

XIII Congreso Mexicano del Asfalto. 20, 21y 22 de agosto de 2025, Cancún, Quintana Roo, México



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RAP in asphalt mixes: recent research, and cost and environmental considerations



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Asphalt Institute

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Why use RAP in new mixes?
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Review of recent UCPRC research on use of RAP for the California Department of Transportation:

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Why Use RAP in HMA and RHMA?

- **Cost-Effectiveness:** can reduce cost for material producer and buyer
 - Virgin binder costs a lot more than binder in RAP
- **Environmental Benefits:** can reduce global warming potential and other environmental impacts
 - Depending on transport, processing and use of recycling agents
- **Finite Resource Conservation:** reduces use of finite aggregate sources



AGGREGATE SUSTAINABILITY IN CALIFORNIA

Fifty-Year Aggregate Demand Compared to Permitted Aggregate Reserves

By

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2018

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Milton Fonseca



LEGEND

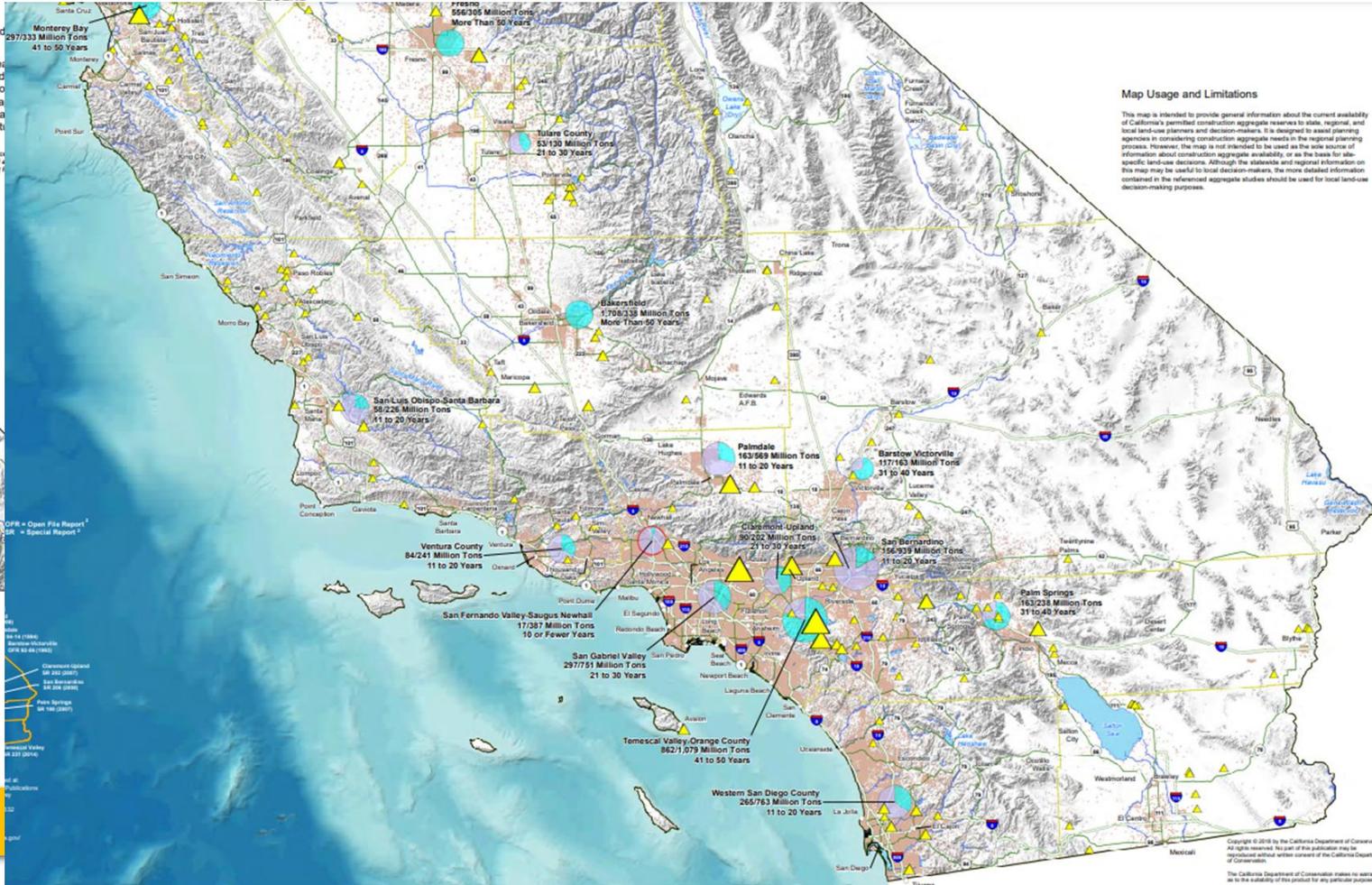
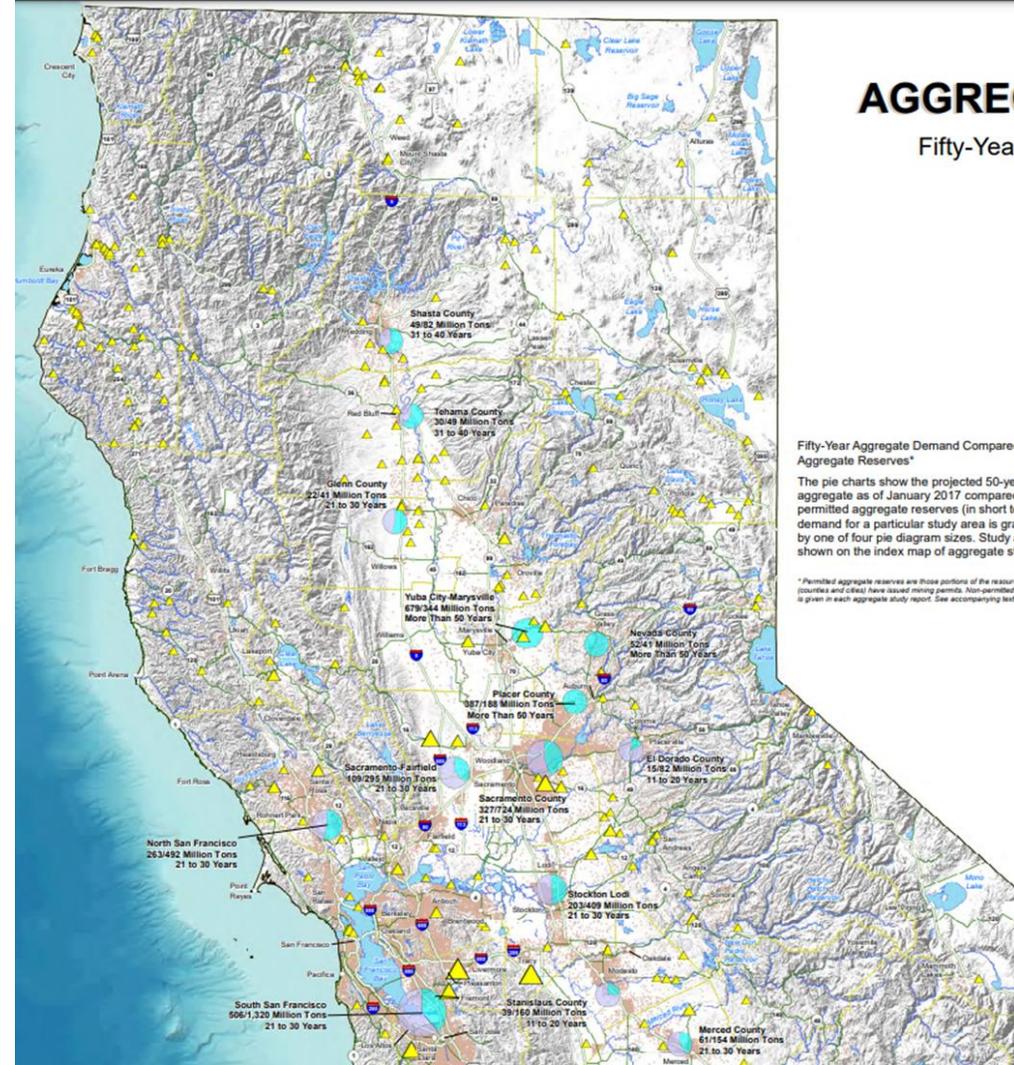
Fifty-Year Aggregate Demand Compared to Permitted Aggregate Reserves*

The pie charts show the projected 50-year aggregate as of January 2017 compared to permitted aggregate reserves (in short to demand for a particular study area is given by one of four pie diagram sizes. Study a shown on the index map of aggregate st

*Permitted aggregate reserves are those portions of the resource counties and cities have issued mining permits. Non-permitted is given in each aggregate study report. See accompanying text

Map Usage and Limitations

This map is intended to provide general information about the current availability of California's permitted construction aggregate reserves to state, regional, and local land-use planners and decision-makers. It is designed to assist planning agencies in considering construction aggregate needs in the regional planning process. However, the map is not intended to be used as the sole source of information about construction aggregate availability, or as the basis for site-specific land-use decisions. Although the statewide and regional information on this map may be useful to local decision-makers, the more detailed information contained in the referenced aggregate studies should be used for local land-use decision-making purposes.

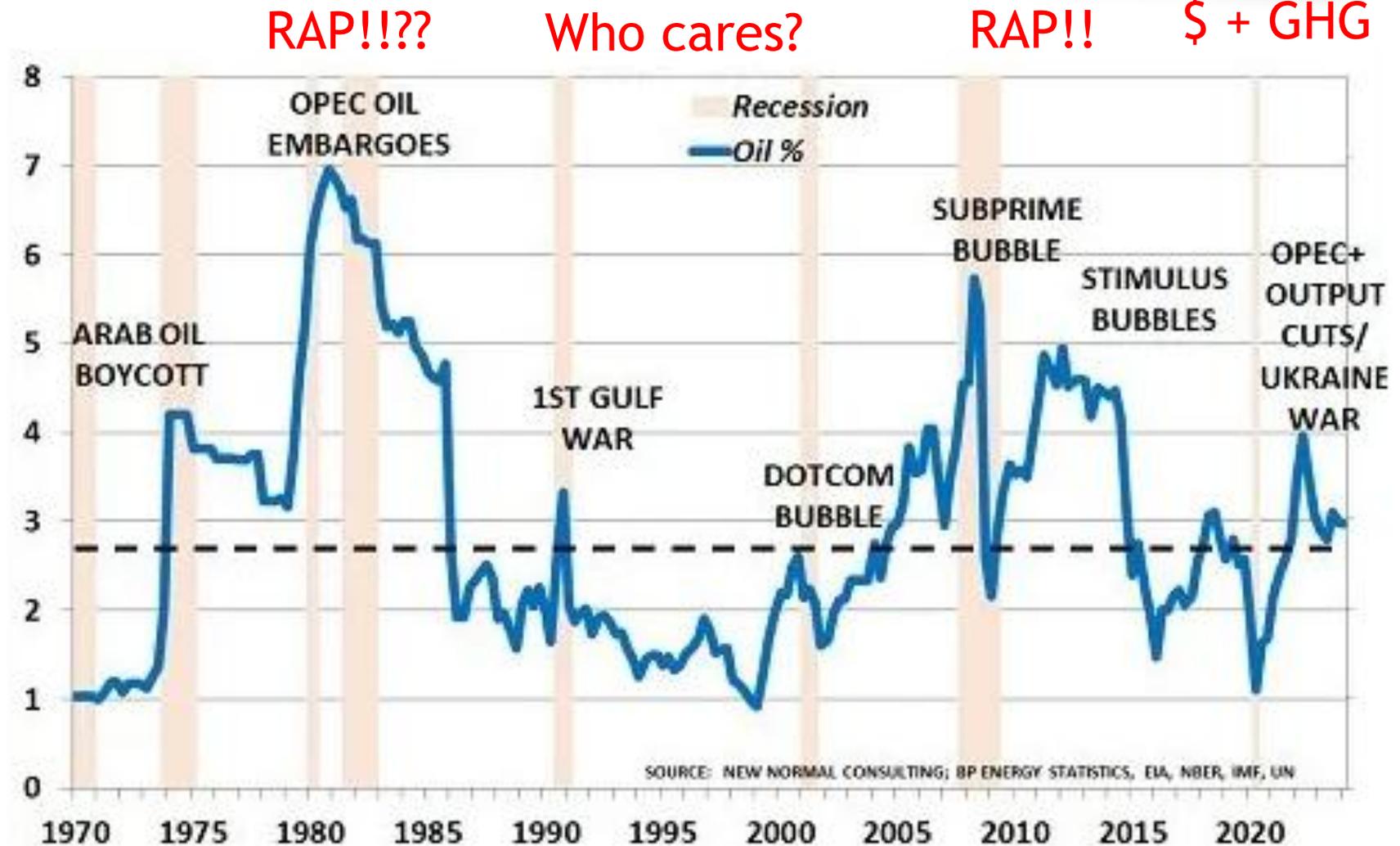


Many parts of California near urban areas will run out of virgin aggregate in next 15-30

History of RAP studies

- Use of RAP became “hot” topic in late 1970s
 - Doubt about whether “black rock” or binder blending
- Hot again since mid-2000s
- Development of advanced recycling agents (RA) in last 5-10 years

<https://www.energy.gov/eere/vehicles/articles/fact-986-july-17-2017-price-barrel-crude-oil-2016-was-lowest-2003>



If the RAP and virgin binder blend, is it beneficial to include RAP in new mixes?

- **Age-related cracking leading to block cracking:** All asphalt pavements everywhere
 - Softer at intermediate and low temperatures in top 100 mm, particularly top 50 mm
 - **Do not let RAP increase the mix stiffness at low, intermediate temperatures**
- **Fatigue cracking:** Only asphalt pavement with heavy vehicle loading
 - Keep softer in surface layer (45-75 mm), stiffer in layers below
 - Even stiffer in bottom 100 mm if > 150mm, keep top soft
 - **RAP can help increase the mix stiffness for bottom of thicker asphalt layers**
- **Rutting:** Only asphalt pavement with heavy vehicle loading
 - Not too soft in the top 50-100 mm at high temperatures
 - **RAP can help increase mix stiffness at high temperatures**
- **RAP: another tool for engineering asphalt mix properties**



Ing. Goldilocks
The right stiffness in the right layer

Caltrans Standard Specifications

39-2.02B(2) Type A Hot Mix Asphalt Mix Design

- If 15% or less RAP, no adjustments required in mix
 - This causes greater risk of age-related cracking
- For RAP substitution **greater than 15 percent and not exceeding 25 percent**, the grade of the virgin binder must be the specified grade of asphalt binder for Type A HMA with the upper and lower temperature classification reduced by 6 degrees C.
 - This assumes good blending of virgin and RAP binders



Blended Binder Performance (PG) Grading

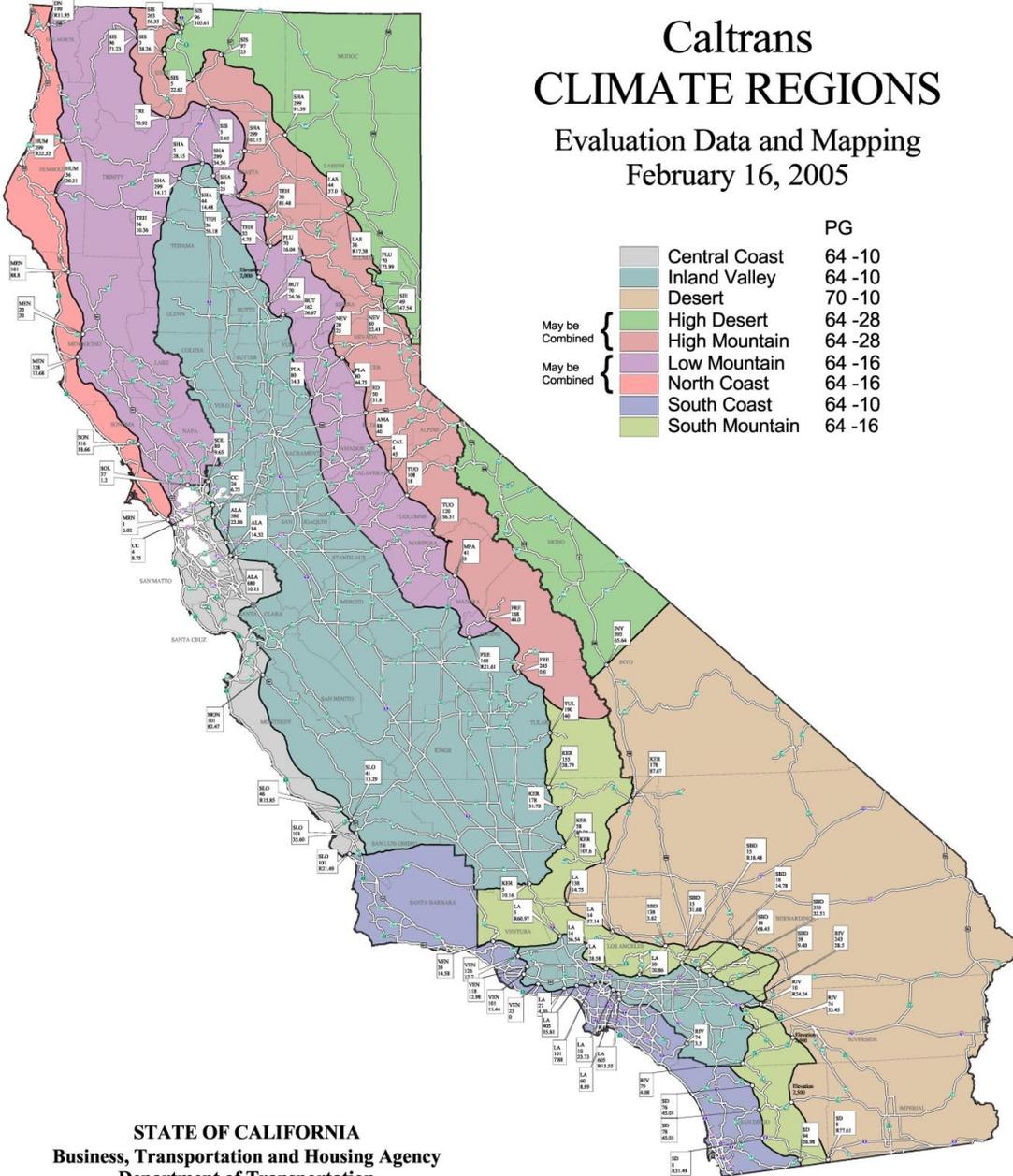
- “True PG grade” = the PG grade of the blended RAP and virgin binder
- Find the ranges of RAP that result in meeting the PG temperature requirements:
 - Minimum high temperature stiffness
 - Maximum intermediate temperature stiffness (after aging)
 - Maximum low temperature and creep modulus (after aging)
- Can increase the RAP content by using a softer virgin binder
 - Current Caltrans and Greenbook specifications require one “step down” lower virgin PG binder for 15 to 25% RAP without doing the testing
 - Example: use PG 58-22 instead of PG 64-16



Image: Rutgers University

Caltrans CLIMATE REGIONS

Evaluation Data and Mapping
February 16, 2005



STATE OF CALIFORNIA
Business, Transportation and Housing Agency
Department of Transportation



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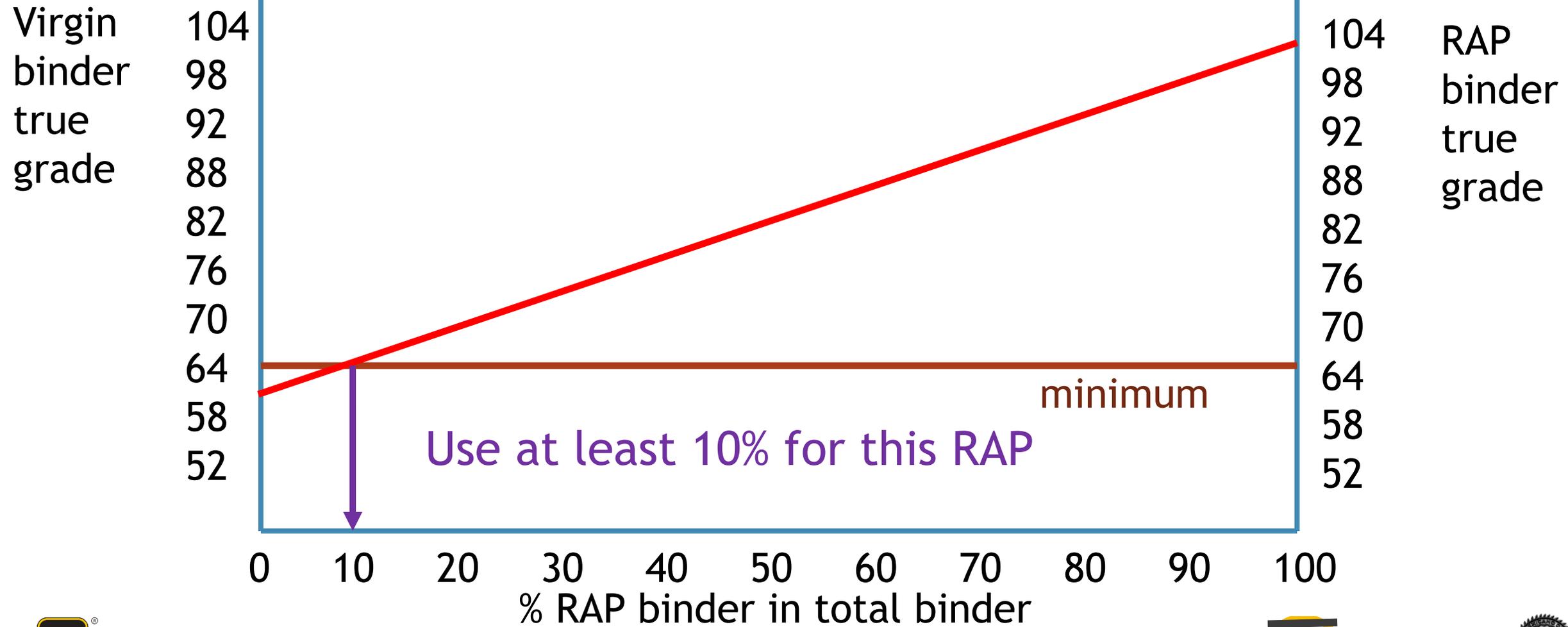
• Caltrans PG binder map

- PG64-10
- PG64-16
- PG64-28
- PG70-10
- Also used in rubberized asphalt
- Polymer modified
 - PG58-34M
 - PG64-28M



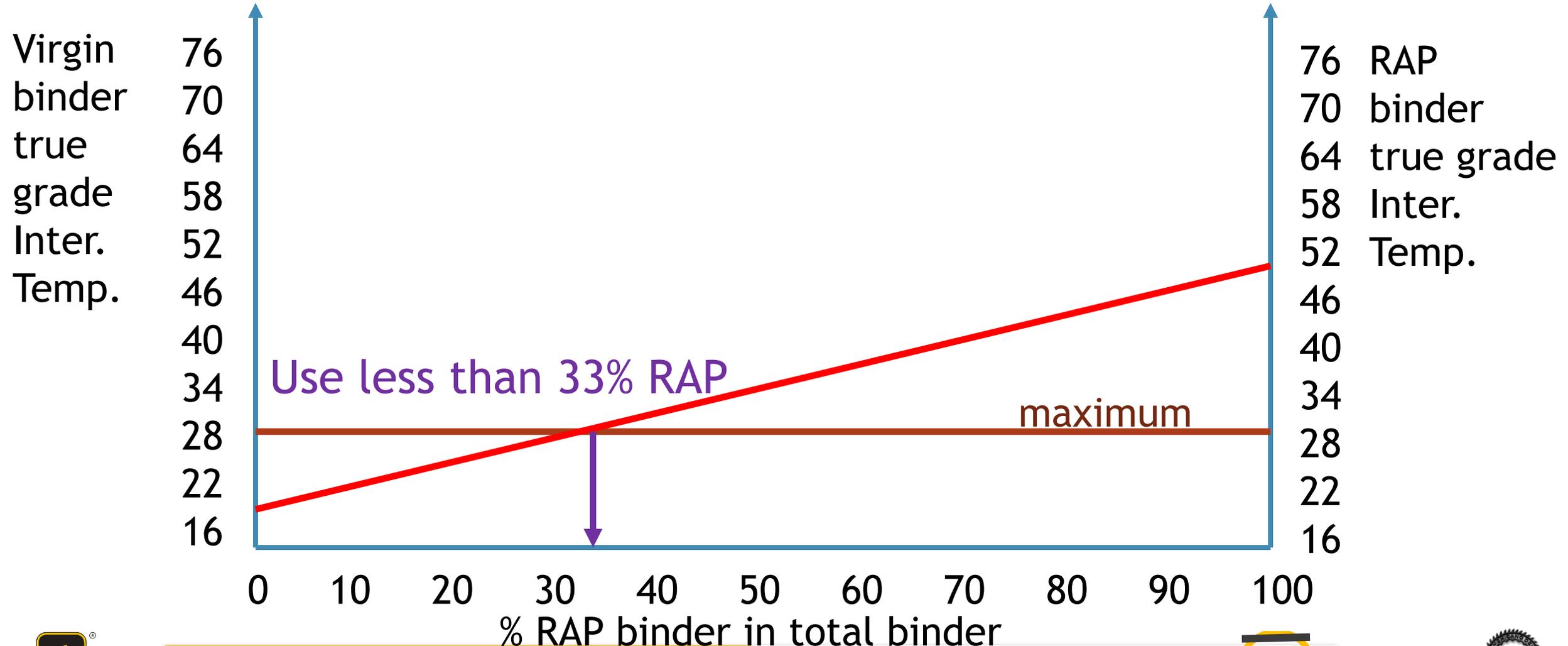
Blended Binder PG Grading: High Temperature

PG 64-16 requires minimum 64°C; how much RAP if PG 58-22 used?



Blended Binder PG Grading: Intermediate Temperature

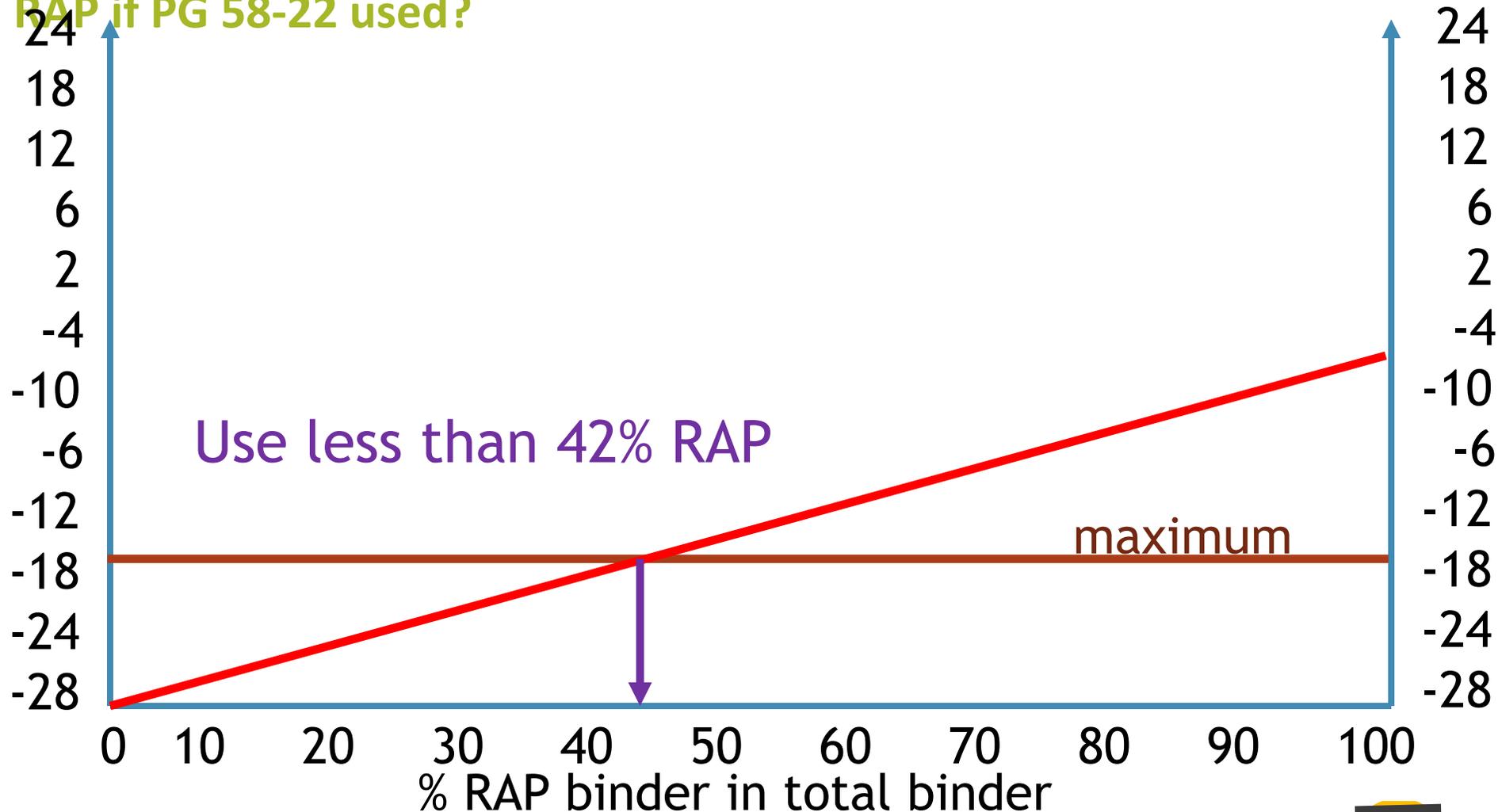
PG 64-16 requires maximum 28°C; how much RAP if PG 58-22 used?



Blended Binder PG Grading: Low Temperature

PG 64-16 requires maximum -16°C for critical property (m, S);
how much RAP if PG 58-22 used?

Virgin
binder
true
grade



RAP
binder
true
grade

Use less than 42% RAP

maximum



Questions for moving ahead with > 25% RAP and RAS

- Is there complete or nearly complete blending of virgin and RAP/RAS binders?
 - Can the properties of high RAP/RAS mixes be engineered to match those of mixes with no RAP?
 - Including changes in properties with aging
 - What is the role of recycling agents in engineering mix properties?
 - If can get same or better performance
 - What are the cost benefits?
 - What are the environmental benefit
- **Caltrans, industry and UCPRC working on further development of higher RAP content mixes**
 - **Goals:**
 - Same or better performance**
 - Lower life cycle cost**
 - Lower environmental impact**
 - Constructable**

Analysis of Recycling Agent Effects on the Mechanical Properties of HMA with High Recycled Binder Ratios

4.79 Project: Guidance, Tests, and Specifications for High Recycled Asphalt Pavement/Recycled Asphalt Shingle Contents in HMA and RHMA Mixes

John T. Harvey, Angel Mateos, Jeffrey Buscheck, Mohammad Rahman, Julian Brotschi, Julia Fonturbel, Anai Cazares-Ramirez, Mohamad Elkashef, David Jones

<https://escholarship.org/uc/item/7cc775ms?>

Introduction

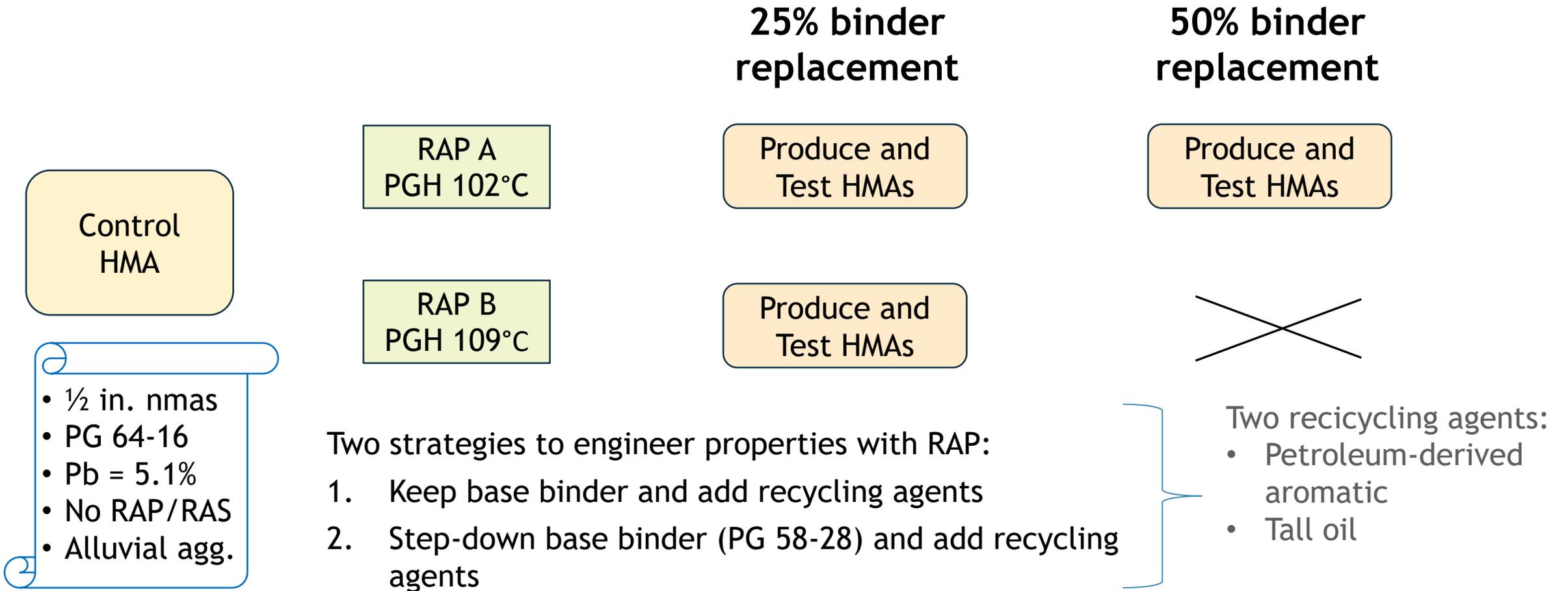
- Little known about RAP/RAS impact on mechanical properties of HMA
- Little known about recycling agents impact on mechanical properties of HMA
- What is the best approach to dose recycling agent?

Goal: Study how the mechanical properties of the HMA change upon the addition of high contents of RAP and RAS (between 25 and 50% binder replacement) and how the negative changes (e.g. decrease in cracking resistance) can be offset by using recycling agents

1. What are the effects of the addition of high RAP content on the mechanical properties of the HMA?
2. Can the RAP addition effects be predicted based on testing of the blended binder?
3. What are the effects of the recycling agent addition on the mechanical properties of HMA with high RAP content?
4. By using recycling agent, can the mechanical properties of the HMA with high RAP content be restored back to the properties of the HMA with low RAP content?
5. Are there specific considerations required for addition of RAS compared to addition of RAP?
6. What is the recommended approach to determine recycling agent dose?

Experiment

Based on mixes fabricated in the laboratory



Experiment

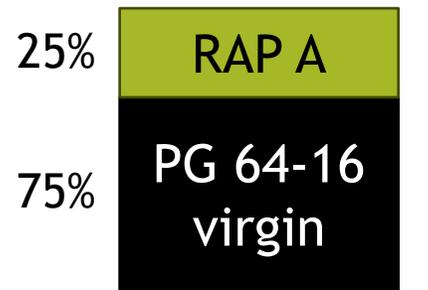
- Lab characterization of binders (RAP and RAS binders extracted/recovered; binders blended in the lab)
 - PG grading
 - Stiffness (dynamic shear rheometer)
 - FTIR (Carbonyl and sulfoxide contents)
- Lab characterization of HMA:
 - Stiffness (AMPT and 4PB)
 - Fatigue resistance (4PB)
 - Rutting resistance
 - Ideal cracking test
- Important issues not tested in this study:
 - Long-term recycling agent effect (all mixes tested after STOA)
 - Moisture sensitivity

Recycling Agent Dose Determination

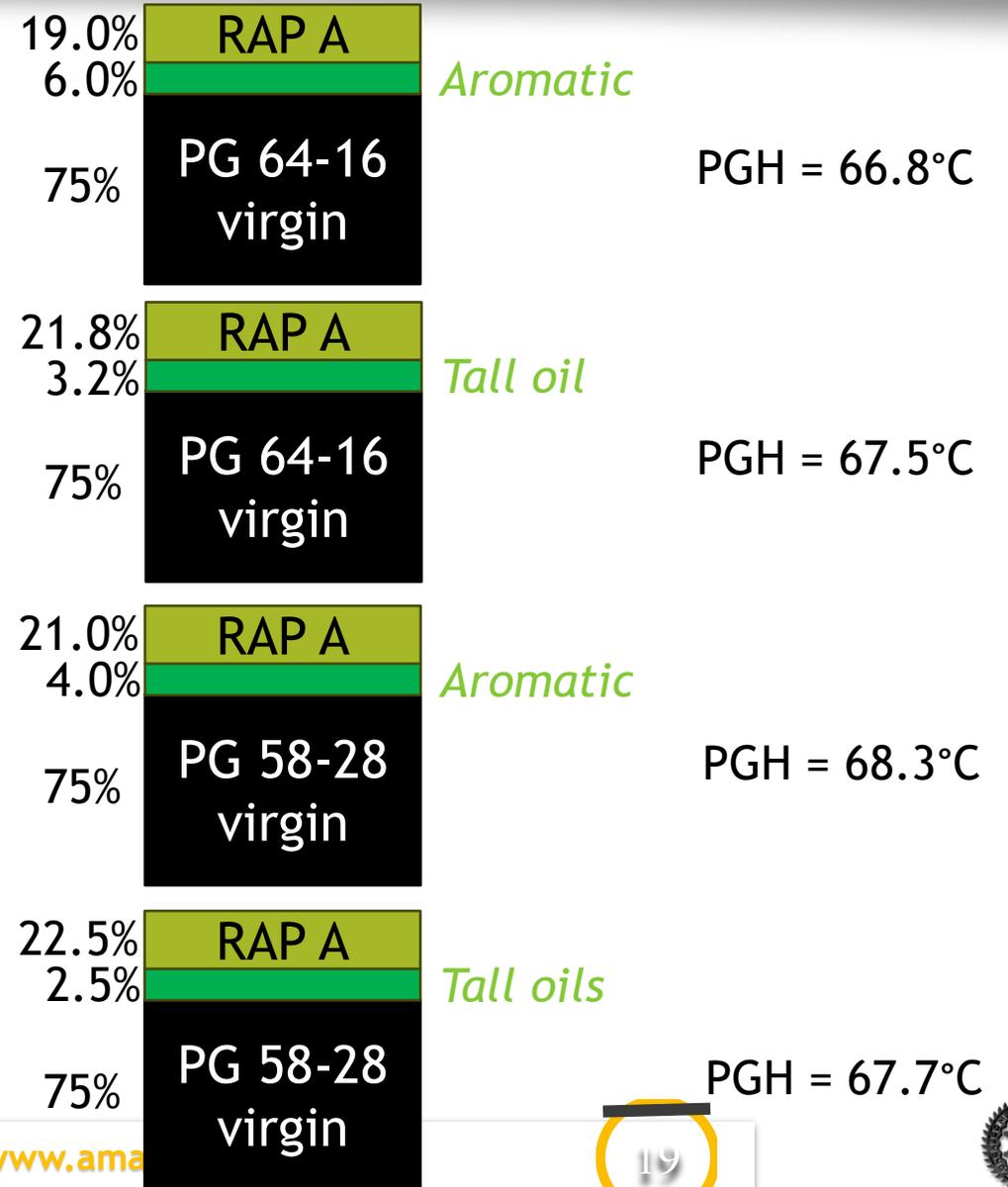
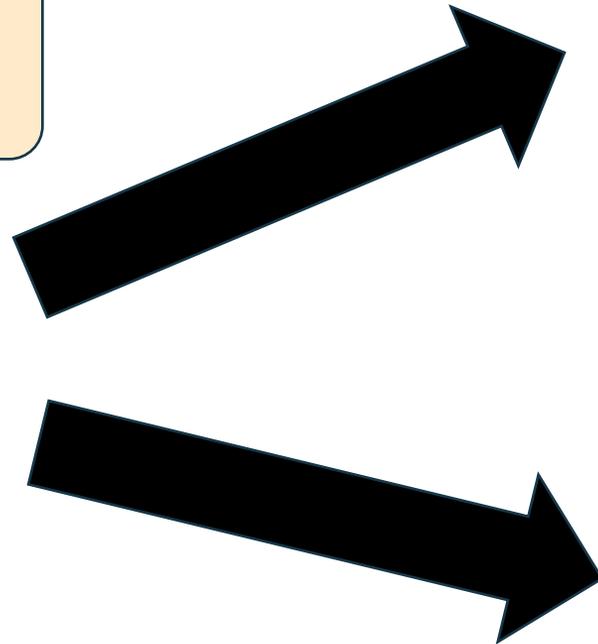
- Restore high PG of the Control mix virgin binder (Target PGH = 67.5°C)

Example...

Mix with 25% RAP A



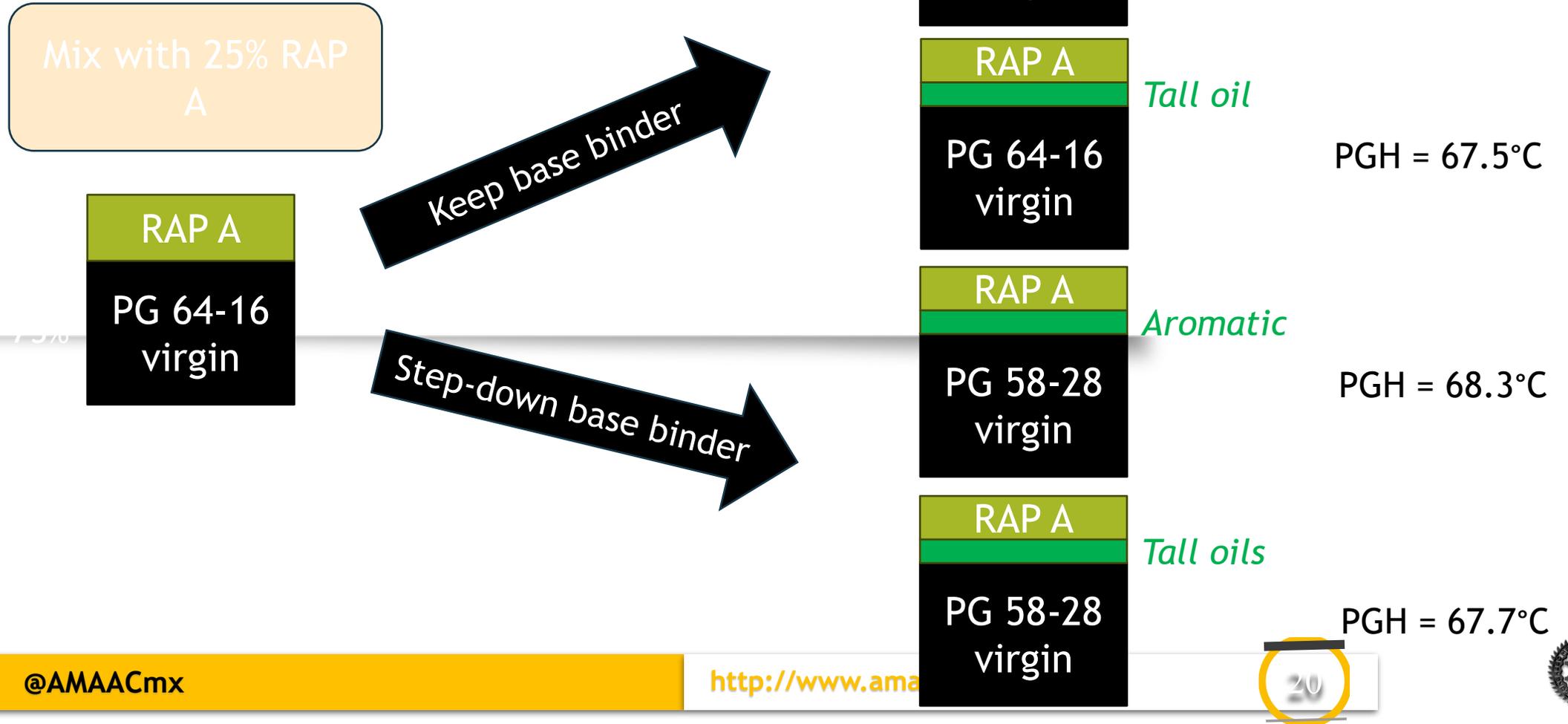
PGH = 74.8°C



Recycling Agent Dose Determination

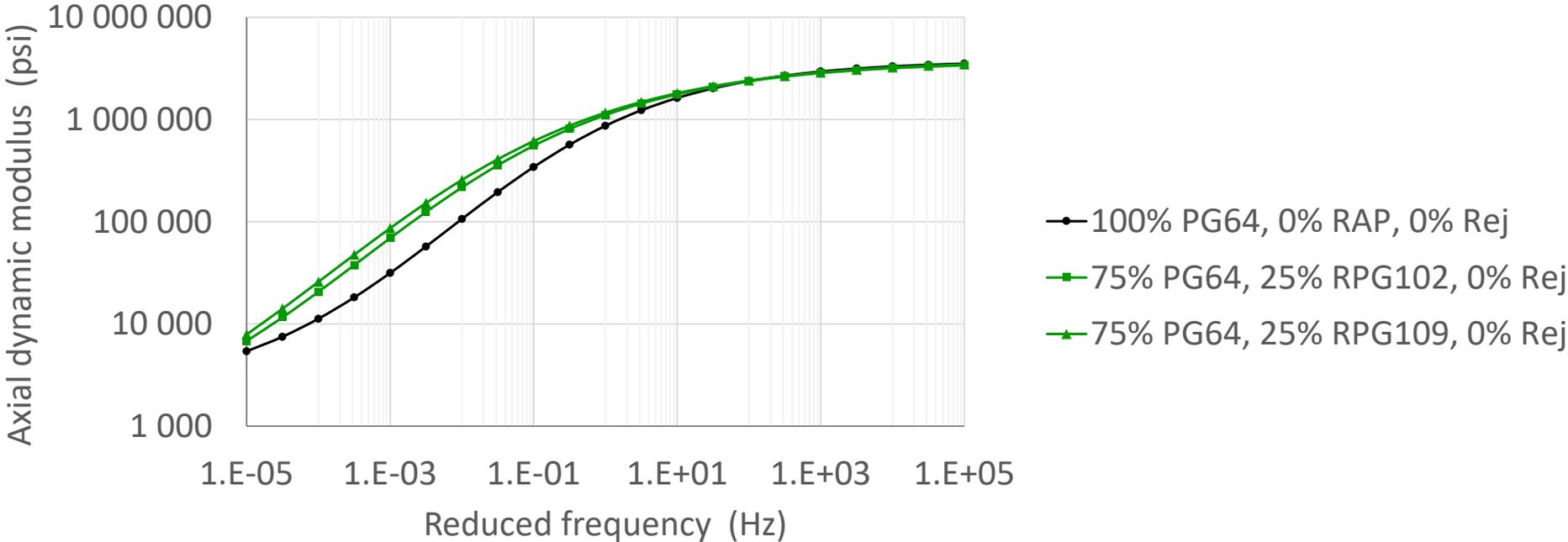
- Restore high PG of the Control mix virgin binder (Target PGH = 67.5°C)

Example...



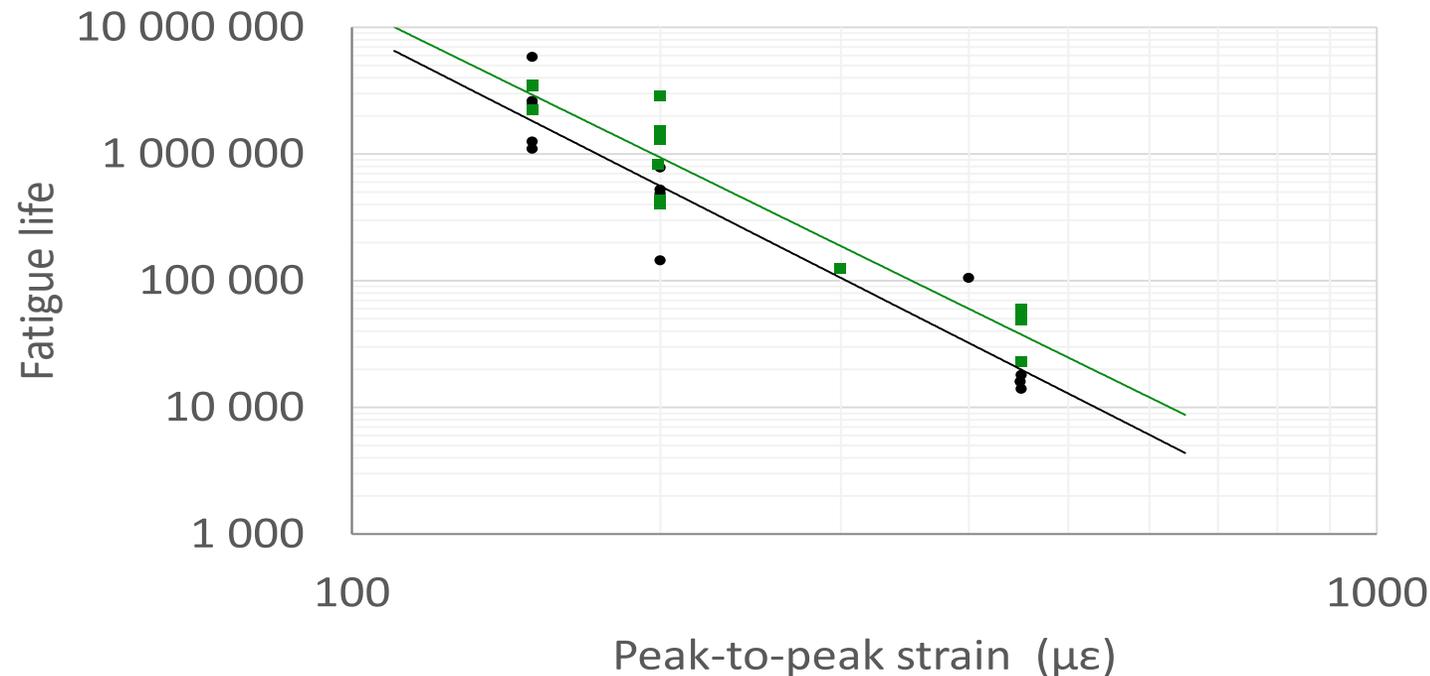
What are the effects of the addition of high RAP content on the mechanical properties of the HMA?

Property	What we were expecting	What we measured
Stiffness	Increase in stiffness, particularly at high temperatures	As expected



What are the effects of the addition of high RAP content on the mechanical properties of the HMA?

Property	What we were expecting	What we measured
Stiffness	Increase in stiffness, particularly at high temperatures	As expected
Fatigue resistance	Decrease	Opposite!!!

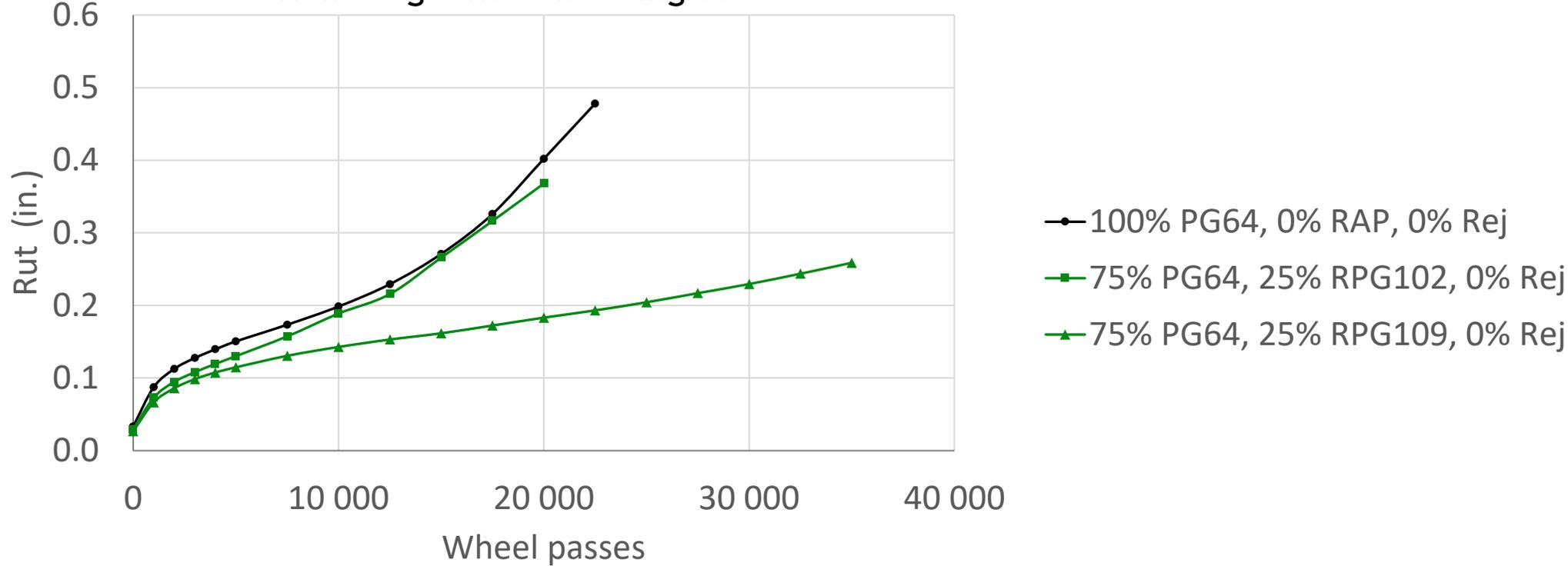


- 100% PG64, 0% RAP, 0% Rej
- 75% PG64, 25% RPG102, 0% Rej

What are the effects of the addition of high RAP content on the mechanical properties of the HMA?

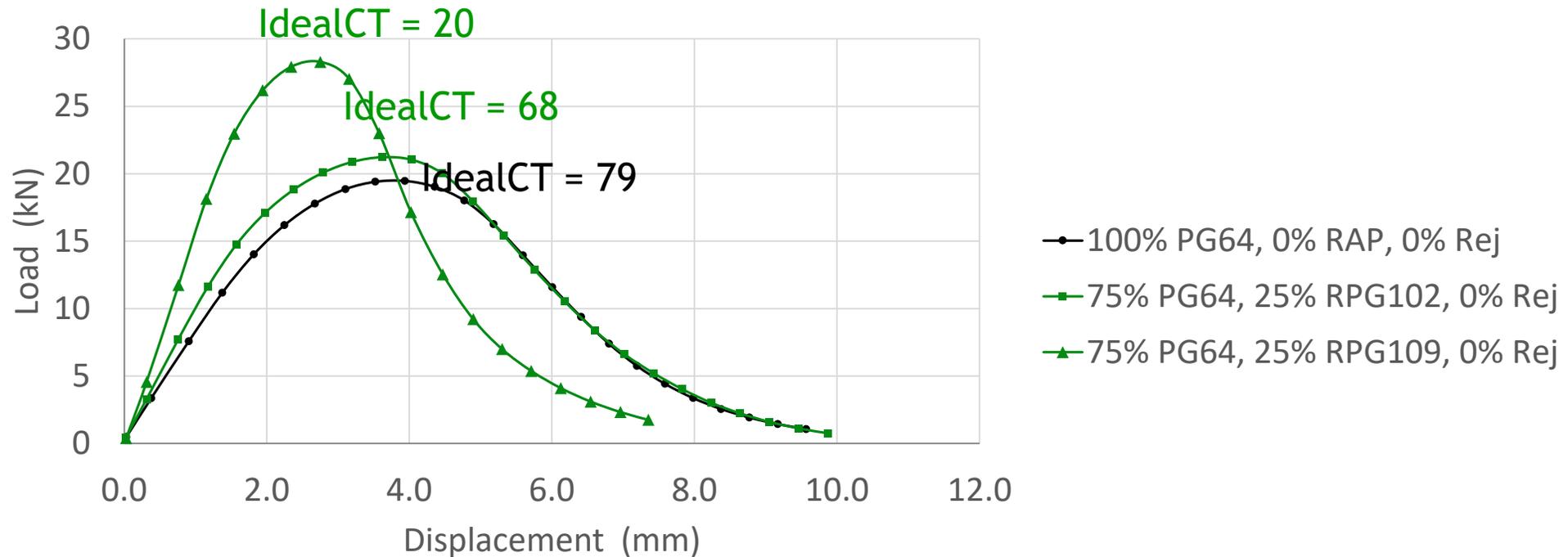
Property	What we were expecting	What we measured
Stiffness	Increase in stiffness, particularly at high temperatures	As expected
Fatigue resistance	Decrease	Opposite!!!
Rutting resistance	Improve	As expected

Hamburg Wheel Tracking Test



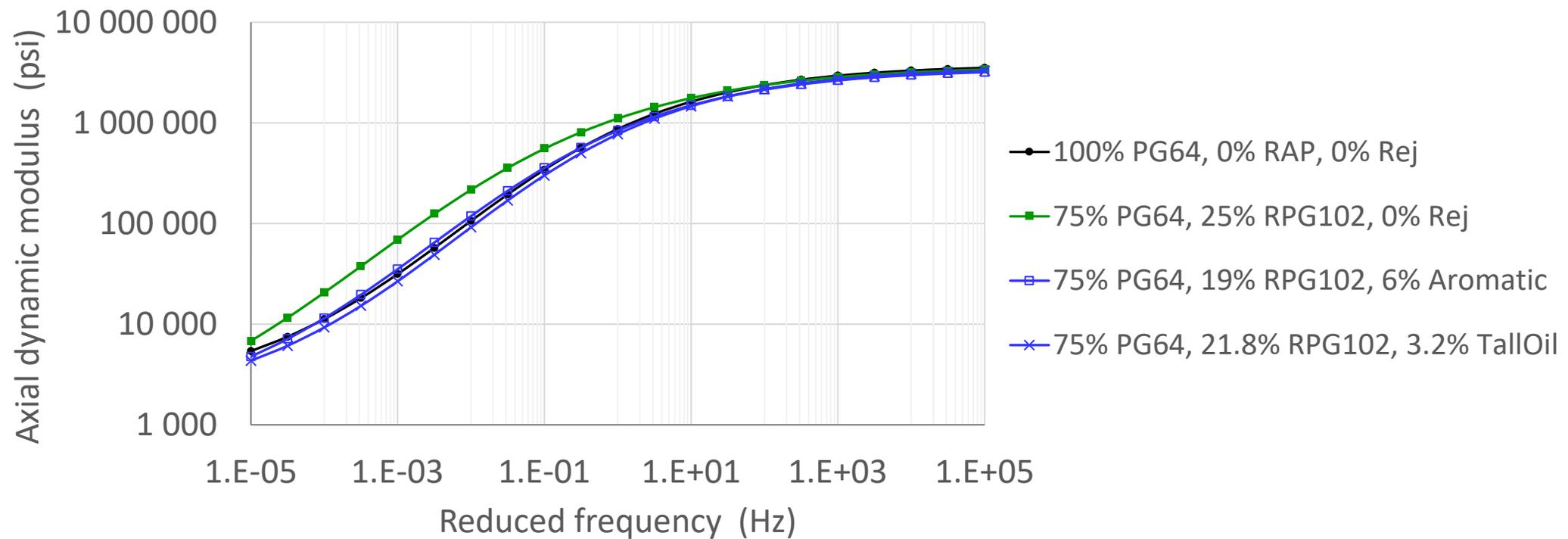
What are the effects of the addition of high RAP content on the mechanical properties of the HMA?

Property	What we were expecting	What we measured
Stiffness	Increase in stiffness, particularly at high temperatures	As expected
Fatigue resistance	Decrease	Opposite!!!
Rutting resistance	Improve	As expected
Ideal Results	Strength increase & IdealCT decrease	As expected



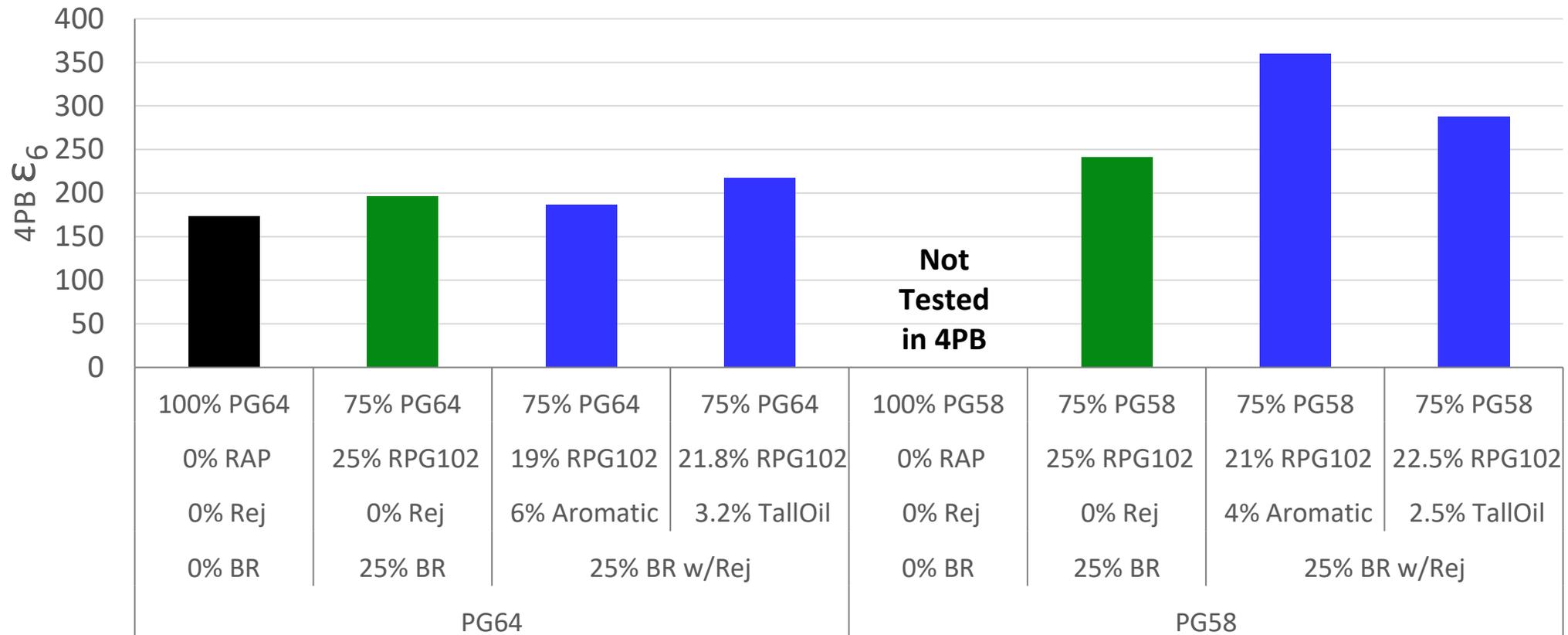
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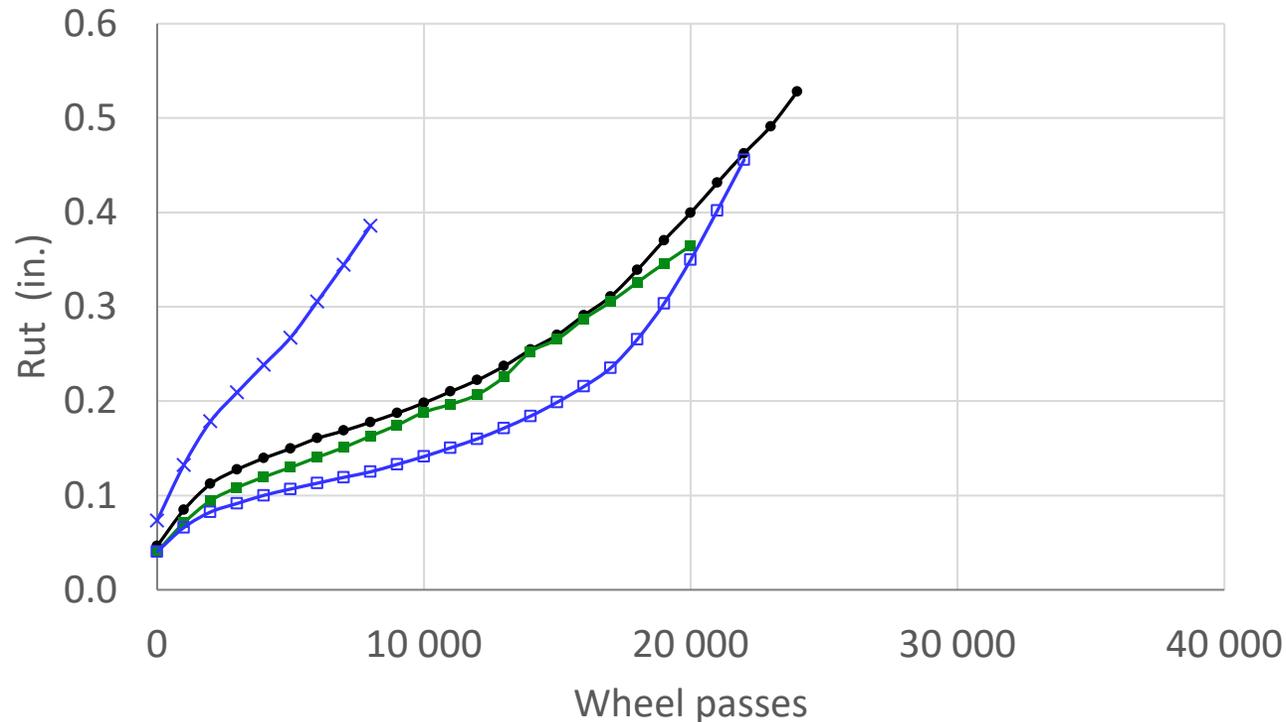
What are the effects of the addition of high RAP content on the mechanical properties of the HMA?

Property	What we were expecting	What we measured
Stiffness	Decrease in stiffness, particularity at high temperatures	As expected
Fatigue resistance	Increase	No effect for PG64-16!!! As expected for PG 58-28



What are the effects of the addition of high RAP content on the mechanical properties of the HMA?

Property	What we were expecting	What we measured
Stiffness	Decrease in stiffness, particularly at high temperatures	As expected
Fatigue resistance	Increase	No effect for PG64-16!!! As expected for PG 58-28
Rutting resistance	Decrease	Not consistent



In this case, the Aromatic improved rutting resistance while Tall Oil did the opposite...

- 100% PG64, 0% RAP, 0% Rej
- 75% PG64, 25% RPG102, 0% Rej
- 75% PG64, 19% RPG102, 6% Aromatic
- × 75% PG64, 21.8% RPG102, 3.2% TallOil

By using recycling agent, can the mechanical properties of the HMA with high RAP content be engineered to match the properties of the HMA with low RAP content?

- Overall Yes, with some caveats

Stiffness	Yes
Fatigue resistance	??? <ul style="list-style-type: none">• No improvement for PG64-16• Yes for PG58-28• Depends on the relative fatigue performance of the virgin and RAP/RAS binders; virgin mix can have WORSE fatigue performance than stiffer mix with RAP
Rutting resistance	No need to restore; need to check RA does not produce rutting problems
Ideal Results	Overall yes, with exceptions (IdealCT for PG58-28)

What is the recommended approach to determine recycling agent dose?

Initial considerations: What is the goal of adding the recycling agent?

- ✓ Restore the mechanical properties of the mix with high RAP/RAS content back to the properties of the control mix with either no RAP/RAS or low/standard RAP/RAS content
- ✓ Optimizing mix properties within the balanced mix design framework

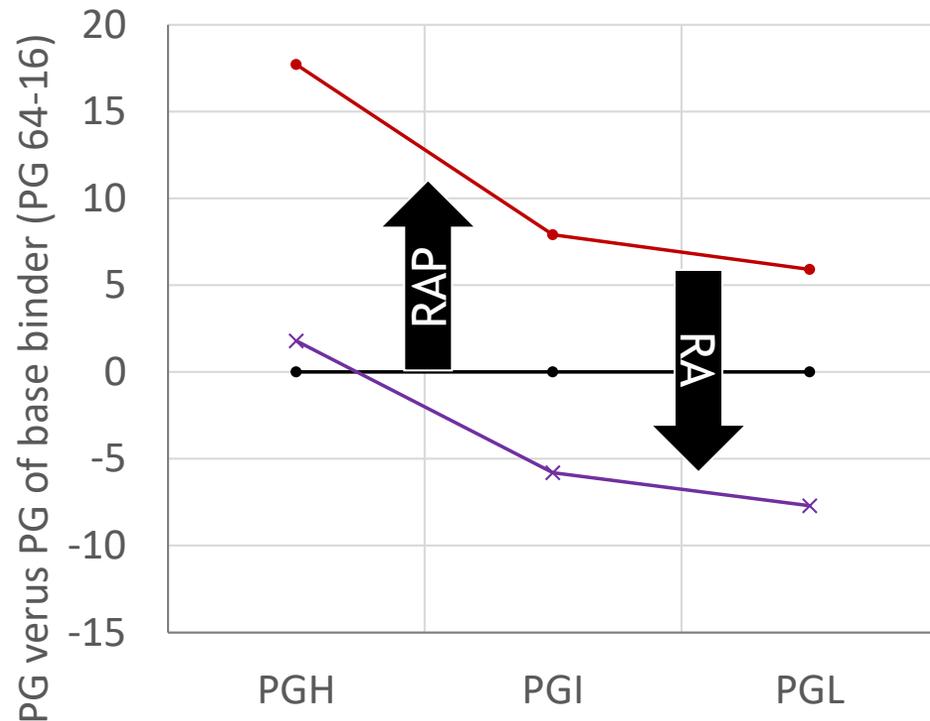
Approach 1

Approach 2

What is the recommended approach to determine recycling agent dose?

Initial considerations: Recycling agent dose Overshooting

What do we mean by “Overshooting”?



- 100% PG64, 0% RAP, 0% Rej
- 50% PG64, 50% RPG102, 0% Rej
- ×— 50% PG64, 41.9% RPG102, 8.1% Talloil

Meeting PGH was more demanding in terms of RA dose than meeting PGI and PGL...

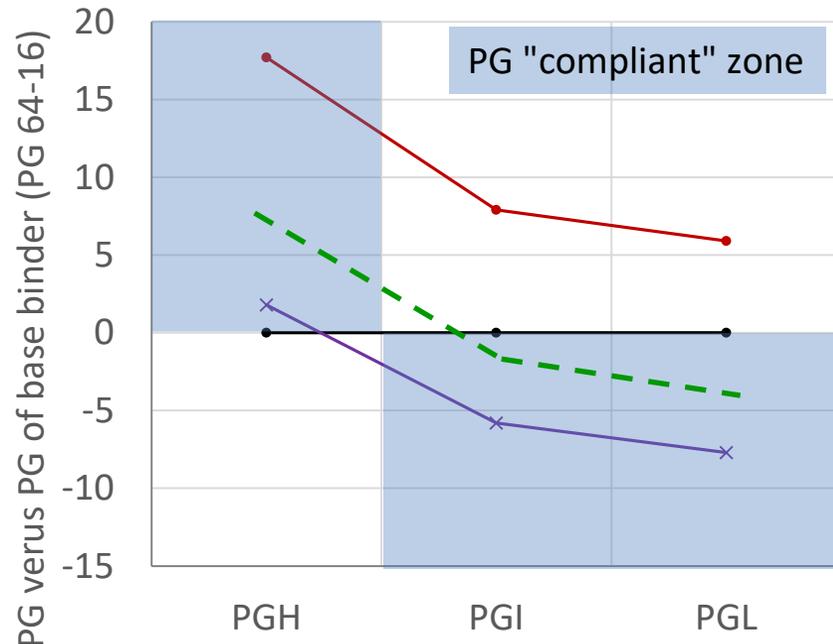
- What is the point of restoring PGH?
- The high RA dose resulted in soft mixes
- In addition to costing more \$ and GHG emissions, soft mixes will underperform in many scenarios (particularly as intermediate layers of relatively thick asphalt pavements)

What is the recommended approach to determine recycling agent dose?

Initial considerations: Recycling agent dose Overshooting

- A common approach to determine recycling agent dose: restore PGH of the base binder

What do we mean by “Overshooting”?



This should be our target

The target should be meeting PG specifications:

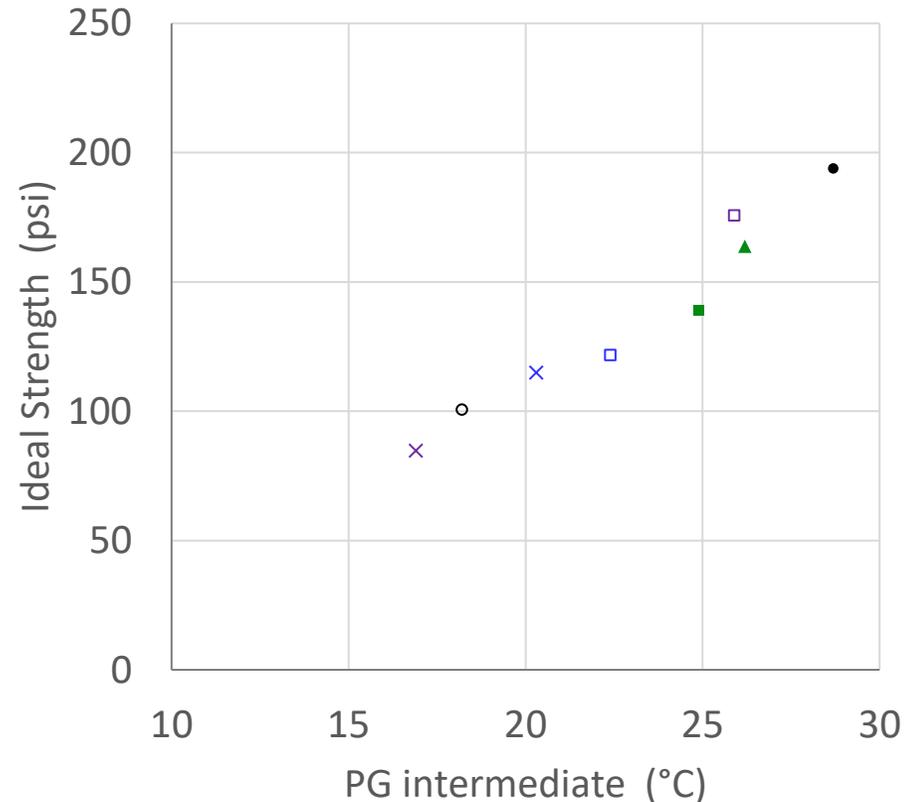
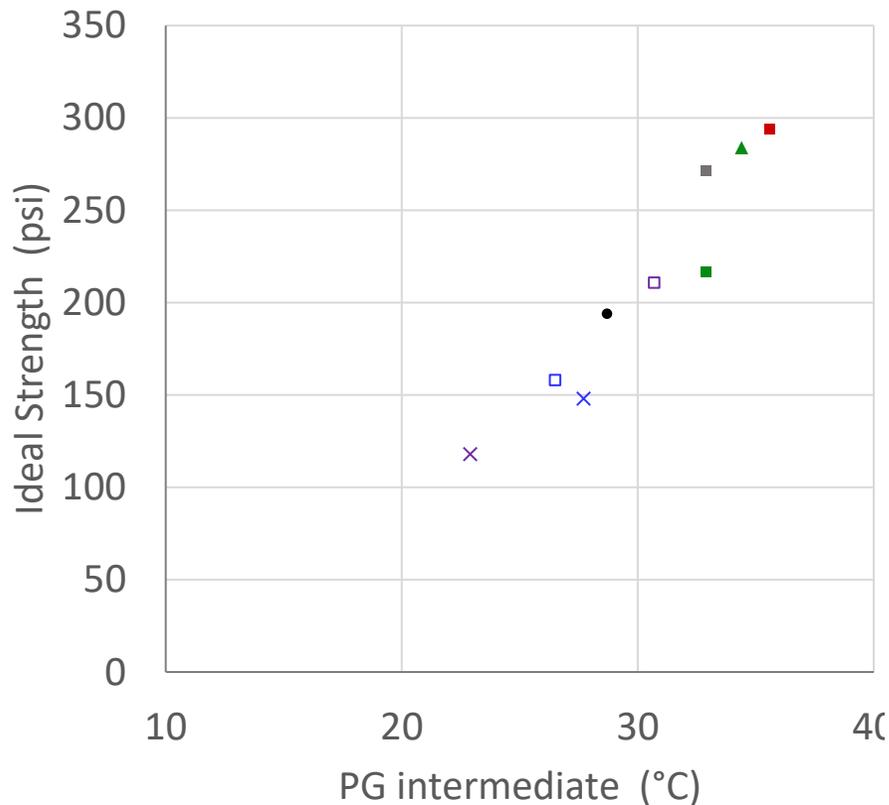
- $PGH \geq \text{Required PGH}$
- $PGI \leq \text{Required PGI}$
- $PGL \leq \text{Required PGL}$

- 100% PG64, 0% RAP, 0% Rej
- 50% PG64, 50% RPG102, 0% Rej
- ×— 50% PG64, 41.9% RPG102, 8.1% Talloil

What is the recommended approach to determine recycling agent dose?

Initial considerations: Does RAP/RAS binder fully blend with the virgin binder and recycling agent?

- Compare a property measured in the actual mix (where full blending questionable) versus a similar property measured in the binder blend (where full blending sure)



- Different replacements ratios (0%, 25%, 50%, RAP and RAS, collapse into a single pattern... Suggesting full blending
- Similar outcome for other HMA mechanical properties

What is the recommended approach to determine recycling agent dose?

Approach 1: Restore Desirable Mechanical Properties of the Control Mix

- RA dosing goal: Restoring stiffness of HMA at intermediate temperature...
 - Based on binder testing: Restore PGI to PGI_R (“R” stands for Required)
 - Based on mix testing: Restore Ideal Strength (ITS) of Control mix
 - ✓ Mix within 0.5 ft of the pavement surface: ITS of MTOA mixes
 - ✓ Mix more than 0.5 ft below the pavement surface: ITS of STOA mixes
- Additional Checks:
 - Binder blend: $PGH \geq PGH_R$ $PGI \leq PGI_R$ $PGH \leq PGL_R$
 - STOA mix (mix more than 0.5 ft below the pavement surface):
 - ✓ Mix passes rutting requirements
 - ✓ Ideal ITS within $\pm 15\%$ Control mix (STOA)
 - ✓ IdealCT within $\pm 15\%$ Control mix (STOA)
 - MTOA mix (mix within 0.5 ft of the pavement surface):
 - ✓ Ideal ITS within $\pm 15\%$ Control mix (MTOA)
 - ✓ IdealCT within $\pm 15\%$ Control mix (MTOA)
 - Wet-conditioned mix (mix conditioning as indicated in the corresponding testing procedure):
 - ✓ Mix passes moisture-sensitivity requirements

Binder PGI and ITS used as surrogate for stiffness

For relevant projects, additional check based on 4PB fatigue may be introduced
JMF verification

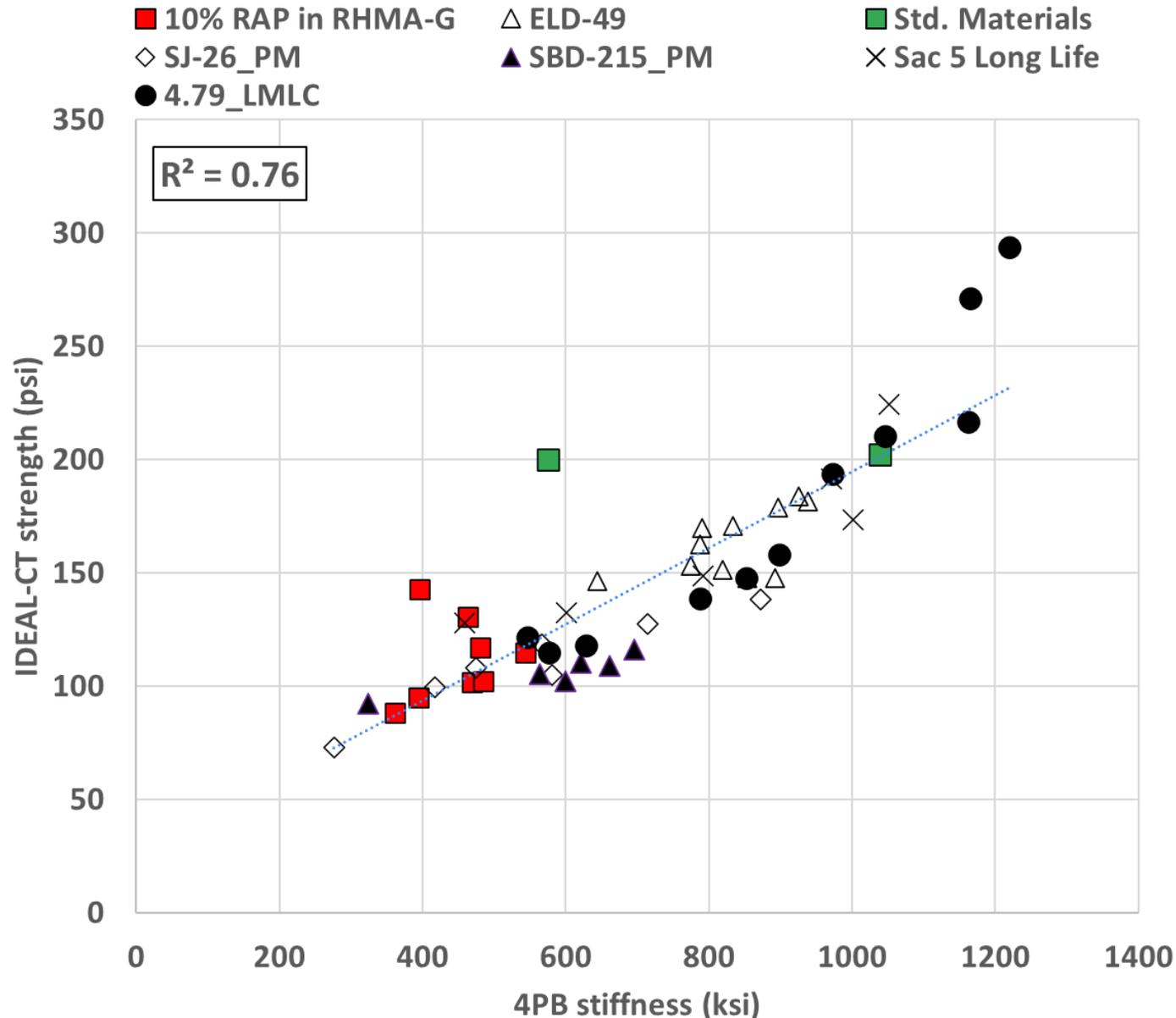
What is the recommended approach to determine recycling agent dose?

Approach 2: Optimize Mix Properties within Balanced Mix Design Framework using performance related specifications (PRS)

- RA dosing goal: Minimum dose that results in the meeting of the performance related specification (PRS) for the mix
- Additional Checks:
 - Binder blend: $PGH \geq PGH_R$ $PGH \leq PGL_R$

- Approach 2 is based on the PRS within BMD framework
- The proposal of the BMD PRS is the goal of an ongoing Caltrans research project

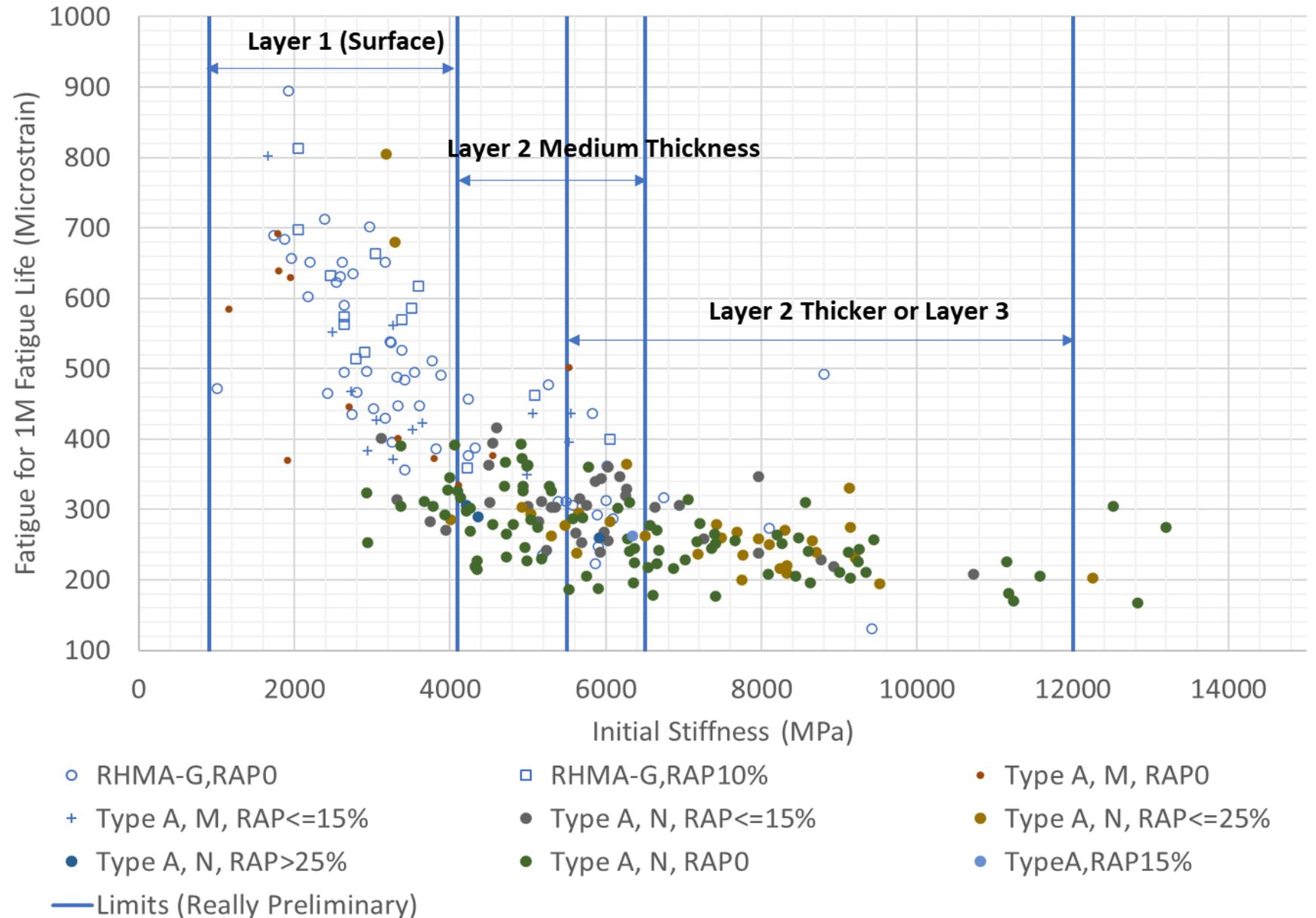
4PB Stiffness vs Ideal Strength (ITS)



- IDEAL-CT Strength is a very good indicator of stiffness
 - Age related cracking
 - Fatigue cracking initial indicator
 - Remember: some mixes have good stiffness but bad fatigue
- With MTOA provides a good indicator of aging

Preliminary recommendations for stiffness ranges and corresponding IDEAL-CT strength (psi)

- Surface: 65-125
- Layer 2: 125-170
- Layer 3+: 150-275



Conclusions

- Most of the negative effects of RAP/RAS addition can be offset by using recycling agents and/or step-down binder
- By using recycling agents and/or step-down binder, introducing high RAP/RAS content (up to 50% binder replacement) in HMA while maintaining performance is doable
- Restoring the PGH of the binder blend may result in unnecessarily high recycling agent dose that may have unintended negative effects on the performance of the HMA with high RAP/RAS content
- Out of the different parameters evaluated in this study, the PGI of the binder blend and the ITS measured in the Ideal cracking test were found to relate to HMA stiffness at intermediate temperature, which is related to 4PB fatigue life
- Two approaches for dosing the recycling agent have been proposed:
 - Approach 1 focuses on restoring the stiffness of the HMA at intermediate temperature
 - Approach 2 focuses on meeting the BMD PRS by using the minimum amount of recycling agent



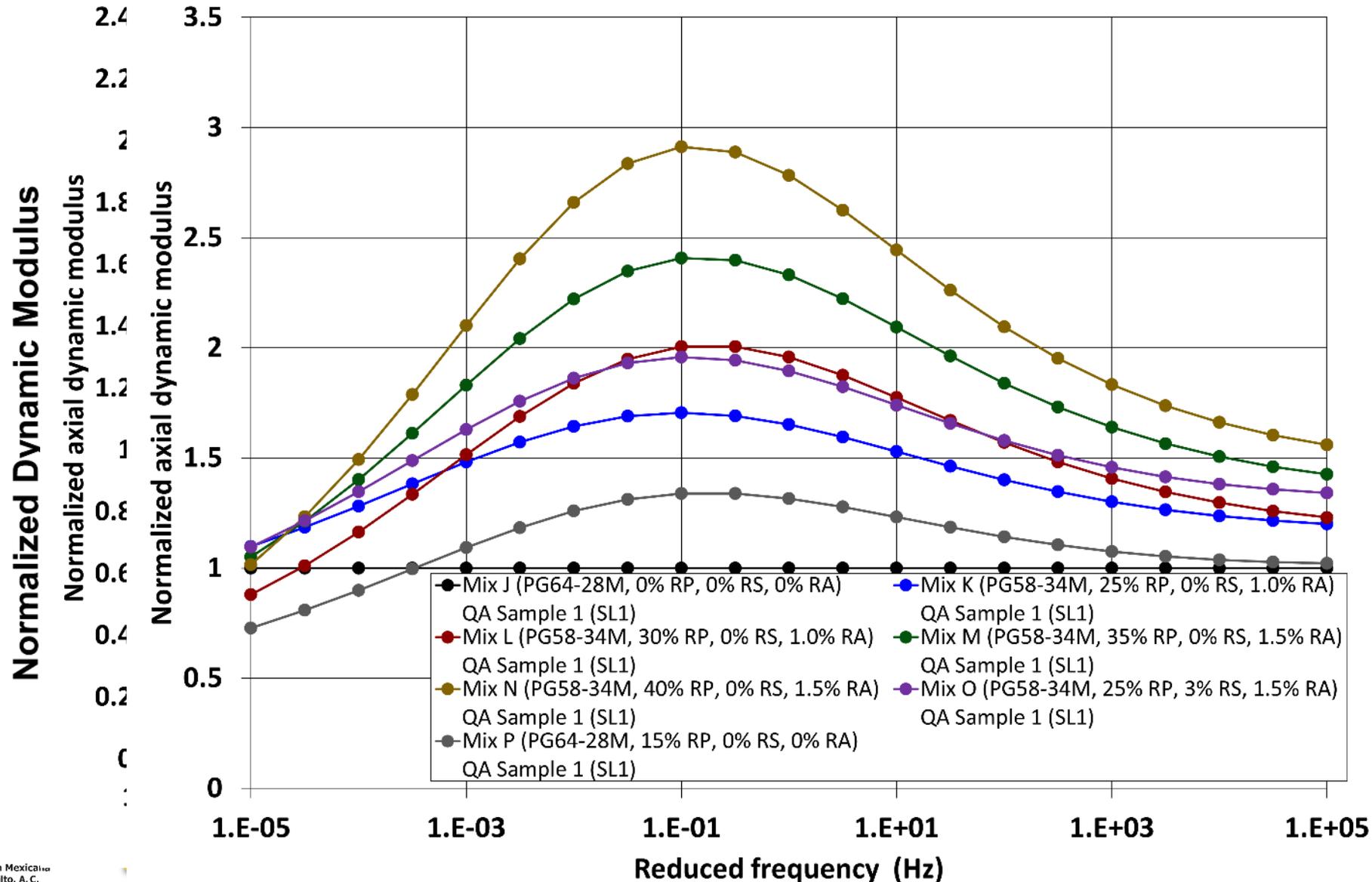
High RAP and RAS pilot projects

- Five pilot projects built by Caltrans and industry, tested by UCPRC:
 - 60 mm overlays
 - Two controls: virgin mix with 0% RAP, and normal mix with X% RAP
 - Contractor uses lower PG grades plus recycling agent to match properties of 0% RAP mix to meet IDEAL-CT and PG high temperature binder of virgin mix
- El Dorado 49: PG64-16 or PG58-22
 - 0% RAP PG64-16, 10% RAP, 3% RAS, 3% RAS + 10% RAP
- San Bernardino 215: PG64-28M or PG58-34M
 - 0, 23% (no RA), 25% (with RA), 30%, 35%, 40% RAP
- San Joaquin 26: PG64-16M or PG58-34M
 - 0, 15% (no RA), 25%, 30%, 35%, 40% RAP, 25% RAP + 3% RAS
- Ventura 150 and Contra Costa 4 pilot testing underway now

Axial dynamic modulus

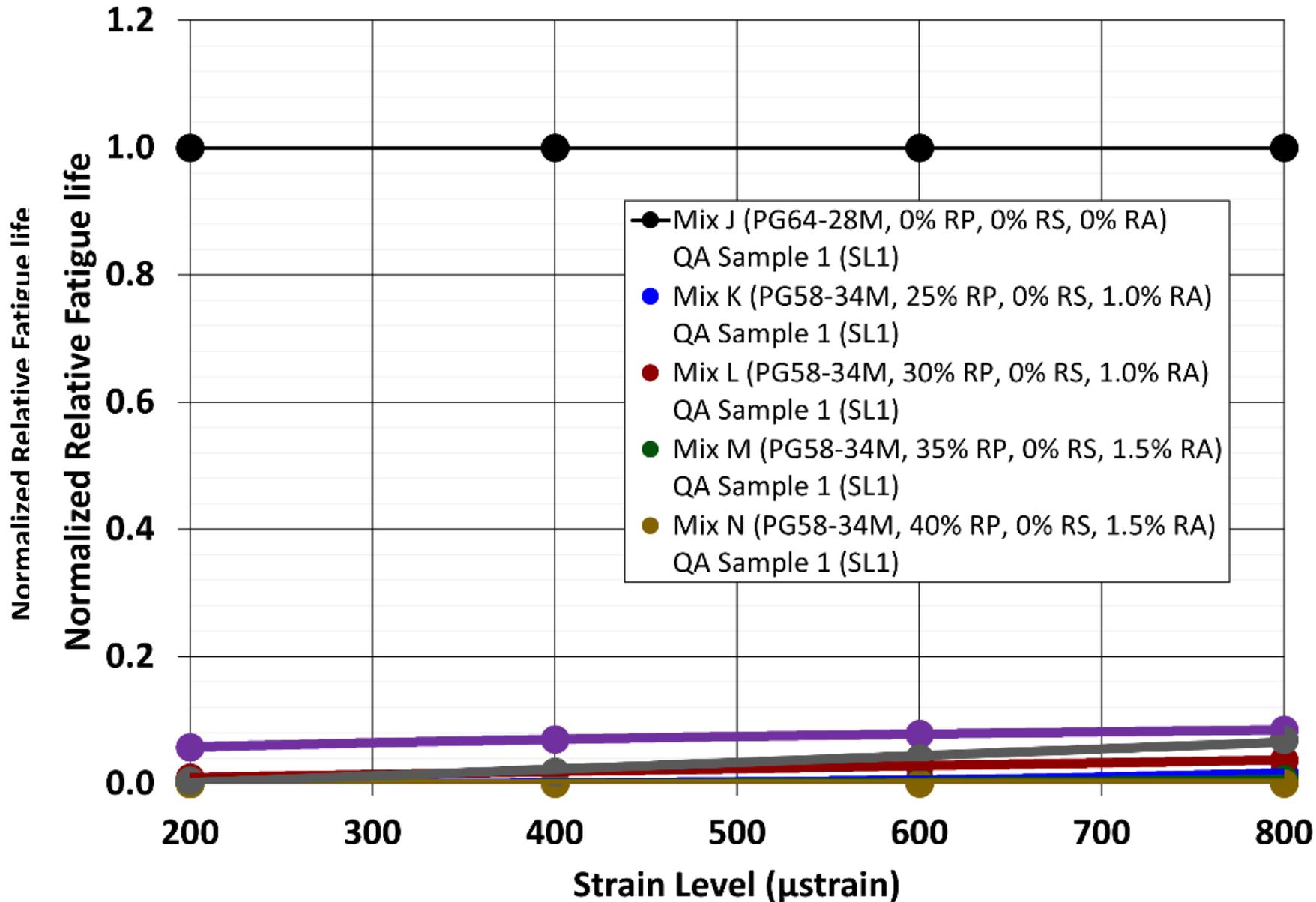
Slow speed, hot

Fast speed, cold



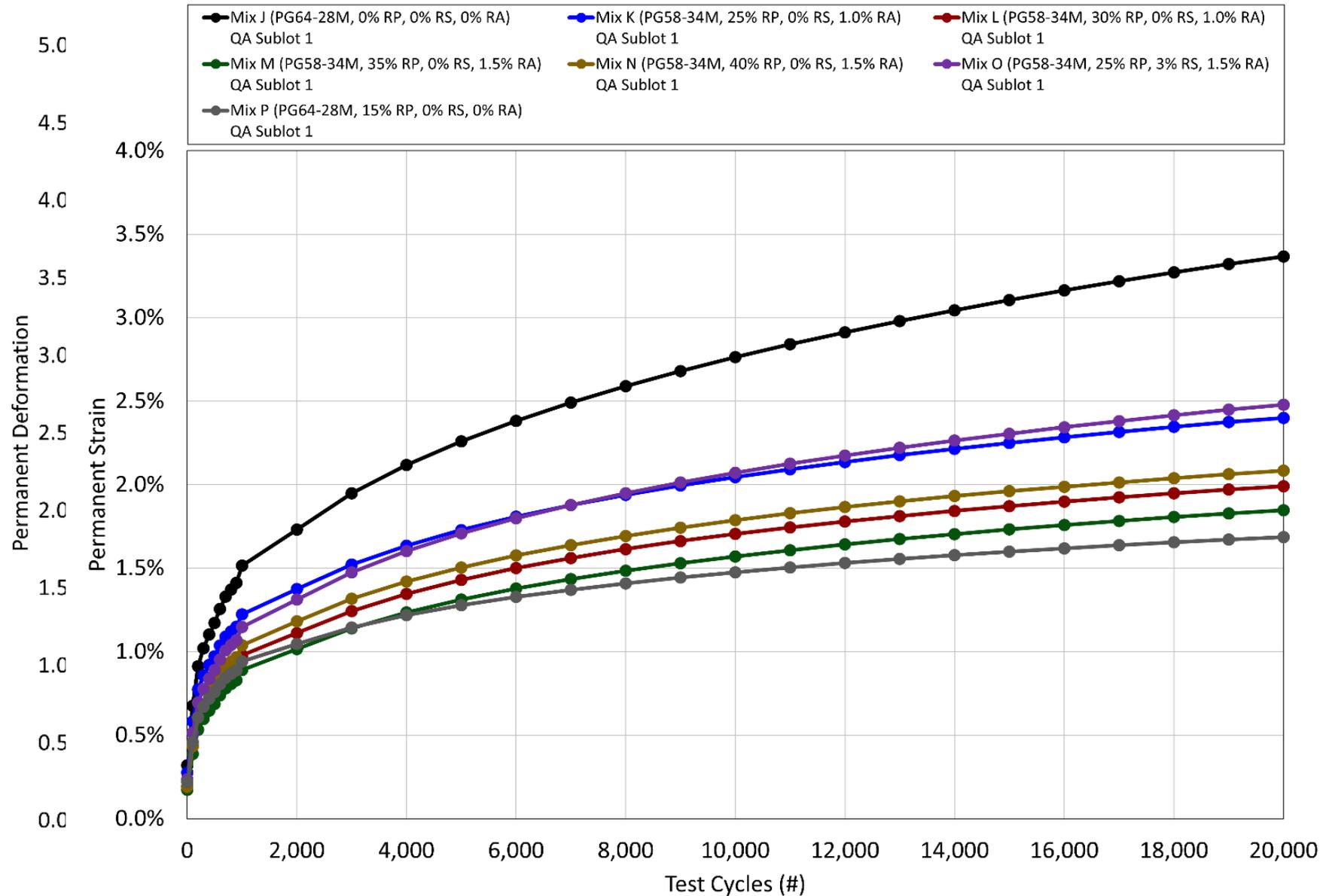
- RAP/RAS effects vary with temperature and speed
- Binder blending appears good

Flexural fatigue



- Variable results for fatigue depending on project
- Replacement of polymer binder with RAP binder generally hurts fatigue
- Binder blending appears good

Rutting – confined repeated load triaxial 55C



- Variable results for rutting depending on project
- Binder blending appears good



Cost-Effectiveness

- **Asphalt binder:**
 - about \$600/ton
- **Virgin aggregate:**
 - about \$40/ton
- **RAP:**
 - about \$40/ton

Material	%	cost/ton	mat cost
virgin asphalt binder	5.0%	\$600	\$30
virgin agg	95.0%	\$40	\$38
RAP (95% agg 5% binder)	0.0%	\$40	\$0
Total material cost	100.0%		\$68

Material	%	cost/ton	mat cost
virgin asphalt binder	3.8%	\$600	\$23
virgin agg	71.3%	\$40	\$29
RAP (95% agg 5% binder)	25.0%	\$40	\$10
Total material cost	100.0%		\$61

Material	%	cost/ton	mat cost
virgin asphalt binder	3.0%	\$600	\$18
virgin agg	57.0%	\$40	\$23
RAP (95% agg 5% binder)	40.0%	\$40	\$16
Total material cost	100.0%		\$57

Environmental Benefits

- Using the National Asphalt Pavement Association(NAPA) Calculator
 - A1 is the materials contribution to Global Warming Potential in kg/short ton
 - Benefits of RAP are reduced if hauling RAP longer distances

Mix	Agg	Neat Binder	Rejuvenator	RAP	Mass Balance	A1 GWP/sh ton
0% RAP Unmodified	95	5	0	0	100	30.3
20% RAP Unmodified	76	4	0	20	100	24.4
40% RAP Unmodified w/ Rejuv	56.96	3	0.042	40	100	20.0

Summary and conclusions

- Summary
 - Finite resource, cost and environmental reasons to increase use of RAP
 - Results of large laboratory (to 50% RAP) study and 3/5 field pilot (to 40% RAP) projects completed
- Conclusions
 - Use of RAP and recycling agent are additional engineering tools to obtain the desired properties
 - Stiffness, fatigue, rutting, moisture
 - The results vary depending on the properties of: virgin binder and grade, RAP source and %, recycling agent dosage
 - Initial results to 25% RAP using step-down binder can be used now
 - Use of performance related testing and specifications need to be brought into practice in California to do better engineering
 - Significant cost and environmental benefits if can get same or better performance

¡ muchas gracias!

Ponente: John Harvey

Contacto: jtharvey@ucdavis.edu



www.ucprc.ucdavis.edu