Problem 6.

Wet cleaning

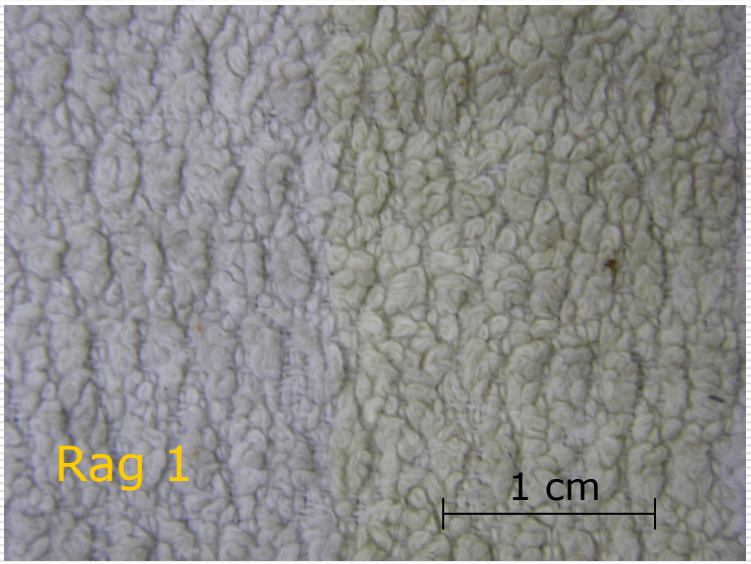
A wet rag is hard to drag when it is spread and pulled across the floor. What does the resistive force depend on?

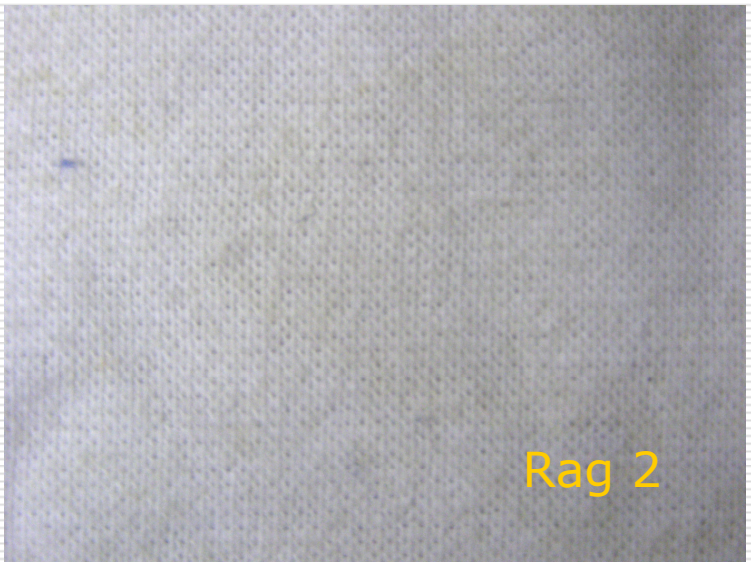
Experimental approach

- Experimental set-up
- Measurements:
  - resistive force vs. drag speed using different rags
  - resistive force vs. drag speed on several surfaces
  - resistive force vs. rag mass
  - resistive force vs. water mass in rag

The rags

- Two rags:
  - Different structures
  - Changing wettability



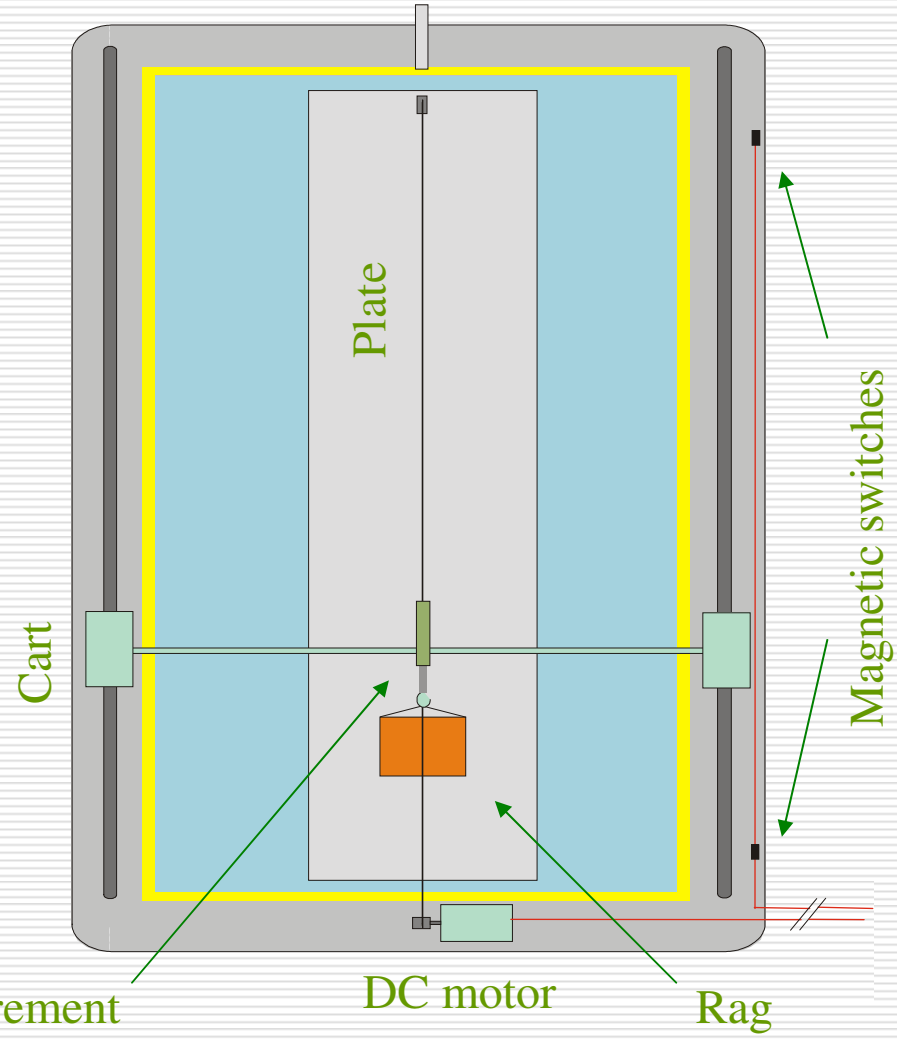


Setup

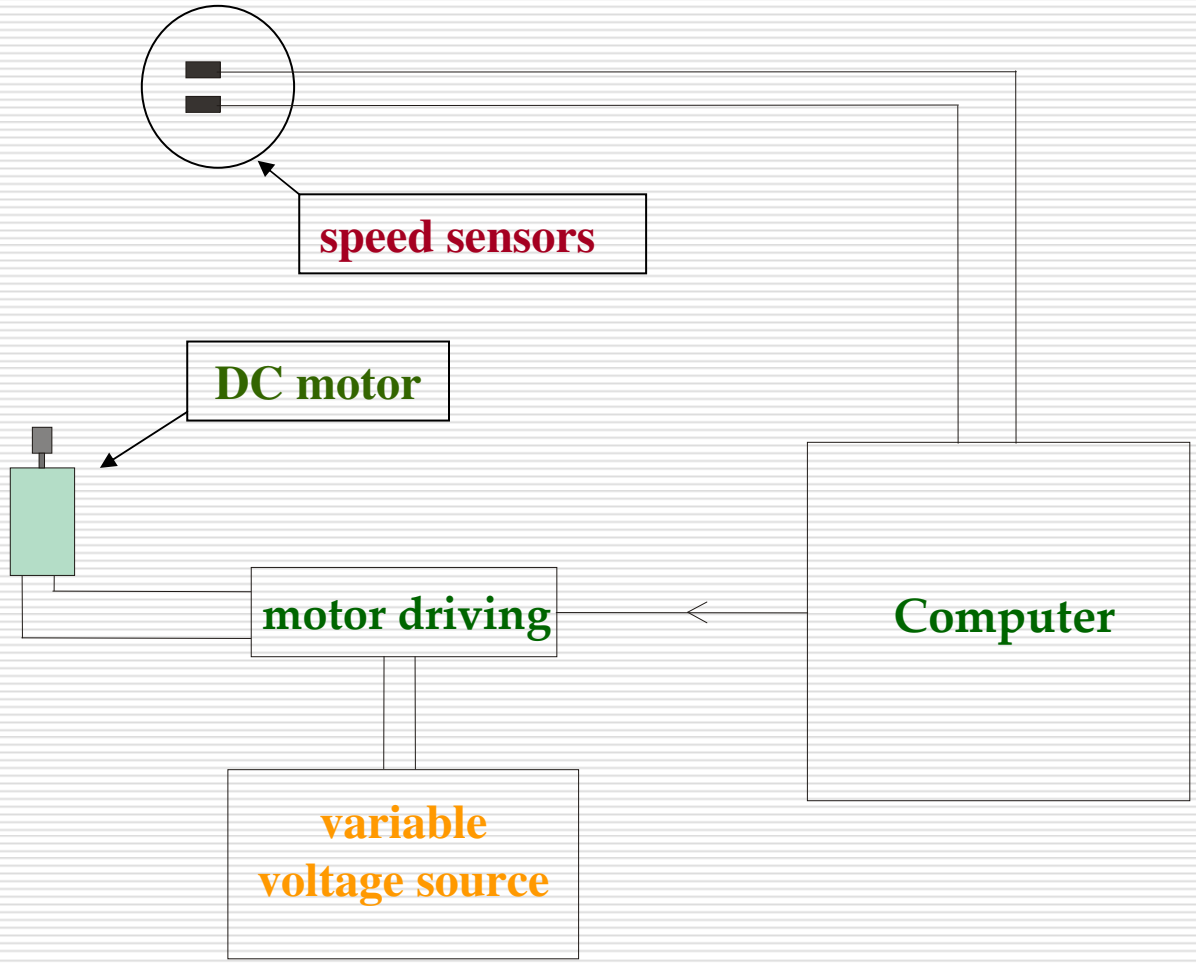
- Two setups:
  - Long translator and plate – for rag properties changing
  - Rotating drum – for velocity measurements and different rags
- Rag mass held constant – wetting after each measurement

Apparatus 1

- Translator system – rag dragging
- Dynamometer on rag cart to measure force
- Timer system – magnetic switches
- Computer controlled

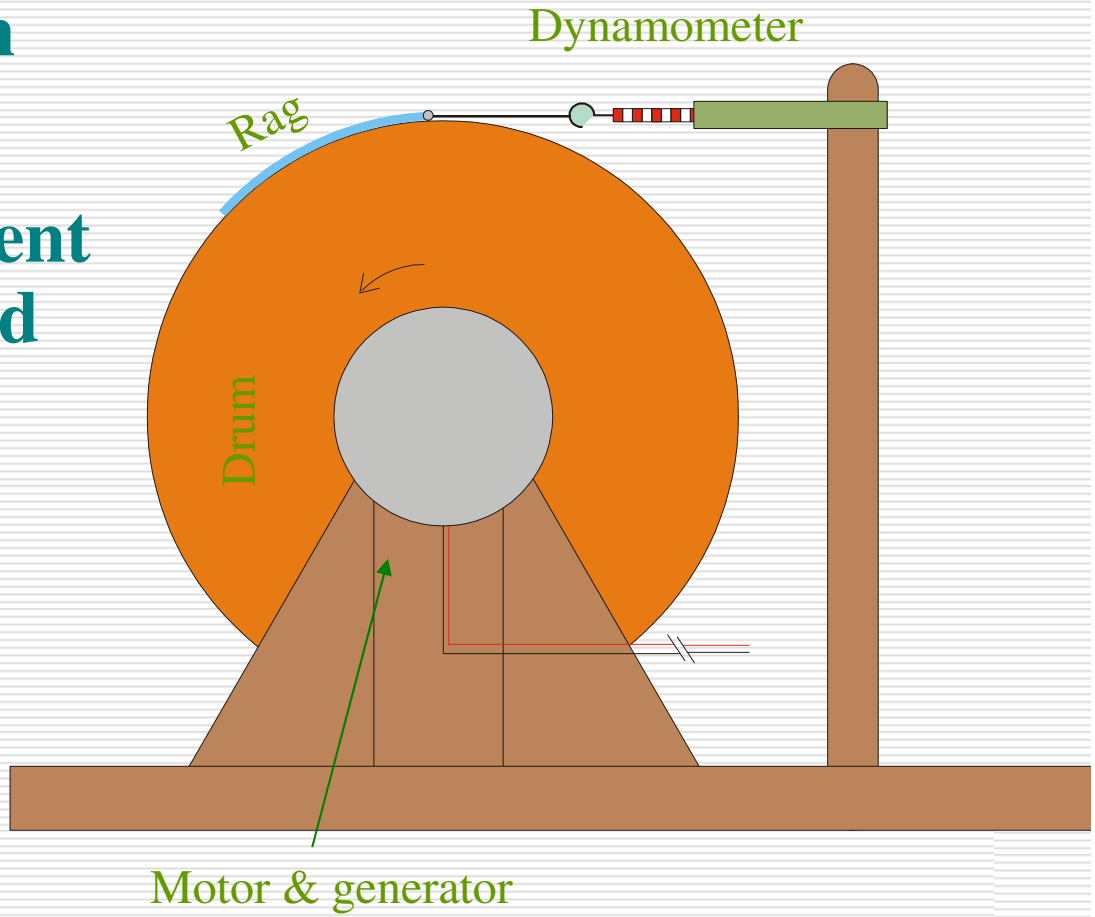


Apparatus 1

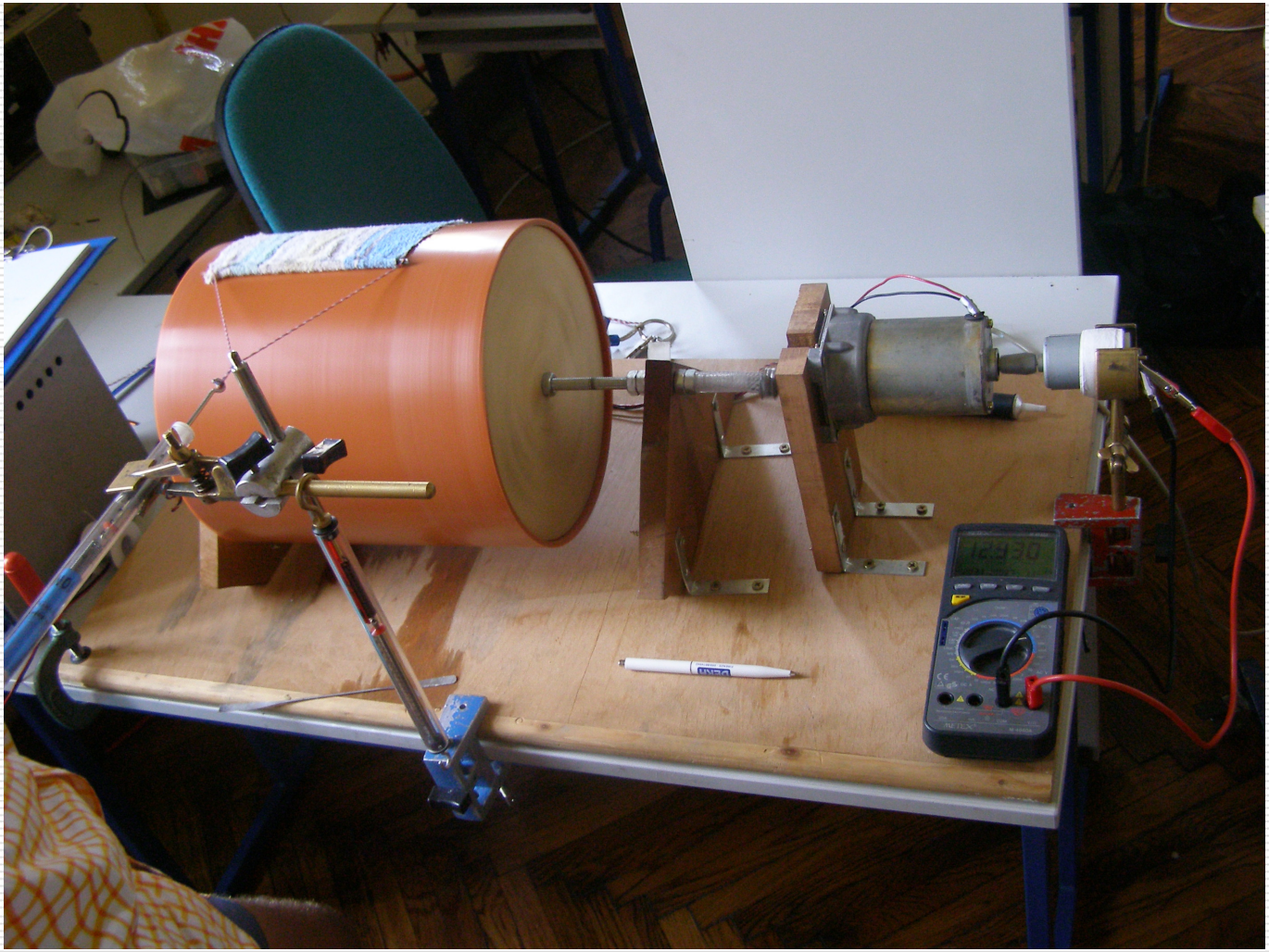

speed sensors
DC motor
motor driving
Computer
variable
voltage source

Apparatus 2

- Rotating drum with radius 12 cm
- Velocity measurement – generator attached to motor shaft
- Dynamometer tangential
- Stroboscope calibrated



Apparatus 2

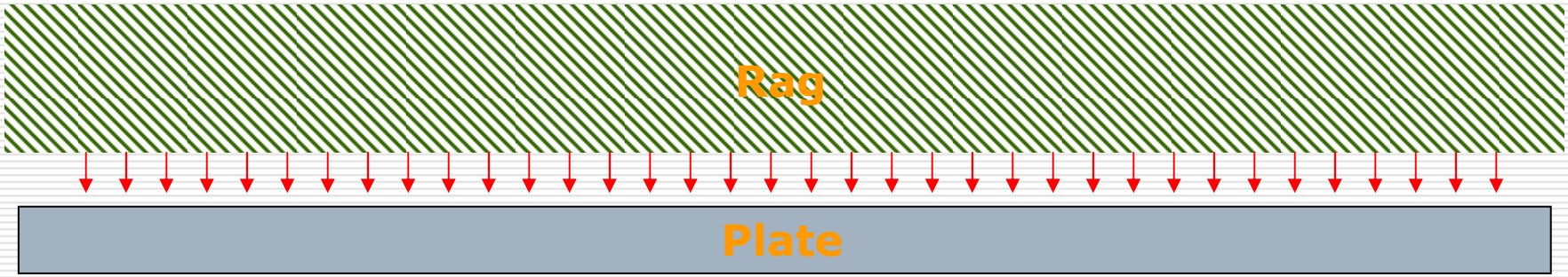


Explanation

- Two main effects:
  - Interfacial tension – adhesion and wetting
  - Viscous friction
- Adhesion – pulls wet rag fibers extremely close to ground
- Large velocity gradient in liquid – fiber layer
- Large viscous drag – effective resistive force

Interfacial force

- Interfacial force: intermolecular forces – electrostatic nature
- Downward force:



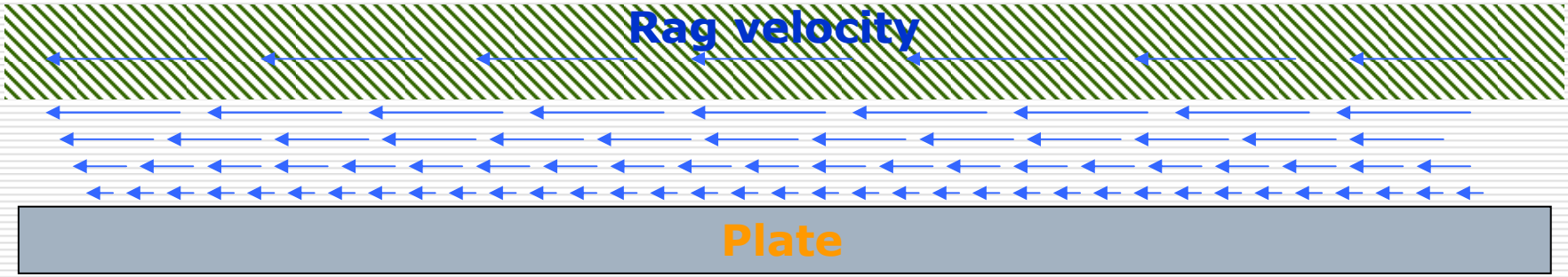
- Depends on:
  - Rag wettability/wettness
  - Plate properties

Interfacial force cont.

- Wetting – attraction between water molecules and hydrophylic solid
- Most fibers – wettable (cellulose derivatives, hydrophylic)
- Plate materials –
    - Most plastics – weak water adhesion
    - Glass, painted plastics – surface charge mobility, larger adhesion

Viscosity

- Viscous drag – due to velocity gradient in moving liquid
- Interfacial forces and gravity – pull fibers towards plate – very small distances
- On plate – no slip boundary condition due to adhesion
- Small distance – large gradient:



Viscosity cont.

- Rag – macroscopically nonhomogeneous surface
- Average distance from plate – fiber density dependent
- Viscous force:

$$\langle \mathbf{F}_v \rangle = \eta S_{eff} \left\langle \frac{d\mathbf{v}}{dz} \right\rangle$$

η – water viscosity

S_{eff} – effective rag surface in contact with plate

$\mathbf{v}$ – water velocity vector

z – vertical coordinate

- For small distances – gradient linearization

Viscosity cont.

$\Rightarrow$ **Spatially averaged force on rag:**

$$\langle \mathbf{F}_v \rangle \approx \eta S_{eff} \frac{V}{\langle h \rangle}$$

η – water viscosity

S_{eff} – effective rag surface in contact with plate

V – rag velocity

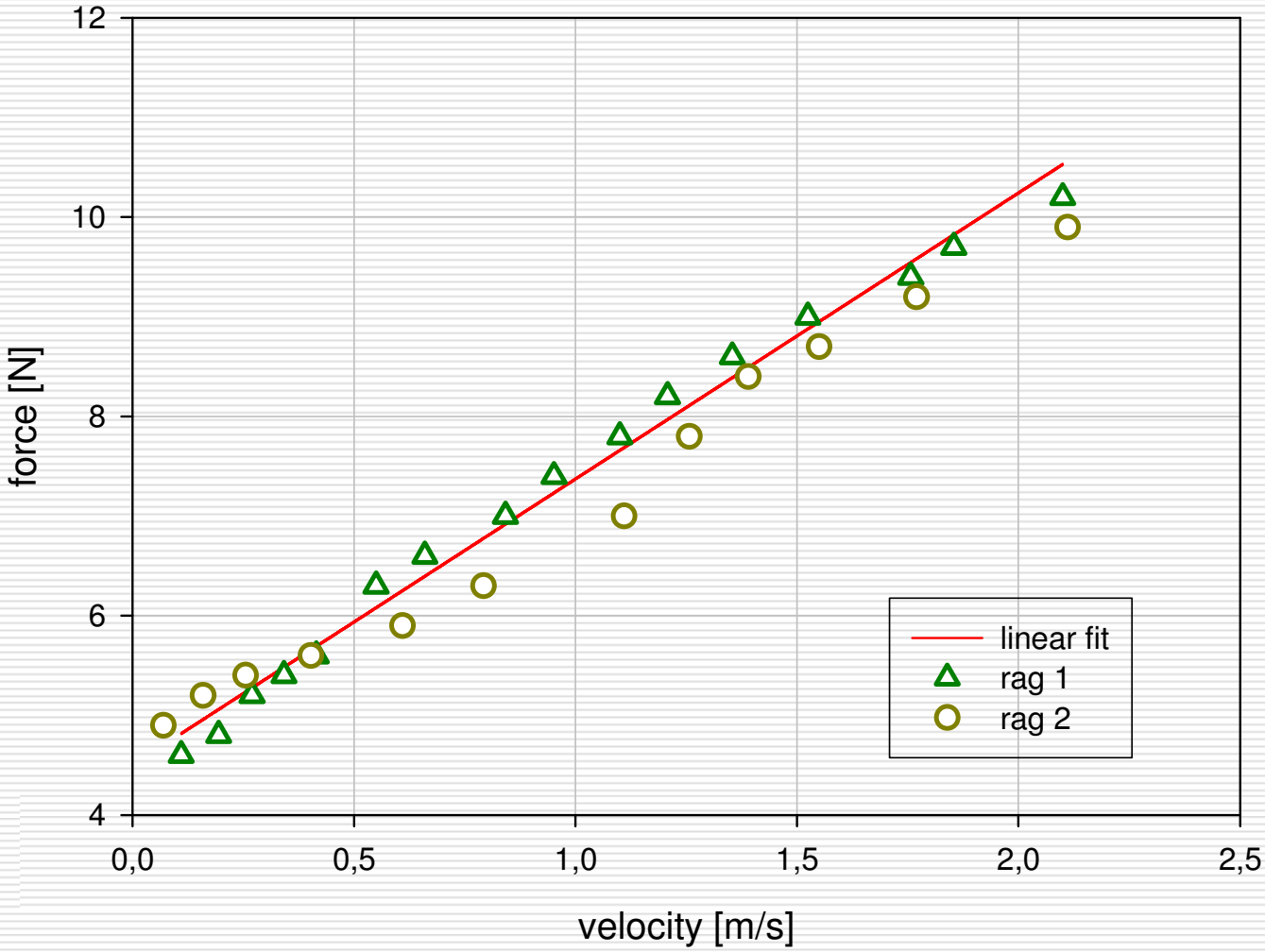
h – average distance from surface

- **Geometrical parameter $\frac{S_{eff}}{\langle h \rangle}$ depends on:**
  - **Rag mass**
  - **Rag water content**
  - **Interfacial tension**

Net horizontal force

- Two contributions:
  - Constant offset force – fiber attachment to surface due to intermolecular forces
  - Velocity – dependent viscous force
- Principal experimental tests:
  - Force - velocity dependence
  - Force – surface area dependence

Force - velocity



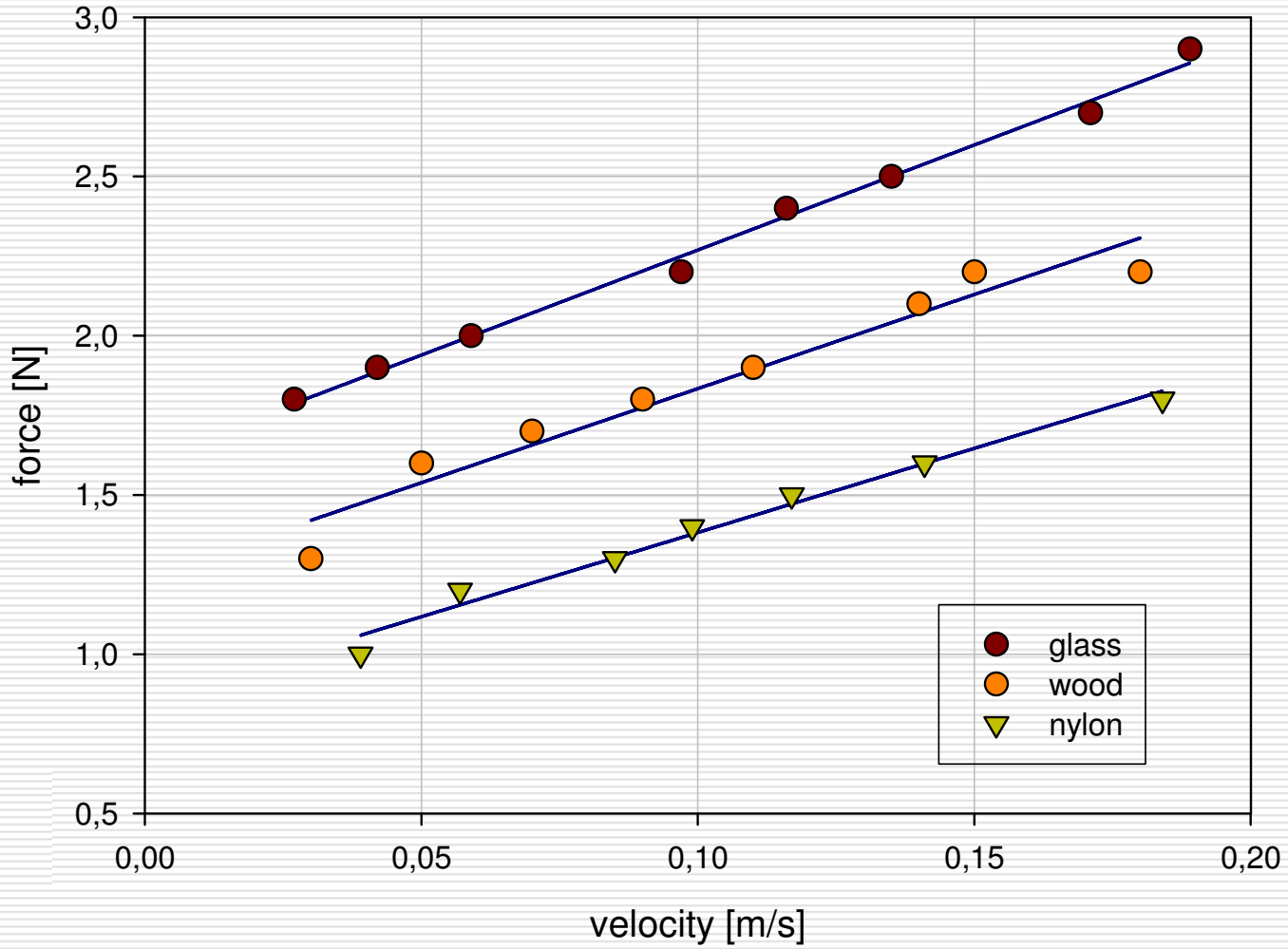
$S = 263\,\mathrm{cm}^2$

$m_{rag} = 53\,\mathrm{g}$

Surface – coloured plastic

$\langle h \rangle = 1.1 \cdot 10^{-5}\ \mathrm{m}$

Force – velocity cont.



$S = 177\ \mathrm{cm}^2$

$m_{rag} = 26\ \mathrm{g}$

Glass:

$\langle h \rangle = 1.0 \cdot 10^{-5}\ \mathrm{m}$

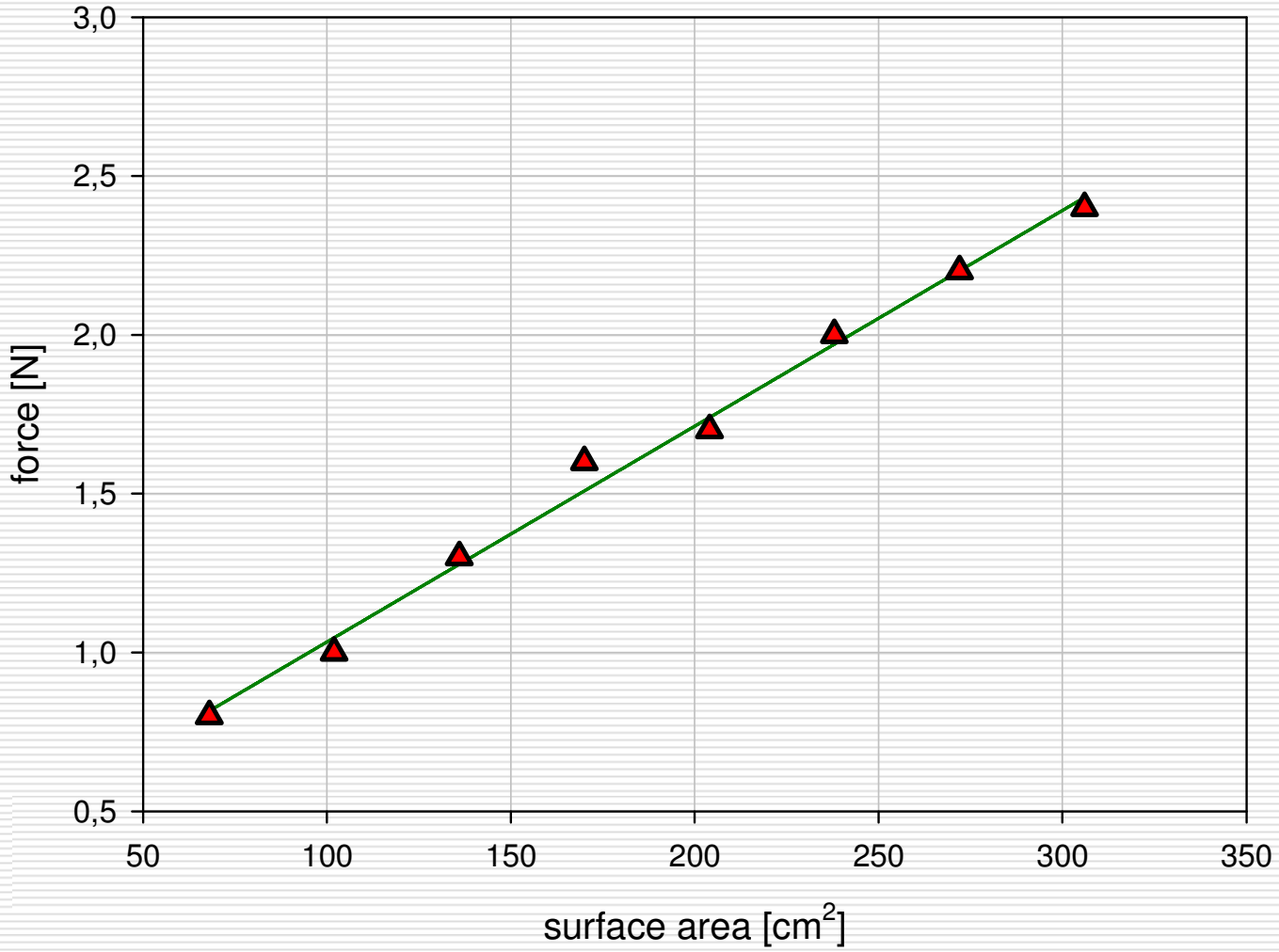
Wood:

$\langle h \rangle = 1.2 \cdot 10^{-5}\ \mathrm{m}$

Nylon:

$\langle h \rangle = 1.4 \cdot 10^{-5}\ \mathrm{m}$

Force - area



$V = 0.3\ \mathrm{m/s}$

$m_{rag} = 26\ \mathrm{g}$

Surface – wood

$\langle h \rangle = 1.2 \cdot 10^{-5}\ \mathrm{m}$

Comparison

- Force dependence forms correctly anticipated
- Average distances:
  - Meaningful values (from microscopical investigations)
  - Similar in both measurements
- For two rags – same force! => effective surface area not strongly rag surface structure dependent
- On hydrophobic surfaces – average height larger as expected

Other parameters

- **Rag mass – simplest superstition:**
  - **Average rag – plate distance inversely proportional to mass:**

$$\langle \mathbf{F}_v \rangle = \eta S_{eff} M_{rag} \frac{V}{\langle \tilde{h} \rangle}$$

η – water viscosity

S_{eff} – effective rag surface in contact with plate

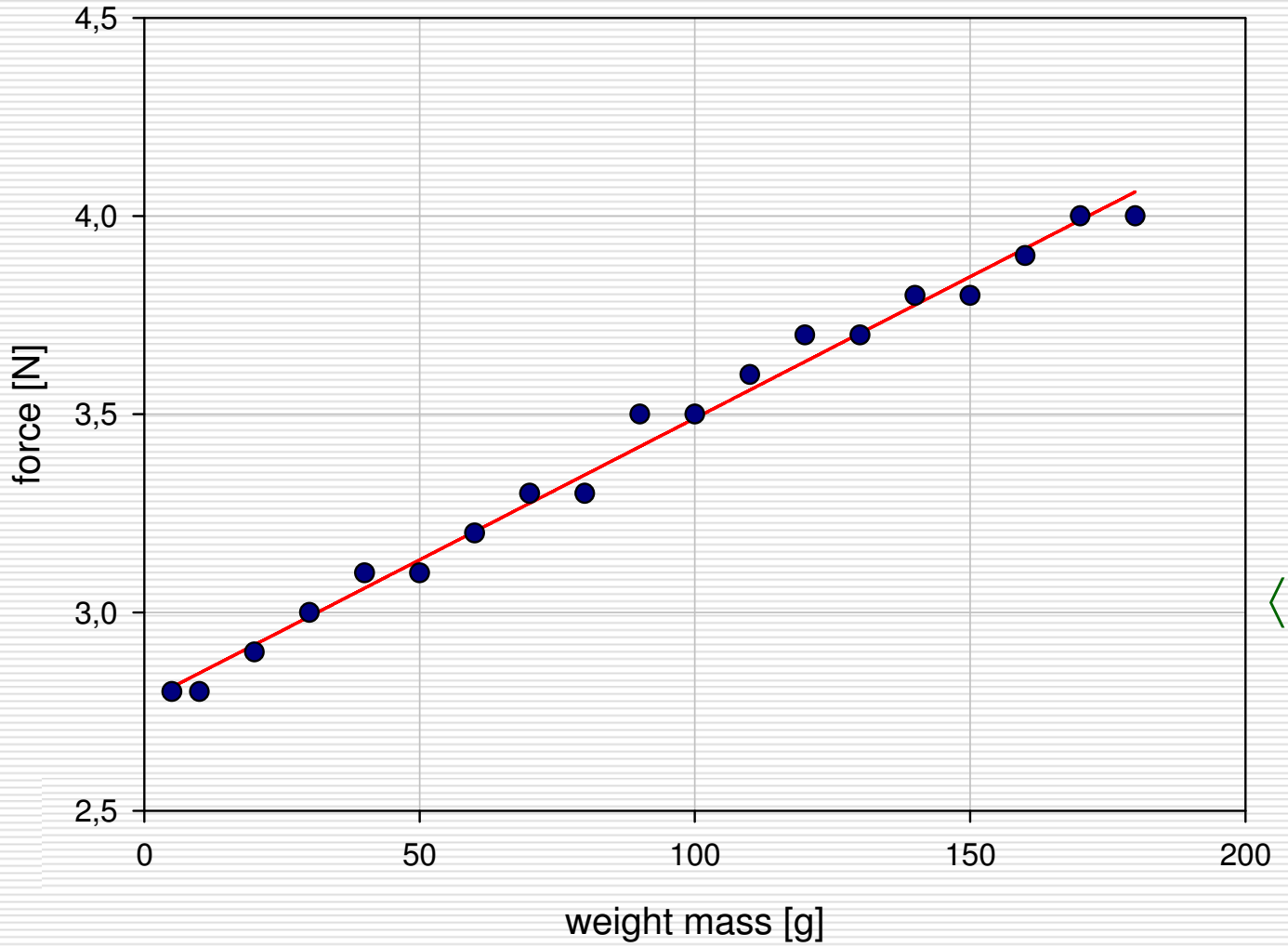
V – rag velocity

M_{rag} – net rag mass

h – reduced distance

- **Experimentally confirmed:**

Other parameters cont.



$S = 150\,\mathrm{cm}^2$

$V = 0.3\,\mathrm{m/s}$

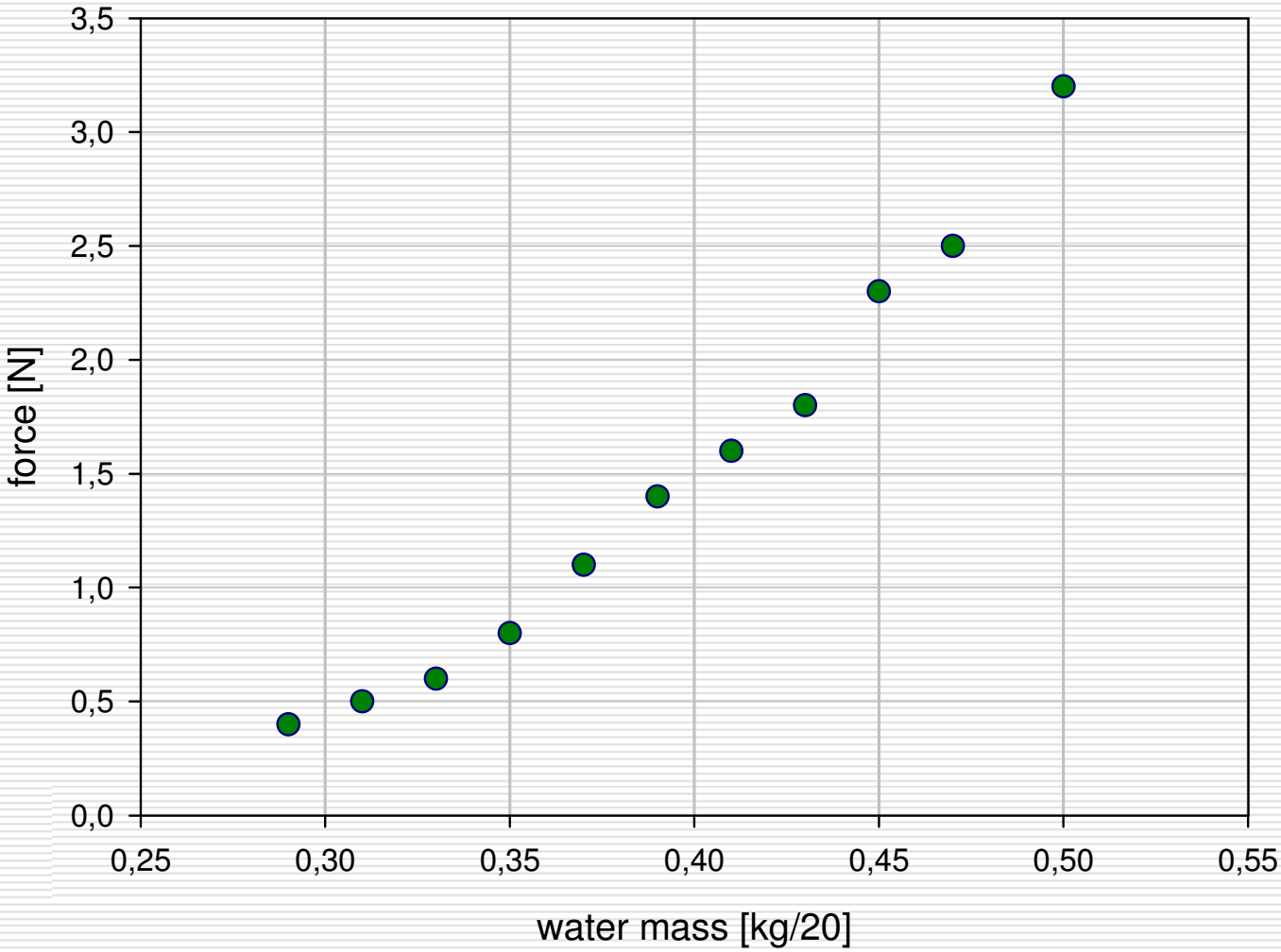
Surface – coloured plastic

$\langle \tilde{h} \rangle = 3.2 \cdot 10^{-5}\ \mathrm{m/kg}$

Other parameters cont.

- Dependence on water weight in rag – two influences:
  - Mass increase
  - Larger water content – larger adhesion area
- Force dependence:
  - Linear component – at high water content
  - Steeper growth at smaller water content
- Experimentally confirmed:

Other parameters cont.



$S = 150\,\mathrm{cm}^2$

$V = 0.3\,\mathrm{m/s}$

Surface – coloured plastic

Conclusion

- bvc