Performance-based Design Method of Asphalt Mixes that Contain Reclaimed Asphalt Pavement (RAP)

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Issues related to usage of high RAP

- **Availability**
- **Variability**
- **Cracking potential**
- **Extraction and recovery of RAP binder**
- **Blending mechanism not fully understood**
- **Lack of performance tests or associated cost**
- **……….**

Outline

- Introduction
- Materials and Experiments
- Results & Discussion
- Conclusions

Introduction

- Aged binder in RAP increased brittleness of mixes, resulting in susceptibility to pavement cracking.
- Softer virgin binder is used based on RAP binder replacement ratio:
  - <17%, no adjustment.
  - 17%~30%, one grade lower.
  - >30%, blending chart is used; complete blending is assumed, which may not be always reasonable.
- Current mix design is based on volumetric properties, not performance-related.

Results of PG of Recovered Binder

- **North RAP Binder: PG 75.8-23.6 (PG70-22)**

	PG of Recovered North RAP binder					
	1	2	3	Average	Std	COV
High Temperature	76.9	74.9	75.5	**75.8**	1.0	1.3%
Low Temperature	-22.7	-24.6	-23.6	**-23.6**	1.0	4.2%

- **South RAP Binder: PG 85.2-16.8 (PG82-16)**

	PG of Recovered South RAP binder					
	1	2	3	Average	Std	COV
High Temperature	85.3	85.1	85.1	**85.2**	0.115	0.14%
Low Temperature	-17.0	-16.7	-16.8	**-16.8**	0.153	0.91%

Materials and Experiments

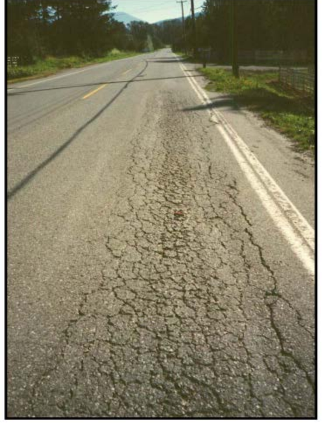
- North mixes
  - N0, N17, N30, N50, and NF30
- South mixes
  - S0, S17, S26, S50, and SF26

North Mixes	PG of Virgin Binder	South Mixes	PG of Virgin Binder
N0	58-28 (Target)	S0	70-28 (Target)
N17	58-28	S17	70-28
N30	52-34	S26	64-34
N50	52-34 (40-34*)	S50	58-34 (58-40*)
NF30	52-34	SF26	64-34

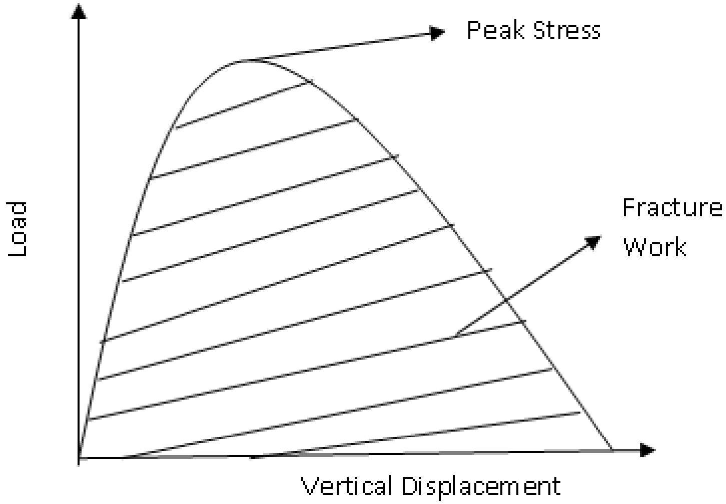
Materials and Experiments

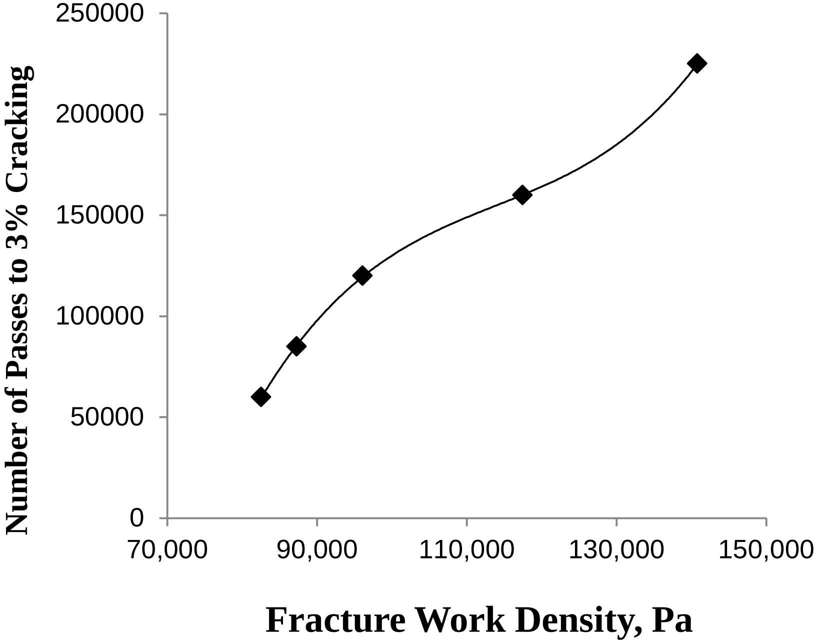
- Short-term and long-term aging
- Dynamic modulus test
- Rutting resistance
  - Flow number test
- Fatigue cracking resistance
  - Indirect tensile test (IDT) at 68ºF.
  - Bottom-up cracking resistance: fracture work density.
  - Top-down cracking resistance: vertical failure deformation.
- Thermal cracking resistance
  - IDT at 14ºF.
  - Fracture work density.

Fracture Work Density



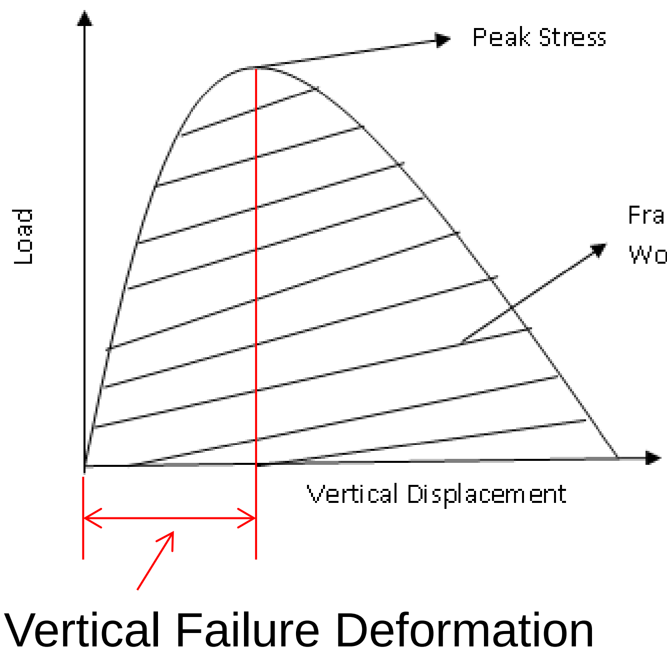
- Bottom-up fatigue cracking - fracture work from Indirect tensile test at 68ºF (Wen et al. 2011)





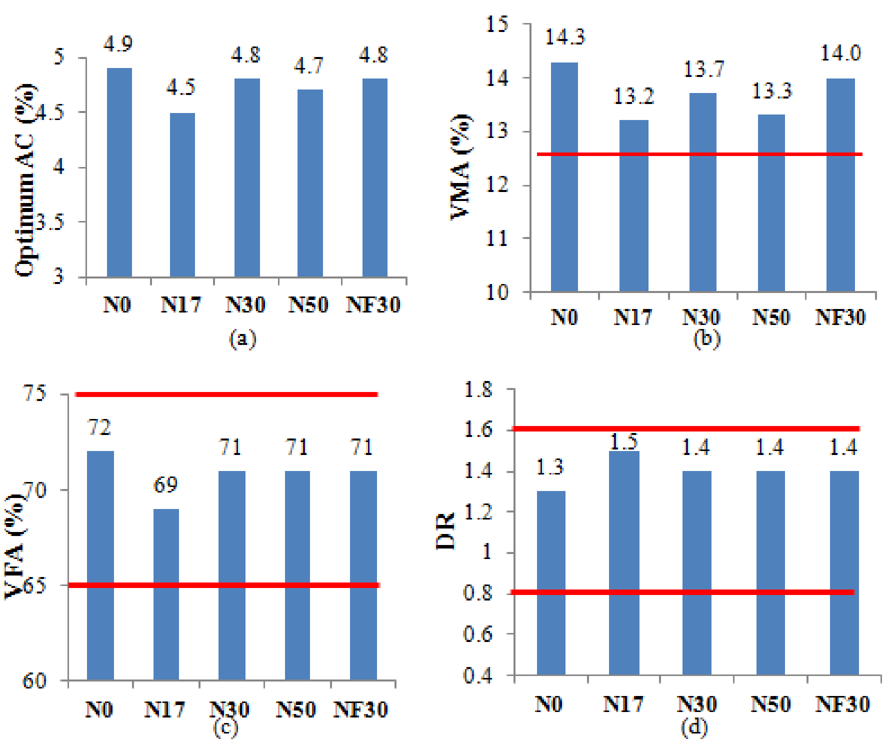
Vertical Failure Deformation

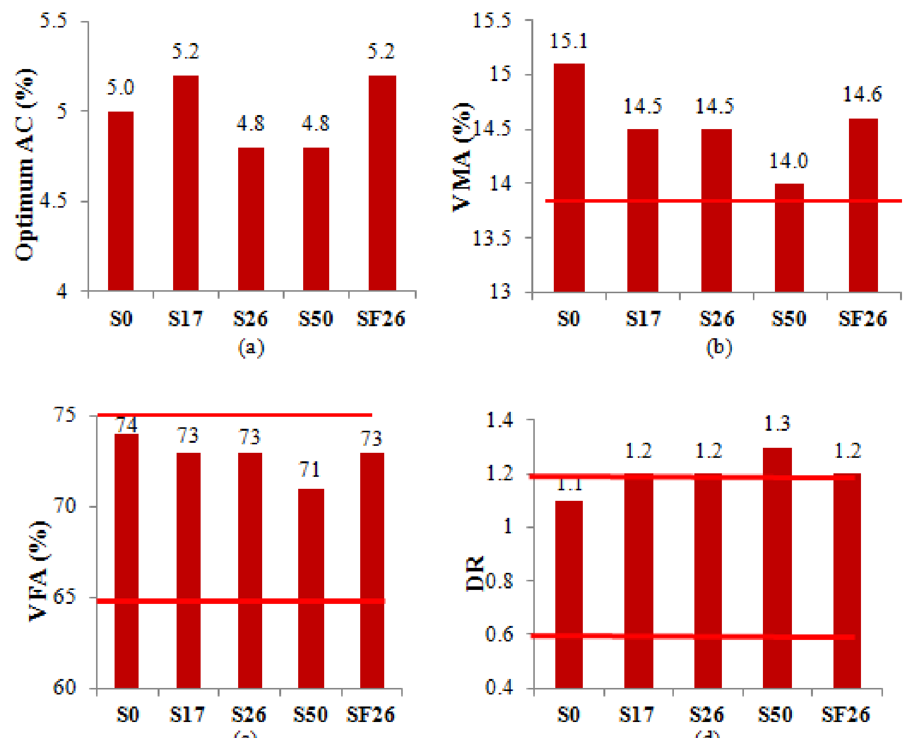
- Top-down cracking – vertical failure deformation (Wen et al. 2015)



Results and Discussion

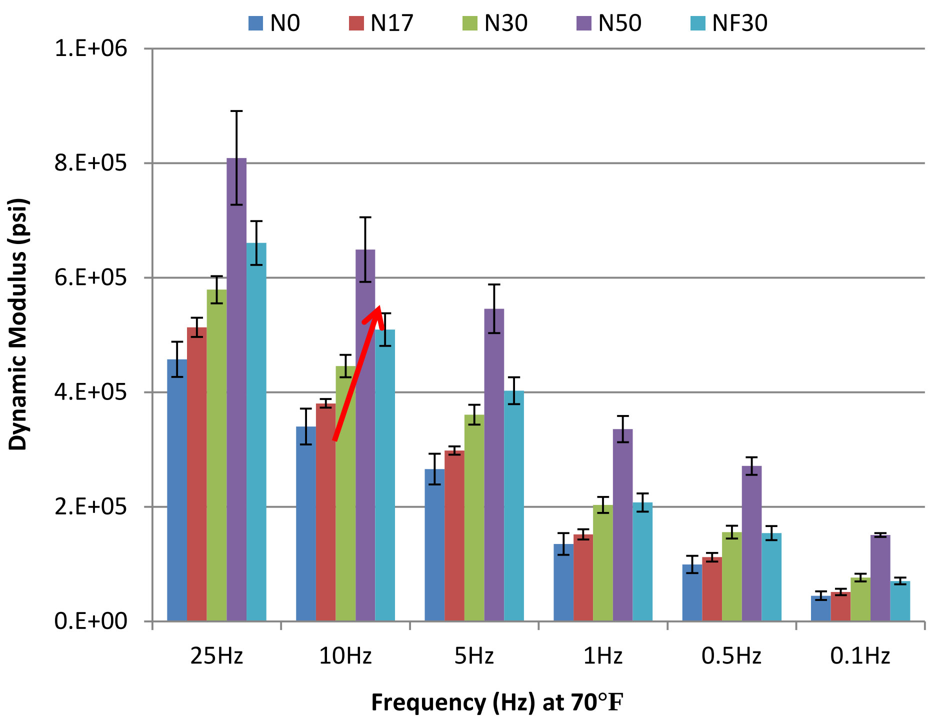
- **Mix Design**-North mixes (blue) & South mixes (red)
  - Mixes contain up to 50 percent RAP could be produced and satisfy the specification requirements of volumetrics.
  - However, inclusion of RAP could significantly change the volumetrics of asphalt mixes, which could affect mix performance.





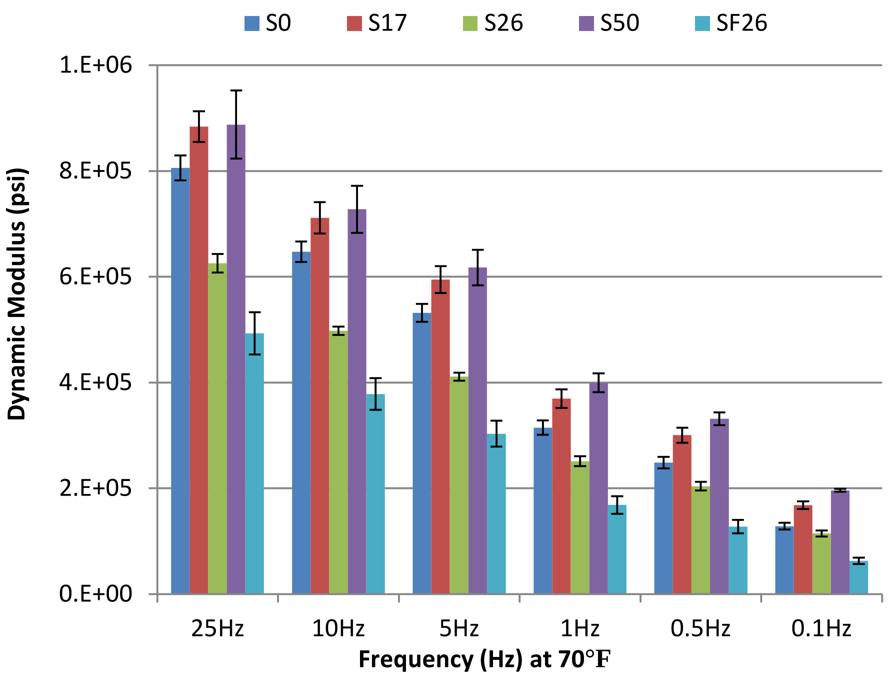
Results and Discussion

- Dynamic modulus test-North mixes:
  - Binder grade adjustment did not offset the stiffening effects of RAP binder.



Results and Discussion

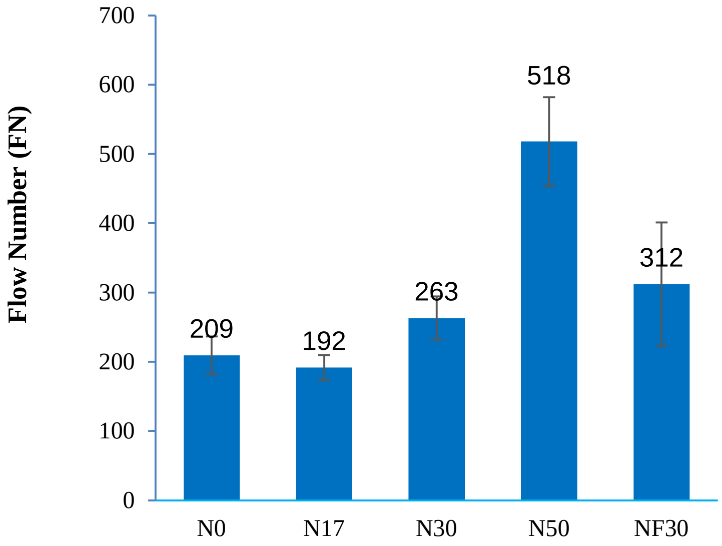
- Dynamic modulus test-South mixes
  - Dynamic modulus values of S0, S17, and S50 mixes are close to each other, and significantly higher than those of S26 and SF26, e.g. at 70ºF.

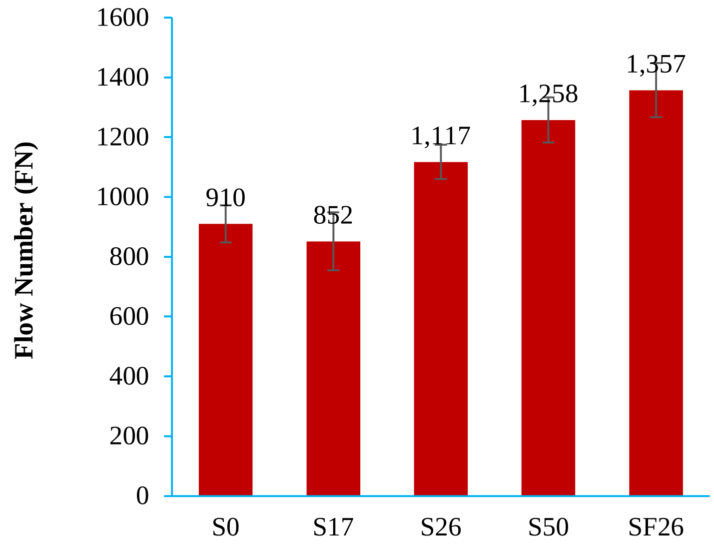


(b)

Results and Discussion

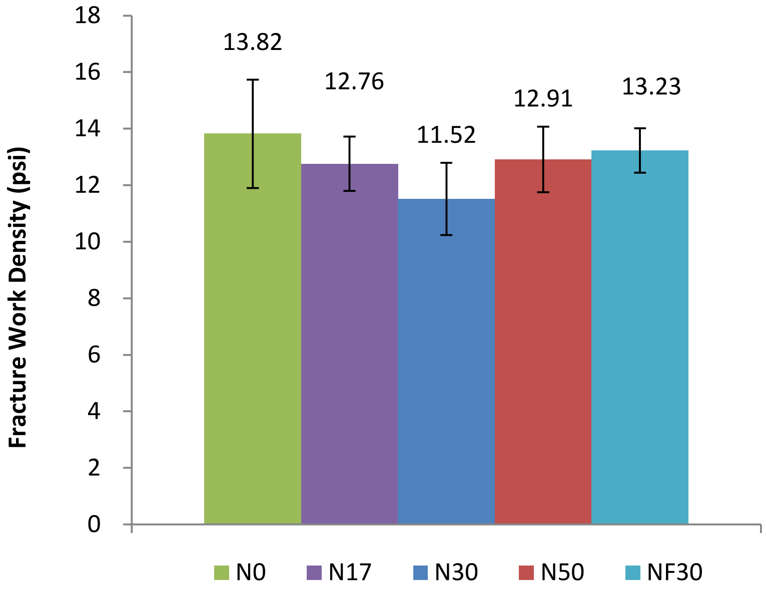
- Rutting resistance-flow number test
  - Mix with low percentage RAP (17% in this study) has similar flow number to control mix.
  - Mixes with high RAP (>17%) has increased flow number, with higher resistance to rutting.
  - Again, binder grade adjustment did not offset the stiffening effects of RAP binder.

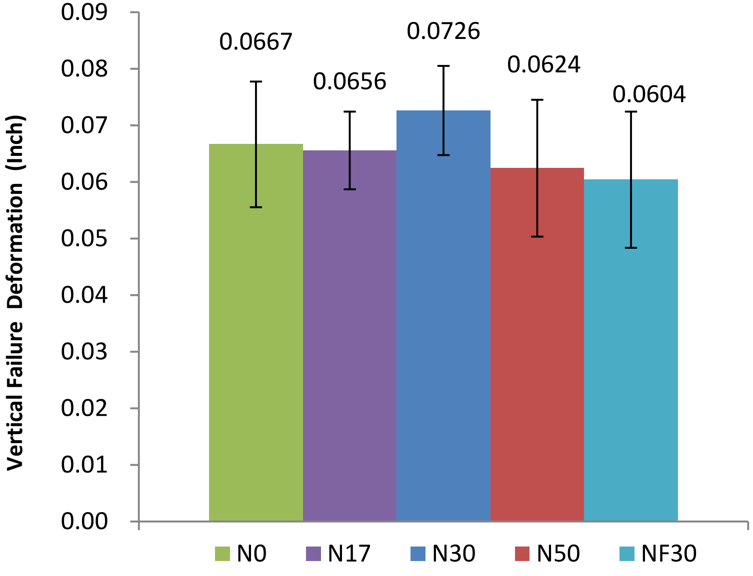




Results and Discussion

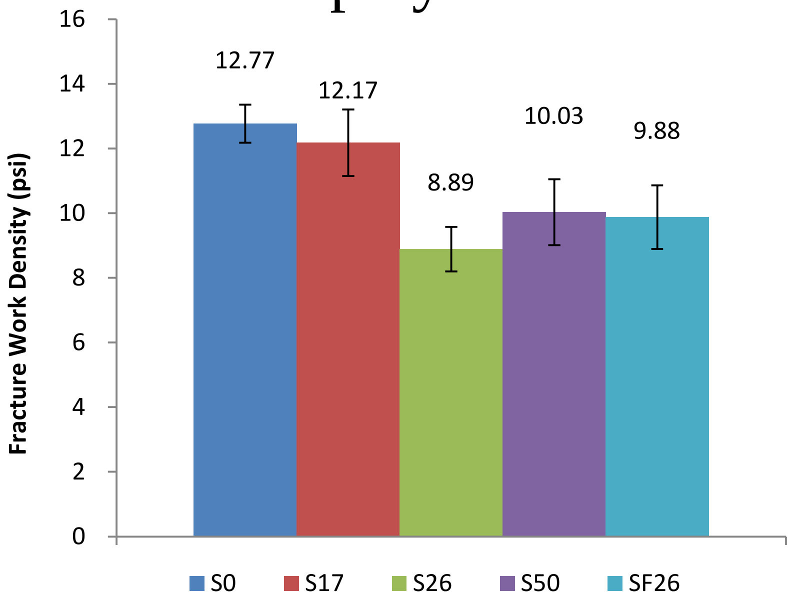
- Fatigue Cracking Resistance-North mixes
  - Target PG of binder is PG58-28.
  - Have comparable resistance to bottom-up and top-down fatigue cracking.





Results and Discussion

- Fatigue Cracking Resistance-South mixes
  - Target PG of binder is PG70-28.
  - S0 and S17 performed identically, and significantly better than S26, S50, and SF26.
  - Loss of polymerization?



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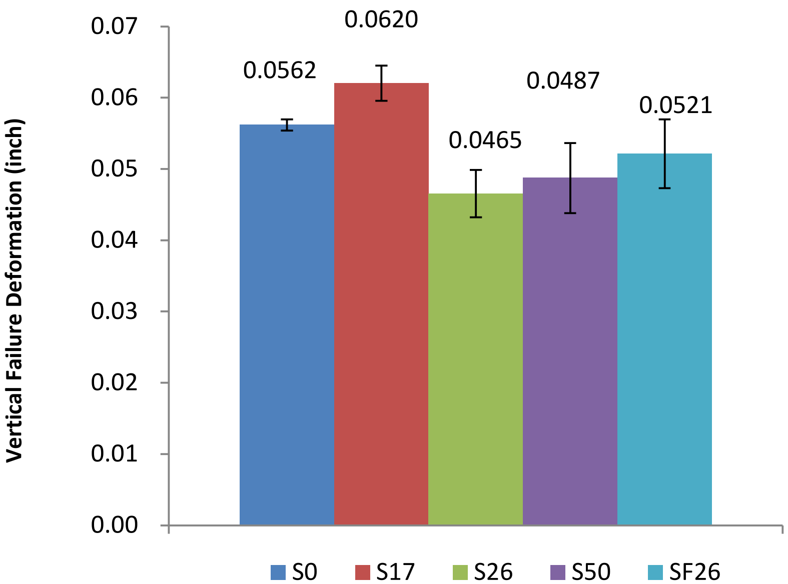

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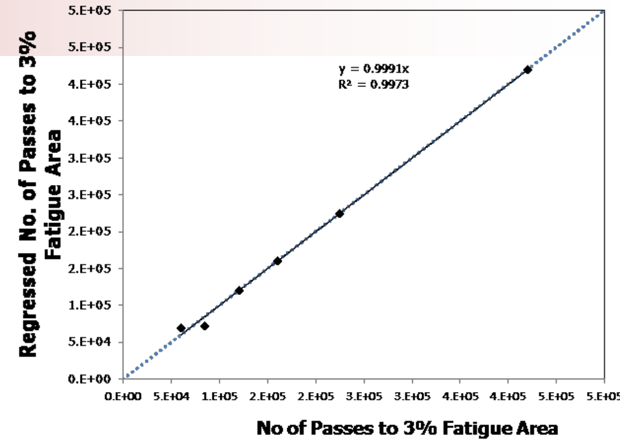
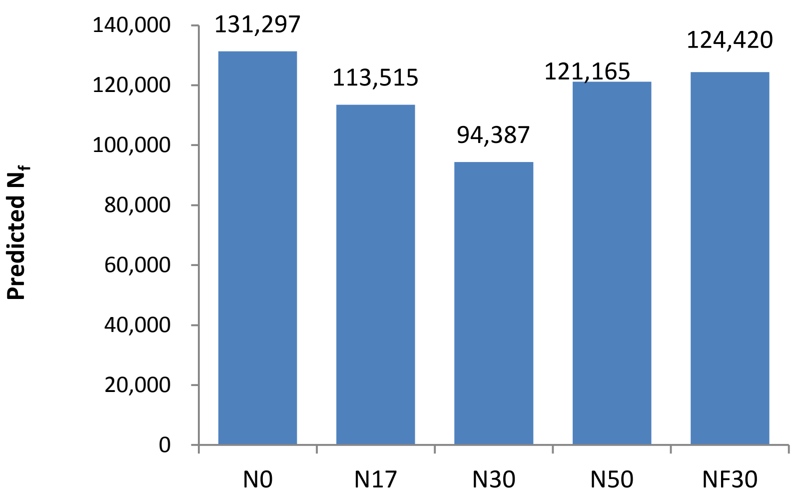
Results and Discussion



- Bottom-up cracking fatigue model

$$N_f = 3.75 \times 10^{-5} (\frac{1}{\varepsilon_t})^{0.147} (FWD)^{1.92} h^{0.135}$$



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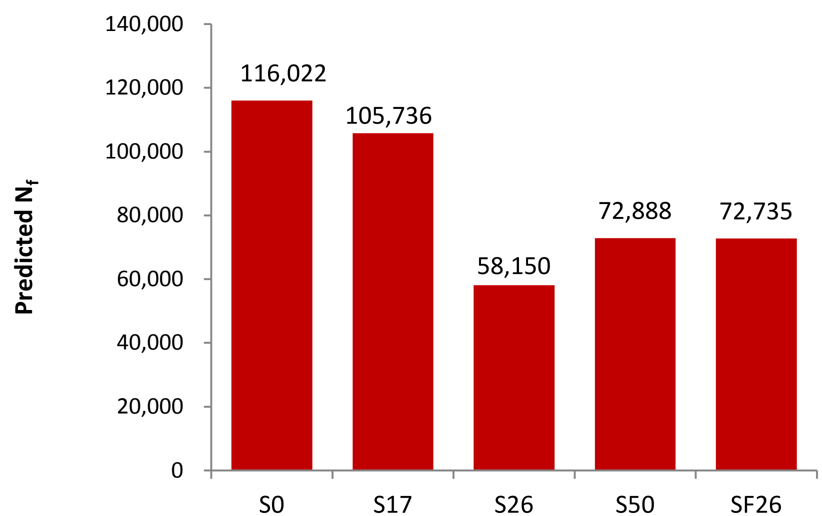


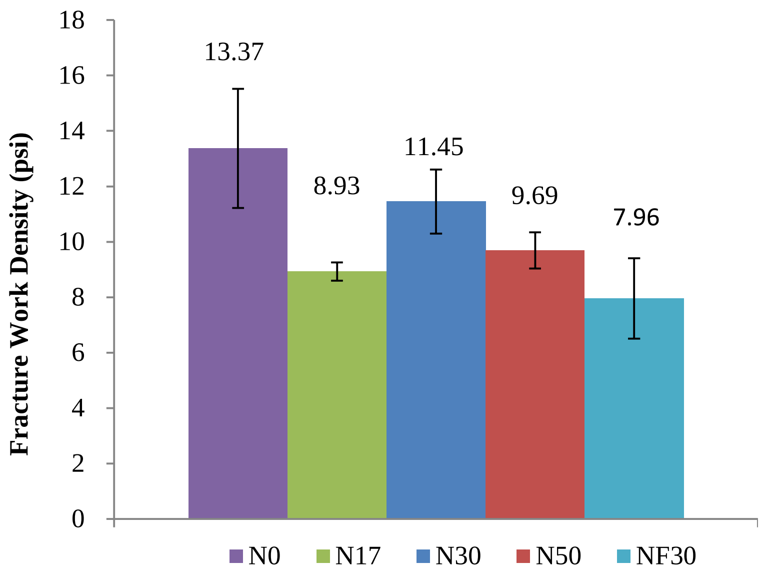
(b)

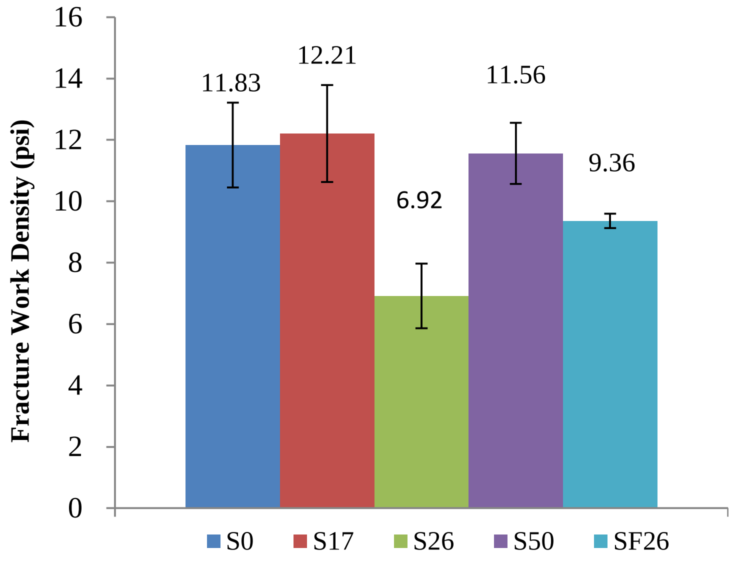
Results and Discussion

- Summary of fatigue cracking resistance
  - Fatigue cracking resistance with low percentage of RAP, e.g. 17%, was comparable to that of control mix.
  - Effects of high percentage RAP (>17%) on fatigue cracking depended on target PG of virgin binder.
    - Low target PG of virgin binder, e.g. PG 58-28: bumping down the grade of virgin binder for high RAP mixes did not affect fatigue resistance, e.g. North mixes.
    - High target PG of virgin binder, e.g. PG 70-28: bumping down the grade of virgin binder for high RAP mixes compromised the fatigue resistance, e.g. South mixes.
  - Recommend to keep the high temperature grade of target binder to avoid elimination or reduction of degree of polymer modification.

Results and Discussion

- Low temperature thermal cracking resistance
  - Inclusion of RAP affected thermal cracking performance of asphalt mixes, but was mix-specific.
  - Cracking performance tests shall be considered in mix design.

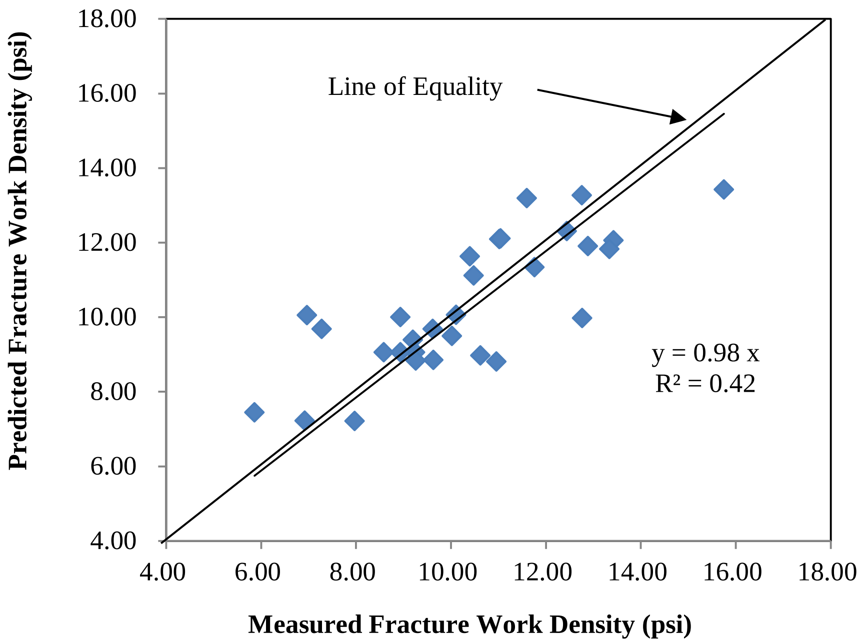




Results and Discussion

- Performance-related empirical mix design
  - Based on fracture work at 14ºF.
  - Predicted model was moderately effective.

$$FWD_{low}=9.437+0.179P_{RAP}-5.209AV+6.690VMA+1.475PG_{virgin\_low}-0.513PG_{virgin\_high}$$



Results and Discussion

- Procedures of performance-related empirical mix design
  - Selection of low temperature PG of virgin binder for a mix with RAP.

$$PG_{virgin\_low}=(FWD_{low}-9.437-0.179P_{RAP}+5.209AV-6.690VMA+0.513PG_{virgin\_high})/1.475$$

    - (1) Design a control mix without RAP using target PG of virgin binder.
    - (2) Estimate FWD_{low} of the control mix.
    - (3) Design a RAP mix to meet volumetrics specification by using target high temperature grade of virgin binder with any low temperature PG.
    - (4) Determine the low temperature PG of the virgin binder based on above equation.
  - Thermal cracking resistance is safeguarded, but binder extraction, recovery, grading of RAP binder, and performance tests of RAP mixes are not needed.

Conclusions

- Inclusion of RAP could significantly affect volumetrics of asphalt mix.
- Inclusion of RAP could improve rutting resistance, regardless of grade bumping
- Inclusion of low percentage (<17%) of RAP does not affect fatigue cracking resistance, and the effect of inclusion of high percentage (>17%) of RAP on fatigue cracking resistance depended on target PG of binder.
- Inclusion of RAP also affected the thermal cracking performance of asphalt mixes, but was mix-specific.
- A performance-related mix design method was developed to guarantee thermal cracking resistance.

Investigation of Effects of Different Blending Stages on Mix Performance

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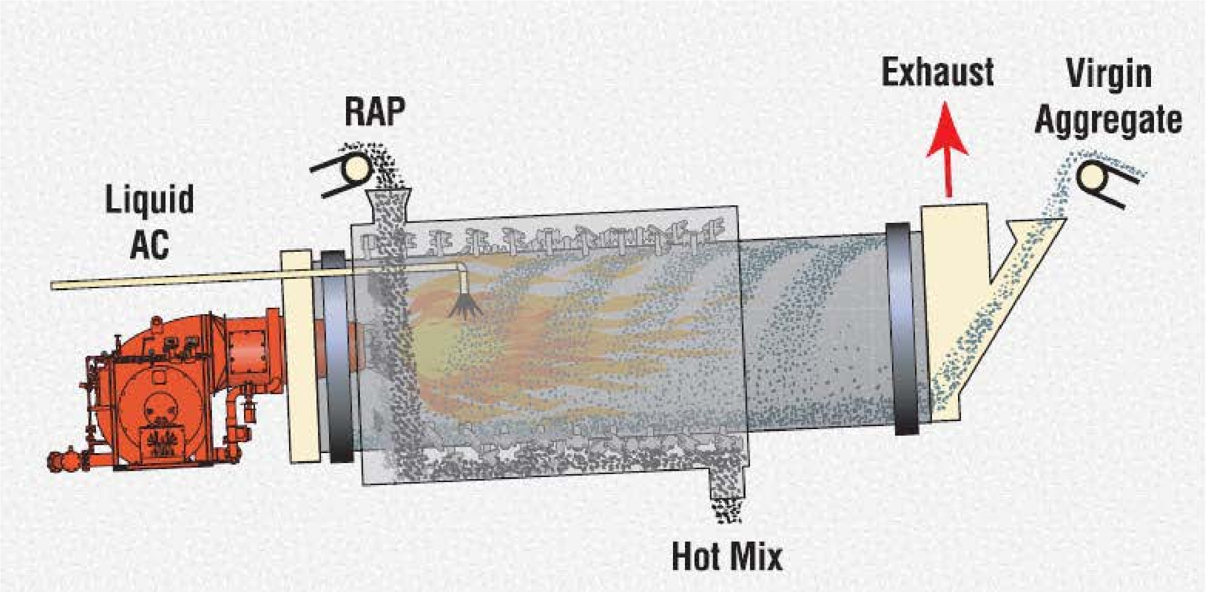
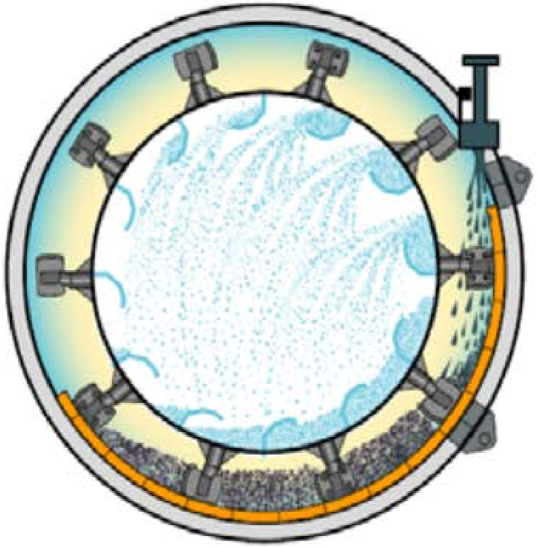
Sept 17, 2015

Investigation of Blending Mechanisms for RAP Binder and Virgin binder

- The production of asphalt mix in asphalt plant greatly affects the blending between RAP binder and virgin binder





(http://www.astecinc.com/products/drying-mixing/sequential-mixing.html)

Introduction

- Three blending stages between RAP binder and virgin binder during production
  - *RAP binder mobilization and transfer to virgin aggregate*

  - *Mechanical blending between RAP binder and virgin binder*
  - *Diffusion* between RAP binder and virgin binder

(After Rad 2013)

Objectives of Study

- Propose a laboratory mixing scheme to distinguish the three blending stages.
- Study the effect of each blending stage on rheological and fracture performance properties of the study mixtures.
- Identify the primary mechanisms of blending of RAP binder and virgin binder.

Materials and Experiments

- RAP Characterization
  - South Idaho RAP
  - POE RAP

	RAP Aggregate Percent Passing, % Sieve Size (mm)										RAP Binder Content	G_{sb} of RAP Aggregate	True PG of RAP Binder
South Idaho RAP	19.0	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075			
	100	95	88	68	54	43	33	21	14	9.4	4.9%	2.583	85.2-16.8

	RAP Aggregate Percent Passing, % Sieve Size (mm)										RAP Binder Content	G_{sb} of RAP Aggregate	True PG of RAP Binder
POE RAP	19.0	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075			
	100	97	89	63	43	31	23	17	13	8.9	4.4%	2.777	83.8-18.3

Materials and Experiments

- Mix Design
  - RAP binder replacement ratio: 26%

South Idaho RAP Mixes	**Sieve Size (mm)**										**Specification**
	19.0	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
Percent Passing, %	100	95	84	62	47	35	26	16	9	5.5	-----
Optimum Binder Content, %	4.8										-----
Air Voids, %	4.0										4.0
VMA, %	14.5										14 min
VFA, %	73										65-75
Dust-to-Asphalt Ratio	1.2										0.6-1.2
PG of Target Binder	70-28										

POE RAP Mixes	**Sieve Size (mm)**										**Specification**
	19.0	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075	
Percent Passing, %	100	93	79	50	33	24	17	13	8	4.8	-----
Optimum Binder Content, %	5.1										-----
Air Voids, %	4.0										4.0
VMA, %	14.2										14 min
VFA, %	72										65-75
Dust-to-Asphalt Ratio	1.1										0.6-1.6
PG of Target Binder	64-28										

Materials and Experiments-Mixing Scheme Design

Heat virgin aggregate (VA) for two hours, and heat virgin binder (VB) and RAP (if in mix design) separately for one hour to mixing temperature

Heat in Oven

Mix VA and VB for 3 min.

- Cool down virgin mix (VM) and RAP separately to room temperature
  - Heat VM and RAP separately at compaction temp for total 2.5 hours
    - Mix VM and RAP by <u>Spatula</u> **(Mix A)**
  - Mix VM and RAP for 3 min. at room temp. **(Mix B)**
- Immediately mix virgin mix with RAP for 3 min. **(Mix C)**

Mix VA and RAP first for 3 min.

- Immediately mix VA and RAP with VB for 3 min. **(Mix D)**

Mix VA and VB for 3 min. **(Mix E and F)**

VM and RAP

Cool down blended mix to room temp. (Mix C, Mix D, Mix E and F)

Heat blended mix for 2.5 hours at compaction temp. (Mix B and the cooled blended mixes)

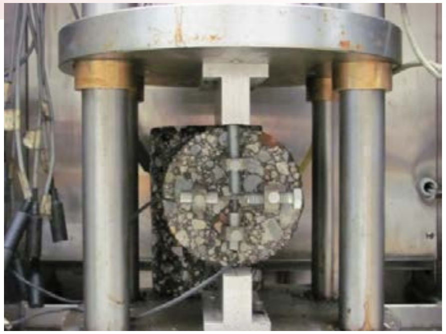
Compact mixes by gyratory compactor to the height of 115 mm.

Cool down compacted samples by fan to room temp.

Materials and Experiments-Mixing Scheme Design

Mixes	Virgin Binder of South Idaho RAP Mixes	Virgin Binder of POE RAP Mixes	RAP Replacement	Blending Stages
Mix A	PG 64-34	PG 58-34	26%	Minimal Diffusion
Mix B	PG 64-34	PG 58-34	26%	Diffusion
Mix C	PG 64-34	PG 58-34	26%	Mechanical Blending +Diffusion
Mix D	PG 64-34	PG 58-34	26%	Binder Mobilization +Mechanical Blending +Diffusion
Mix E	PG 64-34	PG 58-34	0%	NA
Mix F (Target Mix)	PG 70-28	PG 64-28	0%	NA

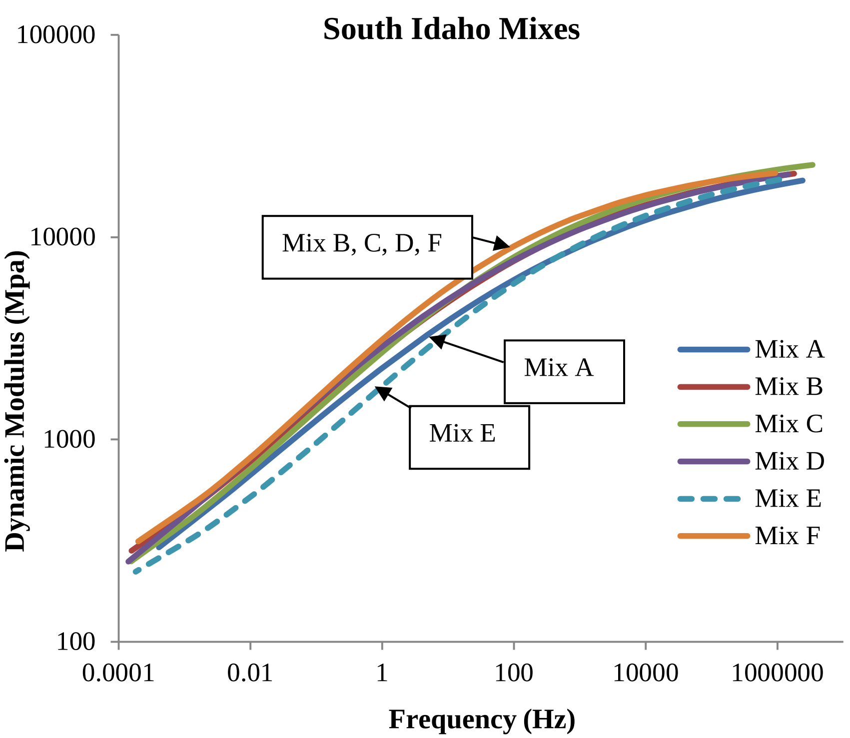
Materials and Experiments

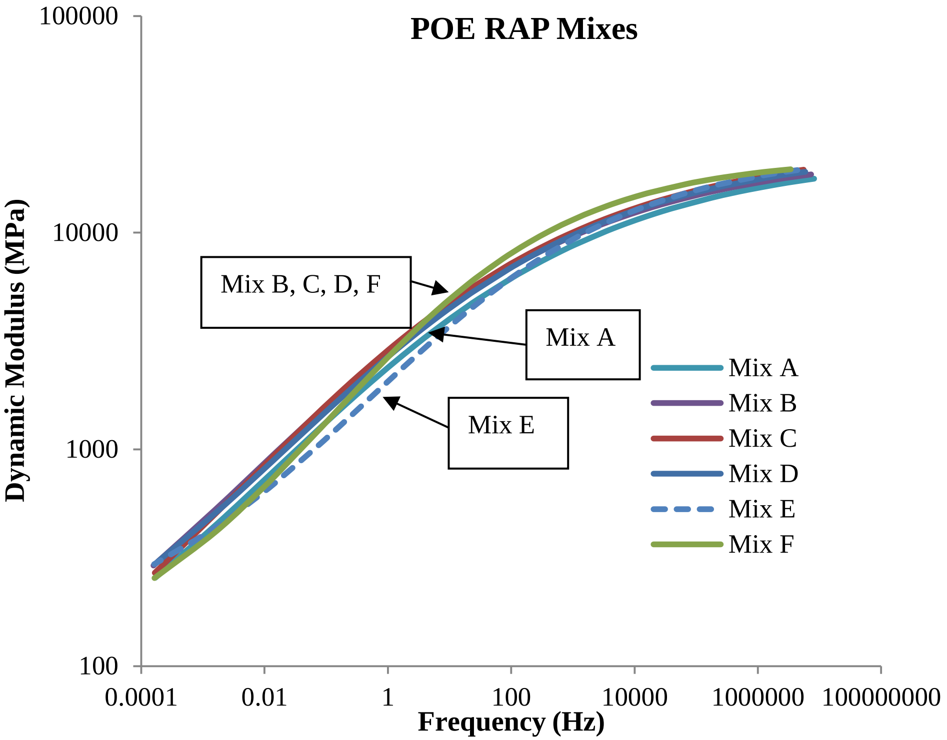


- Make samples
  - 4% air void
  - Short-term and long-term aging
- Rheological performance evaluation
  - Dynamic modulus in indirect tensile (IDT) mode
  - Creep compliance
- Fracture performance evaluation
  - IDT test at 68°F
    - Bottom-up fatigue cracking resistance: fracture work density.
    - Top-down fatigue cracking resistance : vertical failure deformation.
  - IDT test at 14°F
    - Thermal cracking resistance: fracture work density.

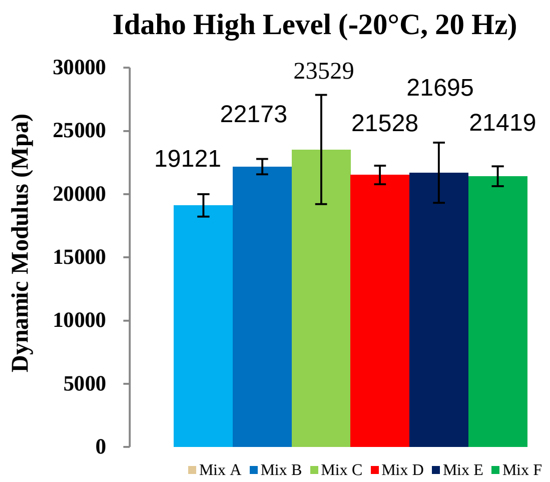
Results and Discussion

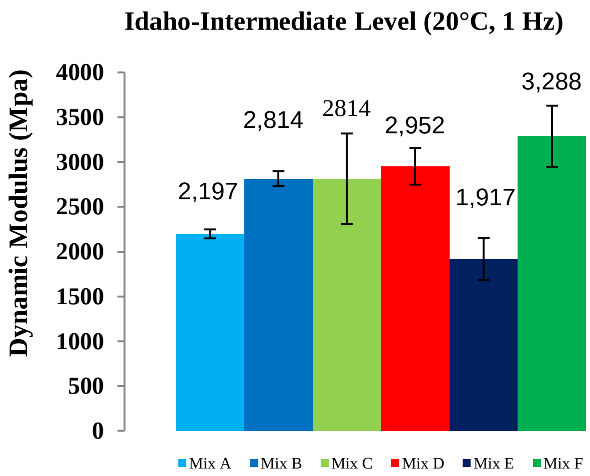
- Rheological properties: dynamic modulus (DM) values
  - Difference was profound at intermediate level
  - RAP mixes has comparable DM values so that diffusion was most dominant stage to affect DM values.

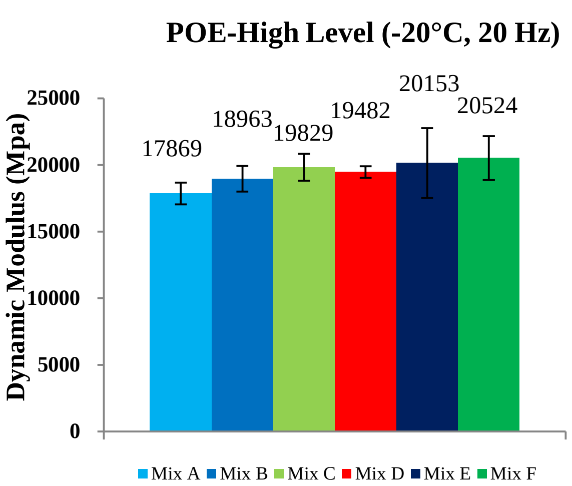


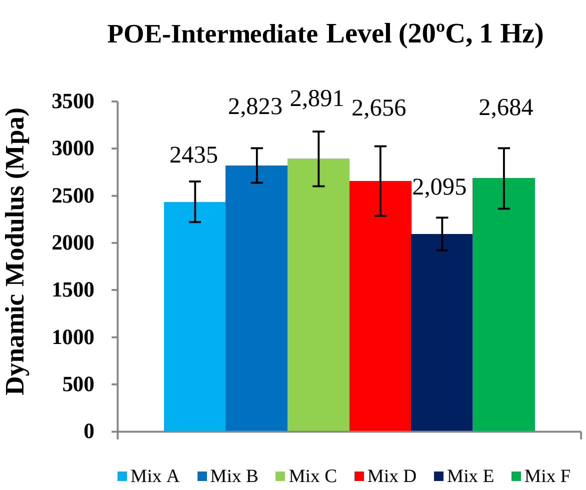


Dynamic Modulus Values at Different Levels



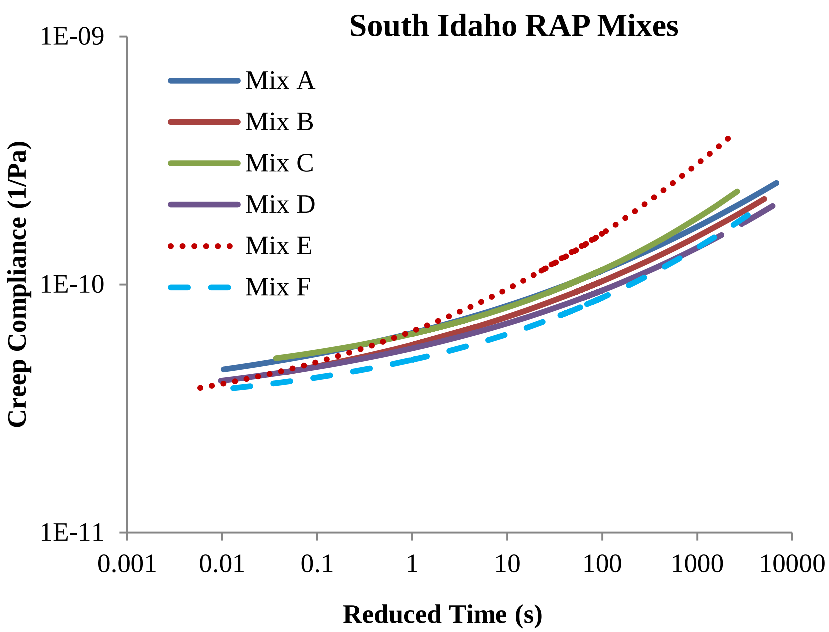


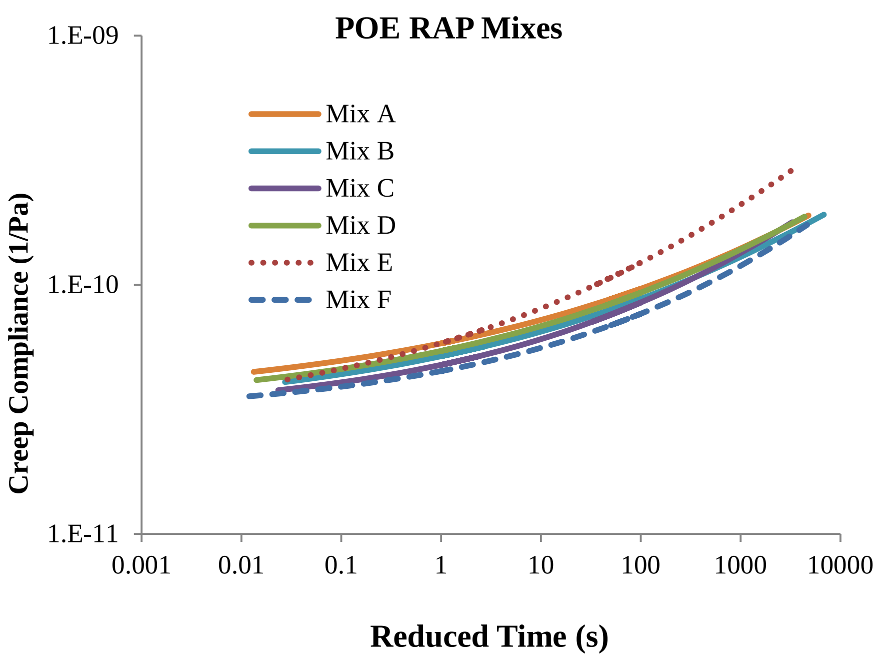




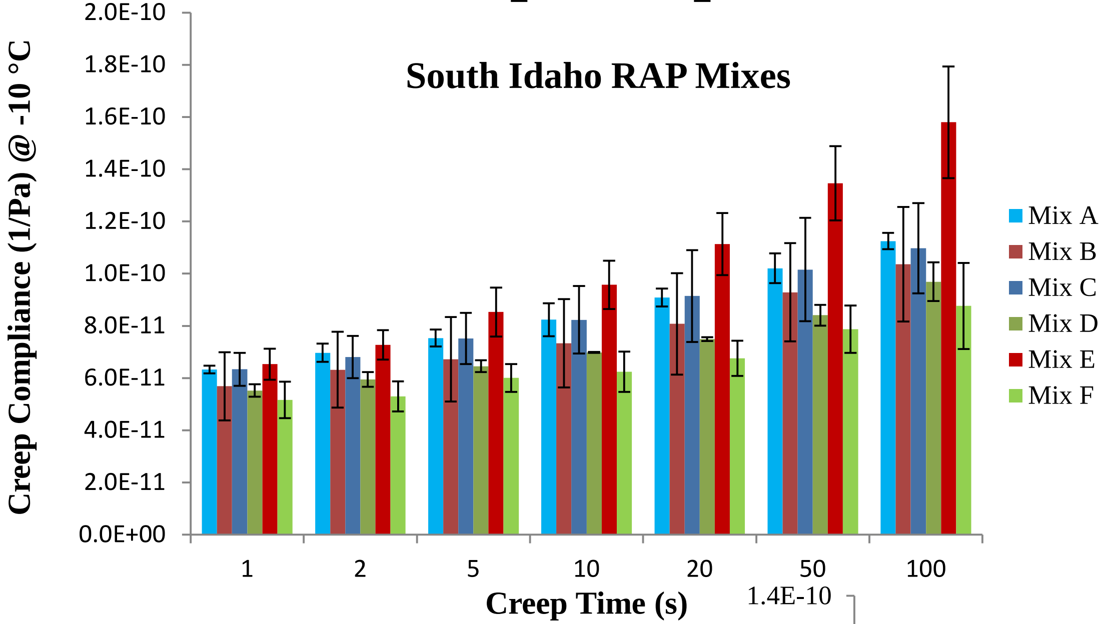
Results and Discussion

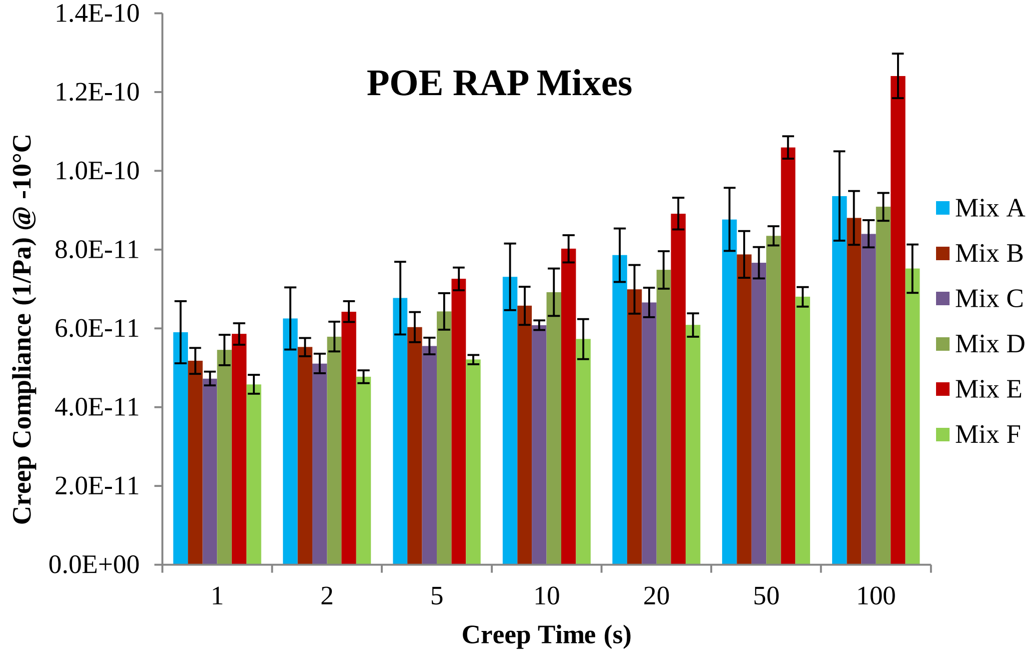
- Rheological properties: ***creep compliance***
  - At a high temperature or reduced time, control mix E has highest creep compliance, while control mix F has similar creep compliance with all four RAP mixes.
  - Again, RAP mixes has comparable creep compliance values and diffusion is most dominating blending stages.





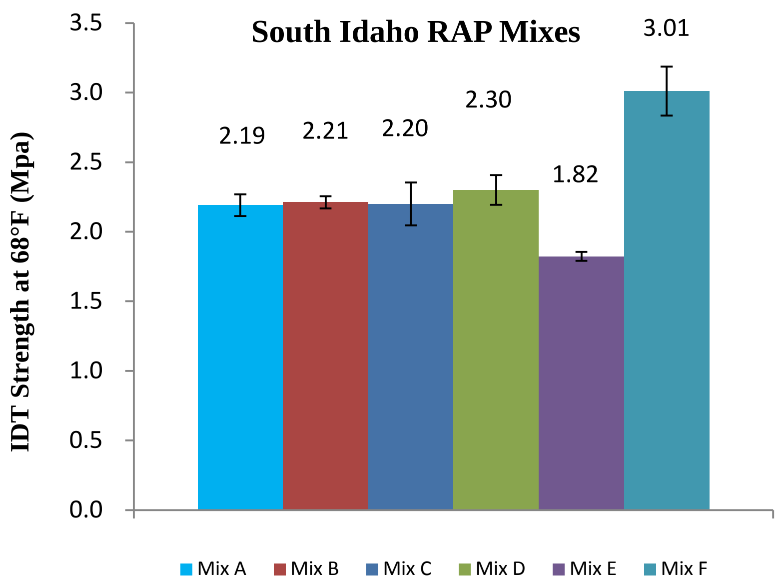
Creep Compliance Values at -10ºC

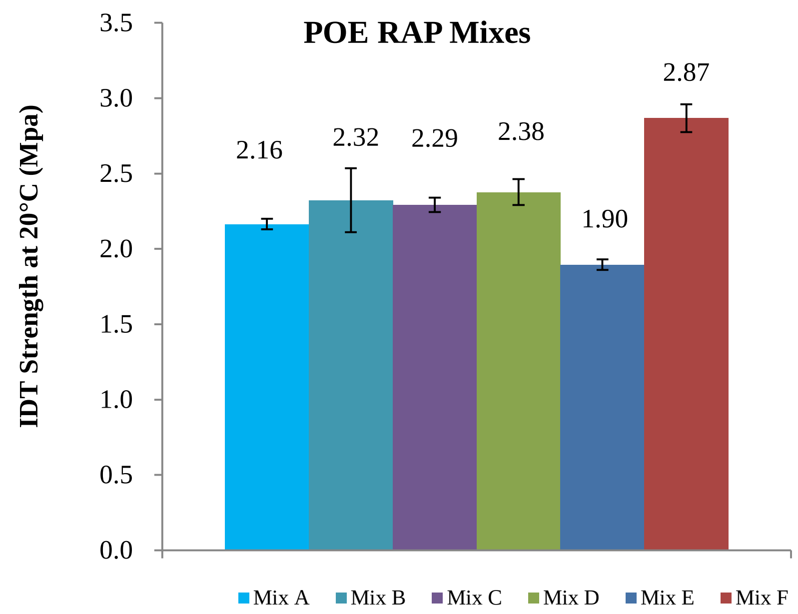




Results and Discussion

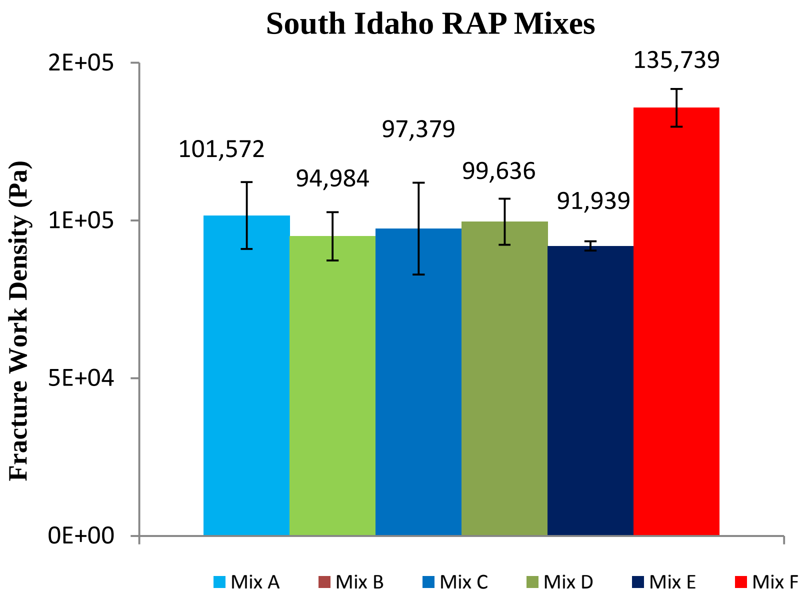
- Facture performance: ***IDT test at 68ºF***
  - IDT strength at 68ºF
    - IDT strength of RAP mixes were **higher** than control mix E with the same PG of virgin binder, and **lower** than control mix F with target PG of virgin binder.
    - Blended binder in RAP mixes dictated the strength.
    - Diffusion is the dominating blending effect between RAP binder and virgin binder.

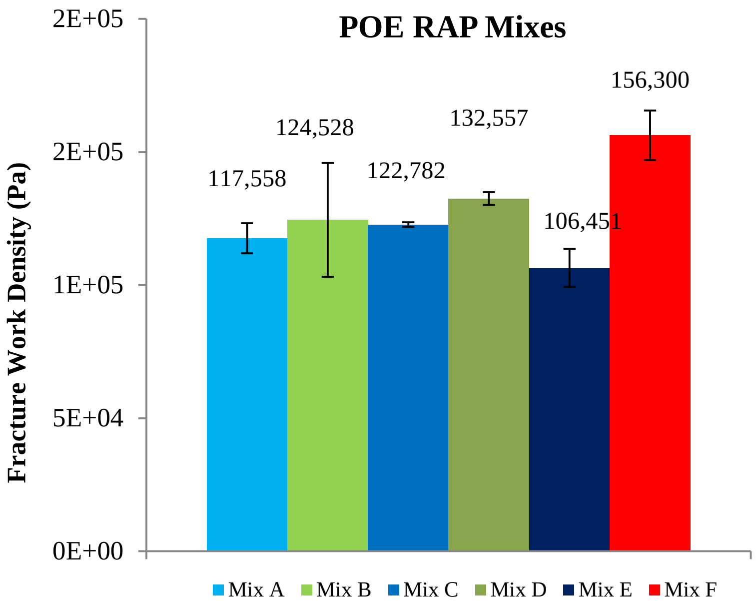




Results and Discussion

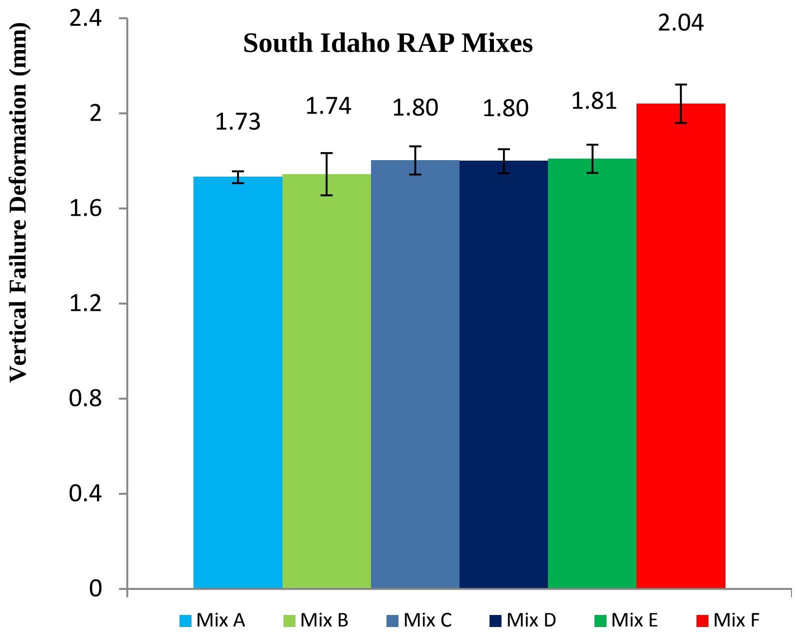
- Facture performance: ***IDT test at 68ºF***
  - Fracture work density-bottom-up fatigue cracking resistance.
    - RAP mixes B, C, and D have comparable fracture work density
    - Keep high PG of target PG is beneficial

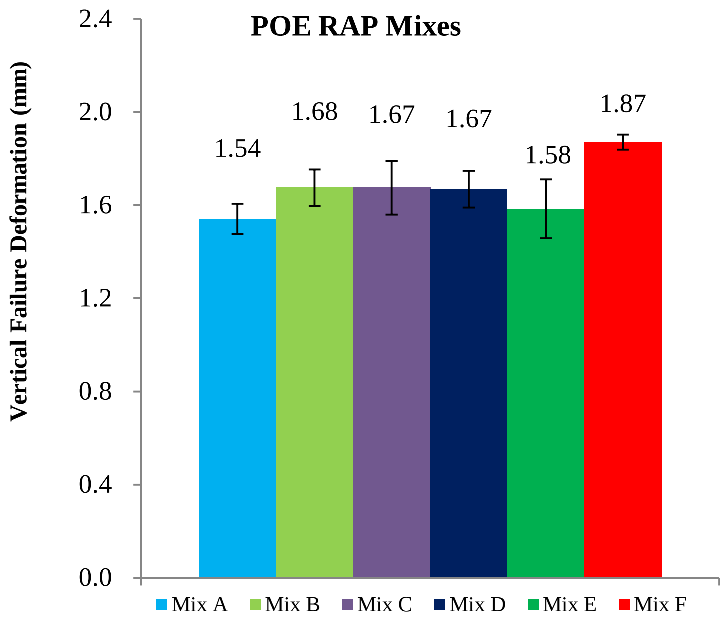




Results and Discussion

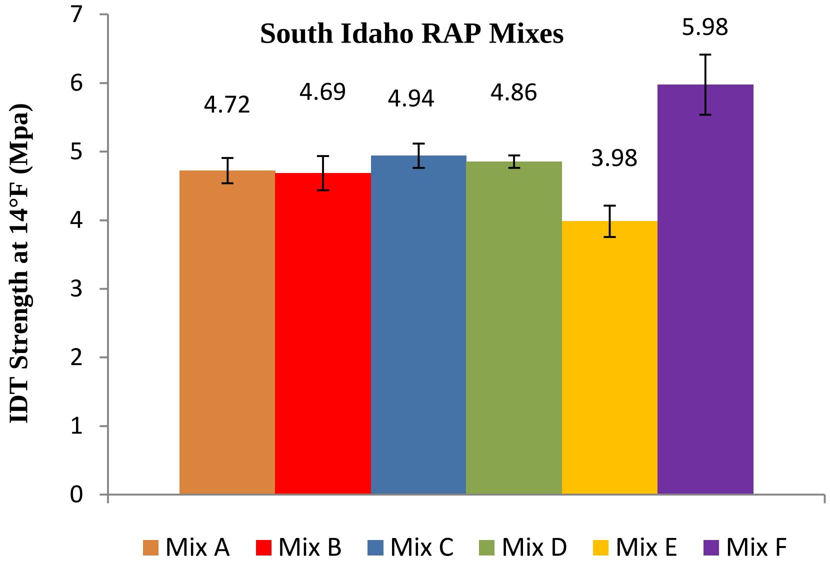
- Facture performance: ***IDT test at 68ºF***
  - Vertical failure deformation-ductility of the mixes
    - Values of RAP mixes are close to control mix with same PG of virgin binder
    - Relatively soft binder controls the ductility of the mix.
    - Keep high PG of target PG is beneficial

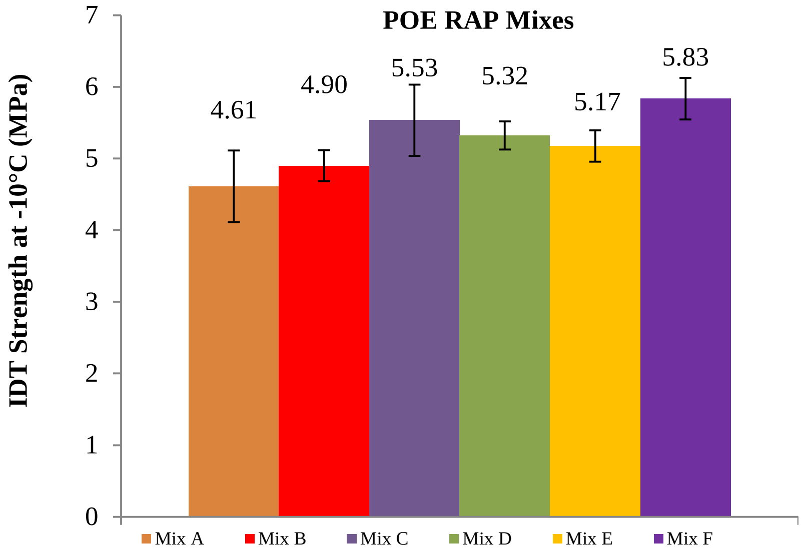




Results and Discussion

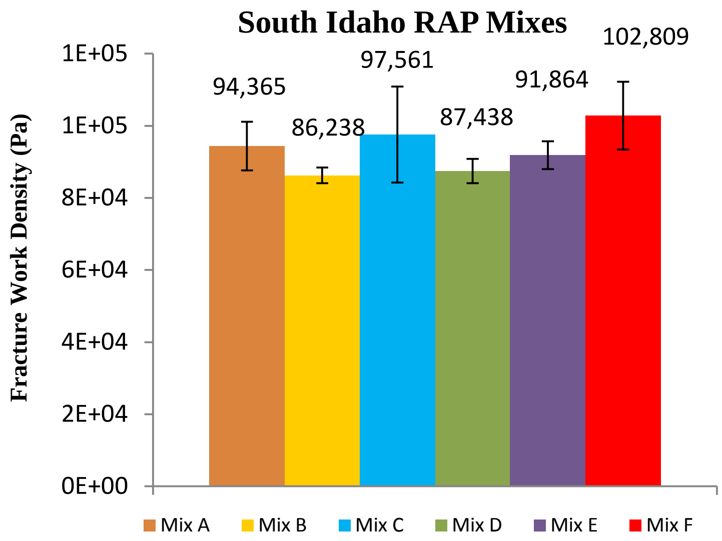
- Facture performance: ***IDT test at 14ºF***
  - IDT strength at 14ºF
    - South Idaho RAP mixes: Same trend as IDT strength of 68ºF
    - POE RAP mixes: No significant difference between mixes , except Mix A and Mix F. The effect of aggregate properties on low temperature fracture performance is more apparent.
    - Diffusion dominates the behavior of RAP mixes compared to RAP binder transfer and mechanical blending .

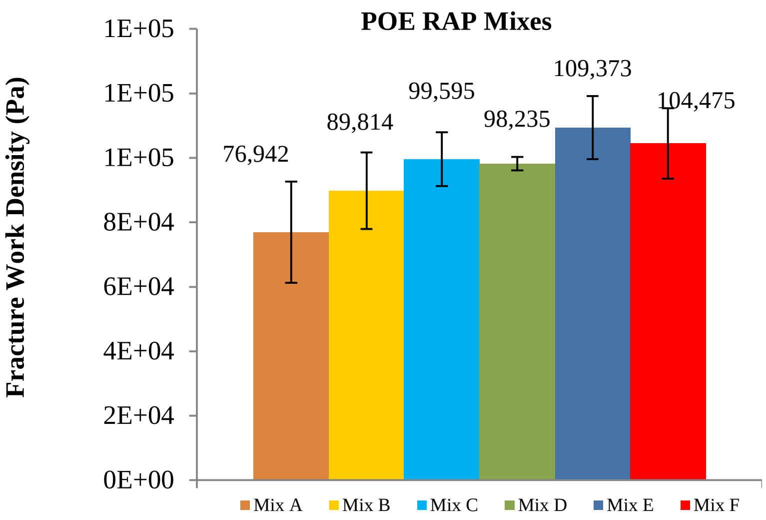




Results and Discussion

- Facture performance: ***IDT test at 14ºF***
  - No significant difference among mixes





Conclusions

- Diffusion was the most dominant in affecting rheological and fracture properties of RAP mixes.
- Relatively softer binder controls ductility of the mix, and active blended binder dictates the strength of mixes at intermediate temperature.

Thank you!