# MECHANISTIC CHARACTERIZATION OF ANTI-STRIPPING ADDITIVES IN SASKATCHEWAN ASPHALT MIXES

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**Paper prepared for presentation at the**
**Annual Conference of the**
**Transportation Association of Canada**
**Calgary, Alberta**

**September 18-25, 2005**

## ABSTRACT

Saskatchewan Highways and Transportation commonly uses hydrated lime and liquid anti-stripping additives to mitigate asphalt-aggregate stripping susceptibility of hot mix asphalt mixes. Based on empirical experience of observed field performance in Saskatchewan, the addition of lime is thought to not only improve stripping resistance, but also the mechanical behaviour of the mix. However, the addition of lime requires adequate voids in the mineral aggregate of the mix, and contractors have the added difficulty of handling lime during construction, making liquid anti-stripping products more appealing. Although the influence lime has on Saskatchewan mixes has been evaluated in the past, none of the investigations involved determining its effect in terms of fundamental mechanistic mix behaviour. In addition, the long-term performance of liquid anti-stripping additives has not been well established in Saskatchewan field state conditions.

This laboratory study investigated the mechanistic behaviour of a typical Saskatchewan hot mix asphalt concrete modified with hydrated lime, with a liquid anti-stripping additive, and without any anti-stripping treatment as control. Specifically, triaxial frequency sweep characterization was performed to evaluate the various mixes. The mechanistic properties of the various asphalt mixes considered in this research were characterized across dynamic stress states, across a range of load frequencies, at 20°C.

In summary, this research found that hydrated lime improved the mechanistic behaviour of asphalt concrete mixes relative to the unmodified specimens and the samples modified with liquid anti-stripping additive at 20°C. Minimal difference was observed in the mechanistic behaviour of the unmodified asphalt concrete specimens and the specimens modified with liquid anti-stripping additive. However, liquid anti-stripping additive appeared to increase the radial strain behaviour of the asphalt mix considered in this study. This increase in radial strain resulted in a similar Poisson's ratio behaviour to that of the lime-treated mix.

*Key Words*: anti-stripping additives, hydrated lime, asphalt mixes, mechanistic performance

## INTRODUCTION

Most of the province of Saskatchewan has been glaciated several times, making glacial gravel deposits the primary source of rock suitable for hot mix asphalt aggregate production. The majority of the aggregate deposits tend to be siliceous in nature, and are known to exhibit susceptibility to stripping. Saskatchewan Highways and Transportation (DHT) commonly uses hydrated lime or liquid anti-stripping additives to mitigate asphalt-aggregate stripping susceptibility of hot mix asphalt concrete mixes. Based on empirical experience of observed field performance in Saskatchewan, the addition of lime is thought to not only improve anti-stripping properties, but also the mechanical behaviour of the mix. Similar observations have been documented by other agencies (1,2). However, the addition of lime requires adequate voids in the mineral aggregate of the mix. As well, contractors have the added difficulty of handling lime powder during construction. Therefore, liquid anti-stripping additives are an attractive alternate. Although the influence of lime and liquid anti-stripping additives on Saskatchewan mixes has been evaluated in the past (3,4), none of the investigations involved determining their effect in terms of fundamental mechanistic mix behaviour.

## STUDY OBJECTIVE

The objective of this study was to investigate and compare the effect of hydrated lime and a common liquid anti-stripping additive on the mechanistic properties of a typical Saskatchewan dense graded hot mix asphalt concrete.

## STUDY SCOPE

This research investigated the effect of hydrated lime and a liquid anti-stripping additive on the mechanical behaviour of a typical Saskatchewan dense graded asphalt concrete mix. The asphalt concrete mix considered in this research was a Type 72 Saskatchewan dense graded mix, with aggregate gradation shown in Figure 1. The Type 72 aggregate gradation has a nominal maximum aggregate size of 9 mm, and is intended for top lifts.

The aggregate employed in this research was sampled from a DHT pavement rehabilitation project of Highway 11, south of Craik (Contract No. M01091). The aggregate was manufactured from a glacial gravel source local to the project, and was determined to have susceptibility to stripping, as per ASTM D 4867. The anti-stripping additives used in this research were hydrated lime added at a concentration of one percent by weight of aggregate, and a common liquid anti-stripping additive commercially available in Saskatchewan, added at a concentration of 0.7 percent by weight of asphalt cement. It is important to note that for the mix treated with hydrated lime, the lime was substituted for 1 percent of the aggregate passing the 71 µm sieve.

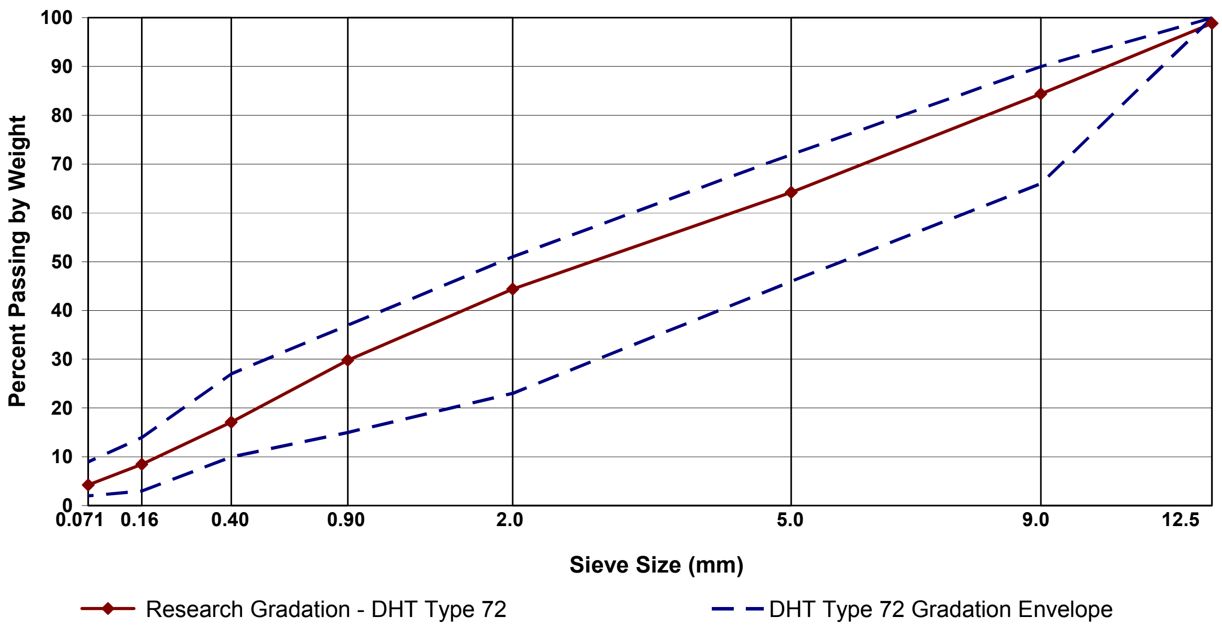


**Figure 1. Asphalt Mix Aggregate Gradation**

The asphalt concrete mix used to create research samples for the purpose of this study was designed based on the mix design used for the Highway 11 rehabilitation project. Considering the 15-year desin traffic loading of 7.84 million ESALs, DHT utilized a 75 blow Marshall design, with 150/200 A asphalt cement for this project. The mix design properties of the research mix are shown in Table 1. The asphalt concrete mix had a design asphalt cement content of 5.4 percent by weight of aggregate.

**Table 1. Asphalt Concrete Research Mix Design Properties**

| | DHT Specifications | Mix Design Results |
|---|---|---|
| **Volumetric Properties** | | |
| **Density, kg/m$^3$** | - | 2386 |
| **Air Voids, %** | 3.0 -5.0 | 4.1 |
| **Voids in Mineral Aggregate %** | 14.0 – 16.0 | 14.6 |
| **Voids Filled with Asphalt, %** | 65.0 – 78.0 | 72.2 |
| **Film Thickness, µm** | Min. 7.5 | 8.53 |
| **Aggregate Properties** | | |
| **Flat and Elongated Particles, %** | - | 4.4 |
| **Fine Aggregate Angularity, %** | - | 42.9 |
| **Coarse Aggregate Fracture, %** | Min. 95.0 | 95.9 |
| **Lightweight Aggregate, %** | Max. 1.0 | 0.3 |
| **Marshall Properties** | | |
| **Stability, Newton** | Min. 7000 | 10084 |
| **Flow, mm** | 1.5 – 3.5 | 1.9 |

## METHODOLOGY

It has been seen in the past that the addition of lime increases the Marshall stability of asphalt concrete mixes (5). However, conventional Marshall stability and flow measurements do not provide fundamental mechanistic material properties and can be relatively insensitive to minor changes in mix design (6). Repeated load triaxial testing is one method of mechanistic testing that has been used to characterize hot mix asphalt concrete mixes (7-9). The triaxial frequency sweep testing equipment available at the University of Saskatchewan was employed in this study in an attempt to evaluate the mechanistic behaviour of modified and unmodified asphalt concrete mixes. This particular testing equipment has been described in more detail elsewhere (6,7), and has been successfully implemented in the past in asphalt concrete mix characterization studies (10-12).

Five repeat samples were manufactured for the unmodified mix, ten for mix modified with a locally available liquid anti-stripping additive, and ten for mix modified with lime. The research samples were compacted using the Superpave™ Level 1 gyratory compaction protocol, with a design number of gyrations ($N_{des}$) of 96, based on the 15-year design traffic loadings for the Highway 11 project. All the specimens tested in the frequency sweep characterization were subject to four load frequencies at three different applied traction states, at 20°C, as summarized in Table 2:

**Table 2. Triaxial Frequency Sweep Testing Parameters**

| | Frequency (Hz) | | | |
|---|---|---|---|---|
| | **0.5** | **1** | **5** | **10** |
| **Stress State 1** | | | | |
| **Vertical Traction (kPa)** | 600 | 600 | 600 | 600 |
| **Confinement Traction (kPa)** | 230 | 230 | 230 | 230 |
| **Deviatoric Stress (kPa)** | 370 | 370 | 370 | 370 |
| **First Invariant $I_1$ (kPa)** | 1060 | 1060 | 1060 | 1060 |
| **Second Deviatoric Invariant $J_2$ (kPa)** | 45,633 | 45,633 | 45,633 | 45,633 |
| **Stress State 2** | | | | |
| **Vertical Traction (kPa)** | 600 | 600 | 600 | 600 |
| **Confinement Traction (kPa)** | 175 | 175 | 175 | 175 |
| **Deviatoric Stress (kPa)** | 425 | 425 | 425 | 425 |
| **First Invariant $I_1$ (kPa)** | 950 | 950 | 950 | 950 |
| **Second Deviatoric Invariant $J_2$ (kPa)** | 60,208 | 60,208 | 60,208 | 60,208 |
| **Stress State 3** | | | | |
| **Vertical Traction (kPa)** | 600 | 600 | 600 | 600 |
| **Confinement Traction (kPa)** | 100 | 100 | 100 | 100 |
| **Deviatoric Stress (kPa)** | 500 | 500 | 500 | 500 |
| **First Invariant $I_1$ (kPa)** | 800 | 800 | 800 | 800 |
| **Second Deviatoric Invariant $J_2$ (kPa)** | 83,333 | 83,333 | 83,333 | 83,333 |

The range of applied tractions was chosen to simulate typical field state conditions and the resultant stress states common within asphalt concrete mixes. The applied deviatoric stress state ranged from 370 kPa to 500 kPa. The first invariant of stress tensor ($I_1$) ranged from 800 kPa to 1060 kPa, and the second invariant of deviatoric stress tensor ($J_2$) ranged from 45,633 kPa to 83,333 kPa.

The range of applied frequency was chosen to simulate typical traffic speeds ranging from near highway speed (10 Hz) to slow urban speed (0.5 Hz). Data recorded from each frequency sweep test was used to calculate dynamic modulus, Poisson's ratio and phase angle across the alternate mixes, stress states, and load frequencies.

## THEORETICAL BACKGROUND

Hot mix asphalt concrete is a multi-phase particulate composite material. Due to the asphalt cement binder rheological properties, HMAC mixtures behave as viscoelastic solids under typical ranges in Saskatchewan field state conditions. For viscoelastic materials, the stress-strain relationship under a continuous sinusoidal loading can be defined by a complex number, E*, that is comprised of a real and an imaginary component. The real component is considered the recoverable (elastic) portion of the deformation, and the imaginary component is the non-recoverable (viscous) portion.

The Complex Modulus is a ratio of the amplitude of the time-dependent sinusoidal stress applied to the material and the amplitude of the time-dependent sinusoidal strain that results from the stress application (13). This relationship can be expressed as follows:

$$E^* = \frac{\sigma}{\varepsilon} = \frac{\sigma_{11p} e^{i\omega t}}{\varepsilon_{11p} e^{i(\omega t - \delta)}}$$ **Equation 1**

where:

- $E^*$ = Complex Modulus (Pa)
- $\sigma$ = Applied stress (Pa)
- $\varepsilon$ = Strain response to applied stress (μm/μm)
- $\sigma_{11p}$ = Peak stress applied in the X1 coordinate direction (Pa)
- $\omega$ = Angular load frequency (radians per second)
- $t$ = Load duration (seconds)
- $\varepsilon_{11p}$ = Peak strain response in X1 coordinate direction (μm/μm)
- $\delta$ = Phase angle (radians)

A higher stiffness modulus indicates that a given applied stress results in lower strain in the mixture (14). Implemented for ease of interpretation, the dynamic modulus is a measure of the absolute value of peak stress to peak strain during material response. For an elastic material, the applied stress results in instantaneous strain, and the phase angle is zero, therefore, after manipulating Equation 1, the dynamic modulus can be expressed as the absolute value of the complex modulus, E* (13):

$$E_D = \left|E^*\right| = \frac{\sigma_{11p}}{\varepsilon_{11p}}$$ **Equation 2**

The phase angle in a repeated sinusoidal load test is the shift between the applied stress and the resultant strain, and can be used to indicate the viscoelastic properties of the material (14). In a purely elastic response, the phase angle will be zero, whereas a purely viscous response will be indicated by a phase angle of 90 degrees. Phase angle can be expressed as (15):

$$\delta = \frac{t_i}{t_p}(360°)$$ **Equation 3**

where:

- $\delta$ = Phase Angle (degrees)
- $t_i$ = Time lag between a cycle of sinusoidal stress and a cycle of strain (sec)
- $t_p$ = Time for a stress cycle (sec)

Poisson's ratio is the relationship of the lateral strain to the axial strain, resulting from an applied load in the axial direction. When continuous radial confinement is applied to a sample in triaxial testing, radial and axial strains are monitored directly, and Poisson's ratio can be expressed as (6):

$$\nu_{11}(t) = \frac{\varepsilon_{22}(t)}{\varepsilon_{11}(t)} = \frac{\varepsilon_{33}(t)}{\varepsilon_{11}(t)}$$ **Equation 4**

where:

- $\nu$ = Poisson's Ratio in $X_1$ coordinate direction

$\varepsilon_{11}$ = Strain in $X_1$ coordinate direction (axial)
$\varepsilon_{22}$ = Strain in $X_2$ coordinate direction (radial)
$\varepsilon_{33}$ = Strain in $X_3$ coordinate direction (radial)

Because particulate composite materials are capable of generating significant ranges in Poisson's ratio, Poisson's ratio can be a critical measure of mechanistic behaviour of road materials and can significantly influence the behaviour of road structures, depending on the materials' placement in the road structure.

## DYNAMIC MODULUS CHARACTERIZATION TEST RESULTS

The average dynamic modulus results for the number of repeat specimens across stress state and frequency are shown in Figure 2. The error bars in all the figures indicate +/- two standard deviations about the mean. As seen in Figure 2, the average dynamic moduli ranged from 922 MPa to 2236 MPa for unmodified mix, from 906 MPa to 2193 MPa for mix modified with liquid anti-stripping additive, and from 1167 MPa to 3160 MPa for mix modified with lime. The dynamic modulus for samples with lime was consistently higher at each stress state and frequency when compared to the liquid-treated samples and the untreated samples. Therefore, lime significantly increased the dynamic modulus of the asphalt mix. As also seen in Figure 2, the average dynamic modulus values were more sensitive across the applied frequency than across the applied deviatoric stress state, clearly increasing with increased load frequency, and slightly decreasing with increasing deviatoric stress state. In addition, it can be seen that the variability around the mean for the lime-treated mix increased with increased load frequency, and with increasing mean of the dynamic modulus.

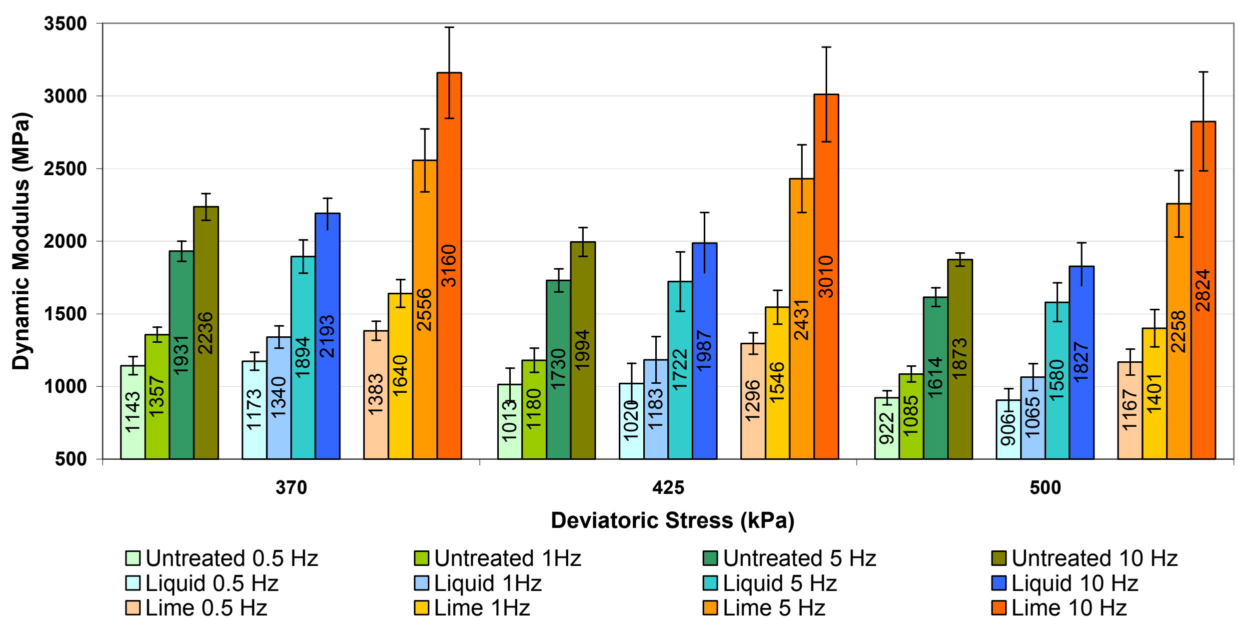


**Figure 2. Dynamic Modulus across Anti-Stripping Treatment, Deviatoric Stress State, and Frequency**

The statistically significant differences of dynamic modulus across anti-stripping treatment, deviatoric stress state, and frequency, were tested using Tukey's homogenous groups and are summarized in Table 3 and Table 4. Each homogeneous group identifies a set of values that do not differ from each other statistically, based on a 95 percent confidence interval. As seen in Table 3, the average dynamic modulus of the mix modified with lime was significantly higher than the average dynamic modulus of the unmodified mix and mix modified with liquid anti-stripping additive, regardless of deviatoric stress state. However, no significant difference was observed in the dynamic modulus of the untreated control mix and the mix treated with liquid anti-stripping additive, at each stress state. The dynamic modulus decreased with increased deviatoric stress, for each treatment type.

**Table 3. Tukey's Homogenous Groups of Average Dynamic Modulus across Anti-Stripping Treatment and Deviatoric Stress State**

| Anti-Stripping Treatment | Deviatoric Stress (kPa) | Average Dynamic Modulus (MPa) | Tukey's Homogenous Groups | | | | | |
|---|---|---|---|---|---|---|---|---|
| Liquid | 500 | 1344 | A | | | | | |
| Untreated | 500 | 1373 | A | | | | | |
| Liquid | 425 | 1478 | | B | | | | |
| Untreated | 425 | 1479 | | B | | | | |
| Liquid | 370 | 1650 | | | C | | | |
| Untreated | 370 | 1677 | | | C | | | |
| Lime | 500 | 1913 | | | | D | | |
| Lime | 425 | 2071 | | | | | E | |
| Lime | 370 | 2185 | | | | | | F |

As shown in Table 4, the average dynamic modulus of the mix treated with lime is significantly higher than those that are liquid-treated and untreated mixes, at each load frequency. However, no significant difference was observed in the dynamic modulus of the untreated control mix and the mix treated with liquid anti-stripping additive, at each load frequency. The dynamic modulus increased with increased frequency, for each treatment type. There was a visible grouping of average dynamic modulus at low frequencies and high frequencies.

**Table 4. Tukey's Homogenous Groups of Average Dynamic Modulus across Anti-Stripping Treatment and Frequency**

| Anti-Stripping Treatment | Frequency (Hz) | Average Dynamic Modulus (MPa) | Tukey's Homogenous Groups | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Liquid | 0.5 | 1033 | A | | | | | | | |
| Untreated | 0.5 | 1040 | A | | | | | | | |
| Liquid | 1.0 | 1196 | | B | | | | | | |
| Untreated | 1.0 | 1207 | | B | C | | | | | |
| Lime | 0.5 | 1282 | | | C | | | | | |
| Lime | 1.0 | 1529 | | | | D | | | | |
| Liquid | 5.0 | 1732 | | | | | E | | | |
| Untreated | 5.0 | 1758 | | | | | E | | | |
| Liquid | 10.0 | 2002 | | | | | | F | | |
| Untreated | 10.0 | 2034 | | | | | | F | | |
| Lime | 5.0 | 2415 | | | | | | | G | |
| Lime | 10.0 | 2998 | | | | | | | | H |

## PHASE ANGLE CHARACTERIZATION TEST RESULTS

The average phase angle values across the various test mixes are shown in Figure 3. The average phase angle ranged from 19.1 degrees to 21.4 degrees for unmodified mix, from 18.4 degrees to 21.2 degrees for mix modified with liquid anti-stripping additive, and from 22.0 degrees to 29.5 degrees for mix modified with lime. As seen in Figure 3, the phase angle was highest for the asphalt mix treated with lime. This may indicate an extension of the viscoelastic behaviour of the asphalt mix with the addition of lime. There was a general increasing trend in the phase angle as the load frequency increased, especially in the mix modified with lime. It is interesting to note that the magnitude of the phase angle between the untreated and liquid-treated mixes was relatively the same, and for both mixes the phase angles reached a maximum at the frequency of 5 Hz, and decreased at higher frequency.

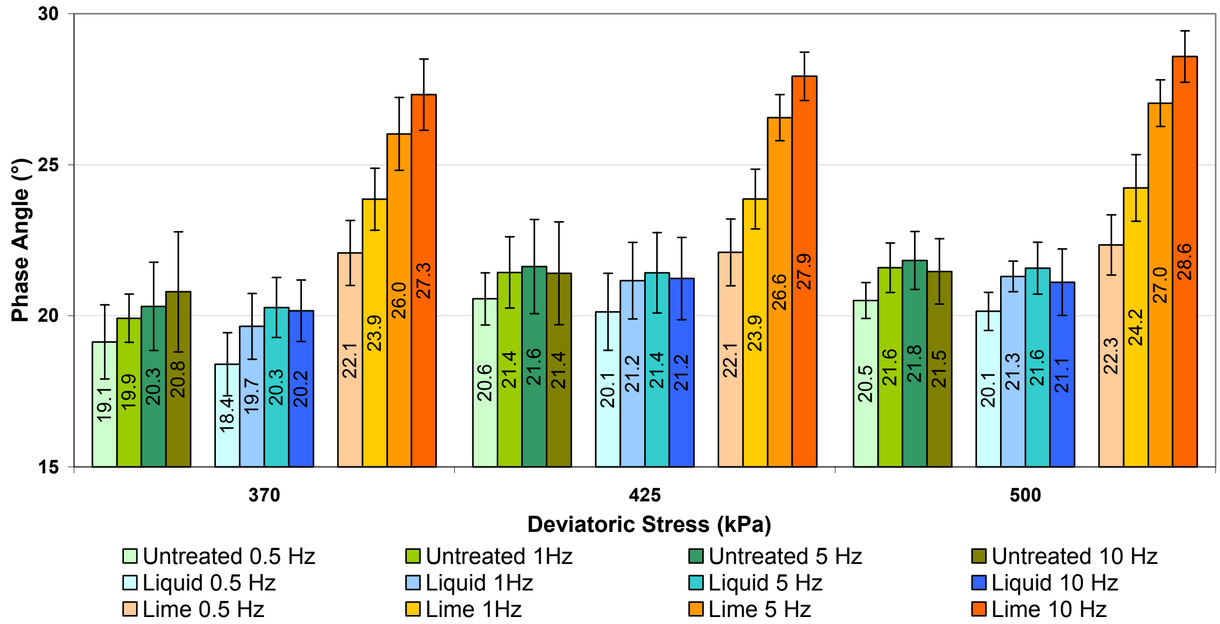


**Figure 3. Phase Angle across Anti-Stripping Treatment, Deviatoric Stress State, and Frequency**

The statistically significant differences of phase angle across anti-stripping treatment, deviatoric stress state, and frequency, were tested using Tukey's homogenous groups and are summarized in Table 5 and Table 6. As seen in Table 5, the average phase angle for the mix treated with lime was significantly higher than the phase angle in the liquid-treated and untreated mix, respectively, at each deviatoric stress state. There was no significant difference between the phase angle for the liquid-treated and untreated mixes, at any deviatoric stress state.

**Table 5. Tukey's Homogenous Groups of Average Phase Angle across Anti-Stripping Treatment and Deviatoric Stress State**

| Anti-Stripping Treatment | Deviatoric Stress (kPa) | Average Phase Angle (degrees) | Tukey's Homogenous Groups | | | |
|---|---|---|---|---|---|---|
| Liquid | 370 | 19.62 | A | | | |
| Untreated | 370 | 19.95 | A | | | |
| Liquid | 425 | 20.99 | | B | | |
| Liquid | 500 | 21.04 | | B | | |
| Untreated | 425 | 21.26 | | B | | |
| Untreated | 500 | 21.35 | | B | | |
| Lime | 370 | 24.82 | | | C | |
| Lime | 425 | 25.11 | | | C | |
| Lime | 500 | 25.55 | | | | D |

As shown in Table 6, the average phase angle for the mix modified with lime is significantly higher than the phase angle for the liquid-treated and untreated mix, respectively, at each load frequency. The average phase angle of the mix modified with liquid anti-stripping additive is not significantly different than the average phase angle of the untreated mix, regardless of load frequency. The phase angle increased with increased load frequency for the mix modified with lime.

**Table 6. Tukey's Homogenous Groups of Average Phase Angle across Anti-Stripping Treatment and Frequency**

| Anti-Stripping Treatment | Frequency (Hz) | Average Phase Angle (degrees) | Tukey's Homogenous Groups |
|---|---|---|---|
| Liquid | 0.5 | 19.56 | A |
| Untreated | 0.5 | 19.95 | A |
| Liquid | 1.0 | 20.71 | B |
| Liquid | 10.0 | 20.84 | B |
| Untreated | 1.0 | 20.98 | B |
| Liquid | 5.0 | 21.09 | B |
| Untreated | 10.0 | 21.22 | B |
| Untreated | 5.0 | 21.26 | B |
| lime | 0.5 | 22.18 | C |
| lime | 1.0 | 23.99 | D |
| lime | 5.0 | 26.54 | E |
| lime | 10.0 | 27.95 | F |

## RECOVERABLE AXIAL STRAIN CHARACTERIZATION TEST RESULTS

The average recoverable axial micro-strains across the number of repeat specimens are shown in Figure 4. The average recoverable axial micro strains ranged from 260 to 648 for unmodified mix, from 267 to 659 for mix modified with liquid anti-stripping additive and from 184 to 512 for mix modified with lime. Therefore lime treatment appears to reduce the observed recoverable axial strain of the asphalt mix. As seen in Figure 4, the average axial micro-strains in each mix were observed to decrease with increasing load frequency, and minimally increase with increased deviatoric stress state. Therefore, the average recoverable axial micro strains were more sensitive across the applied frequency than across the applied stress state, clearly illustrating the viscoelastic behaviour of asphalt mixes. In general, the variability around the mean across test samples for each mix was observed to decrease with increasing load frequency.

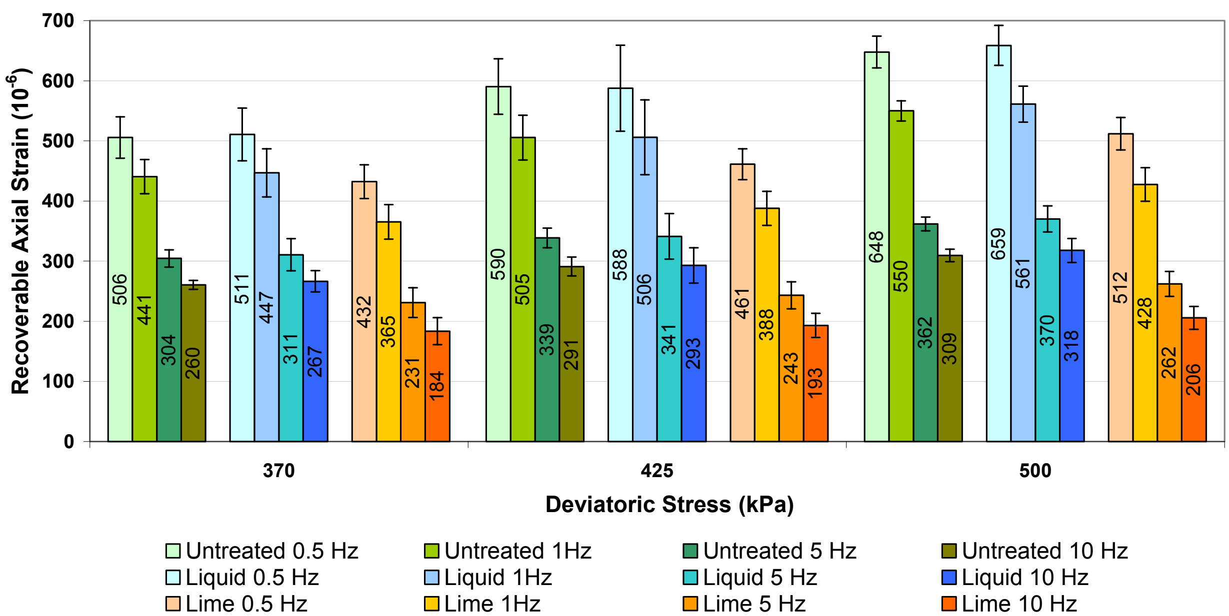


**Figure 4. Recoverable Axial Strain across Anti-Stripping Treatment, Deviatoric Stress State, and Frequency**

The statistically significant differences of recoverable axial strain across anti-stripping treatment, deviatoric stress state, and frequency, were tested using Tukey's homogenous groups and are summarized in Table 7 and Table 8. As seen in Table 7, the average recoverable axial strain of mix modified with lime was significantly lower than the average recoverable axial strain of unmodified mix and mix modified with liquid anti-stripping additive, regardless of deviatoric stress state. Further, there was no significant difference in the average recoverable axial strain for the mix treated with liquid additive, and for the untreated mix, at each stress state. The recoverable axial strain increased with increased deviatoric stress state.

**Table 7. Tukey's Homogenous Groups of Average Recoverable Axial Strain across Anti-Stripping Treatment and Deviatoric Stress State**

| Anti-stripping Treatment | Deviatoric Stress (kPa) | Average Recoverable Axial Strain ($10^{-6}$) | Tukey's Homogenous Groups |
|---|---|---|---|
| Lime | 370 | 303 | A |
| Lime | 425 | 321 | B |
| Lime | 500 | 352 | C |
| Untreated | 370 | 378 | D |
| Liquid | 370 | 384 | D |
| Untreated | 425 | 431 | E |
| Liquid | 425 | 432 | E |
| Untreated | 500 | 467 | F |
| Liquid | 500 | 477 | F |

As shown in Table 8, the average recoverable axial strain of the mix treated with lime was significantly lower from the average recoverable axial strain of the liquid-treated and the untreated mix, across all frequencies. The average recoverable axial strain increased as load frequency was decreased. There was a visible grouping of the average recoverable axial strain at low frequencies and at high frequencies.

**Table 8. Tukey's Homogenous Groups of Average Recoverable Axial Strain across Anti-Stripping Treatment and Frequency**

| Anti-Stripping Treatment | Frequency (Hz) | Average Recoverable Axial Strain ($10^{-6}$) | Tukey's Homogenous Groups |
|---|---|---|---|
| Lime | 10.0 | 194 | A |
| Lime | 5.0 | 246 | B |
| Untreated | 10.0 | 287 | C |
| Liquid | 10.0 | 292 | C |
| Untreated | 5.0 | 335 | D |
| Liquid | 5.0 | 341 | D |
| Lime | 1.0 | 394 | E |
| Lime | 0.5 | 468 | F |
| Untreated | 1.0 | 499 | G |
| Liquid | 1.0 | 505 | G |
| Untreated | 0.5 | 581 | H |
| Liquid | 0.5 | 586 | H |

## RECOVERABLE RADIAL STRAIN CHARACTERIZATION TEST RESULTS

The average recoverable radial micro strains across the number of repeat specimens are shown in Figure 5. The average recoverable radial micro strains ranged from 68 to 238 for unmodified mix, from 87 to 292 for mix modified with liquid anti-stripping additive, and from 71 to 243 for mix modified with lime. As seen in Figure 5, the average recoverable radial micro strains were more sensitive across the applied frequency than across the applied stress state, decreasing with increased loading frequency, and increasing with increasing deviatoric stress. Similar to recoverable axial strain, the variability in the average recoverable radial strain for each mix decreased with increasing load frequency.

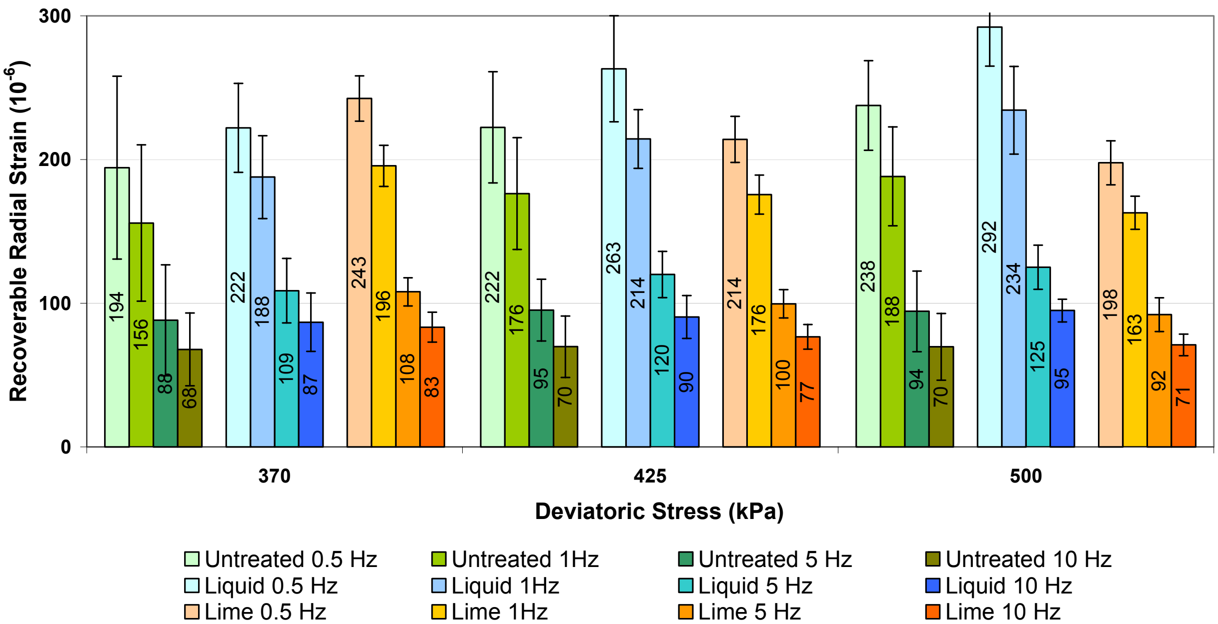


**Figure 5. Recoverable Radial Strain across Anti-Stripping Treatment, Deviatoric Stress State and Frequency**

The statistically significant differences of recoverable radial strain across anti-stripping treatment, deviatoric stress state, and frequency, were tested using Tukey's homogenous groups and are summarized in Table 9 and Table 10. As seen in Table 9, the average recoverable radial strain increased with increasing deviatoric stress state. The variability around the mean also increased with increased load frequency, and was lowest for the mix treated with lime. It is interesting to note that the mix with the liquid anti-stripping additive had the highest average recoverable radial strain, especially at the higher deviatoric stress states.

**Table 9. Tukey's Homogenous Groups of Average Recoverable Radial Strain across Anti-Stripping Treatment and Deviatoric Stress State**

| Anti-Stripping Treatment | Deviatoric Stress (kPa) | Average Recoverable Radial Strain ($10^{-6}$) | Tukey's Homogenous Groups | | | | | |
|---|---|---|---|---|---|---|---|---|
| Untreated | 370 | 125 | A | | | | | |
| Lime | 370 | 131 | A | B | | | | |
| Untreated | 425 | 141 | | B | C | | | |
| Lime | 425 | 141 | | | C | | | |
| Untreated | 500 | 147 | | | C | D | | |
| Liquid | 370 | 151 | | | | D | | |
| Lime | 500 | 157 | | | | D | | |
| Liquid | 425 | 172 | | | | | E | |
| Liquid | 500 | 187 | | | | | | F |

As shown in Table 10, average recoverable radial strain was most sensitive to load frequency, increasing as load frequency decreased. In addition, the highest recoverable radial strain occured in the liquid-treated samples, at each frequency.

**Table 10. Tukey's Homogenous Groups of Average Recoverable Radial Strain across Anti-Stripping Treatment and Frequency**

| Anti-Stripping Treatment | Frequency (Hz) | Average Recoverable Radial Strain ($10^{-6}$) | Tukey's Homogenous Groups | | | | | |
|---|---|---|---|---|---|---|---|---|
| Untreated | 10.0 | 69 | A | | | | | |
| Lime | 10.0 | 77 | A | | | | | |
| Liquid | 10.0 | 91 | | B | | | | |
| Untreated | 5.0 | 93 | | B | | | | |
| Lime | 5.0 | 100 | | B | | | | |
| Liquid | 5.0 | 118 | | | C | | | |
| Untreated | 1.0 | 173 | | | | D | | |
| Lime | 1.0 | 178 | | | | D | | |
| Liquid | 1.0 | 212 | | | | | E | |
| Untreated | 0.5 | 216 | | | | | E | |
| Lime | 0.5 | 218 | | | | | E | |
| Liquid | 0.5 | 259 | | | | | | F |

## POISSON'S RATIO CHARACTERIZATION TEST RESULTS

The average Poisson's ratio values across the number of repeat specimens are shown in Figure 6. The average Poisson's ratio values ranged from 0.225 to 0.369 for unmodified mix, from 0.299 to 0.448 for mix modified with liquid anti-stripping additive, and from 0.387 to 0.474 for mix modified with lime. As illustrated in Figure 6, the average Poisson's ratio values were more sensitive across the applied frequency than across the applied stress state, especially for the unmodified mix and the mix modified with liquid anti-stripping additive. Poisson's ratio decreased with increased load frequency across each of the sample sets. The mix modified with lime had the lowest variability around the mean of Poisson's ratio, while the unmodified mix had the highest variability.

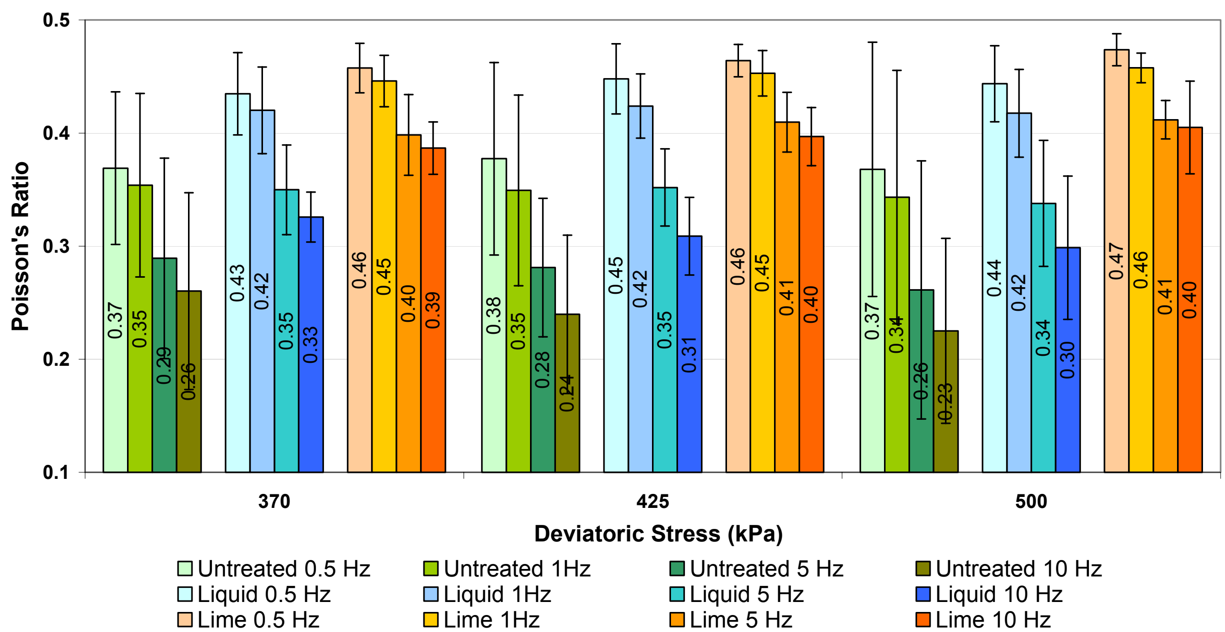


**Figure 6. Poisson's Ratio across Anti-Stripping Treatment, Deviatoric Stress State, and Frequency**

The statistically significant differences of Poisson's ratio across anti-stripping treatment, deviatoric stress state, and frequency, were tested using Tukey's homogenous groups and are summarized in Table 11 and Table 12. As seen in Table 11, the average Poisson's ratio was significantly different across the three anti-stripping treatments, with the highest average Poisson's ratio occurring in the mix modified with hydrated lime, regardless of deviatoric stress state. The untreated mix had the lowest average Poisson's ratio, regardless of stress state. The average Poisson's ratio for the untreated mix decreased slightly with increasing deviatoric stress, whereas in the lime-treated mix Poisson's ratio increased slightly with increasing deviatoric stress, although the trends were statistically insignificant.

**Table 11. Tukey's Homogenous Groups of Average Poisson's Ratio across Anti-Stripping Treatment and Deviatoric Stress State**

| Anti-Stripping Treatment | Deviatoric Stress (kPa) | Average Poisson's Ratio | Tukey's Homogenous Groups | | |
|---|---|---|---|---|---|
| Untreated | 500 | 0.299 | A | | |
| Untreated | 425 | 0.312 | A | | |
| Untreated | 370 | 0.319 | A | | |
| Liquid | 500 | 0.374 | | B | |
| Liquid | 370 | 0.383 | | B | |
| Liquid | 425 | 0.383 | | B | |
| Lime | 370 | 0.422 | | | C |
| Lime | 425 | 0.431 | | | C |
| Lime | 500 | 0.437 | | | C |

As shown in Table 12, the average Poisson's ratio decreased with increasing load frequency, regardless of anti-stripping treatment.

**Table 12. Tukey's Homogenous Groups of Average Poisson's Ratio across Anti-Stripping Treatment and Frequency**

| Anti-Stripping Treatment | Frequency (Hz) | Average Poisson's Ratio | Tukey's Homogenous Groups | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Untreated | 10.0 | 0.242 | A | | | | | | | | | |
| Untreated | 5.0 | 0.277 | | B | | | | | | | | |
| Liquid | 10.0 | 0.311 | | | C | | | | | | | |
| Liquid | 5.0 | 0.347 | | | | D | | | | | | |
| Untreated | 1.0 | 0.349 | | | | D | E | | | | | |
| Untreated | 0.5 | 0.373 | | | | | E | F | | | | |
| Lime | 10.0 | 0.396 | | | | | | F | G | | | |
| Lime | 5.0 | 0.407 | | | | | | | G | H | | |
| Liquid | 1.0 | 0.421 | | | | | | | | H | | |
| Liquid | 0.5 | 0.442 | | | | | | | | | I | |
| Lime | 1.0 | 0.452 | | | | | | | | | I | J |
| Lime | 0.5 | 0.465 | | | | | | | | | | J |

## SUMMARY AND CONCLUSIONS

This study investigated the mechanistic behaviour of a typical Saskatchewan hot mix asphalt concrete modified with lime and with liquid anti-stripping additive, and was compared to a control mix without anti-stripping additives. Ten repeat samples were tested for the mix modified with lime, ten for the mix modified with liquid additive, and five repeat samples were tested for the untreated mix. Specimens were characterized using repeated triaxial frequency sweep loading at three applied traction states (370 kPa, 425 kPa, and 500 kPa) and four load frequencies (0.5 Hz, 1 Hz, 5 Hz, and 10 Hz).

Data recorded from each frequency sweep test was used to calculate dynamic modulus, Poisson's ratio and phase angle. Statistical analysis was performed across the independent variables of anti-stripping treatment, deviatoric stress state and frequency, and the dependent variables dynamic modulus, phase angle, recoverable axial strain, recoverable radial strain and Poisson ratio. For each dependent variable, the statistically significant differences across the independent variables (predictors), were determined using Tukey's analysis of homogenous groups.

Relative to the unmodified mix, the addition of lime significantly increased the dynamic modulus of the asphalt mix, while the addition of liquid anti-stripping additive did not significantly affect the dynamic modulus results. Also, dynamic modulus values were more sensitive across the applied frequency relative to the applied stress state, increasing with increased load frequency. In addition, the variability around the mean increased with increased load frequency and increased modulus.

The addition of lime significantly increased the phase angle of the asphalt mix, while the liquid anti-stripping additive did not affect the phase angle results. Phase angle values for the mix treated with lime increased with loading frequency and with increasing deviatoric stress, while the liquid-treated and untreated mix did not show sensitivity to frequency and deviatoric stress state.

The addition of lime significantly lowered recoverable axial micro strains of the asphalt mix, while the liquid anti-stripping additive did not affect the recoverable axial micro strain results. The average recoverable axial micro strains were more sensitive across the applied frequency than across the applied stress state, decreasing with increasing load frequency, and with increased deviatoric stress state, respectively. In general, the variability around the mean across test samples for each mix was observed to decrease with increasing load frequency.

The addition of the liquid anti-stripping additive significantly increased the average recoverable radial strains of the asphalt mix across frequency and stress state. The addition of lime did not affect the average recoverable radial strains. The average recoverable radial strains were more sensitive across the applied frequency than across the applied stress state, decreasing with increased loading frequency increasing with increasing deviatoric stress. Similar to recoverable axial strain, the variability in the average recoverable radial strain for each mix decreased with increasing load frequency.

The addition of lime significantly increased the average Poisson's ratio of the asphalt mix, primarily as a result of the lower recoverable axial strains. The average Poisson's ratio was lowest for the unmodified mix, as a result of the higher recoverable radial strains. This measure was more sensitive across the applied frequency than across the applied stress state, decreasing with increased load frequency, especially for the unmodified mix and the mix modified with liquid anti-stripping additive. The mix modified with lime had the lowest variability in the average Poisson's ratio, while the unmodified mix had the highest variability.

In summary, this research found significant changes in mechanistic behaviour at 20°C attributable to using different anti-stripping treatments.

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## ACKNOWLEDGEMENTS

The authors would like to thank Saskatchewan Highways and Transportation for sponsoring this research.