

PAVEMENT DESIGN FOR DESIGNERS & NON-DESIGNERS...

And Why You Should Care...



National Concrete Consortium
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Question

Who has said (or thought) something along the lines of?

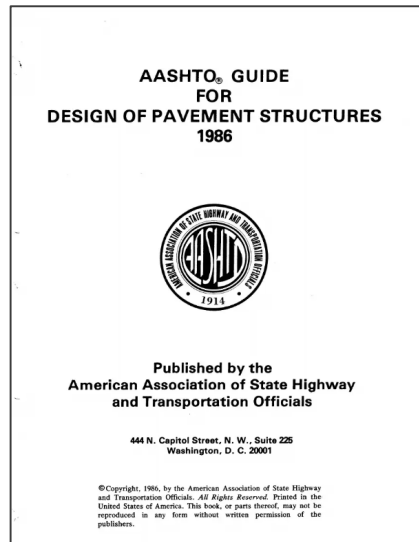
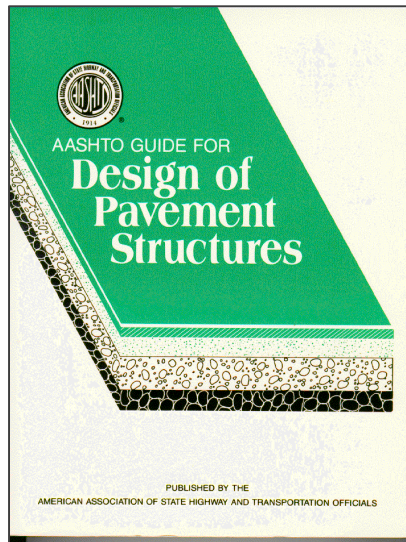
We Don't do Concrete Pavements because...

No matter what the reason, it all starts with Design

There are Many Pavement Design Methodologies

Which one is correct?

AASHTO 93/86/72



Industry Methods



State & University Methods



Pavement ME (PMED)

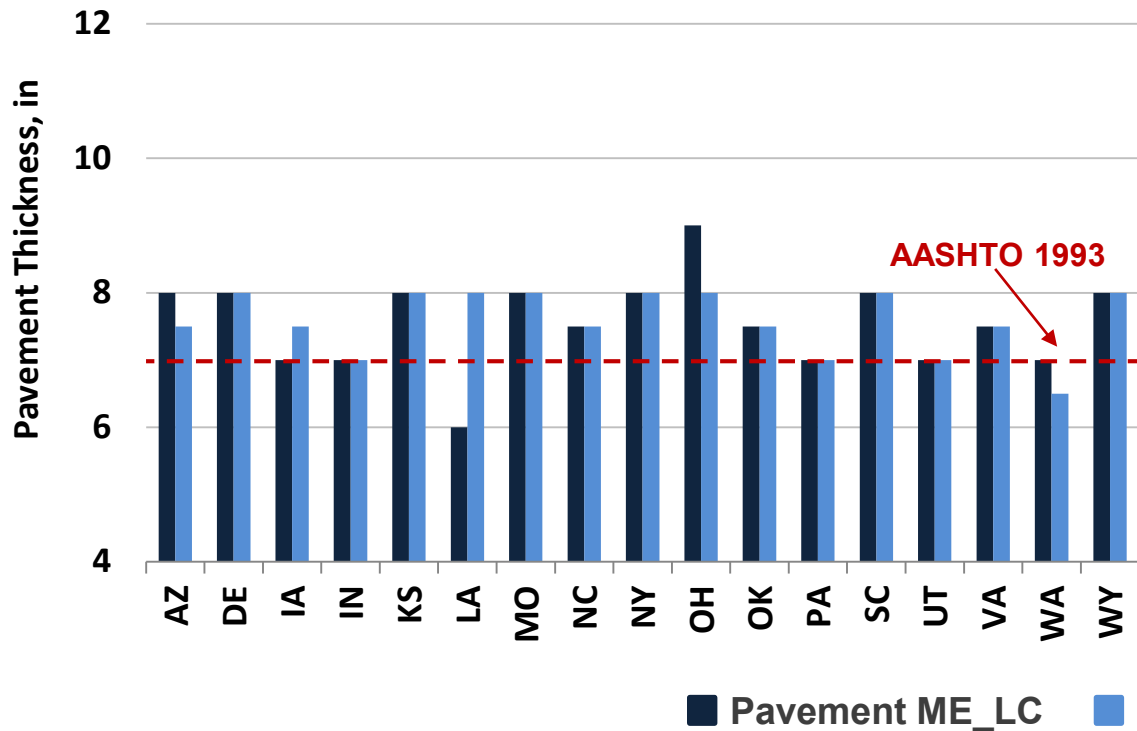


They all can work and give Good Designs (as well as bad)

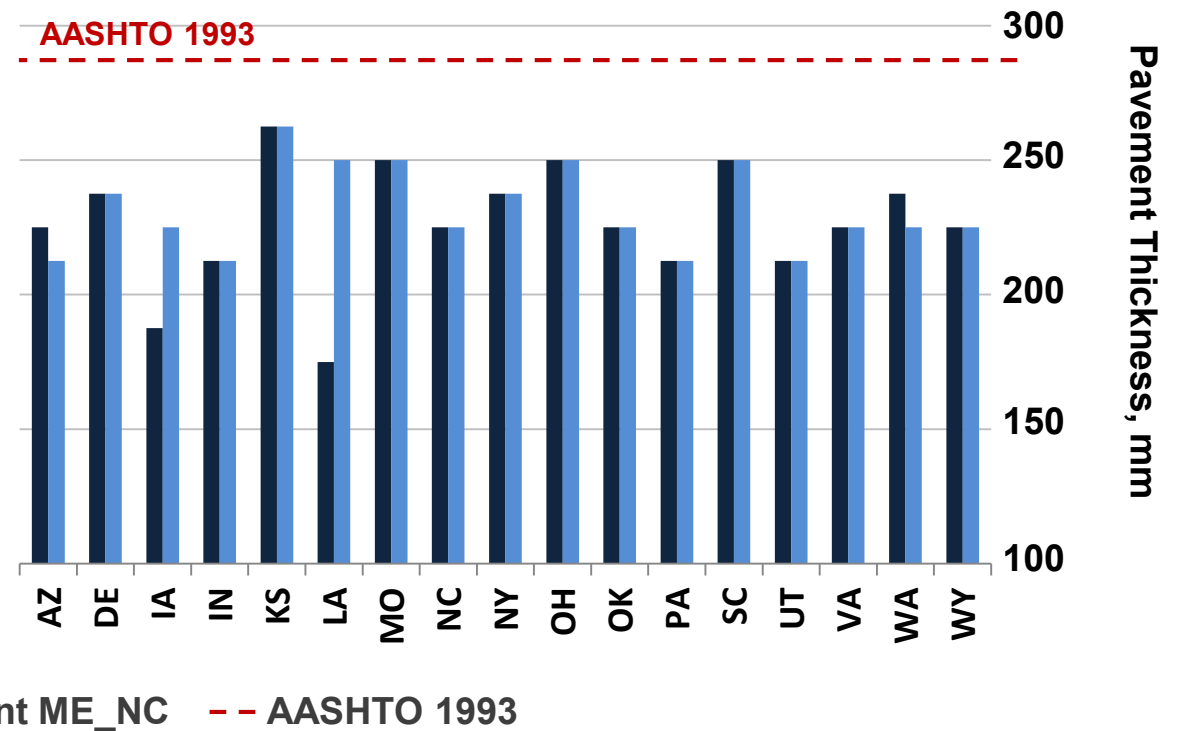
Impact of Design Tools on Pavement Thickness

Local vs National Calibration Impact

Low Volume Application



High Volume Application



However, using Pavement ME result in ~2-3 in thinner JPCPs when compared to the AASHTO 93 guide.

Pavement-ME is the Most Advanced Design Procedure

Covers a wide range of applications, including nearly all new & rehabilitation options

Can account for new and diverse materials and various failure mechanisms

State-of-the practice design procedure based on advanced models & actual field data collected across the US and Canada

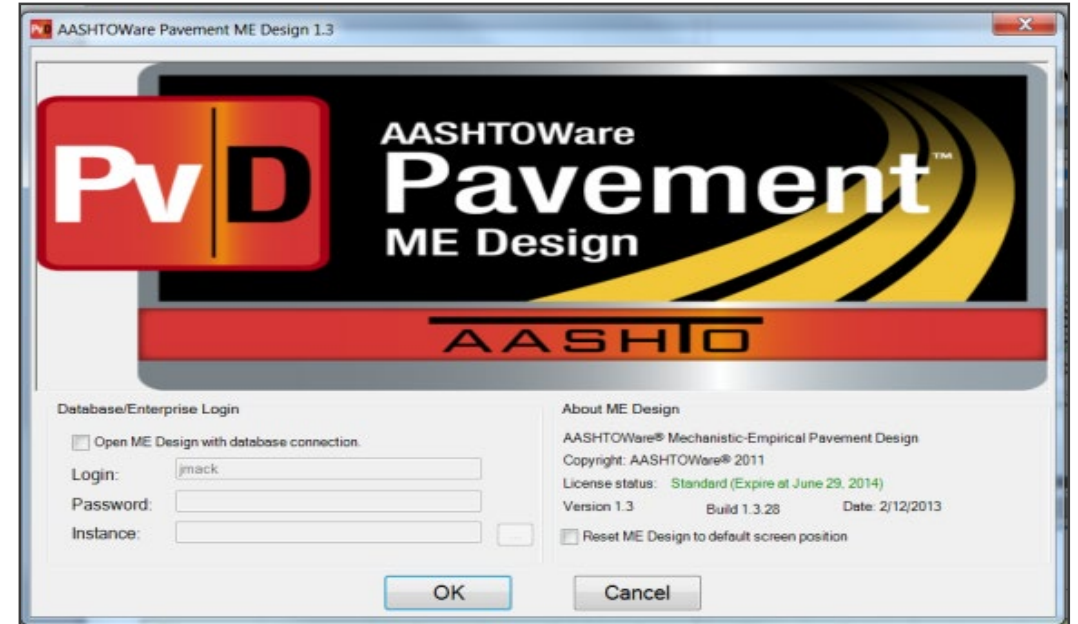
- Adopted by AASHTO in 2011
- Calibrated to more than 2,400 asphalt & concrete pavement test sections, ranging in ages up to ~40+ years

Based on mechanistic-empirical principles that account for site specific:

- Traffic
- Climate
- Materials
- Proposed structure (layer thicknesses and features)

Provides estimates of performance during the analysis period

- Can match rehabilitation activities to performance



New Pavement

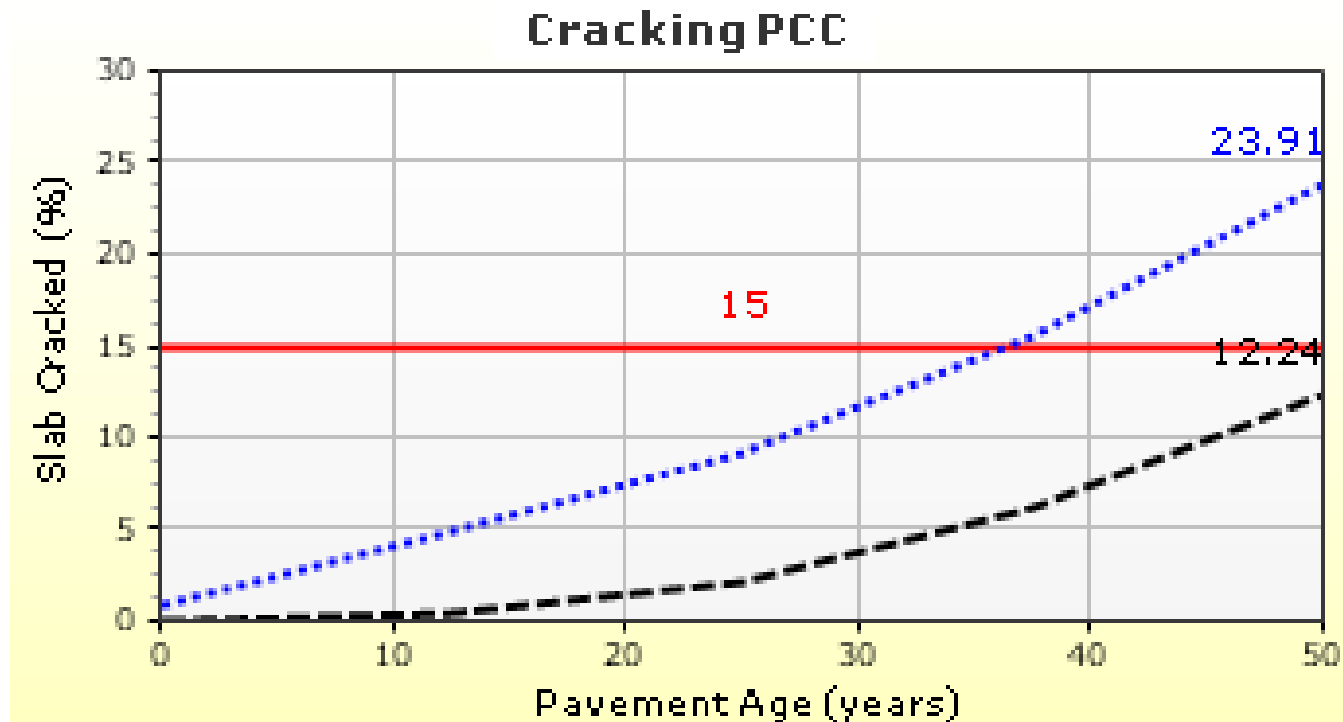
- Asphalt Concrete (AC)
- Jointed Plain Concrete Pavement (JPCP)
- Continuously Reinforced Concrete Pavement (CRCP)

Overlays & Restoration

- AC over AC
- AC over JPCP / CRCP (w/ & w/o fracture)
- Bonded PCC over JPCP / CRCP
- Unbound PCC over JPCP / CRCP
- JPCP /CRCP over AC
- JPCP Restoration

Pavement-ME Defines a Specific Pavement's Performance

Predicting performance of key distresses allows for trade-off analysis with Life Cycle Analysis



Red Line – Predefined Distress Threshold Value. When major rehabilitation is needed (i.e. patching & DG or overlay).

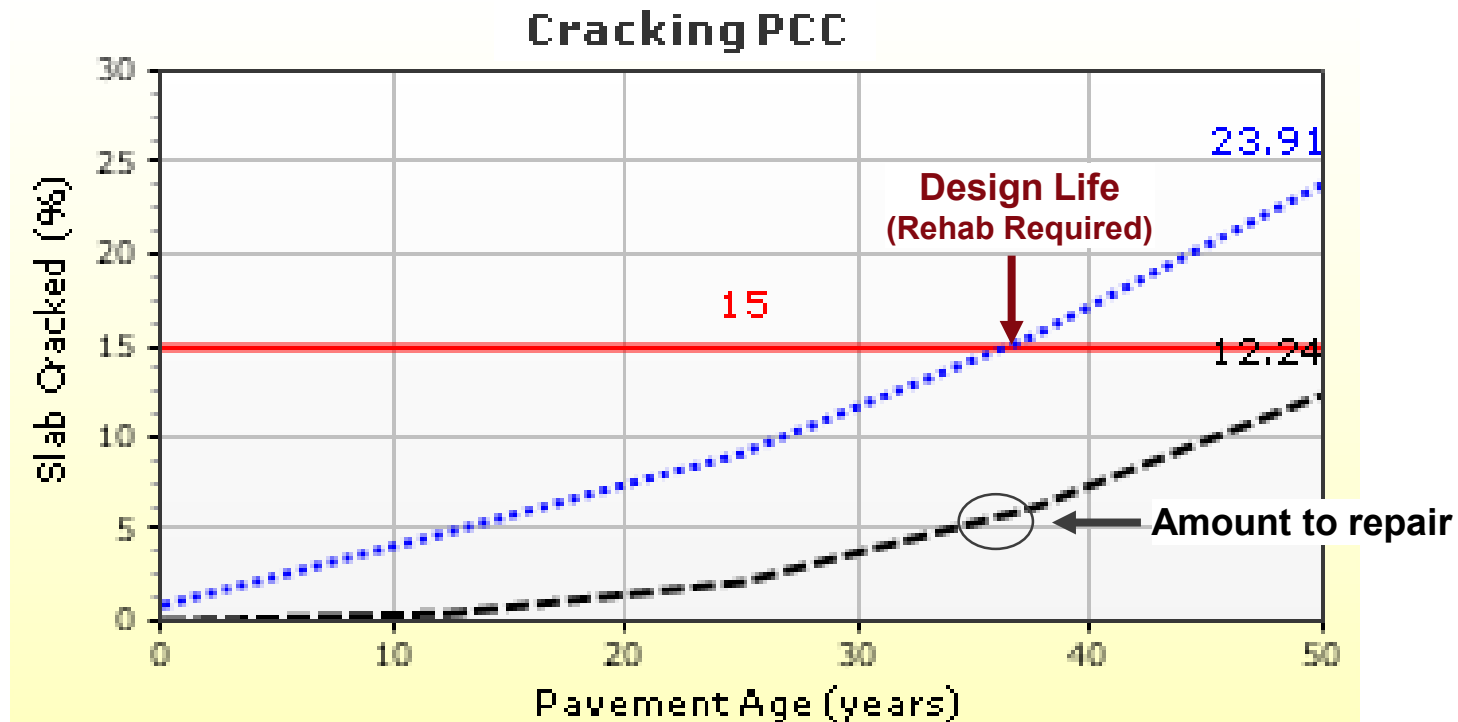
Black Dashed Line - The 50% Reliability (most likely) level of distresses predicted

Blue Dotted Line - The predicted distresses at the Specified Reliability Level (i.e. 90%). Designs are based on when this line hits the defined distress limit

Design life is when the Blue Reliability curve hits red Predefined Threshold Value (~33 years in this case)

Pavement-ME Defines a Specific Pavement's Performance

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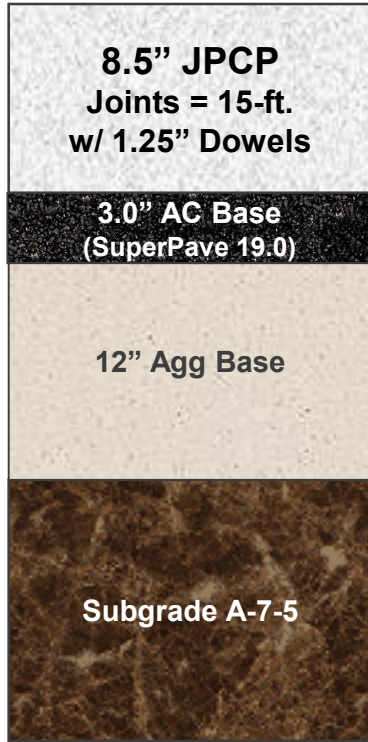
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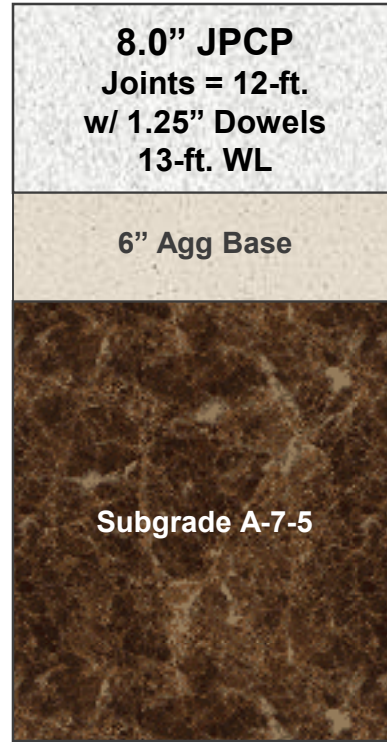
Design life is when the Blue Reliability curve hits red Predefined Threshold Value (~33 years in this case)

Pavement-ME Allows for Comparisons of Different Designs

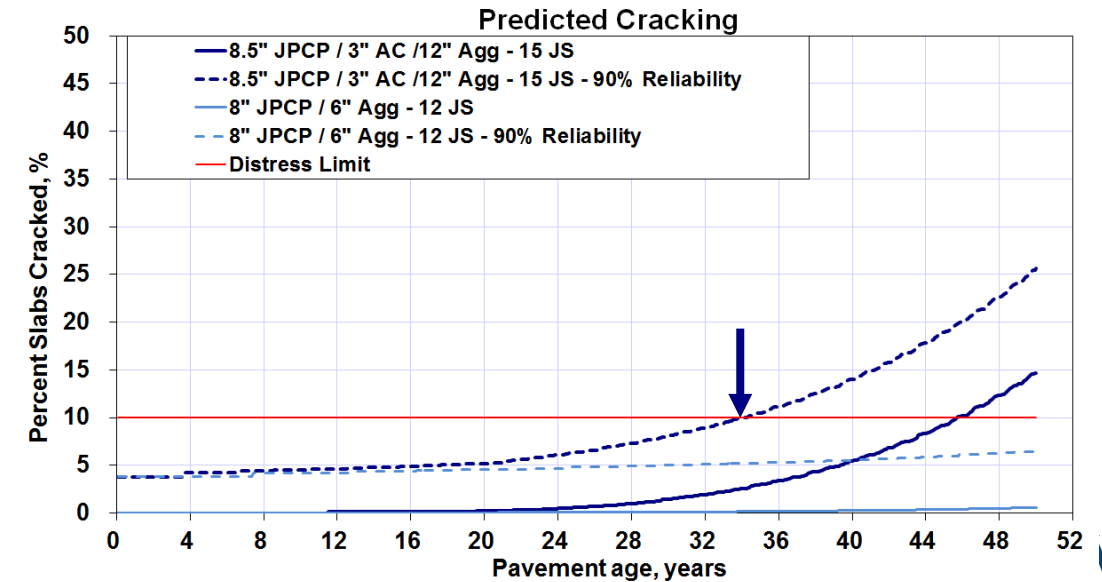
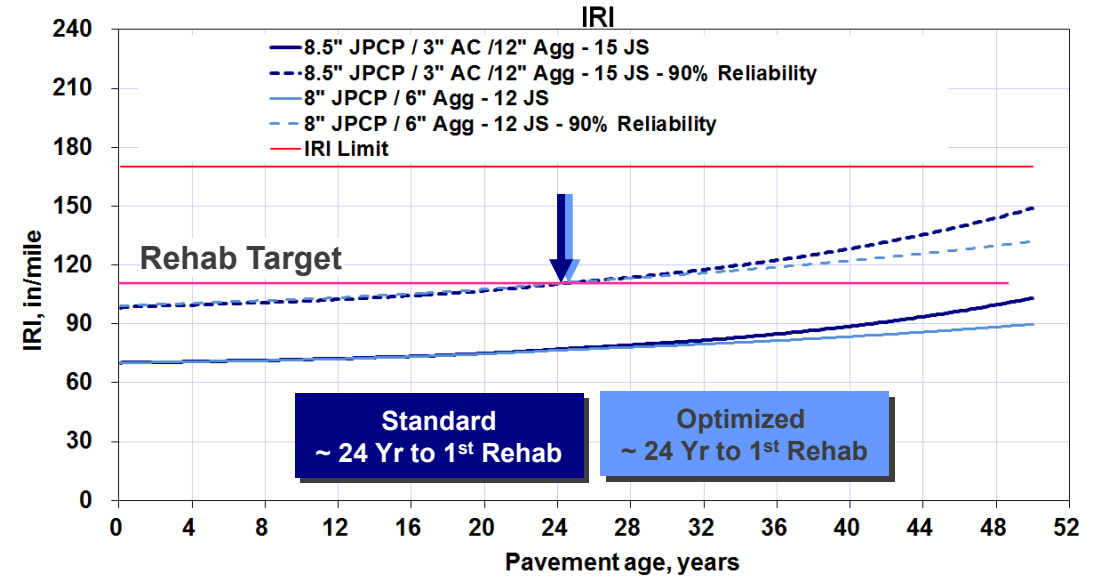
Original Concrete Design



Optimized Concrete Design



Pavement ME gives a repeatable, un-biased process that shows how a specific pavement design will perform



So, While We Think Pavement ME is Amazing & the Best Thing EVER

It is also fairly complex and the models aren't perfect

There are a Few Design Conundrums

- Joint Faulting Predictions
- IRI Predictions

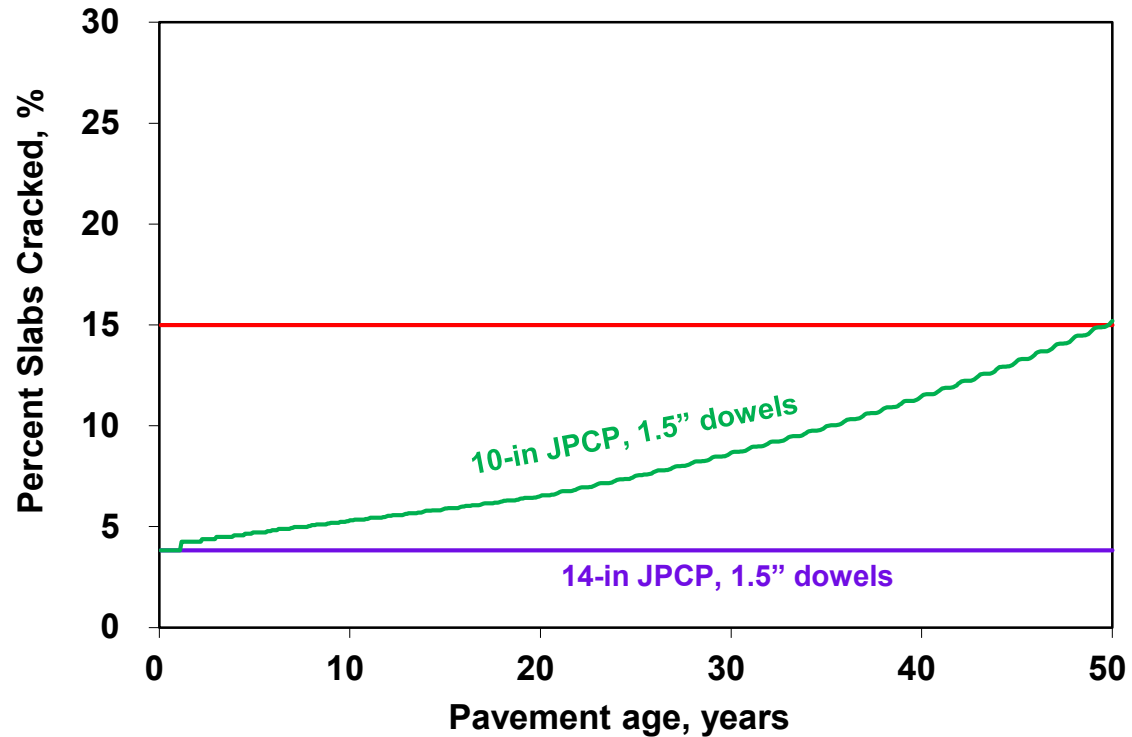
The designs are only as good as the inputs, and with an understanding of what is driving the final results



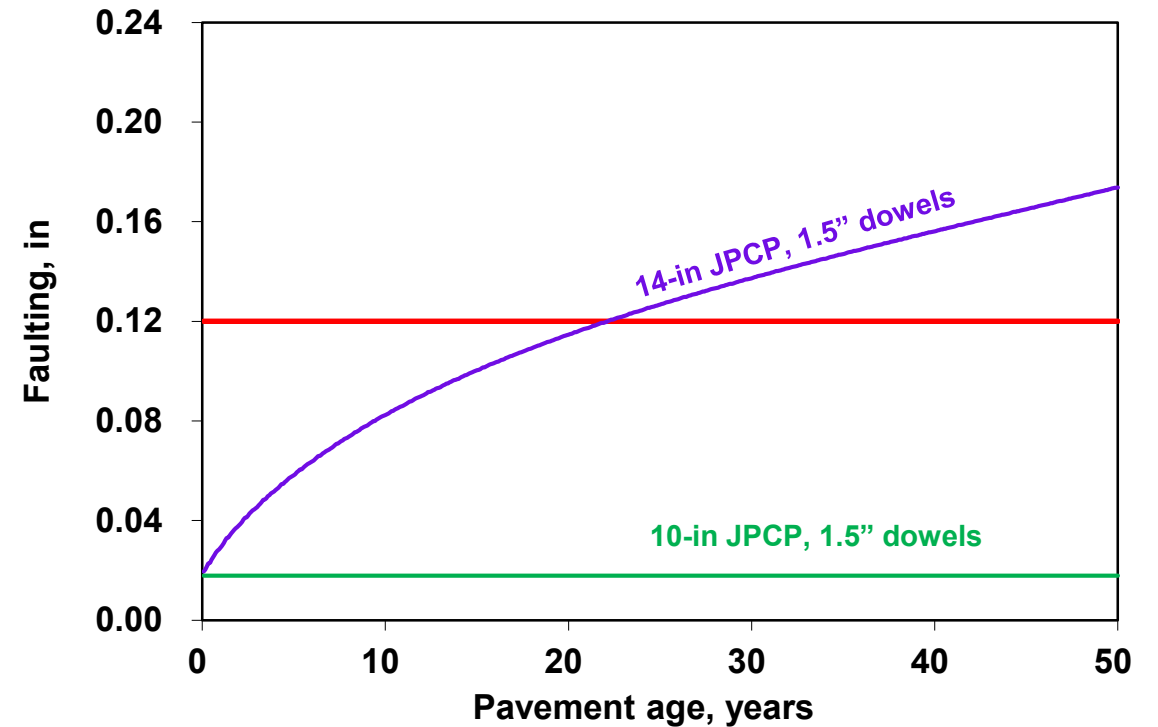
Need people with experience of Concrete Pavements to call “Bulls---” when something is counter intuitive

Joint Faulting Increases For Thicker Concrete Pavements With Dowels

Thicker PCC, Less Cracking



Thicker PCC, More Faulting

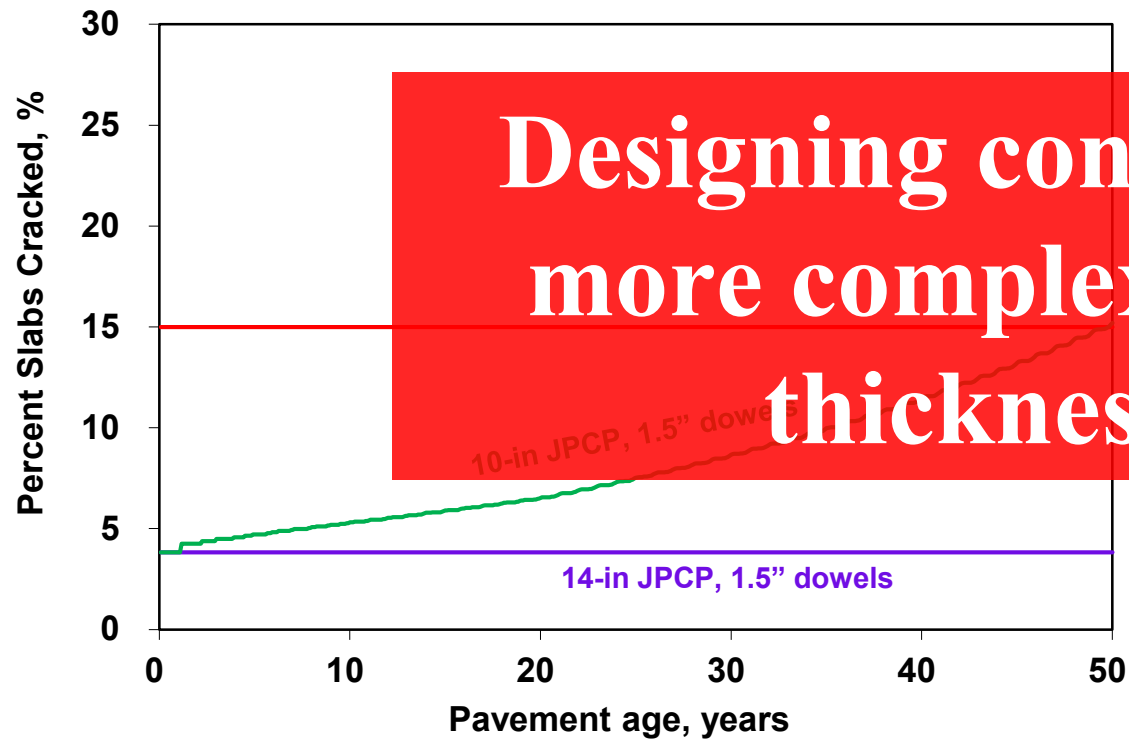


**In Pavement ME, LTE is proportional to Dowel Size/PCC Thick Ratio
(e.g. the same dowel setup is more effective for thinner pavements)**

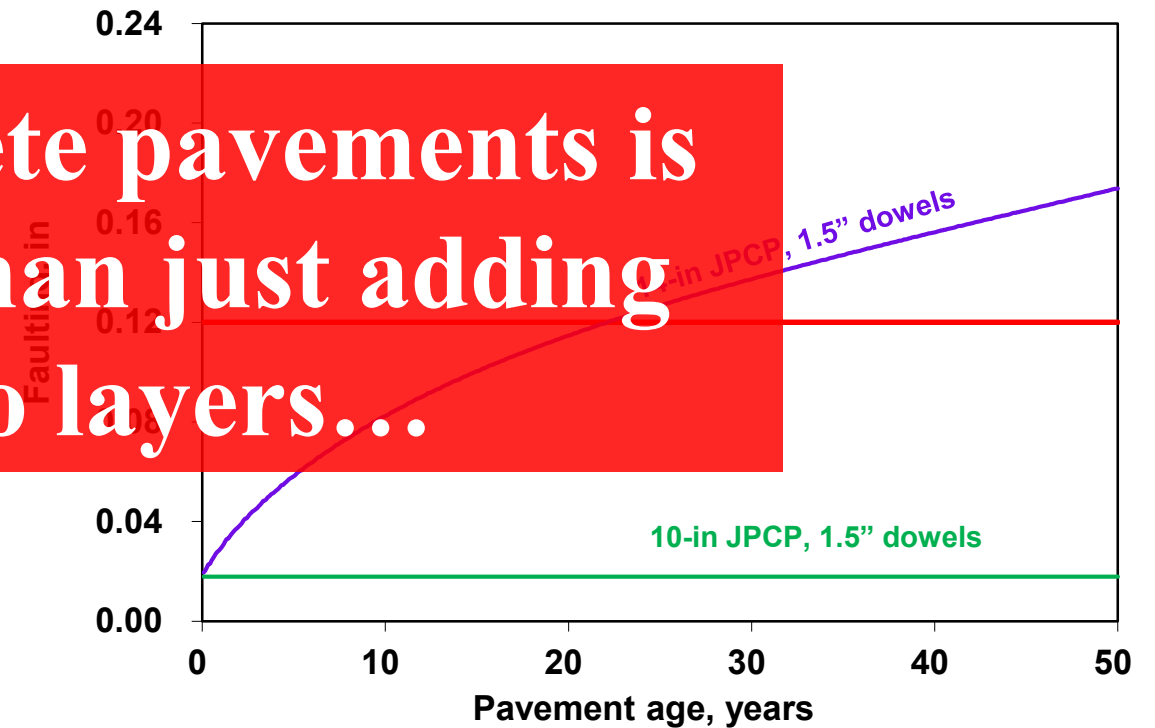
In reality, LTE may be more dependent on the absolute amount of dowels.

Joint Faulting Increases For Thicker Concrete Pavements With Dowels

Thicker PCC, Less Cracking



Thicker PCC, More Faulting



Designing concrete pavements is more complex than just adding thickness to layers...

In Pavement ME, LTE is proportional to Dowel Size/PCC Thick Ratio (e.g. the same dowel setup is more effective for thinner pavements)

In reality, LTE may be more dependent on the absolute amount of dowels.

For some Soil & Climatic Conditions, IRI Design Criteria Can Not be Met ...

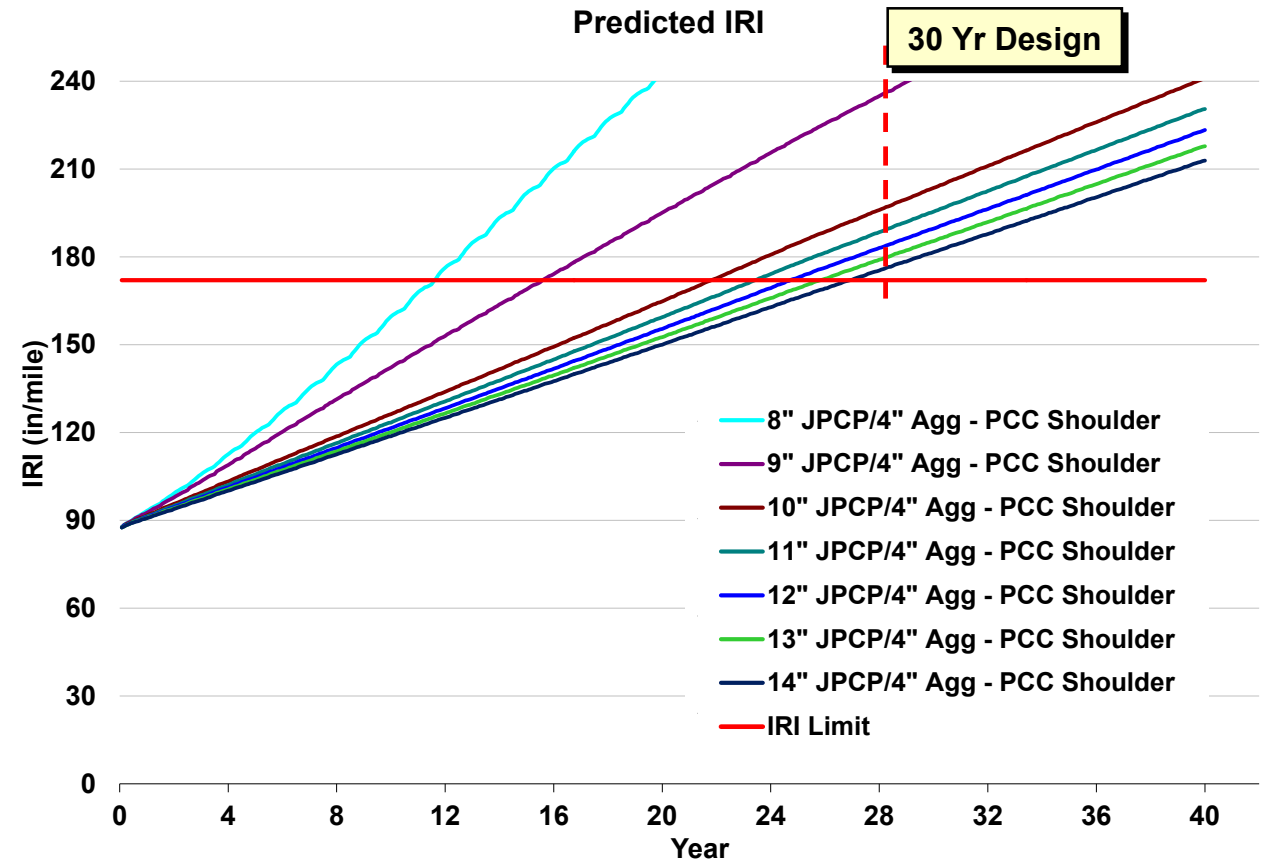
$$\text{IRI} = \text{C1} * (\text{Crack}) + \text{C2} * (\text{Spall}) + \text{C3} * (\text{Fault}) + \text{C4} * (\text{Site Factor})$$

Site Factors

- $\text{SF} = \text{Age} * (1 + 0.5556 * \text{FI}) * (1 + \text{P200}) / 1,000,000$
- FI = Freezing index
- P200 = Percentage of subgrade material passing the 0.075-mm sieve.
- Relates to the potential for soil movements due to frost heaving and settlement

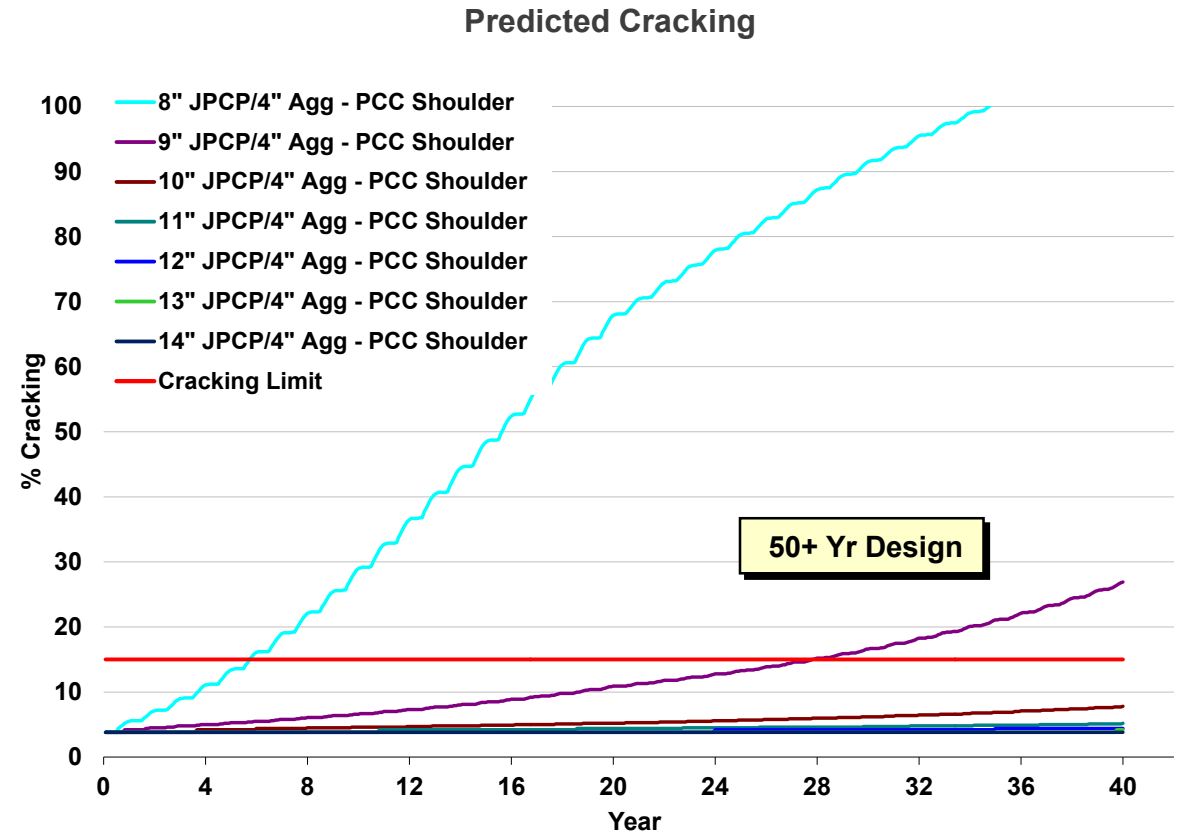
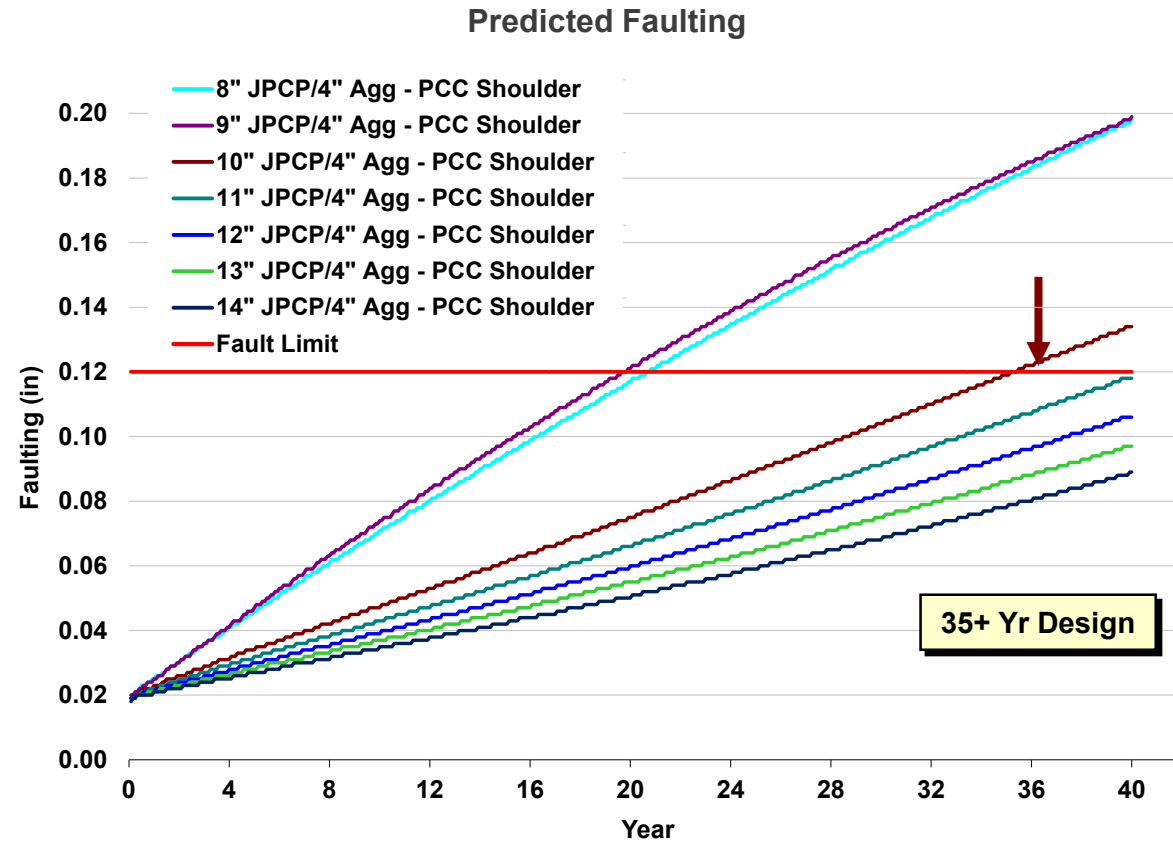
SF is a linear constant increase with age

- For areas with high FI and high P200 soils; the increase is very fast
- When fault and cracking are low, IRI distress level is being controlled by “Site Factors”



No matter the concrete thickness, the 30-year IRI default criteria can not be met

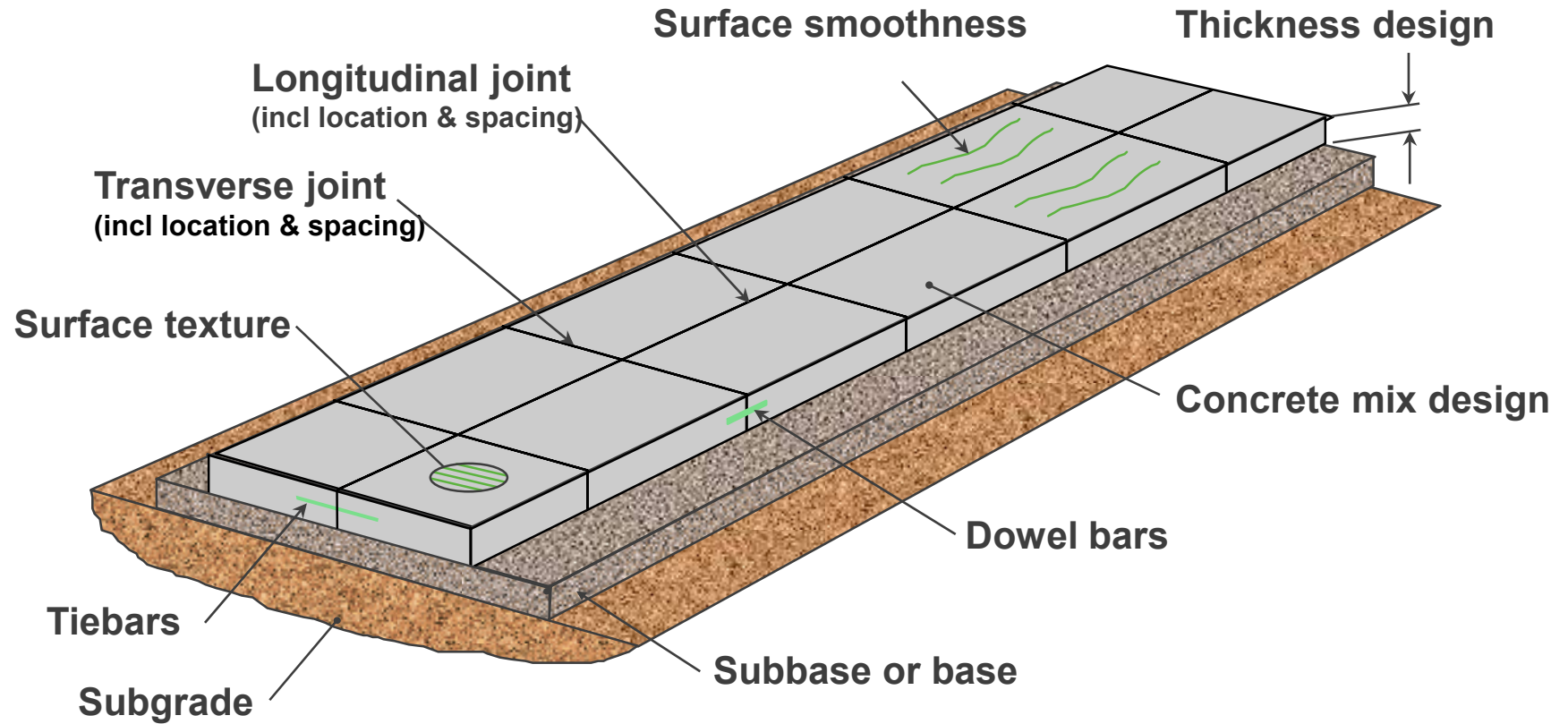
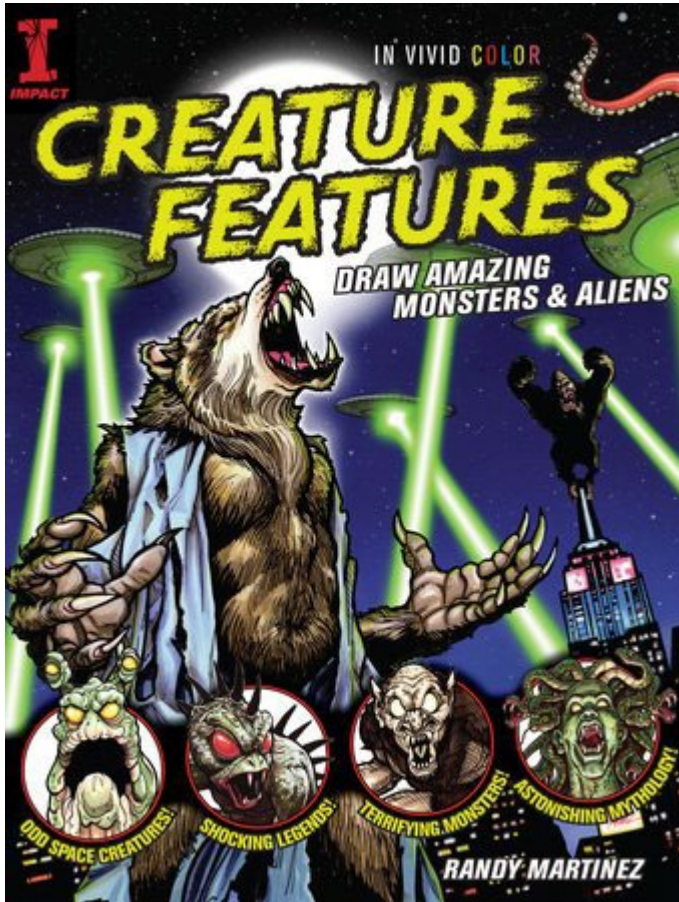
... But Pavement ME Shows Cracking & Faulting Limits can be met with a 10-in Pavement



Question: How does a 14" Pavement IRI increase if there is no faulting or cracking?

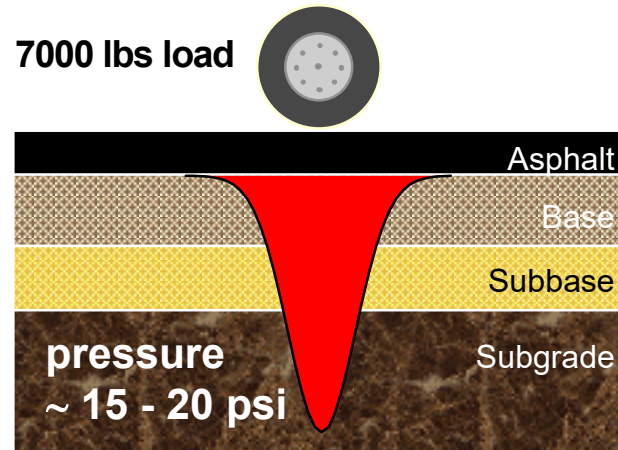
Selecting Features

Concrete Pavements are a Creature of Features



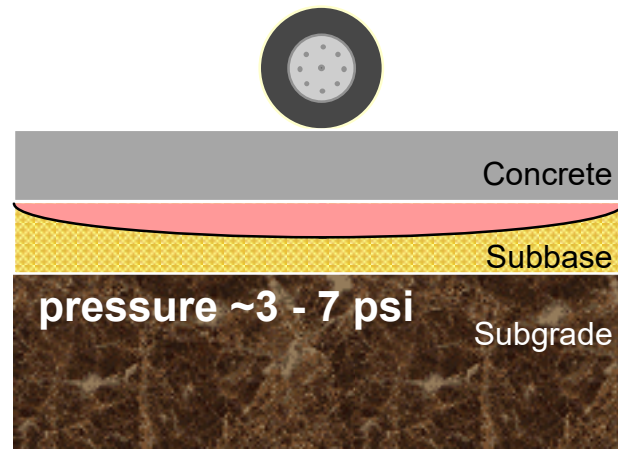
What drives Asphalt & Concrete Pavement Performance is Different

And that difference is reflected in design approaches



Asphalt – Performance is driven by the Materials

- Asphalt Binder type, Master Curves, Balanced Mix Design
- Asphalt Aggregate Gradation
- Strength of underlying support
 - Much more freedom to make Changes



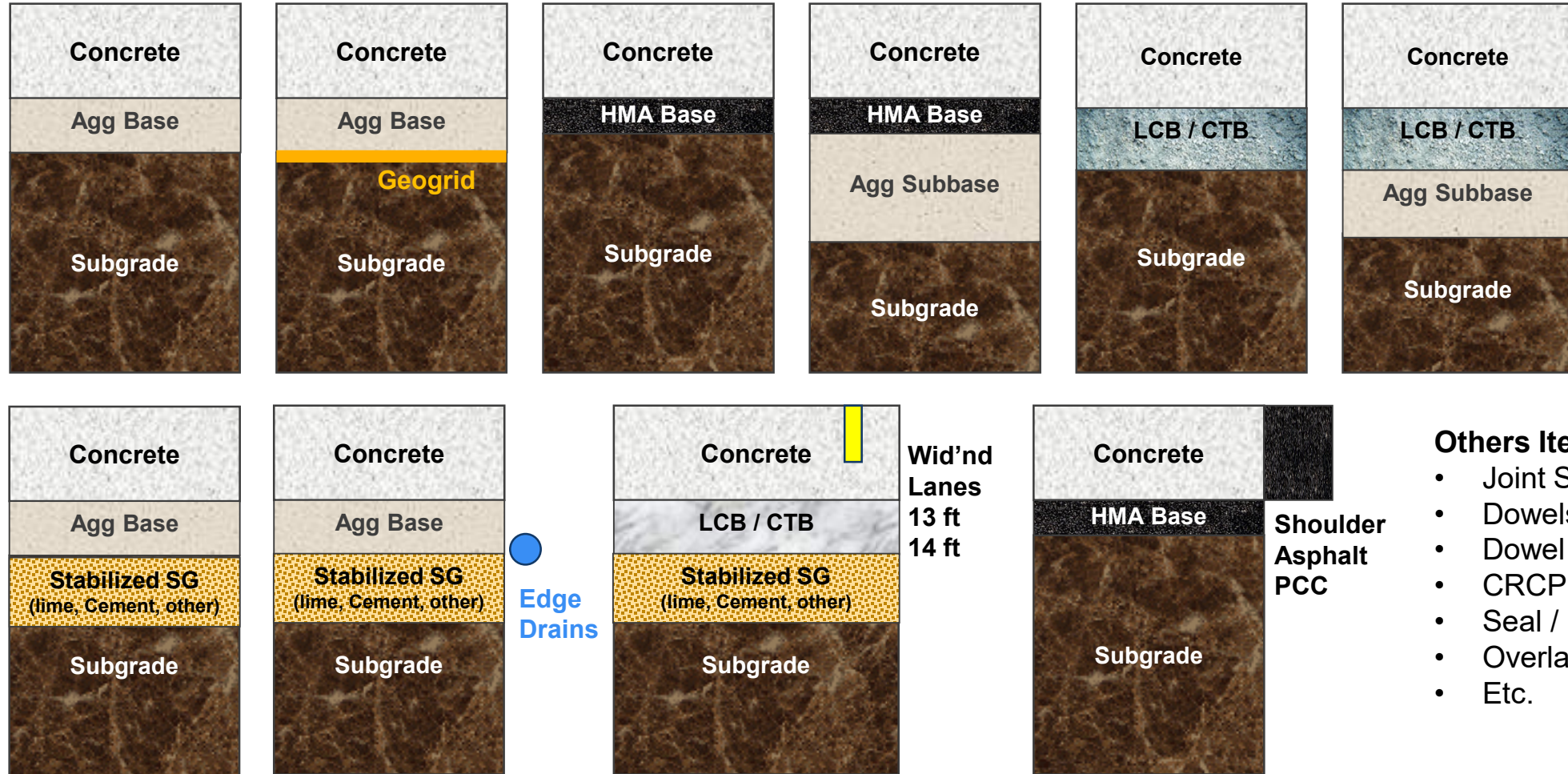
Concrete – Performance is driven by the Features

- Features such as joints, shoulders, dowels, etc. have a significant impact on costs and performance
- Concrete needs to be durable
 - but changing concrete material properties has minimal impact on pavement performance

Most Concrete Features are set by the state with little if any freedom to make changes

There are Many Pavement Designs that are Being Used

All have been used & can be used successfully in most applications



- Others Items**
- Joint Spacing
 - Dowels – Yes or No
 - Dowel Diameter
 - CRCP
 - Seal / No seal
 - Overlays
 - Etc.

Most States have ONE standard pavement structural design that they use in ALL applications

There are Many Pavement Designs that are Being Used

All have been used & can be used successfully in most applications

Creates a false belief that only one design will work

On any specific project, 10 to 15 asphalt & concrete pavement designs will work

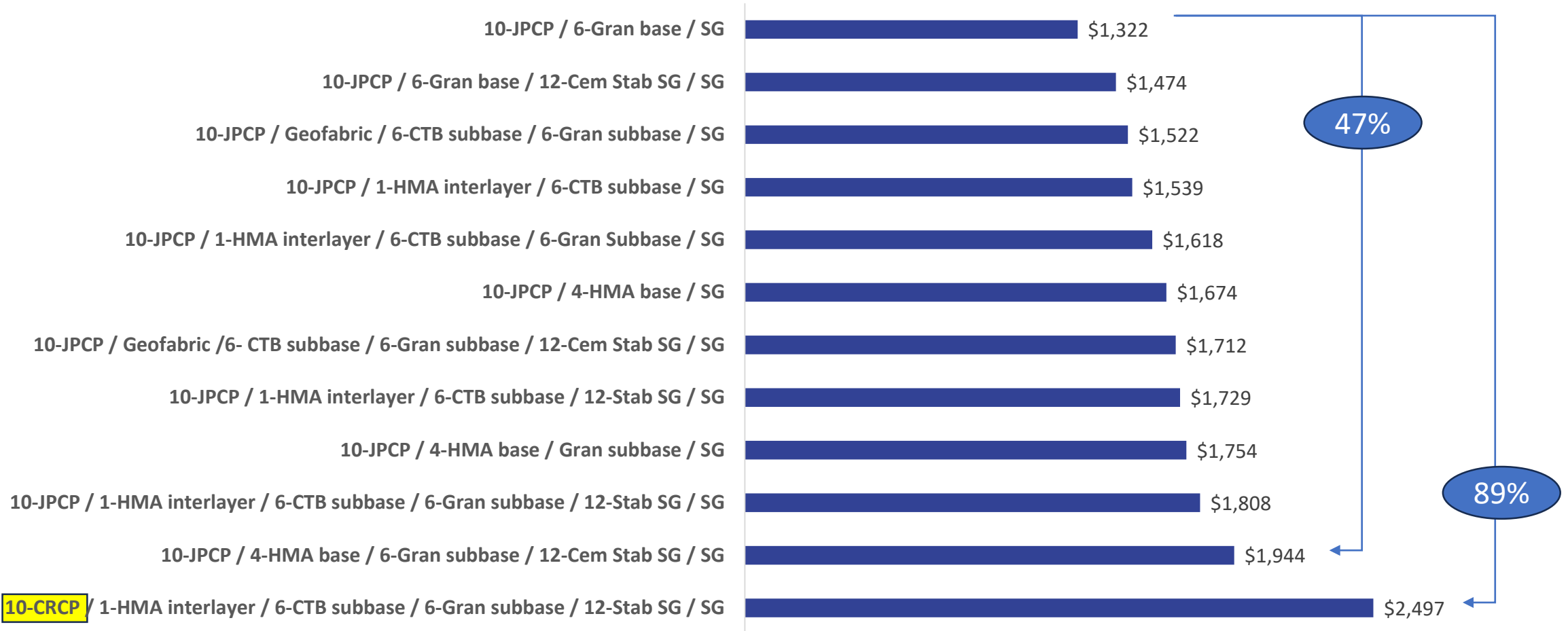
It's the designers and material engineer's role to determine which are feasible and the most COST-EFFECTIVE designs for a given project and its site-specific conditions

The “*This is the way we do things*” severely limits possibilities and can have huge impacts on costs

- Others Items
- Joint Spacing
 - Dowels
 - Lower Diameter
 - CRCP
 - Seal
 - Overlays
 - Etc.

Pavement Structure has a Large Impact on Initial Pavement Cost

Estimated Initial Cost for a 10-inch Concrete Pavement with different base types



Date: June 2024

While standard structures work, additions can lead to overdesigns with no performance credit given

So, Which Features should be used?

Each Design Feature must Balance Performance & Cost

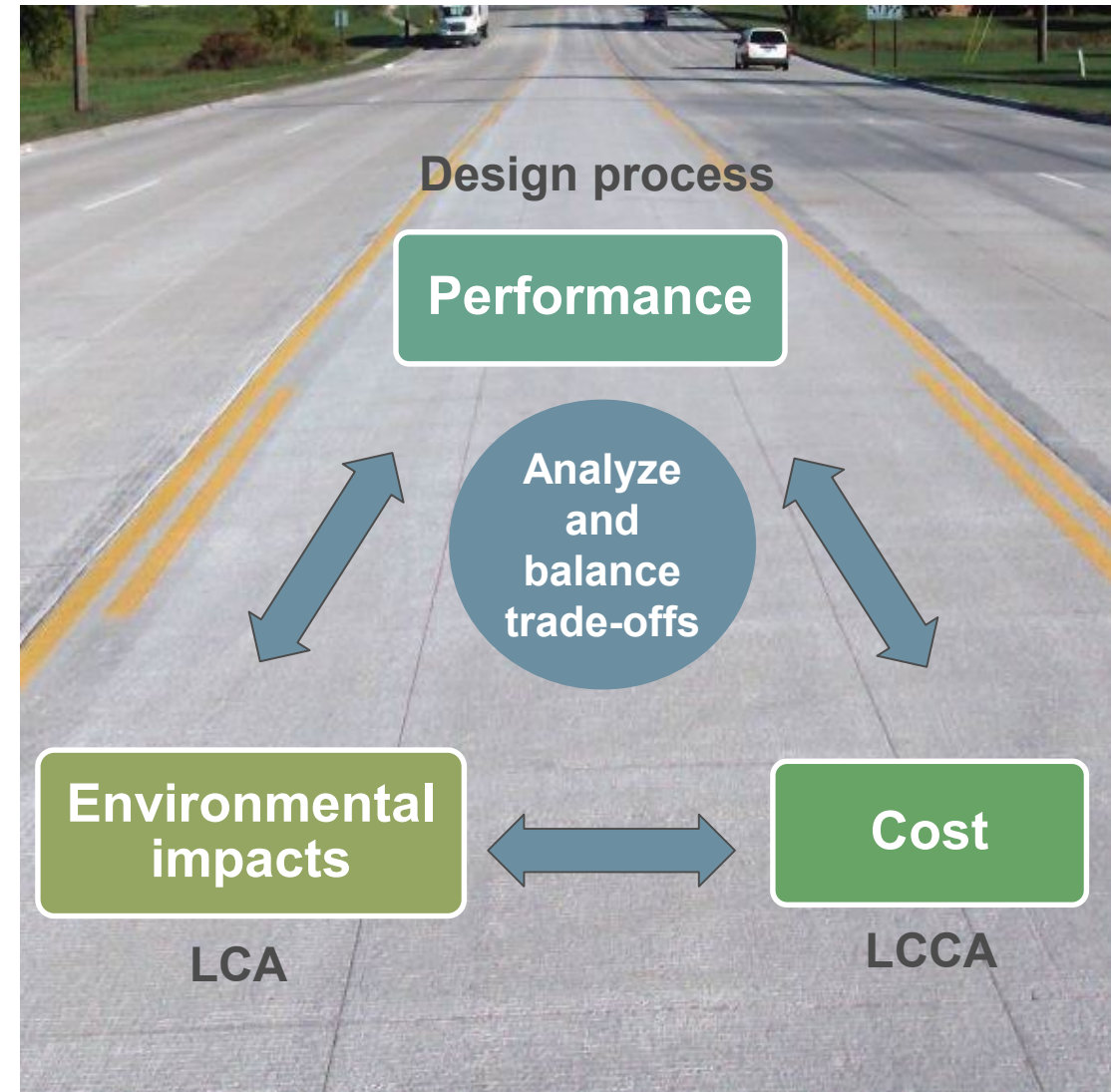
Feature	Benefit or Options
Concrete Pavement Type	Jointed, Jointed reinforced, Continuously reinforced, RCC, Overlays
Optimize Thickness	Reduces overdesign, lowers costs and environmental impact
Joint Spacing	Shorter joints reduces curling & warping stresses (& thickness) but does increase joint sawing and dowel costs
Use >13 ft Widened Lanes	Shifts loading to “interior loading” (reduces thickness)
Dowels / Increase Dowel Size / No Dowels	Increases load transfer, reduces bearing stress reduces faulting
Change Shoulder Design	Tied Concrete vs AC vs RCC; reduced /tapered thickness; no dowels; different mix, etc. (improves edge support)
Optimized aggregate gradation	Reduces cement content, creates denser mix, less shrinkage
Use different concrete mixes	Mainline vs shoulder mixes, 2-layer construction
Change base type	Granular vs asphalt treated vs cement treated, reduce thickness, dense graded vs permeable; subgrade / chemical stabilization
Use single 1/8”-wide single saw cut and filled (not sealed)	Removes second sawing operation and reduces noise
Use Longitudinal tining or Next Generation Concrete Surface (NGCS)	Reduces noise

Tools for Optimizing Designs of a Pavement System in an Iterative Process

TOOLS

- 1 AASHTO Pavement-ME Design Procedure**
Predicts pavement performance over the analysis period
- 2 Life Cycle Cost Analysis (LCCA)**
Determines which pavement design is most cost effective over the analysis period
- 3 Life Cycle Assessment (LCA)**
Determines which pavement design is most “sustainable” over the analysis period

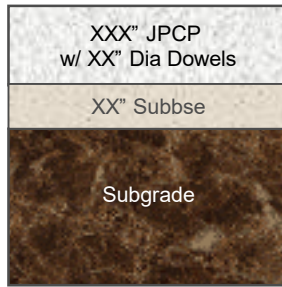
Combining performance with the LCCA / LCA allows designers to make trade-offs that balances costs, sustainability, & performance over the full life cycle



To Evaluate Features, we need to Change HOW we Design Pavements

Designs are developed in a “static mode” and then compared to select the final pavement design

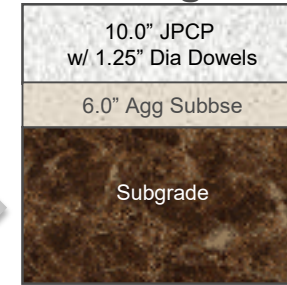
Design Proposal & Context
Layers
Traffic
Climate



Analyze Using
Basic Design Process



Final
Design



Apply Lifecycle Bill of
Activities

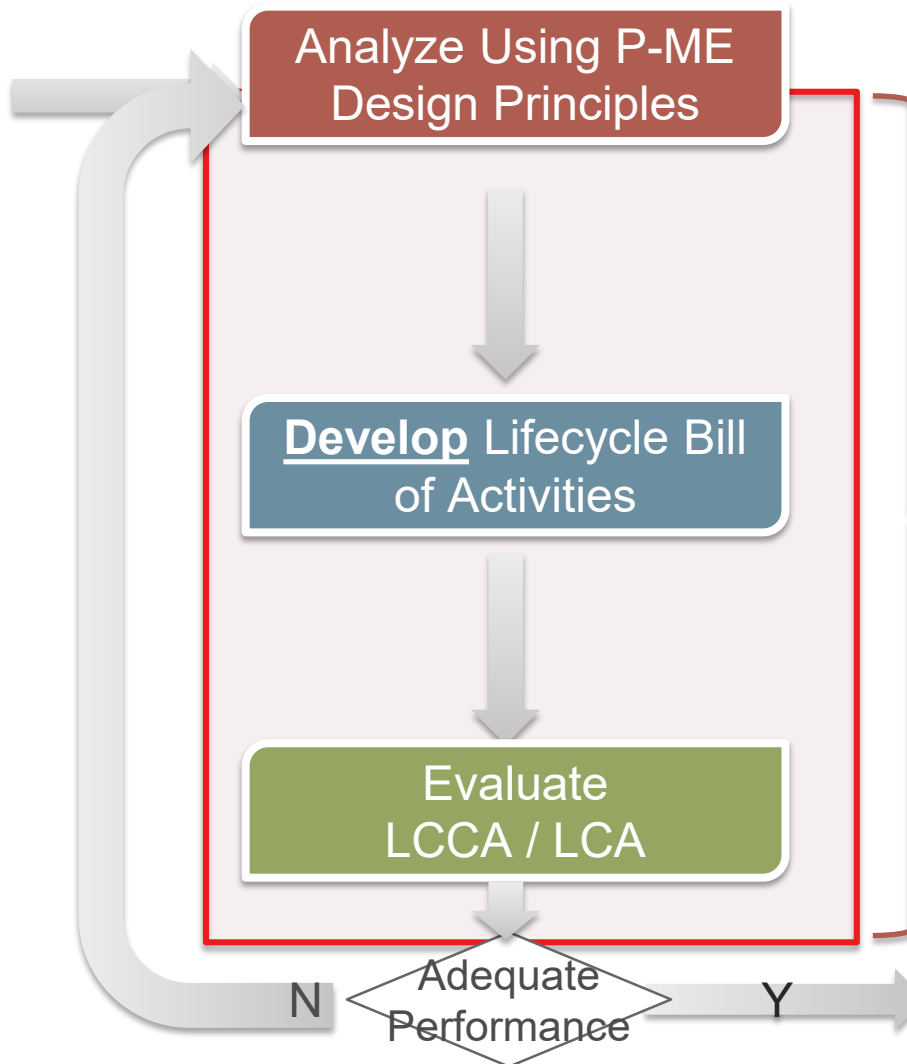
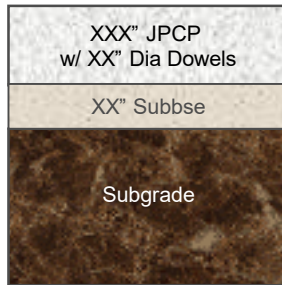
Evaluate
LCCA / LCA

Doing a LCCA/LCA at the end misses opportunities to make design changes

Need to Link Design and Evaluation in an Iterative Process

Assures that performance, costs and CO2 impacts are representative of the actual pavement

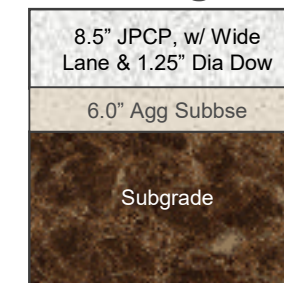
Design Proposal & Context
Layers
Traffic
Climate



Designing pavements in an iterative procedure provides a Feedback Loop

- Improves performance
- Lowers cost
- Lowers environmental impacts

Final Design



Route 67 in Ramona, Ca

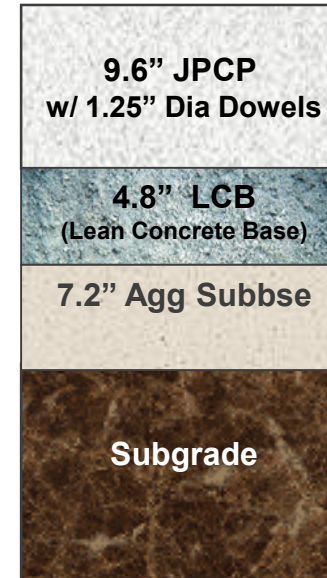
Falls within the *South Coast* CALTRANS climatic region

Route 67 in Ramona, CA (at Route 78 junction)

- Moderate volume road:
- 35-mph urban road
- 2 lanes in each direction (+ middle turn lane)
- 2 inner/2 outer shoulders
- Daily traffic: 23,400 (ADTT = 1,357)
- Initial ESAL = 335,000 / year
- 20-year Design Life / 55-year Analysis Period



CALTRANS Concrete Design



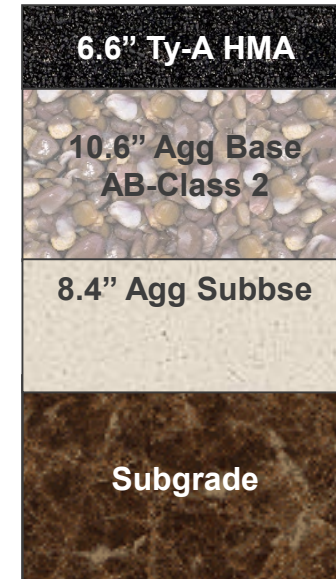
JPCP new construction:

Design life = 20-years

Maintenance Level = 1,2,3

- 2% Patch & DG at year 25,
- 4% Patch & DG at year 30
- 6% Patch & DG at year 40
- 3" Asphalt overlay in year 45 (10-year life)

CALTRANS Asphalt Design



HMA new construction:

Design life = 20-years

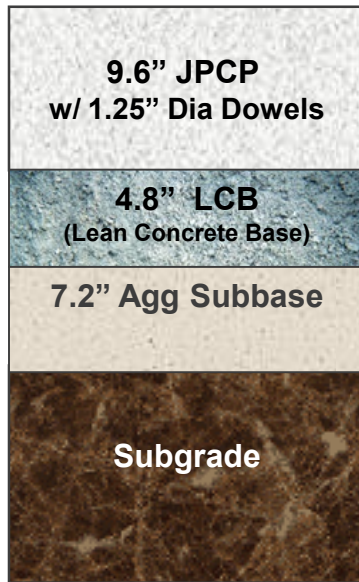
Maintenance Level = 1,2

- 3" AC Overlay in years 20,
- Mill / 4" ACOL in year 25
- Mill / 3" ACOL in year 35
- Mill / 4" ACOL in year 45
- Mill / 3" ACOL in year 50 (5-year life)

Estimated Cost and Environmental Impact for Standard Caltrans Pavement Designs

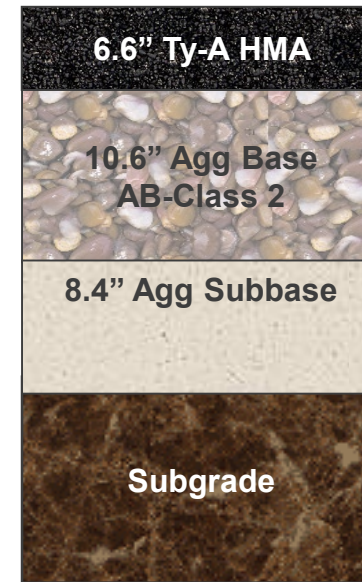
Route 67 - Ramona, CA

CALTRANS Concrete Design



	LCCA (NPV \$/mile)	LCA (tons CO ₂ e/mile)
Initial Const.	\$3,147,585	3,954
<i>Pavement</i>	\$2,229,803	2,860
<i>LCB</i>	\$644,902	781
<i>Agg Subbase</i>	\$272,880	313
Rehabilitation	\$911,663	479
Carbonation		(123)
PVI-Deflection		604
PVI-Roughness		1,912
Total	\$4,059,248	6,826

CALTRANS Asphalt Design



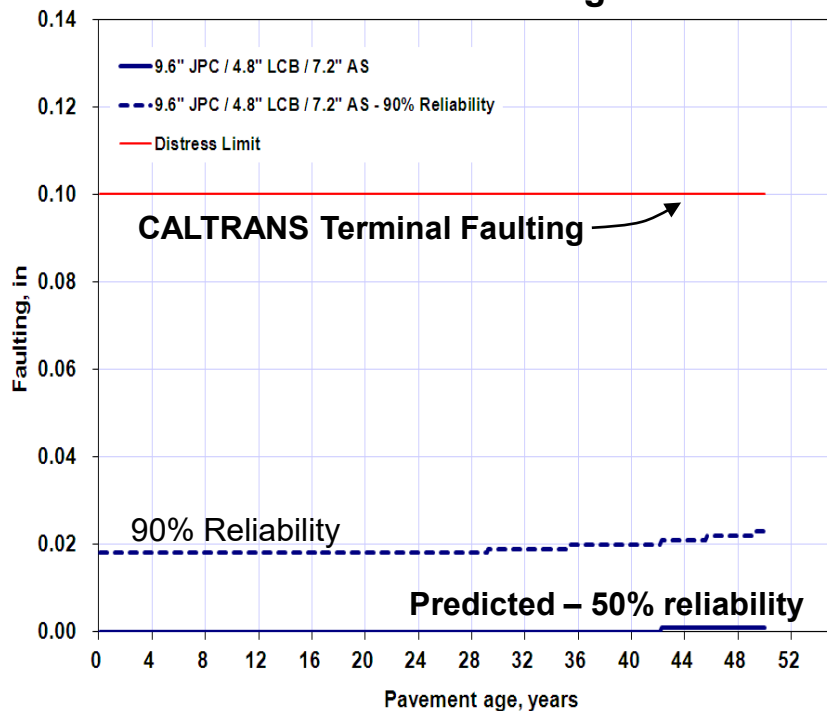
	LCCA (NPV \$/mile)
Initial Const.	\$2,278,102
<i>Pavement</i>	\$1,437,480
<i>AB-Class 2</i>	\$522,262
<i>Agg Subbase</i>	\$318,360
Rehabilitation	\$1,104,504
Total	\$3,382,606

Asphalt is 38% lower in Initial Costs and 20% lower in Life Cycle Costs

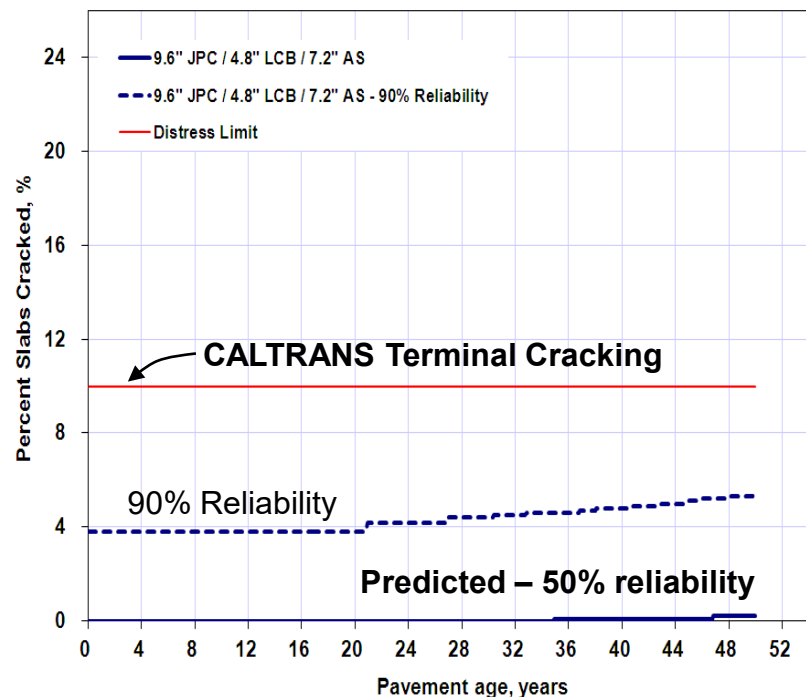
Route 67 Pavement-ME Predicted Performance is High

Faulting, Cracking, & IRI are well below terminal levels for the entire analysis period

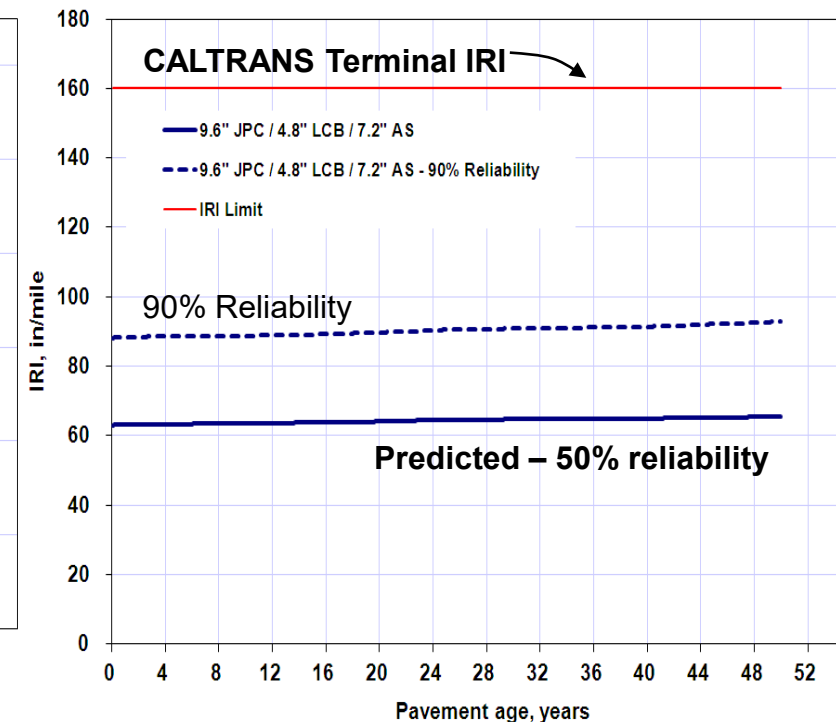
Predicted Faulting



Predicted Cracking



Predicted IRI

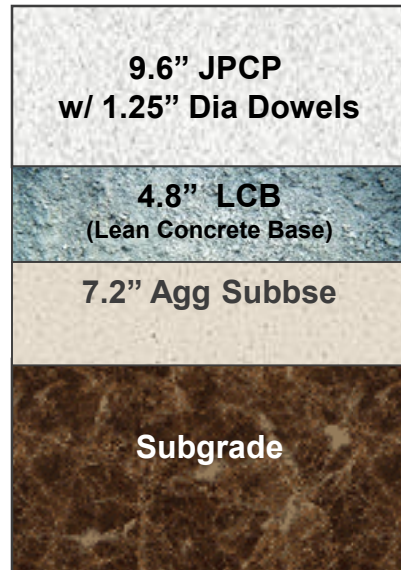


**Pavement is over-designed because it does not need rehabilitation for the entire 50-year analysis period
Creates the opportunity for project specific optimization**

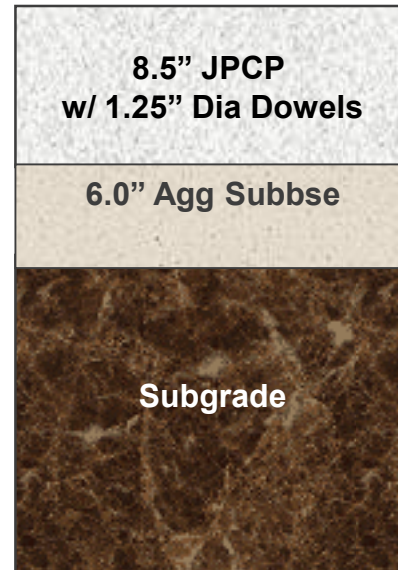
Over-Design Creates the Opportunity for Optimization

Each design feature needs need to balance performance, cost & environmental impact

CALTRANS Concrete Design



Optimized Concrete Design



Features Evaluated

- Iterated Concrete Thickness
 - 9.0"
 - 8.5"
 - 8.0
- Removed 4.8" Lean Concrete Base
 - Accounts for 20% of the initial construction costs & GWP
 - Performance history shows that aggregate bases have worked in similar applications
- Iterated Aggregate base thickness
- Develop rehabilitation activities based on Pavement-ME distresses

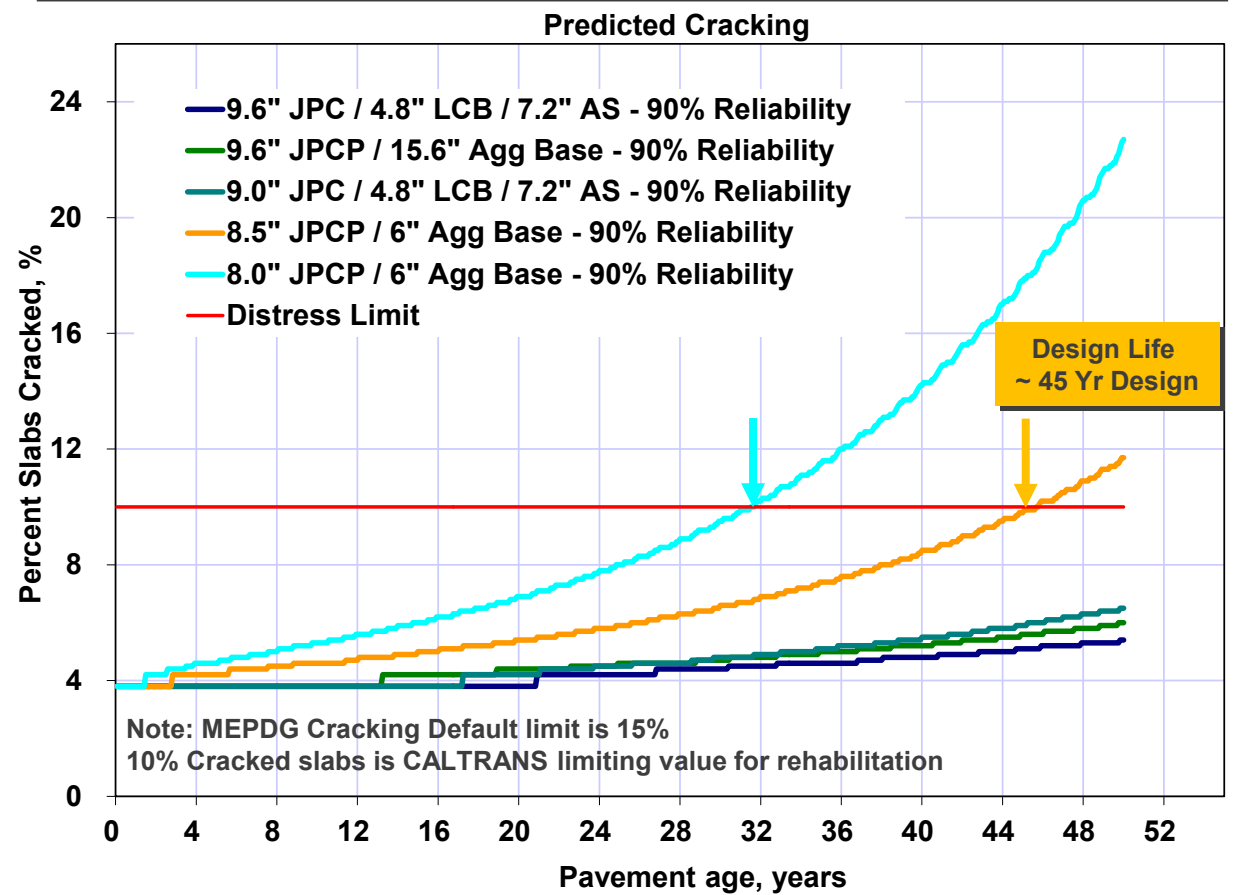
8.5" Jointed Plain Concrete Pmnt w/ Dowels meets the Performance Criteria

Good balance between long term performance and low cost / low GWP

- Performance curves show all the pavement options evaluated exhibited good performance
 - Cracking not an issue until the pavement is at 8.5-inch or less.
 - Faulting and IRI are well below unacceptable levels for all cases
- 8.0-inch pavement met the 20-year design life
- 8.5-inch JPCP design chosen as optimized design
 - Cracking hits terminal level at year 45
 - Good balance between long term performance (and a hedge against increased traffic) and low cost / low GWP

Optimization does not mean choosing the Thinnest (cheapest) Pavement
 It's about selecting the Most Effective

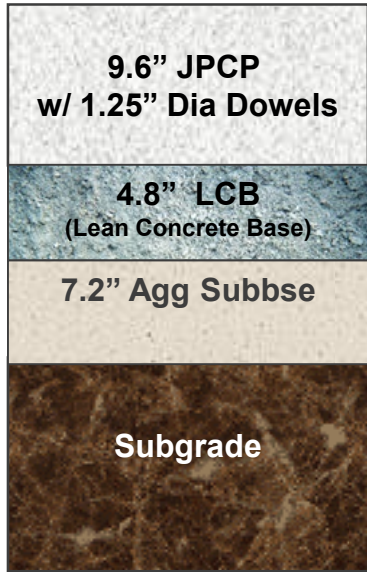
Pavement-ME Predicted Performance



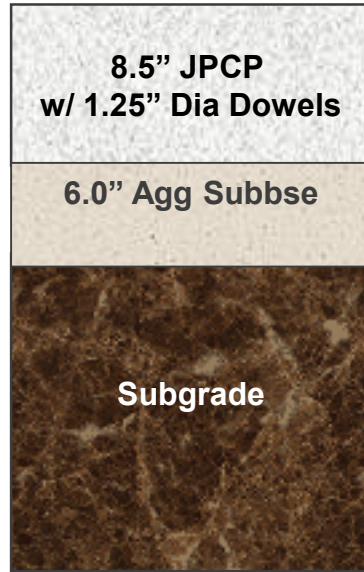
↓ Arrows indicate year of predicted 1st rehabilitation for that given pavement

Project Specific Pavement Optimization Lowers Cost & Environmental Impact

CALTRANS Concrete Design



Optimized Concrete Design



	Original CALTRANS Schedule		Optimized Pavement-ME Design	
	LCA (tons CO ₂ e)	LCCA (NPV \$)	LCA (tons CO ₂ e)	LCCA (NPV \$)
Initial Const.	3,954	\$3,147,585	3,063	\$2,256,638
<i>Pavement</i>	2,860	\$2,229,803	2,803	\$2,021,307
<i>LCB</i>	781	\$644,902	--	--
<i>Agg Subbase</i>	313	\$272,880	260	\$235,331
Rehabilitation	479	\$911,663	54	\$315,798
Carbonation	(123)		(87)	
PVI-Deflection	604		704	
PVI-Roughness	1,912		2,110	
Total	6,826	\$4,059,248	5,844	\$2,572,437

Optimization reduced the initial construction GWP by 890 tons (22.5%) and the life cycle GWP by 980 tons (14.3%)

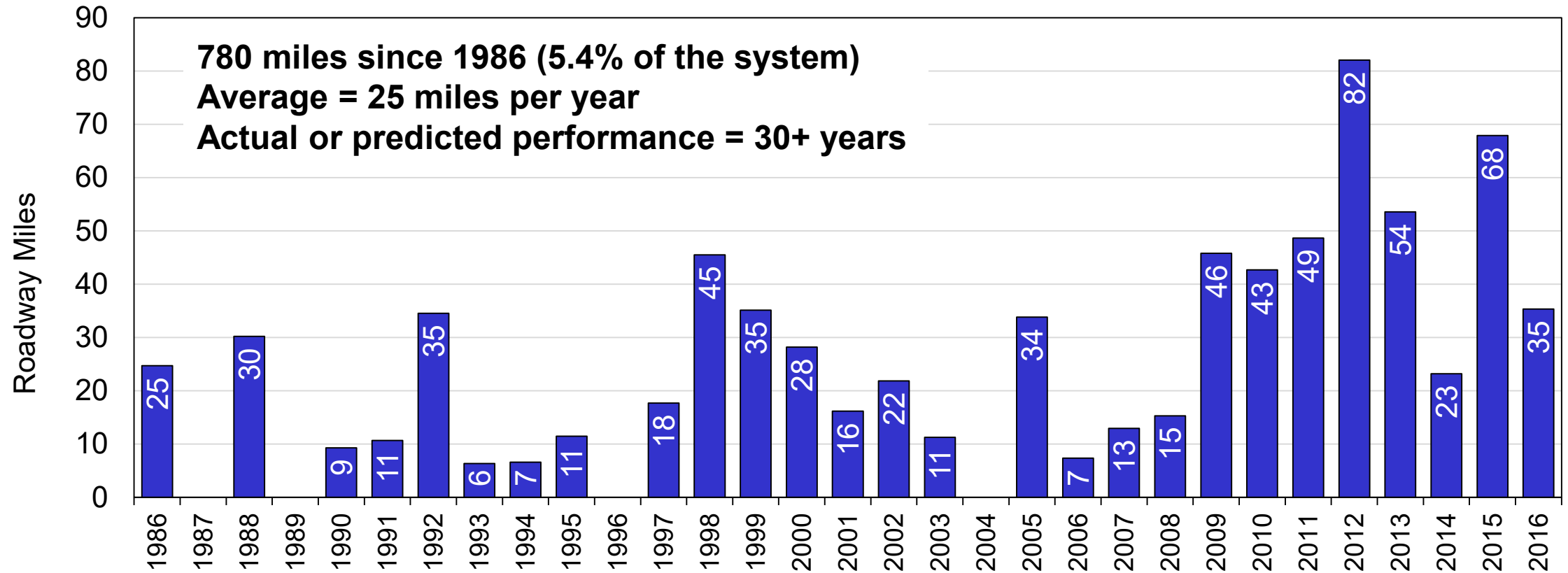
Optimization reduced the initial construction costs by \$890k (28.3%) and the life cycle cost \$1.48M (36.6%)

Some of our Favorite Optimization And Design Features

Overlays are a Great Design Optimization Tool Not Used Often Enough

CPTech Overlay Guides have solutions for elevation, bridges, slopes, traffic control, & other constraints

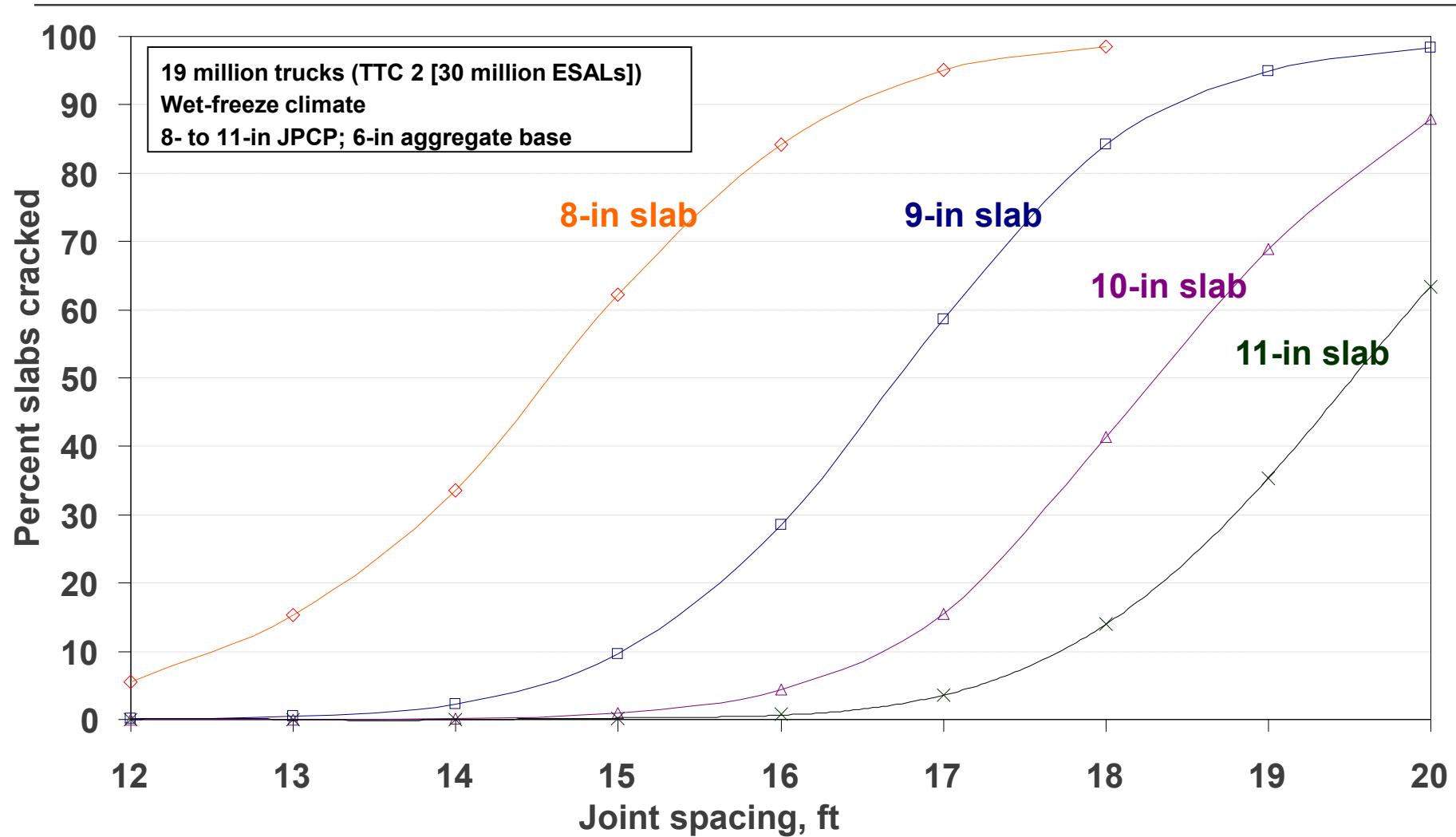
Roadway Miles of Unbonded Overlays In Minnesota (1986-2016)



“Unbonded OL’s last as long or longer at 1/3 of the price” – Maria Masten, MnDOT

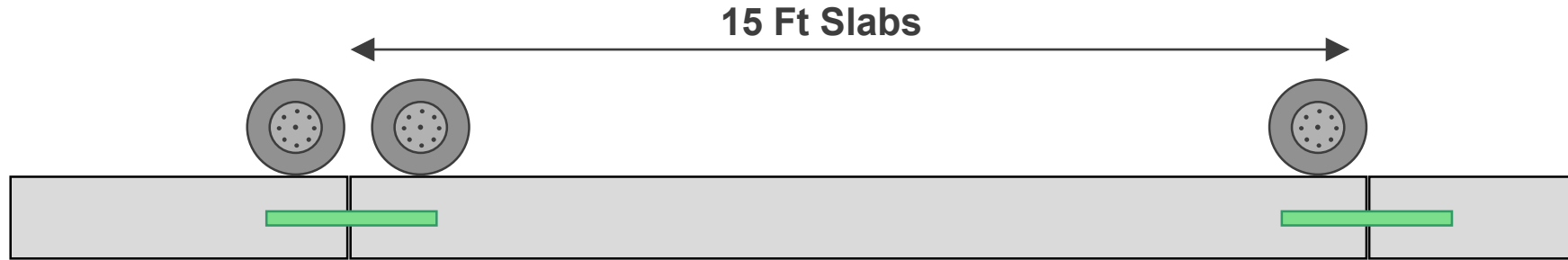
Shorter Joint Spacing Reduces the Required Slab Thickness

Joint Spacing vs. Slabs Cracked

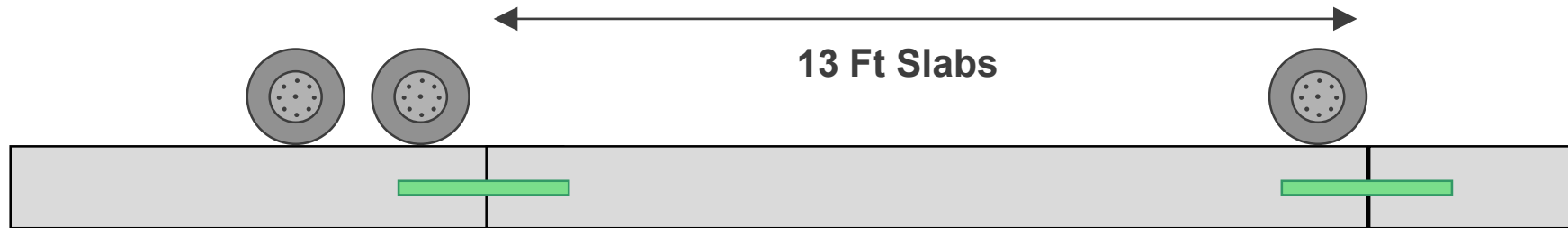


Maximum Joint spacing = 18 to 24 times thickness (15 ft max)

Shorter Joint Spacing Reduces Wheel Loads Stresses



Loading the slab at each end creates additional top-down stresses and causes earlier top-down cracking

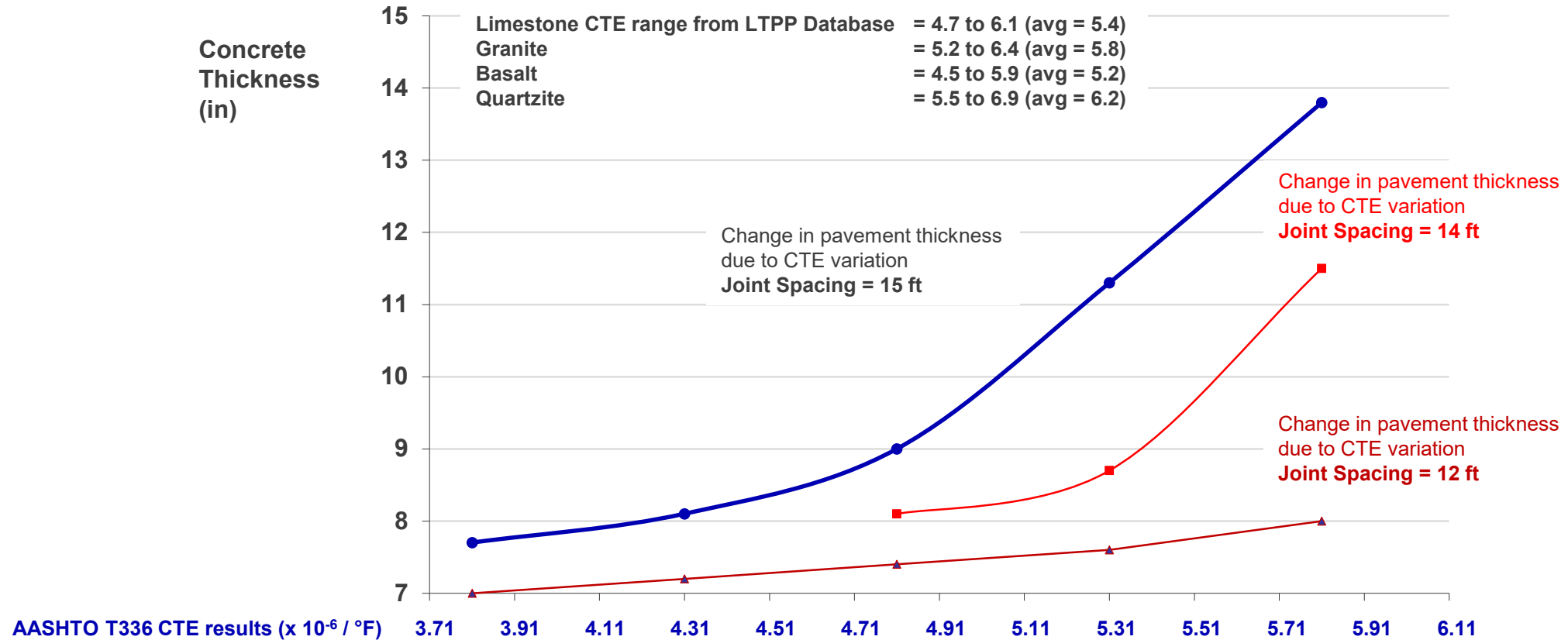


Reducing slab length means only one end is loaded by an axle, which reduces top-down stresses and extends life

**Each foot of reduced joint spacing adds ~0.40% or less to pavement costs
Approximately equal to 1/8 to 1/4-inch of Concrete**

Curling Effect Due to CTE can be Mitigated with Thickness or Joint Spacing

Shorter Joints decrease the moment arm for slab uplift



Issue is not how low CTE is, but how to design pavements based on the CTE value for your aggregates

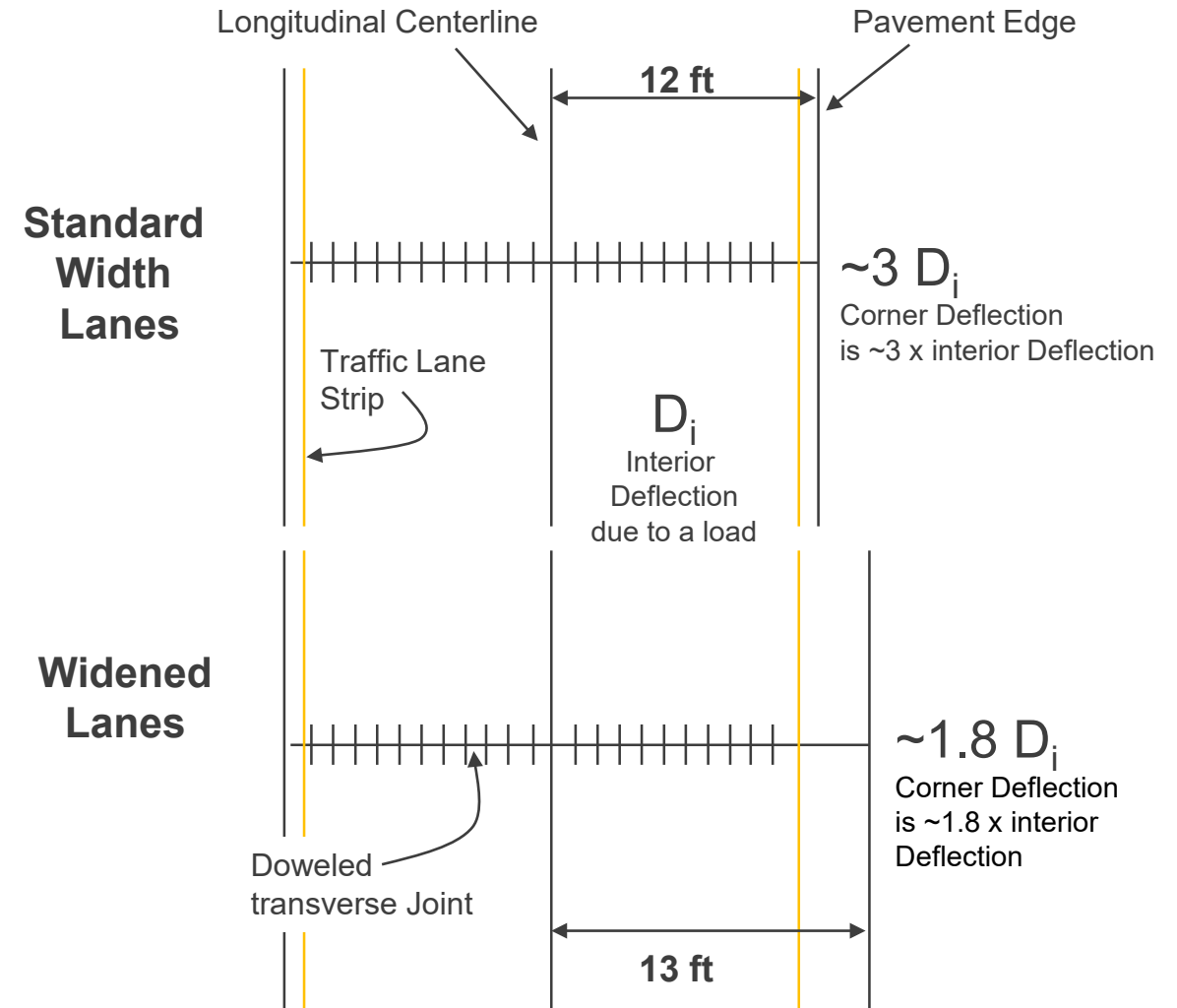
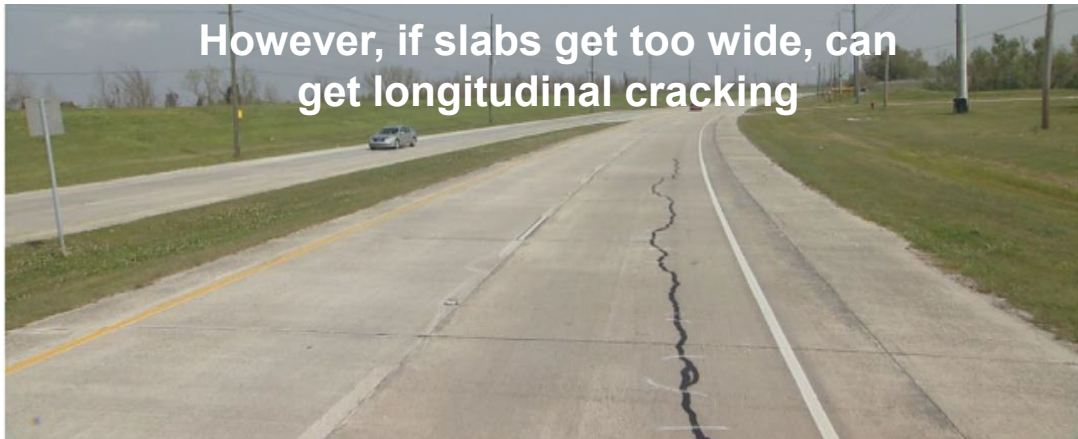


Pavement = 15 ft jointed concrete pavement on 4" AC base on 12" limerock base. Subgrade = A-3 Soil.
 20 Year Design with 2-Way AADTT = 15,000, 2 lanes in each direction (ESAL ~ 127.9 M), Climate = Orlando FL



Widened Lanes Shifts Traffic Away From Edge

Lowers Deflections & Stresses at the Edge and allows for Thinner Pavements

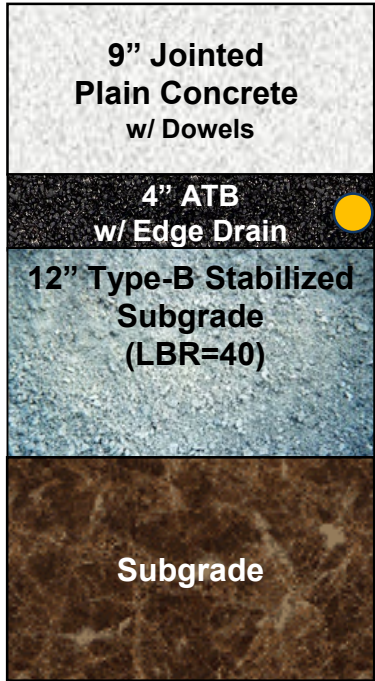


Each foot of lane widening adds ~6 to 8% to Lane Costs
 Approximately equal to 1.25 to 1.50-in of thickness, but cost impact depends on shoulder type

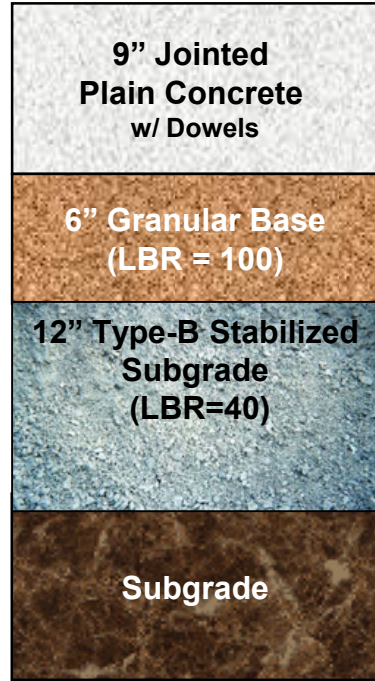
Whether to Add Features should be Based on its Cost / Benefit

If they extend life long enough to cover its NPV, it should be used

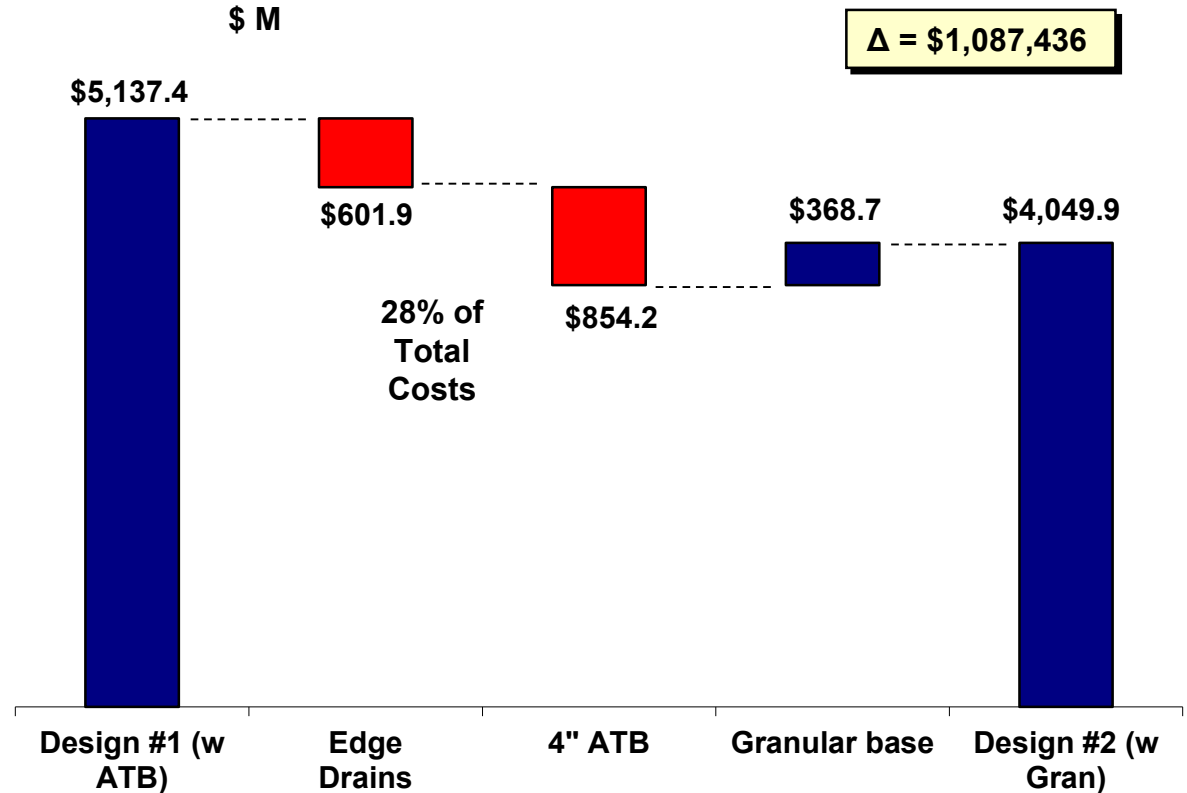
Design #1
(with ATB & Drainage)



Design #2
(6 inch Granular Base)



Component Cost for 1 mile of pavement

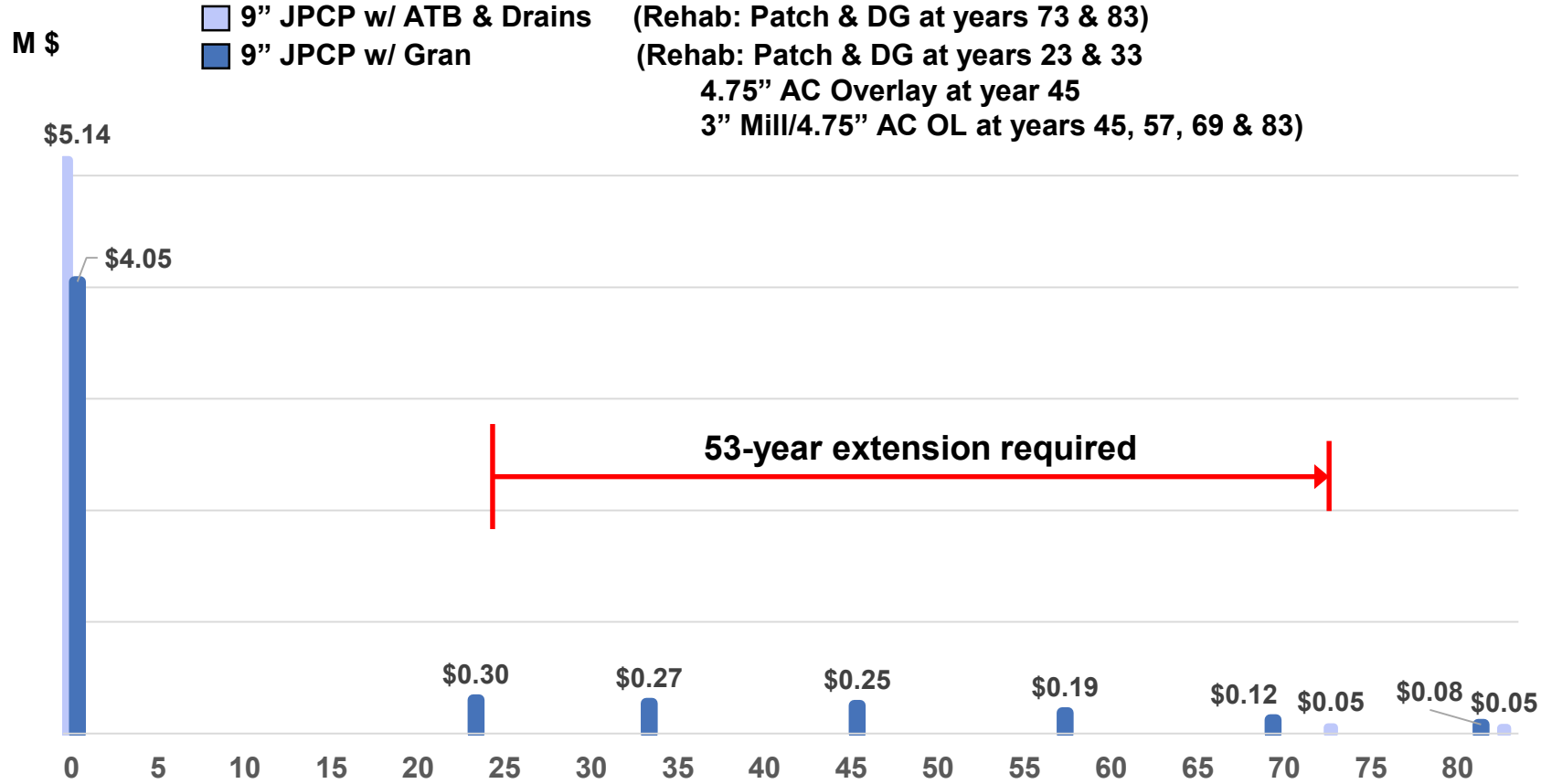


For the drainage and ATB to be effective it must extend the pavements life to overcome \$1,087,436 initial cost differential

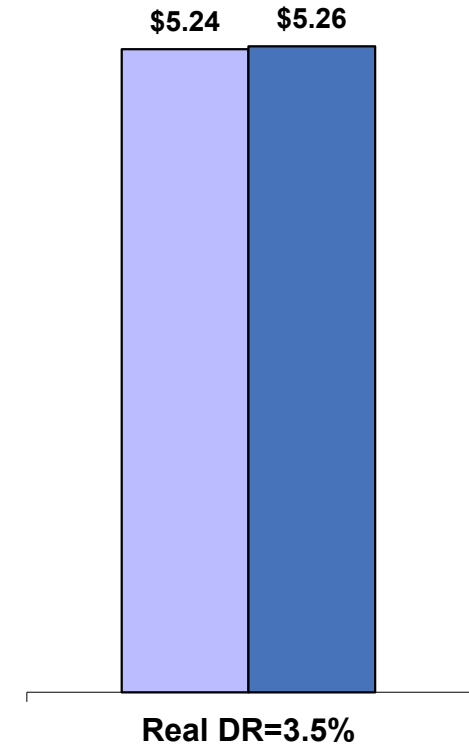
The Pavement with ATB Must Last 73 Years Before First Rehabilitation

Based on an equivalent Life Cycle Costs comparison

NPV expenditures by pavement type for 1 miles (\$ M)



LCC Net Present Value (\$ M)



Design Issue Materials Engineers can help with



Initial costs - Pavement, base, and subgrade stabilization materials and labor

Rehab costs also include other Incidental Costs (striping, mob, etc) - Assumed to be 1%, Traffic Control – 3%, & Engineering & Inspection - 2% of material cost each



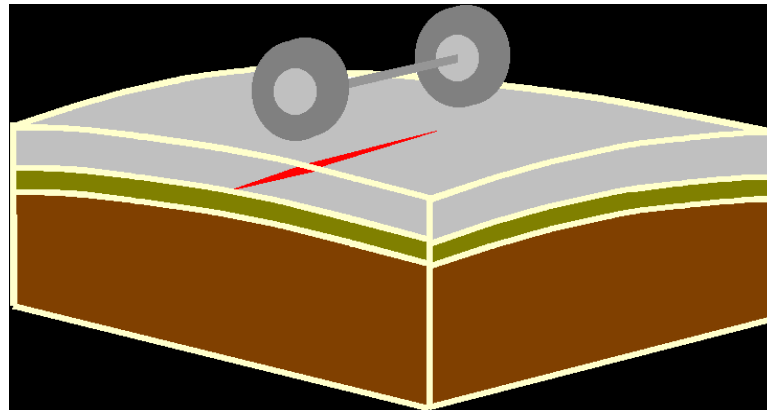
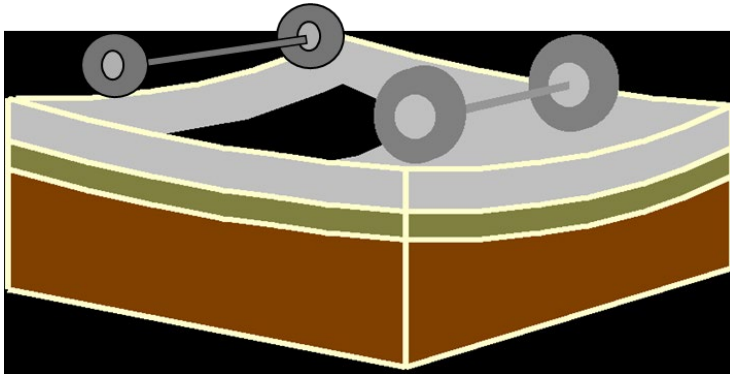
Be The Concrete Pavement Expert Know and Share What Impacts the Models

- Top – Down Cracking

- Increase PCC Thickness
- Increase PCC Strength
- Increase Width of Lanes
- Increase LT w/ Shoulders
- Increase Support Stiffness
- Decrease Joint Spacing

- Bottom – Up Cracking

- Increase PCC Thickness
- Increase PCC Strength
- Decrease Joint Spacing
- Reduce Support Stiffness
- Change PCC / Base Contact Full-Friction Time



- Improve Mechanical LT
 - Increase Dowel Size
 - Decrease Dowel Spacing
- Decrease Joint Spacing
- Increase Width of Lanes
- Reduce Underlying Layer Erosion
 - Increase Erodibility Index
 - Decrease Joint Spacing
- Reduce Thickness
 - Only if Cracking is Passing

All Current Pavement design Programs Assume Good Concrete Mix

But calibration data” & historical data includes pavements with material durability issues

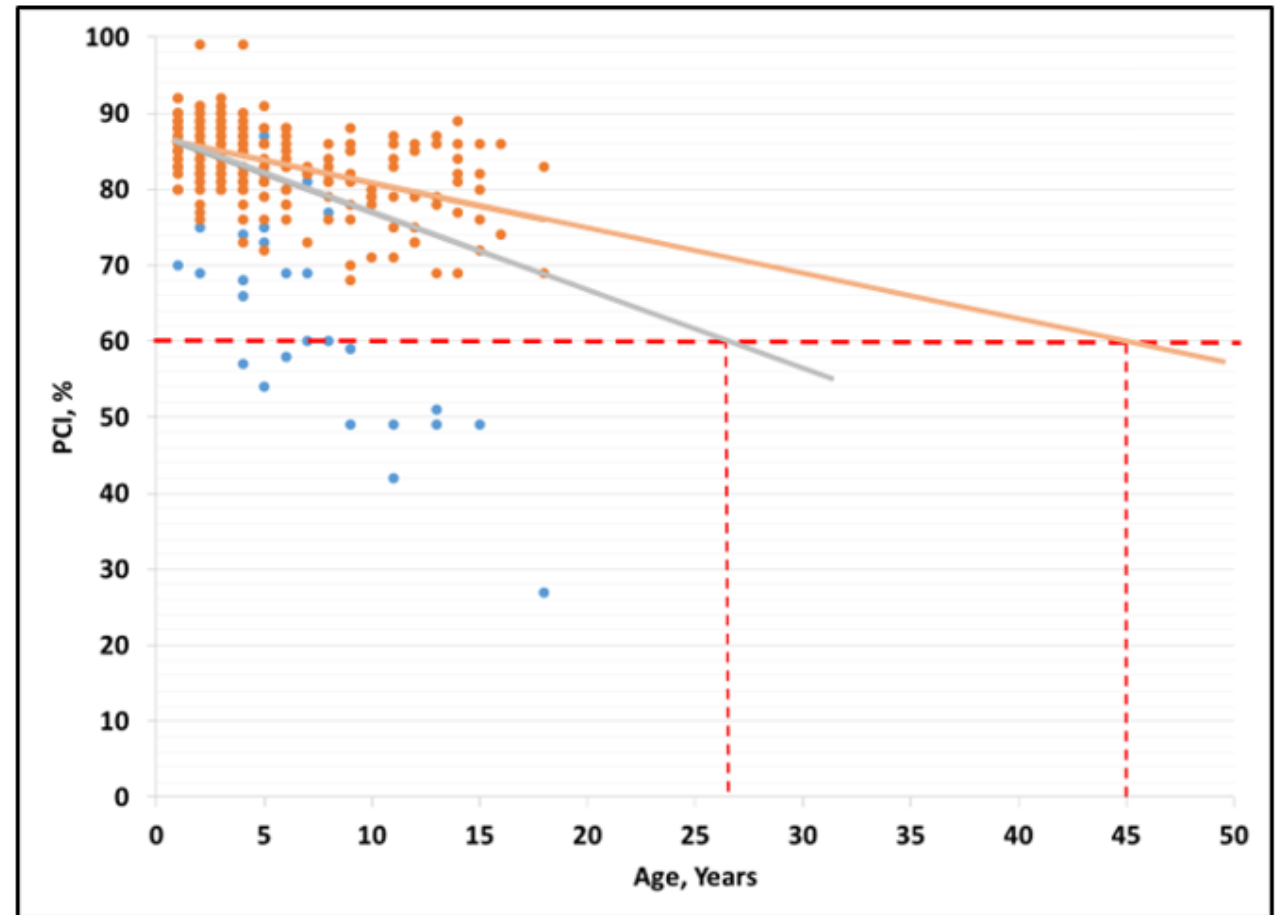
Iowa's Thin Bonded & Unbonded Concrete Overlay Performance

Causes for poor performance & early failure in Iowa concrete overlays:

- **Materials-related distresses (most common)**
- Load-related/under-design
- Rough ride

These are many of the same issues found with conventional concrete pavements

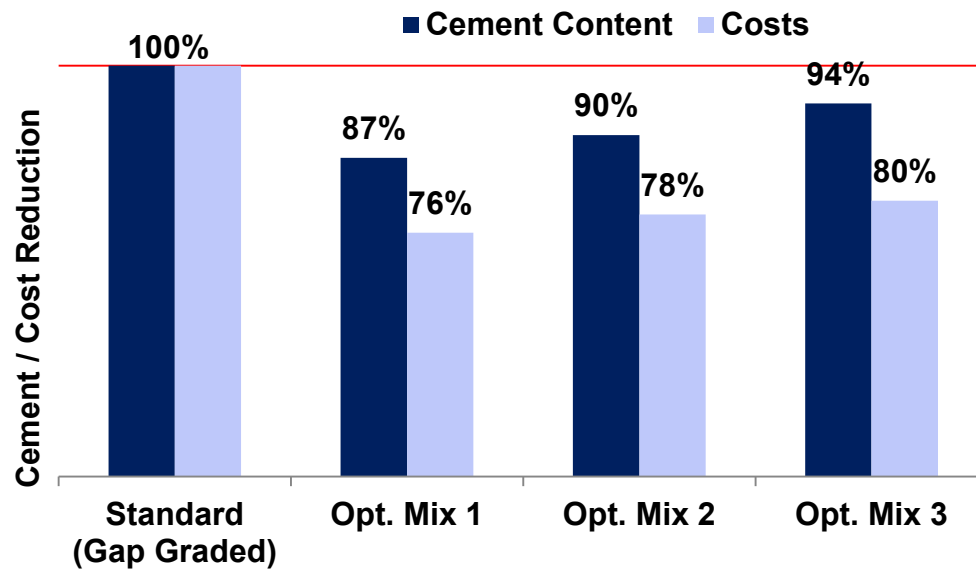
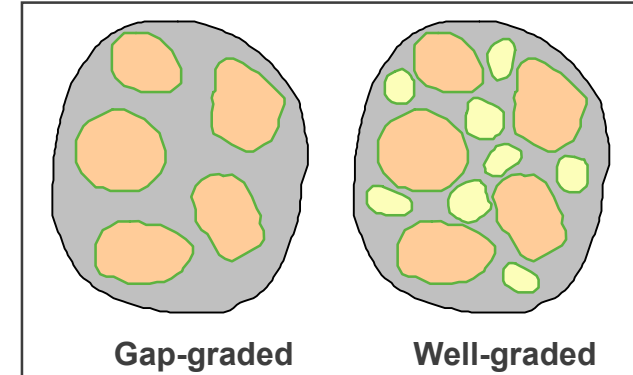
With proper materials & construction, it is reasonable to expect much improved performance (that is not accounted for in design)



Using Well-graded Concrete Aggregate Gradation Improves Performance And Lower Costs

Benefits of Well-graded mixes

- Increases concrete density (improves durability)
- Reduces water demand (decreases shrinkage)
- Improves workability (easier to construct, reduces edge slump)
- Lower cement contents for the same or higher strength (reduces mix costs)



Structural / Synthetic Fibers can Improve Performance

Most useful on Pavements less than 6 inches

- **Fibers do not increase the concrete's strength**
 - Increases toughness
 - Increases post-crack integrity / fatigue
 - Improve ductility
- **Helps control plastic/drying cracking**
 - Does not reduce shrinkage
 - Does not change rules for joint spacing
 - Does not control of movement across random cracks
- **Typical Dosage Rates**
 - Polypropylene ~ 3 lbs./CY
 - Steel ~ 40 to 60 lbs./CY
 - Synthetic ~ 3 to 5 lbs./CY



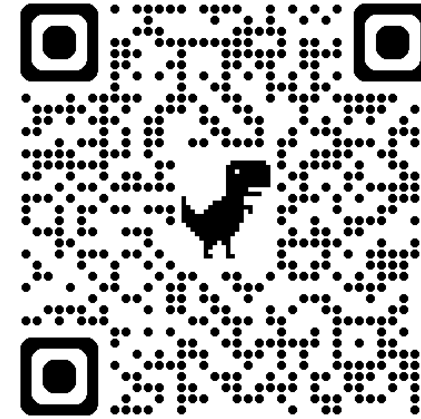
See <https://www.cptechcenter.org/concrete-overlays/>

MIT Streamlined LCA Platform

Optimization in the Future...Today!

w/ LCCA In a Future Update

<http://pavementlca.mit.edu/>



Input Data

Pavement Contexts

Geographical Location

Climatic Conditions

Material Properties

Pavement Geometry

Traffic



MIT CSHub Streamlined Pavement Life Cycle Assessment Tool

- Pavement Context
- Detailed Context
- Concrete Embodied Emission
- Asphalt Embodied Emission
- Pavement Design

Design Name:

	Surface	JPCP <input type="text"/>	Thickness (in)	Min.	Max.
				7	9
	Base	Granular <input type="text"/>	Thickness (in)	6	15
	Subgrade		K-value (pci)	509.50	931.94
	PCC Comp. Strength (psi)	<input type="checkbox"/>	PCC Modules of Rupture (pci): MR	Custom Thickness <input type="checkbox"/>	

Parameters	Min	Max	Mean	Distribution
PCC Elastic Modulus (10 ⁶ psi)	3	5	4	Uniform <input type="text"/>
PCC Comp. Strength (psi)	3500	4500	4000	Uniform <input type="text"/>
PCC Modules of Rupture (psi)	562	637	600	Uniform <input type="text"/>
Coefficient of Thermal Expansion (10 ⁻⁶ in/in/F)	4	6	5	Uniform <input type="text"/>
Joint Spacing (ft)	15	15	15	Uniform <input type="text"/>
Base Resilient Modulus (ESB): psi	20000	40000	30000	Uniform <input type="text"/>

Maintenance and Rehabilitation (M&R) Schedule

Timing (years)		Treatment Type		
Min	Max			
33	38	100% Diamond Grinding w/ Full Dep	0	0
0	0	Unspecified	0	0
0	0	Unspecified	0	0
0	0	Unspecified	0	0
0	0	Unspecified	0	0
0	0	Unspecified	0	0

Thank you. Questions? Feedback?



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