Tribological model system testing of cocoa mass samples with different particle size distributions

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Background and motivation: Food processing, structure and mouthfeel

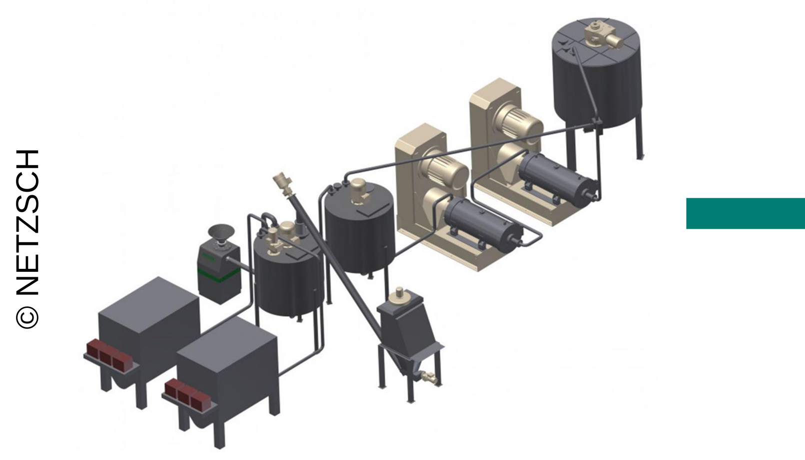

Fig. 1 Model of a confectionery mass production line

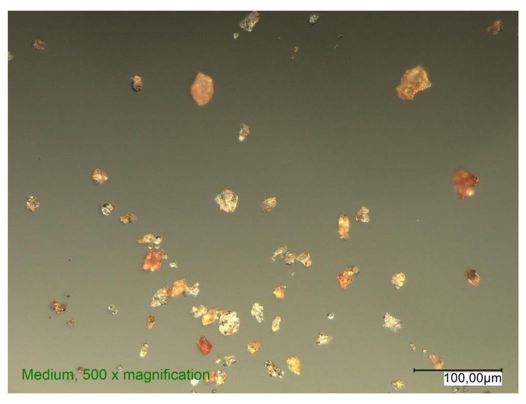
Fig. 2 Light microscopy image of cocoa mass particles

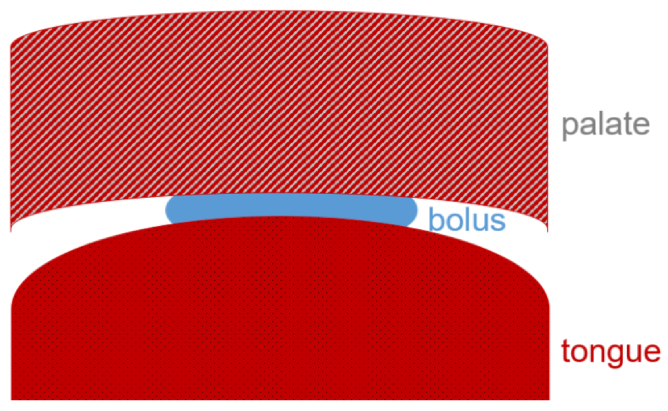

Fig. 3 Real-world tribosystem schematic

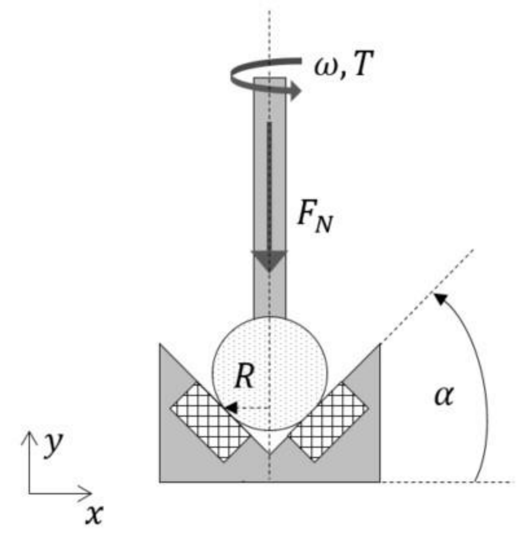

Fig. 4 Model tribosystem schematic

- Cocoa mass is a key component in many confectionery and chocolate products
- Wet grinding is a unit operation in cocoa mass processing
- Cocoa mass wet grinding yields particle size reduction

- Ground cocoa mass consists of particles which differ, e.g. in shape and size
- Wet grinding can also increase the free fat in the cocoa mass

- During food oral processing, the food material is mixed with saliva
- Tribological behavior of the tongue-bolus-palate tribosystem contributes to the mouthfeel
- The food structure and structural changes during food oral processing change the tribosystem behavior

- The real world tribosystem can be represented by tribological model systems with soft specimen
- Model system testing provides insights into the interrelationship between food structure and tribosystem behavior

Cocoa mass: Structure, rheology and tribological testing

Cocoa mass structure

- The same cocoa mass sample was used for every step of the characterization
- Sample was obtained by wet grinding on a horizontal disk mill
- Light microscopy pictures of the cocoa mass particles were taken on a Keyence VHX reflected light microscope equipped with a VH-Z500R objective (Keyence, Osaka Japan) after fat removal using acetone. An example picture can be seen in Fig. 2.
- The cocoa mass samples varied in particle size distribution. The volume equivalence diameter $d_{90,3}$ from laser diffraction measurements based on the Fraunhofer scattering model carried out on a Mastersizer 3000 with wet dispersion unit (Malvern Panalytical, Malvern, United Kingdom) with synthetic mineral oil are shown in Fig. 6.

Cocoa mass rheology

- Viscosity curve measurements were carried out at 40°C using a concentric cylinder measuring geometry on a Kinexus Prime ultra+ rotational rheometer (NETZSCH-Gerätebau GmbH, Selb, Germany).
- A logarithmic shear rate table from 1 s^{-1} to 50 s^{-1} was carried out after pre-shearing the sample at 5 s^{-1} for 2 minutes.
- Shear viscosity data was fitted to the Herschel-Bulkley model $\tau = \tau_0 + K\dot{\gamma}^n$ with the shear stress τ, the yield stress τ_0, the consistency index K, the shear rate $\dot{\gamma}$ and the flow index n. The fitted parameters are shown in Table 1.

Table 1 Herschel-Bulkley fit parameters of tested cocoa mass samples

Sample	τ_0 [Pa]	K [Pa s^n]	n
Coarse $d_{90,3}$ = 33 µm	2.55	2.36	0.951
Medium $d_{90,3}$ = 26 µm	3.88	1.85	0.969
Fine $d_{90,3}$ = 20 µm	3.30	1.55	0.960

Tribological testing

- Testing at model scale was carried out at 40°C using a ball-on-three-pins tribology cell on a Kinexus Prime ultra+ rheometer and a Peltier-plate cartridge (NETZSCH-Gerätebau GmbH, Selb, Germany).
- The ball, 12.7 mm in diameter, was made of borosilicate glass.
- The pins were made of SIL 30 silicone urethane elastomer (Carbon Inc., Redwood City, USA) and were declined at 45°.
- Stribeck curves and extended Stribeck curve measurements (see also Pondicherry et al. 2018) were carried out with a minimum sliding speed of $2.25\cdot10^{-8}$ m·s^{-1} and a maximum sliding speed of $4.5\cdot10^{-1}$ m·s^{-1} and a constant normal force of 1 N after running-in at 15 rad·s^{-1} during 10 min and a 5 min holding phase (see Fig. 5) (Rummel et al. 2023).

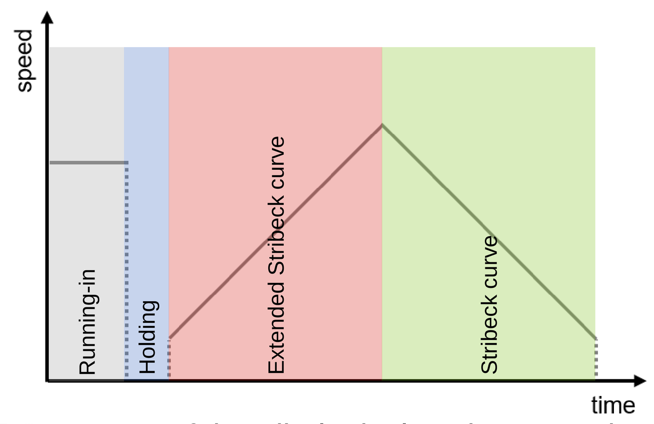

Fig. 5 Sequence of the tribological testing procedure

Stribeck curves, extended Stribeck curves and discussion

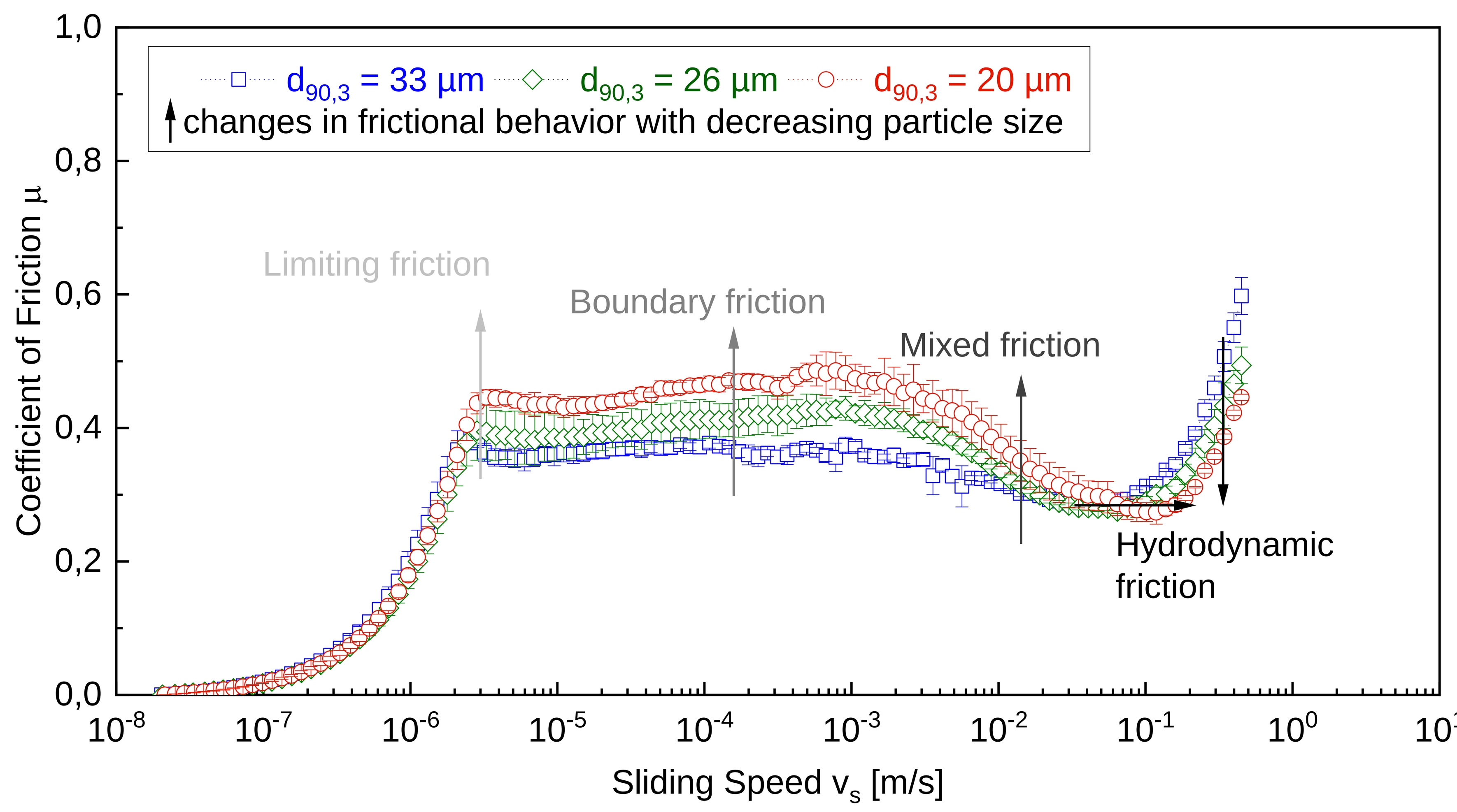

Fig. 6 Extended Stribeck curves for cocoa mass samples with different particle size distributions

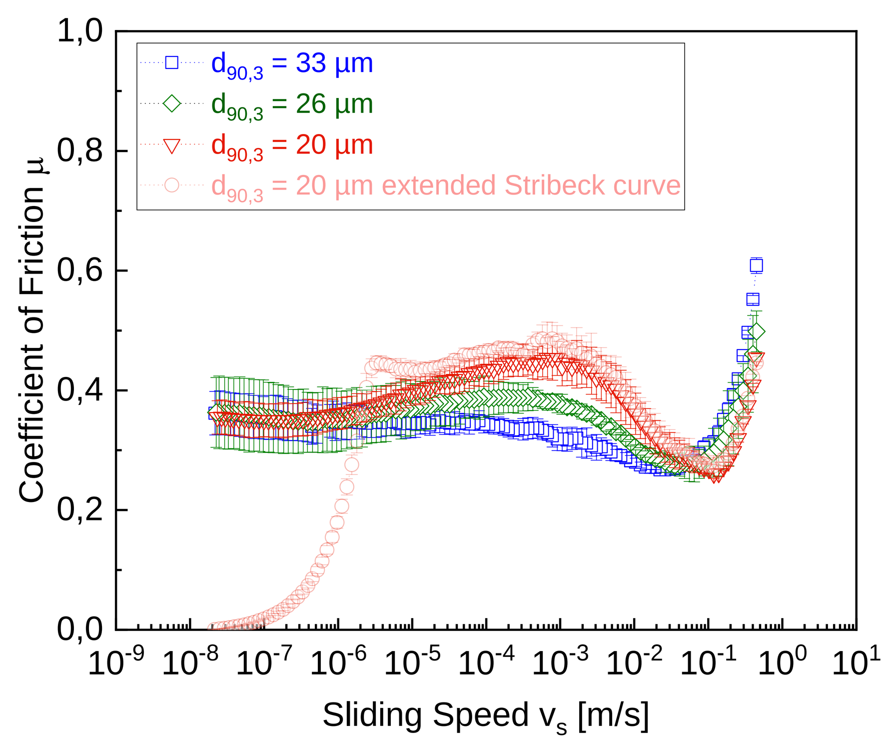

Fig. 7 Stribeck curves for cocoa mass samples with different particle size distributions

Extended Stribeck curves

- Results from extended Stribeck curve measurements are shown in Fig. 6.
- The limiting friction is highest for the fine cocoa mass sample.
- After overcoming the limiting friction, the fine cocoa mass sample curve shows highest friction and the coarse cocoa mass sample exhibits the lowest friction.
- The friction in hydrodynamic regime is highest for coarse cocoa mass sample and lowest for the fine cocoa mass sample.

Stribeck curves

- Results from Stribeck curve measurements are shown in Fig. 7.
- In the mixed friction regime and the hydrodynamic regime, the observed frictional behavior is similar to what was found in the extended Stribeck curve measurements.
- A local maximum in friction at intermediate speed (10^{-3} m/s) can be seen for the fine cocoa mass sample.
- In the boundary friction regime, the curves for all three samples overlap.

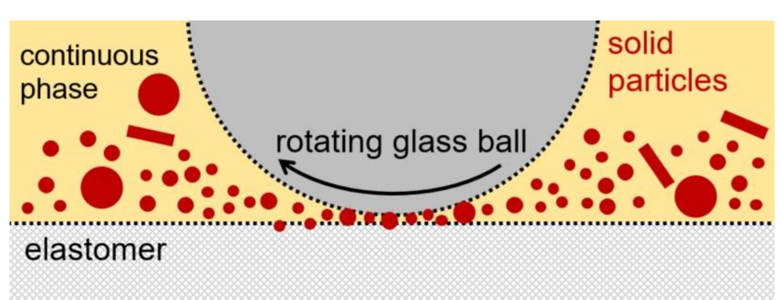

Fig. 8 Schematic of possible lubrication mechanisms

Possible lubrication mechanisms

Fig. 8 supports the understanding of the lubrications mechanisms explained in the following.

1. Coarse particles acting as rollers (Rudge et al. 2020)
2. Coarse particles too big to enter the tribocontact
3. Non-spherical particles sterically hindered from entering the tribocontact
4. Small particles sticking to the glass surface
5. Small particles adhering to the soft elastomer surface (Lee et al. 2004)
6. High numbers of particles causing increased interactions and interlocking. Small particles do not separate the specimen surfaces effectively (see also Rummel et al. 2023)

References

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