Rheology and Fracture Mechanics of Foods by Ton van Vliet

Chapter 13 - Gels

Mathieu Meerts
NNF Summer Reading Group, August 1, 2017

Who is this “Barrel in the Canal”?

- Ton van Vliet
- Prof. at Wageningen University
- Main research topics
  - Structure of food systems
  - Non-linear behavior
  - Fracture mechanics
- Retired in 2010

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Journal of Cereal Science 48 (2008) 1–9

Journal of
CEREAL
SCIENCE

www.elsevier.com/locate/jcs

Review

Strain hardening as an indicator of bread-making performance: A review with discussion

Ton van Vliet[a,b,*]

[a]TI Food and Nutrition, P.O. Box 557, 6700AN Wageningen, The Netherlands
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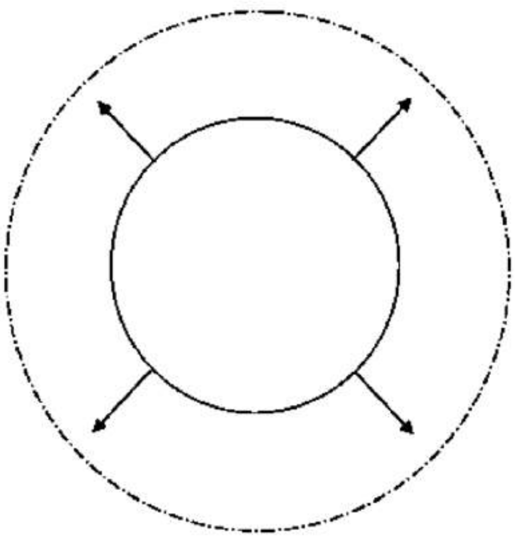
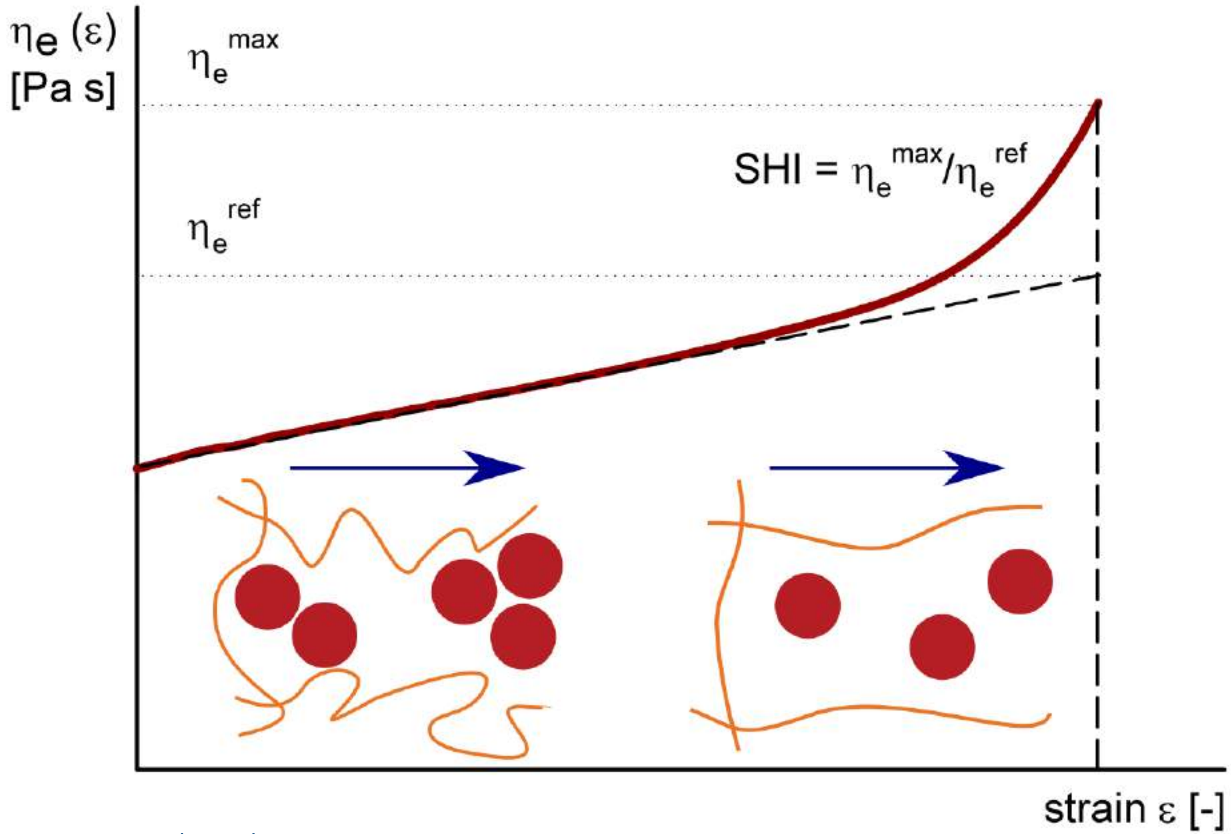
Received 7 August 2007; received in revised form 30 August 2007; accepted 31 August 2007

Side note: van Vliet & dough rheology

Wheat flour dough

- **Gluten proteins** (very broad MW distribution
- **Starch particles** (ellipsoidal 25-40 µm; spherical 5-10 µm)



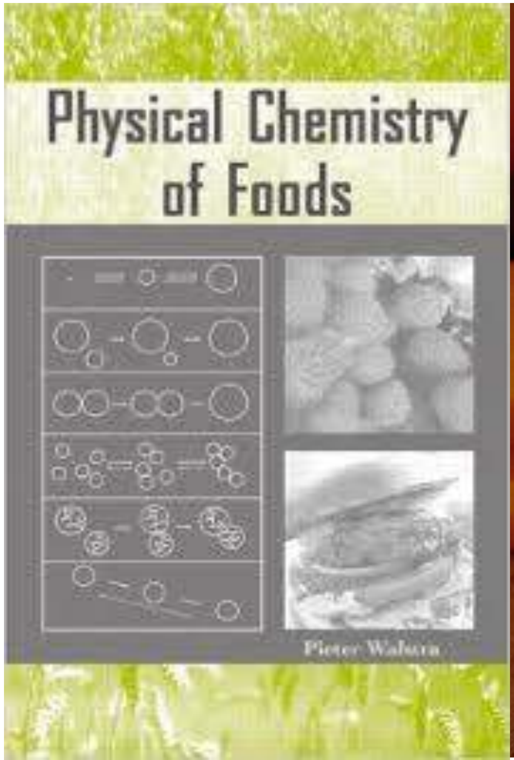


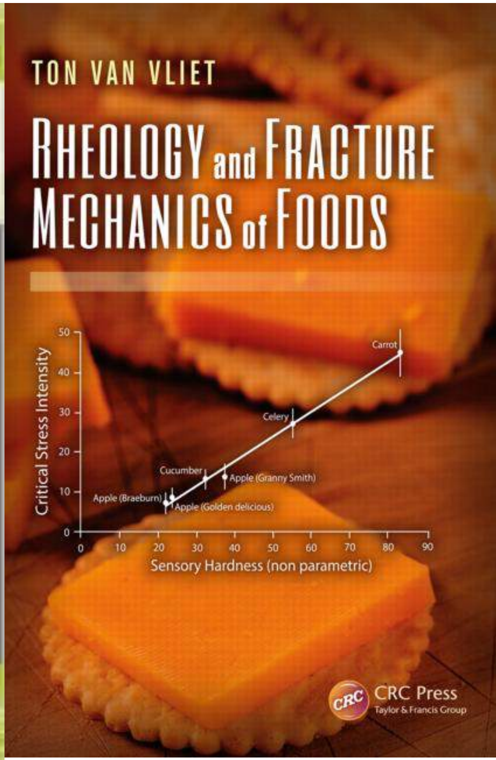
Bloksma, CFW 35, 228-236 (1990); van Vliet, JCS 48, 1-9 (2008)

What is the book about?

- Deformation, flow, and fracture behaviors of food systems
- Relation with structure at mesoscopic & macroscopic scale
- Material classes:
    - Dispersion
    - Macromolecular solution
    - Solid
    - **Gel (Chapter 13)**
    - Emulsion and foam

P. Walstra, Physical Chemistry of Foods
Marcel Dekker (NY), 2003





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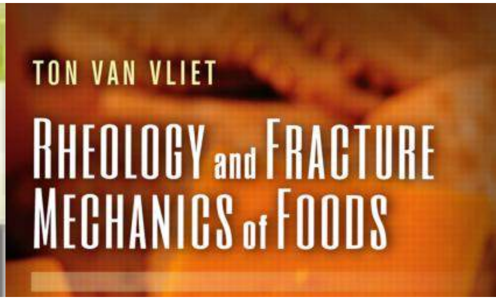

Walstra, Pieter. Physical chemistry of foods /Pieter Walstra. New York : Marcel Dekker, c2003.
Hayden Library - Stacks | TP372.5.W355 2003 - Missing

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Having trouble figuring out what to do next? Ask Us!

What is the book about?

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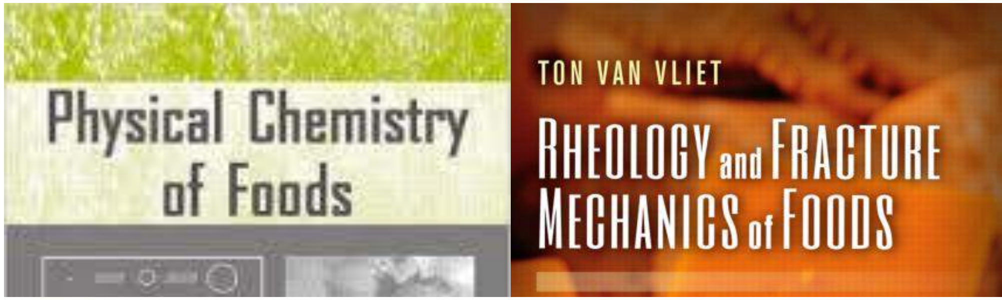

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2003 - Missing

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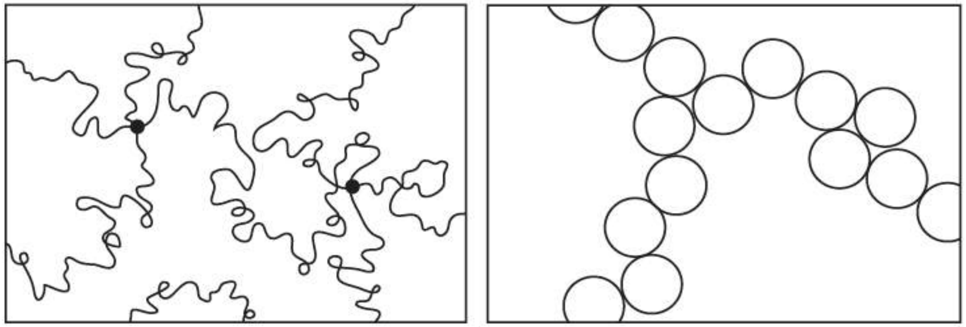
Having trouble figuring out what to do next? Ask Us!

Starting point

Gels in food products



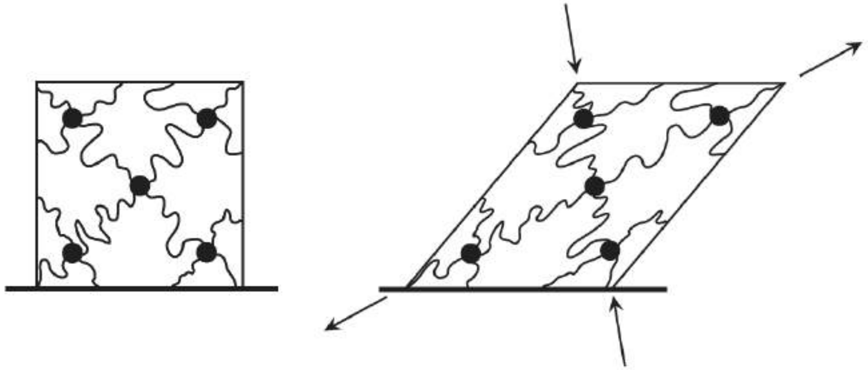
- Polymer networks (cf. Jianyi)
  - Chemically vs. physically
  - Flexible vs. stiff chains

- Particle networks (cf. Yacouba, Bavand, Michela)
  - Hard vs. deformable

- Large deformation properties important for the handling, usage, and eating characteristics of food products

Starting point

Formula for G:



$$\sigma = -N \frac{df_s}{dx} \Delta x$$

N = # stress-carrying strands per cross section

$$\Delta x = C \cdot \gamma$$ (C = a/26 for isotropic gel with straight strands cf. Bavand)

$$f_s = -\frac{dF}{dx}$$ (F = Gibbs energy)

$$G = CN \frac{d^2F}{dx^2} = CN \frac{d(\mathbf{dH} - T\mathbf{dS})}{dx^2}$$

long flexible chains

particle networks

stiff chains

A. Polymer networks

Case study: alginate gels
Side note: pectin gels

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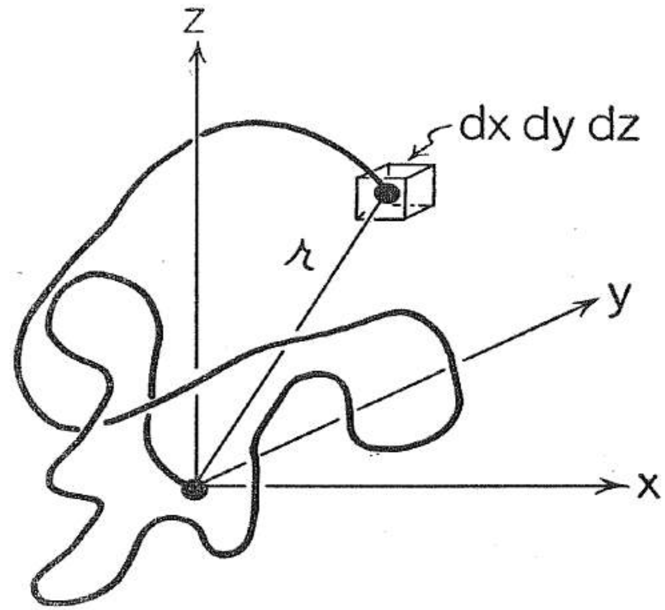
Polymer networks



Formula for G:

$$G = CN\frac{d^2F}{dx^2} = CN\frac{d(dH - TdS)}{dx^2} \approx -CNT\frac{d(dS)}{dx^2}$$

Boltzmann equation: $\mathbf{S = k_B \ln \Omega}$ Ω = probability that situation will occur

- Probability of any given chain having components x_i, y_i, z_i

$$\omega_i = W(x_i, y_i, z_i)\Delta x \Delta y \Delta z$$

- Probability that each chain in the entire system complies with specified set of coordinates

$$\prod_i \omega_i^{\beta_i}$$

- Particular selection of chains is of no importance, so

$$\Omega = \alpha! \prod_i \left(\omega_i^{\beta_i}/\beta_i!\right)$$

Flory, Principles of polymer chemistry (1953), p. 399-407 and p. 464-467

Polymer networks

Formula for G:

$$G \approx -CNT \frac{d(dS)}{dx^2}$$

$$\mathbf{S = k_B \ln \Omega}$$

Ω = probability that situation will occur

- Probability that the chain vector distribution, specified by β_i, will occur

$$\Omega = \alpha! \prod_i \left(\omega_i^{\beta_i} / \beta_i! \right)$$

- Taking logarithm + Stirling's approximation formula: $\ln n! \approx n \cdot \ln(n) - n$

$$\ln \Omega = \sum \beta_i \ln \left(\frac{\omega_i \alpha}{\beta_i} \right)$$

- Substitute in expression for G + use Gaussian function for ω_i + assume constant volume

  α = number of chains between 2 cross-links
  c = g chains between 2 cross-links per unit volume
  M_C = av. molecular weight of chain between 2 cross-links

$$\mathbf{G = \frac{\alpha k_B T}{V} = \frac{c R_g T}{M_c}}$$

Flory, Principles of polymer chemistry (1953), p. 464-470

Polymer networks

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$\mathbf{G \sim T}$

$\mathbf{G \sim c}$

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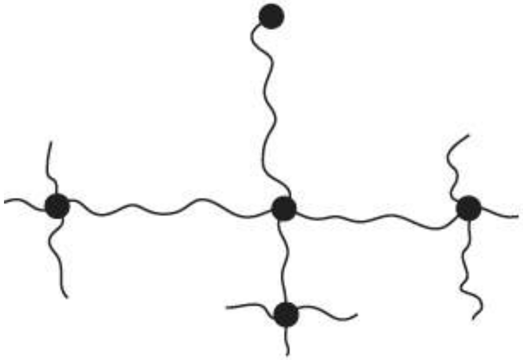
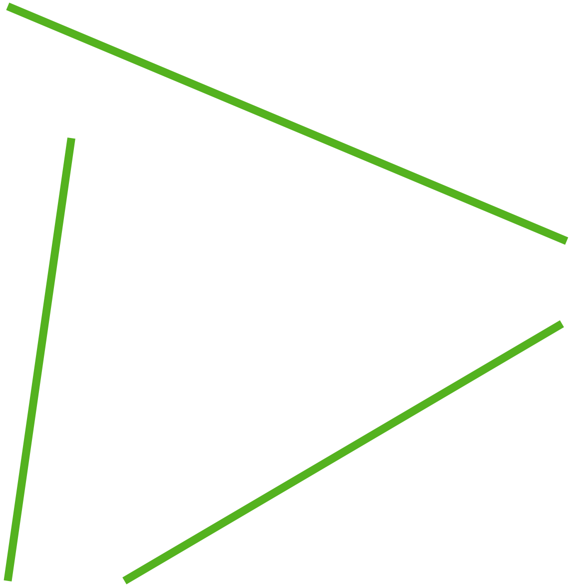
Flory, Principles of polymer chemistry (1953), p. 464-470

Polymer networks

Correction for dangling ends





Flory, Principles of polymer chemistry (1953), p. 458-463

Polymer networks

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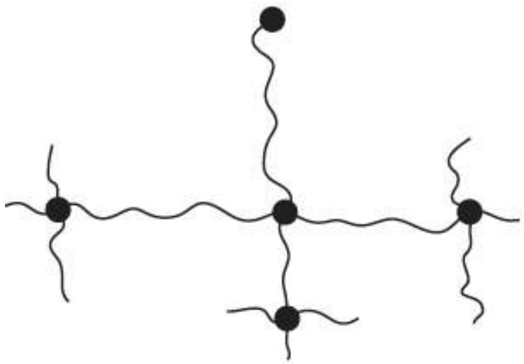

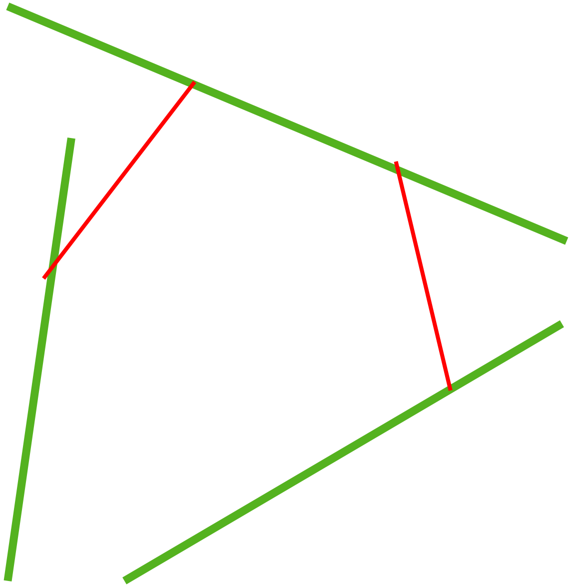

- N – 1 cross-links to create giant molecule

Flory, Principles of polymer chemistry (1953), p. 458-463

Polymer networks

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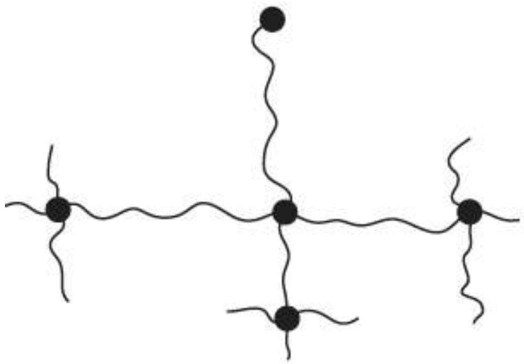
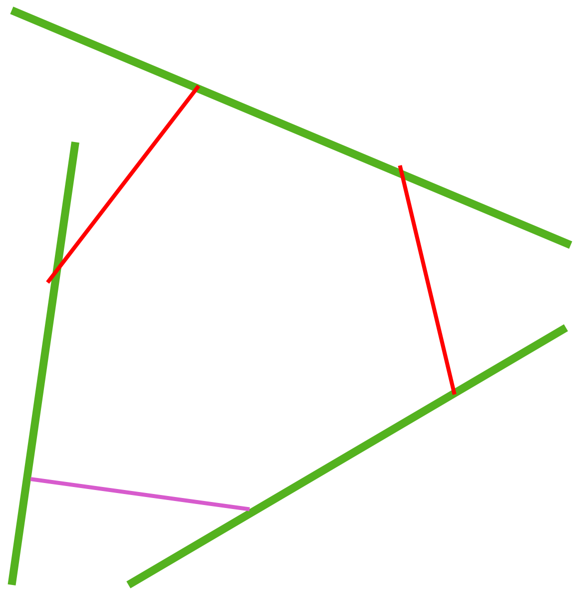


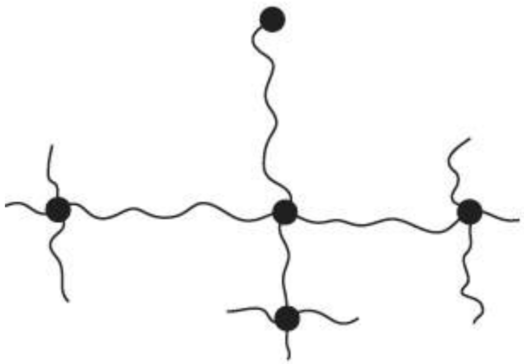


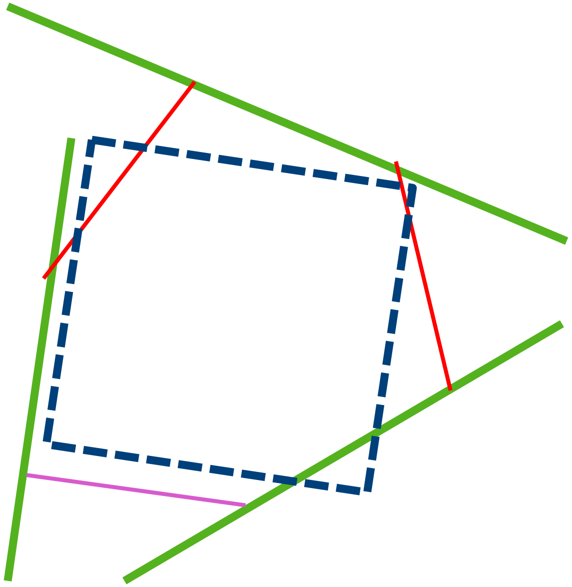
- N – 1 cross-links to create giant molecule
- Each additional cross-link

Flory, Principles of polymer chemistry (1953), p. 458-463

Polymer networks

Correction for dangling ends



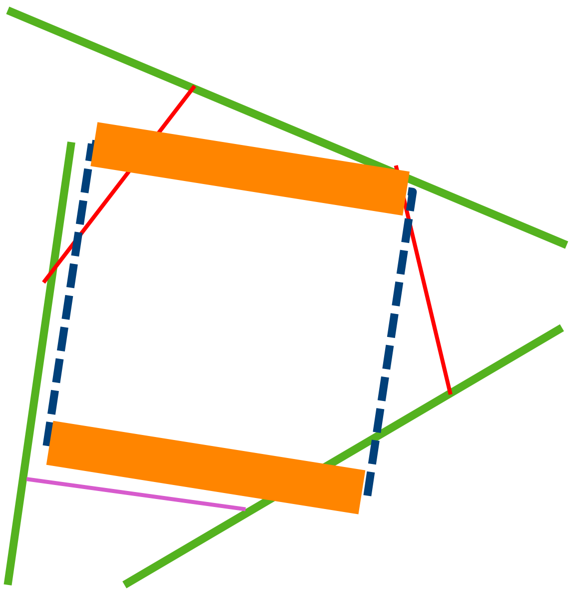


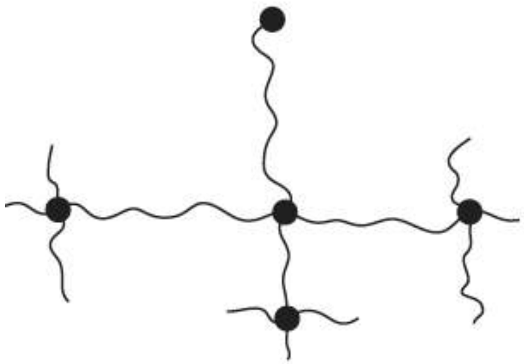
- N – 1 cross-links to create giant molecule
- Each additional cross-link = closed-loop circuit

Flory, Principles of polymer chemistry (1953), p. 458-463

Polymer networks

Correction for dangling ends





- N – 1 cross-links to create giant molecule
- Each additional cross-link = closed-loop circuit
- Closed-loop circuit = 2 elastic elements

Flory, Principles of polymer chemistry (1953), p. 458-463

Polymer networks

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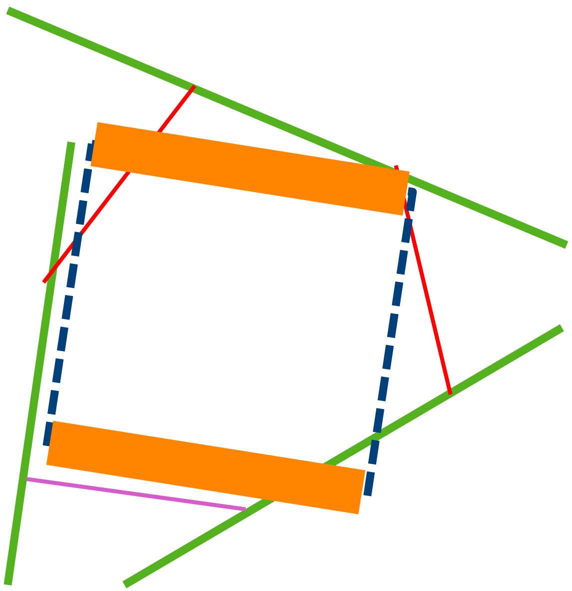
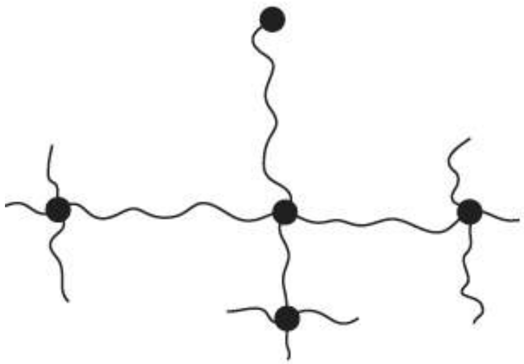




- N – 1 cross-links to create giant molecule
- Each additional cross-link = closed-loop circuit
- Closed-loop circuit = 2 elastic elements

$$\alpha_e/2 = \alpha/2 - N$$

$\alpha_e/2$ = number of effective cross-links
$\alpha/2$ = number of cross-links
N = number of primary chains

Flory, Principles of polymer chemistry (1953), p. 458-463

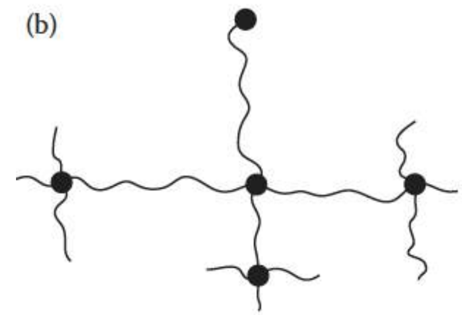
Polymer networks

Correction for dangling ends

$$\alpha_e/2 = \alpha/2 - N$$

$\alpha_e/2$ = number of effective cross-links
$\alpha/2$ = number of cross-links
N = number of primary chains

(b)



$$\alpha_e = \alpha - 2N = \alpha(1 - 2N/\alpha)$$

α_e = number of chains between 2 cross-links
= twice the number of loops

with

$$N = \frac{N_0 M_0}{M_N} = \frac{V}{\bar{v} M_N}$$

$$\alpha = \frac{N_0 M_0}{M_C} = \frac{V}{\bar{v} M_C}$$

$$G = \frac{k_B T \boldsymbol{\alpha_e}}{V} = \frac{k_B T \boldsymbol{\alpha}}{V}\left(\mathbf{1 - 2\frac{M_C}{M_N}}\right)$$

N_0 = number of units

M_0 = molecular weight of unit

$\bar{v}$ = specific volume

M_N = number average molecular weight of primary molecules

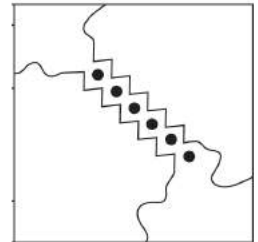
M_C = average molecular weight of chain between two cross-links

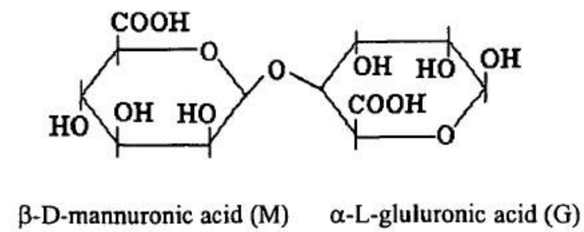
Other complications:
sol fraction, formation of entanglements

Flory, Principles of polymer chemistry (1953), p. 458-463

Polymer networks

Case study: alginate gels*

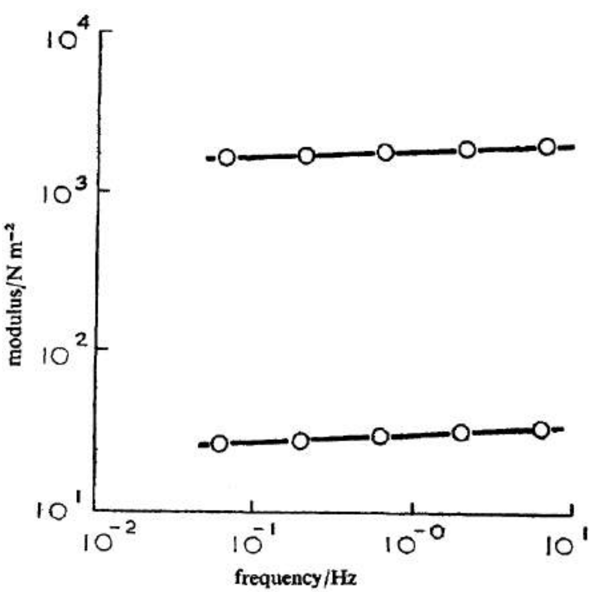




Alginate = polysaccharide from algae cell walls

= linear copolymer of M-blocks, G-blocks and MG-blocks

Dilute aqueous solution ⟶ gel by cross-linking corresponding blocks with Ca^{2+}



$\mathbf{G} \neq \mathbf{f(\omega)}$; $\mathbf{G \sim T}$ ⟶ rubber elasticity?

$$\mathbf{G = \frac{cR_gT}{M_c}}$$

M_C = average molecular weight of chain between two cross-links

M_C = 12 kg/kmol

M = 130 kg/kmol

⟶ 11 cross-links per alginate molecule

[η] indicates **only 2 statistical chain elements between 2 cross-links**

* Segeren et al. Faraday Discuss. Chem. Soc. 57:255-262 (1974)

Polymer networks

Limitations of the Rubber Elastic Theory

- Linear behavior

Why did it work for the case study?*

Long, **flexible** chains with many statistical elements

⟷ polysaccharide chains are **stiffer** (bulky side groups)

⟶ no Gaussian distribution: ~~**Rubber Elastic Theory**~~ in linear behavior

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Polymer networks

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⟶ no Gaussian distribution: ~~**Rubber Elastic Theory**~~ in linear behavior

- Non-linear behavior

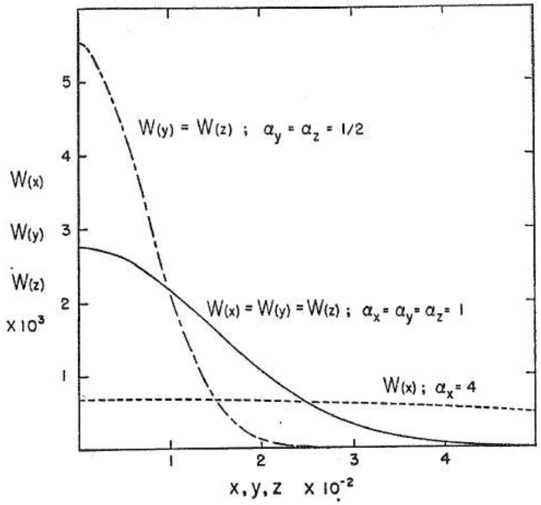
Deformation: **distortion** of Gaussian distribution

Finite chain extensibility: increase in **enthalpy**

(Strain-induced crystallization)

⟶ ~~**Rubber Elastic Theory**~~ in non-linear behavior

⟶ **Treloar theory****



* Segeren et al. Faraday Discuss. Chem. Soc. 57:255-262 (1974) ** Treloar. The physics of rubber elasticity (1975) Chapter 6

Side note


Innovative Food Science and Emerging Technologies 42 (2017) 138–150

Contents lists available at ScienceDirect

Innovative Food Science and Emerging Technologies

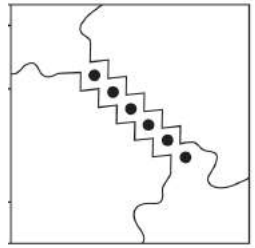
journal homepage: www.elsevier.com/locate/ifset

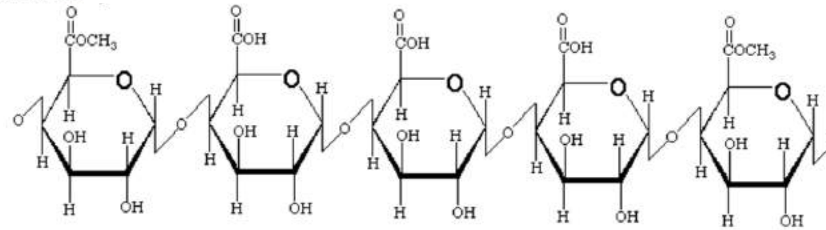
ELSEVIER

Pectin based food-ink formulations for 3-D printing of customizable porous food simulants

Valérie Vancauwenberghe[a,*], Louise Katalagarianakis[a], Zi Wang[a], Mathieu Meerts[b], Maarten Hertog[a], Pieter Verboven[a], Paula Moldenaers[b], Marc E. Hendrickx[c], Jeroen Lammertyn[a], Bart Nicolaï[a]

Case study: pectin gels*





Pectin = polysaccharide from plant cell walls

= galacturonan backbone (or other) + partially methyl esterified

Low methoxyl pectin: strong gels with **Ca^{2+} ions** through egg-box junctions

Ca^{2+}/ pectin

* Vancauwenberghe et al. IFSaET 42:138-150 (2017)

B. Particle networks

Case study: casein gels

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Particle networks

Small deformation properties for fractal particle gels

- Starting point: $G = CN\frac{d^2F}{dx^2}$

N = # stress-carrying strands per cross section

Particle networks

Small deformation properties for fractal particle gels

- Starting point: $G = CN\frac{d^2F}{dx^2}$ N = # stress-carrying strands per cross section
- Fractal clusters are **scale invariant**: **N** $\propto R_g^{-2}$

Particle networks

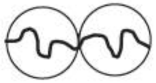
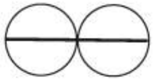
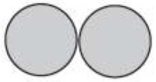
Small deformation properties for fractal particle gels

- Starting point: $G = CN\frac{d^2F}{dx^2}$

  N = # stress-carrying strands per cross section

- Fractal clusters are **scale invariant**: **N** $\propto R_g^{-2}$

- In a similar fashion, **C** and $\frac{d^2F}{dx^2}$ also relate to R_g, but the exact scaling relation depends on the **structure of the strands**

Structural Model	Structure	$l_a/2R$	$C \propto R_g 2R/l_a$	d^2F/dx^2	$NC(d^2F/dx^2)$
Fractal strands		R_g^x	R_g^{1-x}	R_g^{-2}	$R_g^{-(3+x)}$
Hinged strands		–	R_g	R_g^{-2}	R_g^{-3}
Stretched strands		R_g	–	–	R_g^{-2}
Weak links		–	R_g	–	R_g^{-1}

Particle networks

Small deformation properties for fractal particle gels

- Starting point: $G = CN\frac{d^2F}{dx^2}$ N = # stress-carrying strands per cross section

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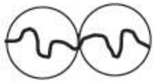
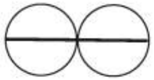
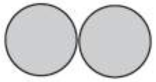
- So we can write:

$$G = CN\frac{d^2F}{dx^2} \propto R_g^{-k}$$

Structural Model	Structure	$l_a/2R$	$C \propto R_g 2R/l_a$	d^2F/dx^2	$NC(d^2F/dx^2)$
Fractal strands		R_g^x	R_g^{1-x}	R_g^{-2}	$R_g^{-(3+x)}$
Hinged strands		–	R_g	R_g^{-2}	R_g^{-3}
Stretched strands		R_g	–	–	R_g^{-2}
Weak links		–	R_g	–	R_g^{-1}

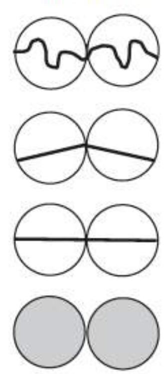
Particle networks

Small deformation properties for fractal particle gels

- Starting point: $G = CN\frac{d^2F}{dx^2}$ N = # stress-carrying strands per cross section
- Fractal clusters are **scale invariant**: **N** $\propto R_g^{-2}$
- In a similar fashion, **C** and $\frac{d^2F}{dx^2}$ also relate to R_g, but the exact scaling relation depends on the **structure of the strands**
- So we can write:

$$G = CN\frac{d^2F}{dx^2} \propto R_g^{-k}$$

$$G \propto R_{eff}^{-\alpha}\varphi^{\alpha/(3-D_f)}$$



Structural Model	Structure	$l_\alpha/2R$	$C \propto R_g 2R/l_\alpha$	d^2F/dx^2	$NC(d^2F/dx^2)$	α
Fractal strands		R_g^x	R_g^{1-x}	R_g^{-2}	$R_g^{-(3+x)}$	3 + x
Hinged strands		–	R_g	R_g^{-2}	R_g^{-3}	3
Stretched strands		R_g	–	–	R_g^{-2}	2
Weak links		–	R_g	–	R_g^{-1}	1

Particle networks

Small deformation properties for fractal particle gels

To prove: $\mathbf{N \propto R_g^{-2} \propto R_{eff}^{-2} \varphi^{2/(3-D_f)}}$ N = # stress-carrying strands per cross section

- Starting point:

$$N_p \propto \left(\frac{R_{agg}}{R_p}\right)^{D_f}$$

$$N_s \propto \left(\frac{R_{agg}}{R_p}\right)^{3}$$

N_p = # particles in fractal aggregate
R_p = particle radius
R_{agg} = aggregate radius
N_s = # sites that can be occupied in aggregate by particle

Particle networks

Small deformation properties for fractal particle gels

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$$N_s \propto \left(\frac{R_{agg}}{R_p}\right)^{3}$$

$$\varphi_{agg} = \frac{N_{agg}}{N_s} \propto \left(\frac{R_{agg}}{R_p}\right)^{D_f-3}$$

φ_{agg} = volume fraction particles in fractal aggregate

Particle networks

Small deformation properties for fractal particle gels

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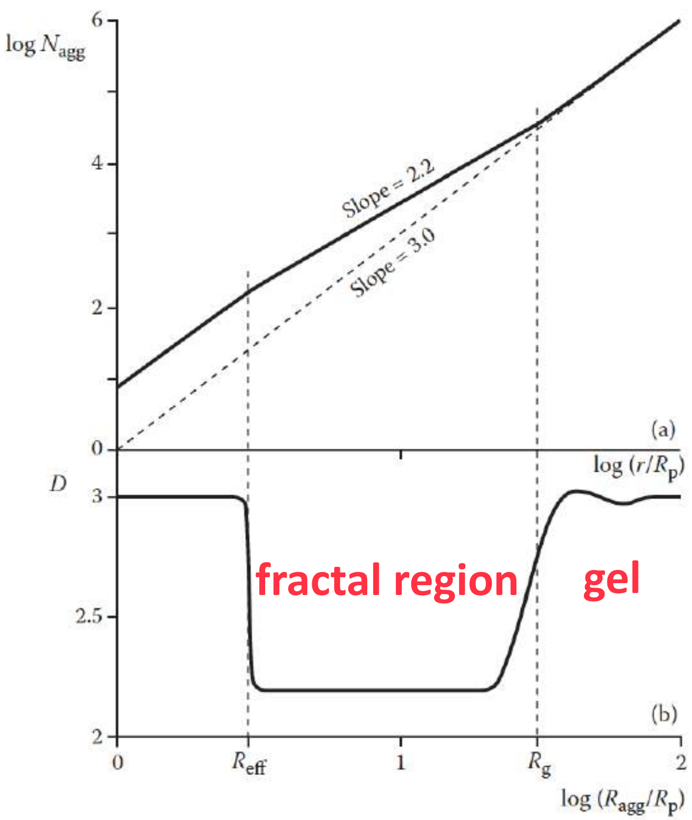
- φ_{agg} decreases as R_{agg} increases
- Aggregates touch each other ⟶ **gel formation**
- At scale >> R_{agg}: gel is homogeneous; **D = 3**

$$\longrightarrow \varphi_{agg} = \varphi$$

$$\longrightarrow \mathbf{R_g \propto R_p \varphi^{1/D_f-3}}$$

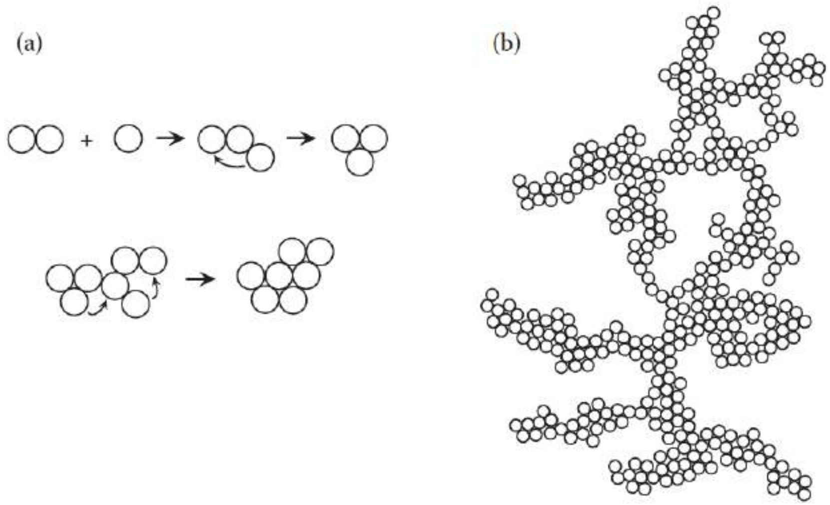
R_g = average radius of fractal clusters forming the gel



Particle networks

Small deformation properties for fractal particle gels

Complication: **interparticle rearrangements** during aggregation



Cluster forming unit ≠ primary particles
= small aggregates

Use R_{eff} instead of R_p:

$$R_g \propto \mathbf{R_{eff}} \varphi^{1/D_f - 3}$$

Particle networks

Small deformation properties for fractal particle gels

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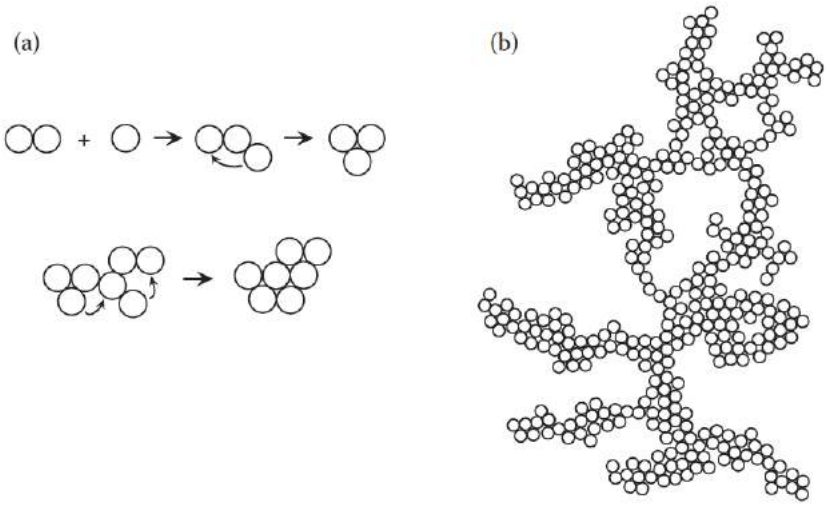

Cluster forming unit ≠ primary particles
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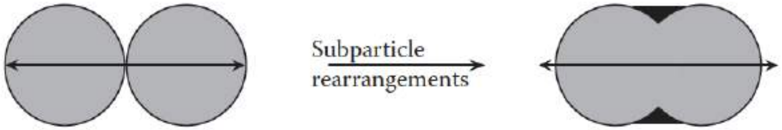
Use R_{eff} instead of R_p:

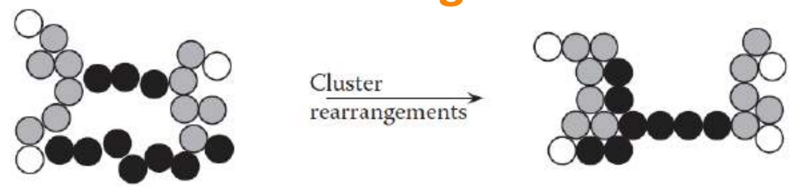
$$R_g \propto \mathbf{R_{eff}} \varphi^{1/D_f-3}$$

Note: other types of rearrangement during gelation and aging are also possible (C&D)

Particle fusion



Strand rearrangement



Particle networks

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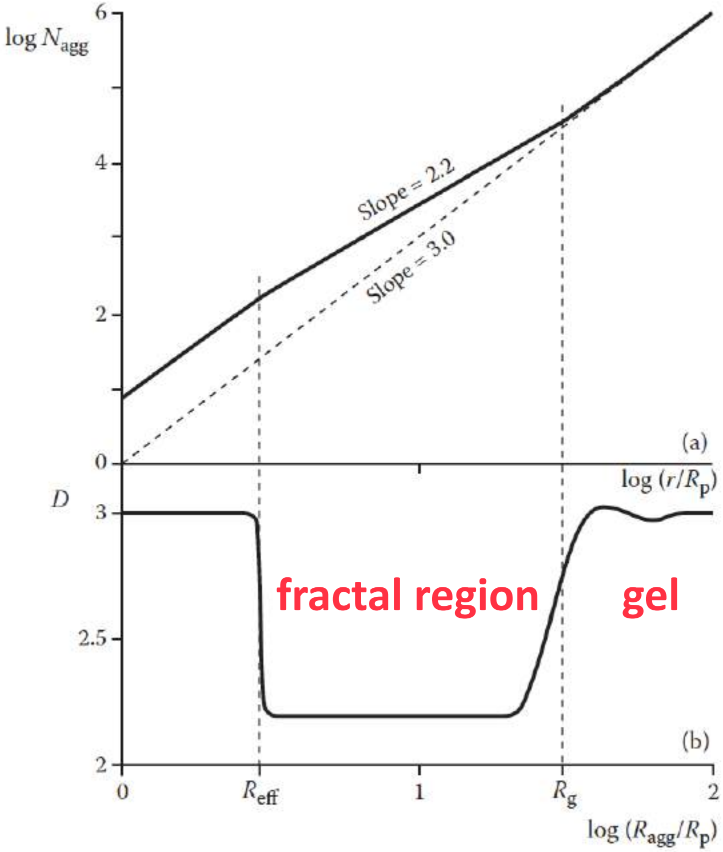


Cluster forming unit ≠ primary particles
= small aggregates

Use R_{eff} instead of R_p:

$$R_g \propto \mathbf{R_{eff}} \varphi^{1/D_f - 3}$$

Fractal behavior only **between R_{eff} and R_p**

For high φ: aggregate no longer fractal

Example: $D_f = 2.34$ and $\varphi = 0.3$:

$R_g \propto R_{eff}\varphi^{1/D_f-3} = 6R_{eff}$

Particle networks

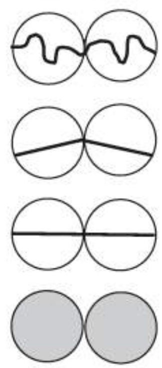
Derivation:
- Mellema et al. J. Rheol. 46:11-29 (2002)
- Lecture Michela

Small deformation properties for fractal particle gels

$$G = CN\frac{d^2F}{dx^2} \propto R_g^{-k}$$

$$R_g \propto R_{eff}\varphi^{1/D_f-3}$$

$$G \propto R_{eff}^{-\alpha}\varphi^{\alpha/(3-D_f)}$$

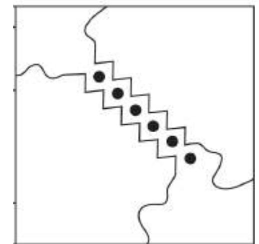


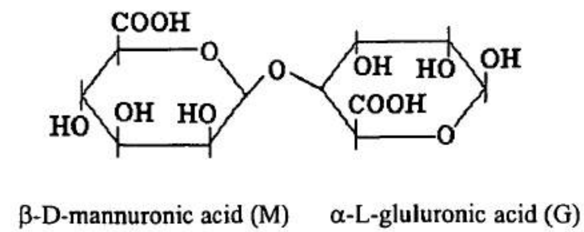
Structural Model	Structure	$l_a/2R$	$C \propto R_g 2R/l_a$	d^2F/dx^2	$NC(d^2F/dx^2)$	α
Fractal strands		R_g^x	R_g^{1-x}	R_g^{-2}	$R_g^{-(3+x)}$	3 + x
Hinged strands		–	R_g	R_g^{-2}	R_g^{-3}	3
Stretched strands		R_g	–	–	R_g^{-2}	2
Weak links		–	R_g	–	R_g^{-1}	1

	Fractal strands	Hinged strands	Stretched strands	Weak links
Rigid units	Particles forming the aggregates	Aggregates, following rearrangements	Particles forming the aggregates	Aggregates, following rearrangements
Type of strands	Fractal strands	Bonds between aggregates	Series of particles linked in a straight line	Weak links between aggregates

Particle networks

Case study: casein gels* (Bavand)





Casein = milk proteins largely composed of proline

= forms micelles in aqueous solutions, kept apart by protruding chains

Isoelectric point (pH 4.6) ⟶ chains collapse and gel is formed

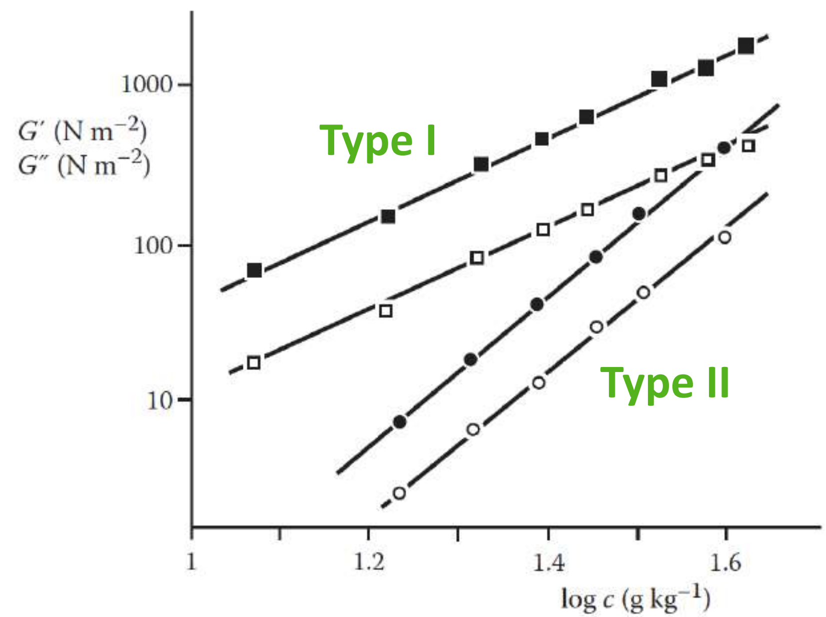
Type I: pH 4.6 @ T = 4°C, heat up to 30°C

⟶ Stretched strands

Type II: T = 30°C, add gluconolactone

⟶ Hinged strands

$$G \propto R_{\mathrm{eff}}^{-\alpha}\varphi^{\alpha/(3-D_f)}$$



* Bremer et al. Colloids Surf. 51:159-170 (1990)

Particle networks

Large deformation properties for fractal particle gels

	Modulus G	Fracture stress σ_{fr}	Fracture strain γ_{fr}
Starting point	$G = CN\frac{d^2F}{dx^2}$	$\sigma_{fr} \propto f_{fr}/R_g^2$	-
General equation	$G \propto R_{eff}^{-\alpha}\varphi^{\alpha/(3-D_f)}$	$\sigma_{fr} \propto R_{eff}^{-\upsilon}\varphi^{\upsilon/(3-D_f)}$	$\gamma_{fr} \propto R_{eff}^{-\beta}\varphi^{\beta/(3-D_f)}$
Parameters	D_f, α	D_f, υ	D_f, β

Structural Model	α (Equation 13.14)	υ (Equation 13.19)	β (Equation 13.20)
Fractal strands	$3 + x$	2	$-x$
Hinged strands	3	2	0
Stretched strands	2	2	0
Weak links	1	2	1

C. Heat-set protein gels

Case study: soy protein isolate

Heat-set protein gels

Formation of protein gels

Parameters inducing the gelation process

- **Temperature** (**case study**: soy protein isolate)
- **pH** (**presentation Bavand**: casein gels)
- Ionic strength
- Addition of specific salts
- Enzyme action

Heat-set protein gels

Case study: soy protein isolate (SPI)*

Soy protein = combination of β-conglycinin and glycinin

= hydrophobic and sulfhydryl (-SH) protein residues

T↑ (A) **Denaturation** of globular proteins

⟶ exposure of functional groups

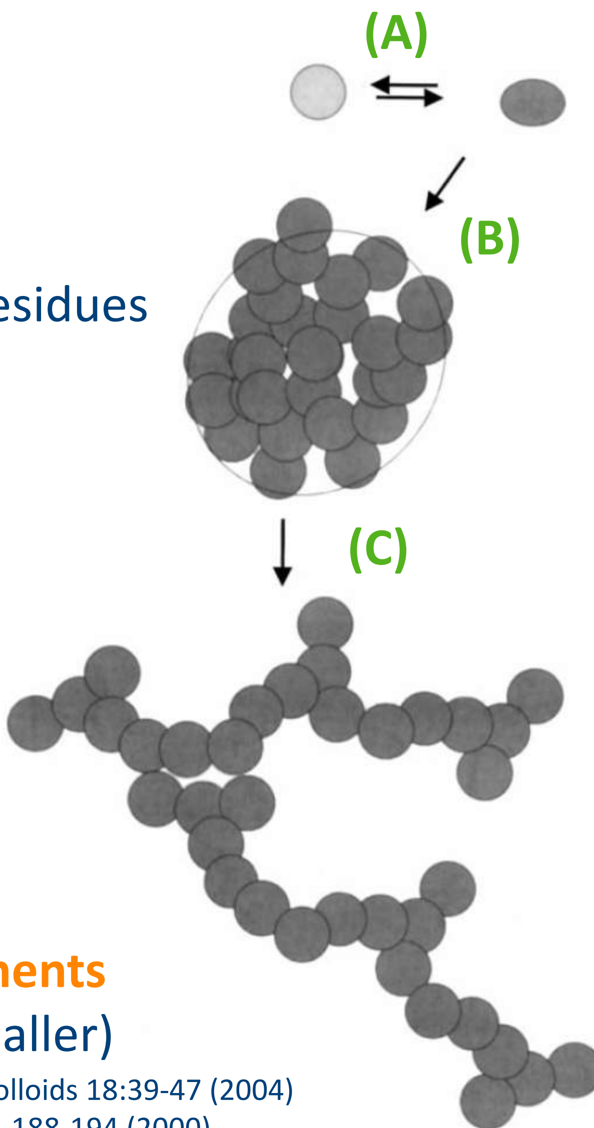
(B) **Aggregation** to form spherical particles

⟶ SS bridges, hydrophobic, H-bonds

(C) Particles form **network**

⟶ initially more or less fractal

⟶ loss of fractality due to **rearrangements** (strands just become thicker, pores smaller)



* Renkema and van Vliet. J. Agri. Food Chem. 50:1569-1573 (2002) & Renkema. Food Hydrocolloids 18:39-47 (2004) & Walstra. Physical chemistry of foods (2003), Chapter 15 & Gosal and Ross-Murphy, COCIS 5,188-194 (2000)

Heat-set protein gels

Case study: soy protein isolate (SPI)*

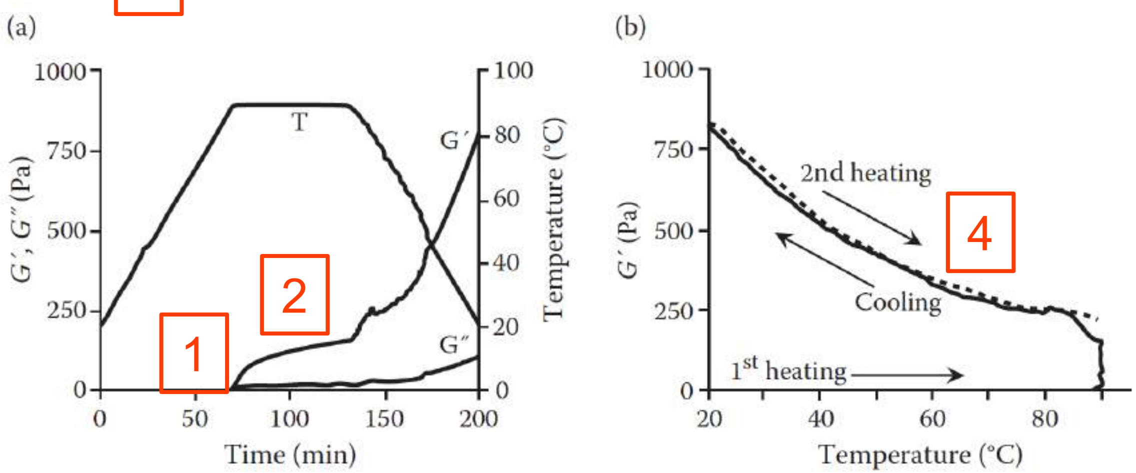
Effect of temperature

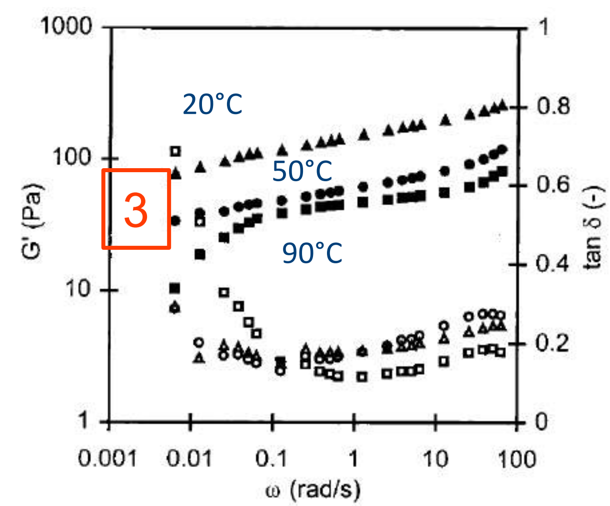
1 Denaturation is a prerequisite for gel formation

2 Increasing network strength by incorporation of protein and rearrangements

3 Short lifetime ⟶ no covalent SS bonds

4 Reversibility ⟶ no covalent bonds/fracture of strands





* Renkema and van Vliet. J. Agri. Food Chem. 50:1569-1573 (2002)

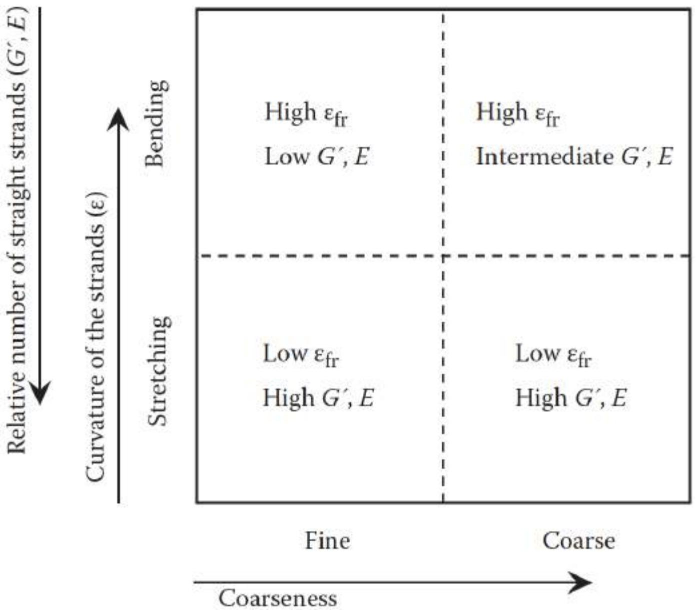
Heat-set protein gels

Case study: soy protein isolate (SPI)** **Effect of pH and ions**

Factors affecting rheological properties of heat-set network

- Amount of protein incorporated
- Network structure
  - **Coarseness** of strands (< CLSM, permeability) ↑ at isoelectric point or high ionic strength
  - **Curvature** of strands (< fracture strain)

1. Fracture strain ε_{fr} ~ curvature
2. Storage modulus G' ~ curvature + coarseness
3. Fracture stress σ_{fr} ~ coarseness + amount



… provided that interaction forces do not change

** Renkema. Food Hydrocolloids 18:39-47 (2004)

D. Plastic fats

Case study: palm oil in sunflower oil

Plastic fats

Formation of plastic fats

Network of triglyceride **fat** crystals in a triglyceride **oil**

T↓ (1) Formation of fat crystal **nuclei**

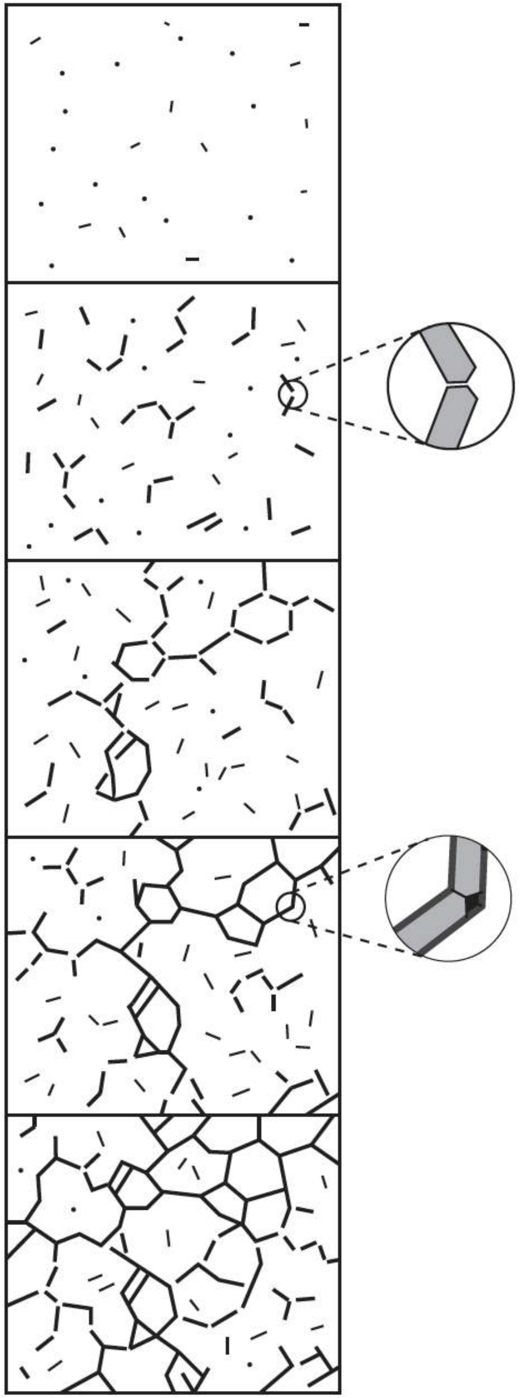
(2) **Growth** of fat crystals

(3) **Aggregation** of fat crystals

Special characteristics of these particle gels

- Processes occur simultaneously (slow cryst.*)
- **Sintering** (particle fusion, cf. part B)
- **Recrystallization** (composition/polymorph**)
- Crystals are strongly **anisometric**

no fractal structure



* Kloek, Mechaniclal properties of fat (1998), Chapter 3
** Walstra. Physical chemistry of foods (2003), Chapter 15

Plastic fats

*Kloek, Mechaniclal properties of fat (1998), Chapter 3;
Walstra. Physical chemistry of foods (2003), Chapter 15;
Walstra et al. Crystallization processes in fats and lipid systems (2001)

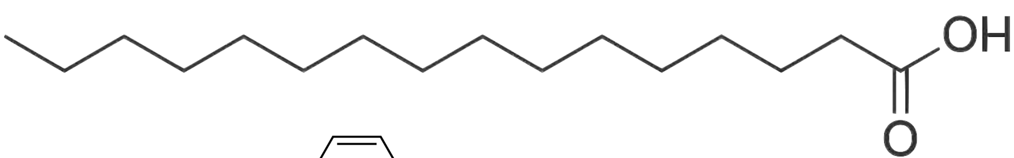
Case study: hydrogenated palm oil in sunflower oil*

Palm oil = reddish pulp of the fruit of oil palms

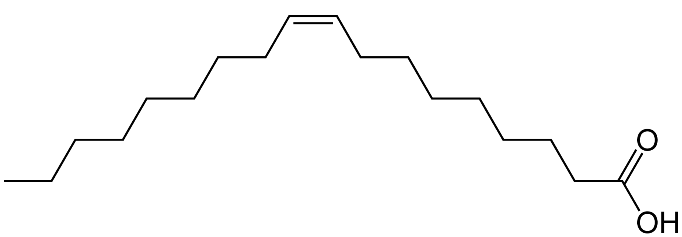
= saturated **palmitic acid** and mono-unsaturated **oleic acid**

Sunflower oil = compressed seeds of sunflower

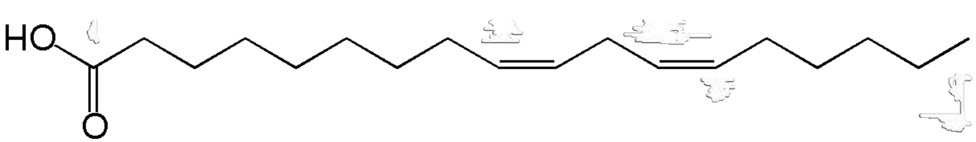
= poly-unsaturated **linoleic acid** and mono-unsaturated **oleic acid**



Palmitic acid



Oleic acid



Linoleic acid

Plastic fats

Case study: hydrogenated palm oil in sunflower oil

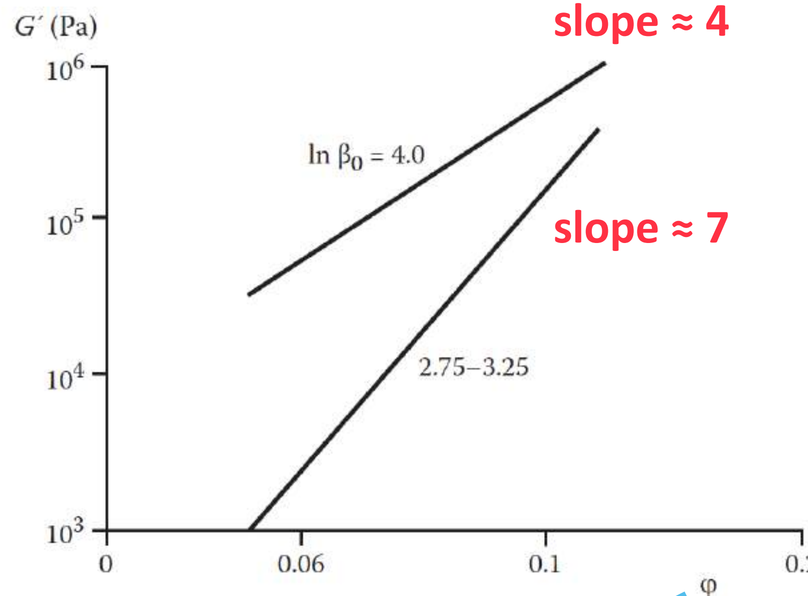
Small deformation properties

- Very small **linearity limit** (10^{-4})
- Scaling law for **shear modulus G**

$$G \propto \frac{\delta^2 F}{\delta H^2}\varphi^{\alpha/(3-D_f)}$$

$$G \propto \frac{A_H}{H_0^3}\varphi^{\alpha/(3-D_f)}$$

A_H = Hamaker constant
H_0 = hardcore inter-particle distance



slope ≈ 4

slope ≈ 7

requires adjustment of T to keep $\beta = x/x_s$ constant

!! Rheology and light scattering do not agree on D_f:

D_f (LS) = 1.7

⟶ **fractal nature is lost**

D_f	slope = 4	slope = 7
α = 1	2.75	2.86
α = 4	2	2.42

Plastic fats

Case study: hydrogena

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H_0 = hardcore inter-particle distance

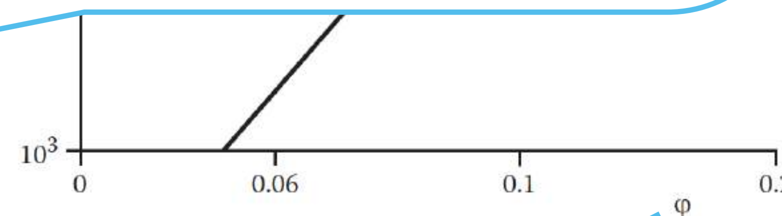
Kamphuis and Jongschaap Colloid & Polymer Sci 263:1008-1024 (1985)

Lennard-Jones energy potential for the potential energy content ΔE of a bond between two spherical nonpolar particles each having a diameter D :

$$\Delta E = \frac{A_H D}{24H}\left\{1 - \frac{1}{420}\left(\frac{r_o}{H}\right)^6\right\}$$

$$f_c = -\frac{\partial \Delta E}{\partial H} = \frac{A_H D}{24H^2}\left\{1 - \frac{1}{60}\left(\frac{r_o}{H}\right)^6\right\}$$

$$\frac{\delta f_c}{\delta H} = \frac{A_H D(15H^6 - r_0^6)}{180H^9}$$ and therefore $\frac{\delta f_c}{\delta H} \propto \frac{A_H}{H^3}$



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Plastic fats

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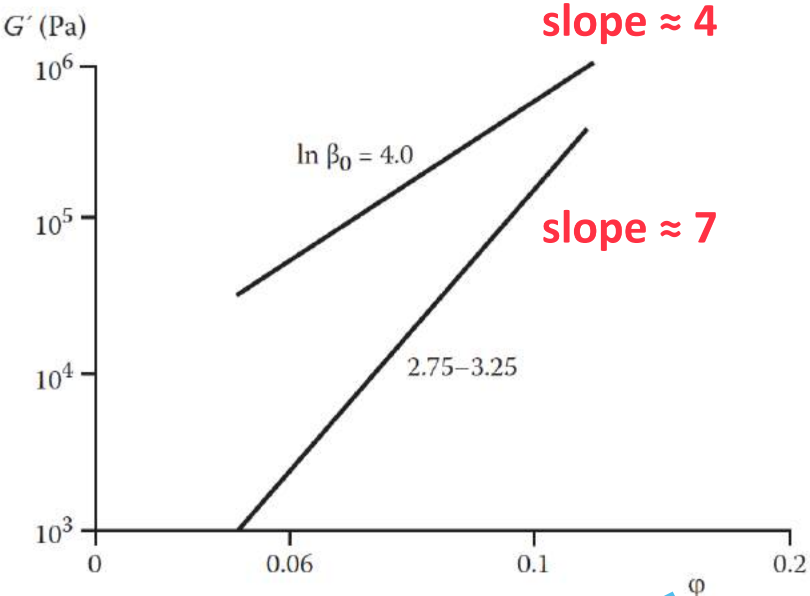

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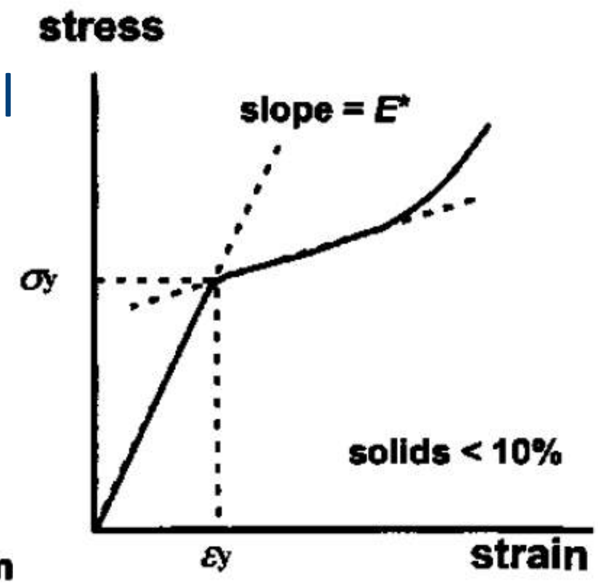

Large deformation properties

- Uniaxial compression/penetration tests
- Very small linear region: E ⟶ E_{app}
- Stress-overshoot
- Yielding (σ_y) (not fracture, unless high ϕ)
- Plastic flow

$$E_{app}, \sigma_y \propto \varphi^{\mu}$$

		High Shear	
Parameter	Rest	20 kg/h	50 kg/h
σ_y	3.9	1.1	1.9
E_{app}	3.8	1.2	2.4