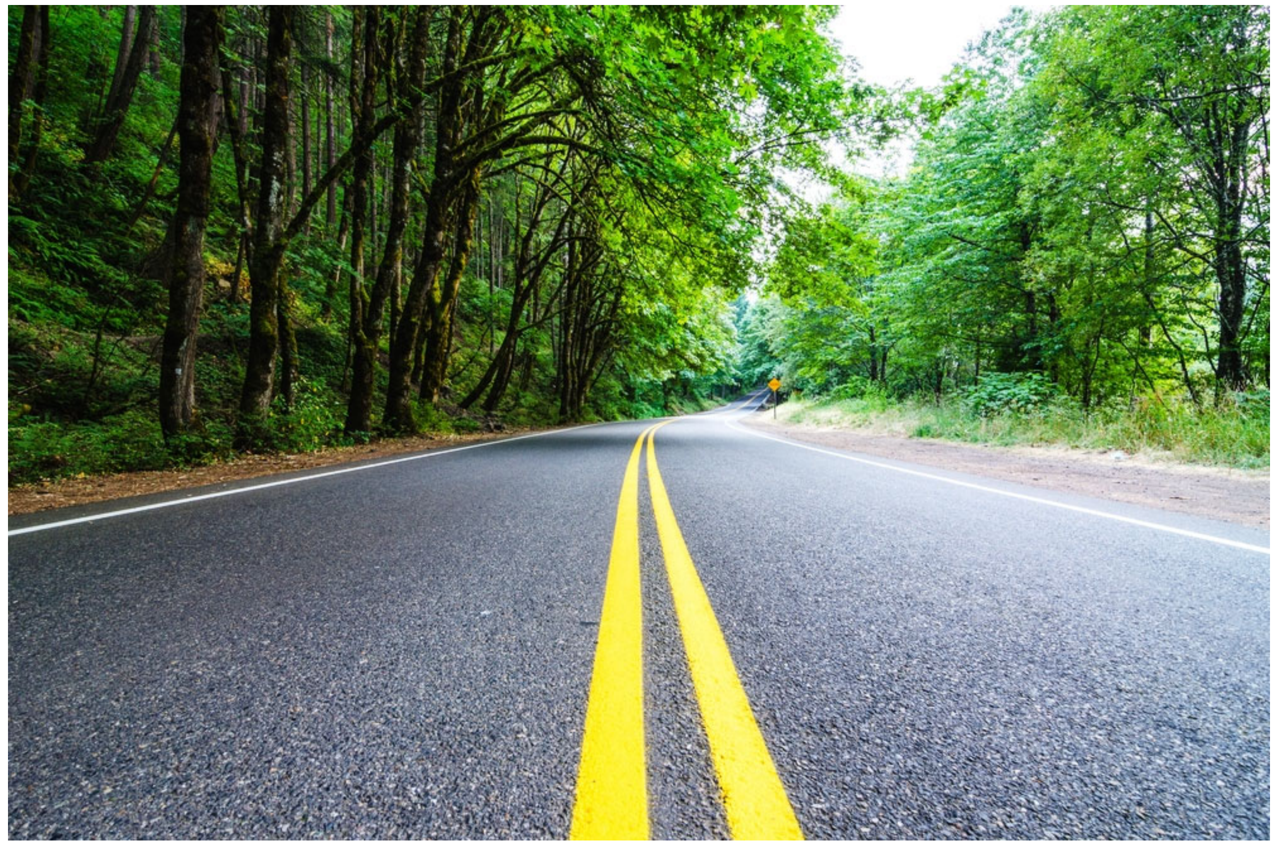
Application of Bio-binders as Sustainable Alternative to Conventional Asphalt Binders



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October 28, 2019

The Researcher

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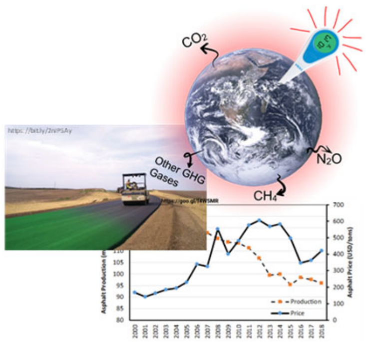
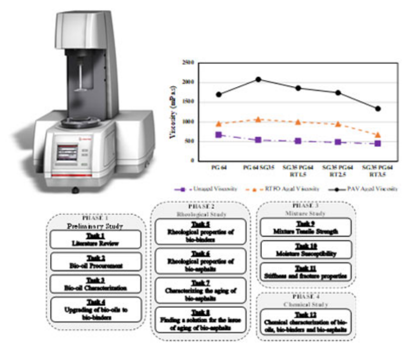
Application of bio-binders in asphalt pavements.



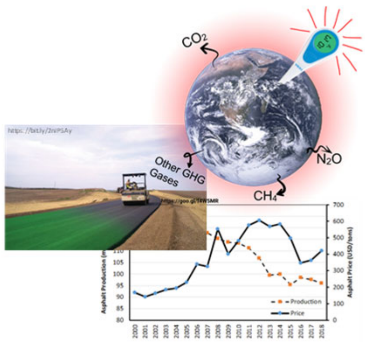
Introduction, background, and problem statement



Discussion of E\experiment and results

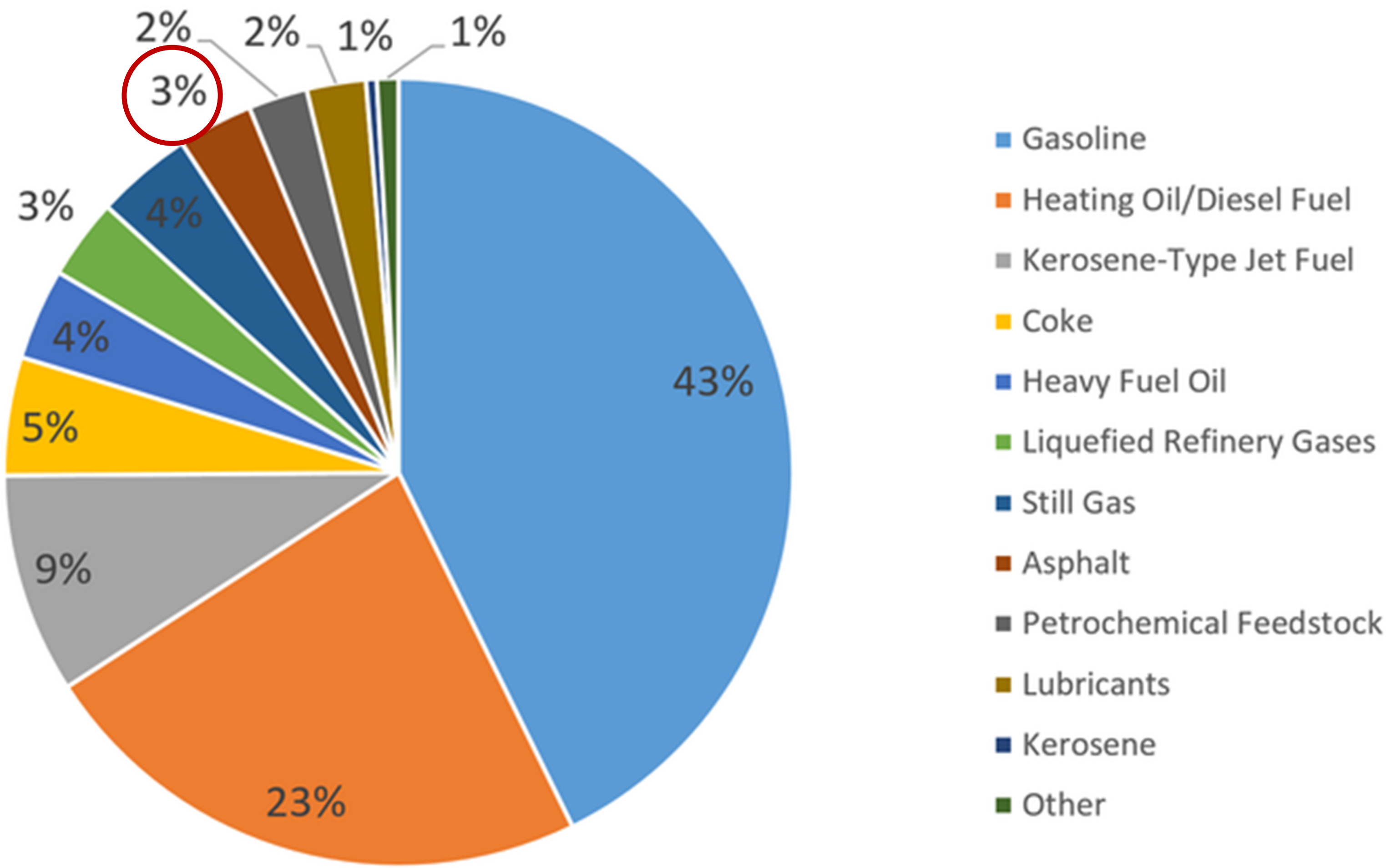
SUMMARY
CONCLUSIONS
FUTURE WORK

Summary, conclusions, and recommendations



Introduction, background, and problem statement

- **Why consider alternatives to asphalt binders?**
- **What are bio-binders?**
- **What materials can be used?**



https://www.quora.com/How-many-gallons-of-gas-can-you-get-to-a-barrel-of-oil

Why need alternatives to asphalt binders?

1) Environment

- **Production of asphalt binders is energy-intensive** ⇨ **Large Carbon Footprint**

Extraction and transport of each ton of crude oil:

130 kg Eq. CO_2 emissions

Production of each ton of asphalt binder from crude oil:

126 kg Eq. CO_2 emissions

Production of bio-oils:

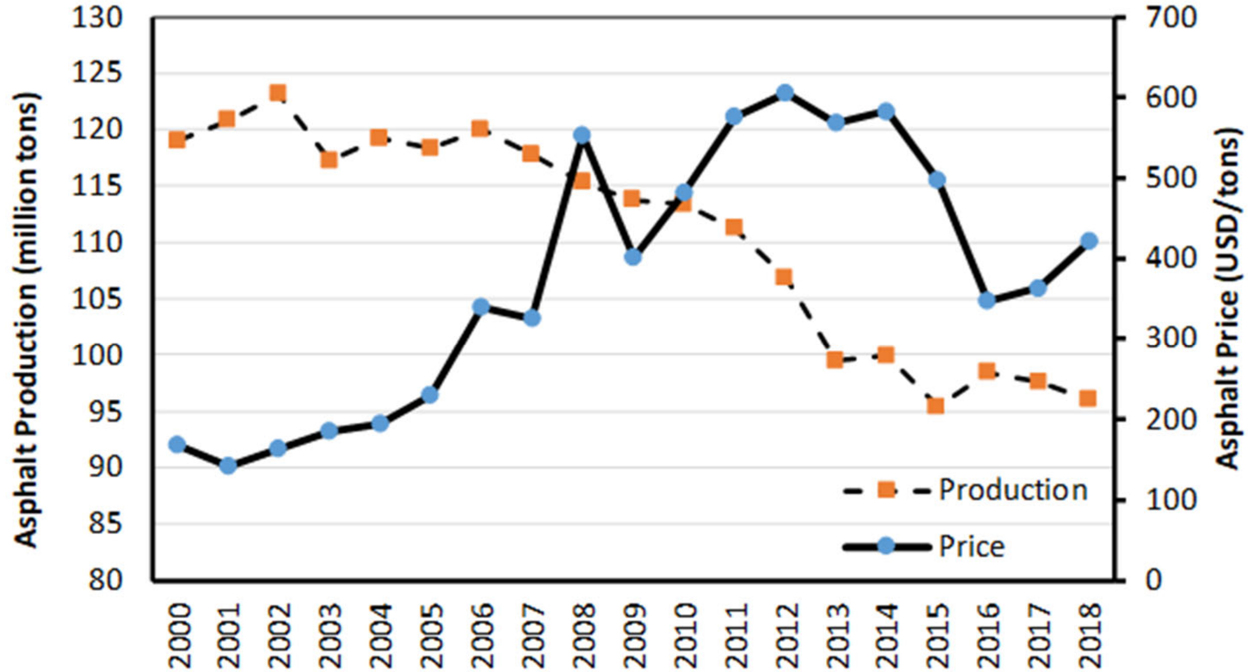
no carbon footprint!

Through use of renewable fuels created during the process

Why need alternatives to asphalt binders?

2) Economy

- **36% drop in production over 12 years!**
- **Demand increases by average rate of 3.3%**
- **Global price of asphalt binder is on an increasing trend**



How are the bio-binders produced?

Bio-binders are made through processing of bio-oils!

Bio-oils are biomass liquefied through different thermochemical processes:

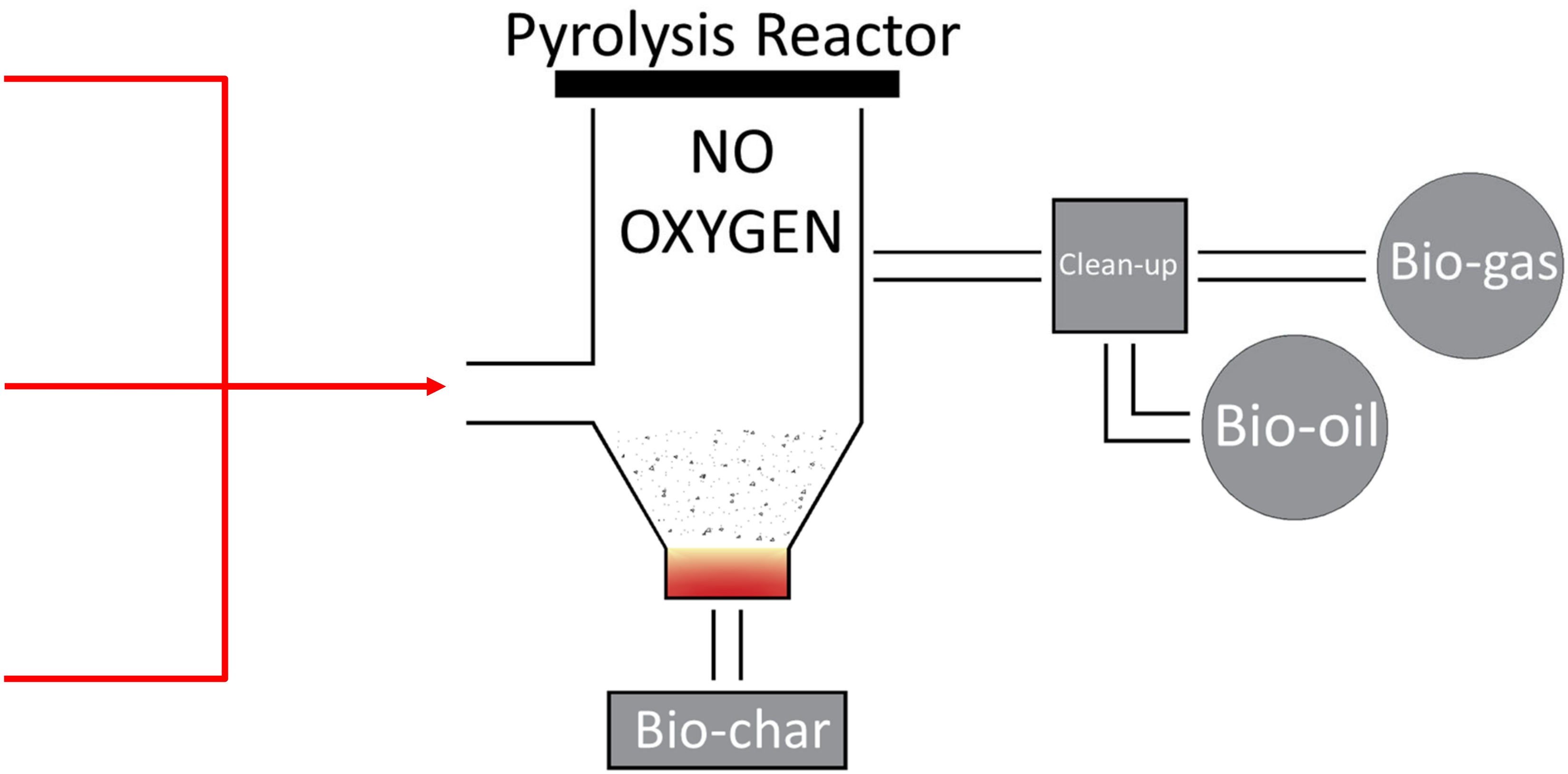
- Steam gasification
- **Pyrolysis**
- Solar gasification
- Supercritical fluid extraction
- Microbial fermentation

Biomass is any organic material (plant or animal based) used for energy production

Production of bio-oil

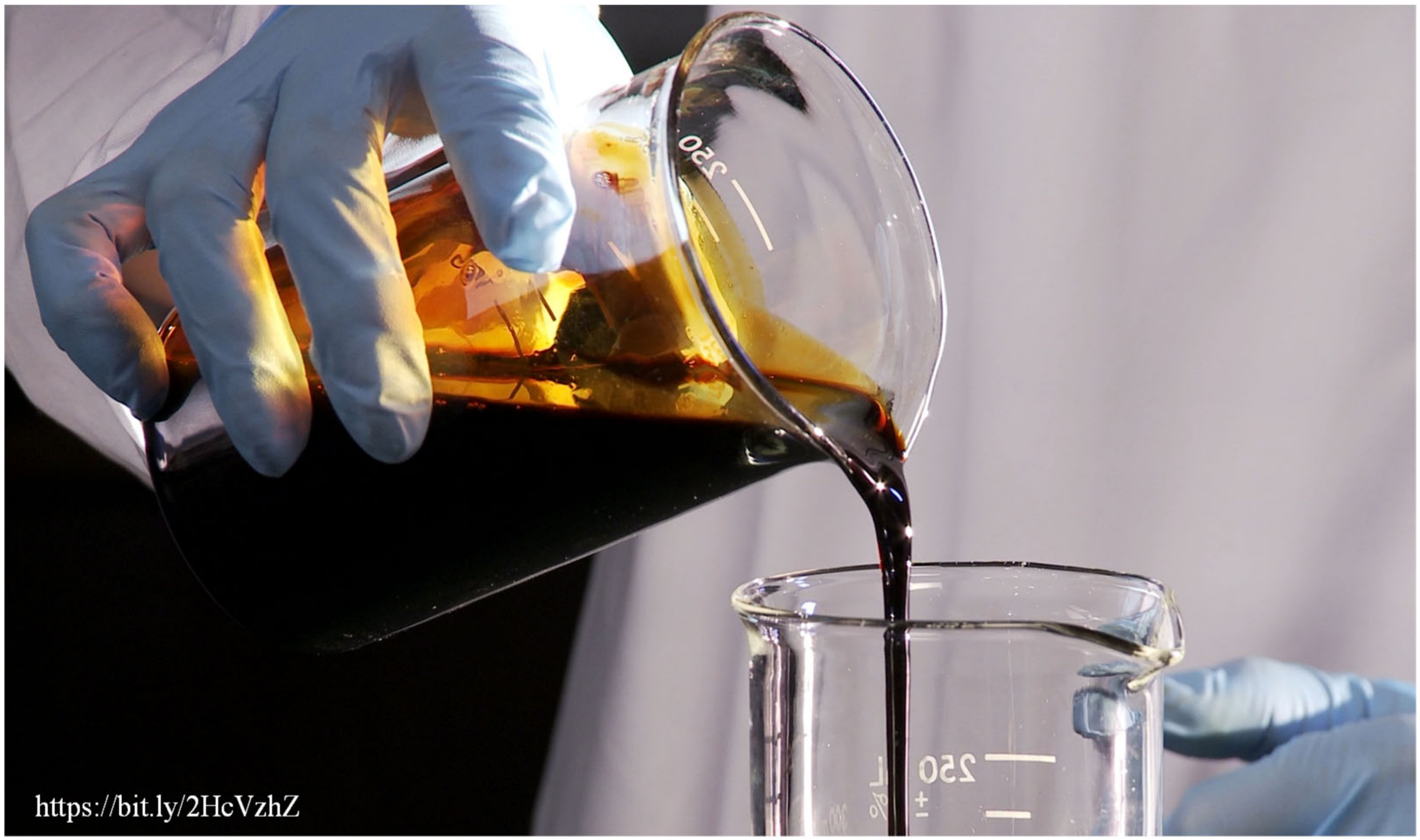
Biomass

Chemical Decomposition at Elevated Temperatures



Production of Bio-Oil

Bio-oil is a thick black-brown substance which smells heavily like burnt wood!



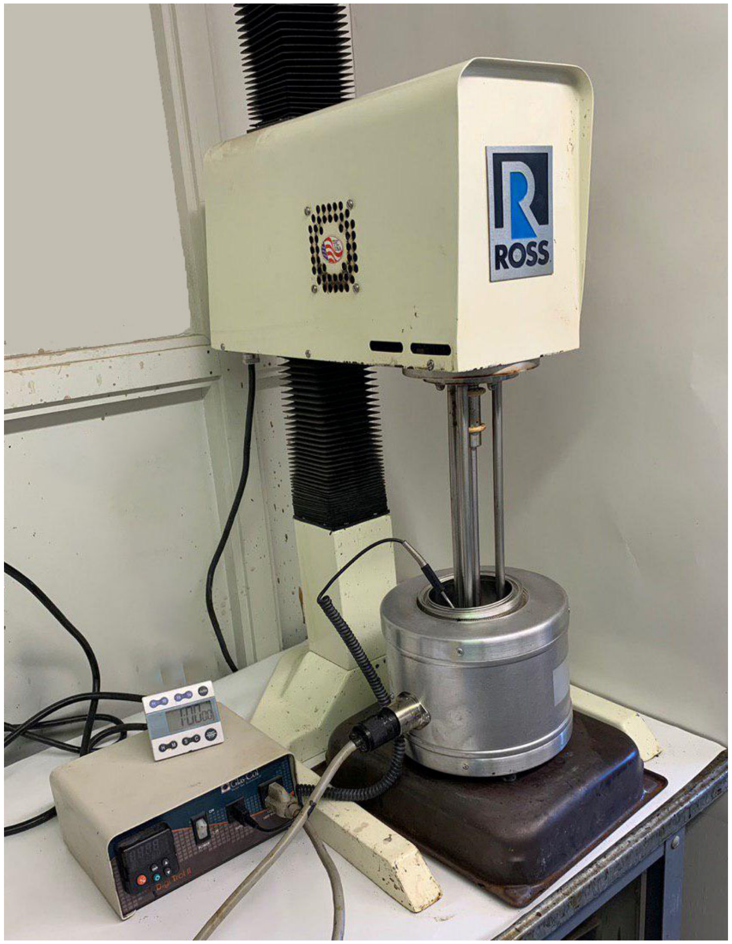
Production of Bio-binder

Bio-oils are treated inside a shear blender at high temperatures to:

- **Remove water and volatiles**
- **Increase viscosity**
- **Improve stability**

The end product is called bio-binder

Blending bio-binder into conventional asphalt produces bio-asphalt



Past studies on bio-binders.

Majority of studies concluded that bio-binders

1) soften asphalt

2) age drastically.

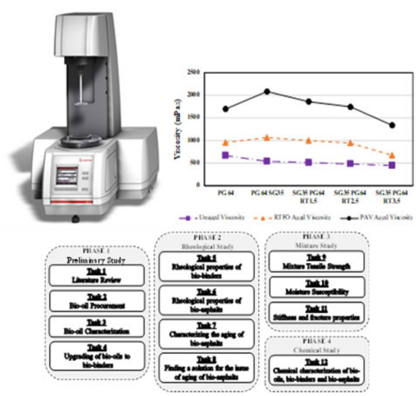
3) manifest brittle behavior at low-temperature

Recommendation to address this issue:

Minimize the bio-binder content in bio-asphalts!

Question:

- Is it possible to replace substantial quantities of petroleum-based asphalt binders with sustainable bio-binders?
- Is there a way to address the severe aging of bio-asphalts to improve low-temperature properties?
- How do mixtures made with bio-asphalts perform?



Discussion of experiments and results

- **Bio-binders used in this study**
- **Properties of bio-oils and bio-binders**
- **Properties of bio-asphalts and effect of aging**
- **Improving the aged bio-asphalt properties**
- **Performance of mixtures with bio-asphalts**
- Chemical characterization of bio-oils, bio-binders and bio-asphalts

Four different plant-based bio-binders were used in this study.

Switchgrass

A non-woody plant

White Pine

A softwood tree

White Oak

A hardwood tree

Four different plant-based bio-binders was used in this study.

Material	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Switchgrass (Sun and Cheng 2002)	33-37	24-40	12-17
Pine wood (Räisänen and Athanassiadis 2013)	35-40	27-32	20-27
Oak wood (Le Floch et al. 2015)	38-42	22-30	25-30

Investigate physical properties of bio-oils, bio-binders and bio-asphalts

Rheological Properties

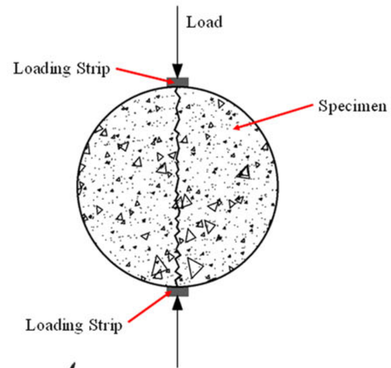
- **Bio-oils**
  - Viscosity
- **Bio-binders, asphalt binders and bio-asphalts**
  - Viscosity
  - Temperature Sensitivity
  - Rutting Potential
  - Cracking Potential
  - Multiple Stress Creep Recovery
  - Linear Amplitude Sweep

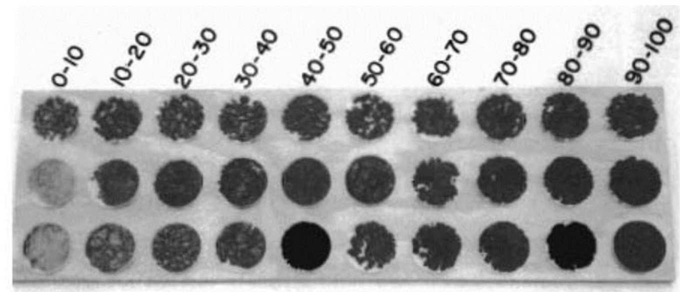
Rotational Viscometer (RV)

Dynamic Shear Rheometer (DSR)

Bending beam Rheometer (BBR)

Evaluate properties of bio-oils, bio-binders and bio-asphalts in asphalt concrete





<u>Mixture Properties</u>

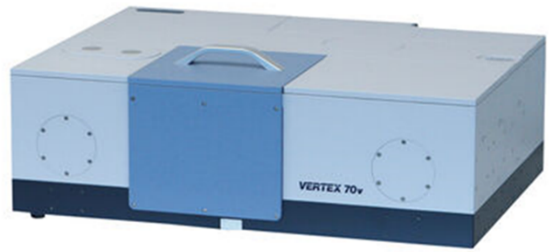
- **Strength of Mixtures**
- **Moisture Damage Resistance**
- **Rutting Resistance**
- **Fracture Properties**

Investigate chemical properties of bio-oils, bio-binders and bio-asphalts

<u>Chemical Composition</u>

- Comparing different bio-oils and bio-binders
- Effect of upgrading
- Effect of aging

Fourier Transform Infrared Spectroscopy (FT-IR)



Gas Chromatography-Mass Spectrometry (GC-MS)

Nuclear Magnetic Resonance (NMR)

Basic Properties of bio-oils

Flash point

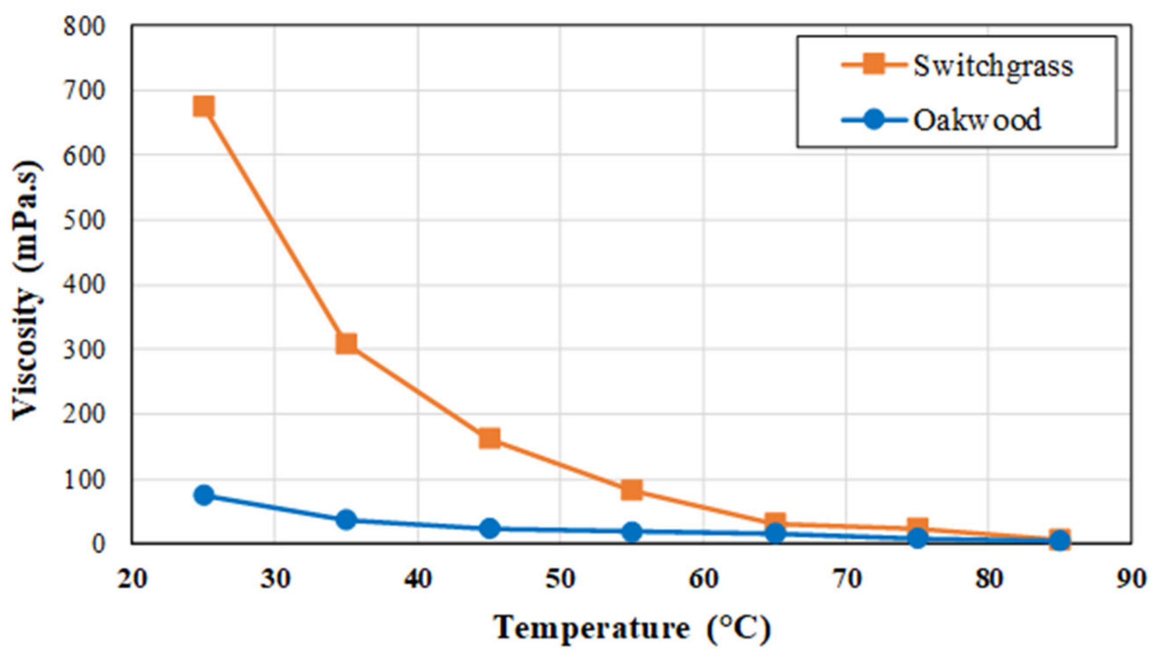
95-100°C for all bio-oils

→ Way below asphalt binders with flash point of above 230 °C

Boiling point

105-110°C for all bio-oils

→ Way below asphalt binders with boiling point of above 350 °C



Effect of temperature

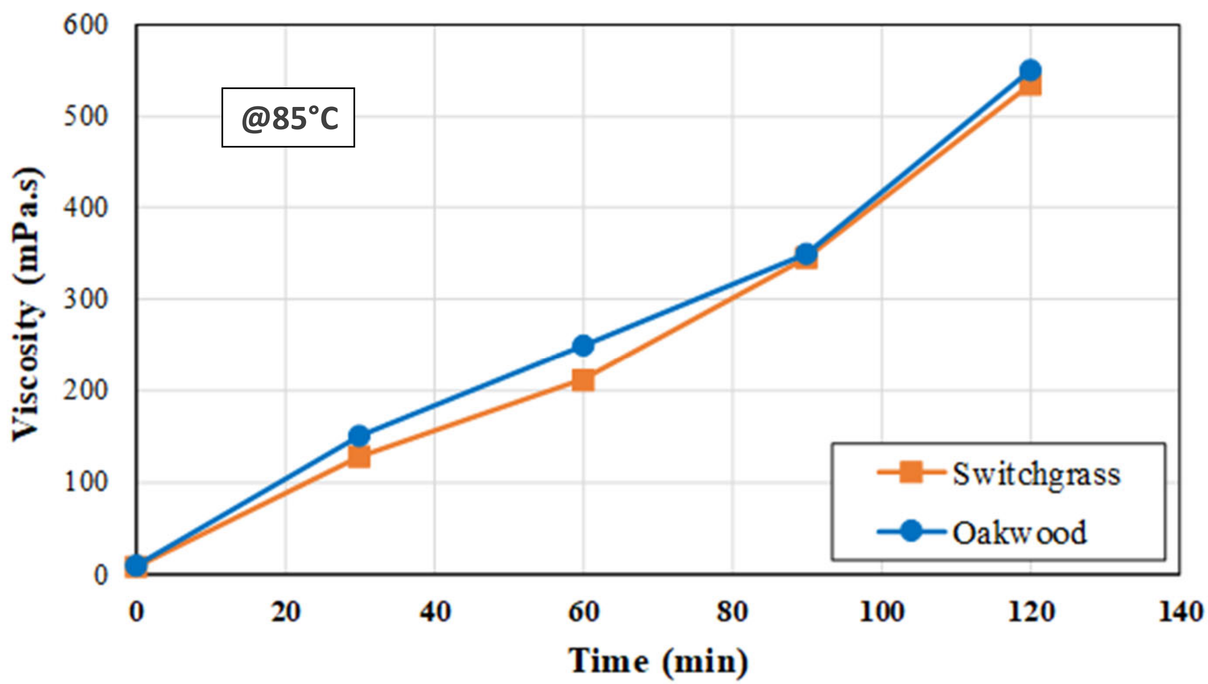
Viscosity decreases with temperature

Basic Properties of bio-oils

Effect of upgrading

Viscosity increases during upgrading

Bio-binders are still softer than asphalt binders (below 3 Pa.s at 135 °C)

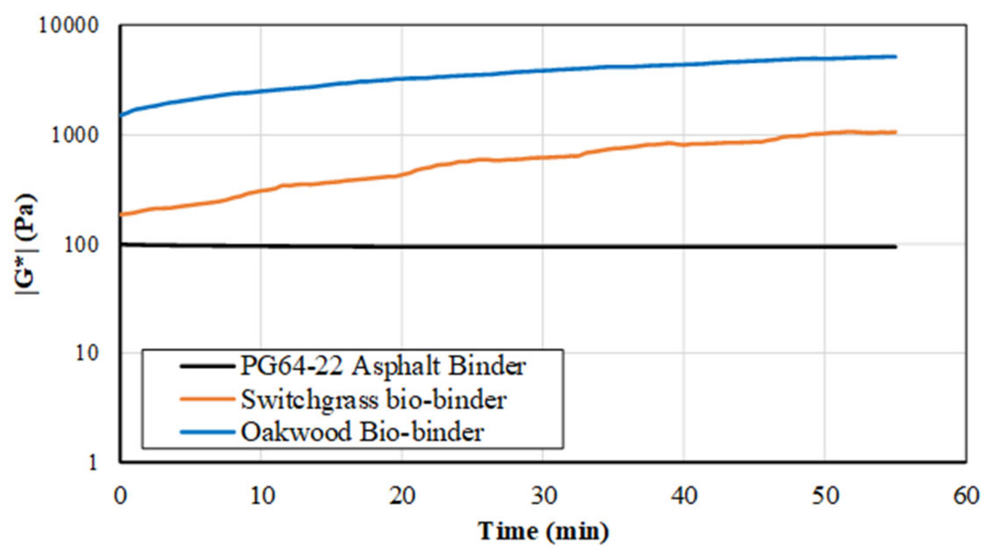


Bio-binders behave differently from asphalt binders.

High-temperature properties

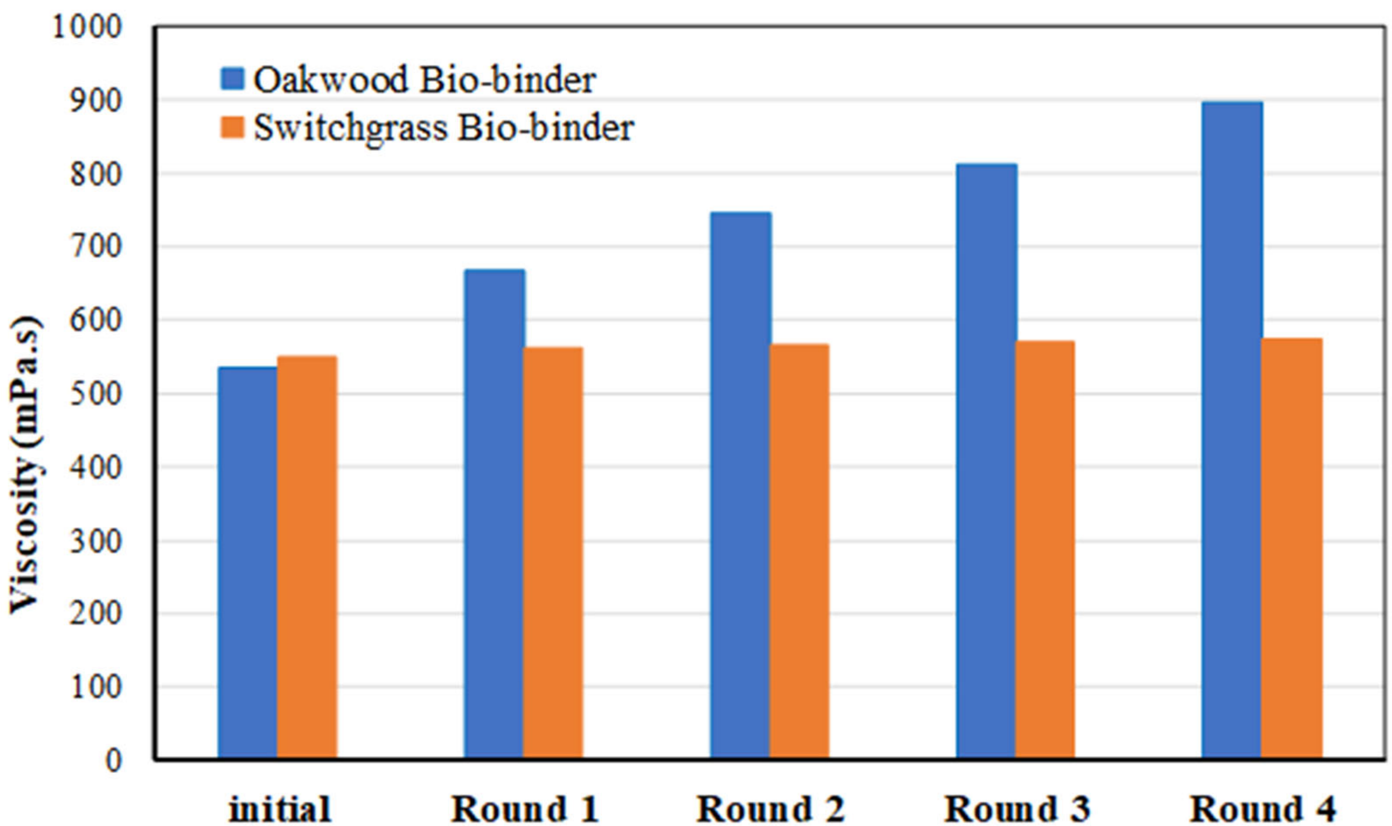
- **Unaged: Comparable with asphalt binders**
- **Aged: Properties changed significantly**

Material	Unaged true grade (°C)	RTFO true grade (°C)
Switchgrass	54.7	82.4
Oakwood	77.2	N/A
B1 Pine	55.2	83.1
B2 Pine	56.7	84.7
PG64-22 binder	68.6	68.1



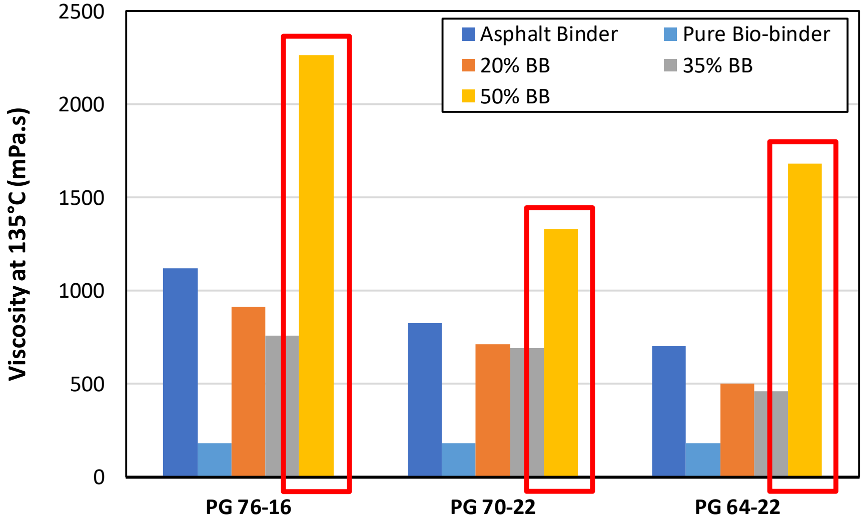
Bio-binders behave differently from the asphalt binders.

Sensitive to reheating



Adding bio-binders to asphalt binders

First step: determining the blending ratio



✓ **Bio-binder content was limited to 35%**

Softening effect on the *unaged* bio-asphalts at 35% replacement

	Bio-binder	Base binder	Continuous grade (°C)
PG64 SG0	N/A	PG 64-22	68.6
PG64 SG35	Switchgrass	PG 64-22	63.9
PG64 B1-35	Blend 1 Pine	PG 64-22	68.2
PG64 B2-35	Blend 2 Pine	PG 64-22	67.3

How does aging impact bio-asphalts?

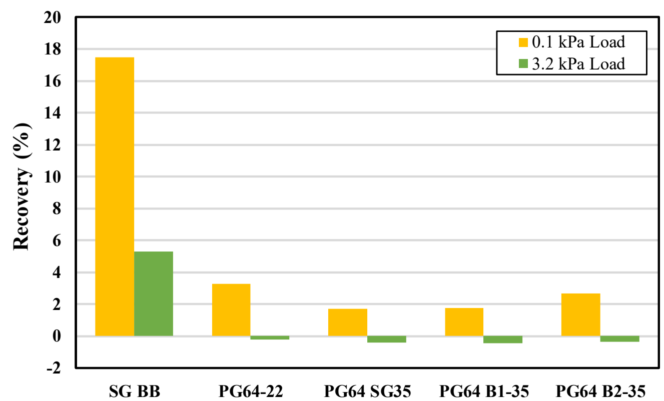
Short-term aged bio-asphalts:

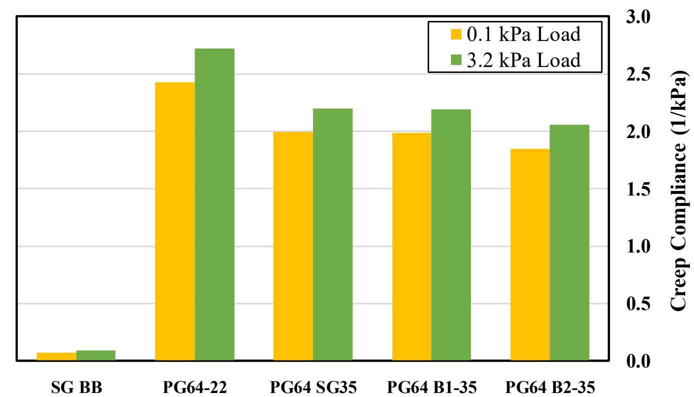
High-temperature grade:

Sample ID	Bio-binder	Unaged Grade Temperature (°C)	Grade Temperature (°C)
PG64 SG0	N/A	68.6 →	**68.1**
PG64 SG35	Switchgrass	63.9 →	**68.2**
PG64 B1-35	B1 Pine	68.2 →	**69.5**
PG64 B2-35	B2 Pine	67.3 →	**69.5**

MSCR results:

1) Lower recovery
2) Lower creep compliance





How does aging impact bio-asphalts?

And Long-term aged bio-asphalts:

Binder Type	Intermediate Temperature (°C)	Bending Beam Rheometer (BBR)			Linear Amplitude Sweep (LAS)	
		Temperature (°C)	Stiffness (kPa)	m-value	N_f at 2.5% binder Strain	N_f at 5.0% binder Strain
SG BB	N/A	N/A	N/A	N/A	N/A	N/A
PG 64 SG0	23.5	-12	207	0.315	9231	152
PG64 SG35	28.3	-12	349	0.287	554	14
PG64 B1-35	28.4	-12	364	0.282	726	15
PG64 B2-35	29.2	-12	399	0.268	533	11

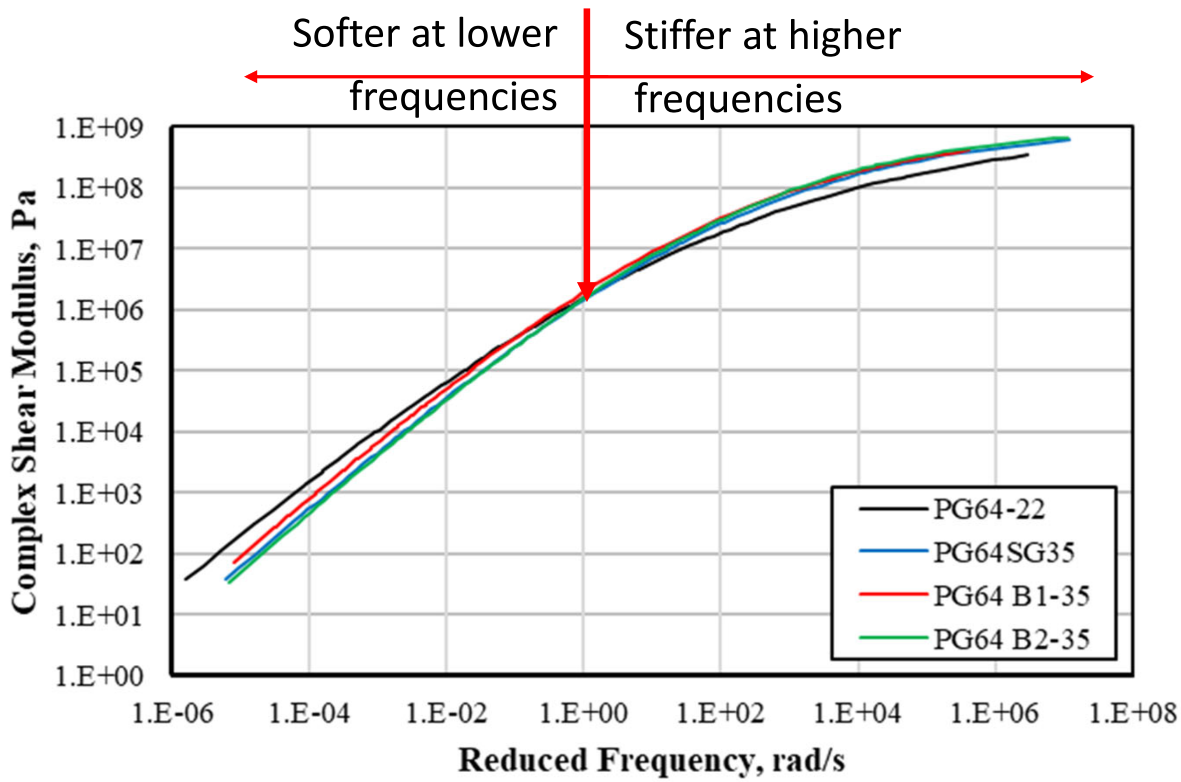
Long-term aging severely affects the properties of bio-asphalts with high bio-binder content

How does aging impact bio-asphalts?

Effect of aging on thermorheological properties of bio-asphalts

Unaged bio-asphalts

Unaged bio-asphalts have higher temperature susceptibility than the base binder



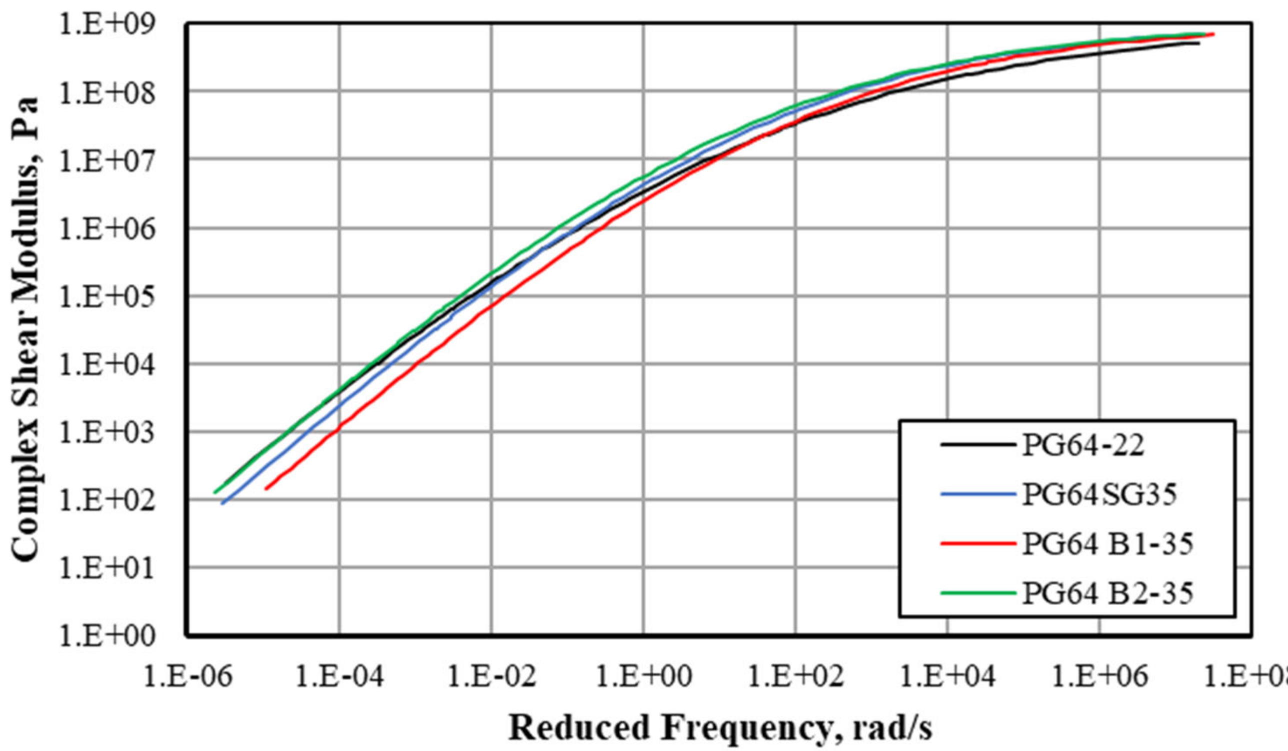
How does aging impact bio-asphalts?

Effect of aging on thermorheological properties of bio-asphalts

Short Term

RTFO-aged bio-asphalts

RTFO-aging does not affect the behavior of bio-asphalts significantly



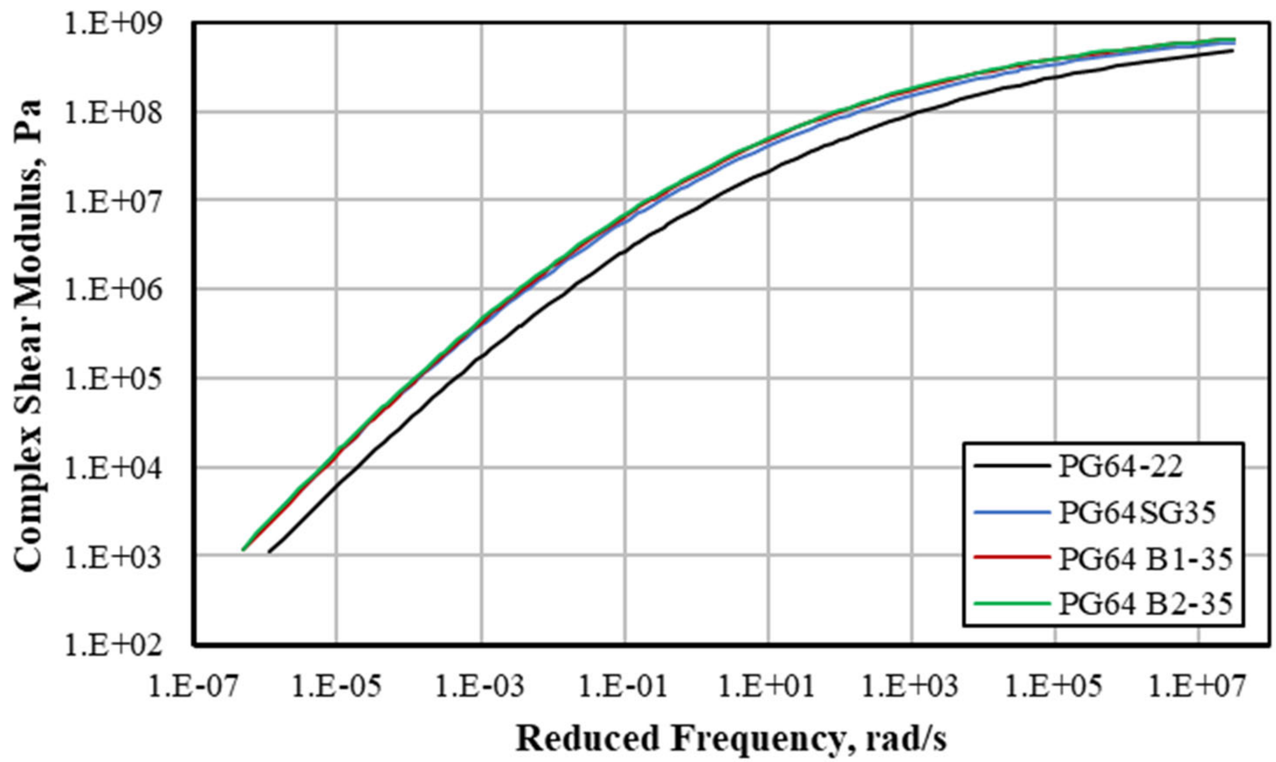
How does aging impact bio-asphalts?

Effect of aging on thermorheological properties of bio-asphalts

Long-Term

PAV-aged bio-asphalts

PAV-aging does not affect the behavior of bio-asphalts significantly



Is there a Practical way to address the aging of bio-asphalts?

Investigate effect of rejuvenators to reduce aging effect

- ✓ **If effective, it can be an inexpensive method to mitigate the effect of aging of bio-binders**

Adding Rejuvenator to Encounter Aging Effect

Effect on Viscosity at high and intermediate temperatures:

Binder Type	Unaged		Short Term Aged		Long Term Aged	
	Grade Temperature (°C)	Viscosity at 135°C (mPa.s)	Grade Temperature (°C)	Viscosity at 135°C (mPa.s)	Intermediate Grade Temperature (°C)	Viscosity at 135°C (mPa.s)
PG 64 SG0	68.6	670	68.1	905	22.1	1695
PG64 SG35	63.9	498	68.2	1065	28.3	N/A
PG64 SG35 RT5%	57.6	335	59.8	550	19.9	1213

Reduces viscosity and stiffness

Adding Rejuvenator to Encounter Aging Effect

PennState

Effect on stiffness and relaxation at low-temperature

Binder Type	-18 °C		-12 °C		-6 °C	
	Stiffness (kPa)	m-value	Stiffness (kPa)	m-value	Stiffness (kPa)	m-value
PG 64 SG0	377	0.28	207	0.32	N/A	
PG64 SG35	N/A		349	0.29	158	0.339
PG64 SG35 RT5%	248	0.30	119	0.36	N/A	

Helps with the low-temperature properties as well!

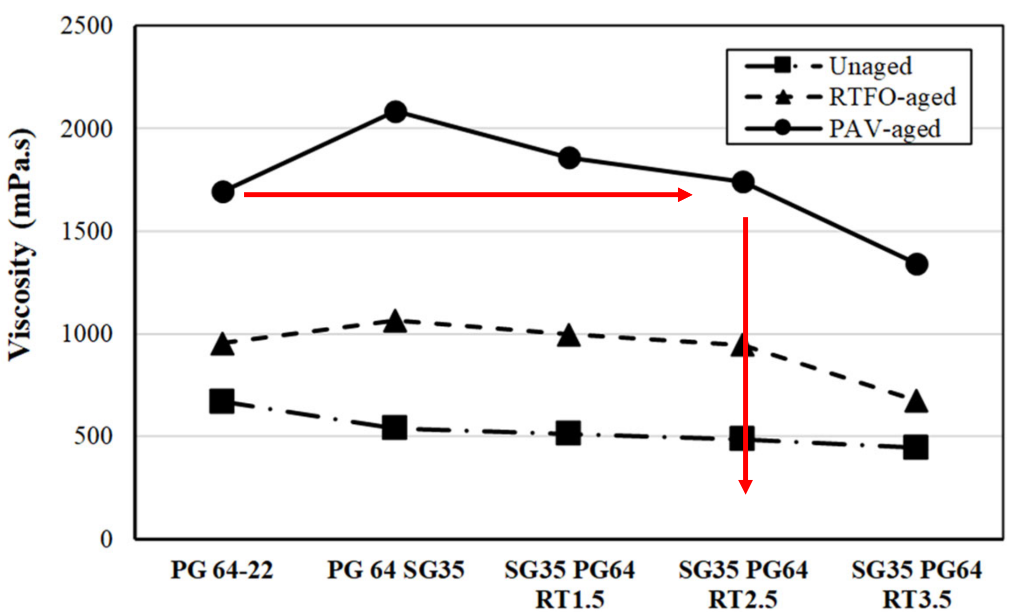
<u>But how much rejuvenator should be used?</u>

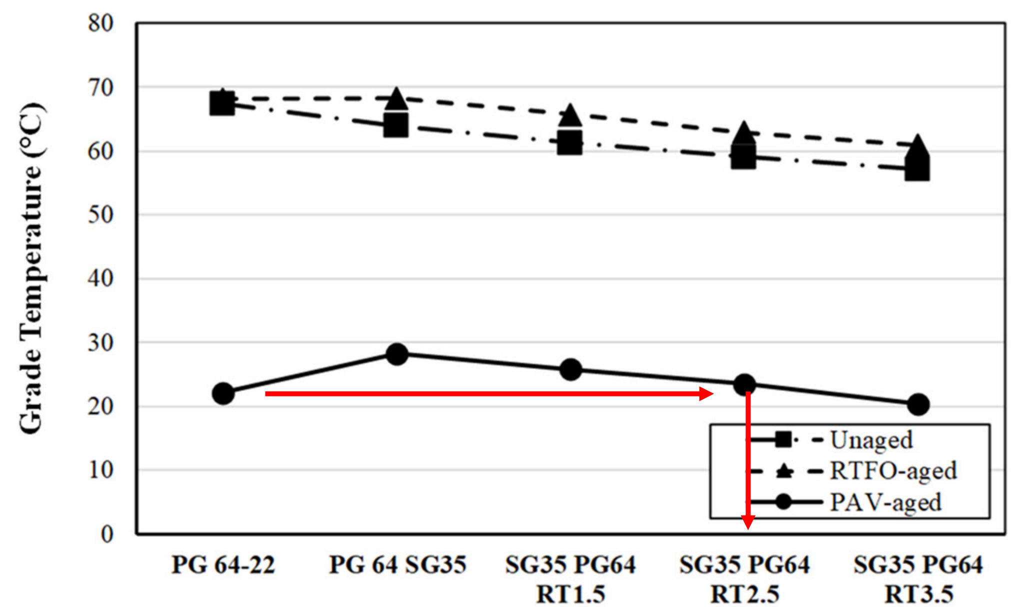
Optimizing the rejuvenator content

Goal: Restore the aged bio-asphalt properties to those of the base asphalt binder

Approach: Prepare bio-asphalts with different rejuvenator contents and look at:

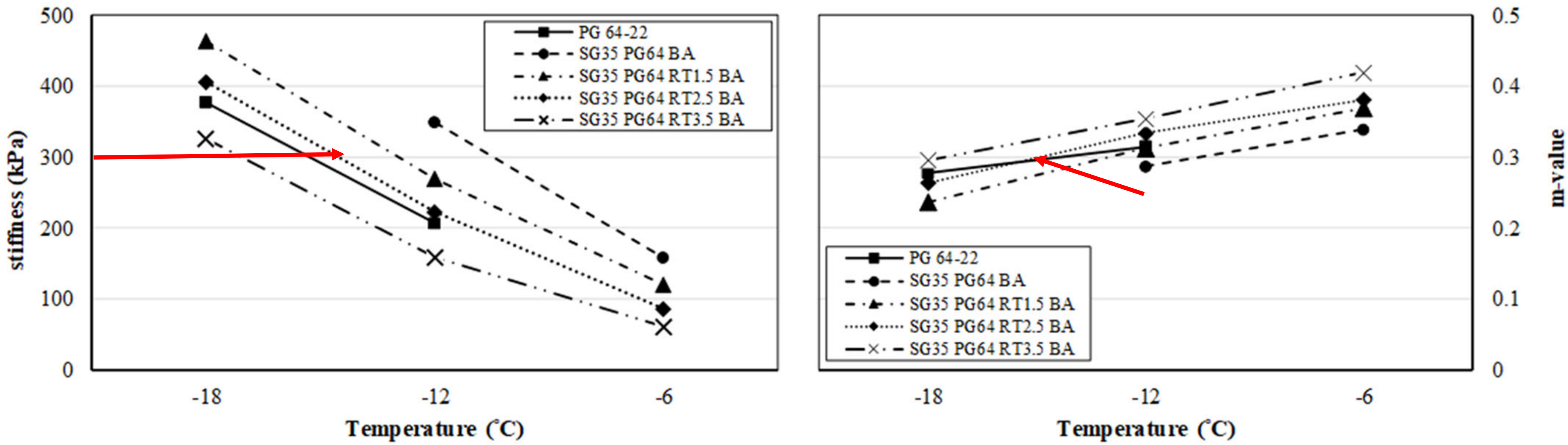
1) Viscosity and intermediate grade temperature of long term-aged binders





Optimizing rejuvenator content

3) Cold temperature properties of PAV-aged binders

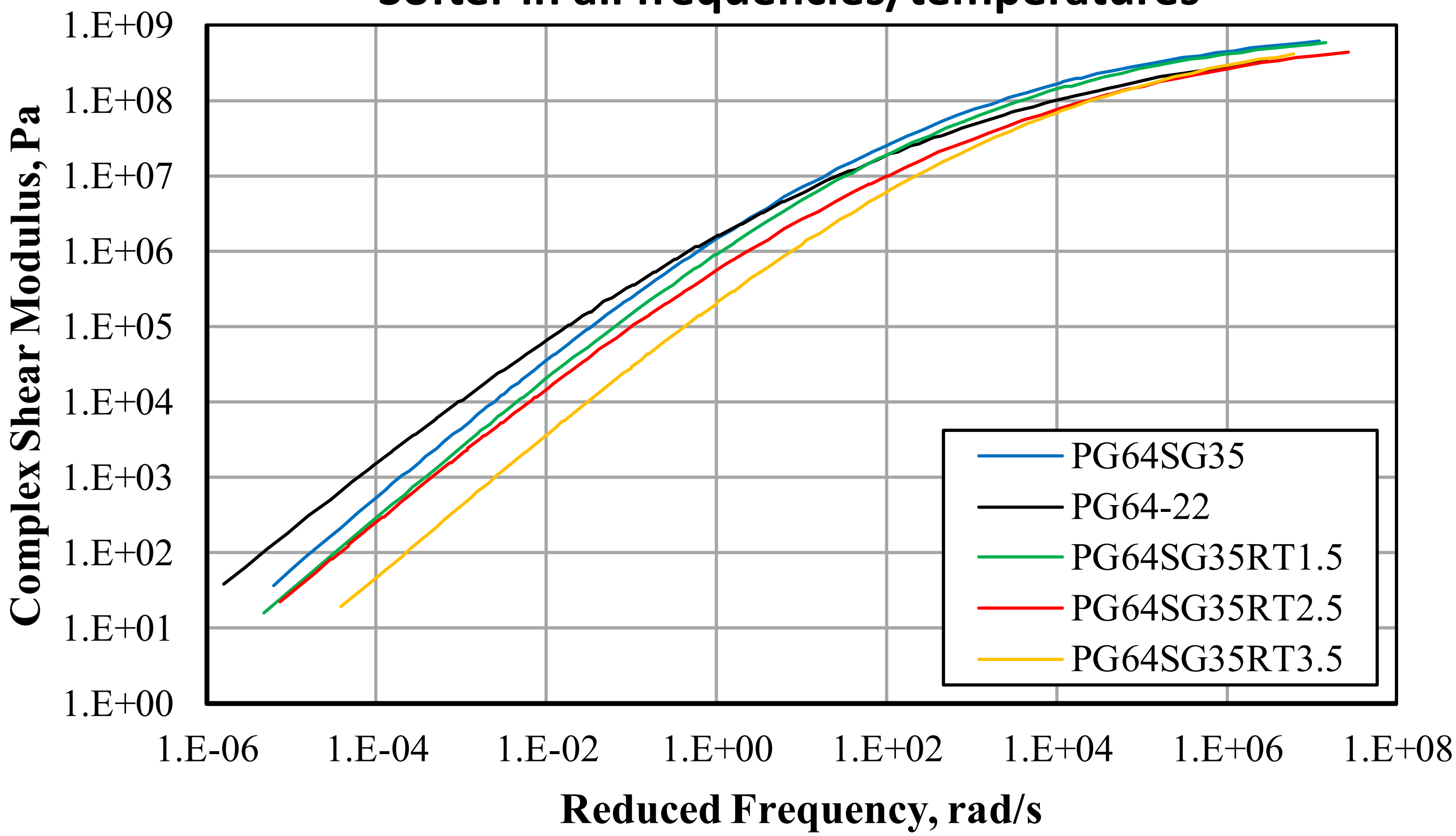


2.5% rejuvenator was considered as optimum for the bio-asphalts in our study.

Effect of rejuvenator content on thermorheological properties

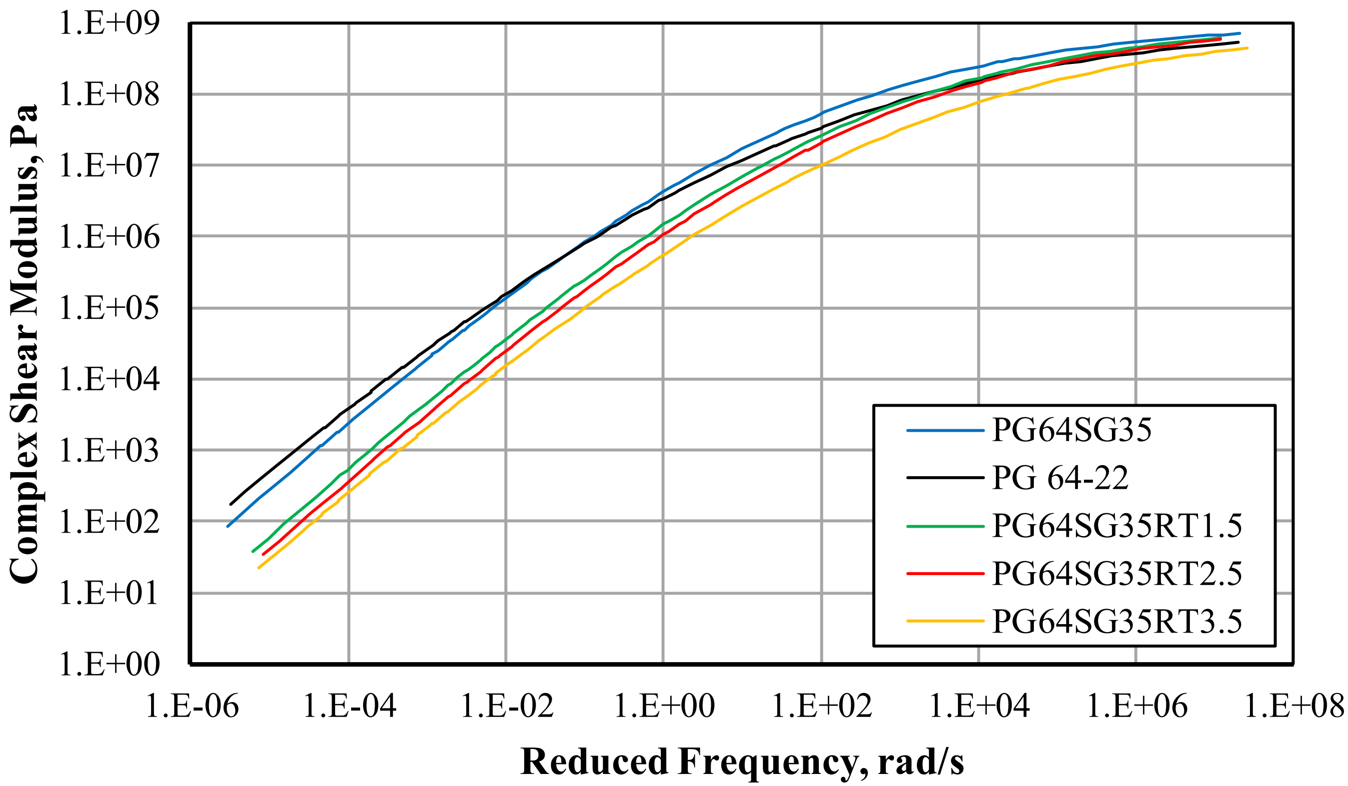
1) Unaged bio-asphalts:

Softer in all frequencies/temperatures



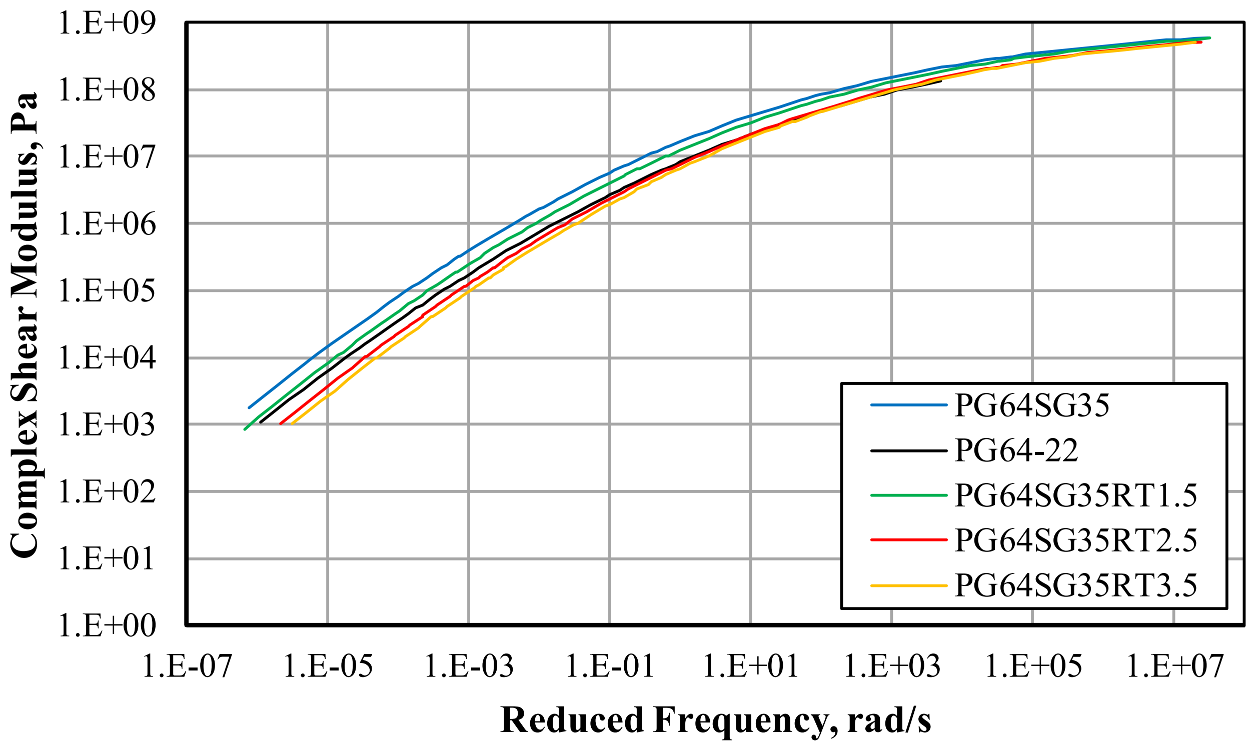
Effect of rejuvenator content on thermorheological properties

2) RTFO-aged bio-asphalts:
Softer in all frequencies/temperatures



Effect of rejuvenator content on thermorheological properties

3) PAV-aged bio-asphalts:

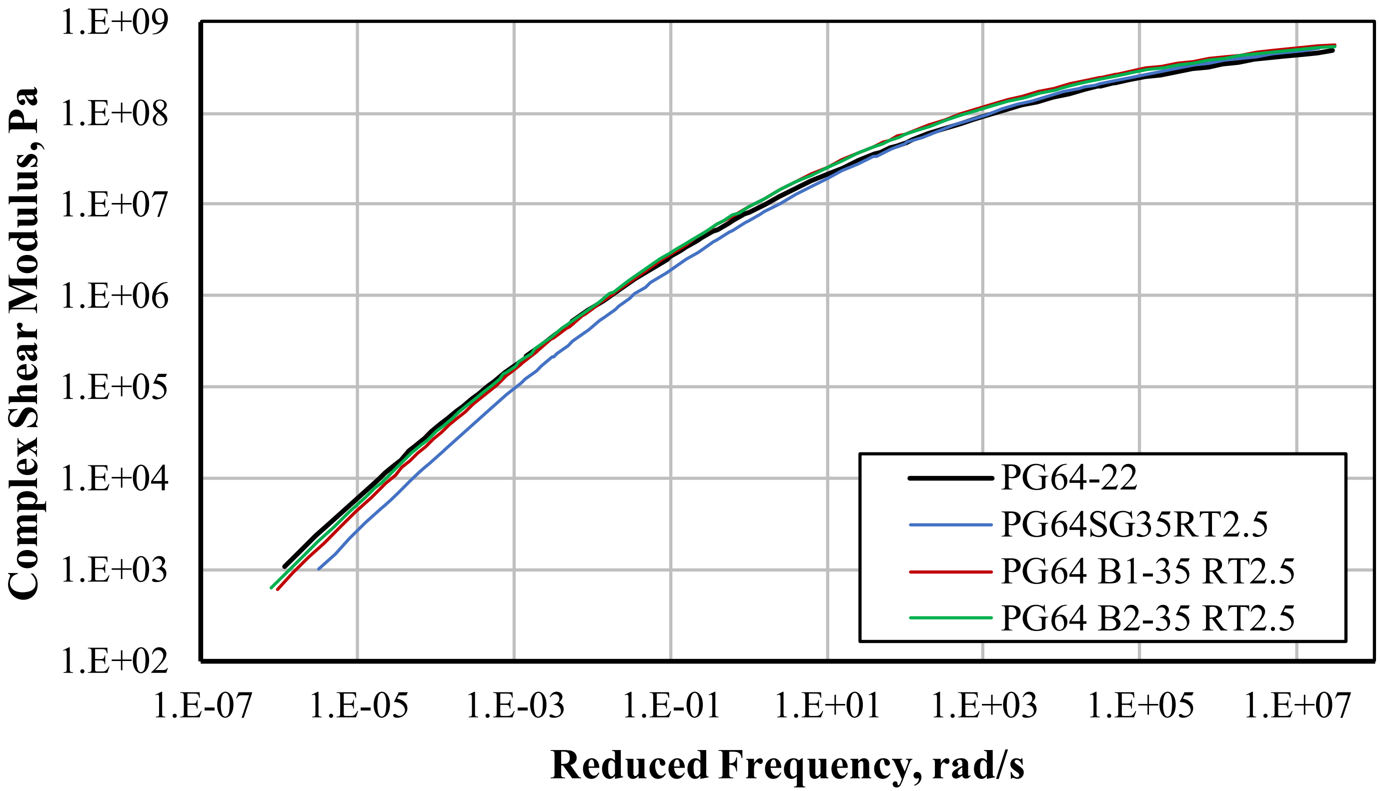


Bio-asphalt with 1.5% to 2.5% rejuvenator has a mastercurve most similarly matching the base asphalt binder.

rejuvenator with other bio-asphalts

PAV-aged bio-asphalts

Behaving very similar to the base binder



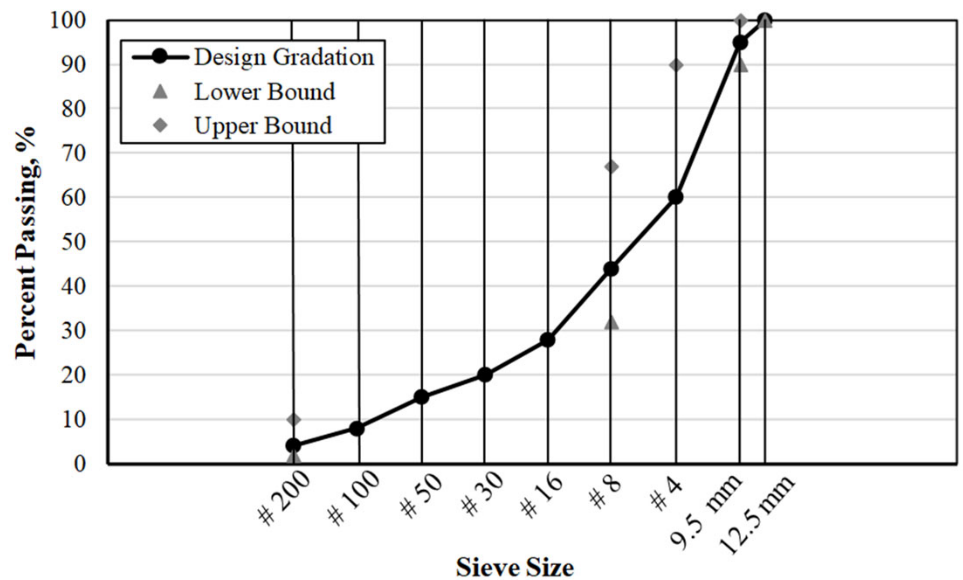
Mixtures performance

A standard 9.5 mm Superpave mix design

Locally sourced dolomite and limestone aggregates was used

Blend of Fine (B3) and Coarse (A8) aggregates

Binder content: 5.4%



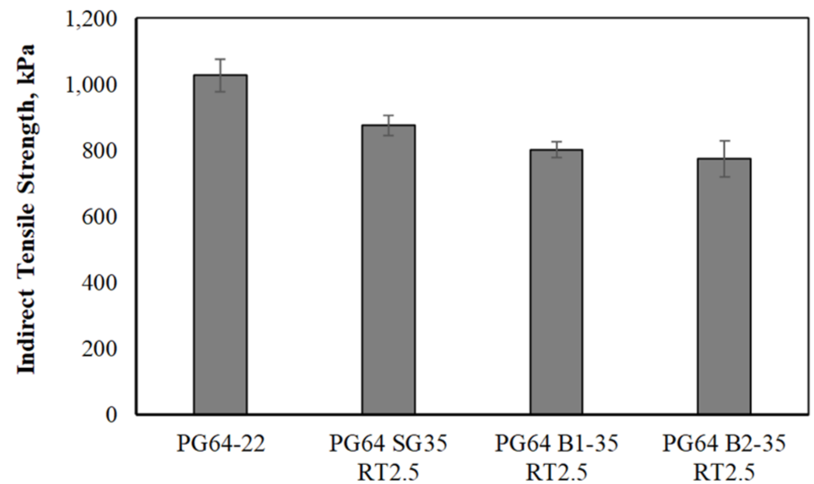
Properties investigated:

- Tensile strength
- Resistance to moisture damage
- Rutting resistance
- Fracture properties

Mixture performance

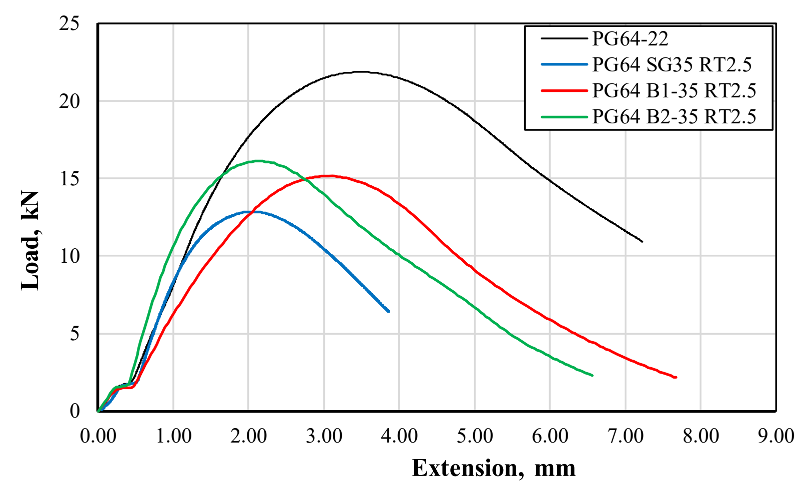
1) Indirect Tensile Strength (IDT)

Material	G* @ 25C	δ @ 25°C
PG 64-22	1.91E+06	54.76
PG64 SG35 RT2.5	1.01E+06	66.77
PG64 B1-35 RT2.5	1.47E+06	63.04
PG64 B2-35 RT2.5	1.20E+06	64.51



However!

Loss of Flexibility with Bio-asphalt

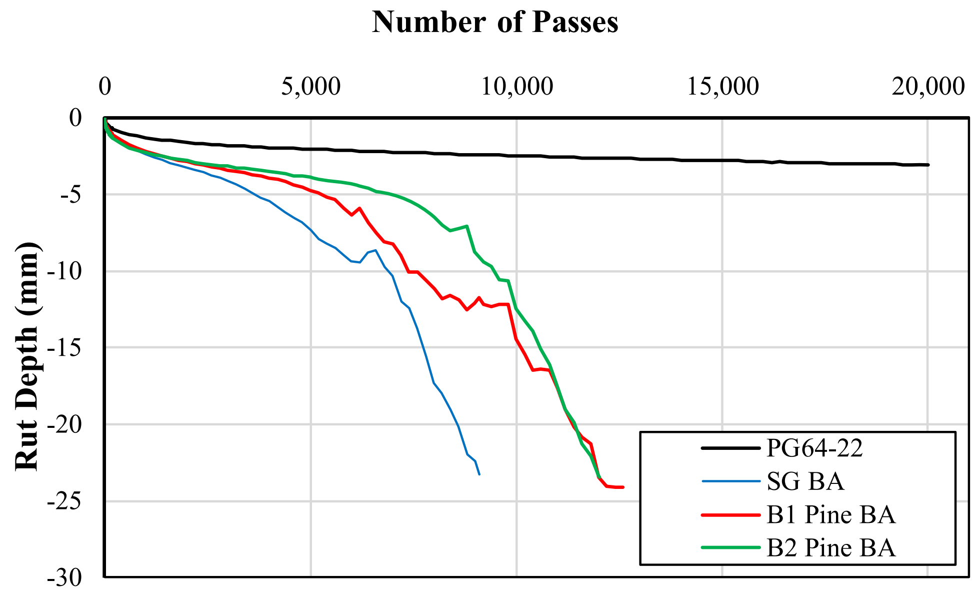


Mixture performance

3) Resistance to rutting and stripping

Hamburg Wheel-Track Testing (HWTT)

Material	PG64-22	Switchgrass BA	B1 Pine BA	B2 Pine BA
Stripping Inflection Point (SIP)	N/A	6616	6534	8375

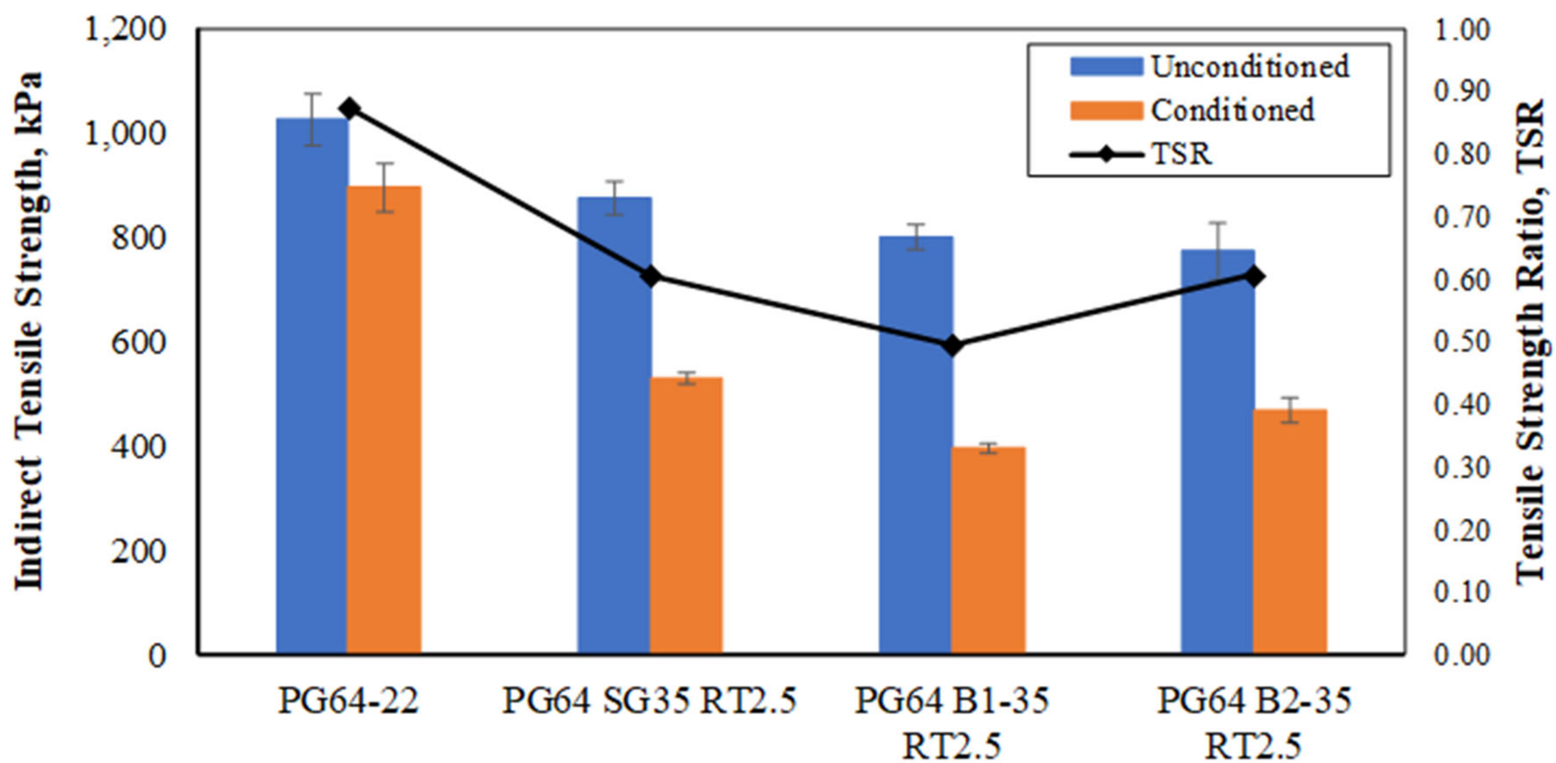


Material	G* @ 50C	δ @ 50°C	Rutting Parameter
PG 64-22	36,598	70.5	38,822
Switchgrass BA	12,218	79.7	12,416
B1 Pine BA	17,673	78.1	18,062
B2 Pine BA	14,803	78.8	15,089

Bio-asphalts at 50°C are considerably softer than the base asphalt binder

Mixture performance

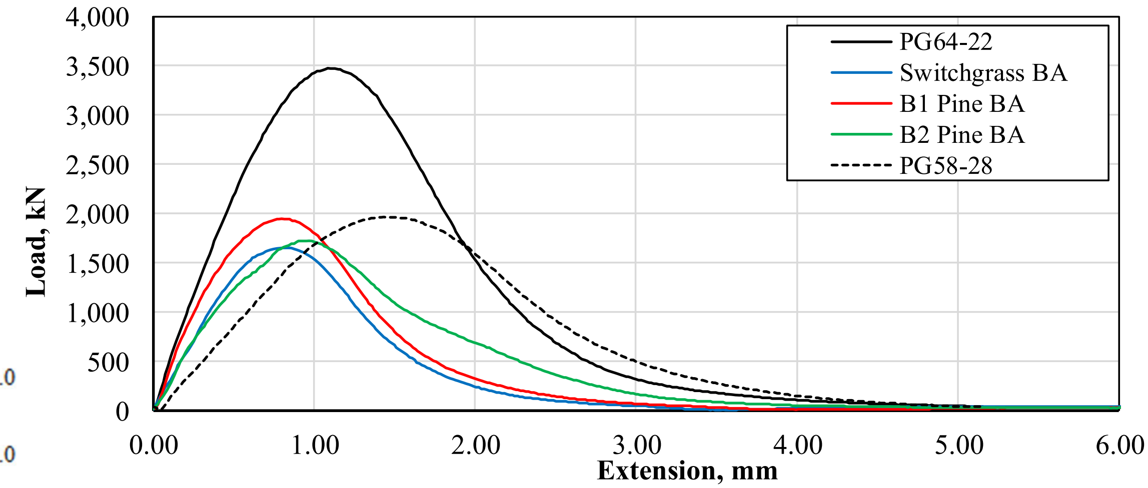
4) Resistance of mixtures to moisture damage through Tensile Strength Ratio (TSR)



Significant strength loss

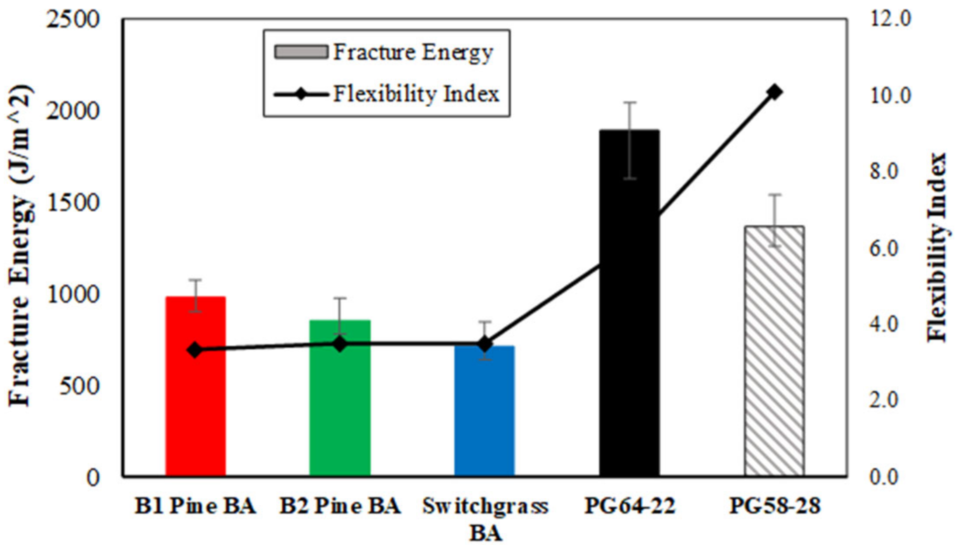
Mixture performance

6) Fracture properties of samples through Semi-Circular Bend (SCB) test



All bio-asphalt samples have:

- lower peak load
- Lower fracture energy
- lower Flexibility



SUMMARY
CONCLUSIONS
FUTURE WORK

Summary, conclusions, and recommendations for future work

Summary and Conclusions:

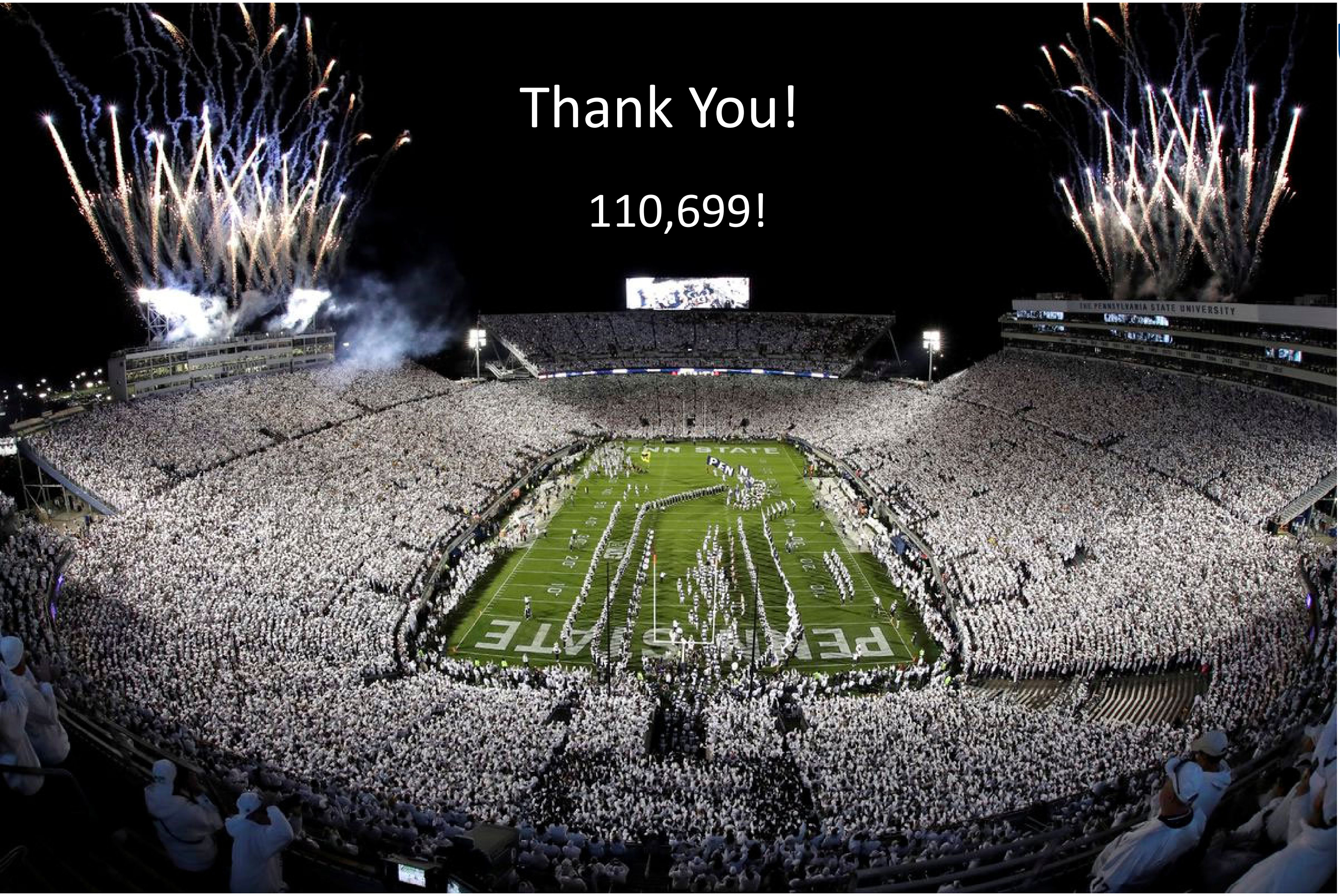
1) Four different plant-based bio-binders were investigated.
2) Bio-oils require upgrading to remove water and volatiles.
3) Unaged and short-term aged bio-asphalts have comparable properties with conventional asphalt binders
4) Properties of pure bio-binders are significantly affected with long-term aging.
5) Incorporation of small quantities of rejuvenator offsets the effect of severe aging.

Summary and Conclusions:

6) Flexibility of mixtures with bio-asphalt is lower than control mixtures
7) Mixtures with bio-asphalts have lower tensile strength, rutting resistance and fracture energy due to the softer nature of binder
8) Moisture resistance of bio-asphalt mixtures was found to be lower than the control mixture

Recommendations:

1) Need methods/additives to facilitate chemical interaction between bio-binders and the base asphalt binder.
2) Need methods/additives to stabilize the bio-oils/bio-binders prior to blending with asphalt binders.
3) Effect of using additives such as cross-linkers such as sulfur, polymers, antistripping agents should be studied.
4) Study should be expanded to include other aggregate types.



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