Multiscale Modeling of Rubber Friction under dry/ wet condition

Vadakkeveetil Sunish and Saied Taheri
Center for Tire Research Organization, Virginia Tech

RPUG Conference 2018

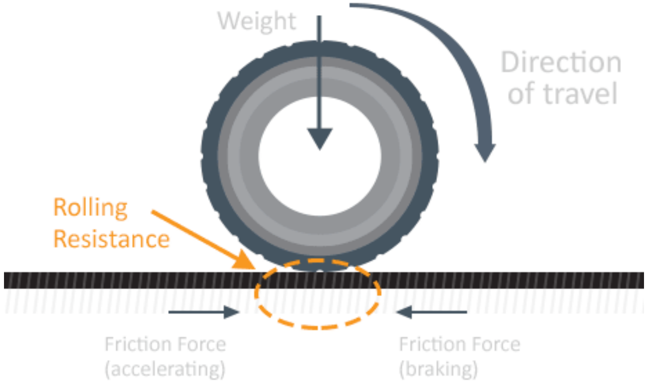
Agenda

- Introduction
- Background
- Analytical Approach
    - Single Scale Hysteretic Friction
    - Multiple Scale model - Persson's Friction
- Model Input Parameters
- Simulation Results
- Friction under wet condition
- Conclusion

Motivation

- Resisting force at the contact interface

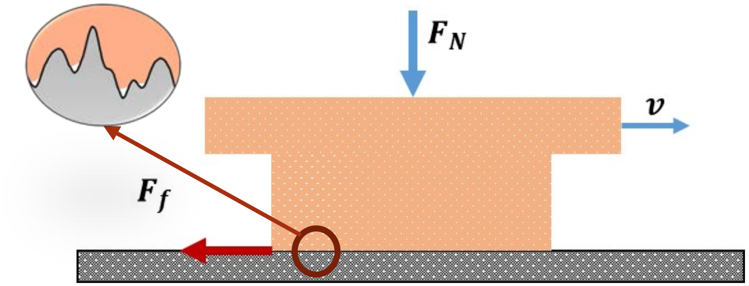
- Provides traction, control and stability to the vehicle
- Also results in rolling resistance and wear



Rolling resistance

Wear

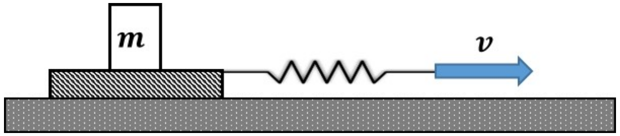
Introduction



$$F_f \leq \mu F_N$$

$$\mu = \frac{F_f}{F_N}$$

Amontons-Coulomb



Static friction

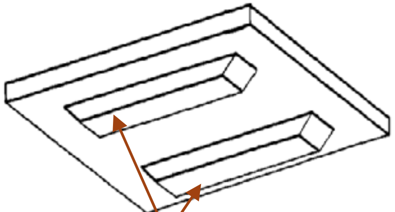
$$\mu_s > \mu_d$$

Dynamic friction

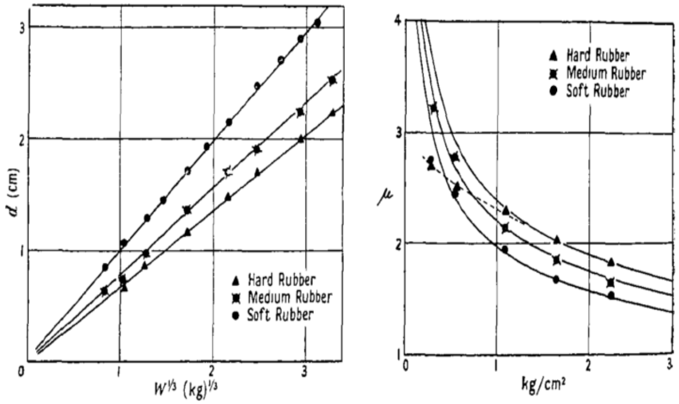
- Minimum force required for motion
- Friction when body sliding at steady state

- Microscopic observations shows the influence of plastic yielding and effective contact area ***[Bowden and Tabor]***
- Static friction shows an increase with increase in time at rest due to plastic relaxation exhibiting memory or hysteretic effects ***[Rabinowicz]***
- Dynamic friction has no universal behavior and is highly dependent on the material and the sliding velocity

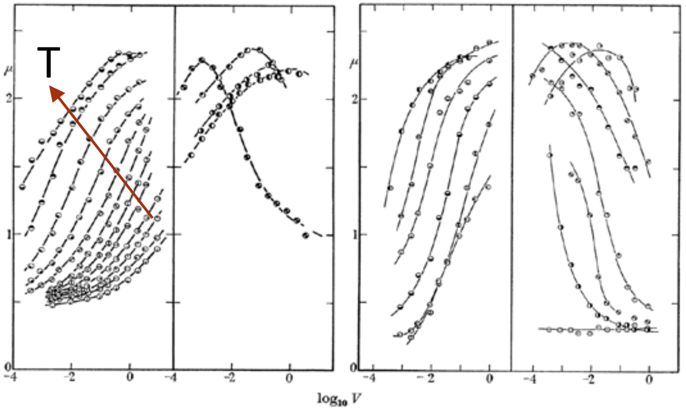
Background on Rubber friction



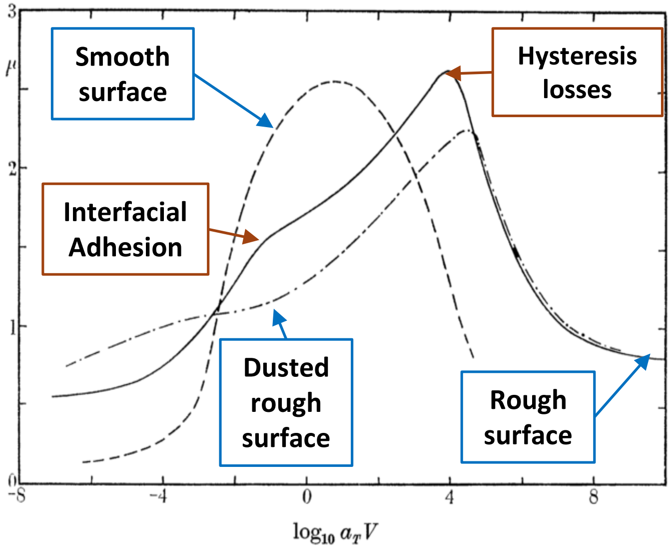
Rubber sample



Schallamach (1952): Load dependence



Grosch (1962): Velocity and Temperature dependence



Smooth surface

Hysteresis losses

Interfacial Adhesion

Dusted rough surface

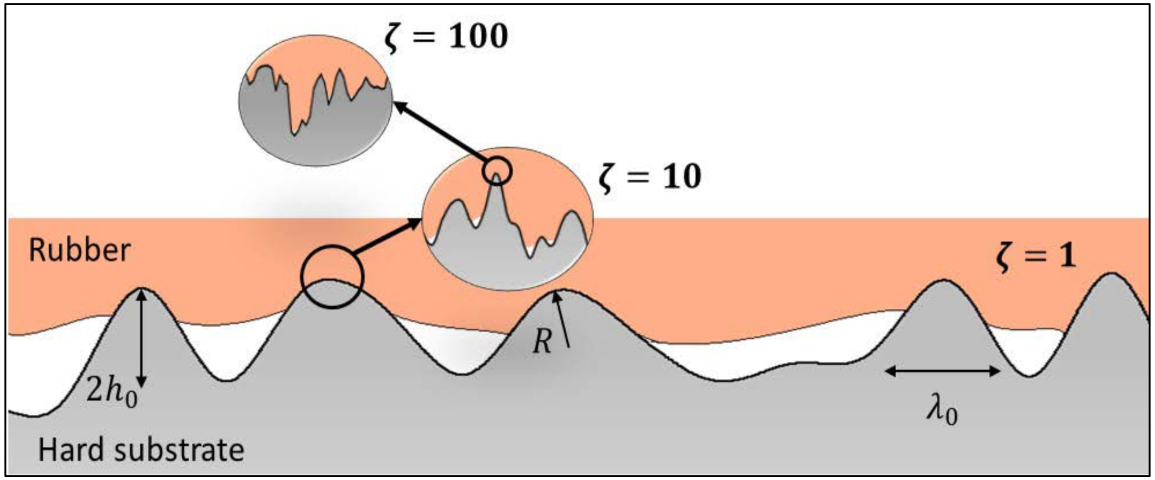
Rough surface

Grosch (1962): Different Surfaces

- **Two peaks**: Hysteresis loses & Interfacial Adhesion
- **Hysteresis**: At higher velocities, deformation loses from undulations of surface, Vanishes for smooth surfaces
- **Interfacial Adhesion**: At low velocities, due to interfacial energy of the surface, stick-slip instability, vanishes for dusted surfaces

Contact Mechanics Theories

- Study of deformation of the bodies occurring at the contact interface
- Surfaces smooth to the naked eyes have some level of roughness at higher length scales
- Roughness causes variation in real contact area, deformations and pressure distribution at the contact interface
- Contact mechanics theories helps in estimating these contact parameters based on the operating condition and the surface profile



Background – Previous Contact Mechanics

- Frictional properties are highly dependent on contact properties especially penetration depth (1) and real contact area (2)
- Hertz – Considered the point on elastic half space with no adhesion to obtain the contact mechanics parameters
- JKR – Included the effect of adhesion to obtain the pull force required at the contact by minimizing the total energy

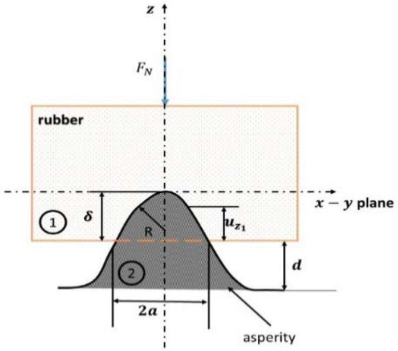
$$F_A = \frac{3}{2}\gamma_{12}\pi R$$

- Greenwood – Williamson – Considered the asperities to be spherical with height distribution, defined the GW function and obtained the parameters at contact

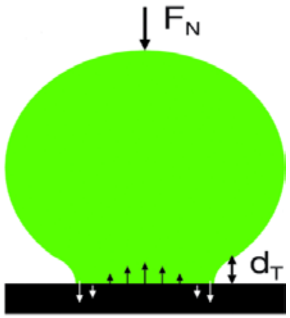
$$F_n(d) = \int_d^{\infty} (z-d)^n \, \phi_s(z) \, dz$$

- Bush et al – Considers the asperities to be paraboloid and obtained the distribution of the curvature and height of asperities,

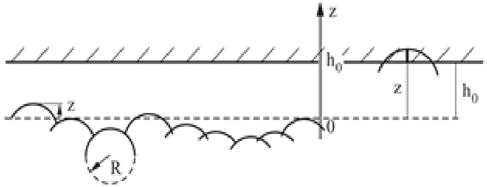
$$A \;=\; \kappa \, F_N \left(\int d^2q \; q^2 C(q) \right)^{-1/2}$$



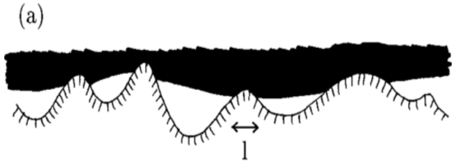
Hertz Contact theory



JKR theory



Greenwood Williamson theory



Bush et al theory

Analytical Approach

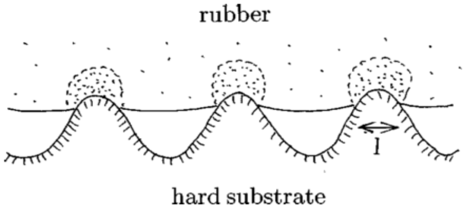
Single Scale Hysteretic Friction

- Asperities considered to be identical with similar wavelength
- Energy dissipated at the contact to the bulk of rubber obtained from the viscous losses (Loss modulus - $Im\left(E(\omega)\right)$)
- Related to the frictional energy losses at contact,

$$\Delta E = \sigma_f A_0 v t$$

- Frequency is dependent on the sliding velocity and wavelength of the asperities

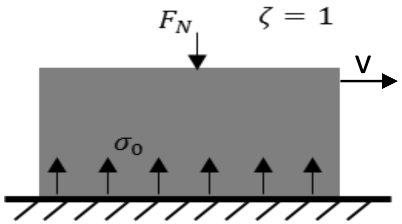
Single Scale friction

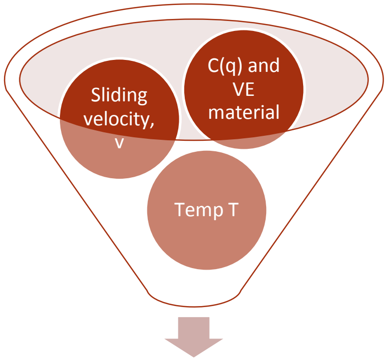


$$\longrightarrow \quad \Delta E \approx N l^3 \sigma_0^2 \omega_0 T \; Im\left(\frac{1}{E(\omega_0)}\right) \quad \longrightarrow \quad \mu = \sigma_0 Im\left(\frac{1}{E(\omega_0)}\right)$$

Model needs to be extended for roughness at different length scales

Persson’s Friction





Sliding velocity, v

C(q) and VE material

Temp T

Persson’s Friction Model

μ_{hys} → σ_f → ΔE → σ, u → Time domain to Fourier domain

Energy dissipated as sum over different length scale

Theory of linear elasticity
- Dynamic equilibrium condition
- Constitutive relation: Isotropic, linear elastic material

Considering complete contact and relating to surface roughness power spectrum

$$\sigma_f = \frac{1}{2}\int d^2q\; q\cos\phi\, C(q)\, Im\frac{E(qv\cos\phi)}{1-\nu^2}$$

Surface roughness power spectrum
q = wavenumber

$$u_z(\boldsymbol{q},\boldsymbol{\omega}) = M_{zz}(\boldsymbol{q},\boldsymbol{\omega})\sigma_z(\boldsymbol{q},\boldsymbol{\omega})$$

$$(M_{zz})^{-1} = -\frac{E(\omega)q}{2(1-\nu^2)}$$

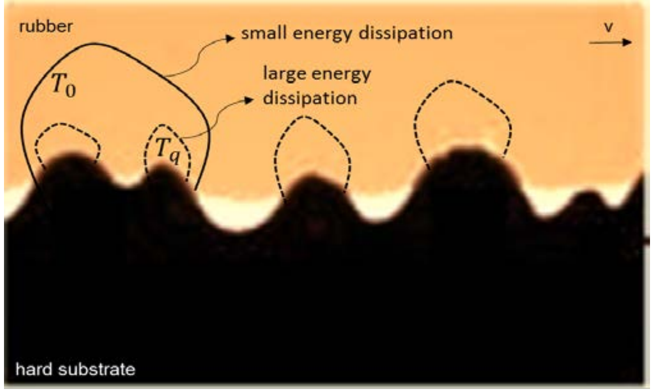
$$\mu = \frac{\sigma_f A(\zeta)}{\sigma_0 A_0}$$

Area ratio, $\boldsymbol{P(q)}$

Obtained by solving diffusion relation of stress probability distribution at different magnifications and pressure

Including Frictional Heating

- Energy dissipated due to friction leads to heat generation at the contact interface
- Increase in temperature at the contact interface effects the material properties
- Temperature rise is obtained by solving the heat diffusion relation



$$T_q = T_0 + \int_0^{\infty} dq' \underbrace{g(q,q')}_{\text{Diffusion term}} \underbrace{f(q')}_{\text{Heat generation}}$$

$$\text{Where, } f(q) = \frac{vq^4}{\rho C_v} C(q) \frac{P(q)}{P(q_m)} \int d\phi \cos\phi \ Im \frac{E(qv\cos\phi, T_q)}{1-\nu^2}$$

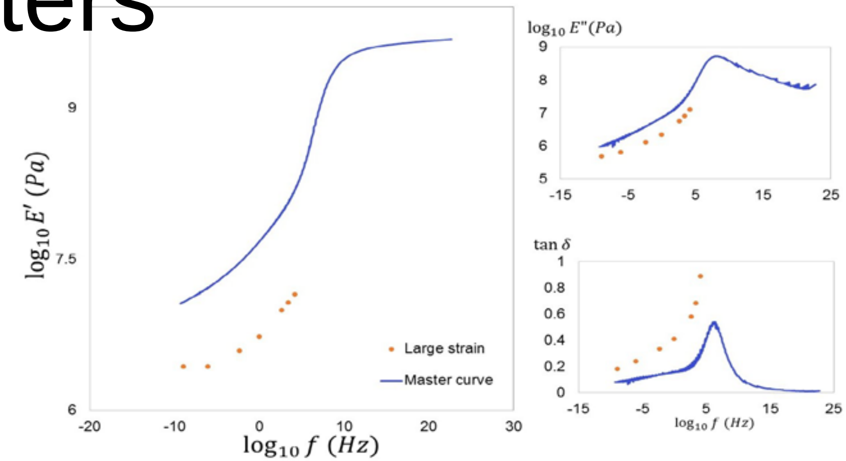
$$g(q,q') = \frac{1}{\pi} \int_0^{\infty} dk \frac{1}{Dk^2} \left(1 - e^{-Dk^2 t_0}\right) \frac{4q'}{k^2+4q'^2} \frac{4q^2}{k^2+4q^2}$$

- Temperature rise is calculated by considering the False Position iterative method with an initial guess for the temperature at different magnification

Model Input Parameters

Material Properties

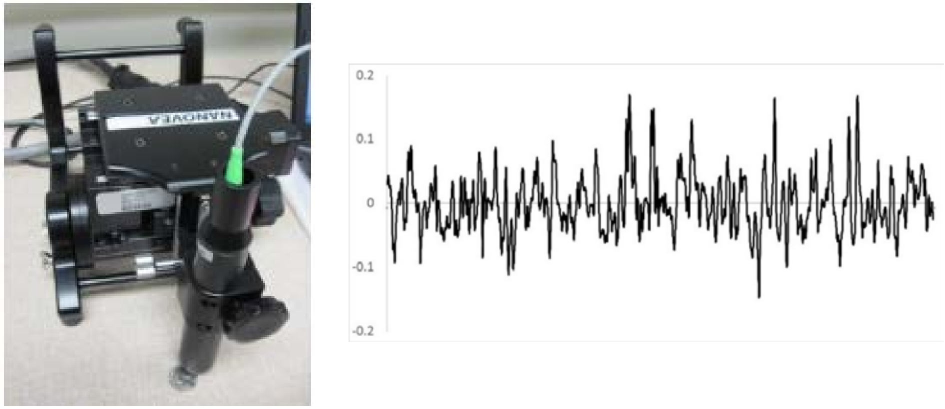
- Frequency dependent material data is obtained using DMA data of Compound A*
- Large strain elastic modulus data is obtained using strain sweep measurements



Frequency Dependent Material Properties:

Surface Roughness

- Surface profiles is measured using Nanovea profilometer
- Measurement resolution - $7\mu m$
- In this case, the surface is considered to be self affine



Nanovea Profilometer and Surface profile of 120 grit surface

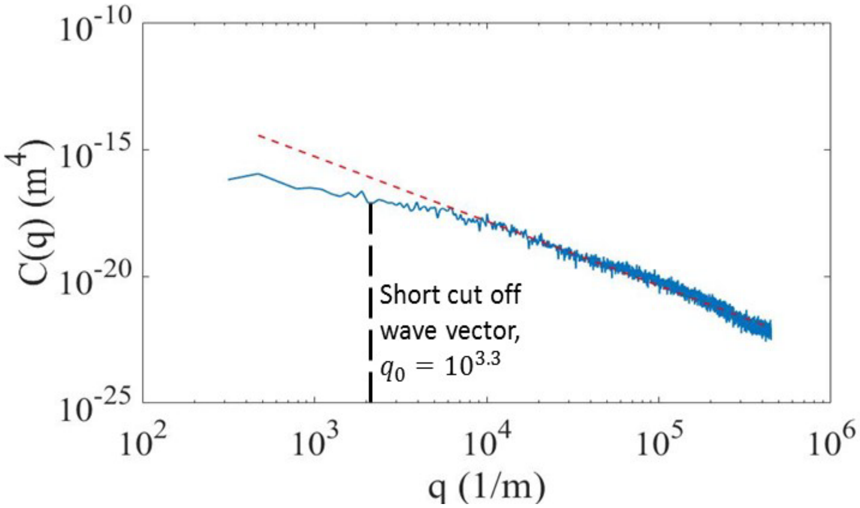
* Sample and experimental data from Bridgestone

Surface characterization of 120-grit and asphalt

- Surface roughness power spectrum $C(q)$ of the measured profiles are obtained
- Surface characteristics are obtained from the spectrum for a self affine surface

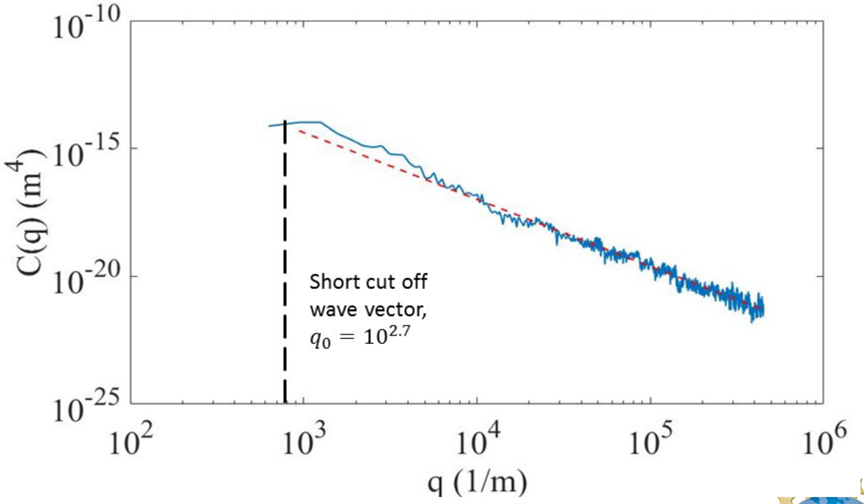
$$C(q) = \left(\frac{h_0}{q_0}\right)^2 \frac{H}{2\pi} \left(\frac{q}{q_0}\right)^{-2\,(H+1)}$$

Surface Property	120 grit	Asphalt
$h_0\ (m)$	$7.5103\ e^{-5}$	$3.74\ e^{-4}$
D_{PSD}	2.2122	2.1855
$q_0 (1/m)$	$10^{3.3}$	$10^{2.7}$
$q_1 (1/m)$	10^{6}	10^{6}



Short cut off wave vector, $q_0 = 10^{3.3}$

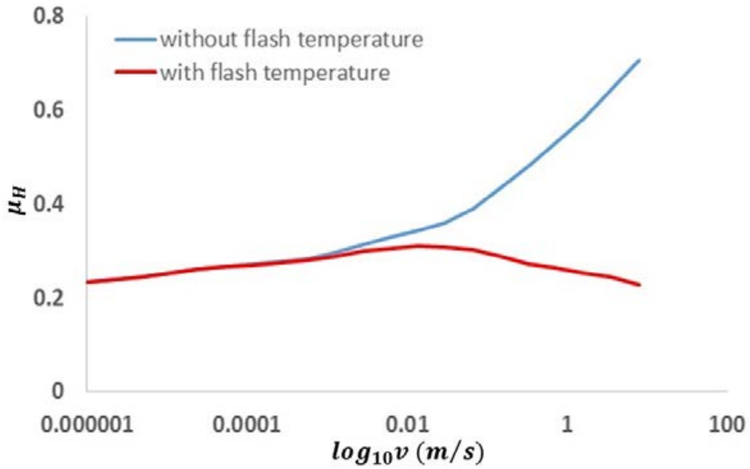
120 grit

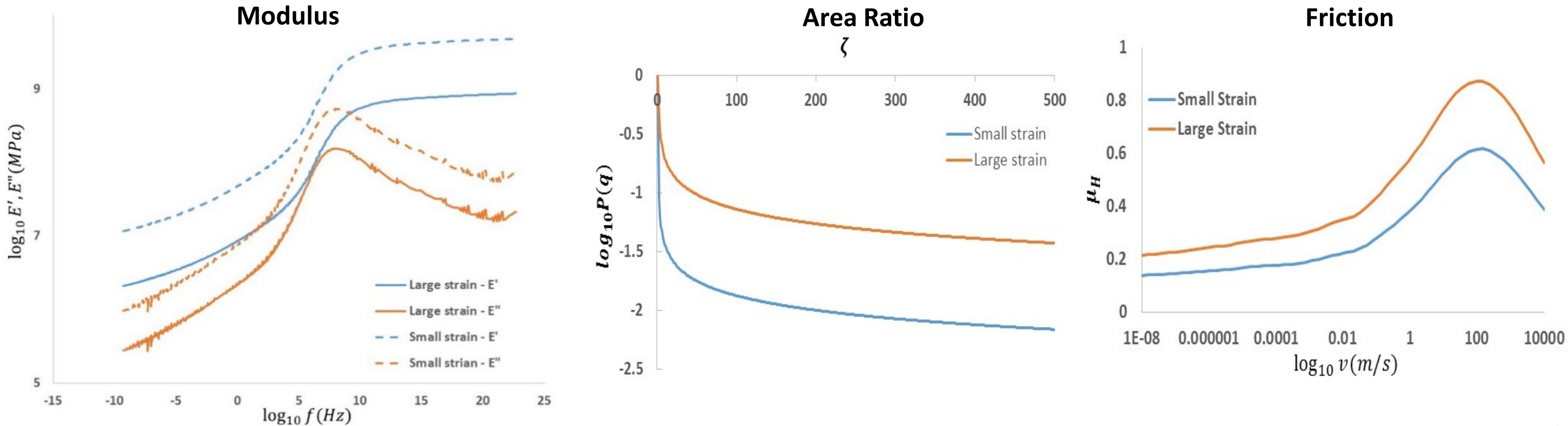


Short cut off wave vector, $q_0 = 10^{2.7}$

Asphalt

Friction Predictions – Compound A on 120 grit




Modulus

Area Ratio

Friction

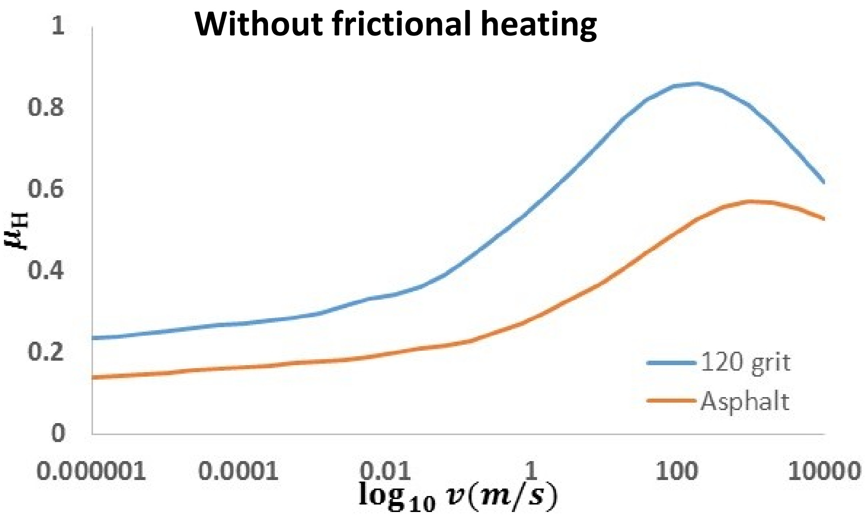
Comparison between Large and small strain

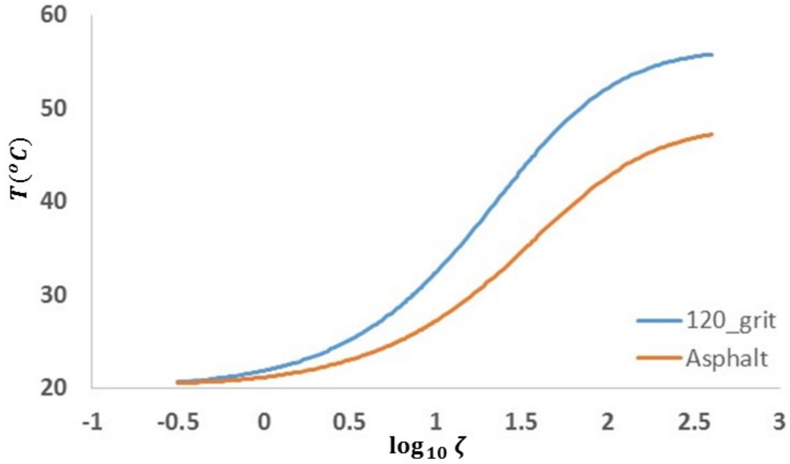
120 grit vs asphalt surface

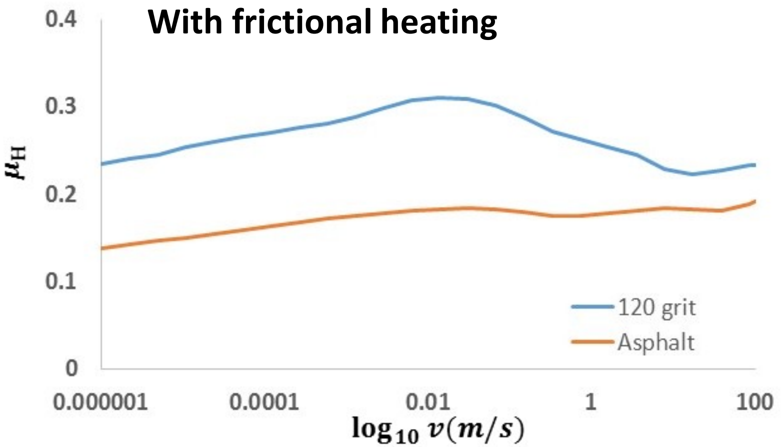
- Material: Compound A
- Surface Parameters:

Surface Property	120 grit	Asphalt
h_0	$7.6573\ 10^{-5}$	$3.3378\ 10^{-4}$
D_{PSD}	2.3	2.15
q_0	$10^{3.3}$	$10^{2.7}$

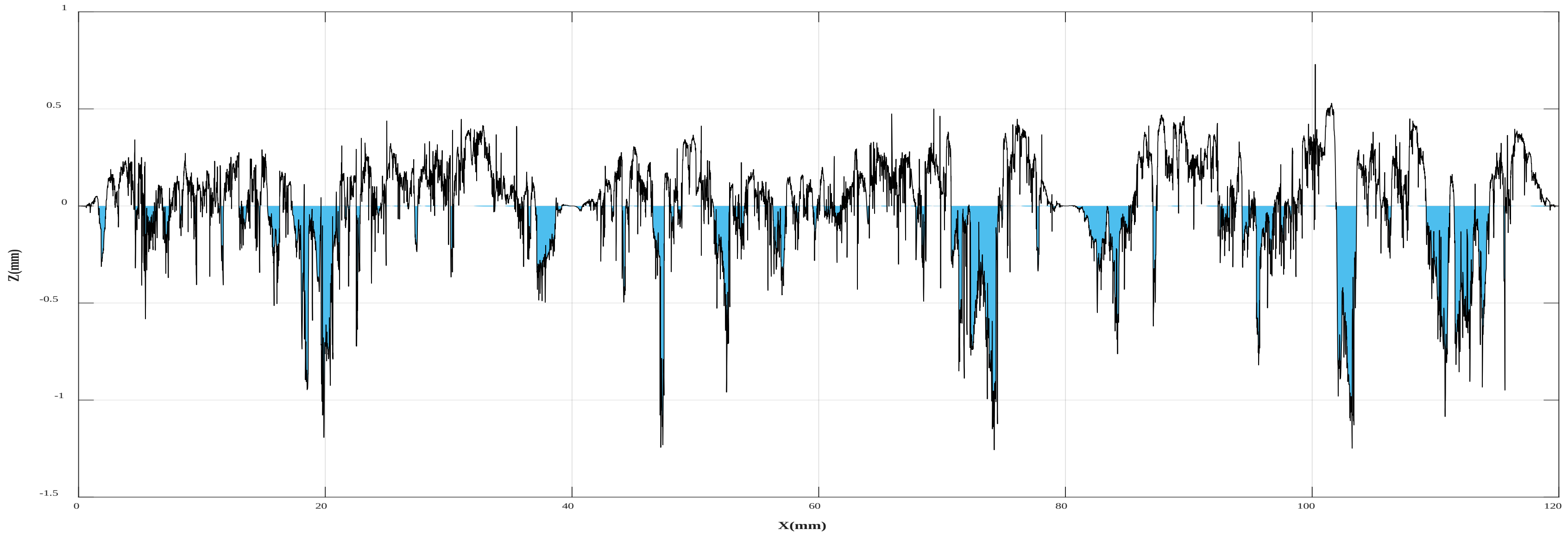
- Asphalt is smoother than 120 grit
- Friction and temperature increase is higher in 120 grit than in asphalt


Without frictional heating



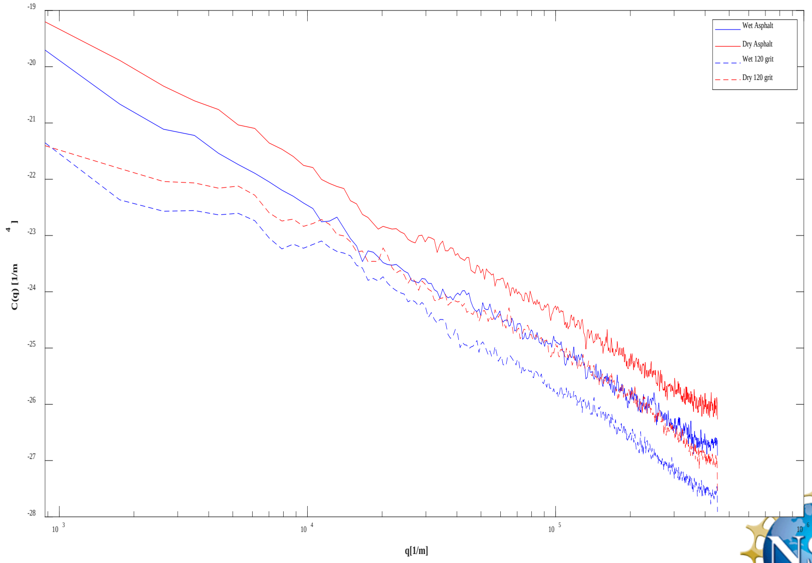

With frictional heating

Surface Roughness Characterization for wet surface

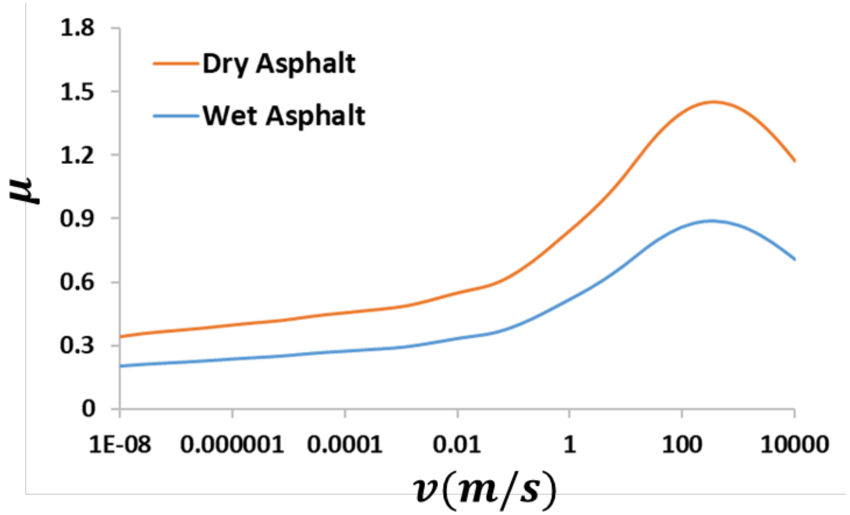


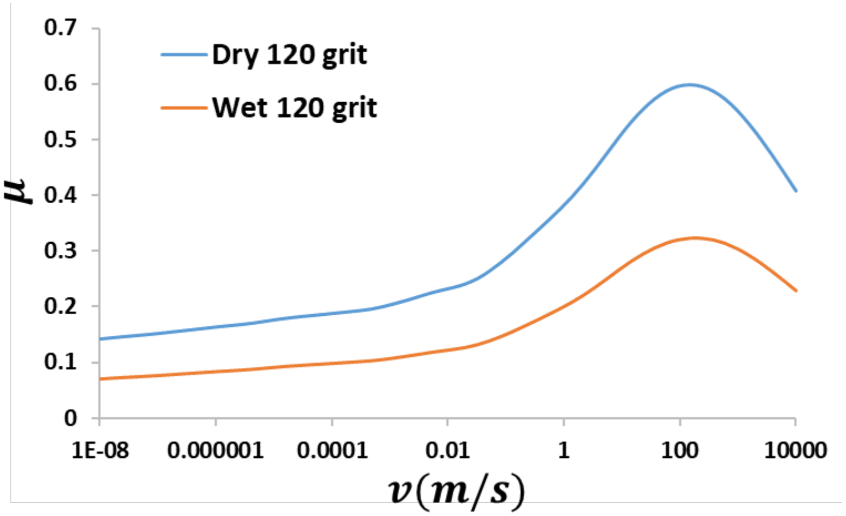
120 Grit	Mean water depth (mm)	D_f	$h_0\ (mm)$	$q_0(1/mm)$
Dry	0	2.2122	$7.51E-02$	5623.413
Wet1	0.234	2.154	$5.11E-02$	5623.413
Wet2	0.134	2.1476	$6.99E-02$	5623.413

Asphalt	Mean water depth (mm)	D_f	$h_0\ (mm)$	$q_0(1/mm)$
Dry	0	2.1855	$3.74E-01$	1000
Wet1	0.234	2.2033	$2.15E-01$	1000
Wet2	0.134	2.1988	$2.28E-01$	1000



Friction Results under Wet and Dry Condition





Conclusion

- Approach towards estimation of friction coefficient considering the surface roughness characteristics
- Temperature rise due to frictional heating results in reduction in friction coefficient
- Considering large strain material modulus showed an increase in friction results due to increase in the viscous losses
- Increase in surface roughness resulted increase in friction as observed in the comparison of 120 grit and asphalt surface
- Under wet condition, the valleys of the surface are filled with water causing the surface to smoothen out and the friction to reduce
- Future work will be focused on improvement of the model for different normal load condition and also validation of the wet friction results

Thank You
Any Questions ?