Correlations between Rheological Properties and Meltdown Behavior of Ice Cream

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Why is important?

Melting Behavior

- Sensory Methods
- Physical Methods

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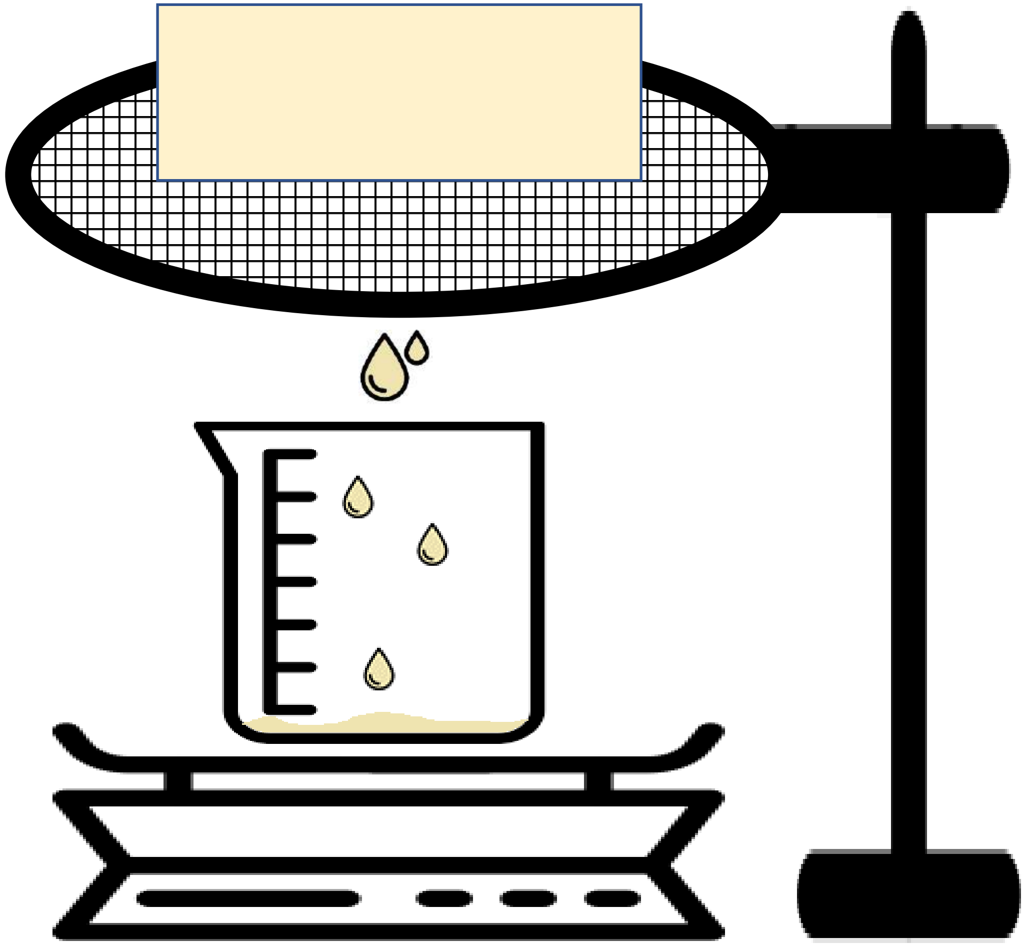
Meltdown Test



Meltdown Properties

Rheological Properties

Experimental Design

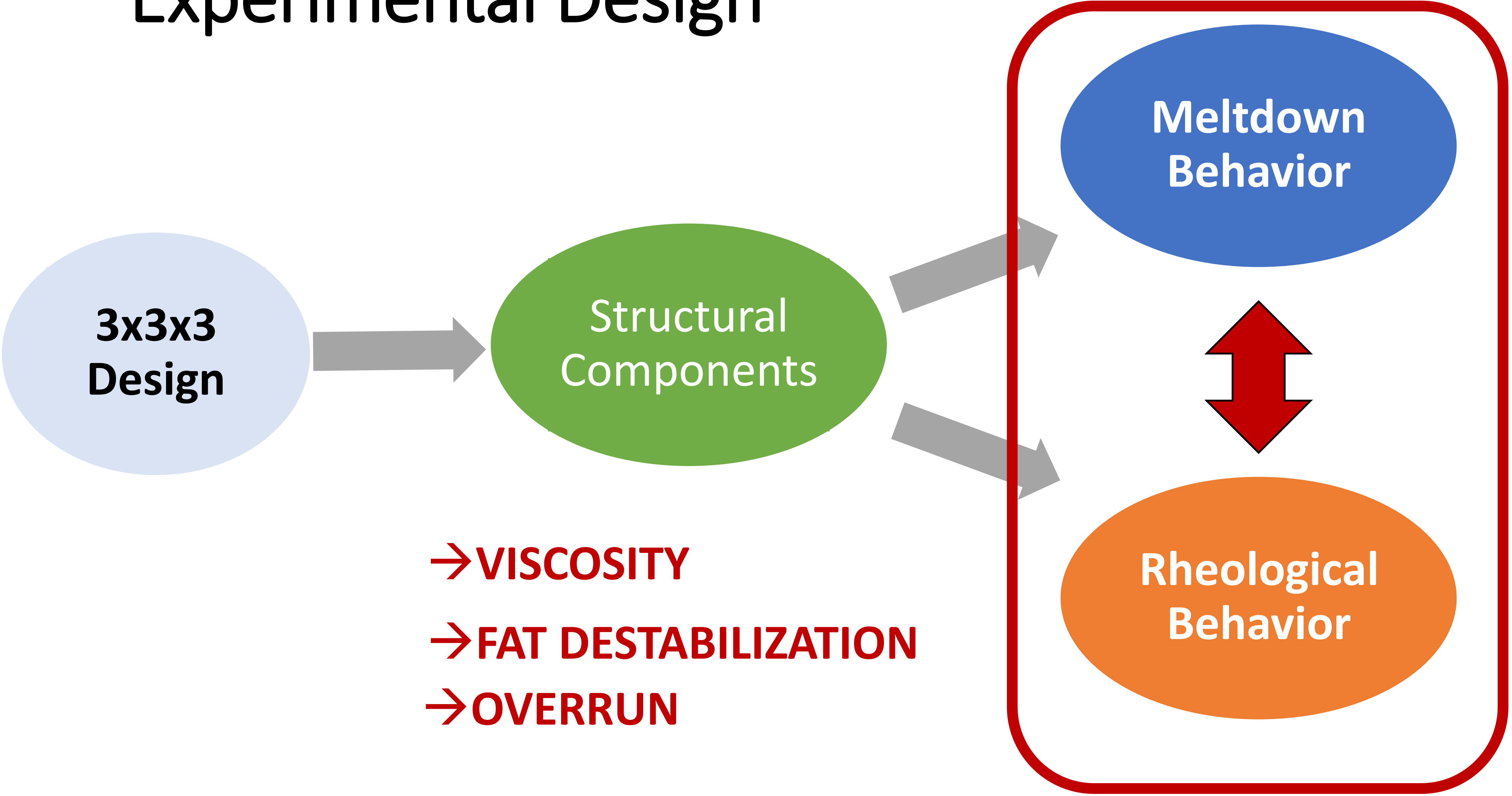
Serum Phase
- Stabilizer: 0, 0.2 and 0.4%

Fat Phase
- PS80: 0, 0.015 and 0.03%

Air Phase
- Target OR: 50, 75 and 100%

3x3x3 Design

Experimental Design



→VISCOSITY

→FAT DESTABILIZATION

→OVERRUN

Material and Methods

Formulation

- 12% milk fat, 11.3% MSNF, 16.9% sucrose, 0.15% MDG

➔PS80: from 0 to 0.03%

➔Stabilizer: from 0 to 0.4%

~40.5% TS and -2.72 ± 0.06°C

Processing

Manual mode / 500RPM / constant pump ratio (1.0±0.0)
Air flow of 2, 3 and 4 gal.h^{-1}

Material and Methods – Structural components

→Mix viscosity at 50s-1

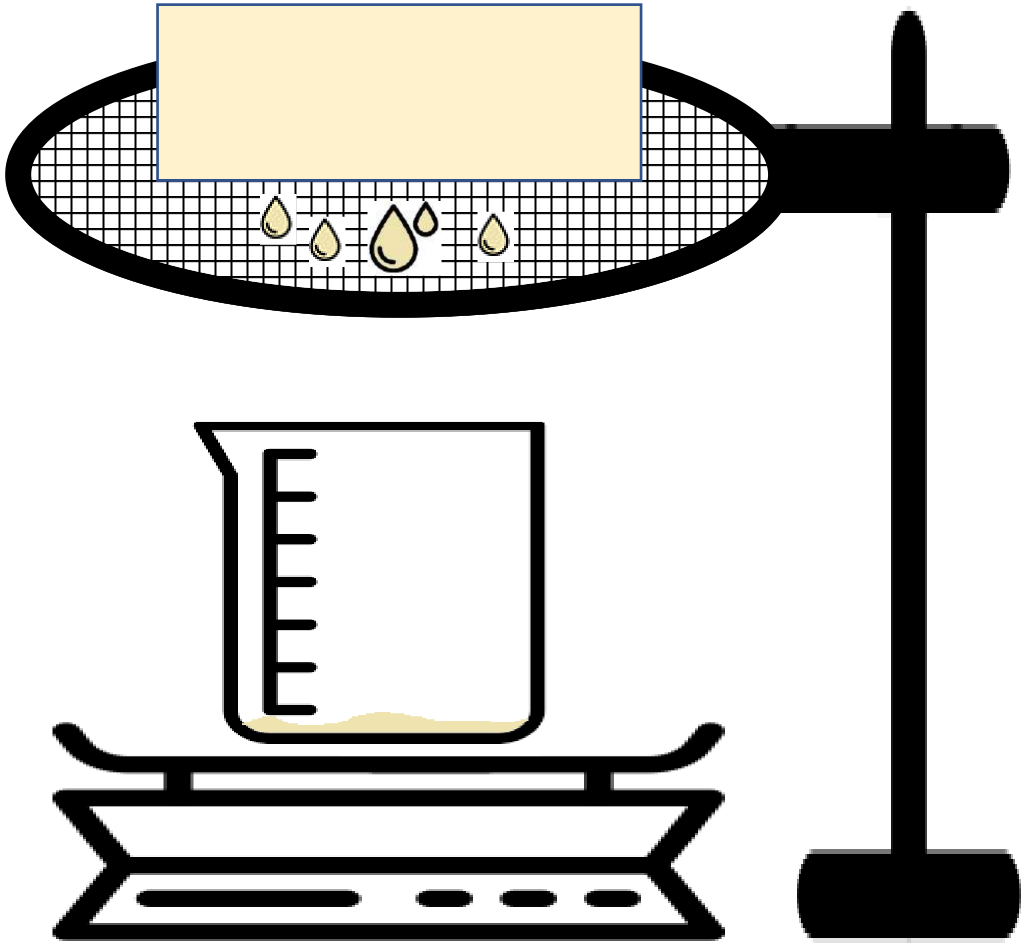
→Fat destabilization

→Overrun

→Air cell size distribution

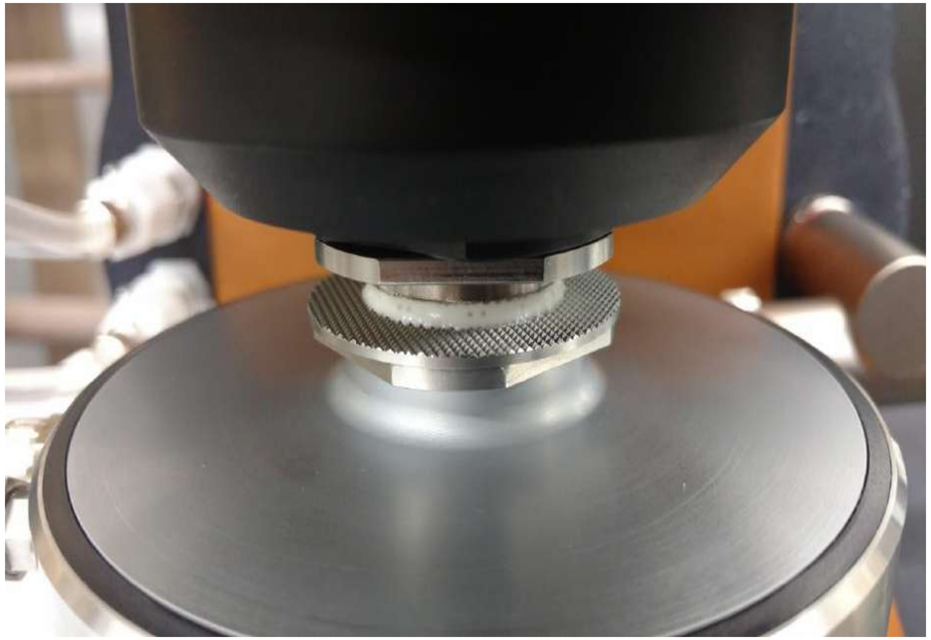
→Ice crystal size distribution

Methods – Meltdown Measurements



- Induction time (min)
- Drip-through rate (DT)
- Final drip-through weight (%) - after 360 minutes
- Height-change rate (cm/min)
- Final height (FH) - after 360 minutes

Methods – Rheological Measurements

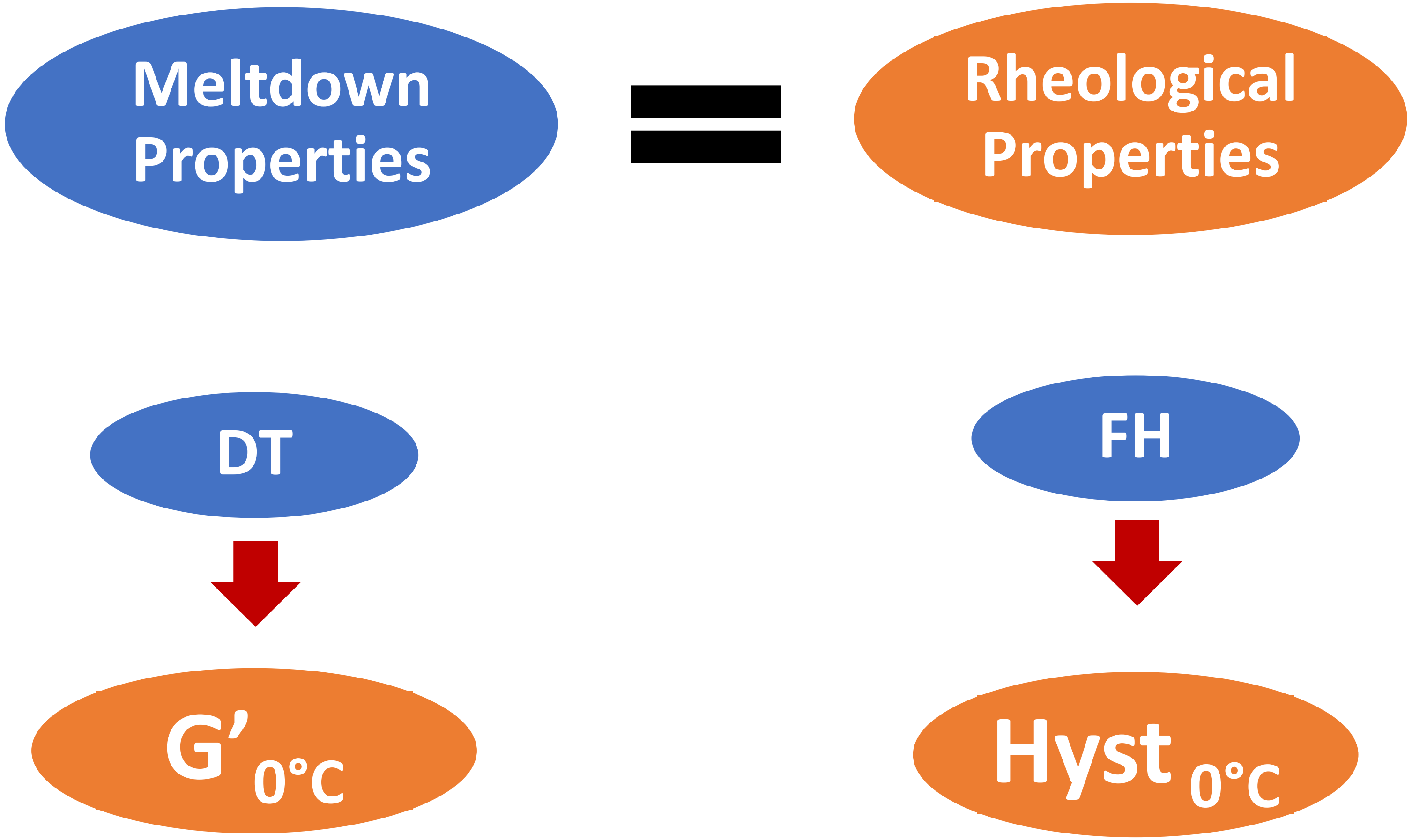


- **Oscillatory Thermo-Rheometry** (OTR) from -15 to 25°C
- **Creep and Recovery** Test at 0°C
- **Stress Growth** Test at 0°C
- **Flow Ramp** Test at 0°C

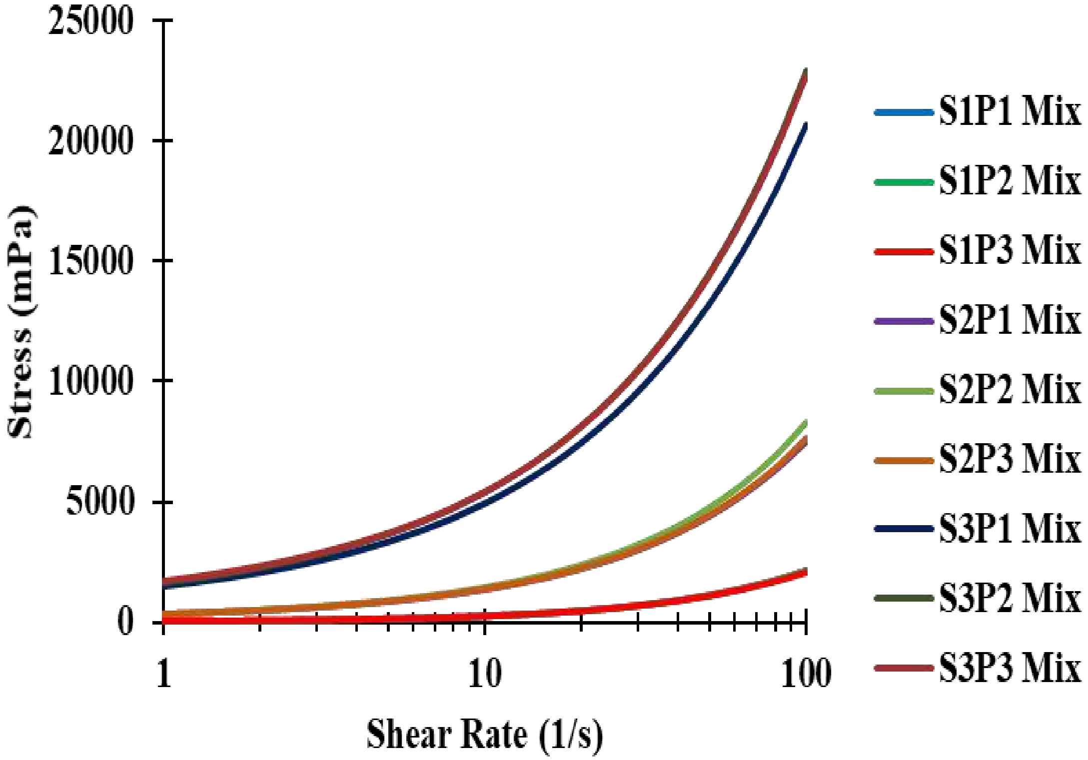
Wildmoser et al. (2004); Granger et al. (2005); Steffe (1996); Dogan et al. (2013); Elliott and Ganz (1977); Rao (2007)

Data Analysis

- **Nonlinear regressions**



Structural Components - Mix Rheology



↑ mix viscosity (serum phase viscosity)

shear thinning behavior more pronounced

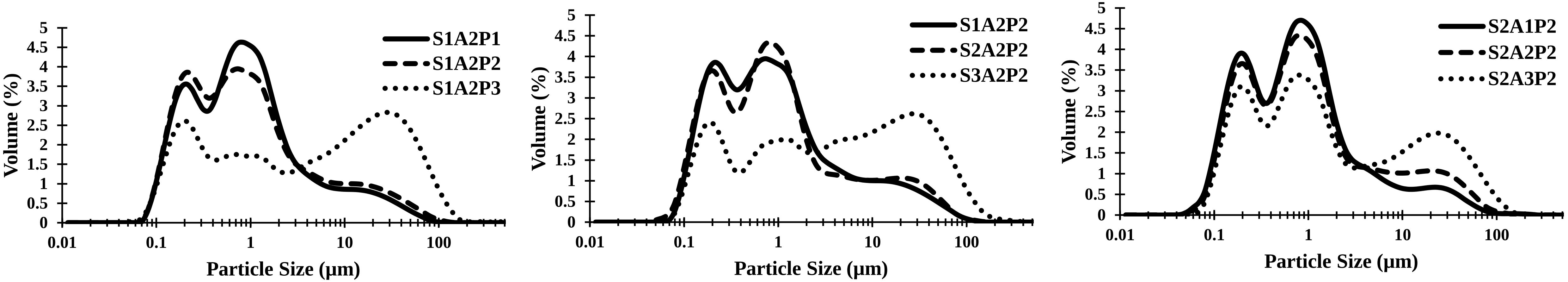
↑ elastic behavior

0.4% stabilizer formed weak gel (G’>G”)

Structural Components - Overrun

Air Flow	Target Overrun
$8 L*h^{-1}$	50.2±0.2%
$11 L*h^{-1}$	75.1±0.2%
$15 L*h^{-1}$	99.6±0.2%

Structural Components - Extent of fat destabilization



(A) (B) (C)

Figure 2.1: Particle size distributions for samples: (A) with different levels of PS80 (P1, P2 and P3 refer to 0, 0.015 and 0.03%, respectively)…; (B) with different levels of stabilizer (S1, S2 and S3 refer to 0, 0.2 and 0.4%, respectively)…; (C) with different levels of target overrun (A1, A2 and A3 refer to 50, 75 and 100%, respectively)...

Structural Components - Air Cell Size*

Air Cell Size*

↓ Air cell size

↑ Overrun

↑ Fat destabilization

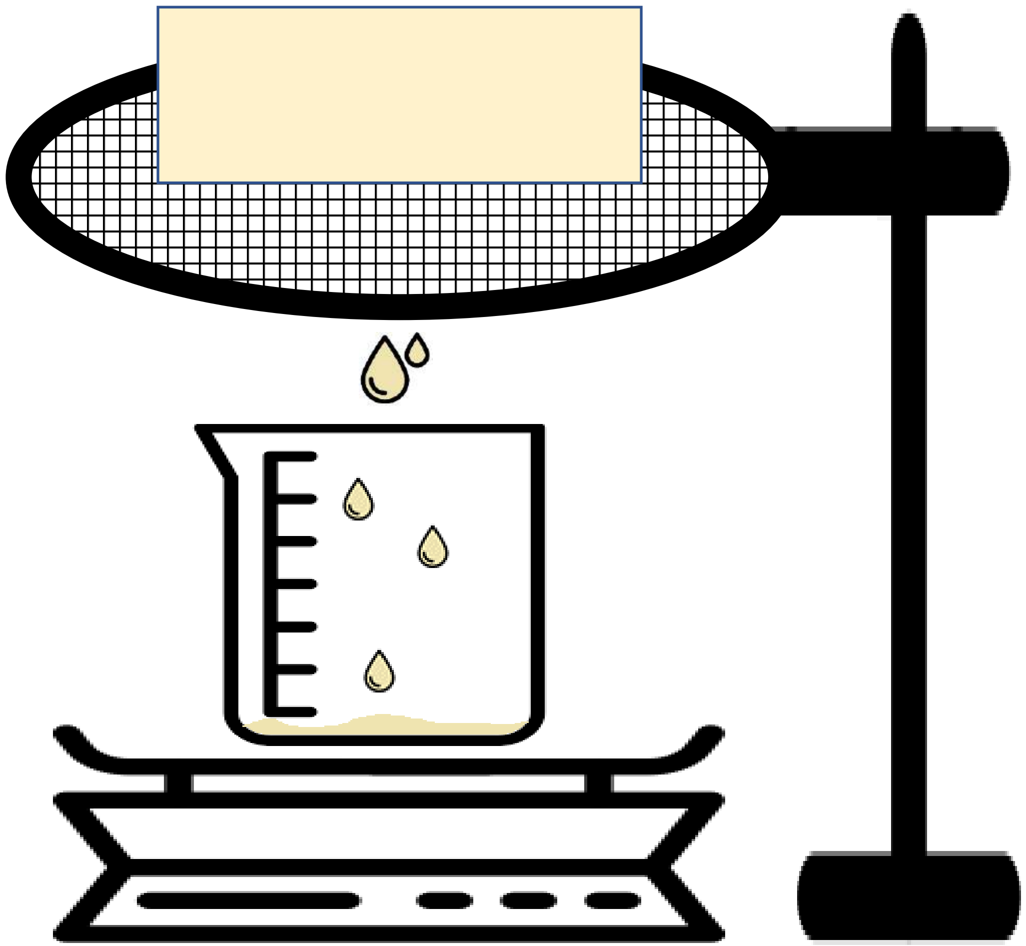
Slight differences in mix viscosity (Amador et al., 2017)

Ice Crystal Size*

Only slight differences were found for the mean ice crystal size

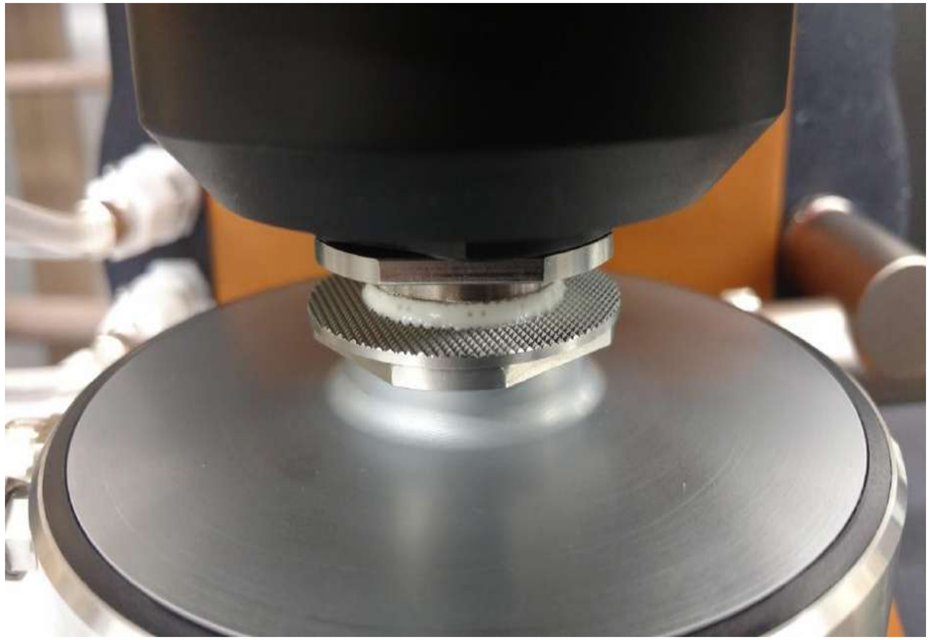
*Variables were not used to build MLR models

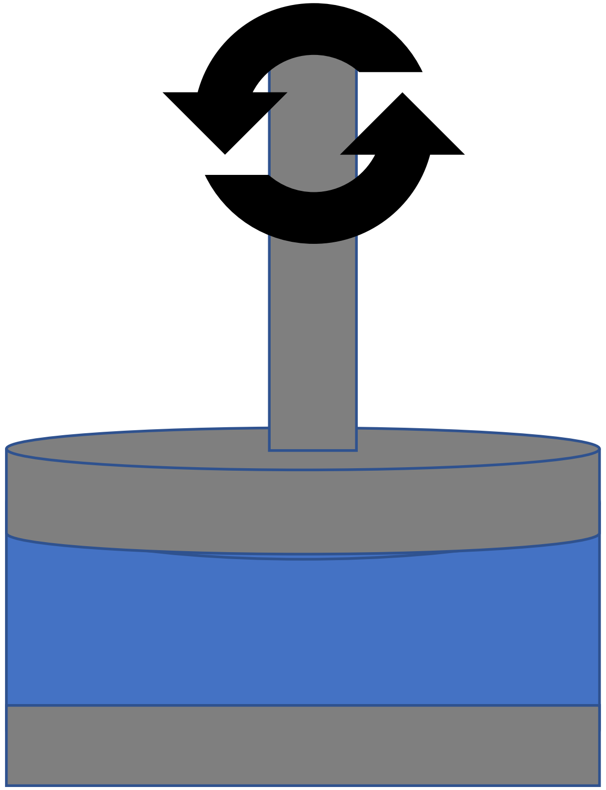
Meltdown Measurements – DT and FH



- DT or FH ➔ Visc and FD
  - Inverse and direct correlations ➔ DT and FH
- Overrun ➔ DT or FH
  - No stabilizer added
- Inverse correlation ➔ overrun and DT
  - direct relationship ➔ overrun and FH.

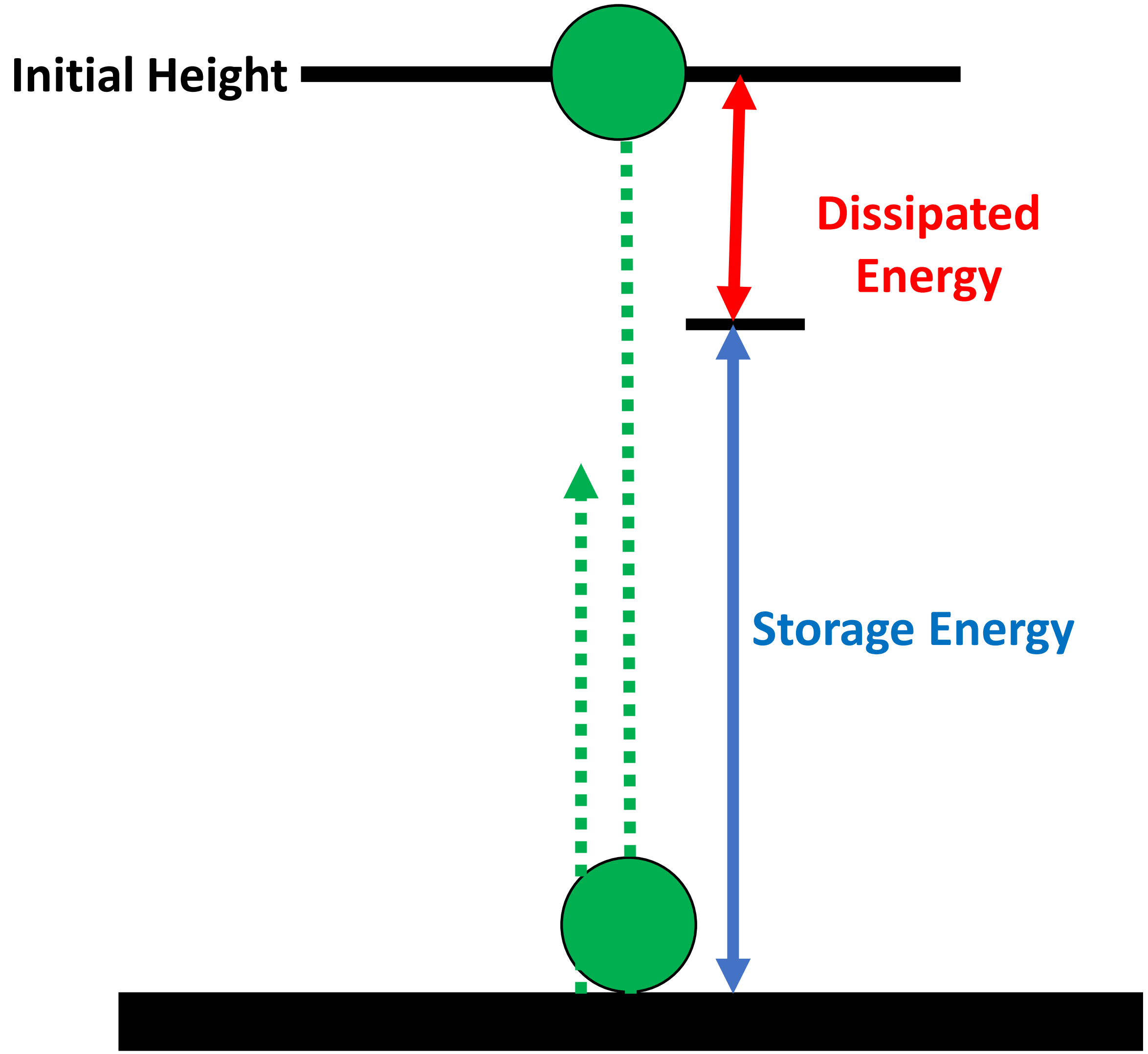
Rheological Measurements – OTR from -15 to 25°C





Wildmoser et al. (2004); Granger et al. (2005)

Oscillatory thermo-rheometry (OTR)



- Storage modulus (G')
- Loss modulus (G")
- Tan (delta) = G"/G'

Rheological Measurements – G'$_{0°C}$ from OTR

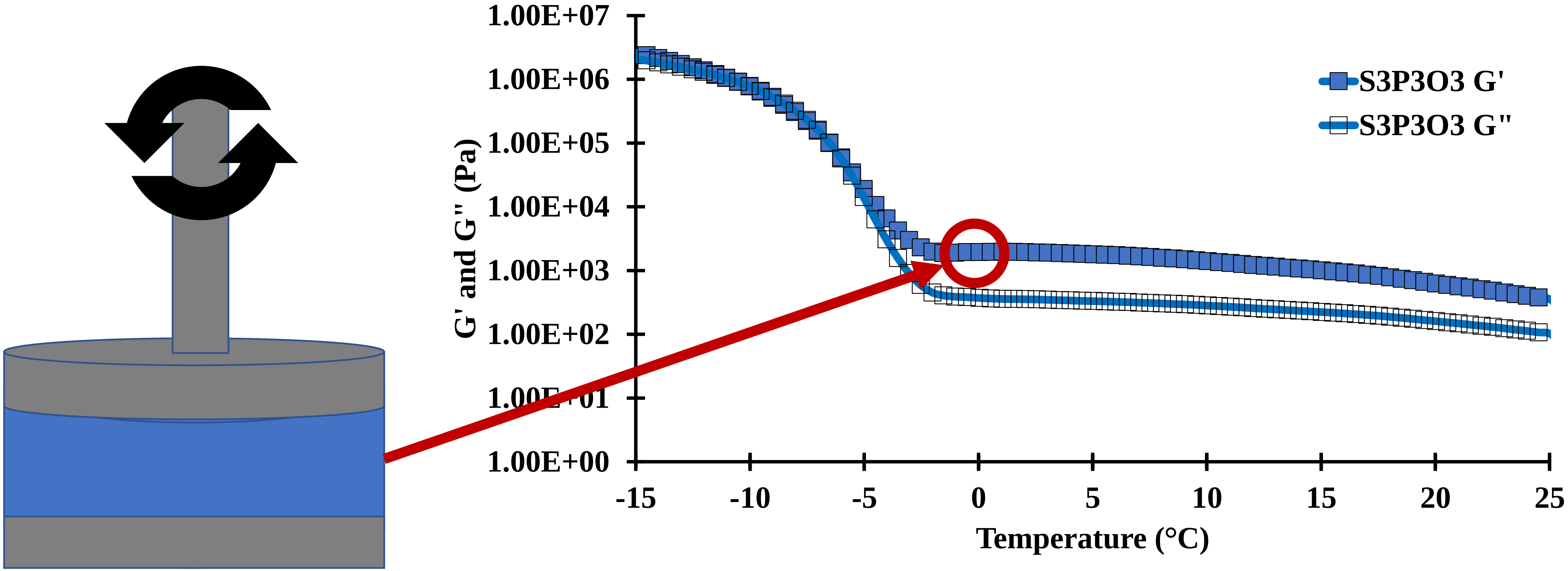
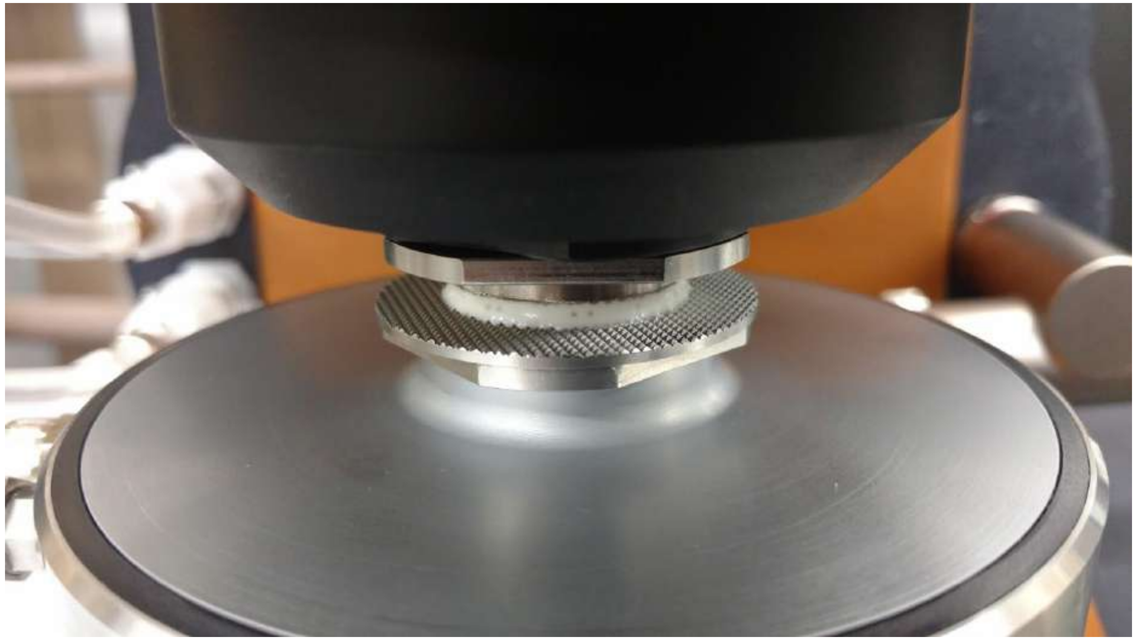


Figure 2.2A Behavior of (a) storage modulus, G', and loss modulus, G", from -15 to 25°C during oscillatory thermo-rheometry of sample S3P3O3.

Wildmoser et al. (2004); Granger et al. (2005)

Rheological Measurements – $G'_{0°C}$



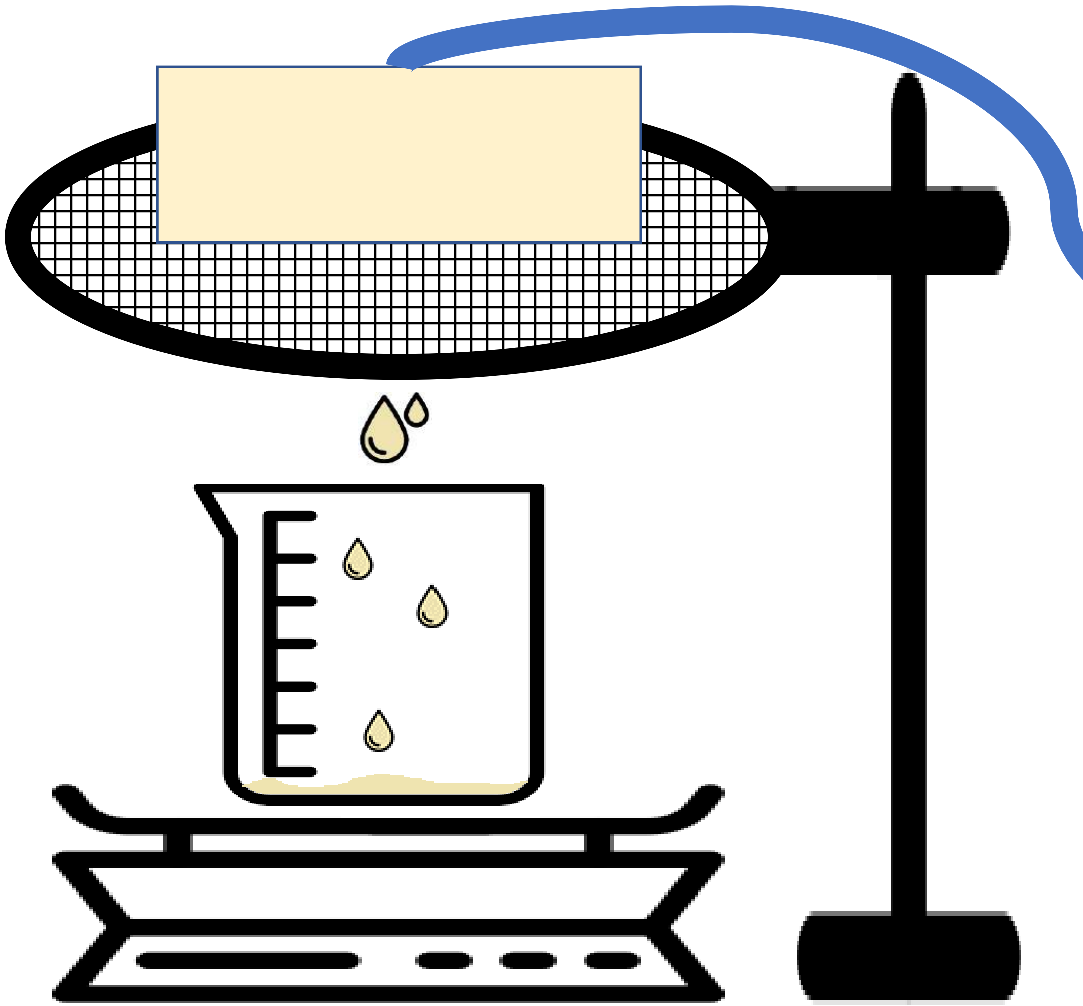
- $G'_{0°C}$ → elastic behavior

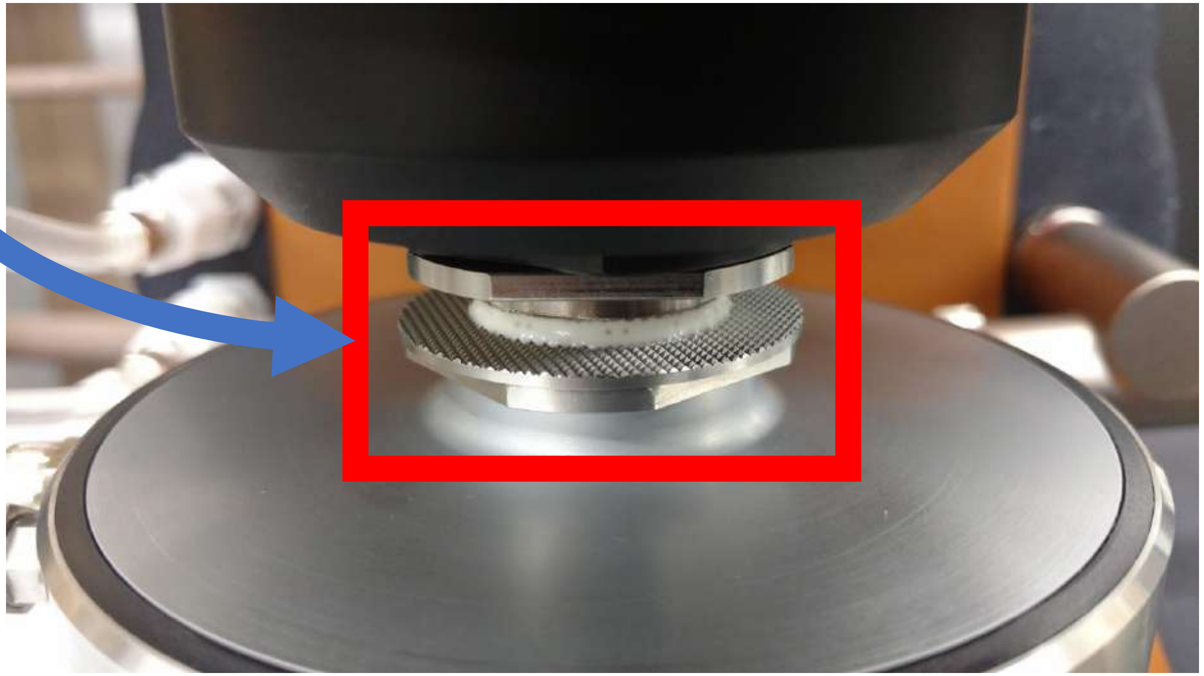
- Direct correlations:

Visc, FD or OR ⟺ $G'_{0°C}$

FD → OR → Visc

Correlations between Rheology and Meltdown Behavior





$$DT = a + b \cdot \exp(c \cdot Rheological\ Parameter)$$

$$FH = a + b \cdot \exp(c \cdot Rheological\ Parameter)$$

Correlations between $G'_{0°C}$ and DT → $R^2 = 0.73$

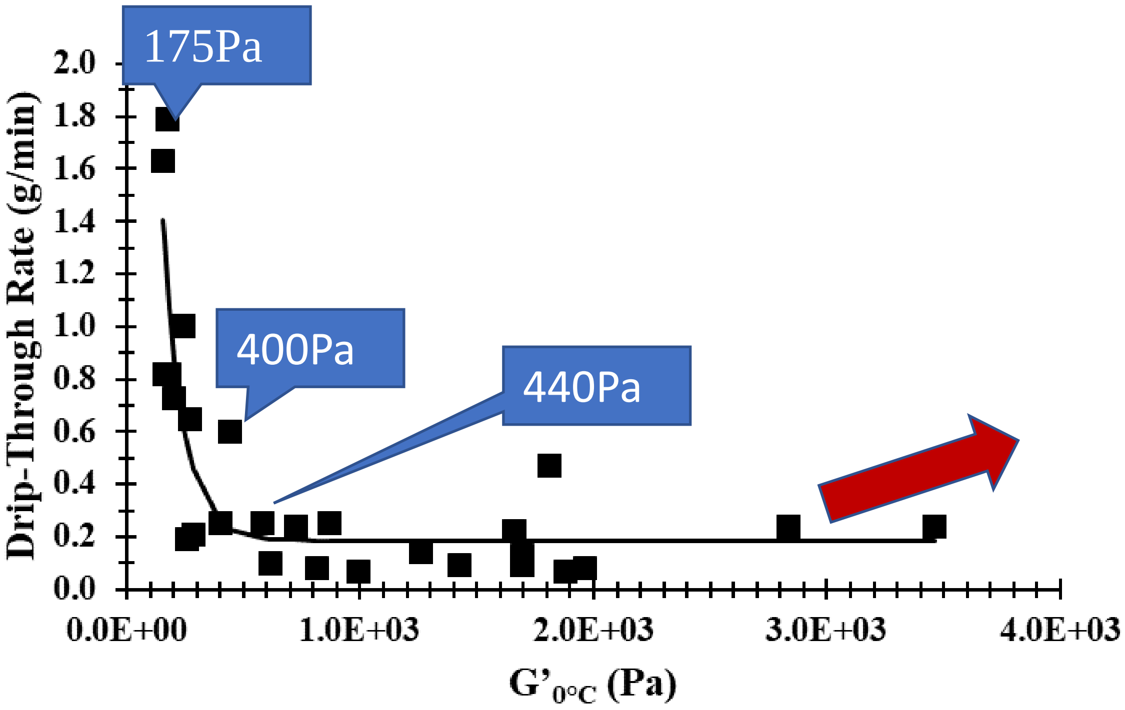
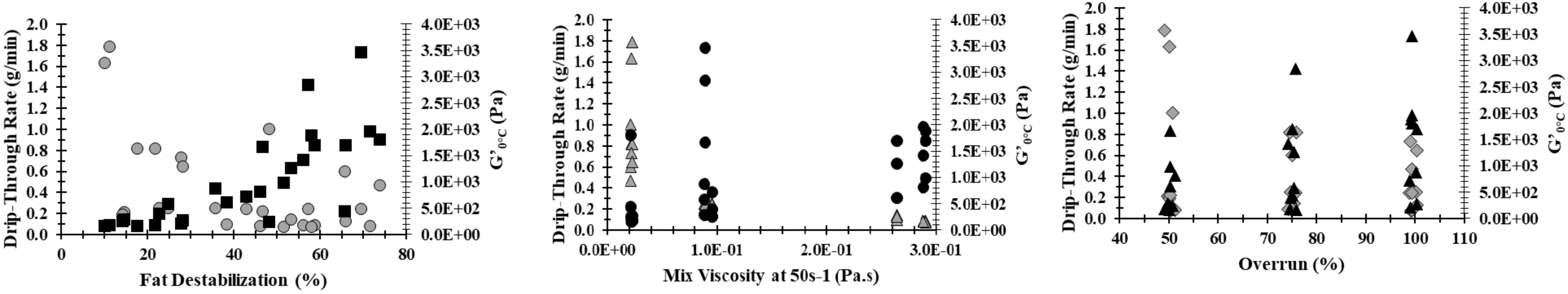


Figure 3.1 Behavior of storage modulus ($G'_{0°C}$) versus drip-through rate (DT) for samples with controlled serum phase viscosity, overrun and extent of fat destabilization [Data compiled from Wu et al. (2019) and Chapter 2]. Line is fitted exponential model.

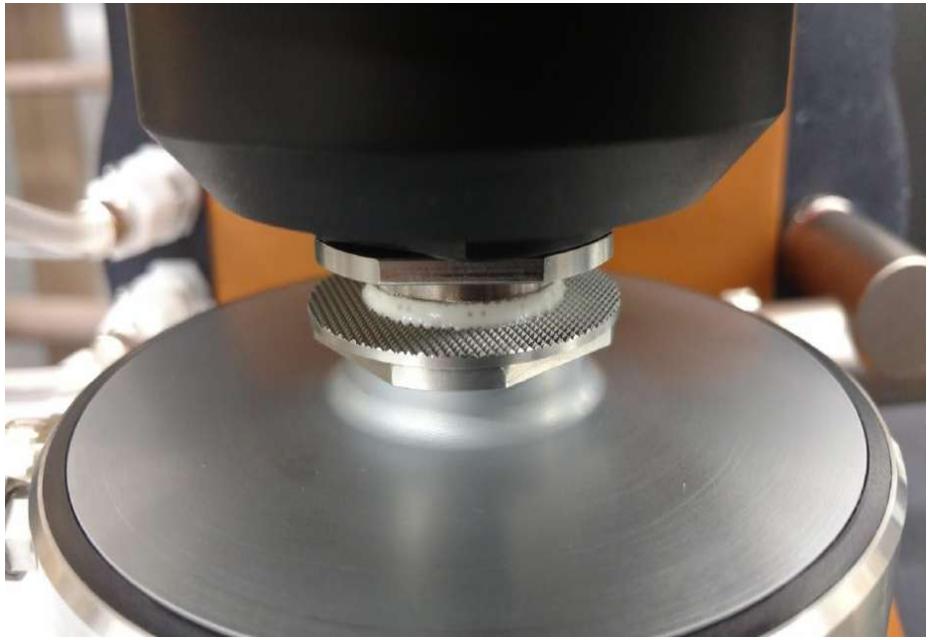
Correlations between G’$_{0°C}$ and DT

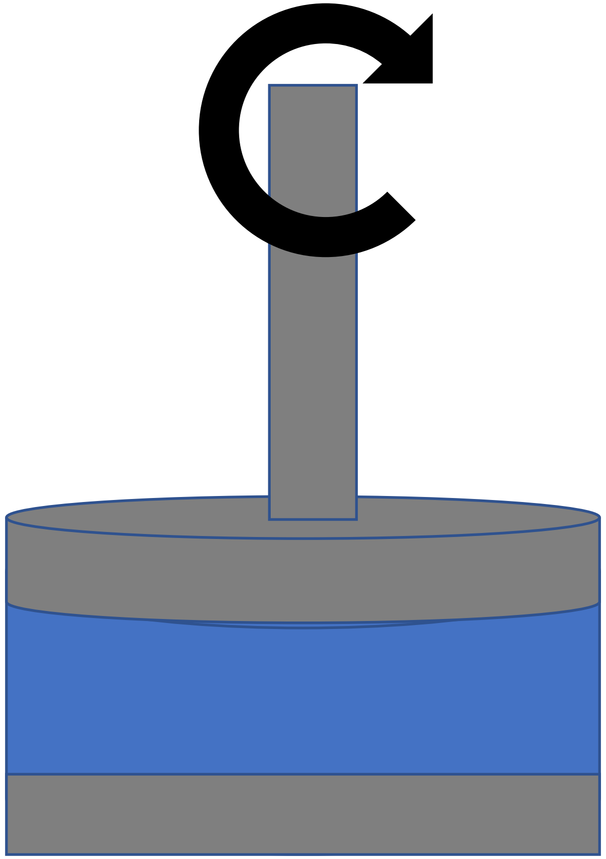


(A) (B) (C)

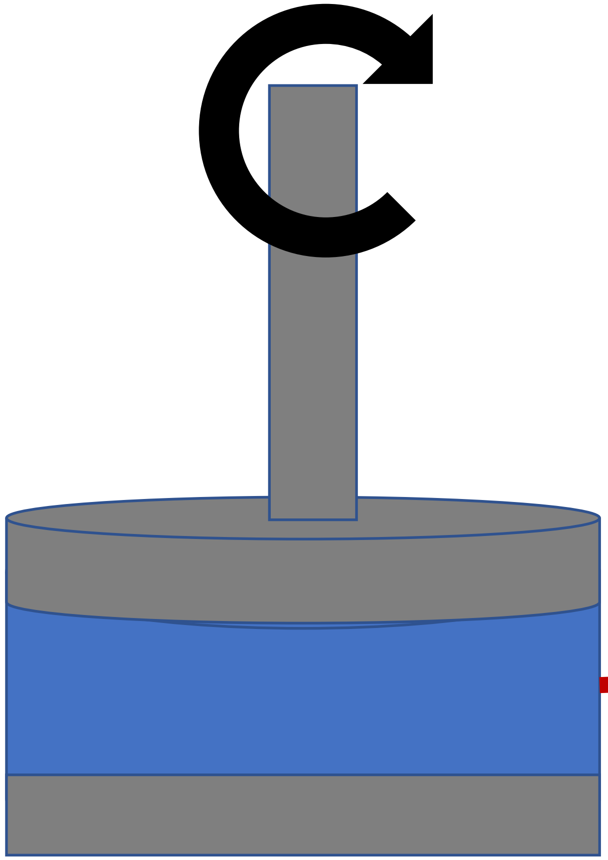
Figure 3.2 (A) Drip-through rate (grey circle) and G’ at 0°C (G’$_{0°C}$) (black square) versus extent of fat destabilization; (B) Drip-through rate (grey triangle) and G’$_{0°C}$ (black circle) versus mix viscosity (at 50s^{-1}); (C) Drip-through rate (grey diamond) and G’$_{0°C}$ (black triangle) versus overrun [Data compiled from Wu, Freire and Hartel (2019) and Chapter 2].

Rheological Measurements – Flow Ramp Test at 0°C





Rheological Measurements – Hyst $_{0°C}$ from Flow Ramp at 0°C



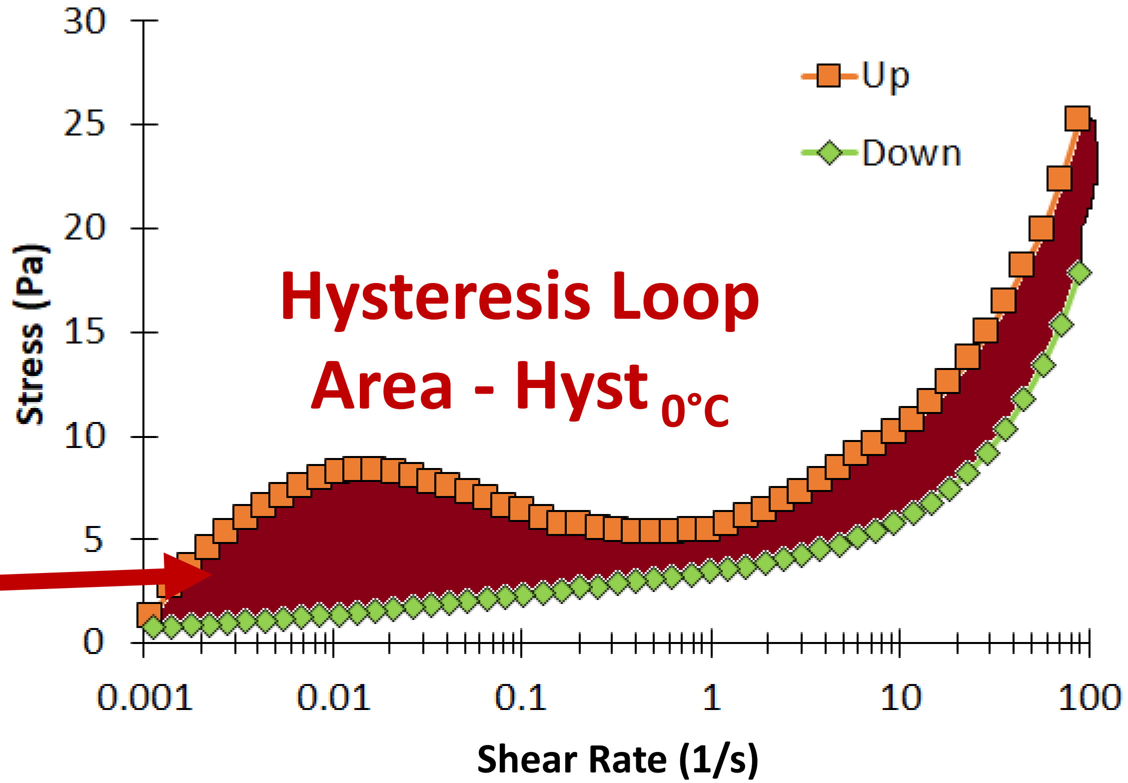
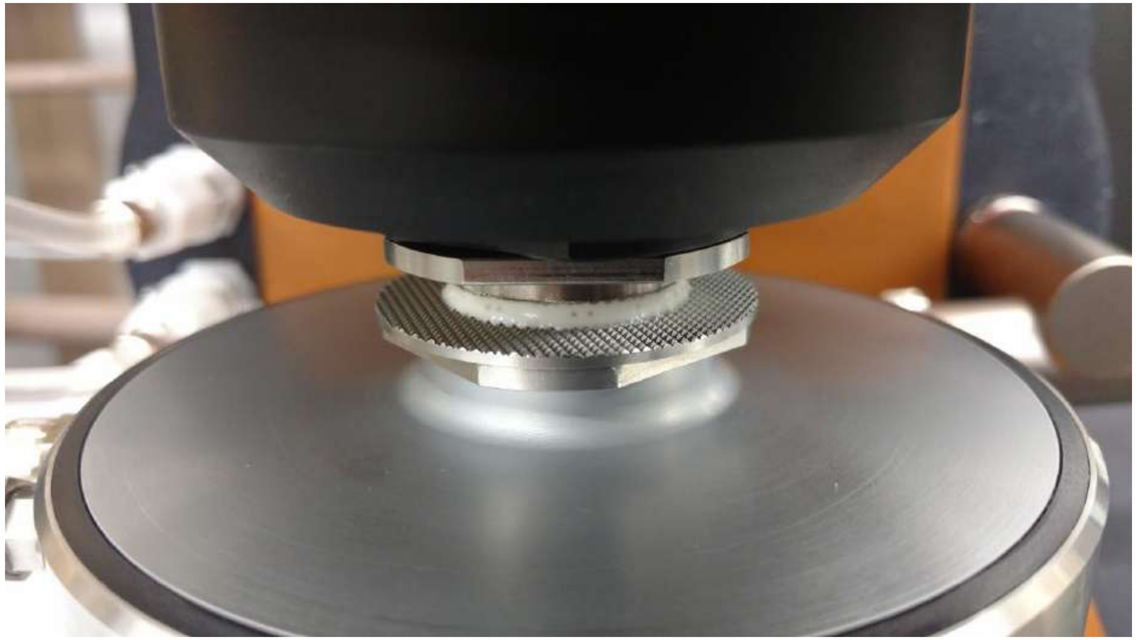


Figure 2.6: (A) Shear stress (up and down) curves for the sample S2A2P2.

Rheological Measurements – Hyst $_{0°C}$



- Hyst $_{0°C}$ → initial structural formation

- Direct correlations:

Visc, FD or OR ⟺ Hyst $_{0°C}$

- Visc → OR → FD

Correlations between Hyst $_{0°C}$ and FH ➔ $R^2 = 0.87$

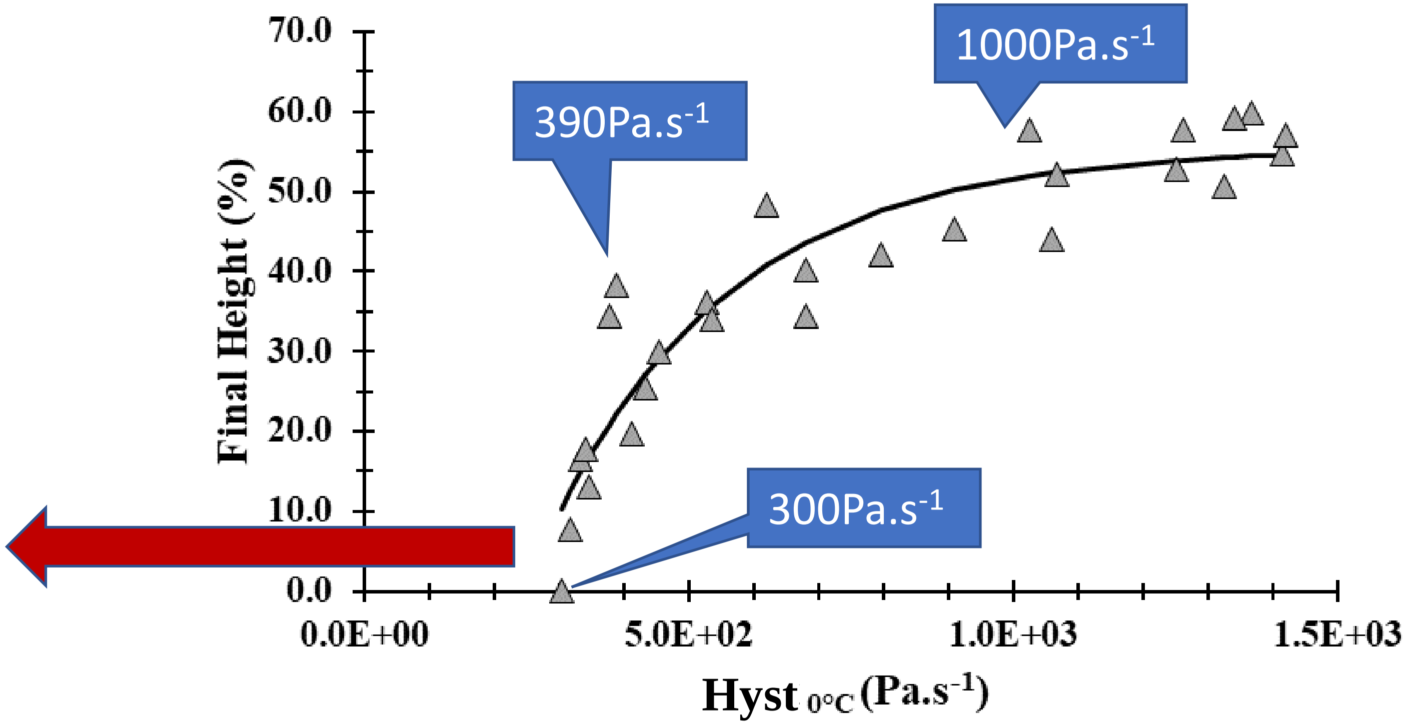
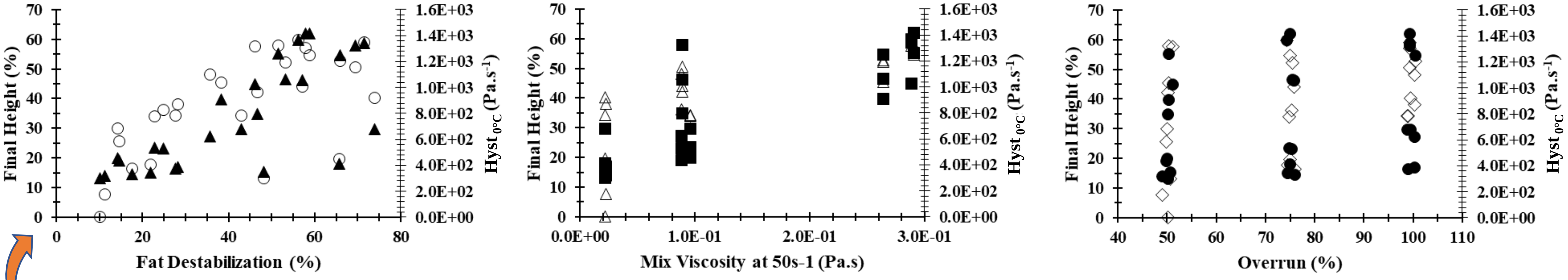


Figure 3.15 Behavior of hysteresis loop area (Hyst $_{0°C}$) versus final height (FH) for samples with controlled serum phase viscosity, overrun and extent of fat destabilization [Data compiled from Wu et al. (2019) and Chapter 2]. Line is fitted exponential model.

Correlations between Hyst $_{0°C}$ and FH



(A) (B) (C)

Figure 3.16 (A) Final Height (hollow circle) and Hyst $_{0°C}$ (black square) versus extent of fat destabilization; (B) Final Height (hollow triangle) and Hyst $_{0°C}$ (black circle) versus mix viscosity (at 50s^{-1}); (C) Final Height (hollow diamond) and Hyst $_{0°C}$ (black triangle) versus overrun [Data compiled from Wu et al. (2019) and Chapter 2].

Conclusions

- Good correlations **rheological and meltdown parameters**
- **$G'_{0°C}$ ➔ DT**
- **Hyst $_{0°C}$ ➔ FH**
- **Serum phase viscosity, extent of fat destabilization and overrun**

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Thank you!

Questions?