*

\* These findings must be prefaced with the estimating technique used to derive this performance measure and the fact that SMAs statistically make up a very small percentage of all the ACOs on the NHS. It should also be remembered that since the mix has been used solely as a wearing course, the influence of different binder mixes under the SMA are not well known. Other States that construct SMA overlays have not formulated numerical life increases, but believe they are worth the effort. For instance, Maryland provides SMA wearing courses for all Interstate AC overlays. The growth in performance years and number of projects will provide more accurate measurements in the future.

### **Superpave Overlays**

The Superpave mix design was conceived to improve the current performance of asphalt hot mixes. The design consists of different procedures that must all be carried out correctly to optimize field performance.

Missouri began Superpave implementation in 1996 at its LTPP SPS-9 site on U.S. 65 north of Sedalia. This was followed by an increase in each of the following years as every district initiated its first project and subsequently adopted full-scale implementation. The earliest projects were overlays on the NHS.

Judging from the modest amount of data available (not enough to justify graphical representation), about four years worth for a handful of projects, Superpave overlays are performing better than conventional ACOs. The reason for the performance difference is that Superpave appears to resist reflective cracking more effectively in the early years.

Besides the statistically low amount of data and the total lack of any Superpave overlay older than five years, it might also be important to point out that the pay factor specifications for Superpave were not fully enforced until 2000. This means that Superpave performance from 2000 on may be influenced by this event, but to what degree cannot be ascertained at present.

### ***What have other states experienced with Superpave?***

Most of the country, like Missouri, began building AC pavements with the Superpave mix design in 1996. The LTPP program has an experiment category, SPS-9, dedicated specifically to the study of Superpave. Outside of the LTPP program, more rigorous testing of Superpave is taking place. The Westrack site in Nevada is the prime example of an accelerated facility focused solely on the study of Superpave mix designs. The test

track at the National Center for Asphalt Technology (NCAT) in Auburn, Alabama is another.

Almost all states have adopted Superpave as their primary mix design method for primary routes. Unfortunately, the five- to six-year period since implementation began has included the usual startup failures and learning curves associated with any major materials specification change. Hence, a survey of several national experts has verified that no state has acquired enough performance information to emphatically quantify a design life increase over their previous assumptions for AC overlays and full-depth pavements. Despite this hesitation, nearly all participants believe that they are producing a better product and it will only be a matter of time before the results can be more accurately stated.

## **AC Pavements**

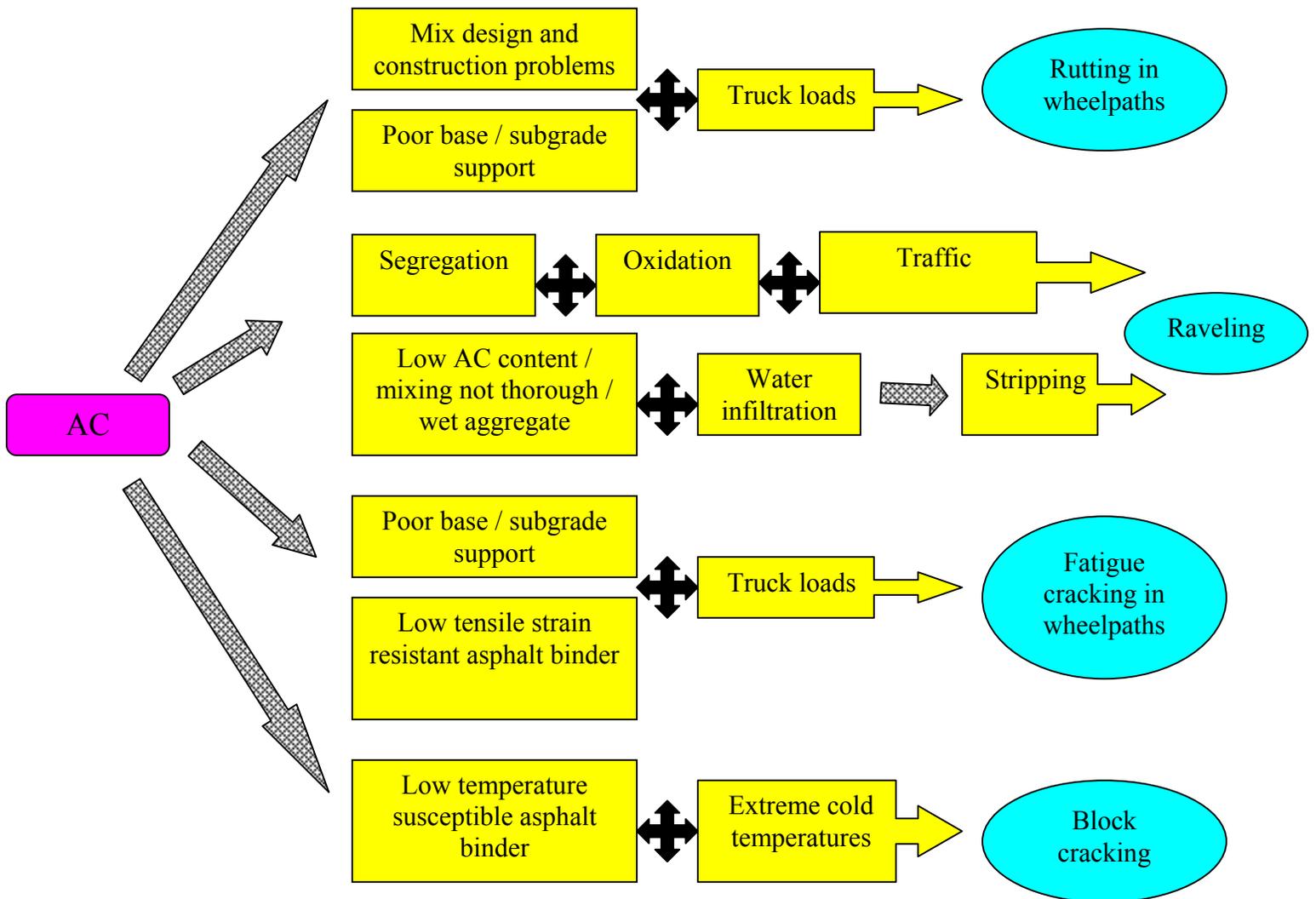
Full depth AC pavements are well represented in all three of Missouri's functional categories; however, they have historically been built on routes of lesser significance. They constitute nearly a fourth of the NHS and three-quarters of remaining arterials (as best as can be determined from inventory data), but are mostly two-lane roads with much lower traffic levels than their functional PCC and AC/PCC counterparts. There are only 14 directional miles (< 1 percent) on the Interstate. Nearly all collector routes are full-depth AC. Unknown or unavailable historical inventory records preclude understanding performance of many AC pavements based on mix quality. Full-depth AC pavements, for the purposes of this discussion, are defined as having any base type other than PCC.

### ***What makes our AC pavements deteriorate?***

Full-depth AC pavements, like AC overlays, are prone to rutting distress. However, in addition to mix problems, they can also rut due to a weak base and/or subgrade. As with AC overlays, rutting has come under better control in recent years with the advent of stone matrix asphalt (SMA) wearing courses and Superpave mix design.

AC pavements do not exhibit reflective cracking, because there are no rigid layer discontinuities below. They will, however, produce fatigue or alligator cracking in the wheel paths from heavy loads.

They also are subject to the same segregation, oxidation, raveling, stripping and block cracking problems that plague AC overlays.



### *How long do our AC pavements last?*

This analysis considers the arterials in one group and the collectors in another. The reason for these groupings is the AC composition. Arterials were probably built with a combination of current specification dense-graded hot mix and to a lesser extent, plant mix, which is of lower quality. Collectors, on the other hand, were built predominantly with plant mix.

This analysis does not differentiate between full-depth AC and AC overlays on AC pavements, because of original construction uncertainty. It is assumed that the vast majority of these pavements are AC overlays because of the recent dates of construction. Therefore, the design lives derived from this analysis can be considered those of AC overlays.

## **Data Sources**

ARAN data was retrieved from the master inventory table in the pavement management system (PMS) database. Data from 1995-98 was used.

Unlike the AC/PCC analysis, historical information for AC pavements was not used because of the great time and effort required to reconcile the logmile limits between the two sources. Even if the history database had been used, greater uncertainty existed about their accuracy for lower classification routes. Besides that, most collectors, which were originally under county jurisdiction, don't have any original construction data because they were built before the State assumed responsibility several decades ago.

## **Study Variables**

Variables considered in the analysis were AADT for arterials and AC type (plant or spec) for collectors. Other variables such as thickness, base and subgrade type and ESALs were not introduced for lack of data. It is assumed that nearly all AC overlays were very thin, in the neighborhood of 1 ¼ inch.

## **Performance Period**

The standard performance period used in this analysis was ten years.

## **Performance Indices**

The performance indices calculated for each year in the analysis were ride, cracking, PSR, rutting, condition and international roughness index (IRI). Trend graphs for these indices were created. PSR trends were created using linear regression analysis, while second-degree polynomial trends best fit the cracking and ride graphs. Average AADTs, weighted by section length, were computed for each set of ACOLs.

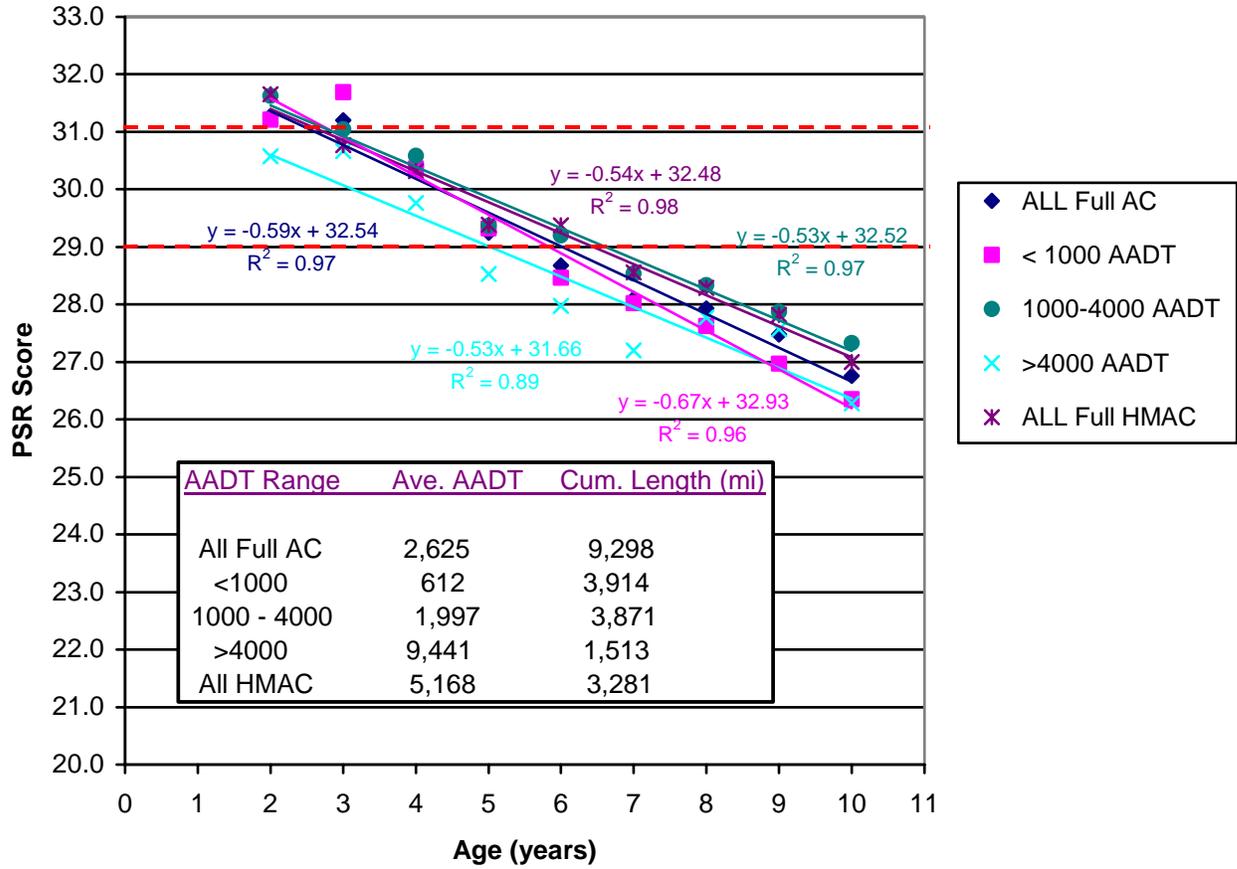
## **Findings for AC/AC Arterials**

The graph below depicts the performance of all full-depth arterial AC pavements. The "All Full AC" category includes plant mix as well as higher quality HMAC, while the "All HMAC" category excludes plant mixes. The "ALL Full AC" category was broken out by AADT into the three ranges.

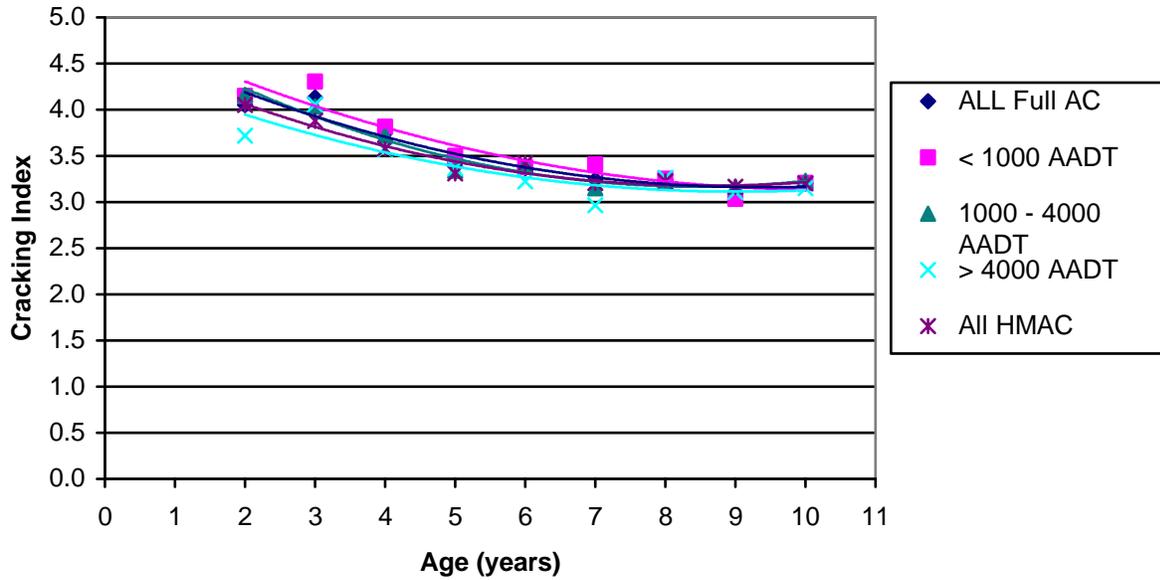
All categories in the graph descend into an unacceptable range between six and seven years, except for the high-volume arterials which breach at five years.

The drop in PSR is equally attributable to increases in fatigue and block cracking and roughness as shown in the following two graphs.

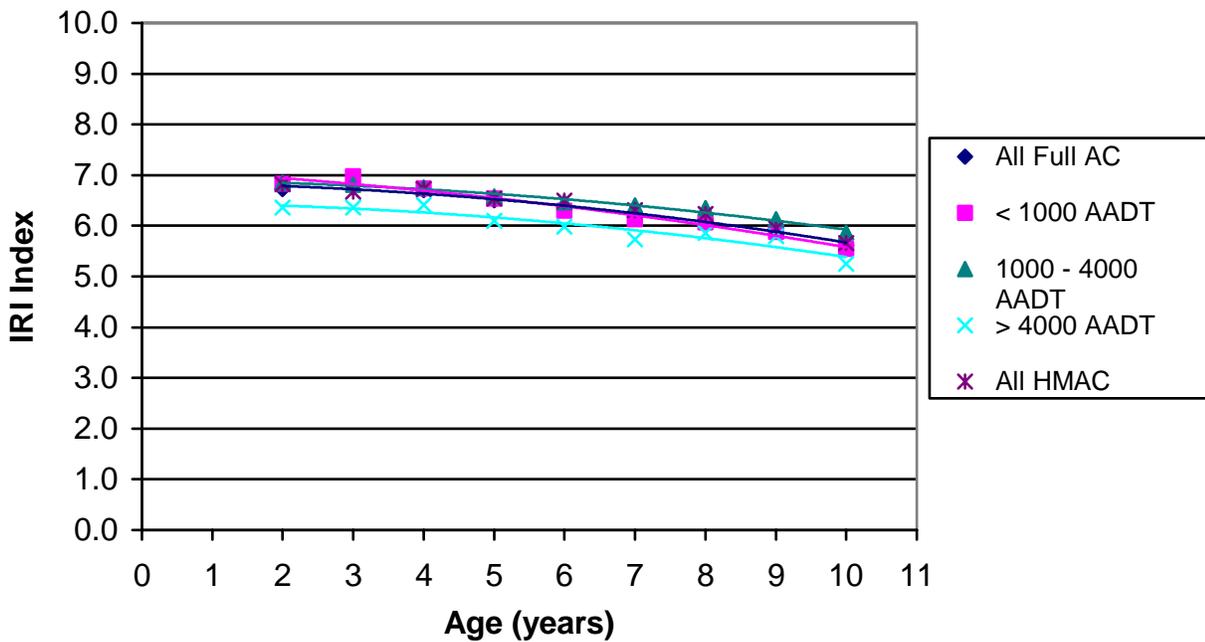
## PSR for AC/AC on Arterials 1995-1998 ARAN Data



## Cracking for AC/AC on Arterials 1995-1998 ARAN Data



## Ride for AC/AC on Arterials 1995 - 1998 ARAN Data



### **Full-Depth Superpave AC**

Missouri has constructed a handful of full-depth Superpave pavements. As with Superpave overlays, the performance of full-depth Superpave mixes in Missouri is difficult to ascertain for the same reasons that no other state has been able to; they haven't been down long enough. We have two to three years of data for two projects, Route 21 in Iron County and U.S. 54 in Camden County. Early performance on these projects has been superb.



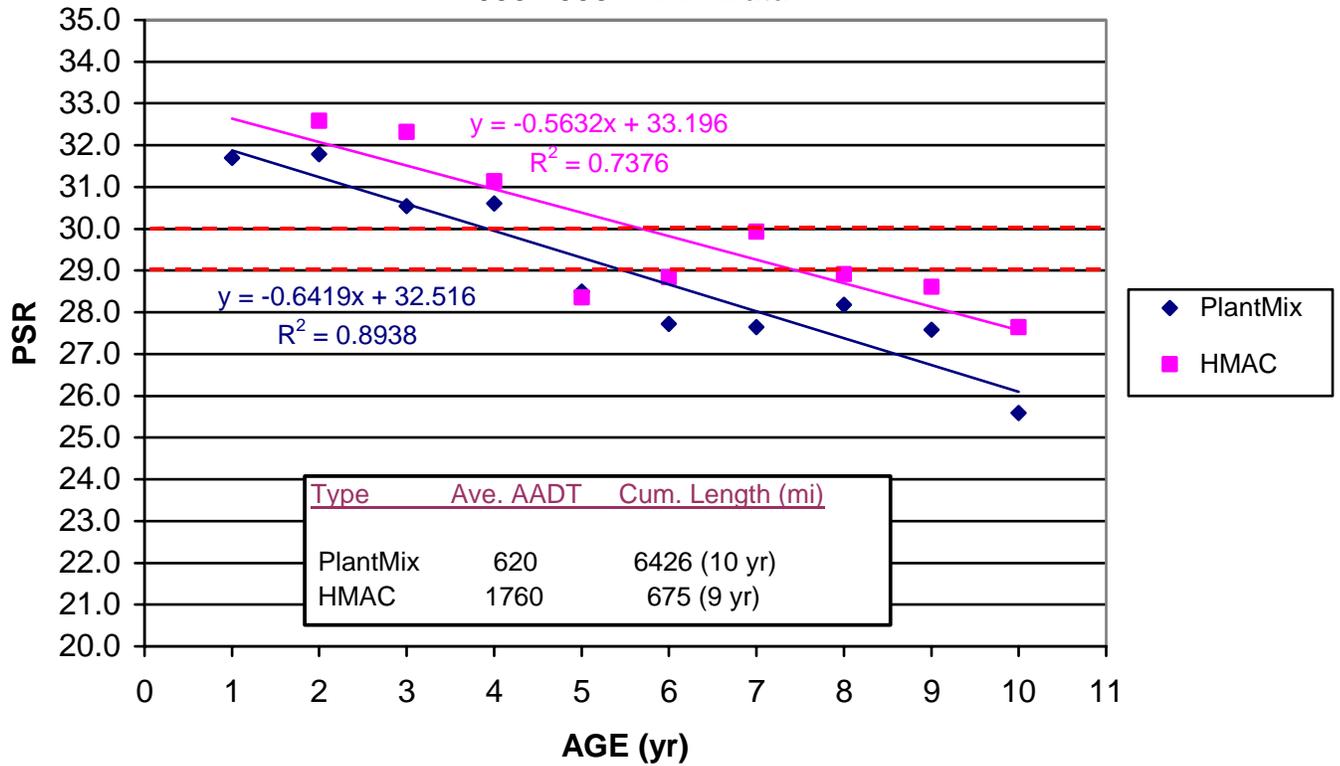
Full depth Superpave pavement on northbound US 63 in Boone County

### **Findings for AC/AC Collectors**

Long-term performance of ACOLs on full depth AC on collectors is similar to that on arterials. The "Plant Mix" category falls into the unacceptable zone at six years. The "HMAC" performs adequately for about a year longer than the "Plant Mix".

## PSR for AC/AC on Collectors

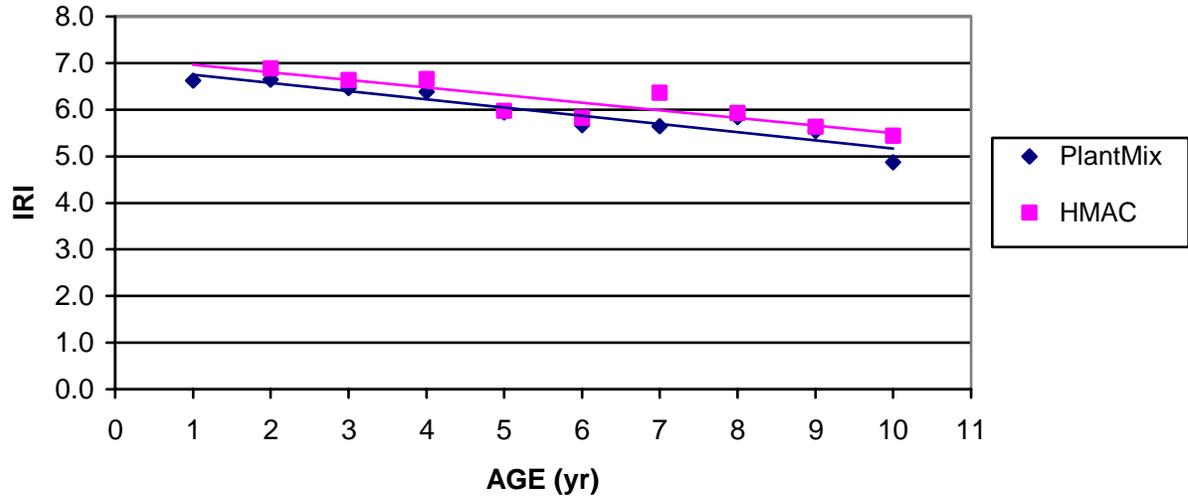
1995-1998 ARAN Data



The IRI and condition graphs below provide a picture of how the full depth AC collectors increase in roughness and visual distress.

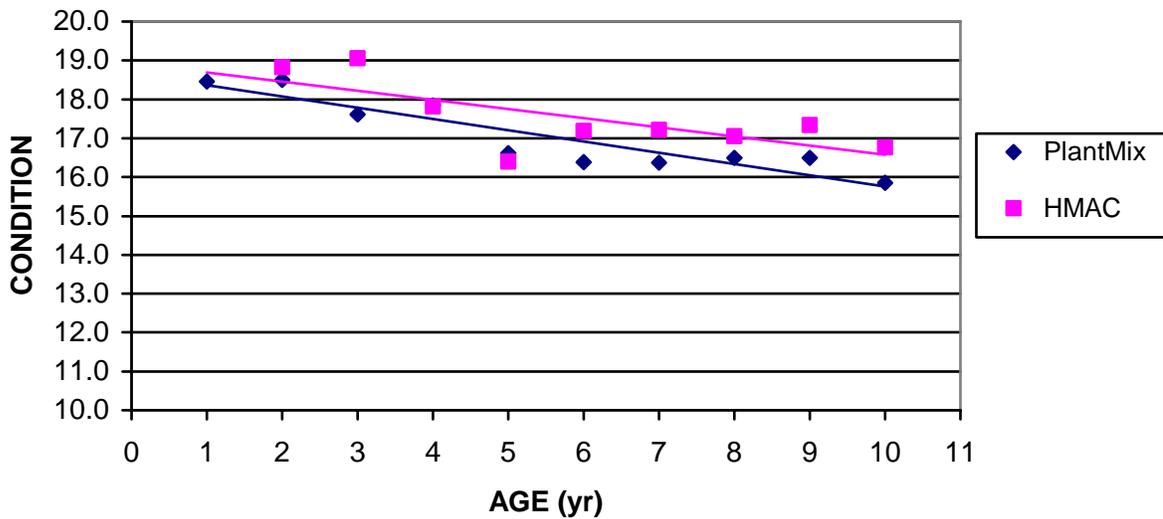
## IRI for AC/AC on Collectors

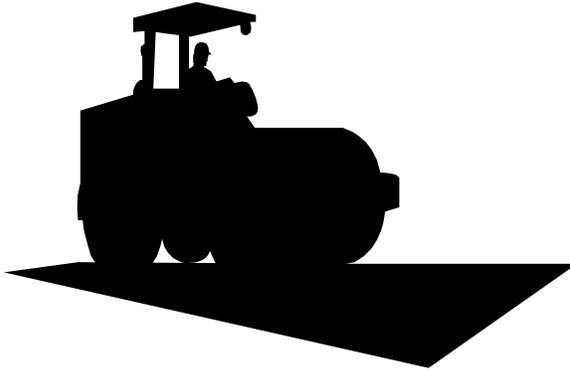
1995-1998 ARAN Data



## Condition for AC/AC on Collectors

1995-1998 ARAN Data





PAST AVERAGE  
PERFORMANCE LIFE  
(at least marginal)  
FOR AC overlays on AC\*  
ON ARTERIALS  
= **6 YEARS**

PAST AVERAGE  
PERFORMANCE LIFE  
(at least marginal)  
FOR AC overlays on AC\*\*  
ON COLLECTORS  
= **7 YEARS**

\* HMAC primarily with some plant mix

\*\* Mostly plant mix

### *What can be done to improve full depth AC performance?*

A combination of factors is already at work to improve full depth AC performance.

First and most importantly, Superpave mix designs are expected to yield high performance dividends. The rigorous mix and binder testing specifications raise the bar for product acceptability.



Full depth Superpave AC on US 54 near Camdenton

Second, the two-foot rock base, when used, provides superior support. Unlike thick PCC, which is theoretically nearly impervious to moderate changes in base and subbase stiffness, AC pavements greatly benefit from stiffness increases. This layer reduces fatigue by decreasing bottom radial strains, and rutting by better withstanding vertical compressive stresses.



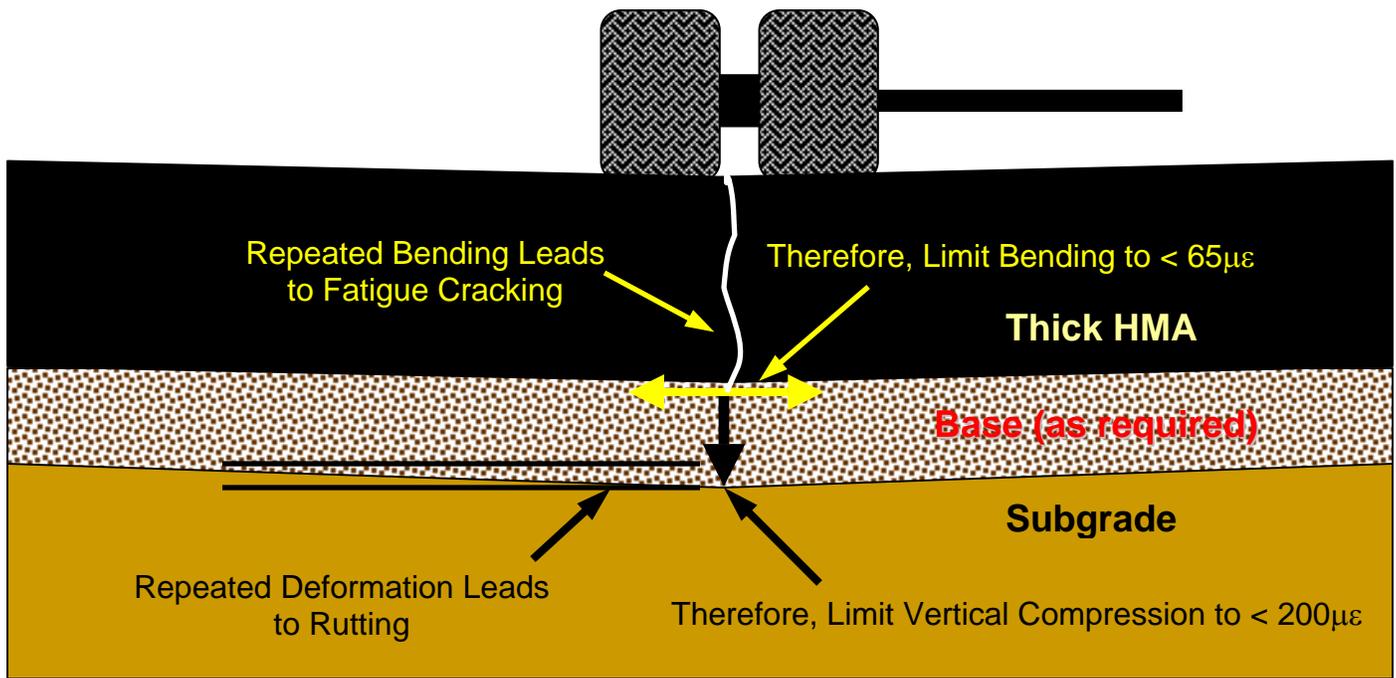
Two-foot rock base on US 54 near Eldon

Also, in cases where the Type 5 base is used, greater subgrade stability can be achieved through lime or flyash stabilization. This technique changes the chemistry of clayey soils with low California Bearing Ratios (CBR) and high plasticity indexes (PI). Illinois stabilizes the subgrade 12 - 18 inches deep on every project with an average Immediate Bearing Value (very close approximation to CBR)  $\leq 6$ . Kansas routinely stabilizes soils over the majority of its geographic area.

Third, greater base permeability should improve performance. The rock base is currently under investigation, but unless disproved, it is believed to drain well. Treated 4-inch permeable bases, alternates to rock bases on heavy-duty routes, have provided ample evidence of freely draining. This does not apply to the Type 5 base, because recent field and lab tests have detected very poor drainage qualities.

### *Is there a long-life AC counterpart to PCC pavements?*

“Perpetual pavement” is an expression coined by the National Asphalt Pavement Association (NAPA) and the Asphalt Institute (AI) to describe a full-depth AC design that pushes back the traditional time for rehabilitation. The concept is not really new, but better defined. Since the two fundamental pavement responses that initiate distresses in AC are tensile strains at the bottom of the AC layer (which lead to fatigue cracking) and compressive stresses on top of the unbound base or subgrade (which leads to rutting), then the pavement need only be designed to minimize them. Providing a stiff, thick surface course on top of an intermediate binder layer dissipates compressive stresses. Constructing a rich, densely compacted bottom layer renders the pavement immune to repetitive tensile strains. The combined layer thickness is significant.



Perpetual Pavement Design

Under ideal circumstances, only infrequent removal and replacement of the wearing surface will be necessary. The remainder of the pavement could be reused indefinitely, assuming that axle loads do not increase over time enough to produce stresses and strains in excess of the original design estimates.

Efforts are underway in at least five states to construct projects using the “perpetual pavement” design. Illinois has developed a design that would include up to 6 inches of SMA on the surface for high-volume routes. Michigan has designed one with a five-year warranty that will be let in 2002. Wisconsin, California, and Texas are also formulating their own versions.

Missouri has, at least partially, adopted a “perpetual pavement” design for AC pavements. The thicker AC pavements built during the past six years should reduce tensile strains in the bottom layer. The specification for the bottom binder lift even allows for a lower gyratory compaction design level, which in turn, allows the use of a richer, more fatigue-resistant mix. However, contractors may, at their discretion, substitute the upper-layer mix instead. Meanwhile, SMA wearing courses, which up until now have only been used in ACOLs, could provide the stiff top layer required to dissipate compressive stresses in new AC pavements.

To date, however, the concept has not borne results that should change Missouri’s rehabilitation assumptions for new AC pavements. The current estimate of resurfacing at 15 and 25 years falls within the expectations realized by other states.

## **Life-Cycle Cost Analysis on NHS**

When a NHS pavement exhibits distress and reaches a condition where maintenance treatments will no longer restore it to an acceptable level of service, then rehabilitation or reconstruction becomes essential. MoDOT currently evaluates four alternatives for 4R work on NHS routes. The options include:

1. full reconstruction with asphalt concrete (AC)
2. full reconstruction with Portland cement concrete (PCC)
3. structural AC overlay
4. unbonded PCC overlay

The analysis is performed over a 35-year design life. The *AASHTO Guide for the Design of Pavement Structures* provides the design methodology for selecting thicknesses for new PCC or AC pavements, however, the process has been simplified to a catalogue table by assuming many variables to be the same for all pavements. In other words, the designer need only know the number of rigid design-life ESALs and whether the shoulders are tied or not for PCC, and the number of flexible design-life ESALs and subgrade support classification for AC.

In the life-cycle cost analysis of these four options there are several basic assumptions:

- Maintenance and salvage value costs are the same and are therefore not included;
- User costs for lane closures are not considered;
- Both AC overlay and AC reconstruction pavements will have their wearing courses cold milled and replaced at ages 15 and 25;
- Both unbonded PCC overlay and PCC reconstruction pavements will have their surfaces diamond ground at age 25 and two percent of the surface area replaced through full depth repairs.

Based on the analysis of ACOLs in the previous sections, the number of new wearing courses required will be increased from two to three. Therefore, instead of resurfacing at 15 and 25 years, they will be performed at 10, 20 and 30 years. The resurfacing assumptions for new full-depth AC pavements will remain the same.

The following table shows the estimated life-cycle costs per mile for each rehabilitation strategy at different traffic levels. The estimates include user costs incurred by construction delays, as well as initial construction and future rehabilitation costs. New AC and PCC construction incur no user costs because they are assumed to be on new lanes. User costs have production rates factored in, which were supplied by both the asphalt and concrete industries.

Rehabilitation Type	AADT				
	18,200	30,540	40,020	145,000	188,000
AC 13"	\$4,308,465				
PCC 9"	3,683,465				
ACOL 3 ¾"	2,425,479				
PCC UBOL 8"	3,035,714				
AC 16"		5,092,922			
PCC 11"		3,830,406			
ACOL 5 ¾"		2,794,165			
PCC UBOL 8"		3,186,564			
AC 17"			7,156,951		
PCC 12"			6,057,221		
ACOL 5 ¾"			3,543,044		
PCC UBOL 8"			3,635,365		
AC 20"				11,579,414	
PCC 14"				9,790,296	
ACOL 7 ¾"				6,416,186	
PCC UBOL 9"				5,349,476	
AC 20"					11,373,288
PCC 14"					9,663,813
ACOL 7 ¾"					6,411,052
PCC UBOL 10"					5,768,063

These estimates could fluctuate depending on changes to different variables, however, rather than focusing on exact dollar figures the following basic observations can be made. New full-depth AC is cost-effective on lower-volume arterials, while new PCC is the choice for higher-volume arterials. For resurfacing, ACOLs are cost-effective on lower-volume arterials, while unbonded PCC overlays are more appropriate for higher-volume arterials. Resurfacing with either AC or PCC overlays appears to be more cost-effective than their full-depth counterparts, however, other circumstances, such as existing pavement conditions and geometric constraints, may tip the scale the other way.

## Conclusions

Conclusions derived from data analysis, according to the Long Range Transportation Direction (LRTP) standards, are:

<i>System</i>	<i>NHS</i>	<i>Remaining Arterials</i>	<i>Collectors</i>
Acceptable PSR	$\geq 32$	$29 - \leq 32$	$< 29$
Marginal PSR	$\geq 31$	$29 - \leq 31$	$< 29$
Unacceptable PSR	$\geq 30$	$29 - \leq 30$	$< 29$

1. PCC pavements on divided NHS, on average, do not become unacceptable for 25 years or more. These ratings do not account for non-resurfacing maintenance treatments that might have been applied.
2. Diamond grinding PCC pavements during construction can provide initial performance well above the acceptable limit.
3. NHS and remaining arterial AC overlays on PCC become unacceptable after an average of ten years.
4. Average performance life varied little for AC overlays on PCC pavements when examined by number of overlays, thickness and AADT range.
5. Reflective cracking in AC overlays on PCC pavement is the primary cause of performance deterioration on NHS and remaining arterial routes.
6. SMA overlays on PCC pavements on NHS routes provide two years more service life than standard AC overlays. This finding is based on estimated extrapolated data and does not take into account the influence of underlying binder courses on performance.
7. Initial scant data for Superpave AC overlays on PCC pavements on NHS routes indicate improved performance over standard AC overlays, but not enough is available to determine performance life trends.
8. Thin AC overlays on AC pavements on NHS and remaining arterial routes become unacceptable after an average of six years.
9. Fatigue and block cracking followed by increased roughness contribute to the deterioration of AC overlays on AC pavements on NHS and remaining arterial routes.
10. Insufficient data is available to determine performance life trends for full-depth Superpave pavements on NHS and remaining arterial routes.
11. AC overlays on AC pavements on collectors become unacceptable after four to seven years on average depending on the type of bituminous mix.

Based on other research findings:

12. Missouri's new JPCP design has performed very well for the first eight years.

13. CRCP is an optimum new PCC design on high-volume urban NHS routes where maintenance-free pavements are critical. Concrete mix design must restrict d-cracking-susceptible aggregate.
14. Initial PCC roughness and hence initial PCC performance can be improved dramatically through diamond grinding.
15. Decreasing initial pavement roughness for any type of pavement can significantly increase future performance life.
16. A bonded PCC overlay is a viable rehabilitation treatment that has historically been technically difficult to construct properly.
17. Unbonded PCC overlays should provide at least 20 years of good performance if properly designed and constructed. PCC thickness should be  $\geq 8$  inches with an AC interlayer  $\geq 1$  inch.
18. Rubblization of PCC with AC overlay is effective if subgrade and base are stable and PCC is not heavily patched with AC. Correct rubblization sequence and avoidance of rubblized layer disturbance is critical for success.
19. Diamond grinding on a moderately faulted PCC without pumping problems should extend the pavement performance life another five to ten years.
20. Design-life assumption for new JPCP can be increased from 35 to 40 years.
21. Retrofitted edge drains have proven marginally successful, at best, in Missouri. However, improved designs exist in other states that may be of benefit.
22. Expected AC overlay lives from other states closely match the findings of Missouri's analysis.
23. Rock base and subgrade stabilization with lime or flyash should improve AC pavement stability.
24. AC "perpetual pavement" design may provide long lasting acceptable performance with infrequent wearing course replacement.
25. General life cycle cost analysis, including construction and work zone user costs, indicates that new AC is more cost-effective on lower arterials, while new PCC is more cost-effective on higher-volume arterials.
26. General life-cycle cost analysis, including construction and work zone user costs, indicates that AC overlays are more cost-effective on lower-volume arterials, while unbonded PCC overlays are more cost-effective on higher-volume arterials.

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