# ECFP: At the interface of industry and academia

Daniel Hodgson

ECFP

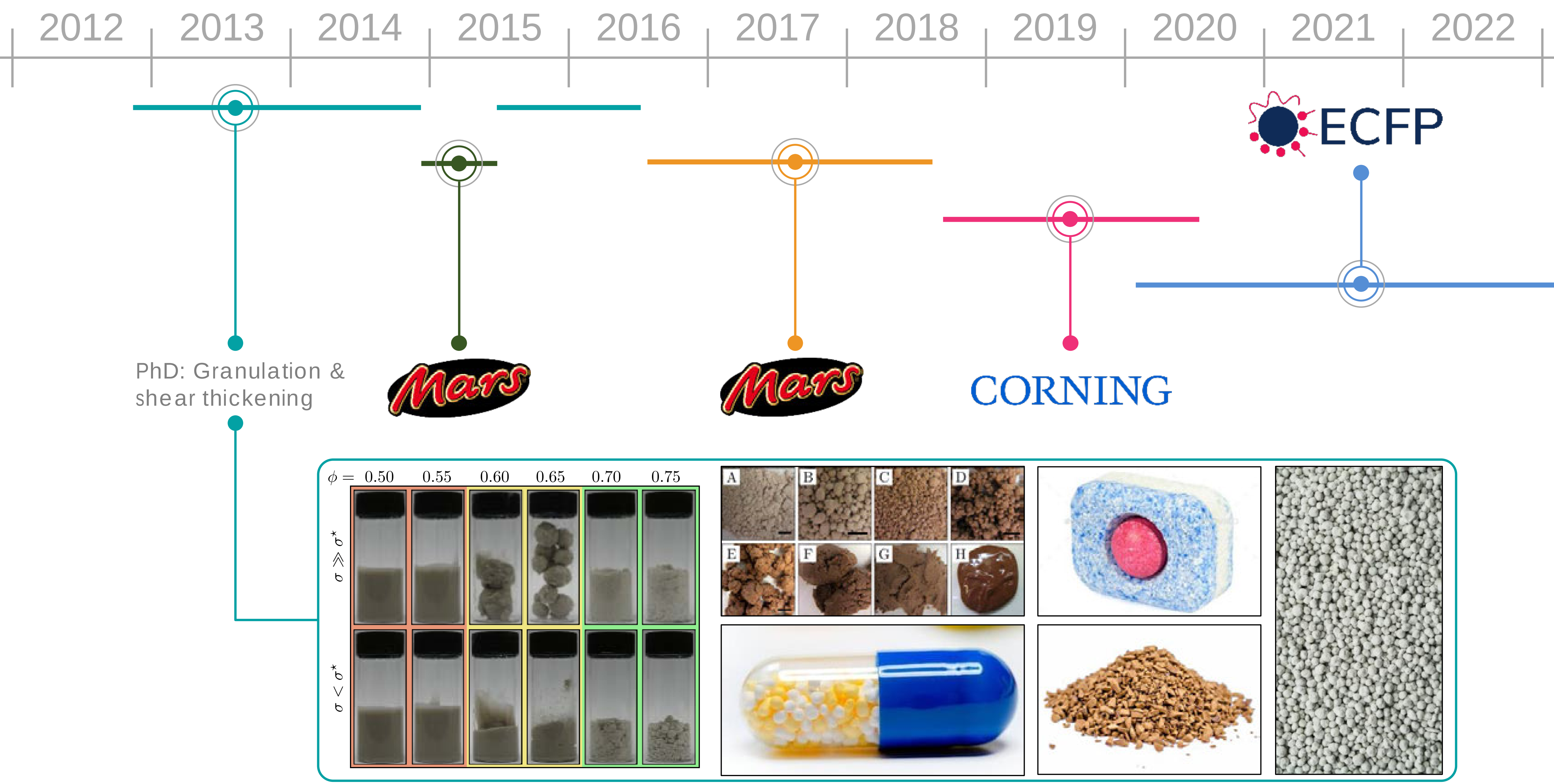
Formulating physics, clarifying complexity

www.edinburghcomplexfluids.com

THE UNIVERSITY of EDINBURGH

# Presentation overview

- What are complex fluids?
- Edinburgh Complex Fluids Partnership
- Case study: making chocolate
- Sustainability and Reformulation

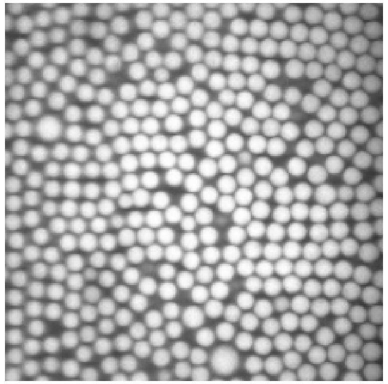


2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
ECFP
PhD: Granulation & shear thickening
Mars
Mars
CORNING
$\phi =$ 0.50 0.55 0.60 0.65 0.70 0.75
$\sigma \gg \sigma^*$
$\sigma < \sigma^*$
A
B
C
D
E
F
G
H

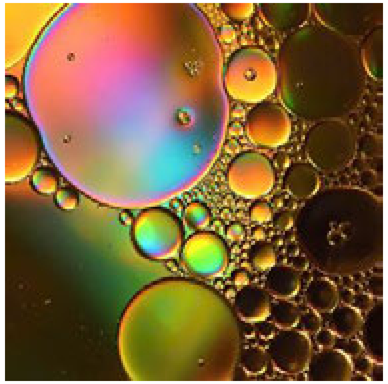
# What are complex fluids?

Liquids with bits in…

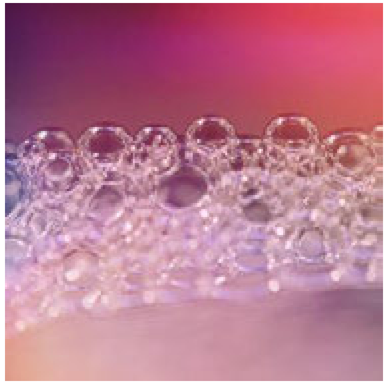
Particles



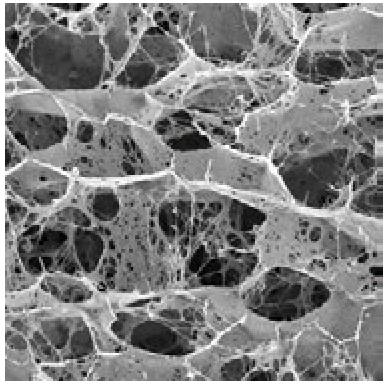
Emulsions



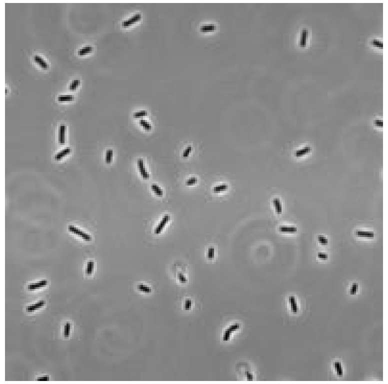
Surfactants



Polymers

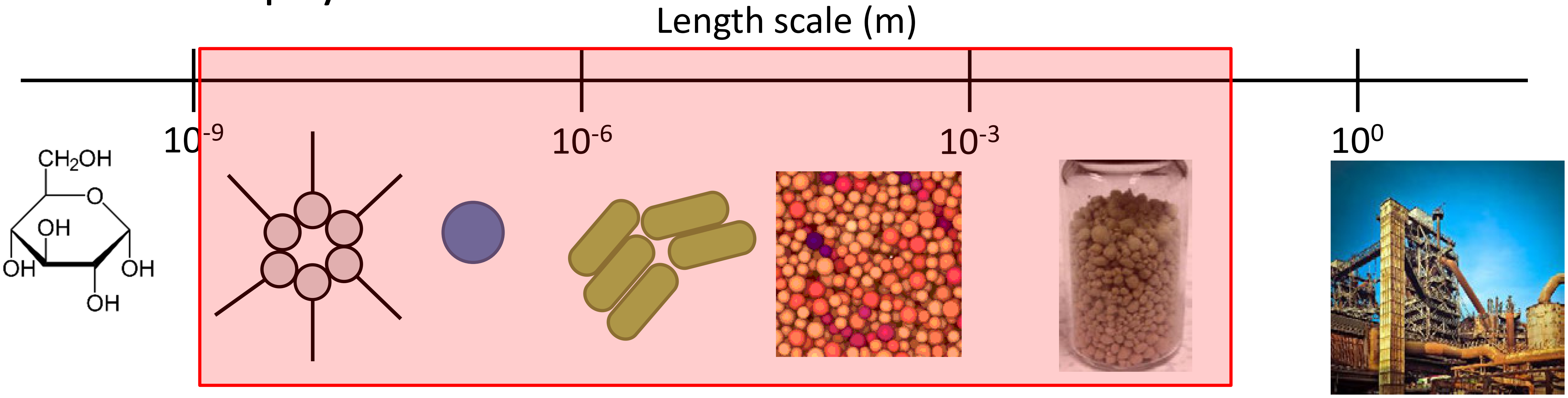


Microbes



Interfaces

# Soft matter physics




**£180 billion**

Per year UK net sales of formulated products

Source: Knowledge Transfer Network 2018

**£28 billion**

Size of UK Food and Drink sector

Source: Food & Drink Federation 2018

# Edinburgh Complex Fluids Partnership

ECFP

THE UNIVERSITY of EDINBURGH
School of Physics
& Astronomy

THE UNIVERSITY of EDINBURGH
School of Chemistry

THE UNIVERSITY of EDINBURGH
School of Engineering

THE UNIVERSITY of EDINBURGH
School of Biological Sciences

**Leading global centre for physics-driven formulation**

- Set up in 2012
- Worked with >50 companies
- SMEs to global blue-chip organisations
- Work across all sectors

- Projects range from 3 days to 3 years
- Consultancy, contract research and collaborative research
- Access a range of funding mechanisms
- Dedicated team of post-docs and academics





# Edinburgh Complex Fluids Partnership

**Industry facing**

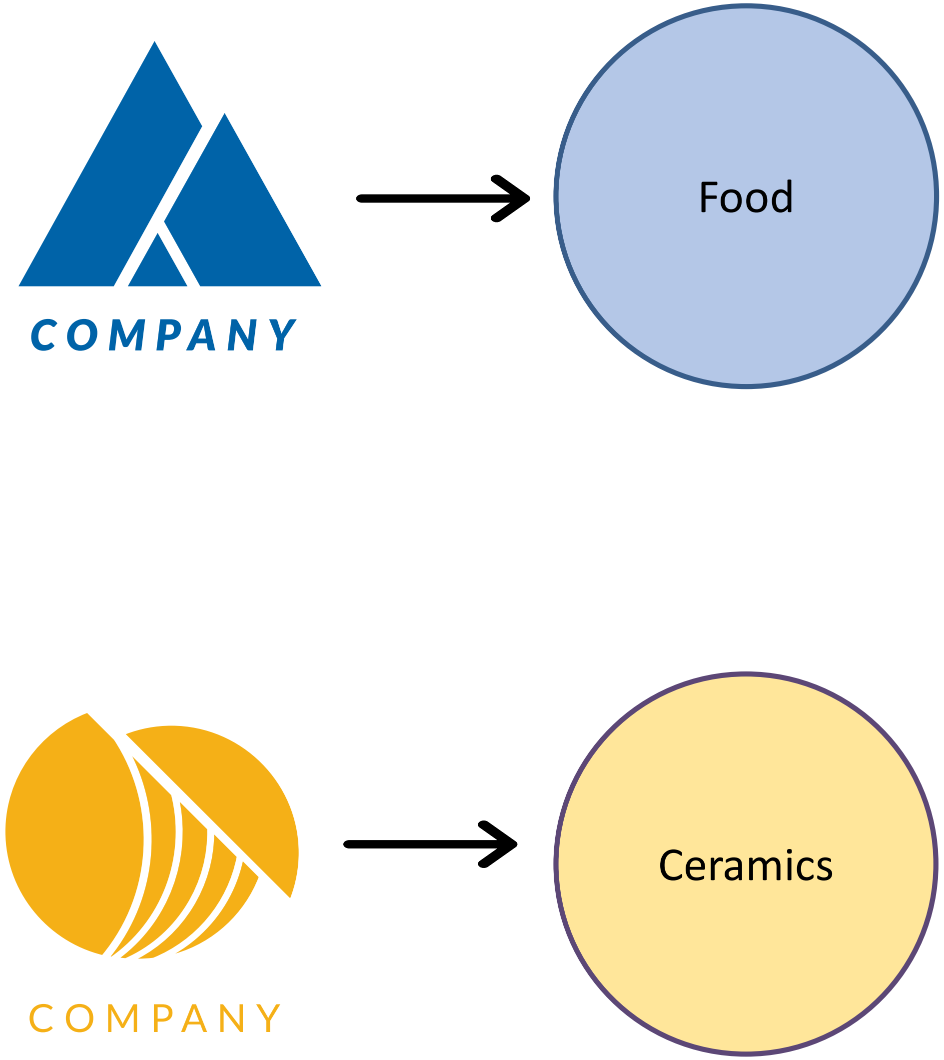
- Help solve industry problems
- Improve product performance & consumer experience
- Innovation and reformulation

**University facing**

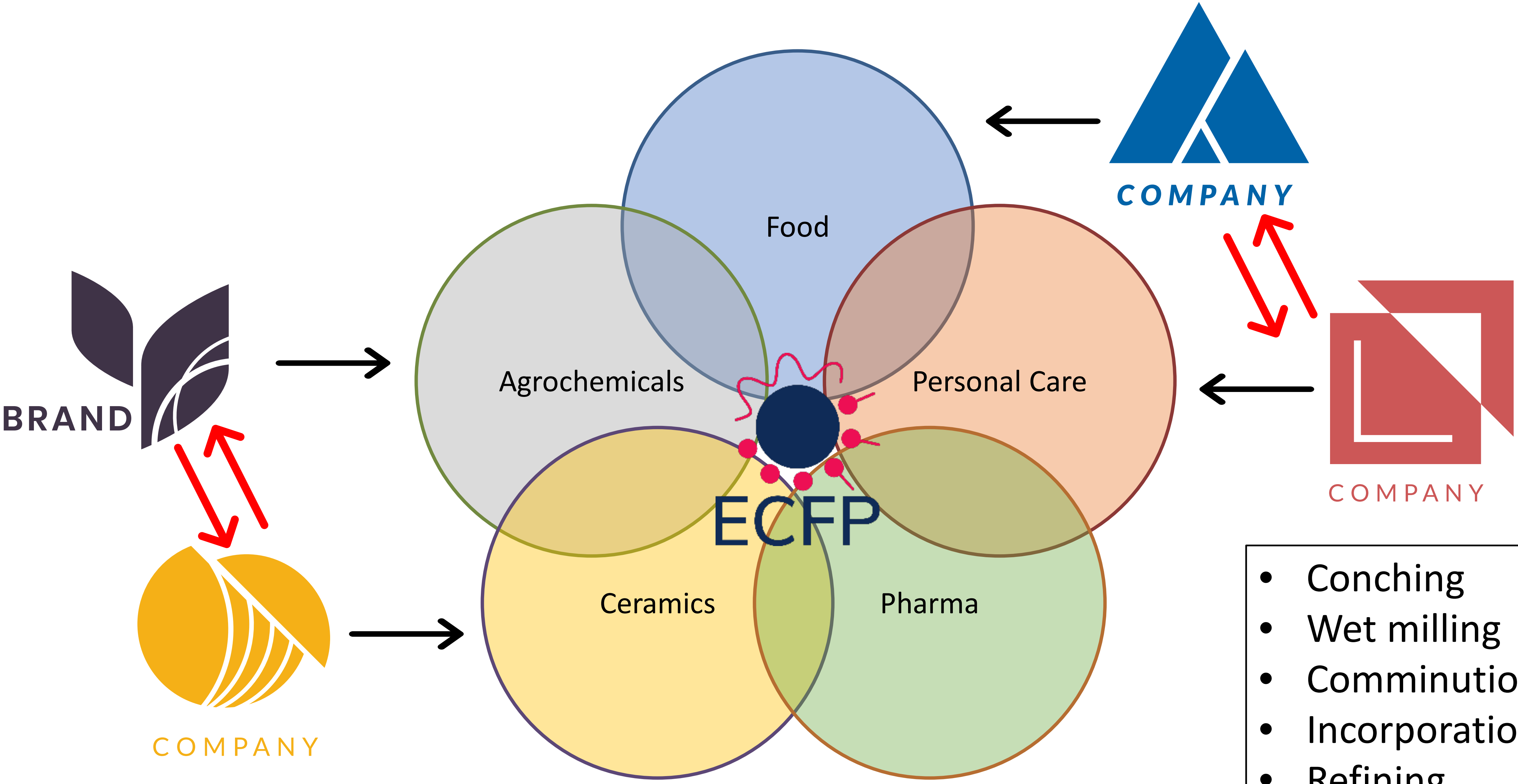
- REF impact cases
- Novel scientific problems
- Provide new employment opportunities within academia

Two-way knowledge exchange: problems and solutions

# Edinburgh Complex Fluids Partnership

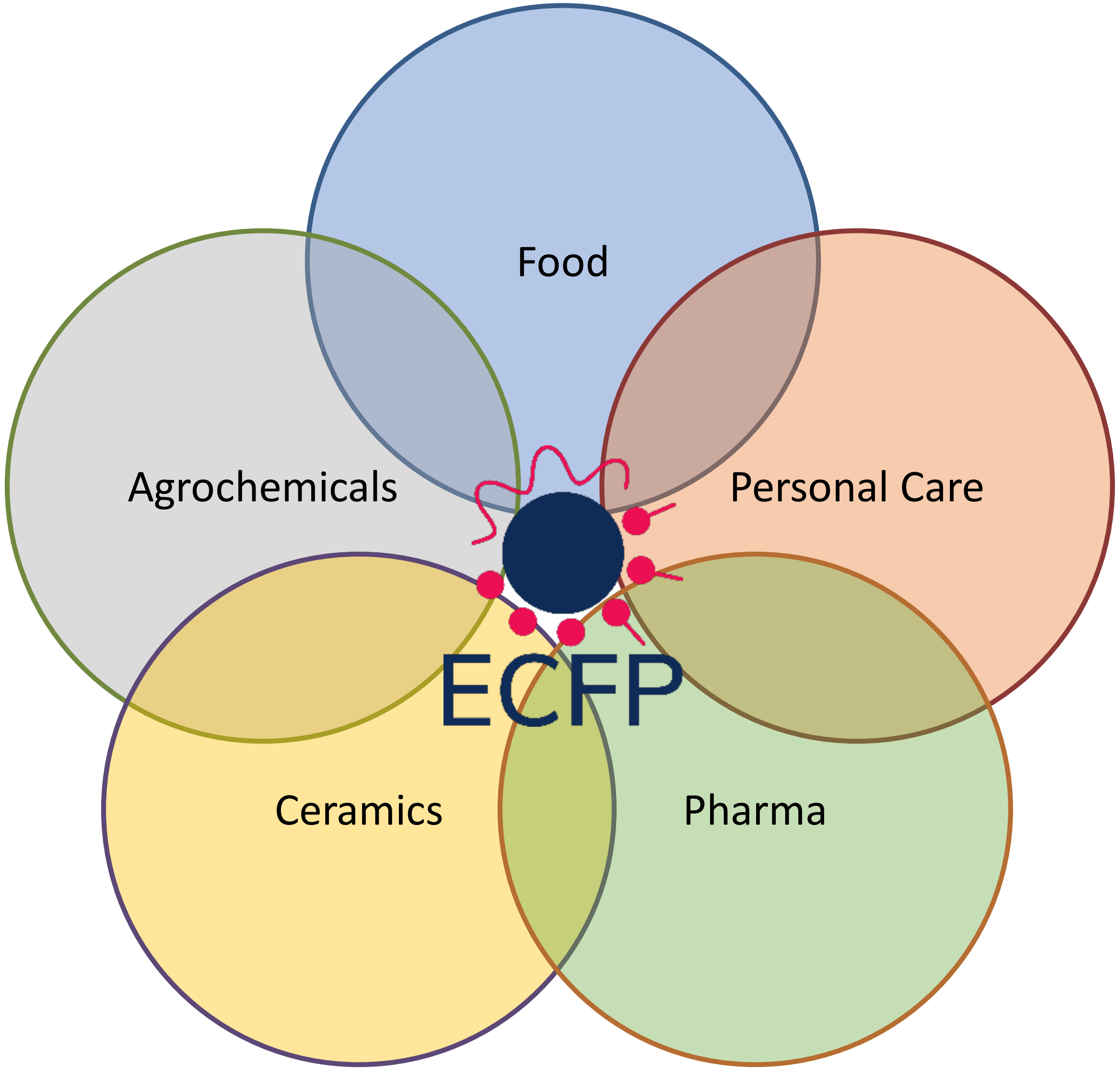


# Edinburgh Complex Fluids Partnership




- Conching
- Wet milling
- Comminution
- Incorporation
- Refining

# Edinburgh Complex Fluids Partnership




- Solutions to problems may exist in other sectors

  Sausage skins ⟷ Opthalmics

  Caramel ⟷ Glass composites

- New understanding applicable across sectors

  Chocolate ⟷ Concrete

- Fundamental understanding and exposure to ideas from other sectors enables innovation

CORNING

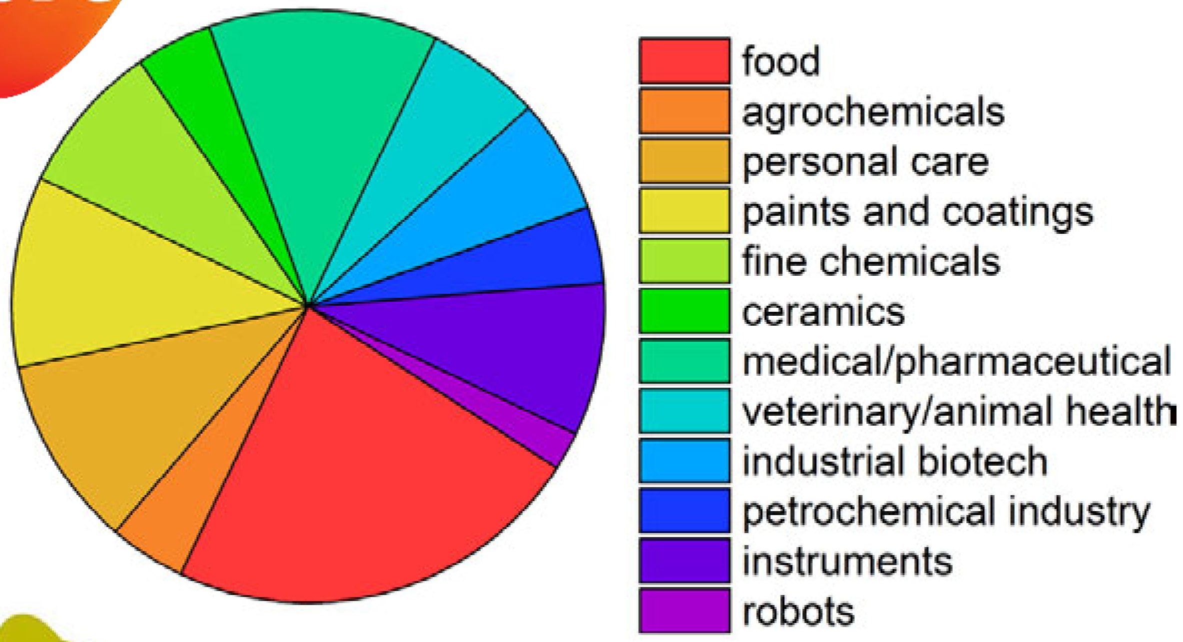
CelluComp sustainable materials

AkzoNobel Tomorrow's Answers Today

gsk

Mars

PREMIER FOODS




JM Johnson Matthey Inspiring science, enhancing life

ZEISS

TOYOTA

MBL MARINE BIOPOLYMERS

GLUTEN FREE Genius

Corbion

Lamellar Biomedical

PEPSICO

SOLVAY

# Case study: making chocolate

# Conching chocolate is a prototypical transition from frictionally jammed solid to flowable suspension with maximal solid content

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Edited by David A. Weitz, Harvard University, Cambridge, MA, and approved April 8, 2019 (received for review February 4, 2019)

The mixing of a powder of 10- to 50-μm primary particles into a liquid to form a dispersion with the highest possible solid content is a common industrial operation. Building on recent advances in the rheology of such "granular dispersions," we study a paradigmatic example of such powder incorporation: the conching of chocolate, in which a homogeneous, flowing suspension is prepared from an inhomogeneous mixture of particulates, triglyceride oil, and dispersants. Studying the rheology of a simplified formulation, we find that the input of mechanical energy and staged addition of surfactants combine to effect a considerable shift in the jamming volume fraction of the system, thus increasing the maximum flowable solid content. We discuss the possible microscopic origins of this shift, and suggest that chocolate conching exemplifies a ubiquitous class of powder–liquid mixing.

chocolate | rheology | jamming | incorporation

The incorporation of liquid into dry powder with primary particle size in the granular range (~ 10 μm to 50 μm) to form a flowing suspension with solid volume fraction $\phi \gtrsim 50\%$ is important in many industries (1). Often, maximizing solid content is a key goal. Cements for building or bone replacement and ceramic "green bodies" are important examples, where higher $\phi$ improves material strength (2). Another example is chocolate manufacturing, where high solid content [= lower fat (3)] is achieved by "conching."

Conching (4), invented by Rodolphe Lindt in 1879, is important for flavor development, but its major physical function is to turn an inhomogeneous mixture of particulates (including sugar, milk solids, and cocoa solids) and cocoa butter (a triglyceride mixture) into a homogeneous, flowing suspension (liquid chocolate) by prolonged mechanical action and the staged addition of dispersants. In this paper, we focus on this effect, and seek to understand how mechanical action and dispersants together transform a nonflowing, inhomogeneous mixture into a flowing suspension, a process that has analogs in, e.g., the ceramics and pharmaceuticals sectors (1).

We find that the key physical processes are friction-dominated flow and jamming. Specifically, two of the key rheological parameters in chocolate manufacturing, the yield stress, $\sigma_y$, and the high-shear viscosity, $\eta_2$, are controlled by how far the volume fraction of solids, $\phi$, of the chocolate formulation is situated from the jamming volume fraction, $\phi_J$. We demonstrate that the first part of the conche breaks apart particulate aggregates, thus increasing $\phi_J$ relative to the fixed mass fraction. In the second part of the conche, the addition of a small amount of dispersant reduces the interparticle friction and further raises $\phi_J$, in turn reducing $\sigma_y$ and $\eta_2$, resulting in fluidization of the suspension, i.e., a solid to liquid transition. Such "$\phi_J$ engineering" is common to diverse industries that rely on the production of high-solid-content dispersions.

## Shear Thickening Suspensions

We first review, briefly, recent advances in granular suspension rheology (5–14). The viscosity of a high-$\phi$ granular suspension increases from a low-stress Newtonian value when the applied stress, $\sigma$, exceeds some onset stress, $\sigma^*$, reaching a higher Newtonian plateau at $\sigma \gg \sigma^*$: The suspension shear thickens. The low- and high-stress viscosities, $\eta_1$ and $\eta_2$, diverge as

$$\eta_r = A\left(1 - \frac{\phi}{\phi_J(\sigma)}\right)^{-\lambda}, \quad [1]$$

where $\eta_r = \eta_{1,2}/\eta_0$ with $\eta_0$ as the solvent viscosity, $A \simeq 1$, and $\lambda \simeq 2$ for spheres (15, 16). The jamming point, $\phi_J$, is a function of both the interparticle friction coefficient, $\mu$, and the applied stress, $\sigma$. The latter begins to press particles into contact when it exceeds $\sigma^*$. With $\mu \to 0$, no shear thickening is observed, and $\eta_r$ diverges at random close packing, $\phi_J = \phi_{rcp}$. At finite $\mu$, the low-stress viscosity $\eta_1(\phi)$ still diverges at $\phi_{rcp}$, but $\eta_2(\phi)$, the high-stress viscosity, now diverges at some $\phi_J = \phi_m^\mu < \phi_{rcp}$. For monodisperse hard spheres (Fig. 1A) $\phi_{rcp} \approx 0.64$ and $\phi_m^{\mu\to\infty} \approx 0.54$ (where "∞," in practice, means $\mu \gtrsim 1$) (8, 17).

**Significance**

Chocolate conching is the process in which an inhomogeneous mixture of fat, sugar, and cocoa solids is transformed into a homogeneous flowing liquid. Despite the popularity of chocolate and the antiquity of the process, until now, there has been poor understanding of the physical mechanisms involved. Here, we show that two of the main roles of conching are the mechanical breakdown of aggregates and the reduction of interparticle friction through the addition of a dispersant. Intriguingly, the underlying physics we describe is related to the popular stunt of "running on cornstarch."

Author contributions: M.H., P.M.C., M.E.C., I.V.D., and W.C.K.P. designed research; E.B., D.J.M.H., R.B., and G.L.H. performed research; E.B., D.J.M.H., M.H., R.B., and G.L.H. analyzed data; and D.J.M.H. and W.C.K.P. wrote the paper.

Conflict of interest statement: This work is, in part, funded by Mars Chocolate UK Ltd.

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Data Deposition: All data plotted in this work can be downloaded from Edinburgh DataShare (https://datashare.is.ed.ac.uk/handle/10283/3281).

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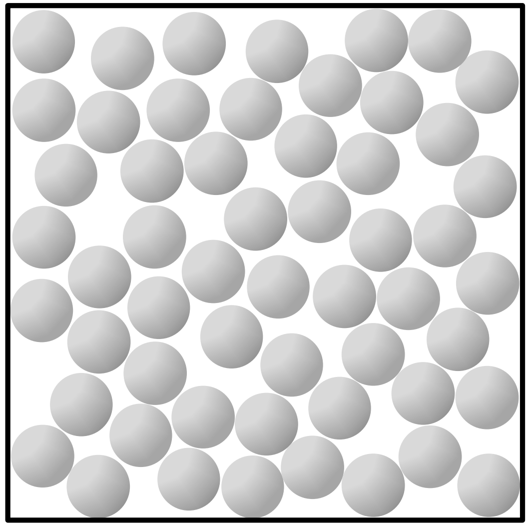
# Case study: making chocolate

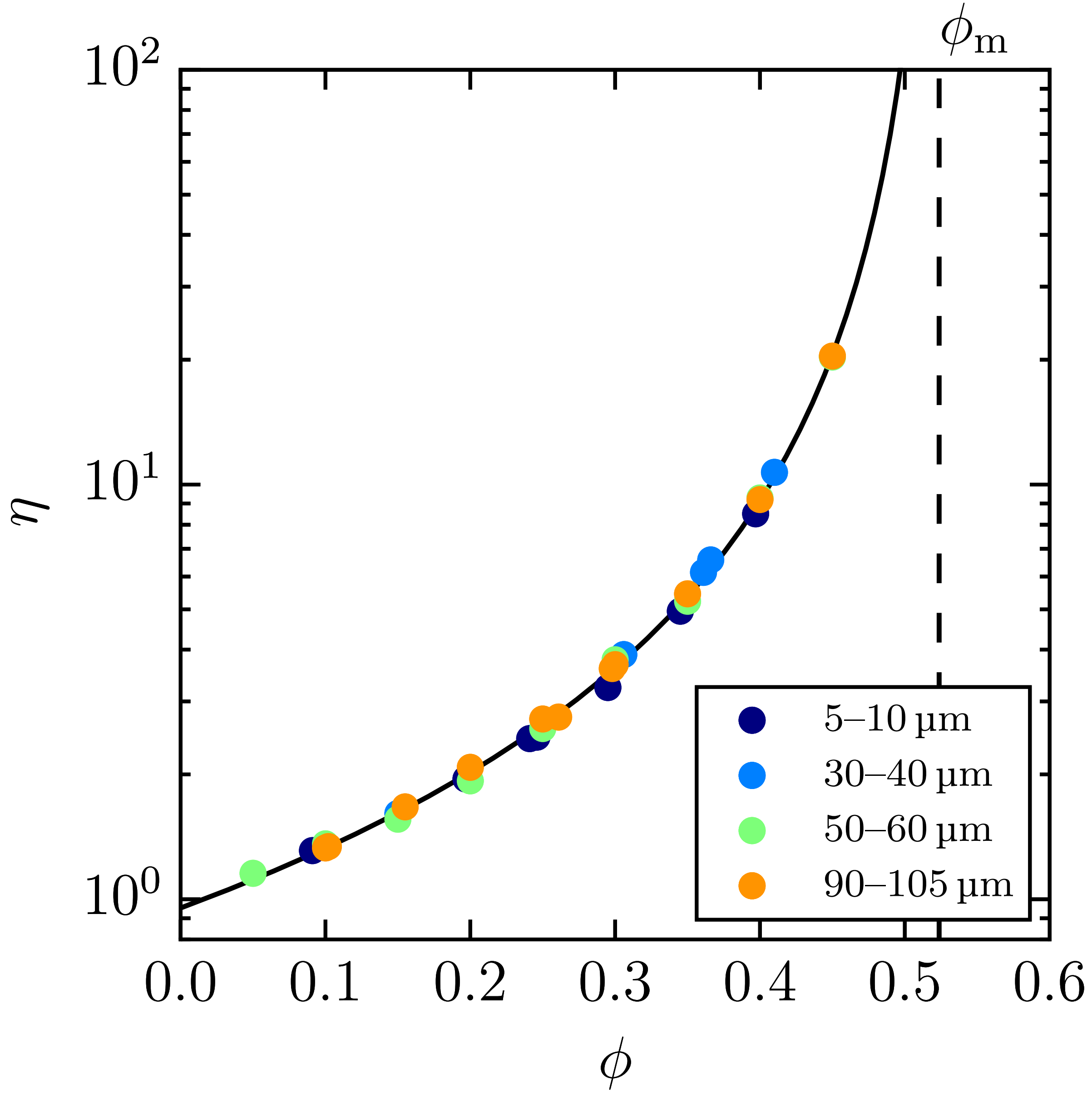
Maximum packing fraction



$$\phi_{\mathrm{m}}$$

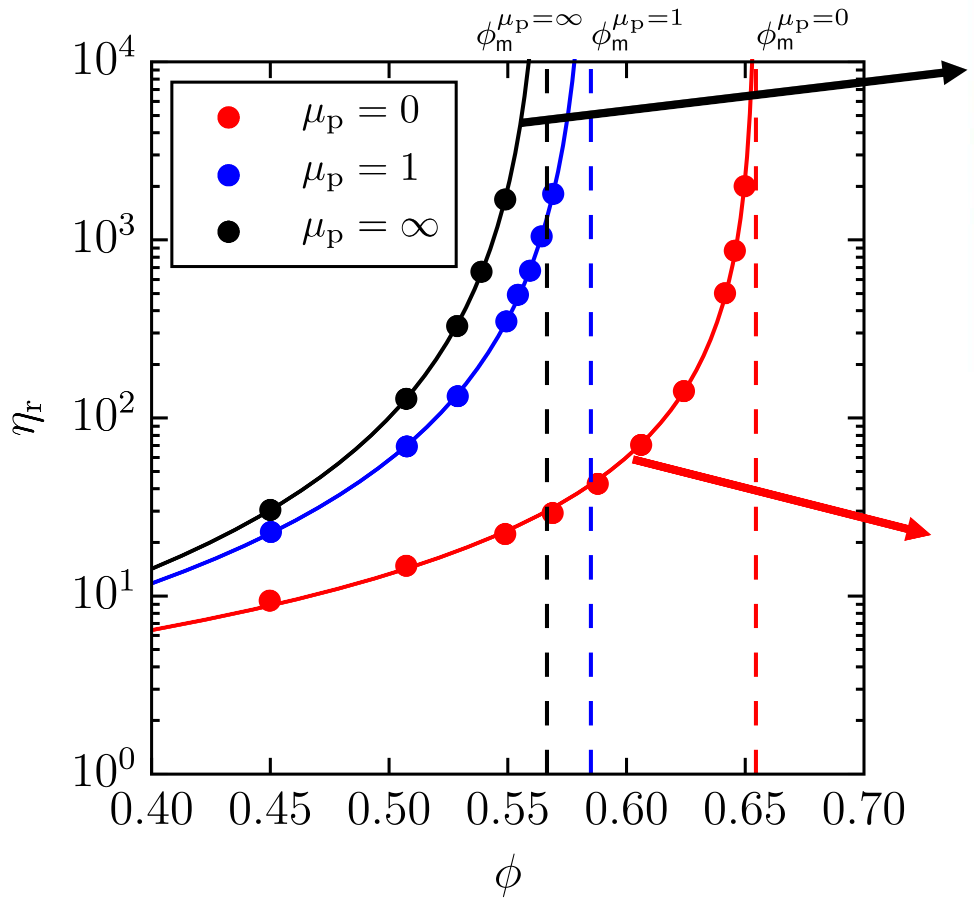
Krieger-Dougherty

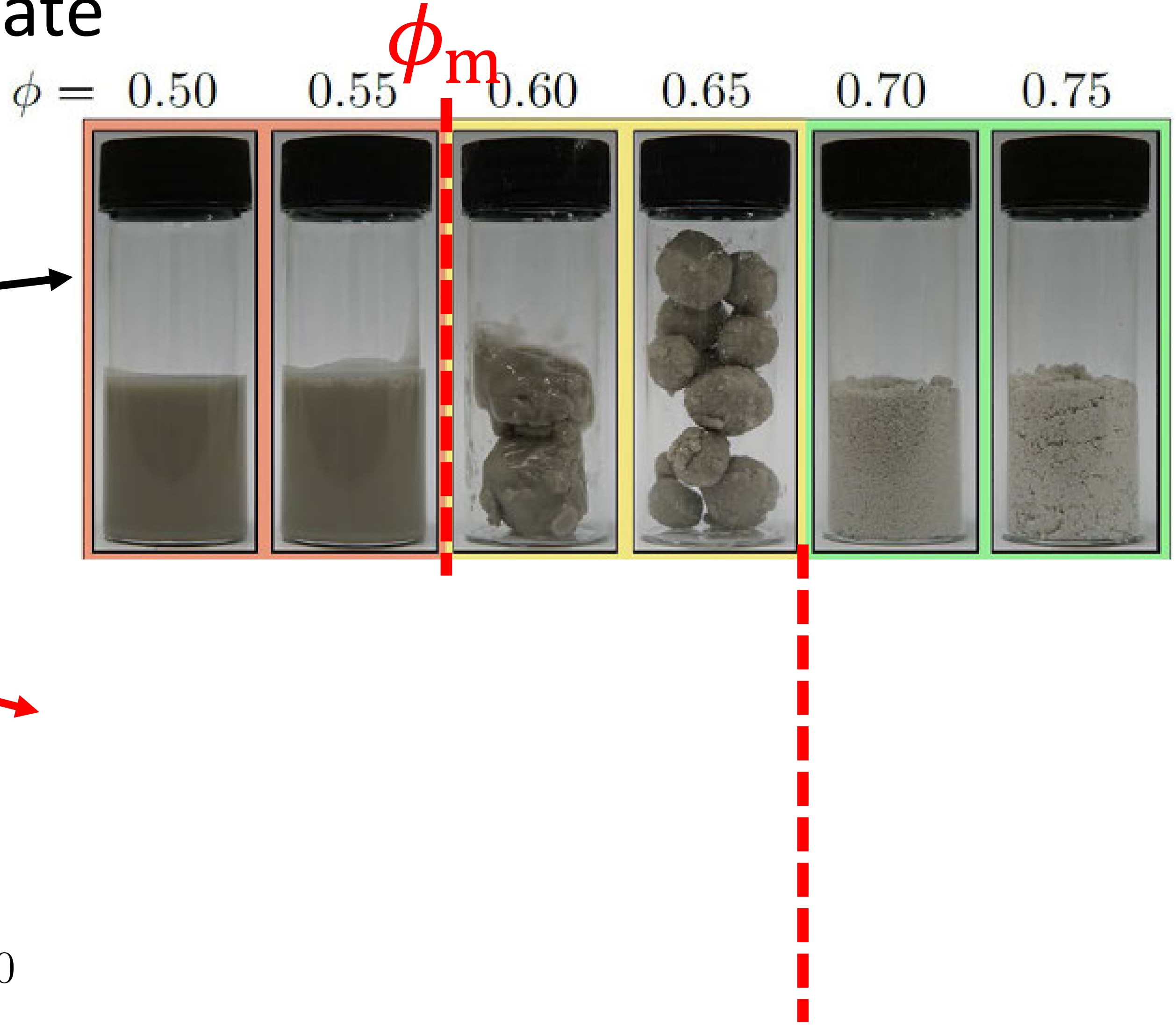
$$\eta = \left(1 - \frac{\phi}{\phi_{\mathrm{m}}}\right)^{-2}$$



# Case study: making chocolate

Maximum packing fraction



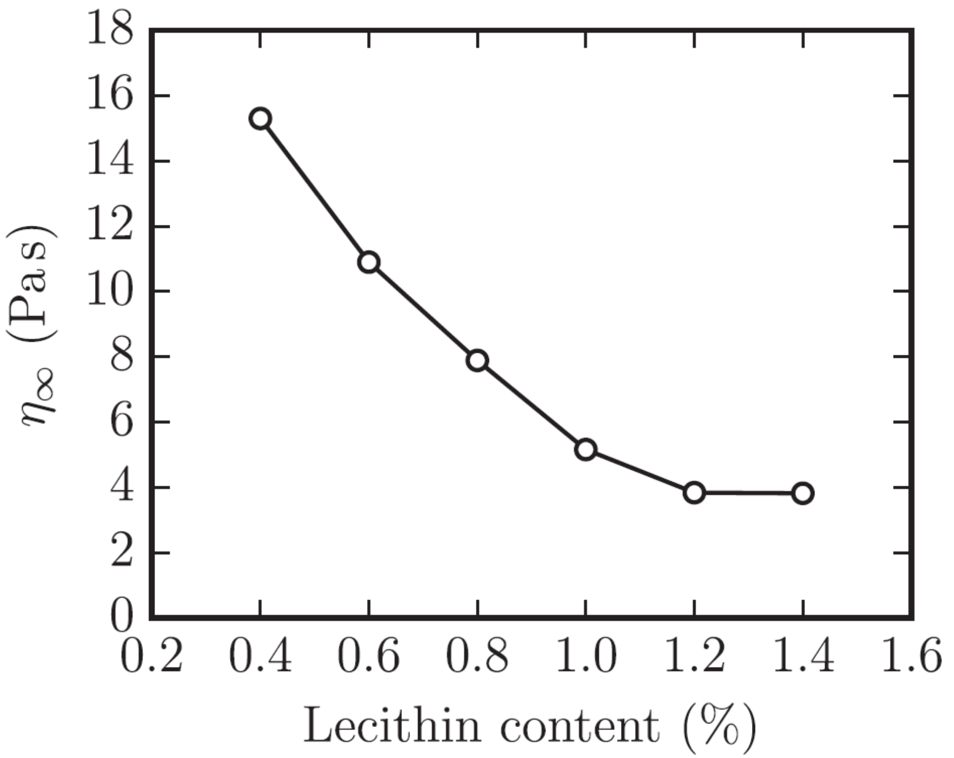



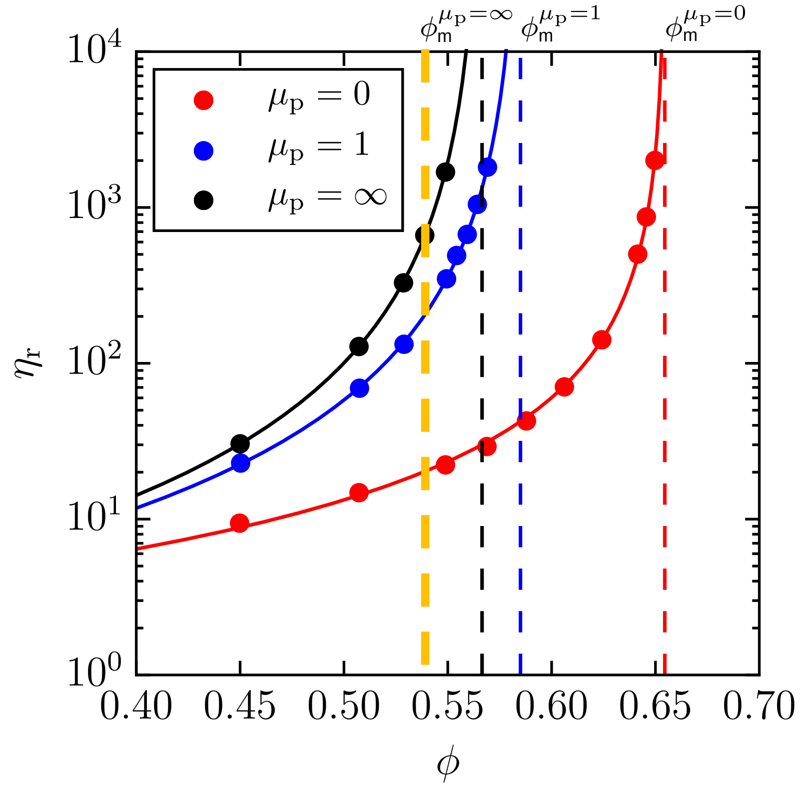

Mari et al., Journal of Rheology 58.6 (2014): 1693-1724.

# Case study: making chocolate

## Engineering maximum packing

- Final stages of chocolate making – lecithin is added
- Conventional understanding: promotes wetting of sucrose surfaces, steric stabiliser

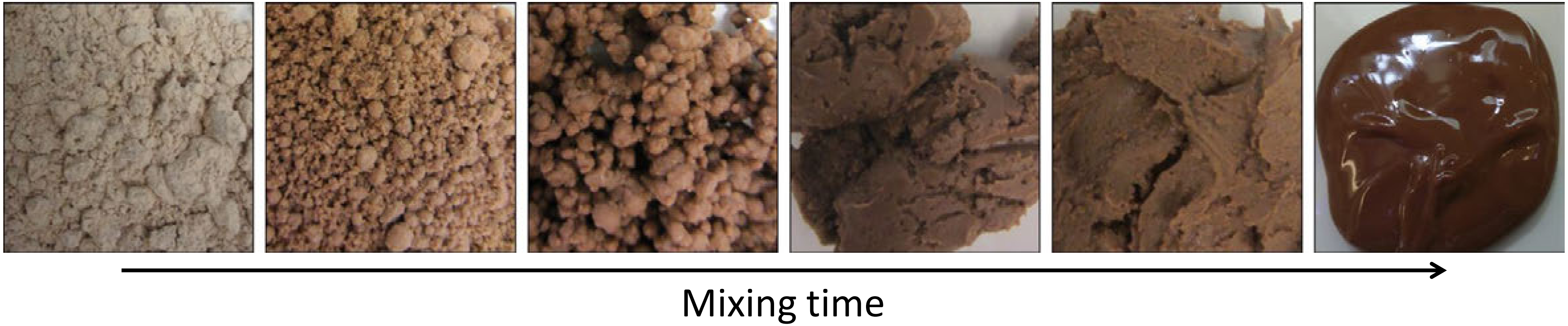


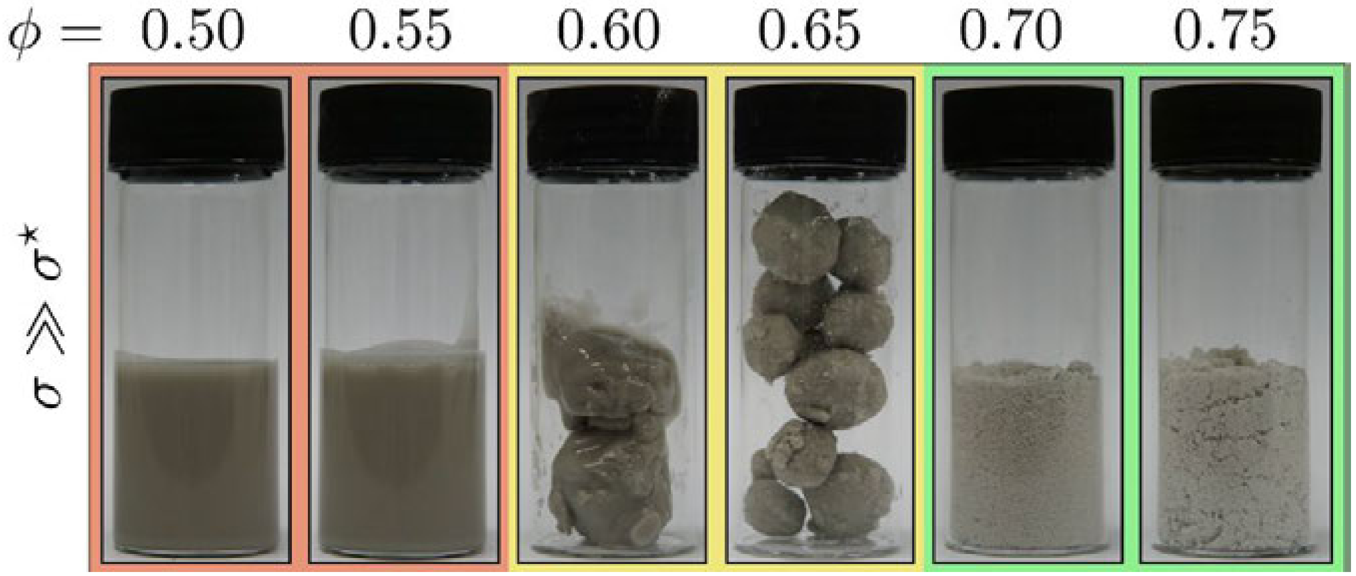

Lecithin in fact reduces friction between sucrose particles

# Case study: making chocolate

## Engineering maximum packing

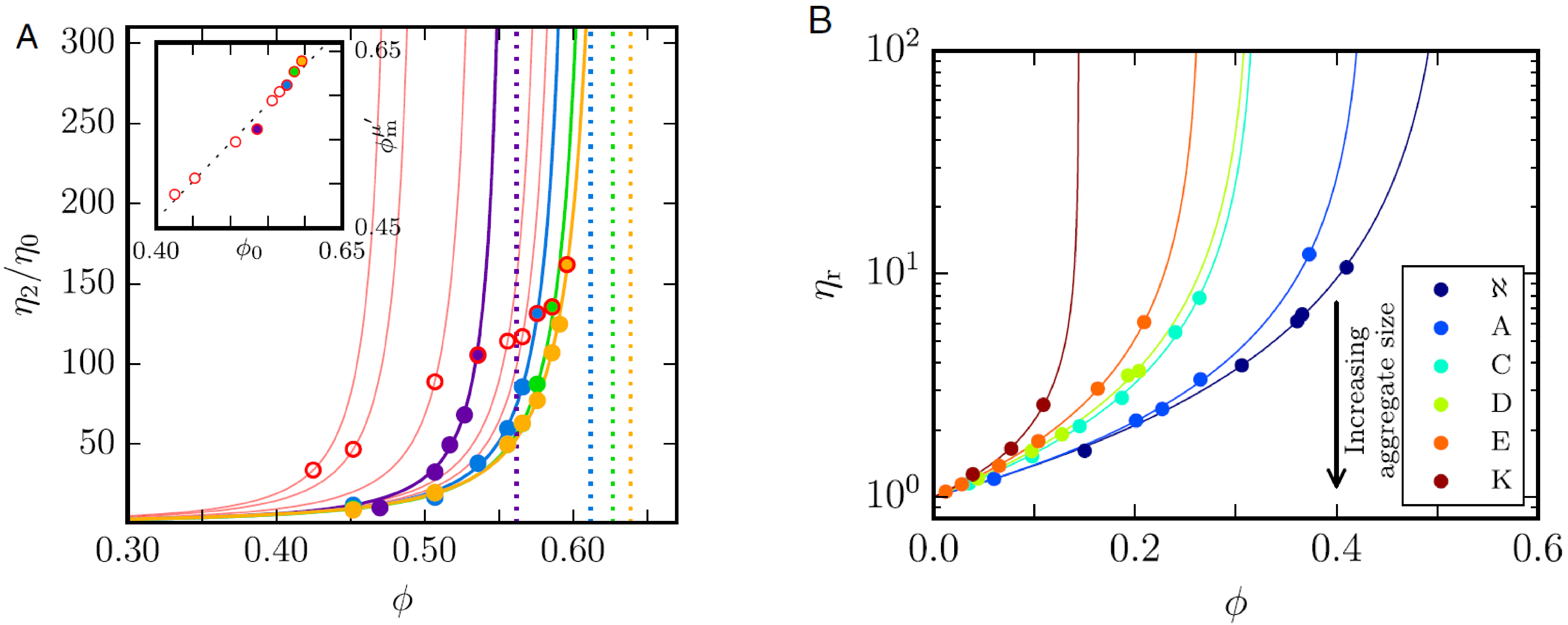



- Conching – dry powder to smooth, flowing chocolate



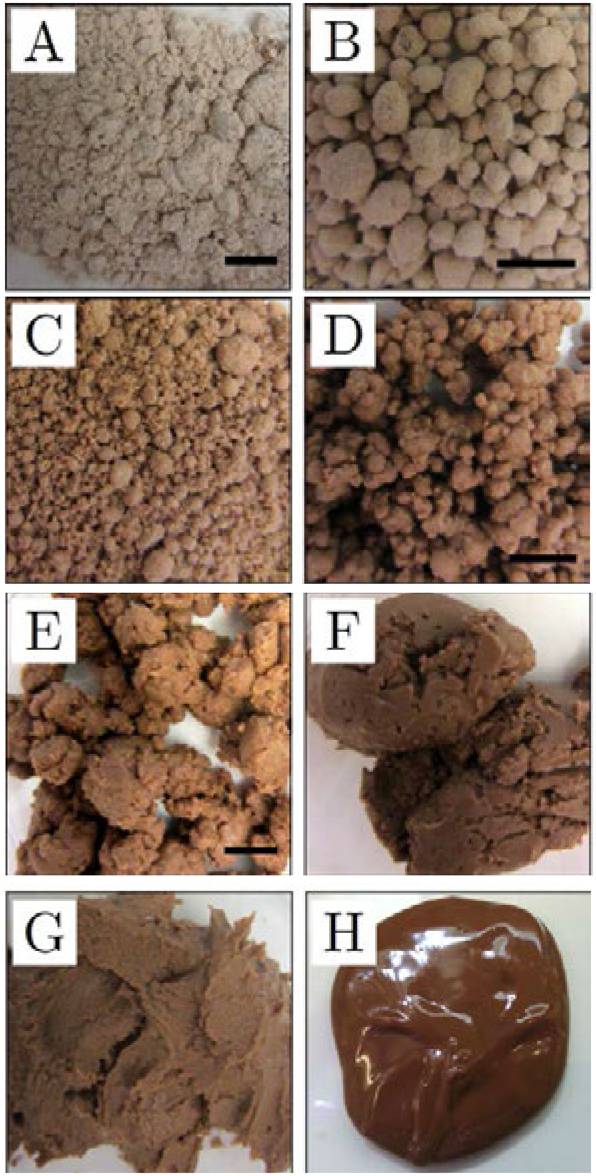
# Case study: making chocolate

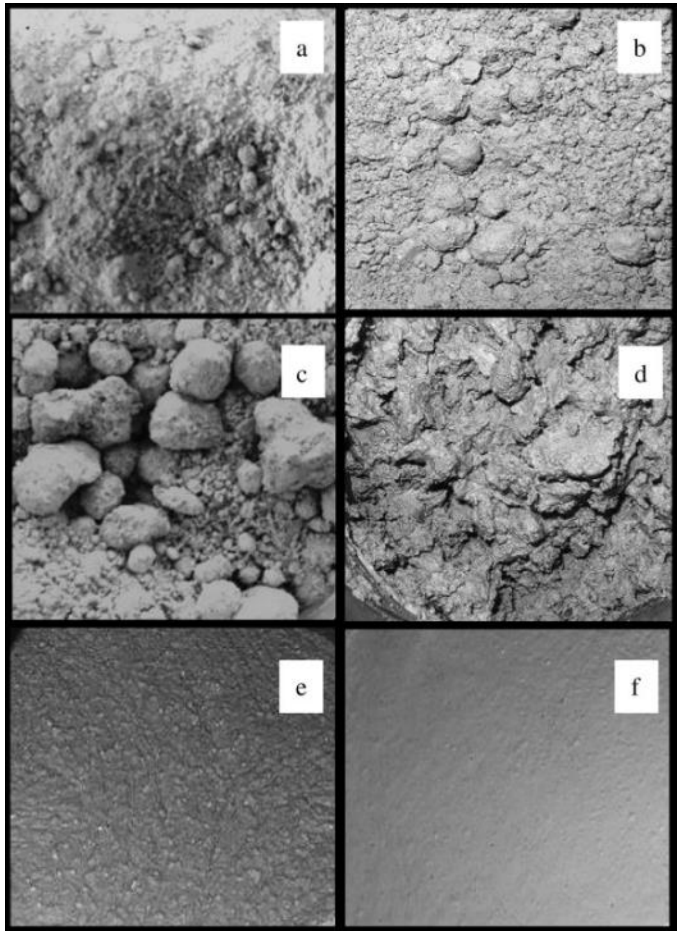
## Engineering maximum packing



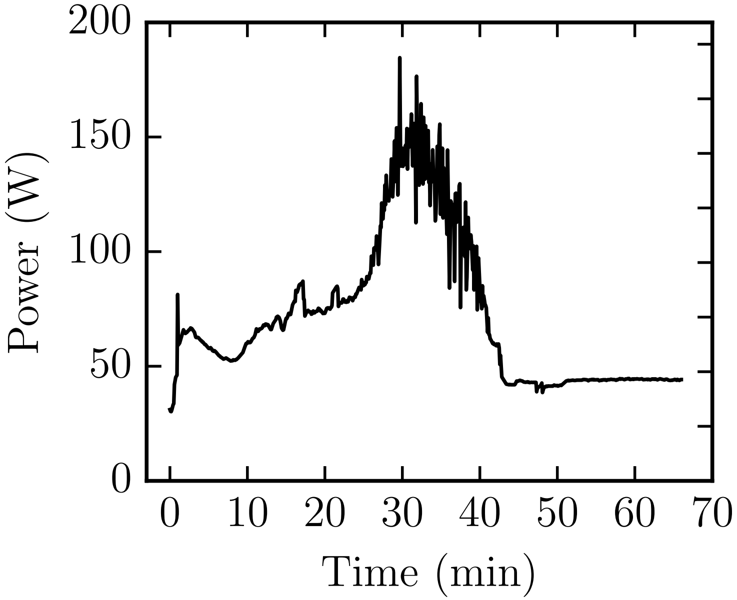

Conching increases $\phi_m$ by breaking up aggregates

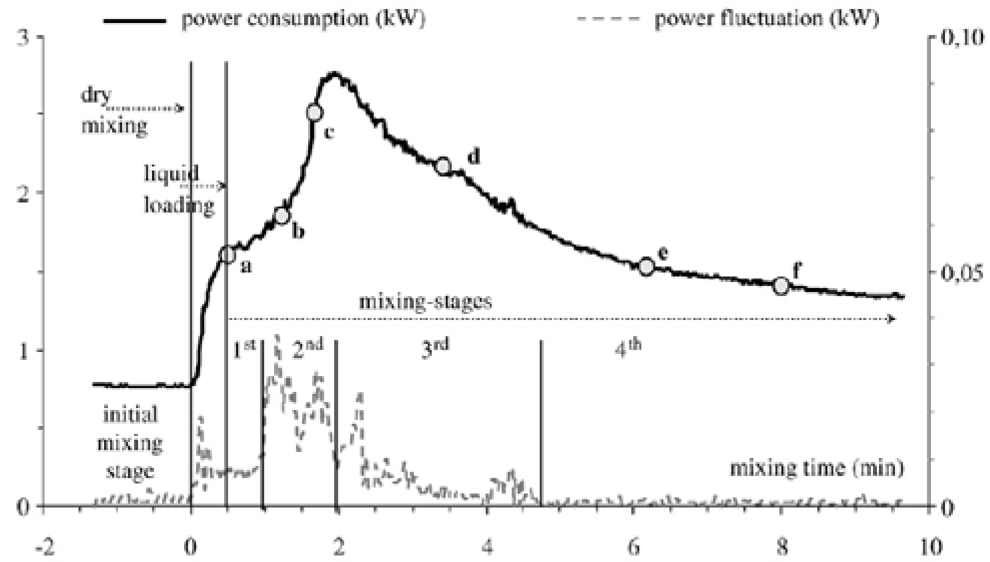
# Beyond chocolate



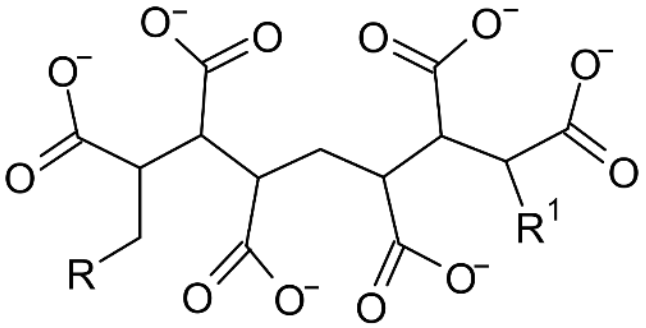

Cazacliu B, Roquet N (2009) Concrete mixing kinetics by means of power measurement. *Cem Concr Res* 39:182–194.

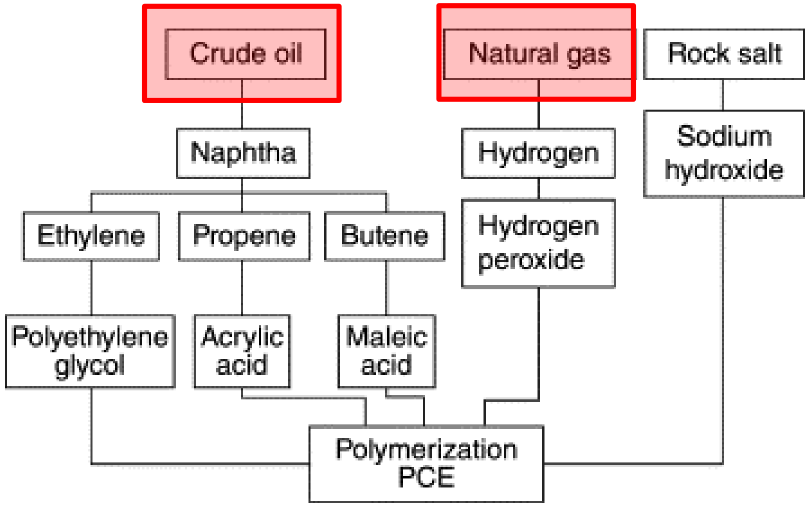


# Superplasticisers in high-strength concrete

- Superplasticisers reduce water by up to 15%
- Enable higher solid content whilst retaining flowability
- Conventional understanding: steric stabilisers
- Perhaps acts as a friction modifier




# Sustainability and reformulation

- General trend across many sectors – regulation, consumer awareness, innovation

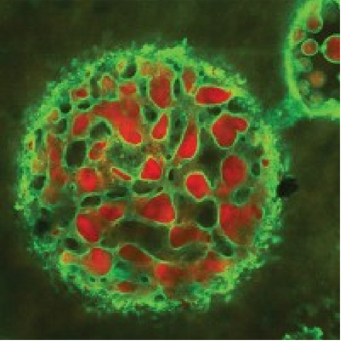
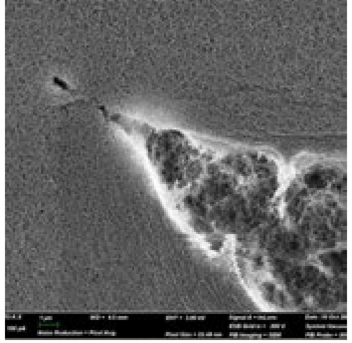
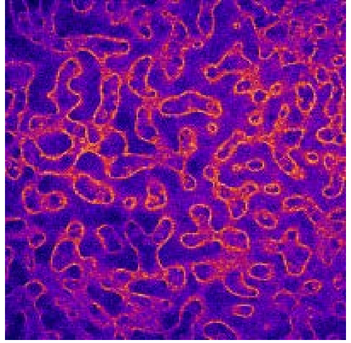
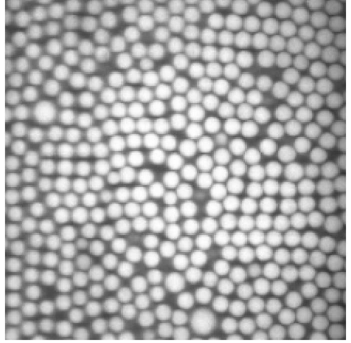
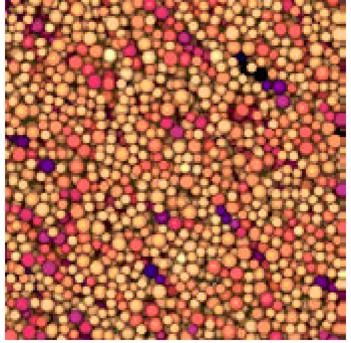
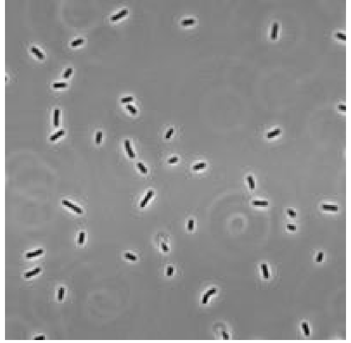
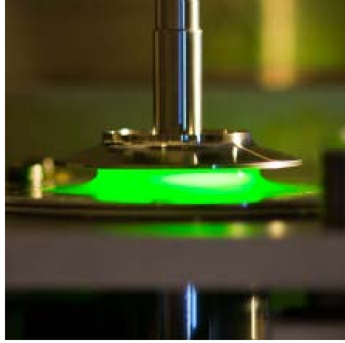
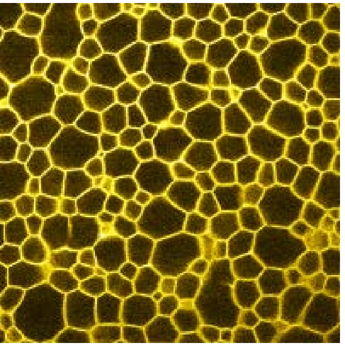
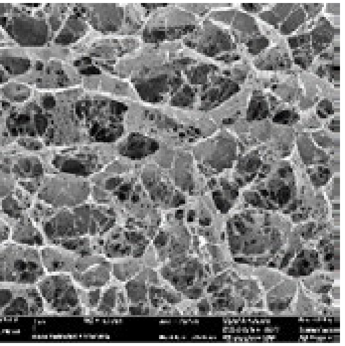
**Clean Home. Clean Planet. Clean Future.**

*"aim to replace 100% of the carbon derived from fossil fuels in our Home Care formulations…by 2030."*

- Problem: existing formulations no longer work, function of ingredients not well understood

- Lots of work to be done

- Good news for early-career formulation scientists! ☺

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