Freezing, Melting and Shrinkage of Ice Cream

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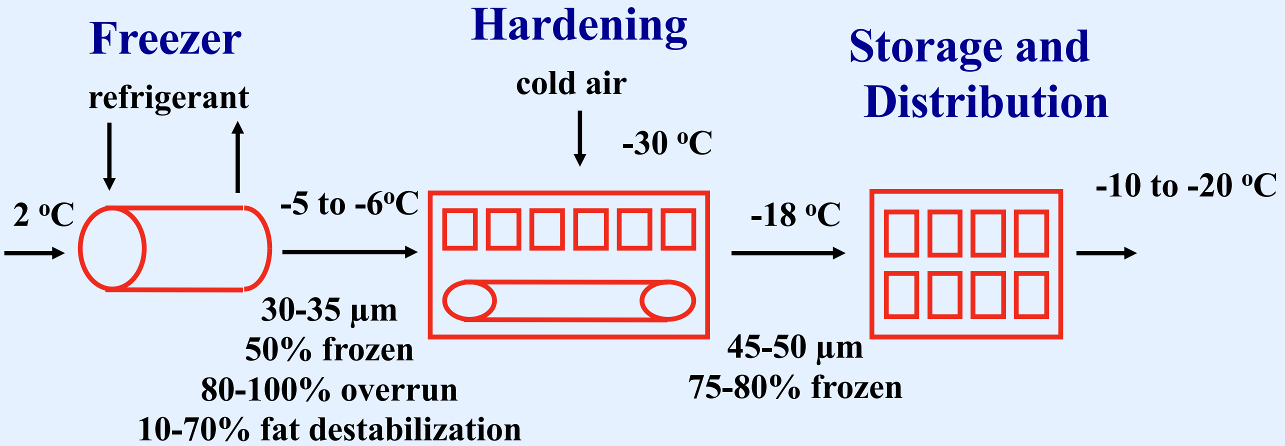
Funding: USDA, NDC

Ice Cream Processing



Ice
- nucleation
- growth

Air
- incorporation
- breakdown

Lipid
- growth
- partial coalescence

Ice
- growth

Air
- coalescence

Lipid
- growth

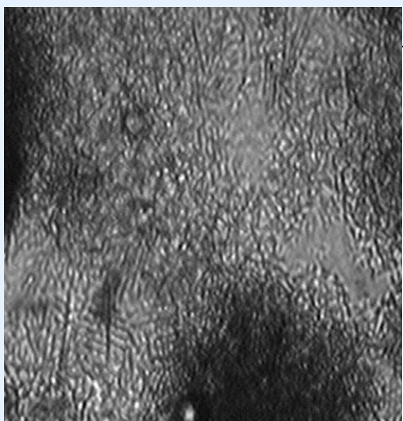
Ice
- melting
- growth
- ripening

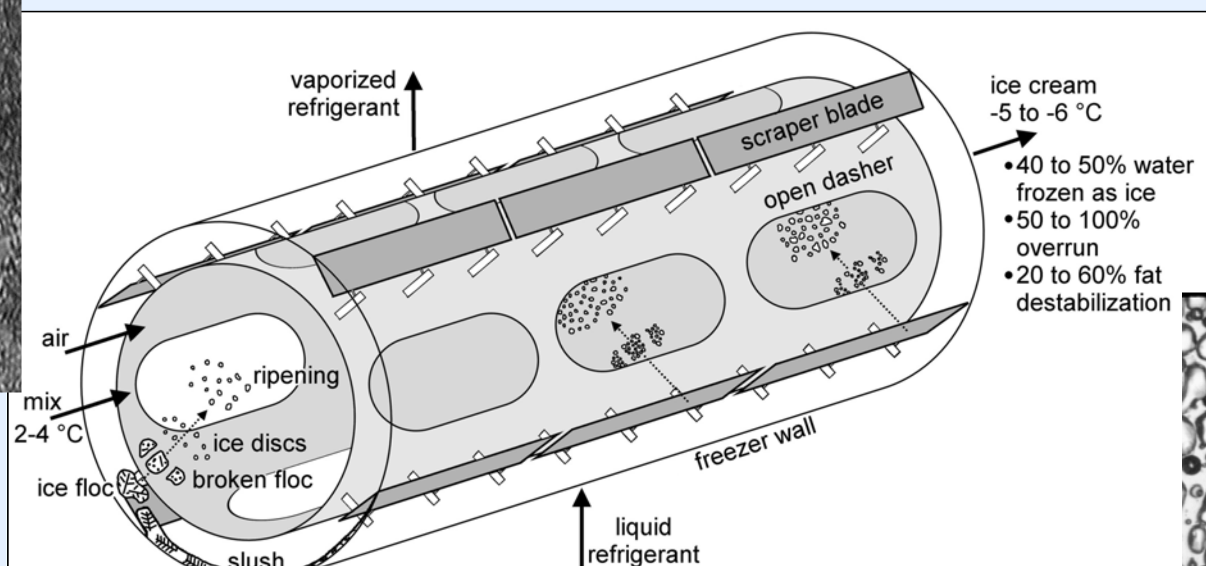
Air
- coalescence

Lactose
- crystallization

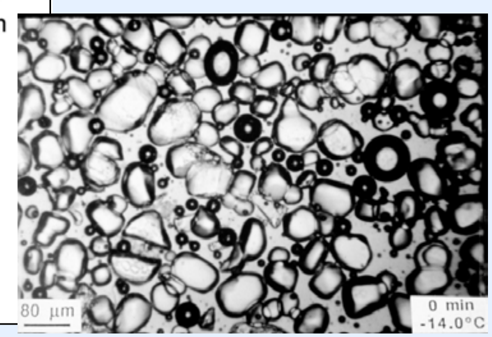
Scraped Surface Freezer (SSF) Development of Ice Phase

- Formation of ice crystals
  - Scraping of slush off wall of freezer; mixing of slush in center of barrel; ripening and growth to form ice crystal size distribution





Cook & Hartel, 2010



Experimental Design

How long after start-up does it take the freezing process to stabilize?

Sampling Frequency

- Every 1 min for the first 20 min
  - Hardened only
- Every 6 min for 78 min
  - Draw and hardened

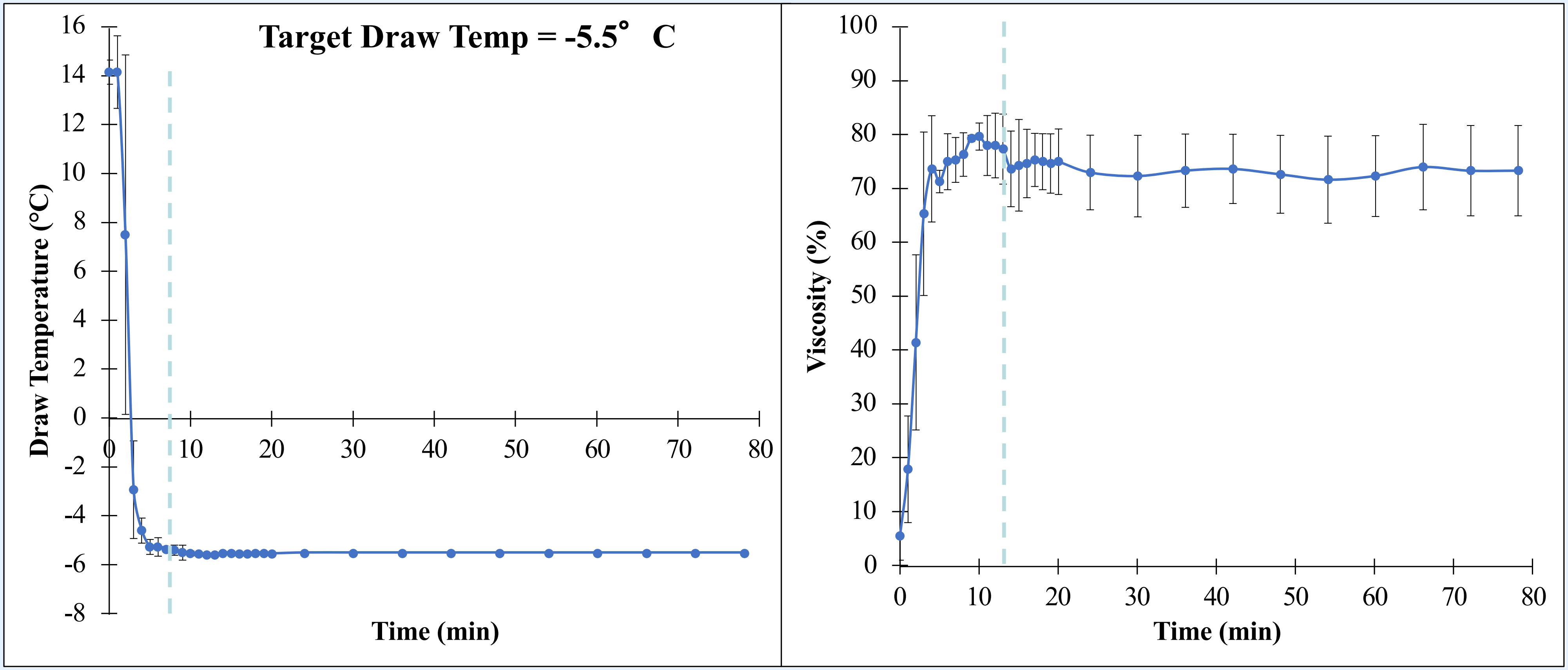
Theoretical Residence Times (s)

Overrun		50% OR	75% OR			100% OR
Throughput Rate		300 L/h	200 L/h	300 L/h	400 L/h	300 L/h
Dasher Assembly	Solid	81	141	94	71	108
	Multi + Solid	104	181	121	91	138
	Standard + Solid	110	193	129	96	147
	Multi + Wing	160	281	187	140	214
	Standard + Wing	167	291	194	146	222

Measurements

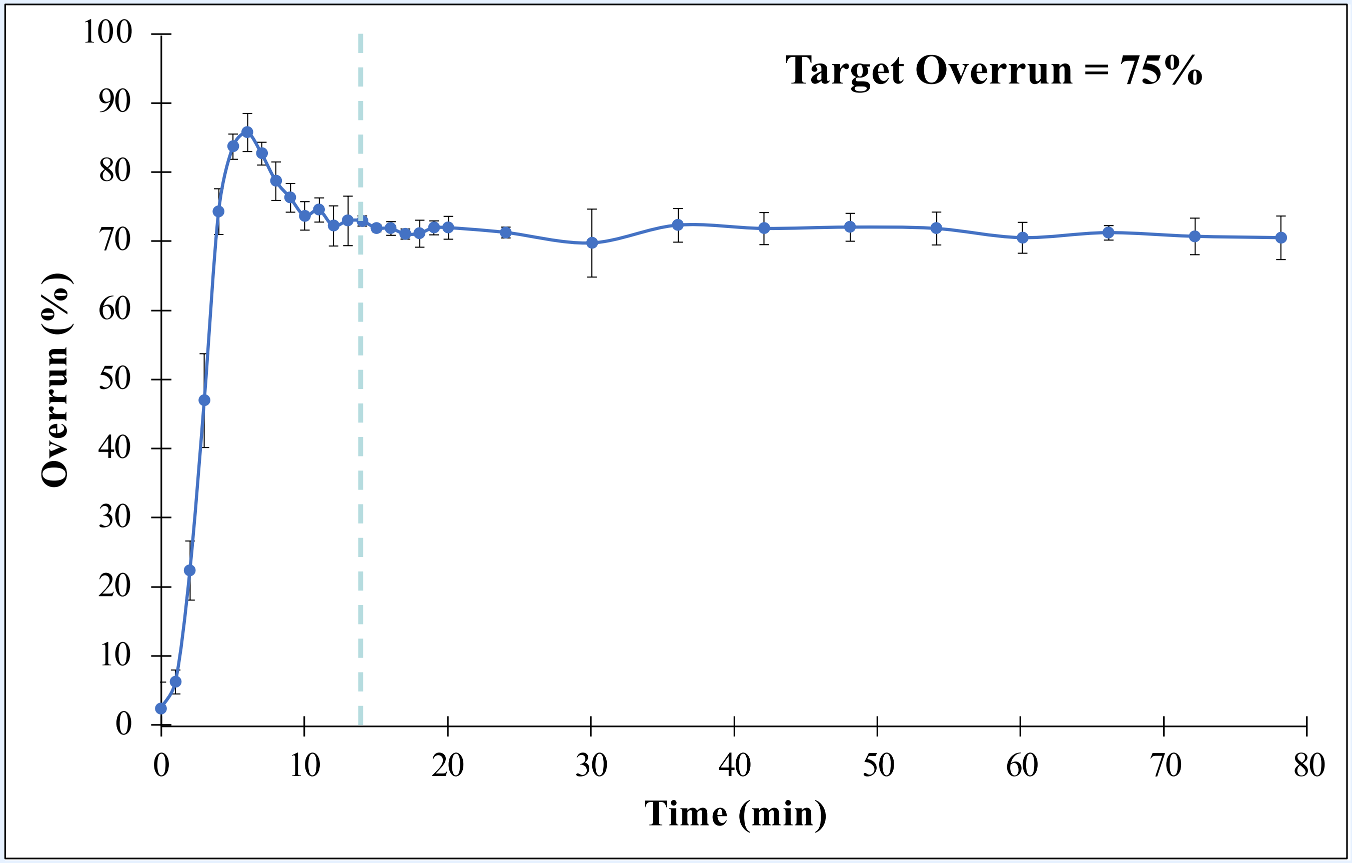
- Draw Temperature
- “Viscosity”
- Overrun
- Microstructure
  - Ice
  - Air
  - Fat

Processing Parameters after Start-up

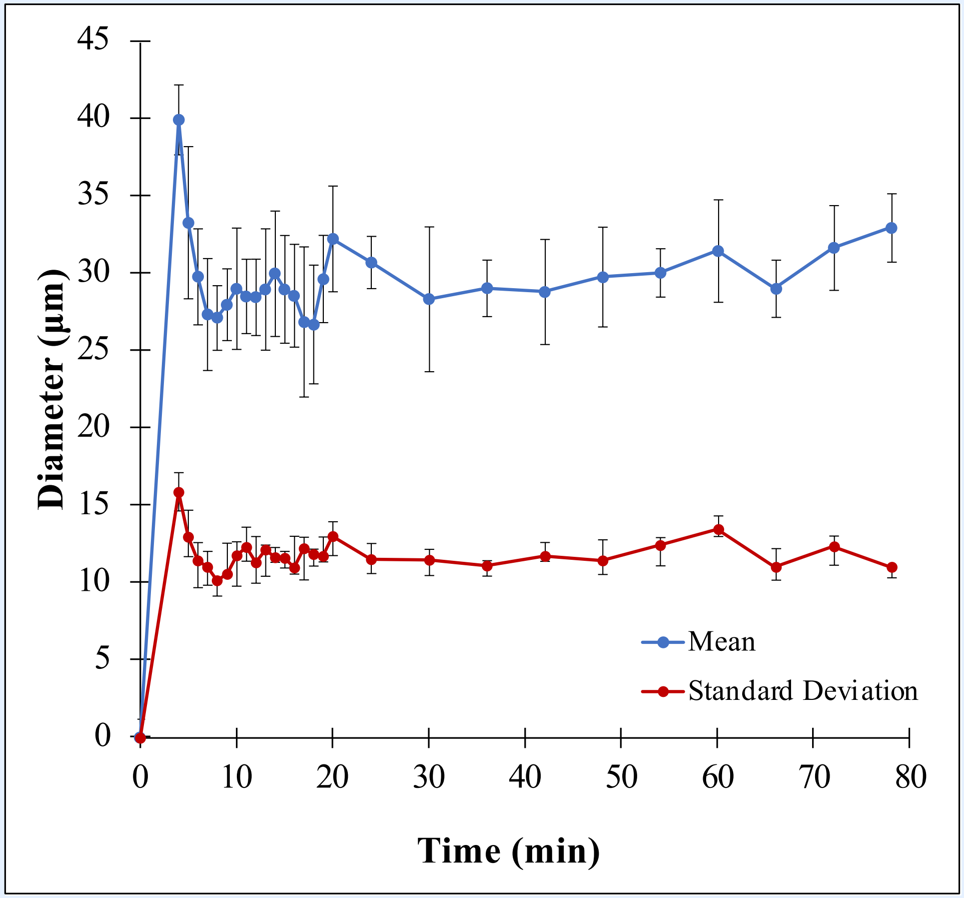


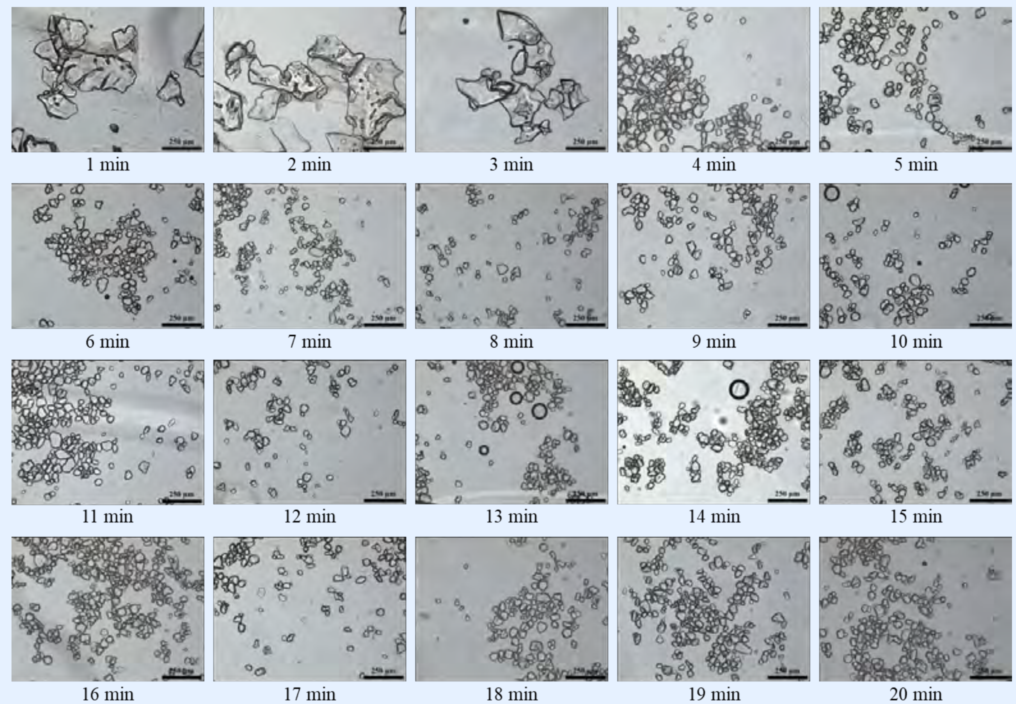
“Viscosity” = torque on dasher motor as the percentage of its total capacity

Processing Parameters after Start-up



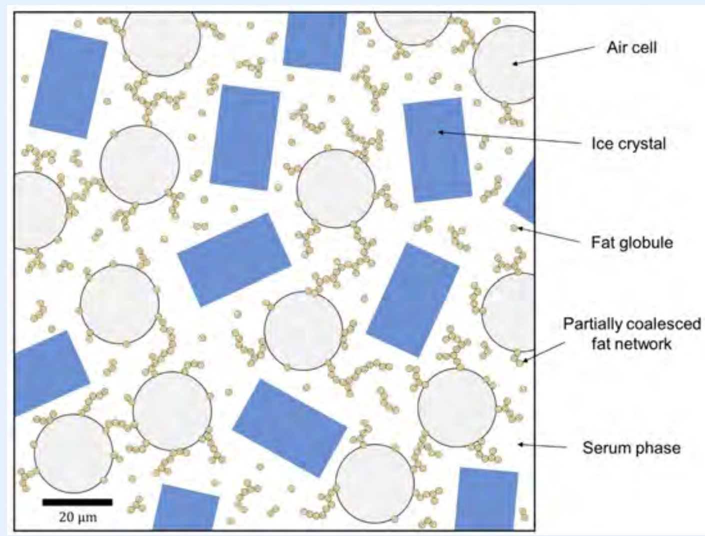
Microstructural Attributes after Start-up





Ice Cream at a Structural Level

- Ice crystals
  - Provide cooling effect and hardness
- Air cells
  - Reduce density
- Partially-coalesced fat globule network
  - Affects melt-down rate and hardness of ice cream
- Proteins and hydrocolloids
  - Network in serum phase
- Serum phase
  - Dissolved sugars, minerals, proteins, etc.
  - Some liquid even at very low temperature



Van Wees et al., 2021

“No-Melt” Ice Cream

- Periodical uproar about ice cream that doesn’t ”melt”
- Of course it melts, it just doesn’t collapse because of the structures

https://www.dailydot.com/news/why-dont-nestle-drumsticks-melt/

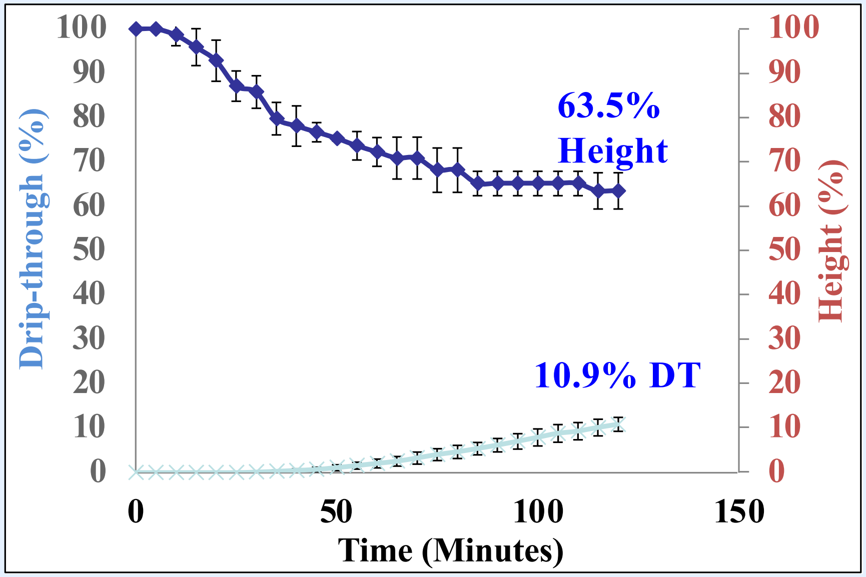
Ice Cream Melting

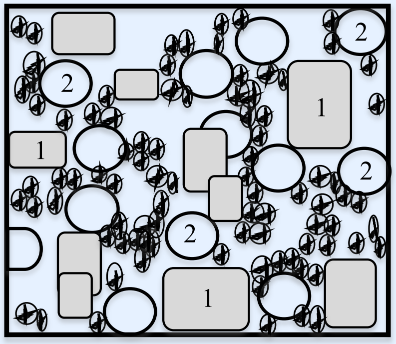
- Not all ice creams are created equal – or melt in the same way
- Drip-through test – slabs on mesh, measure drip through weight and height change

Which is better? That's up to you and what the manufacturer wants

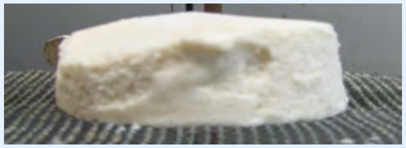
High Fat Destabilization
Minimal Collapse

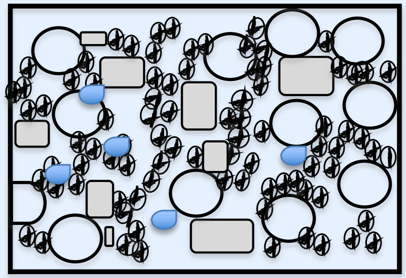
- 1 - Ice crystals
- Fat/destabilized fat
- -Free water
- -Serum phase
- 2 - Air cells



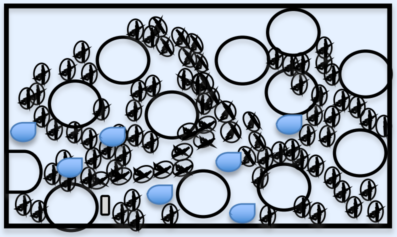


t = 0 minutes



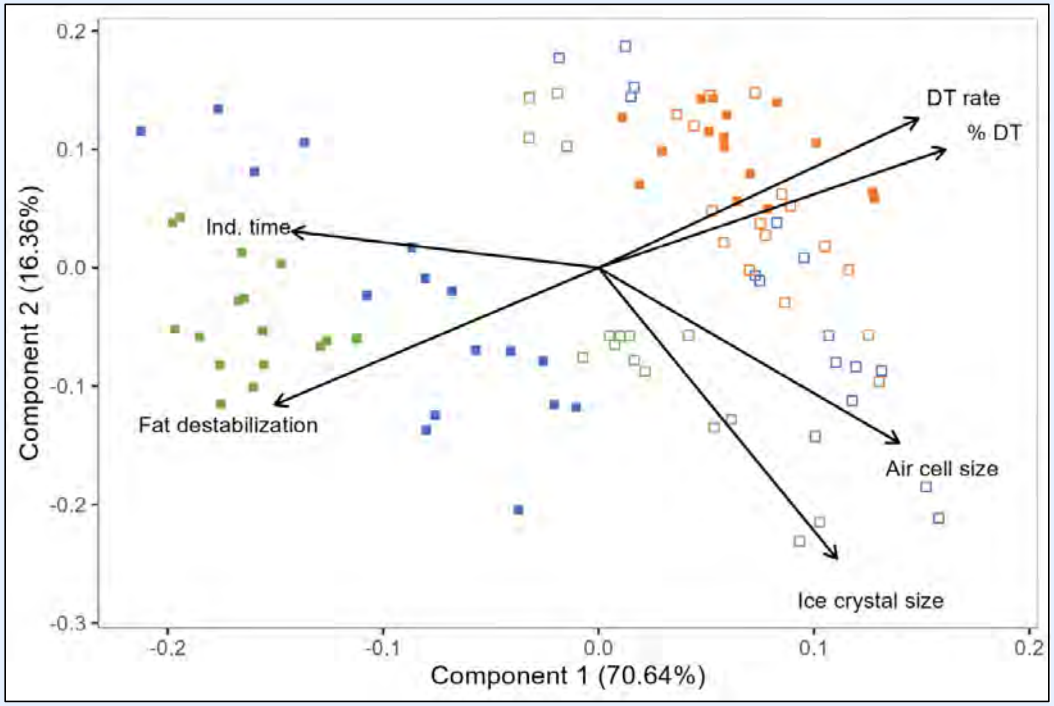


t = 60 minutes



t = 120 minutes

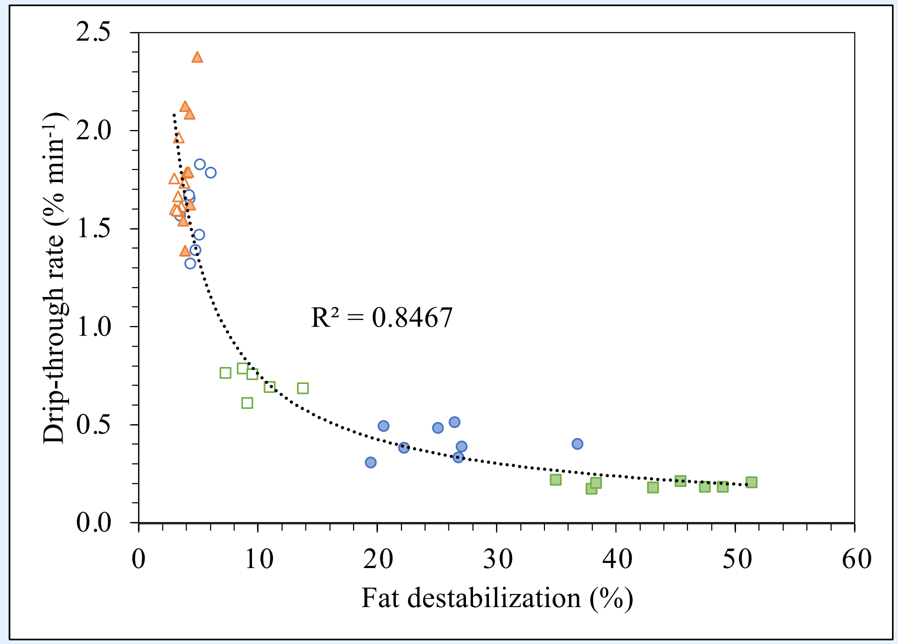
Structures and Melt-Down



MPC ( ) NaCN ( ) WPI ( )

VanWees, 2024

Fat destabilization plays a critical role in how ice cream melts down



$$\text{DT rate} = 5.12(FD)^{-0.828}$$

MPC (○ ●) NaCN (△ ▲) WPI ( )

No-Melt Ice Cream?

- Japanese ”no-melt” ice cream
  - Strawberry extract added
  - (juice concentrate, citric acid & pectin?)
- After 2 hours, all the ice is melted, these ice creams just don’t collapse

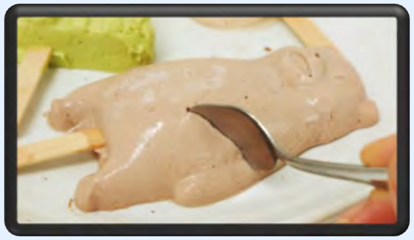
“no-collapse” ice cream

- Must be related to the structures
  - Fat globules, protein

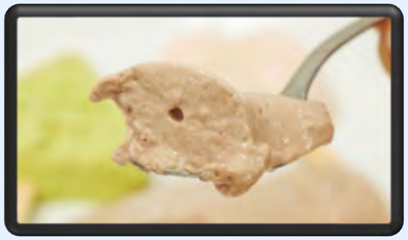
“Polyphenol liquid has properties to make it difficult for water and oil to separate so that a popsicle containing it will be able to retain the original shape of the cream for a longer time than usual and be hard to melt”

Tomihisa Ota
Professor Emeritus of Pharmacy at Kanazawa University,
Co-Developer of Ice Cream

https://youtu.be/GFE91TTJfN8



After 30 mins



Bringing delight by investigating a no-melt ice cream

June 10, 2024 | By Elise Mahon

https://www.youtube.com/watch?v=4fRVqG96vFM&t=2s

Evaluate tannic acid in frozen dessert systems with different fat/protein content.

Ice cream formulations

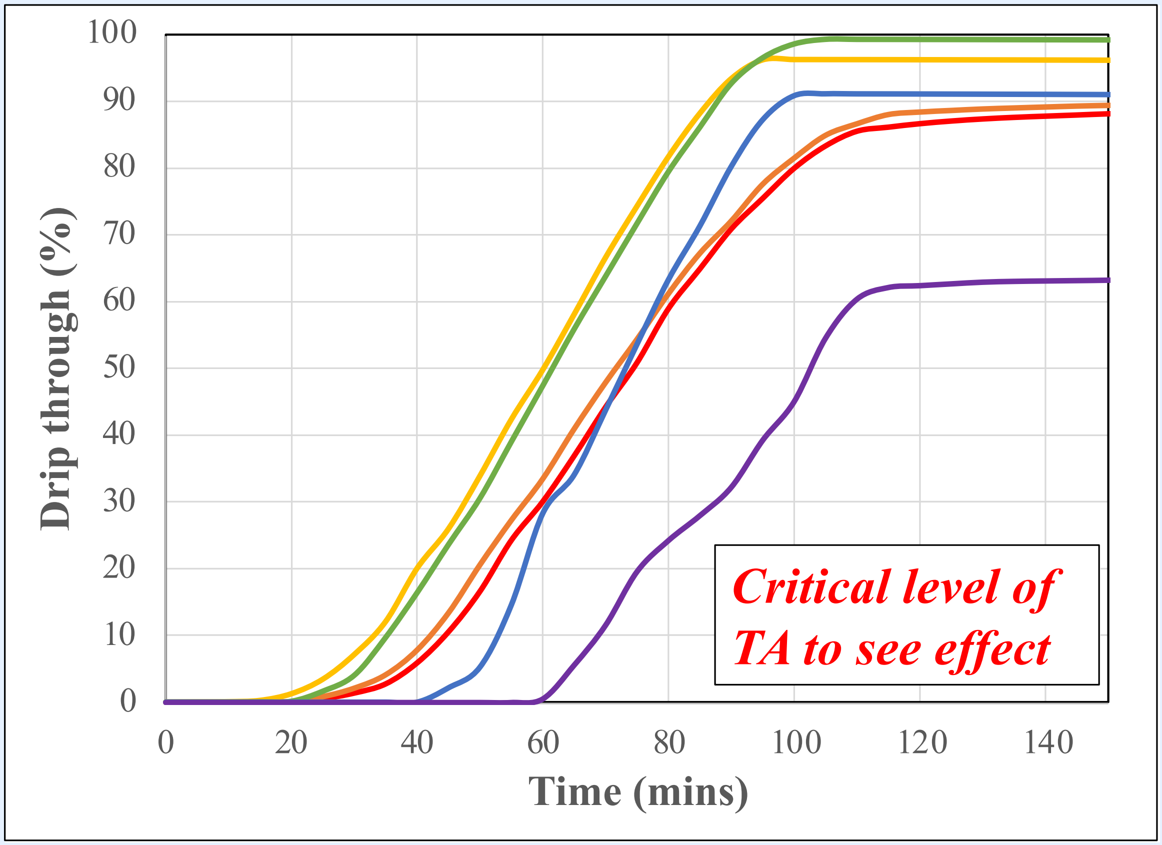
	fat (%)	protein (%)	TA (%)
Base	12	3	0
	12	3	0.5
	12	3	1
	12	3	1.5
	12	3	2
	12	3	2.5
Higher Protein	12	5	0
	12	5	2.5
Higher Fat	15	3	0
	15	3	2.5

Methods:

- Mix Preparation with polyphenol
- Batch freezing
- Fat globule Size Distribution
- Microscope Images
- pH of mix
- Overrun
- Rheology
- Melting Rate
- Ice Recrystallization

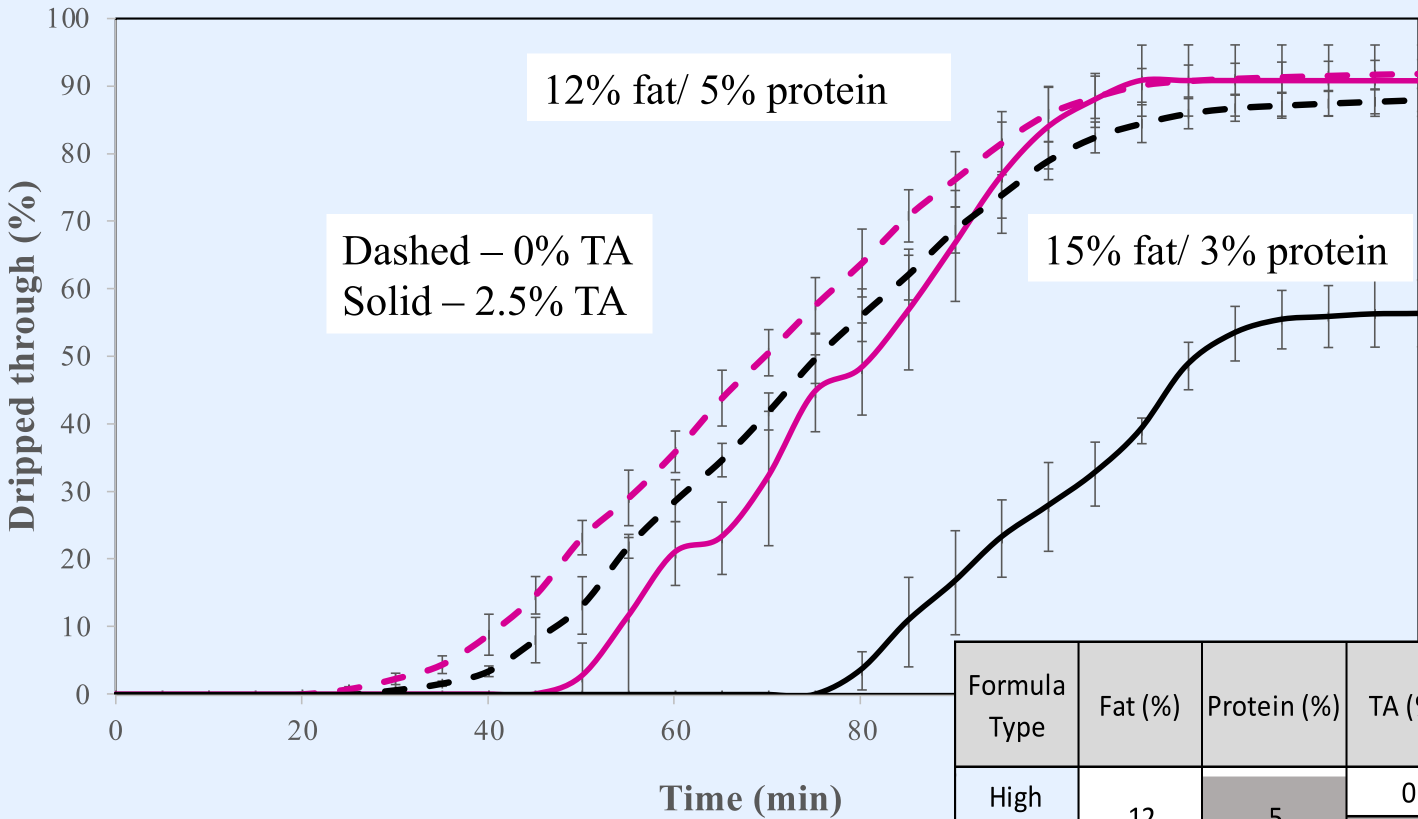
Melting Profiles

for Base (12% fat / 3% protein) ice creams with increasing TA%



TA (%)	Melting Rate (%/min)	Residual (%)
0	1.29[bc]	10.9[b]
0.5	1.38[ab]	9.8[b]
1	1.55[ab]	3.7[b]
1.5	1.55[ab]	0.7[b]
2	1.75[a]	8.8[b]
2.5	0.72[d]	36.2[a]

Melting Profiles



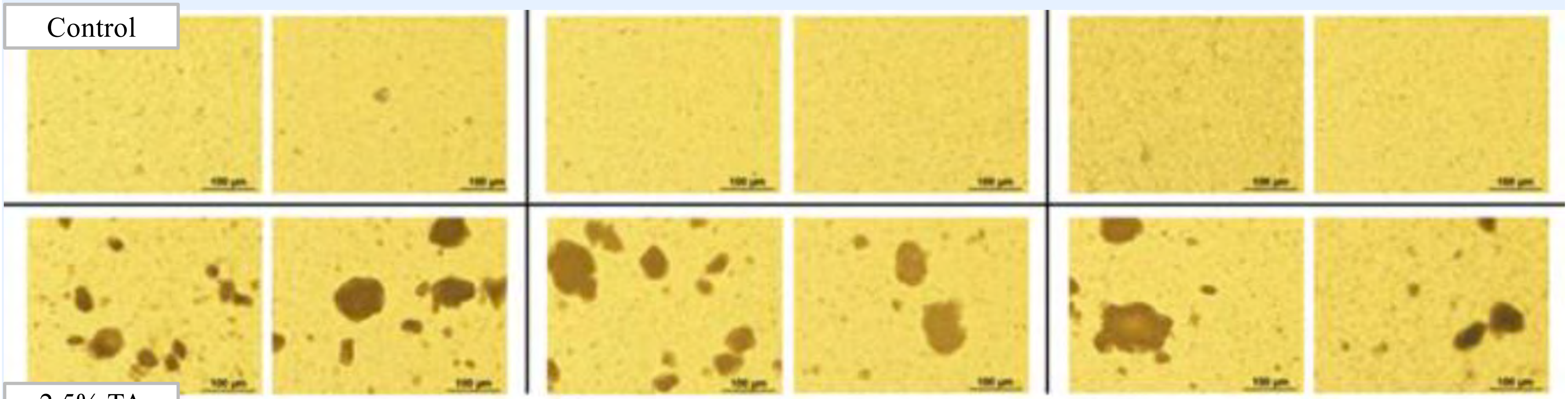
Fat content seems to be more important factor to melt-down than protein level

Formula Type	Fat (%)	Protein (%)	TA (%)	Melting Rate (%/min)	Induction Time (min)	Residual Weight on Screen (%)
High Protein	12	5	0	1.43 ± 0.01[ab]	18 ± 0.0[c]	7.4 ± 1.4[b]
			2.5	1.74 ± 0.07[a]	51.7 ± 2.5[b]	9.2 ± 2.9[b]
High Fat	15	3	0	1.39 ± 0.05[ab]	25.8 ± 0.0[c]	10.5 ± 0.6[b]
			2.5	0.91 ± 0.15[cd]	79.2 ± 1.7[a]	42.9 ± 4.0[a]

Tannic Acid in IC Mix: Microscope Images

BASE: 12% fat & 3% protein	**HIGH PROTEIN:** 12% fat & 5% protein	**HIGH FAT** 15% fat & 3% protein

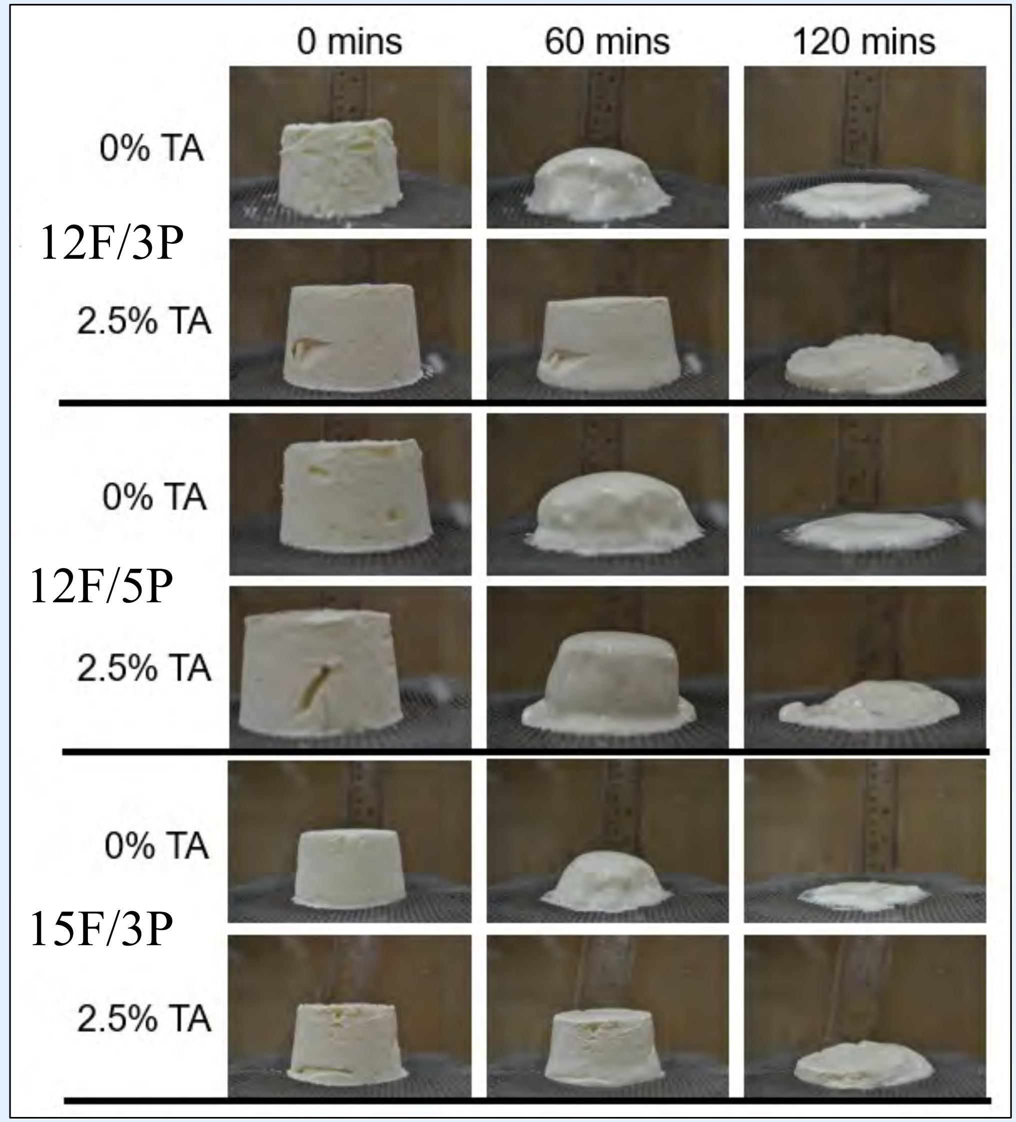
Control



2.5% TA

Melting Ice Cream

- None are really what could be called “no melt or collapse” ice creams
- Some effect of tannic acid at 2.5%, but not complete stopping of melt-down



Ice Recrystallization

- TA inhibits ice recrystallization in storage
  - Not clear how the aggregated structures influence ice crystal growth?

Formula Type	TA (%)	Week 0	Week 2	Week 4
Standard	0	36.4±3.7^{DEFGH}	53.2±5.7^{ABCDE}	67.9±9.4^{A}
	0.5	31.6±0.0^{FGH}	51.7±0.0^{ABCDEFG}	58.3±0.0^{AB}
	1.5	33.8±4.9^{EFGH}	42.9±1.4^{BCDEFGH}	52.0±2.1^{ABCDEF}
	2.5	29.8±2.2^{H}	41.1±2.5^{BCDEFGH}	42.7±0.7^{BCDEFGH}
Higher Protein	0	33.9±0.9^{EFGH}	56.4±4.5^{ABCD}	71.1±7.0^{A}
	2.5	31.3±3.1^{FGH}	32.7±0.6^{EFGH}	36.8±3.3^{CDEFGH}
Higher Fat	0	30.6±3.0^{GH}	57.9±4.5^{ABC}	67.6±3.3^{A}
	2.5	32.5±4.0^{EFGH}	34.8±0.2^{EFGH}	38.7±0.7^{BCDEFGH}

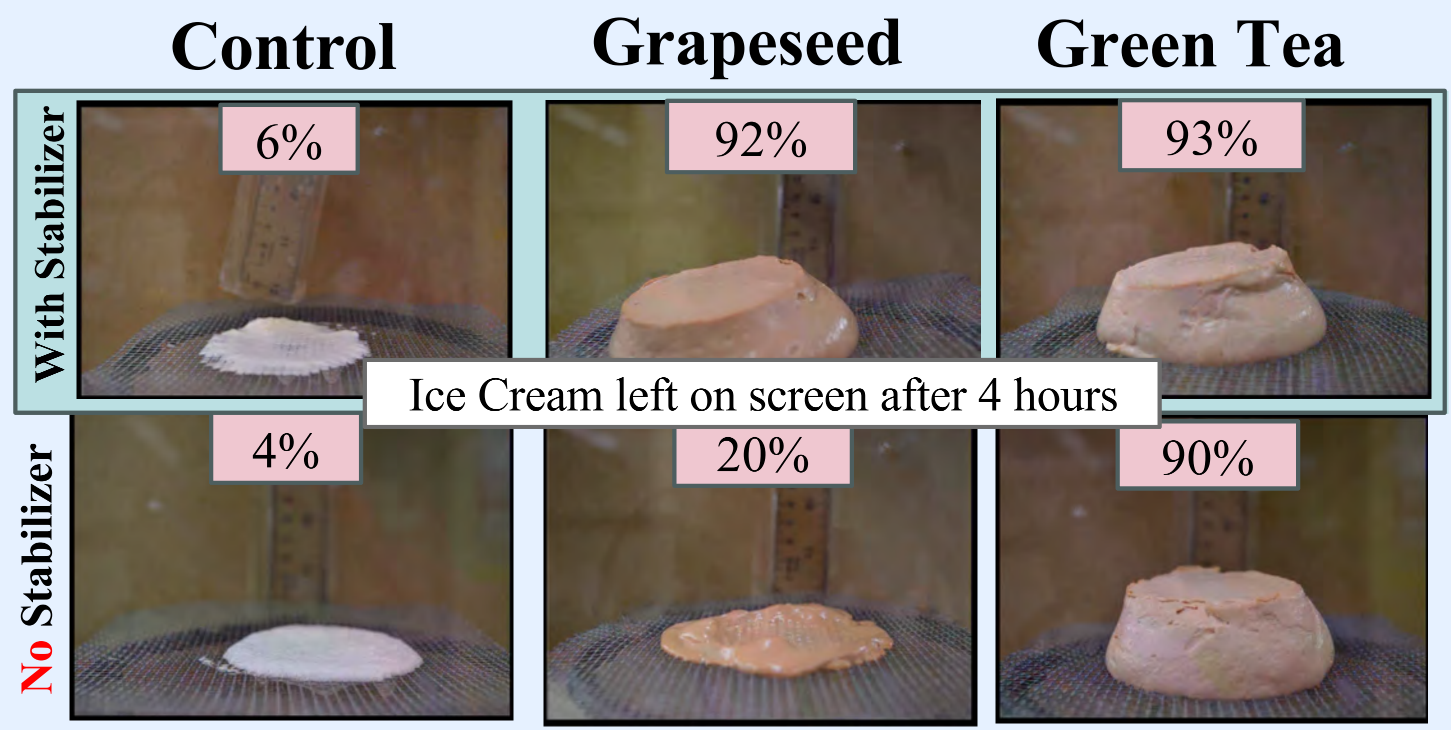
Phenolic Extracts

- Polyphenol extracts (high phenolic %) shown to decrease melting rate in previous studies
- Could these extracts replace stabilizers in ice cream?

Each extract has at least 85% Polyphenols

	With Stabilizer	**Without Stabilizer**
Control	Control + Stabilizer	Control + No Stabilizer
Grapeseed	Grapeseed + Stabilizer	Grapeseed + No Stabilizer
Green Tea	Green Tea + Stabilizer	Green Tea + No Stabilizer

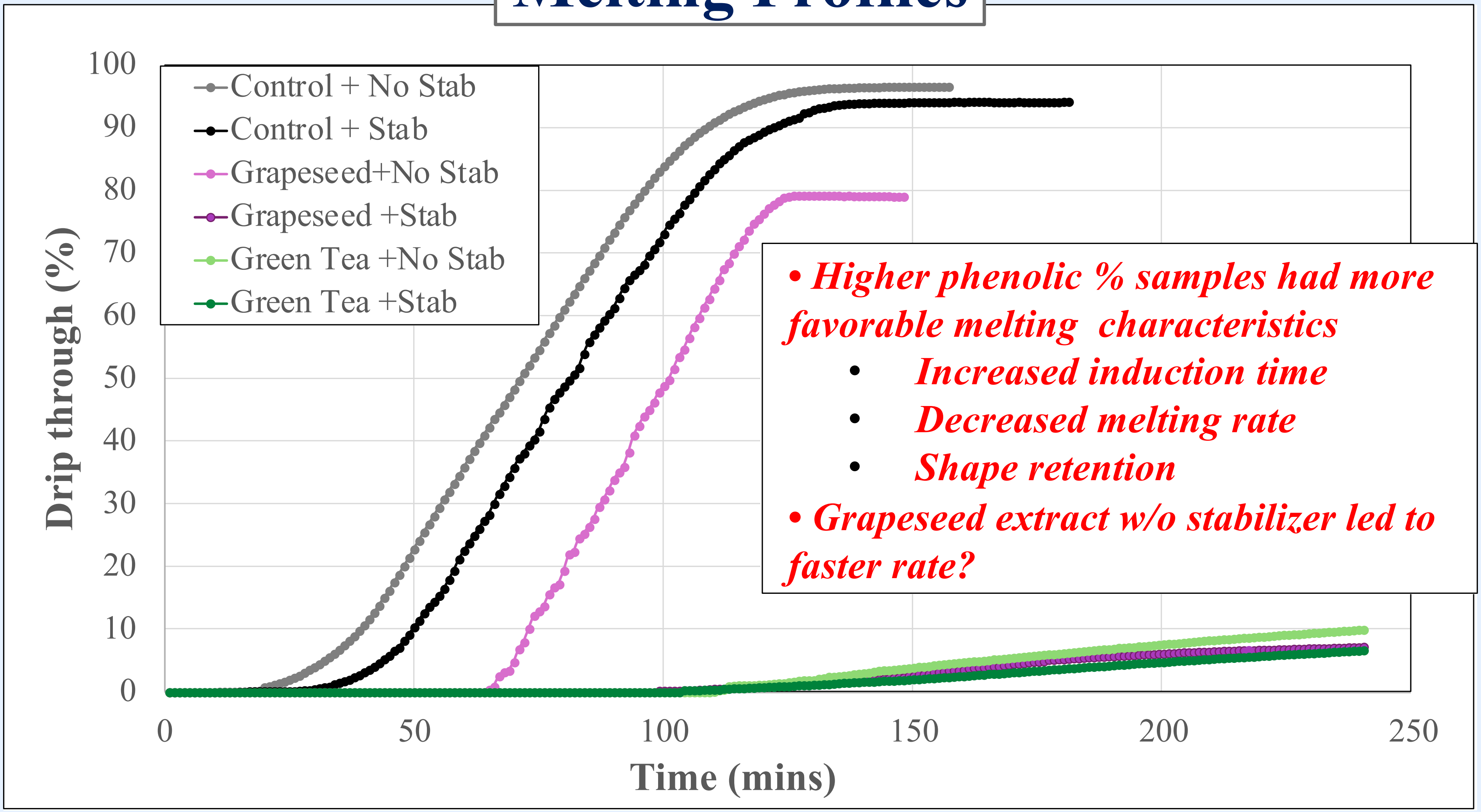
Stabilizer blend
locust bean gum, guar gum, and carrageenan



Extract	Total polyphenols in extract (%)	Total PAC in extract (%)	Total polyphenols in ice cream (%)	PAC content in ice cream (%)
green tea extract	97.6 ± 8.0	38.7 ± 7.4	2.9	1.2
grape seed extract	80.7 ± 7.0	13.8 ± 0.3	2.4	0.4

Type of PP different between samples

Melting Profiles



- ***Higher phenolic % samples had more favorable melting characteristics***
  - ***Increased induction time***
  - ***Decreased melting rate***
  - ***Shape retention***
- ***Grapeseed extract w/o stabilizer led to faster rate?***

Ice Recrystallization

- Both extracts inhibit ice recrystallization in storage

Extract	Stabilizer (%)	Week 0	Week 4
Control	0	36.2±0.2[B]	86.4±14[A]
	0.2	39.5±4.3[B]	82.5±13[A]
Grapeseed	0	34.2±1.7[B]	33.2±3.8[B]
	0.2	31.1±3.2[B]	35.7±0.1[B]
Green Tea	0	32.7±0.2[B]	34.9±0.9[B]
	0.2	32.9±1.3[B]	37.6±0.7[B]

Again, mechanism for inhibition effect is unknown.

Fruit Extract/Sources in Ice Cream

- Some previous studies have shown that fruit extracts can inhibit melting, as in the Japanese "no melt" popsicles

Ice Cream Formula
15% fat
3% protein

Extract Phenolic Content
- Strawberry = ~1%
- Blueberry = 30%
- Cranberry = 15%

Experimental Design:

% Addition to Ice Cream

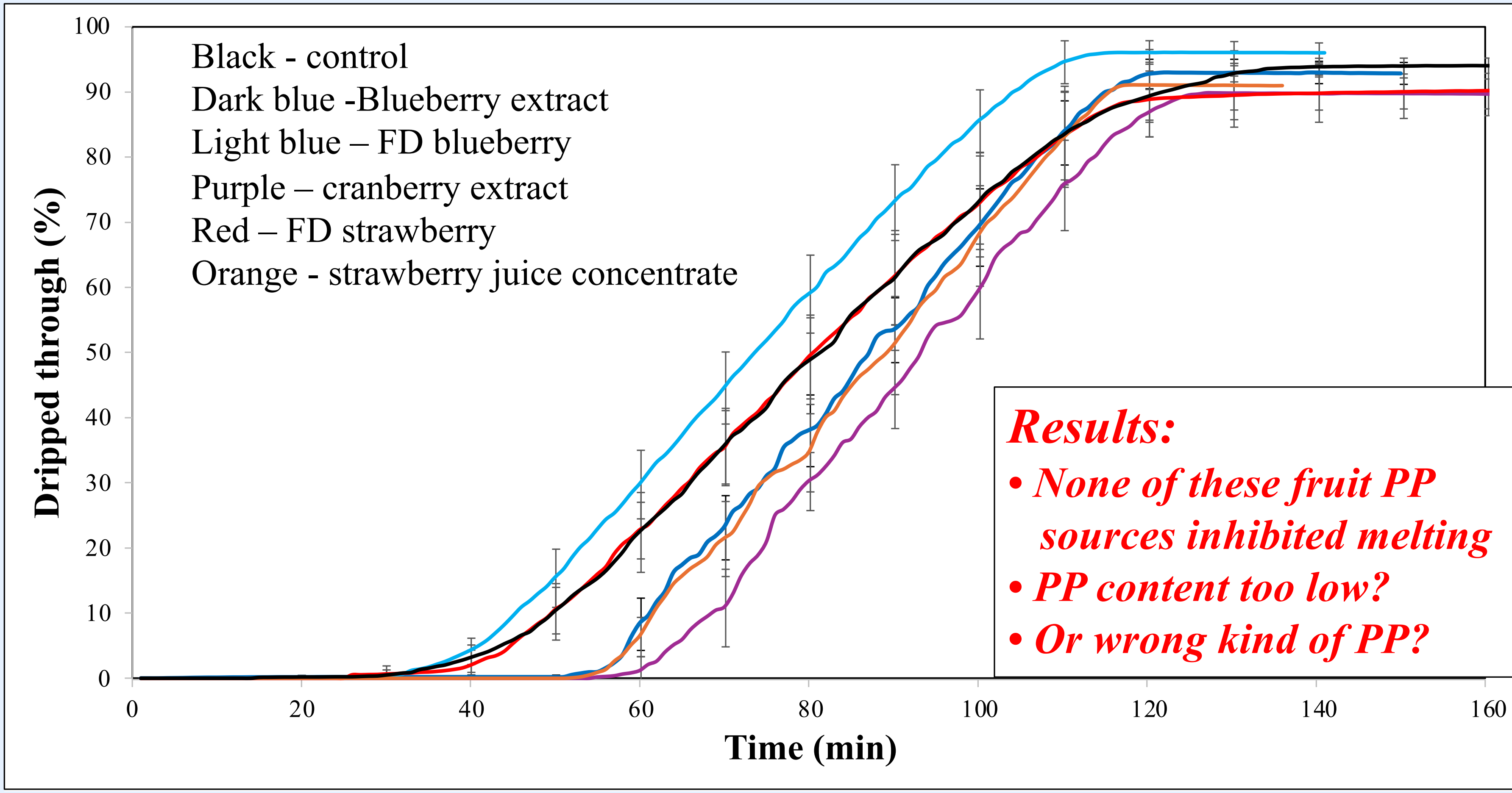
Fruits	Standardized extract	Freeze-dried powder	Juice concentrate
Strawberry	**3.5%**	3.5%	20%
Blueberry	3.5%	3.5%	
Cranberry	3.5%		

Fruit Extract/Sources in Ice Cream

- Lower polyphenol (and proanthocyanadin, PCA) content, below the threshold value found in our previous studies
  - May contain fibers and other compounds

Crude Extract	Total polyphenols in source (%)	Total PAC in source (%)	Total polyphenols in ice cream (%)	PAC content in ice cream (%)
Blueberry extract	39±1.3	5.3±0.4	1.4	0.2
Cranberry extract	36±0.2	3.4±0.3	1.2	0.1
Strawberry freeze-dried powder	0.3±0.01	0.02±0.0	0.01	0.001
Blueberry freeze-dried powder	0.8±0.06	0.06±0.001	0.03	0.002
Strawberry juice concentrate	1.1±0.1	0.042±0.001	0.04	0.001

Melting Profiles



Results:

- ***None of these fruit PP sources inhibited melting***
- ***PP content too low?***
- ***Or wrong kind of PP?***

Summary of Polyphenols in Ice Cream

- Although it seems the effects of polyphenols relate to the protein-mediated fat globule aggregates, the mechanisms are not so clear
  - Concentration effect
  - pH effect
  - Interactions with other components (e.g., stabilizers)
  - Specific type of polyphenol is probably important
    - Another focus of this study showed that effect of viscosity and protein-aggregated fat globules was mostly dependent on degree of polymerization of the PP – longer chains resulted in stronger bonding with proteins

- How do PP affect ice crystal growth?

Shrinkage in Ice Cream

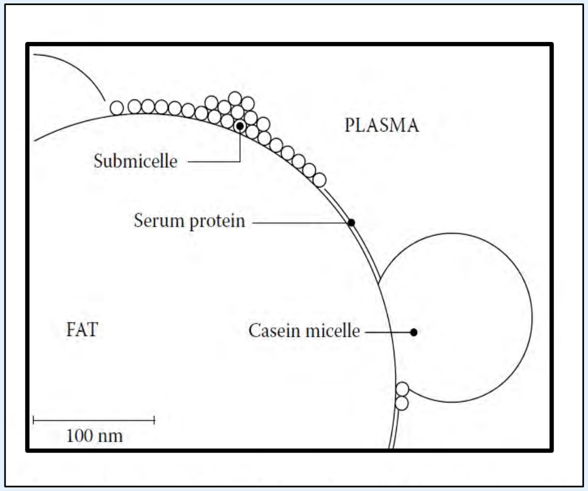
- Texture defect in the air phase of frozen desserts
- Product no longer fills the volume of the container
- Destabilization and collapse of the frozen foam

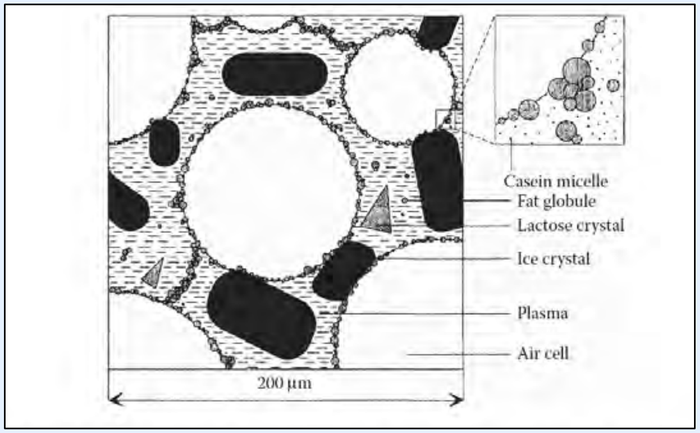
Dr. Sam VanWees
Funding: Dairy Management Inc.

Proteins in Frozen Desserts

- Functionality
  - Emulsification
  - Foaming
  - Water-holding capacity
- Structure-function relationships within highly complex emulsions and foams
- Storage stability, shrinkage, and air interface viscoelasticity

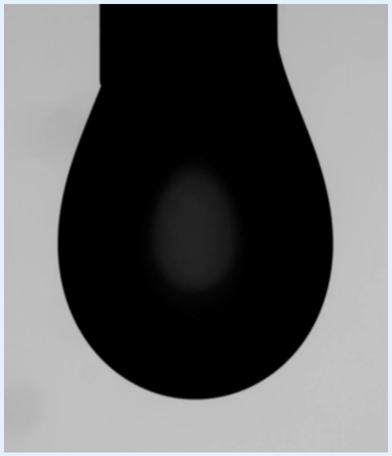
How do interfacial proteins respond to expansion and contraction?
Could this correspond to shrinkage?



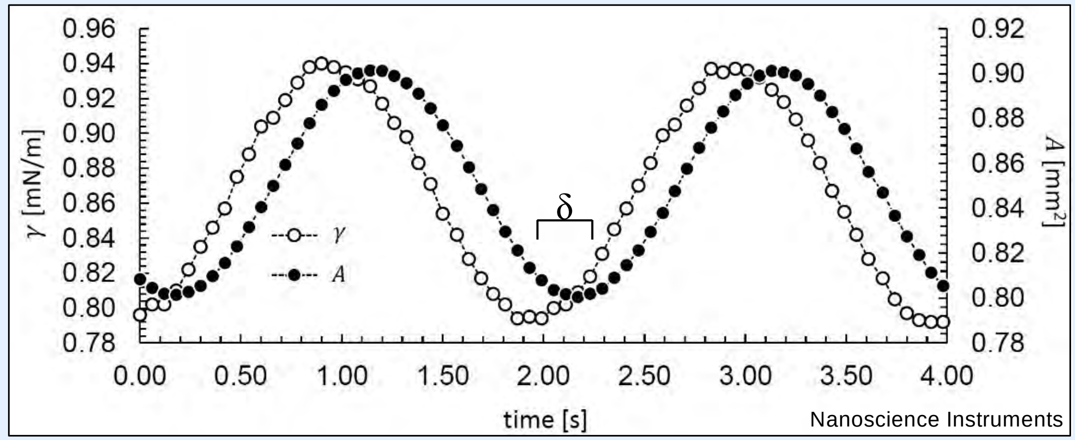


Walstra et al. (2006)

Oscillatory Dilatational Rheology



Pulsating drop

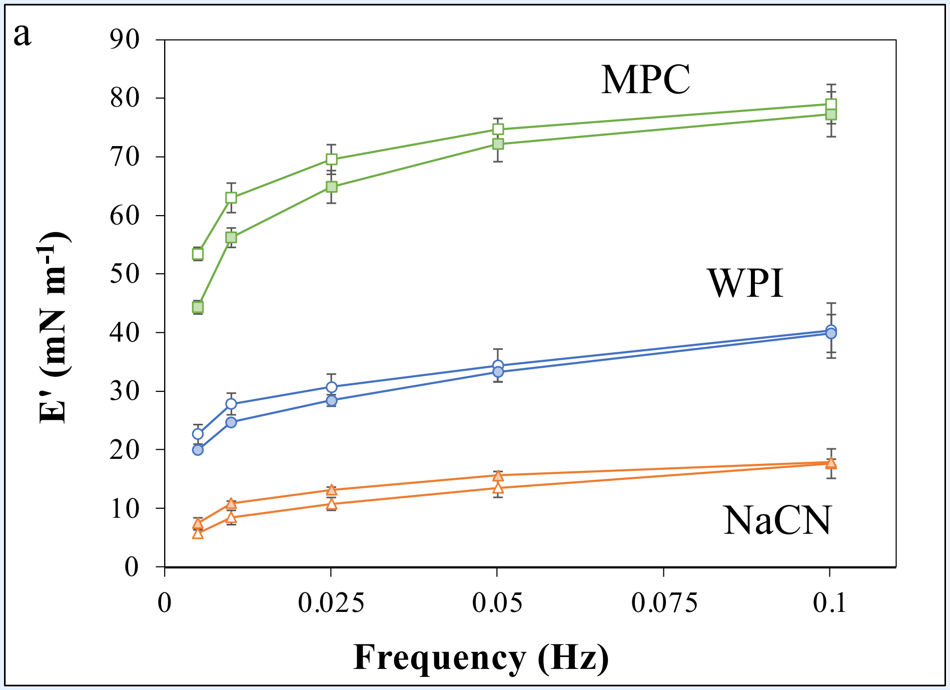


Dilatational modulus $$\boldsymbol{E = \frac{\Delta\,\gamma}{\Delta\,ln\,A}}$$

$$\boldsymbol{E' = E\,cos\,\delta} \qquad \boldsymbol{E'' = E\,sin\,\delta}$$

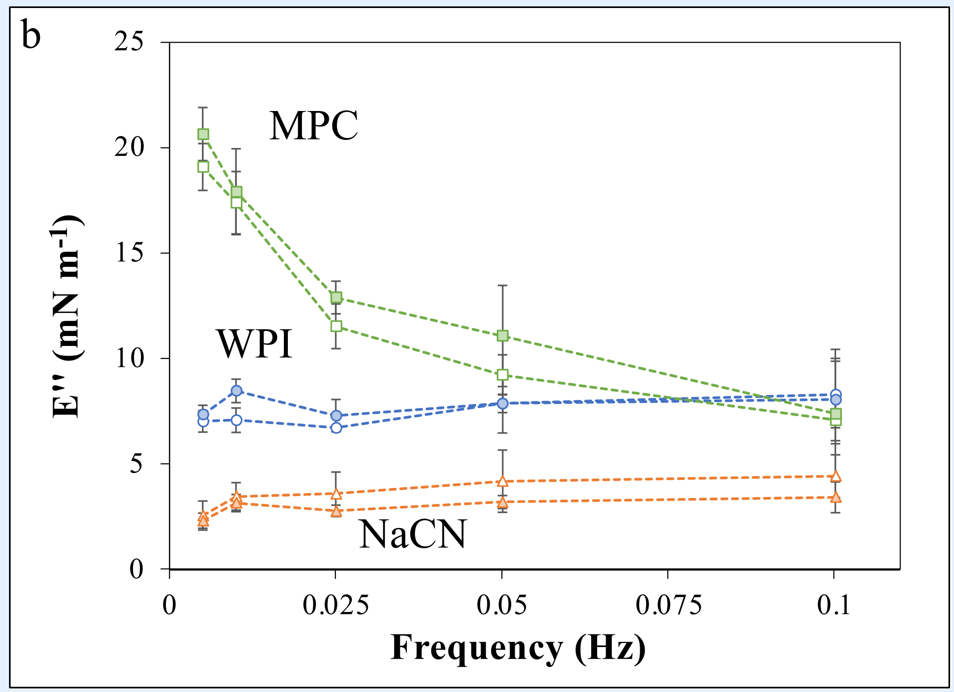
$$\boldsymbol{E(\omega) = E'(\omega) + iE''(\omega)}$$

- ***What air interfacial properties are stabilized by dairy proteins?***
- ***Does protein concentration affect rheological properties?***
- ***How might different structure-function relationships impact air cell stability?***



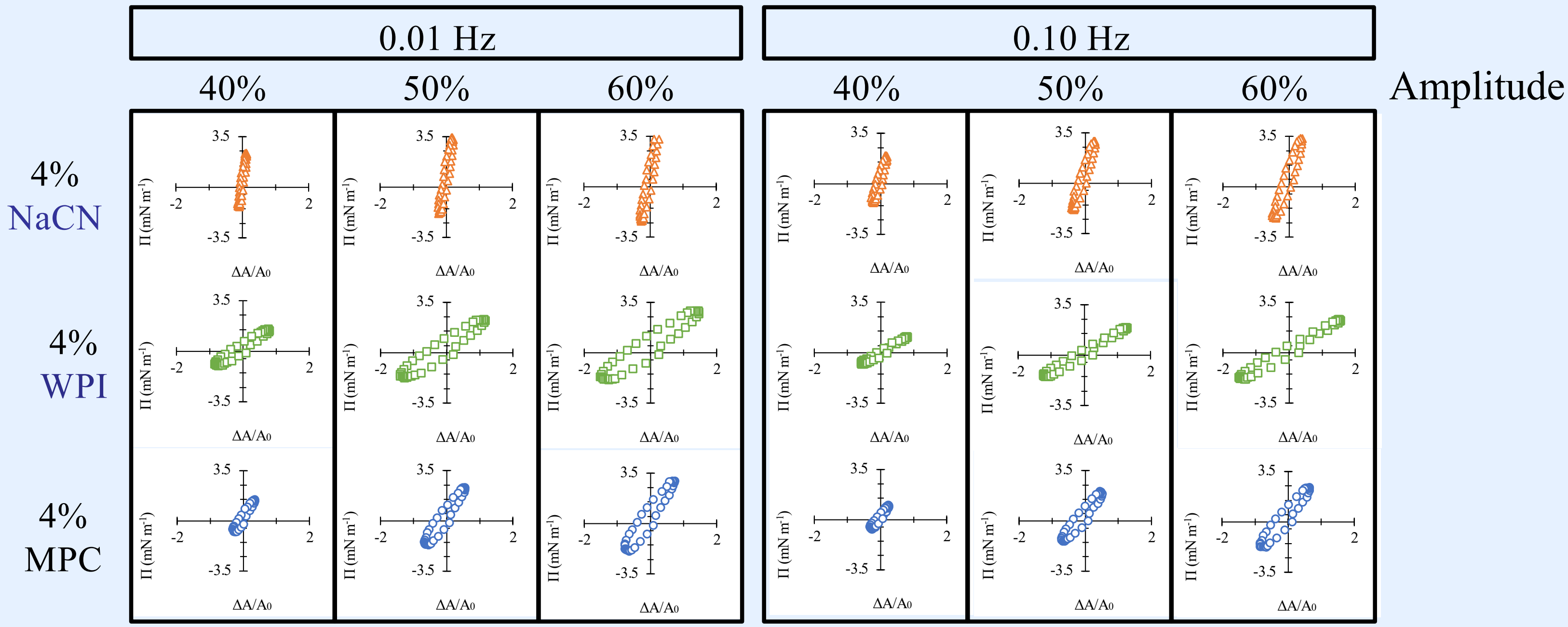
MPC creates a much firmer interface than NaCN, with WPI between

Open – 4% protein
Closed – 8% protein



Large Angle Oscillatory Dilation

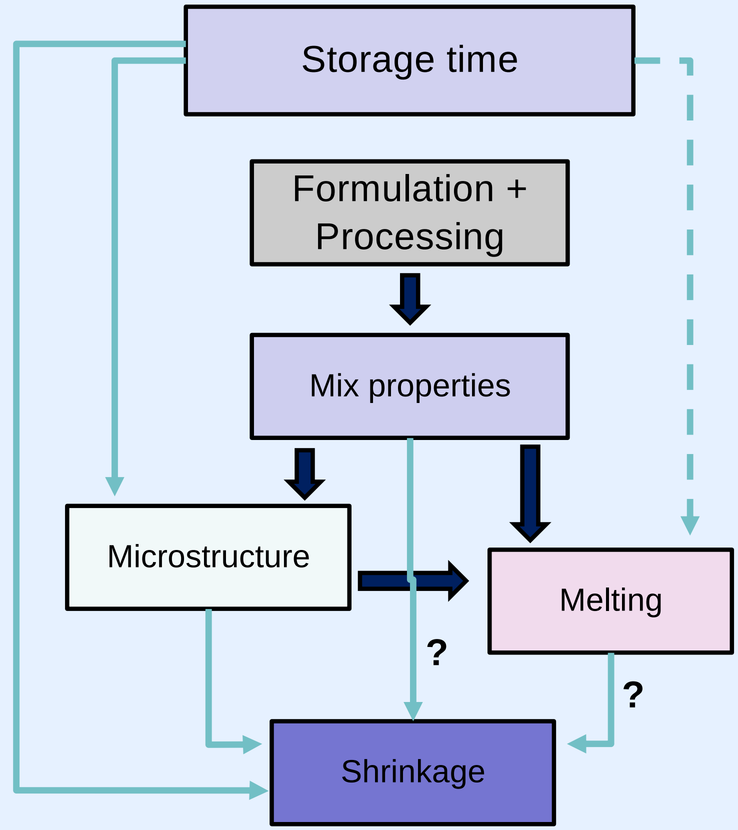
- No obvious asymmetry, which would be reflective of stress/strain hardening, but these are high concentrations of protein an effects might not show up



Evaluate Ice Creams

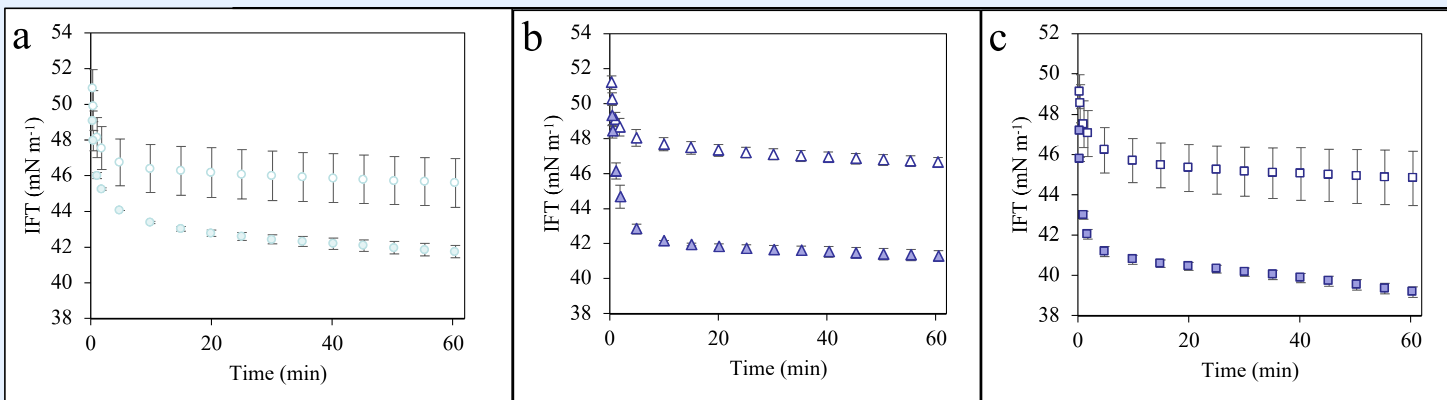
- Protein source
  - Milk protein concentrate (MPC)
  - Sodium caseinate (NaCN)
  - Whey protein isolate (WPI)
- Emulsifier addition
  - 0.0%; 0.15% MDG
- Overrun
  - 100%; 150%
- Storage time
  - 0, 2, 4, 6 weeks

Fat	12.0%
MSNF	13.3%
- Protein	6.0%
- Lactose	6.3%
Milk minerals	1.0%
Sucrose	14.5%
Stabilizer	0.2%
MDG	0.0 or 0.15%
Total solids	40%



Mix Properties

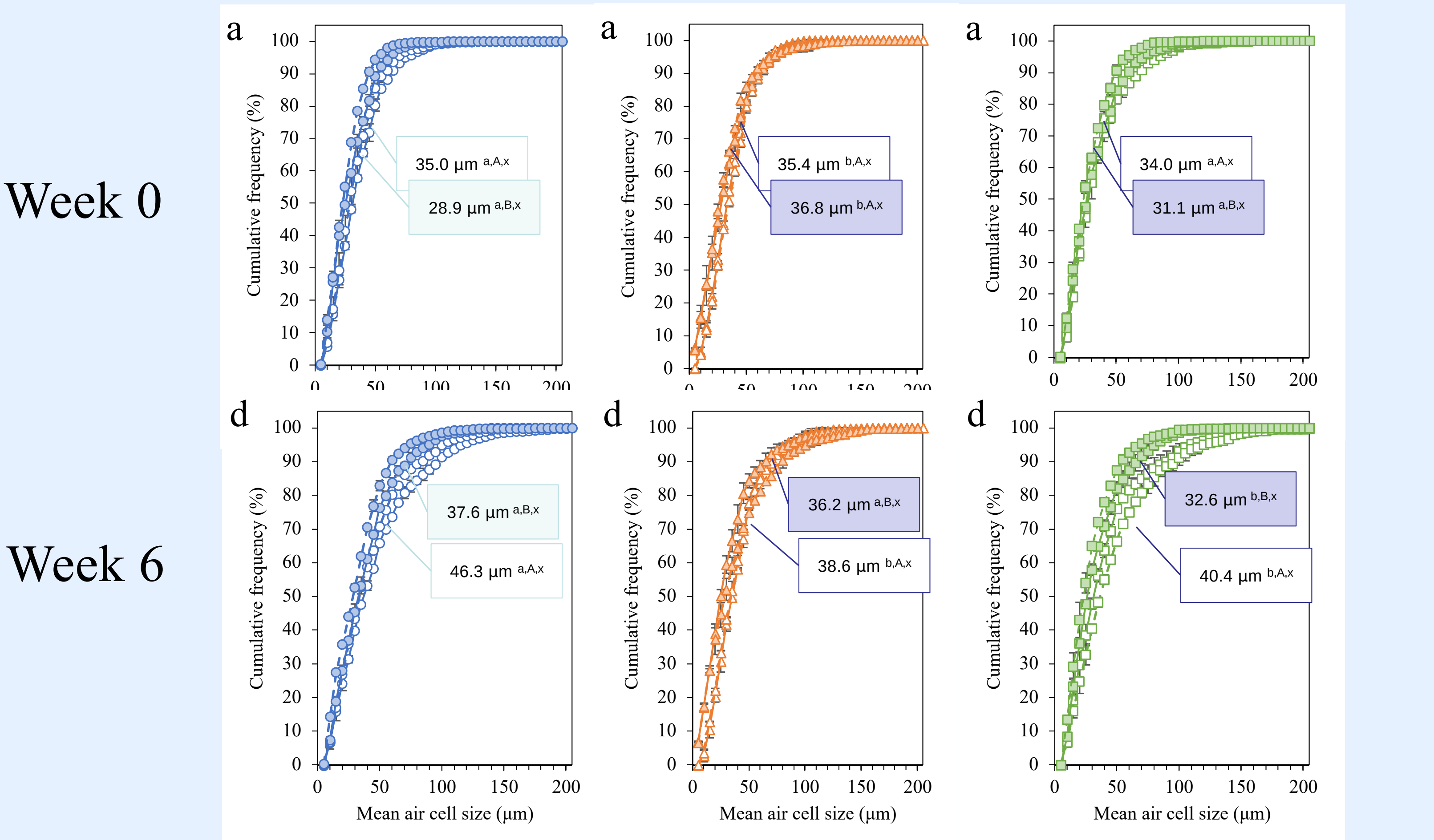
Protein source	MDG (%)	Density (g mL^{-1})	IFT (mN m^{-1})	Viscosity (50 s^{-1}) (mPa·s)
MPC	0.0	1.11 ± 0.00 $^{a, A}$	45.6 ± 1.36 $^{a, A}$	299 ± 7.30 $^{a, A}$
	0.15	1.12 ± 0.00 $^{a, A}$	41.8 ± 0.35 $^{a, B}$	359 ± 19.4 $^{a, B}$
NaCN	0.0	1.12 ± 0.01 $^{a, A}$	46.7 ± 0.28 $^{a, A}$	466 ± 22.2 $^{b, A}$
	0.15	1.12 ± 0.01 $^{a, A}$	41.3 ± 0.31 $^{ab, B}$	507 ± 30.5 $^{b, A}$
WPI	0.0	1.11 ± 0.01 $^{a, A}$	44.8 ± 1.36 $^{a, A}$	123 ± 0.57 $^{c, A}$
	0.15	1.13 ± 0.01 $^{a, A}$	39.2 ± 0.26 $^{b, B}$	134 ± 3.90 $^{c, A}$



	0.0%	0.15%
MPC	○	●
NaCN	△	▲
WPI	■ (grey)	■

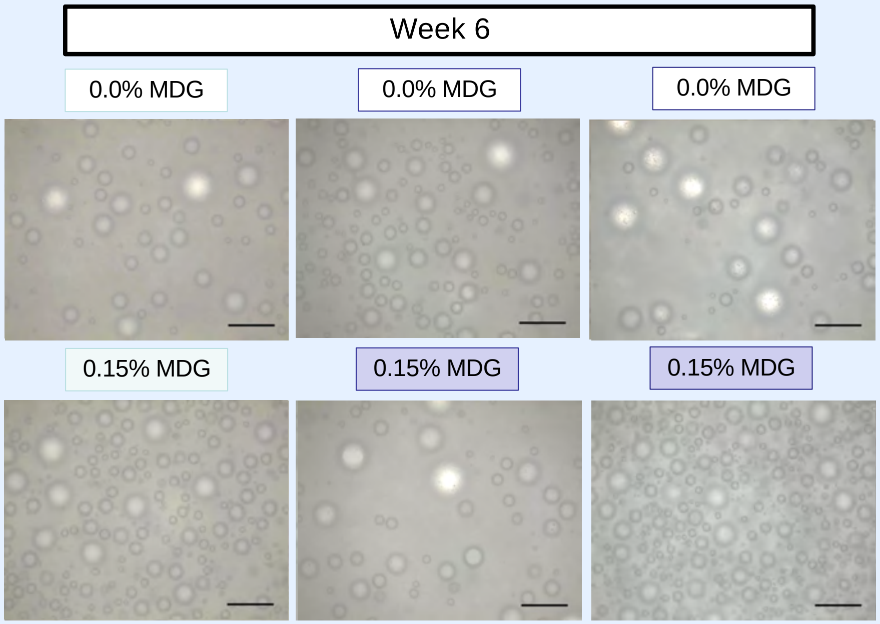
MPC (○●) NaCN (△▲) WPI (■■) $^{a, b, c}$ = by protein source; $^{A, B}$ = by MDG addition

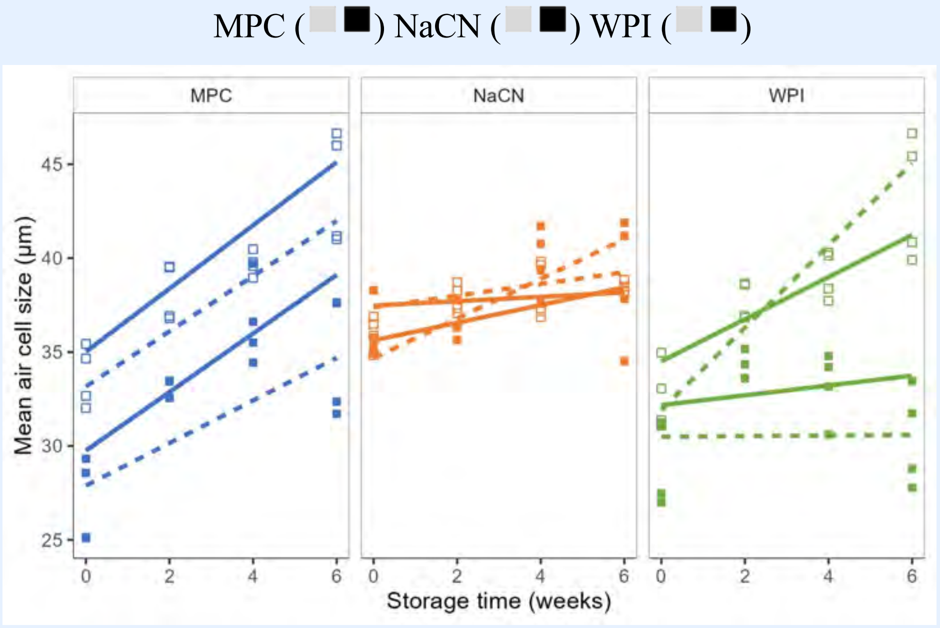
Air Cells



MPC ( ) NaCN ( ) WPI ( ) a, b, c = by protein source; A, B = by MDG addition; x, y = by overrun

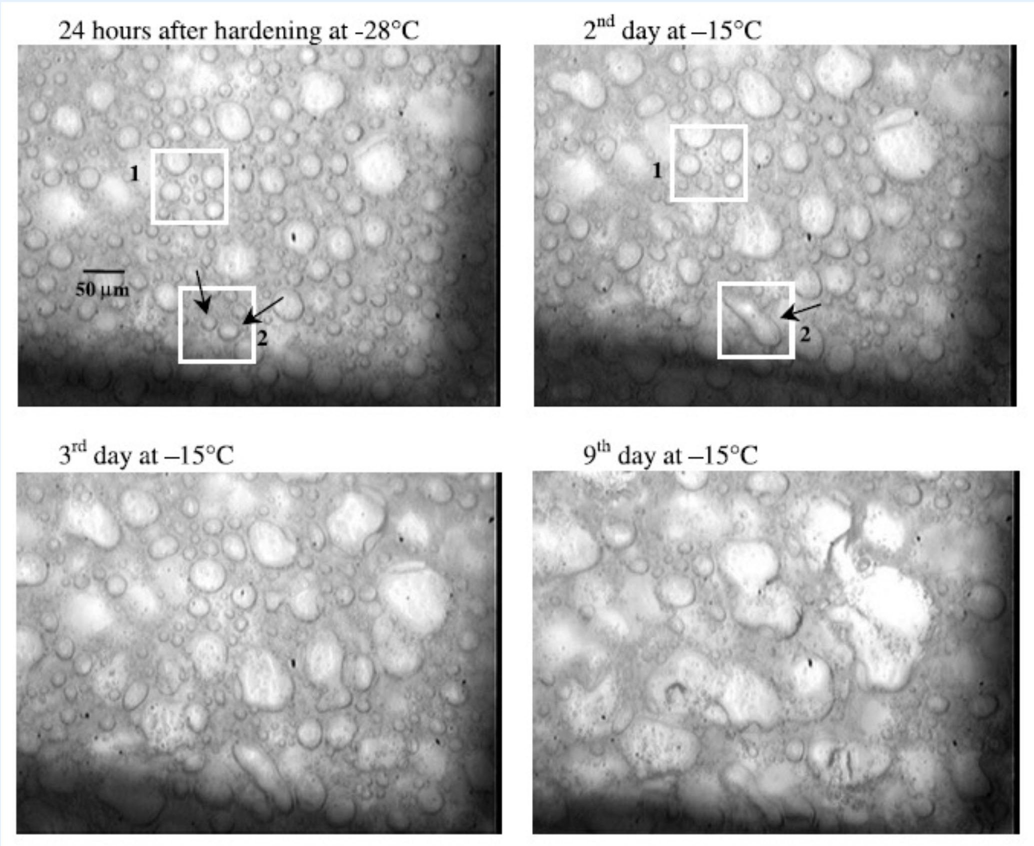
Air Cell Coarsening





- *Coalescence, disproportionation, drainage*
- *Matrix phase properties; interfacial properties*

Air Cell Accretion



Chang and Hartel (2002)

NaCN, 0.15% MDG, 150% OR, 2 weeks

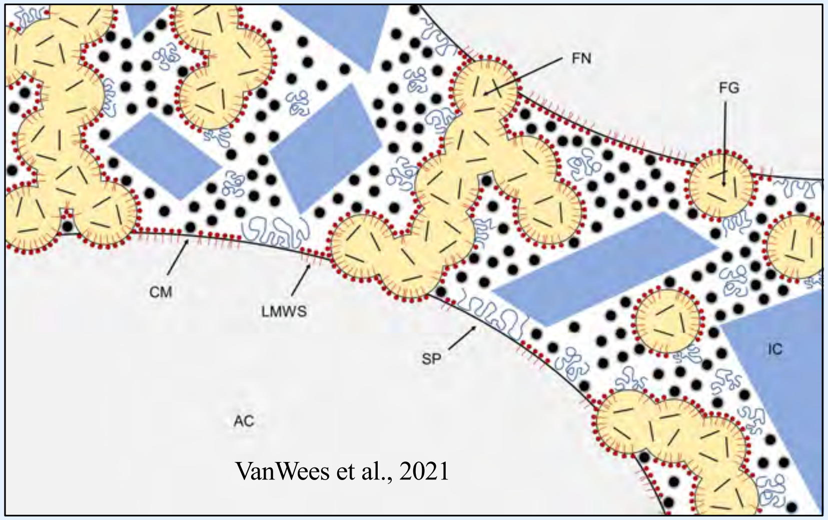
Shrinkage

Protein source	MDG (%)	OR (%)	Storage time (weeks)			
			0	**2**	**4**	**6**
MPC	0.0	100	NS	2.82 ± 2.10 $^{a, A, x}$	1.83 ± 3.50 $^{a, A, x}$	0.84 ± 3.50 $^{a, A, x}$
		150	NS	3.56 ± 1.05 $^{a, A, x}$	1.58 ± 2.45 $^{a, A, x}$	0.59 ± 1.05 $^{a, A, x}$
	0.15	100	NS	3.06 ± 3.85 $^{a, A, x}$	2.82 ± 2.10 $^{a, A, x}$	3.61 ± 0.979 $^{a, A, x}$
		150	NS	2.57 ± 0.350 $^{a, A, x}$	2.07 ± 1.05 $^{a, A, x}$	5.54 ± 0.350 $^{a, B, x}$
NaCN	0.0	100	NS	2.92 ± 0.559 $^{a, A, x}$	0.84 ± 3.50 $^{a, A, x}$	2.82 ± 2.10 $^{a, A, x}$
		150	NS	5.09 ± 0.280 $^{a, A, x}$	1.09 ± 2.45 $^{a, A, x}$	3.66 ± 1.19 $^{a, A, x}$
	0.15	100	NS	1.21 ± 0.168 $^{a, A, x}$	0.34 ± 1.40 $^{a, A, x}$	1.18 ± 1.05 $^{a, A, x}$
		150	NS	**14.6 ± 3.64 $^{b, B, y}$**	**14.7 ± 2.10 $^{b, B, y}$**	**32.0 ± 1.40 $^{b, B, y}$**
WPI	0.0	100	NS	0.59 ± 3.15 $^{a, A, x}$	2.32 ± 1.40 $^{a, A, x}$	1.53 ± 3.08 $^{a, A, x}$
		150	NS	1.18 ± 0.210 $^{a, A, x}$	6.28 ± 1.40 $^{a, A, x}$	4.30 ± 1.40 $^{a, A, x}$
	0.15	100	NS	0.59 ± 1.05 $^{a, A, x}$	2.32 ± 1.40 $^{a, A, x}$	1.53 ± 0.280 $^{a, A, x}$
		150	NS	3.56 ± 1.05 $^{a, A, x}$	5.09 ± 0.280 $^{a, A, x}$	3.31 ± 2.80 $^{a, A, x}$

$^{a, b, c}$ = by protein source; $^{A, B}$ = by MDG addition; $^{x, y}$ = by overrun NS = no shrinkage

Understanding Shrinkage

- Air phase destabilization is thermodynamically favorable, the best we can do is kinetically inhibit it
- Dependent upon:
  1. Composition and rheological properties of the air interface
  2. Composition and rheological properties of the matrix
  3. Ability of matrix to withstand temperatures and/or pressure changes.



VanWees et al., 2021

The problem of shrinkage remains an issue

Ice cream is complex!

Questions?

Thanks to all the students who have contributed to these studies
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