Physics of contacts and cohesion effects in granular media

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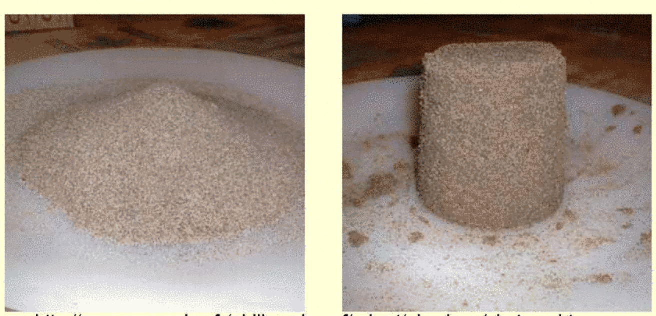
Humidity affects friction properties of a number of materials

- Time and velocity dependent friction in rocks (Dieterich & Conrad 1984)
- Stiction in Micro-Electro-Mechanic-Systems (Scherge & Schaefer 1998)
- Granular materials (Hornbaker & al 1997)



http://perso.wanadoo.fr/philippe.boeuf/robert/physique/chateau.htm

This talk : Time dependent friction in granular material

Dieterich & Conrad 1984, friction of rocks :

« Drying inibits the time-dependant increases in the coefficient of friction of nominally stationnary surfaces »

Is there a similar effect in a granular material ?

What are the mechanisms ?

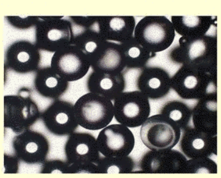
Time-dependant static friction in a granular medium

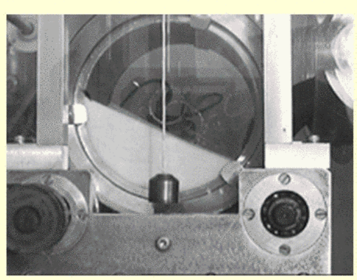
L.Bocquet, E. Charlaix, S. Ciliberto, J. Crassous Nature 1998

Restagno, Ursini, Gayvallet, Charlaix, PRE 66 021304 (2002)

Maximum stability angle of a granular heap
in a rotating drum
as a function of resting time

Glass beads :
200 - 250 μm



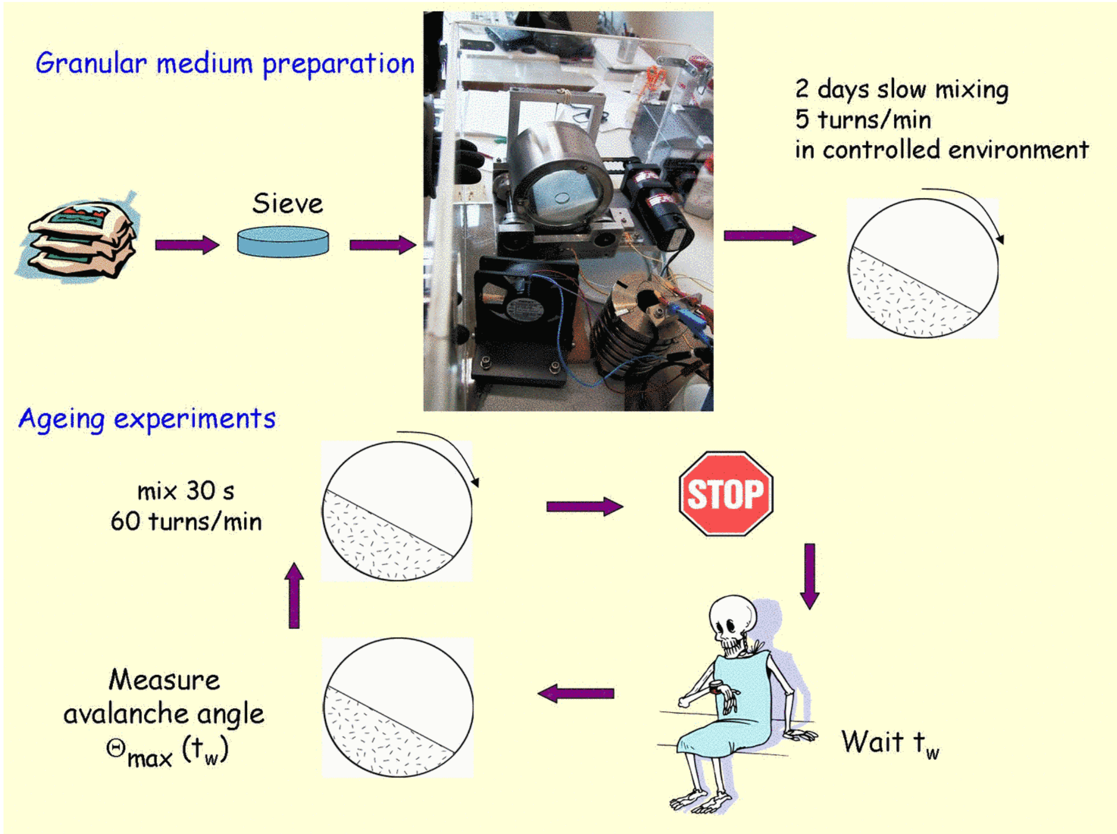


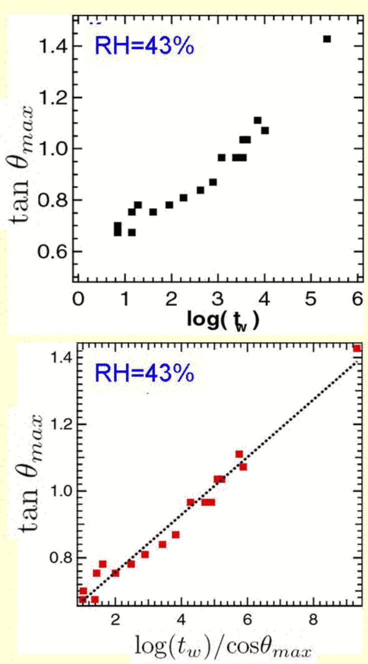
Environment:

Temperature
29,0±0,1 °C

Humidity controlled
at ± 0,5 %

RH = P_V/Psat





- Slow increase of friction in time (5 time decades)
- Evidence of cohesion effects

$\theta_{max} > 90°$ at RH > 50% and large t_w

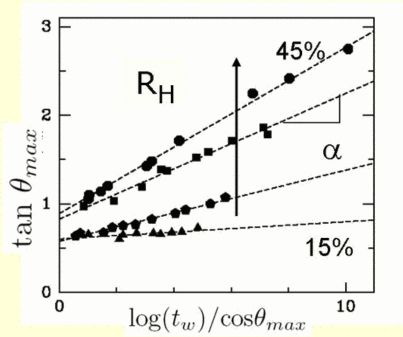
Coulomb's law with adhesion

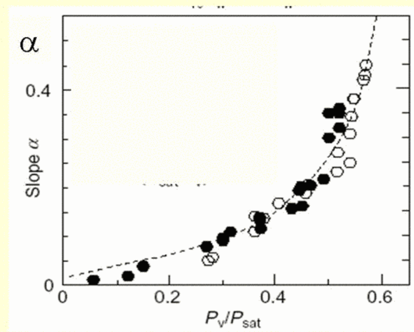
$$\tan\theta_{max} = \mu_s\left(1 + \frac{F_{adh}}{N\cos\theta_{max}}\right)$$

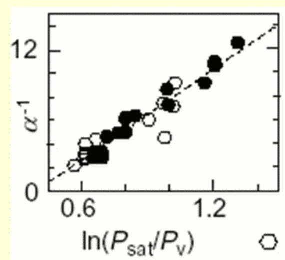
Weight and adhesion force
for the layer above failure plane

Influence of humidity on time-dependant friction

L.Bocquet, E. Charlaix, S. Ciliberto, J. Crassous Nature 1998







No ageing at low RH

Empirical dependance : α ~ 1/ ln RH

Physico-chemical mechanisms for water-induced effects on friction :

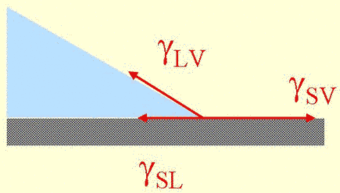
- Water-assisted plastic deformation
- Contact strenghening (hydrogen bonding, desorption of water)
- Pressure solution
- Subcritical crack growth
- Capillary condensation

BASICS OF WETTING

γ_{SL} : solid-liquid surface tension

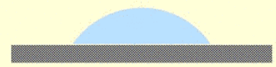
γ_{SV} : solid-liquid surface tension

γ_{LV} : solid-liquid surface tension

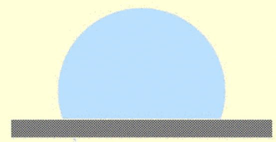


equilibrium contact angle :
Young Dupré relation

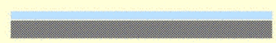
$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta$



partially wetting liquid : θ < 90°

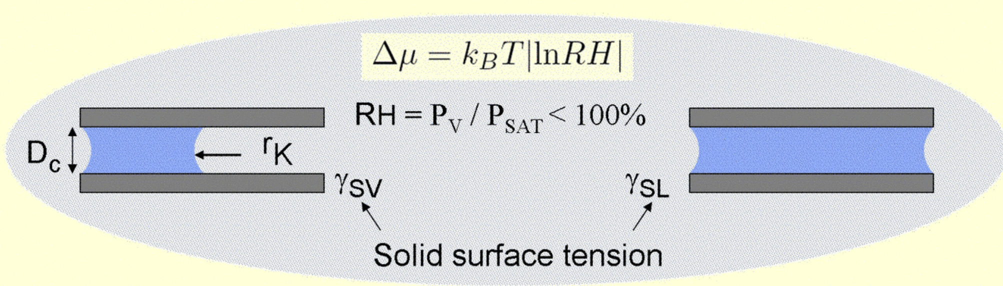


non wetting liquid : θ > 90°



perfect wetting liquid : θ =0°

Capillary condensation between surfaces



Liquid phase stable if

$D < D_c = 2\, r_K \cos\theta$

partial wetting θ >0

$$r_K = \frac{\gamma_{LV}}{\rho_L k_B T ln(P_{sat}/P_V)}$$

Kelvin radius :
equilibrium curved LV
interface in undersaturation

Water :

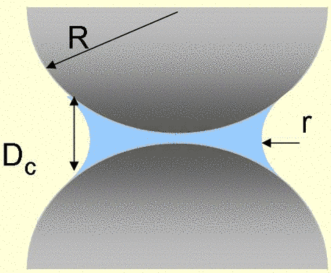
RH	50%	77%
r_K	7,8 Å	2nm
Pressure in the liquid phase	100 MPa	35 MPa

Fisher & Israelachvili JCIS 80 528 (1981)

Capillary force between smooth grains

roughness << Liquid Bridge height
macroscopic capillarity
R >> LB height

$$F_{cap} = 2\pi R \gamma_{LV}\left(\cos\theta - \frac{D}{2r}\right)$$



partial wetting θ >0

- Maximum capillary force : $F_{cap} = 2\pi R \gamma_{LV} \cos\theta$
- Estimation of the normal stress induced by capillary adhesion in a g.m. :

$$\sigma_{adh} = 2\pi R \gamma_{LV} \cos\theta \, \frac{N_{bead}}{\text{unit area}} \sim \frac{2\pi \gamma_{LV} \cos\theta}{R}$$

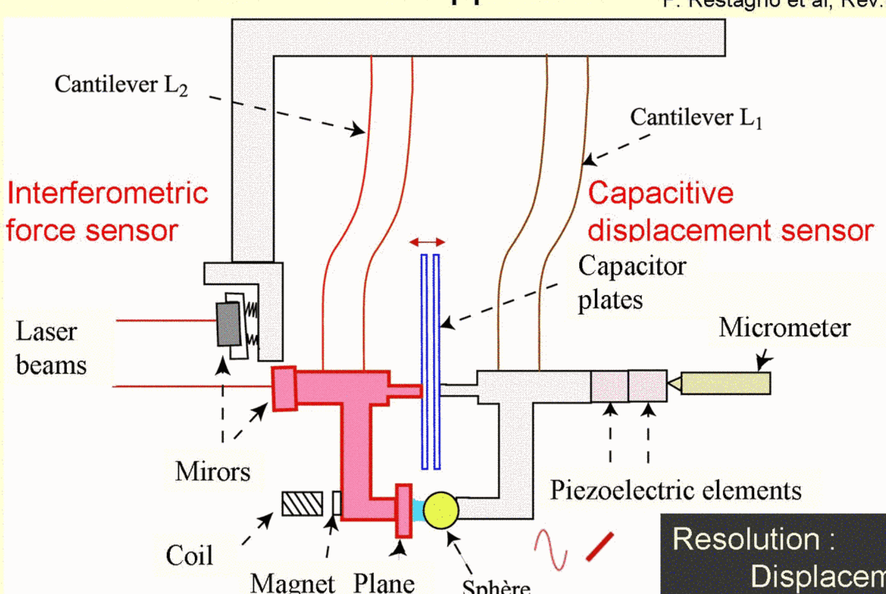
- "Capillary length" in a g.m. : $\rho g l_{cap} = \sigma_{adh}$ $\quad l_{cap} \sim \frac{2\pi \gamma_{LV} \cos\theta}{\rho g R}$

water, θ=0, R=10µm $\quad \sigma_{adh}$ ~ 0.02 MPa $\quad l_{cap}$ ~ 1 m

R=10nm $\quad \sigma_{adh}$ ~ 20 MPa

Surface Force Apparatus

F. Restagno et al, Rev.Sci. Inst. 2002



Resolution :

	Displacement	Force
Static	0.1 nm	600 nN

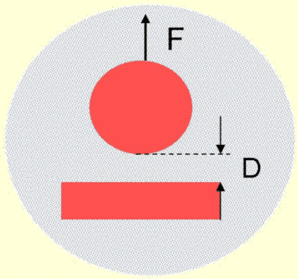
Israelachvili et al, JCIS 1981, PRB 1989, PNAS 2003

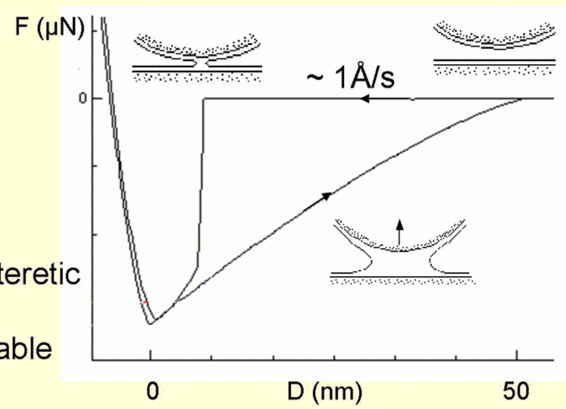
Christenson et al, JCIS 1988, JCIS 1989, PRL 1994, J Phys Cond Mat 2001

Crassous et al, Europhys Letter 1994, J. Chem Phys 2005

Capillary condensation between smooth grains :

Surface Forces experiments

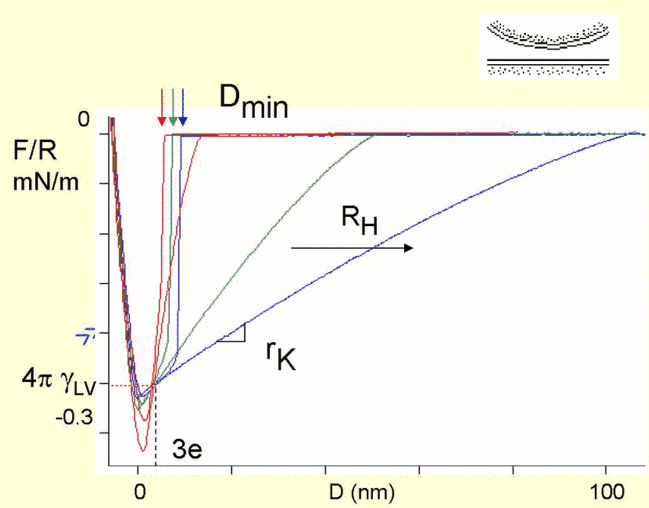




Crassous, Loubet Charlaix, Europhys Letter 1994

- Capillary force is strongly hysteretic
- Liquid is stable, vapor metastable
- How does the LB form ?

Liquid Bridges in perfect wetting (θ=0)



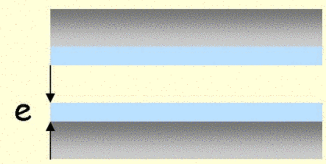
The LB forms by spinodal decomposition (instability of the wetting films covering the surfaces)

Christenson et al, PRL 1994
Crassous et al, EPL 1994

Van der Waals interactions :

$$\frac{\gamma_{LV}}{r_K} = \frac{-A_{SLV}}{6\pi e^3}$$

A_{SLV} : Hamaker constant

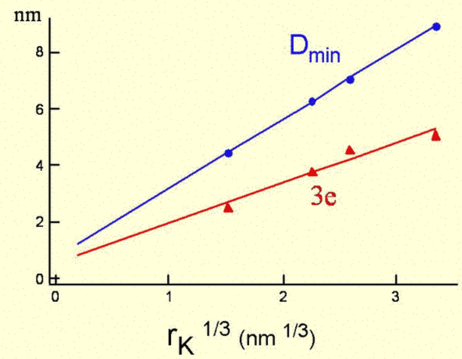


Capillary force :

$$F_{cap} = 4\pi R \gamma_{LV} \left(1 - \frac{D - 3e}{2 r_K}\right)$$

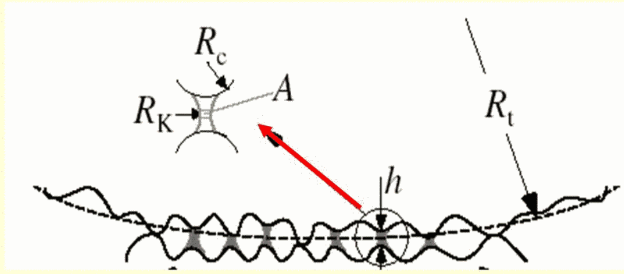
Distance for films instability

$$D_{sp} = e\ f\left(\frac{A_{SLV}}{A_{LL}}\right)$$



Slow kinetics of capillary condensation on rough surfaces

Bocquet, Charlaix, Ciliberto, Crassous Nature 1998



Surface parameters

Radius of curvature Rc of asperities

Random gap h at condensation sites

Width of h distribution : λ

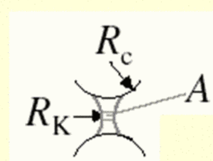
N_{site} ($\leq$h) = $N_o + h/\lambda$

Fluid parameters

Undersaturation

$$\Delta\mu = k_B T |\ln RH|$$

Kelvin's radius $r_K = \dfrac{\gamma_{LV}}{\rho_L \Delta\mu}$



- Activation energy at a given site

$$E^*_{ACT} = \rho_L \Delta\mu A h$$

- Typical condensation time for an asperity of height h

$$t = t_A \exp\left(\frac{\Delta\mu\ \rho_L\ Ah}{k_B T}\right)$$

- Maximum height of asperity having condensed at time tw :

$$h(t_w) = \frac{\ln(t_w/t_A)}{|\ln \mathrm{RH}|\rho_L A}$$

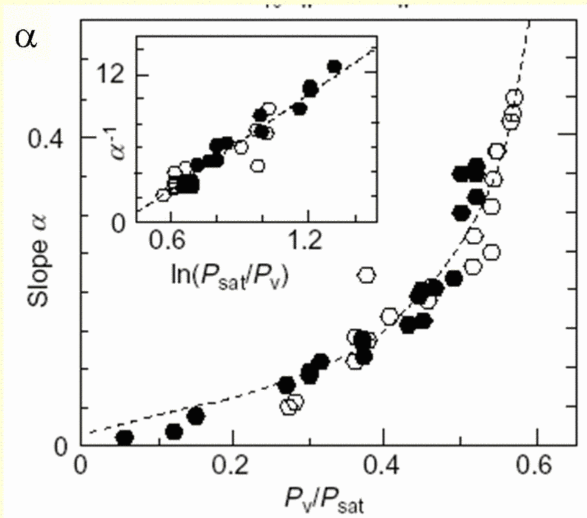
- Capillary force at time t_w : $F_{cap}(t_w) = 2\pi\gamma_{LV} R_c N_{site}[h \leq h(t_w)]$

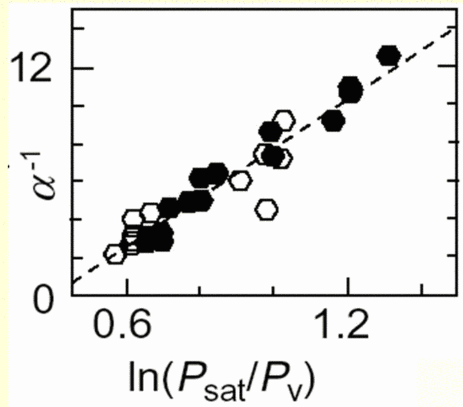
$$= \underbrace{\frac{R_c}{\lambda A}}_{\text{roughness}} \underbrace{\frac{2\pi\gamma_{LV}}{\rho_L |\ln RH|}}_{\text{environment}} \ln\frac{t_w}{t_o}$$

- Friction at contact age t_w :

$$\mu_S = \mu_o + \alpha \ln t_w / t_A$$

Humidity dependance in glass beads

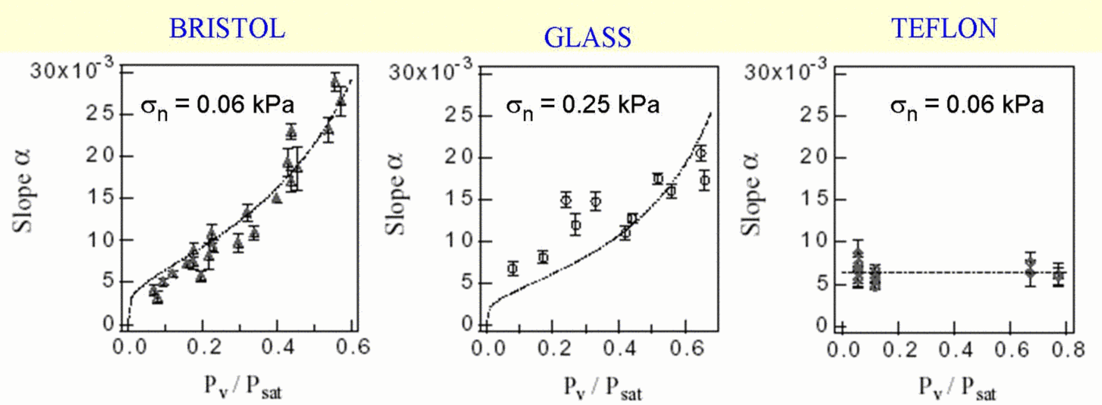




Ageing of static friction in humidity of bristol paper, glass and teflon

$\mu_S = \mu_o + \alpha \ln t_w$

Crassous, Bocquet, Ciliberto, Laroche EPL 1999



Highly hydrophilic hydrophilic hydrophobic

Amplitude of ageing induced by activated LB condensation

In this mechanism the increase in friction is due to the increase in cohesion :

$$\Delta\mu = \mu \frac{F_{adh}}{N}$$ ← external normal load

The amplitude of ageing depends on the ratio of capillary pressure to external normal stress

$$\frac{\Delta\mu}{\mu} = \frac{P_{cap}}{\sigma_n} \frac{\Delta A_{LB}}{A}$$

σ_n: external normal stress

$\frac{\Delta A_{LB}}{A}$: fraction of surface area lying in LB

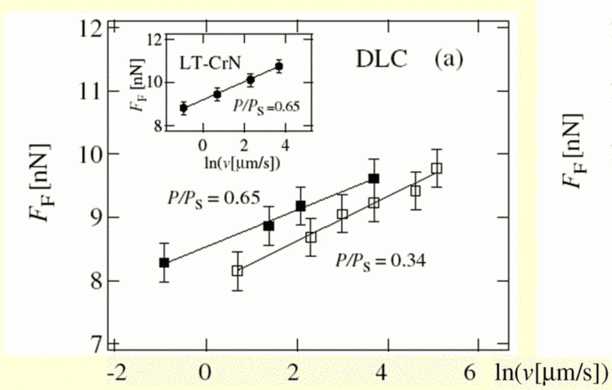
In Crassous & al experiments :

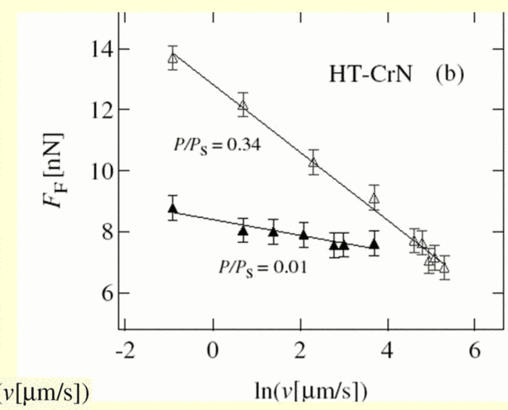
Over 10^4s at RH=50% : Δμ=0.015 ⟹ $\frac{\Delta A_{LB}}{A} \sim 7\ 10^{-7}$

Kinetics of capillary condensation in sliding nanoscopic friction

E. Riedo, F. Levy, H. Brune, PRL 2002

Sliding friction measure with an AFM silicon tip





Hydrophobic materials :
Diamond Like Carbon (θ=85°)
LT- CrN (θ=93°)

Friction is strenghening with velocity
Low influence of humidity

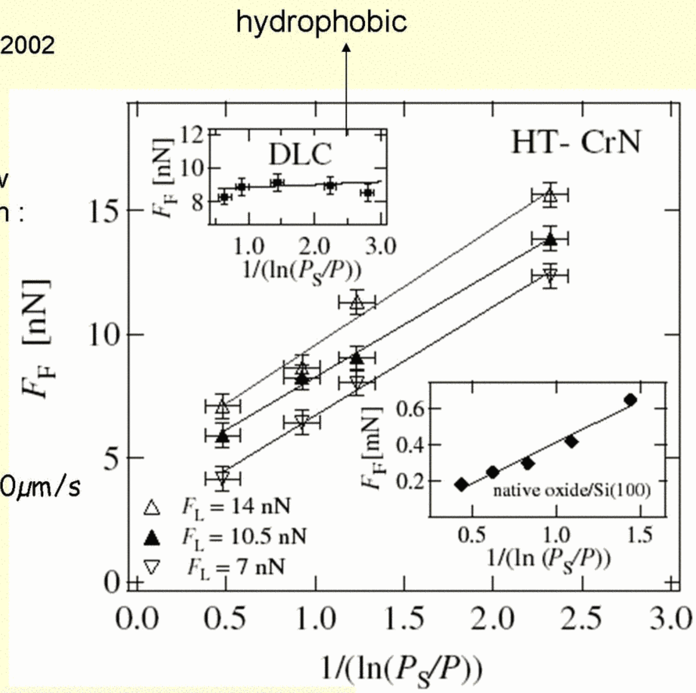
Hydrophilic material
HT- CrN (θ=45°)

Friction is weakening with velocity
High influence of humidity

E. Riedo, F. Levy, H. Brune, PRL 2002

At fixed velocity : empirical law
for effect of humidity on friction :

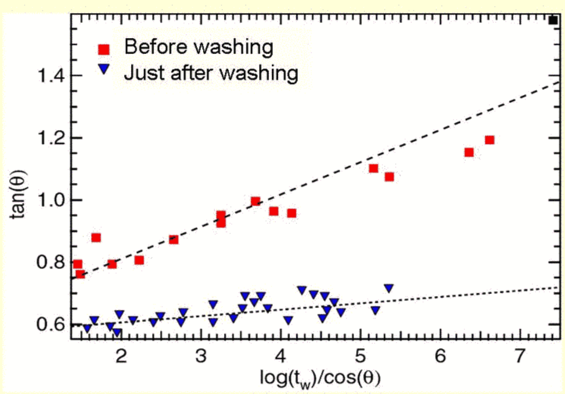
$$F_{\rm F} = F_{0\rm p} + F_{1\rm p}\frac{1}{\ln\frac{P_S}{P}}.$$

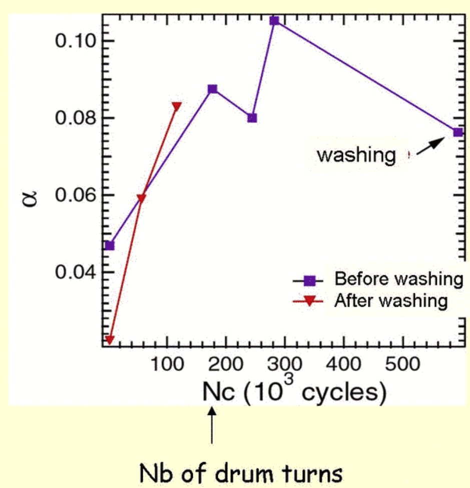


$$F_F = \mu F_N + m\ln\frac{v}{v_B} - \mu\frac{2\pi R\cos\theta}{\lambda A\rho_L}\frac{1}{|\ln R_H|}\ln\frac{v}{v_A}$$

Influence of wear

Restagno, Ursini, Gayvallet, Charlaix, PRE 66 021304 (2002)





- Washing : suppresses fine particules
- Ageing increases with wear

Summary

- Humidity induces logarithmic ageing of static friction in granular media (glass beads), as measured by the maximum avalanche angle
  - ➡ The increase in friction is associated with cohesion effects
  - ➡ The amplitude of ageing (slope of the ln t dependence) follows an empirical law in 1/ln RH
- These features can be reproduced by a model of thermally activated condensation of liquid bridges between rough surfaces
- This mechanism also accounts for ageing of static friction in materials (glass, bristol) at low normal load
- Ageing is significantly enhanced by the presence of fine particules created by wear