29th international Conference on
Rheology of Building Materials
OTH- Regensburg, Germany March 11 - 12, 2020

Rheology of concrete in industrial context: issues, methods, achievements and perspectives

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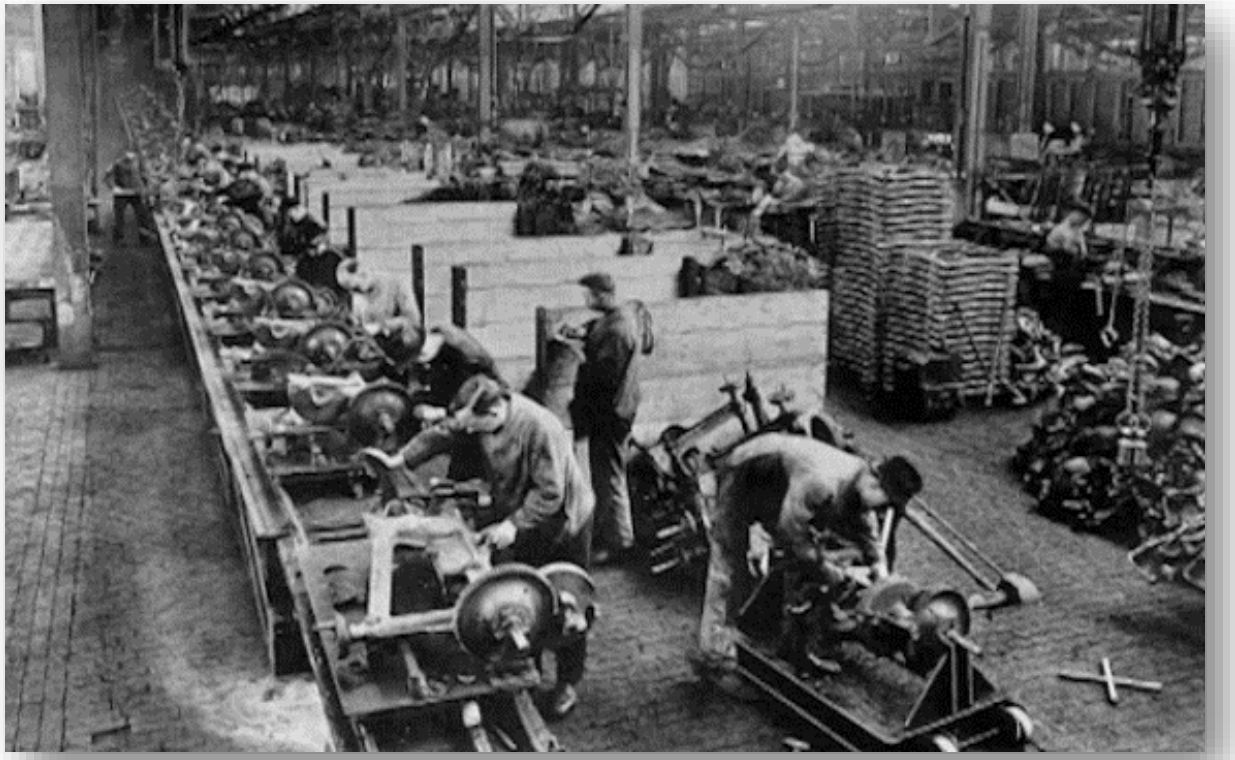
OSTBAYERISCHE
TECHNISCHE HOCHSCHULE
REGENSBURG

1. An historical prelude

A major industrial transformation: taylorism

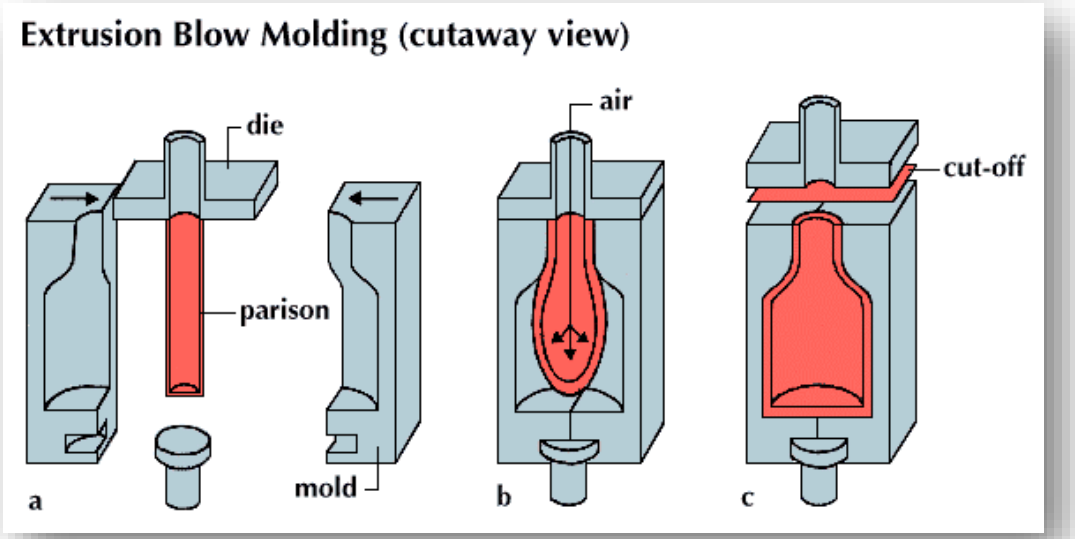
- Mostly handmade work
- Low labour specialization
- On demand, single-piece artifact

- Machine-assisted work
- Task-specialized labour
- Standard artifact serial production



Process industry directly impacted by flow properties

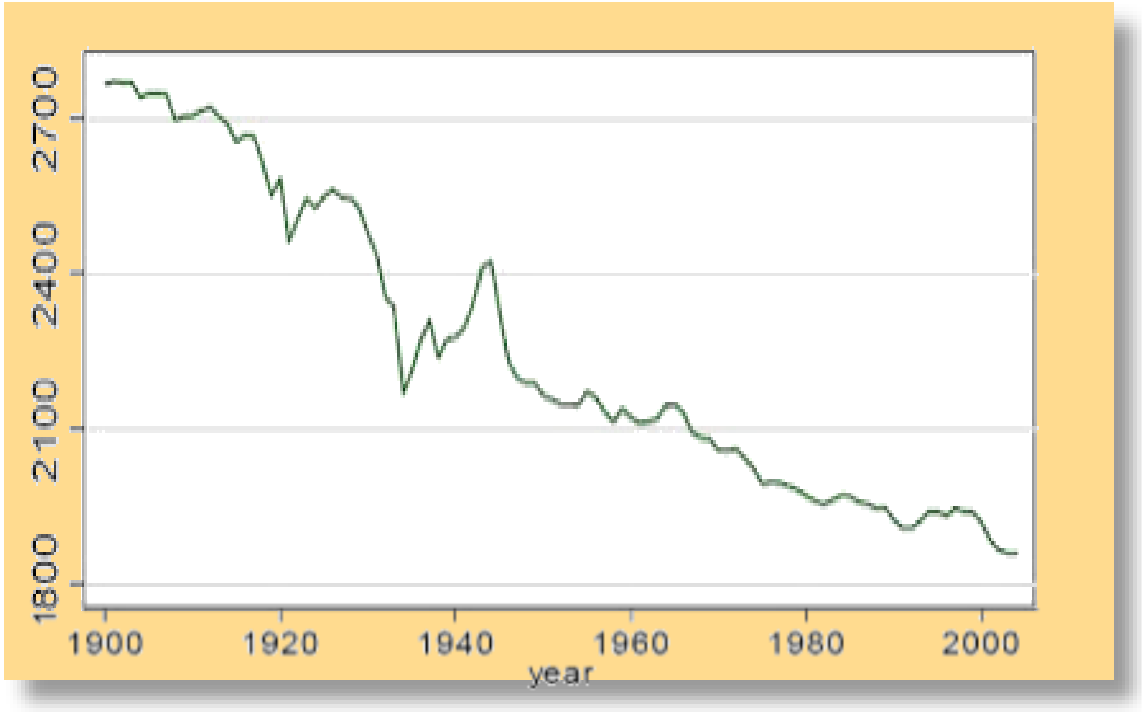
Food and cosmetic industry



Plastic industry

Higher productivity directly bound to worked hours reduction

Average worked hours/year in the US

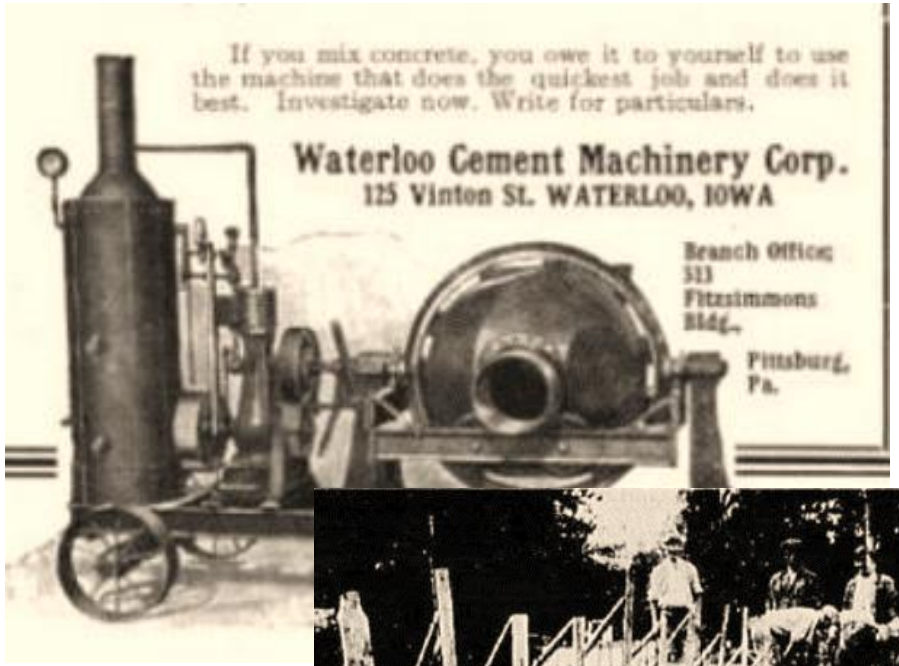


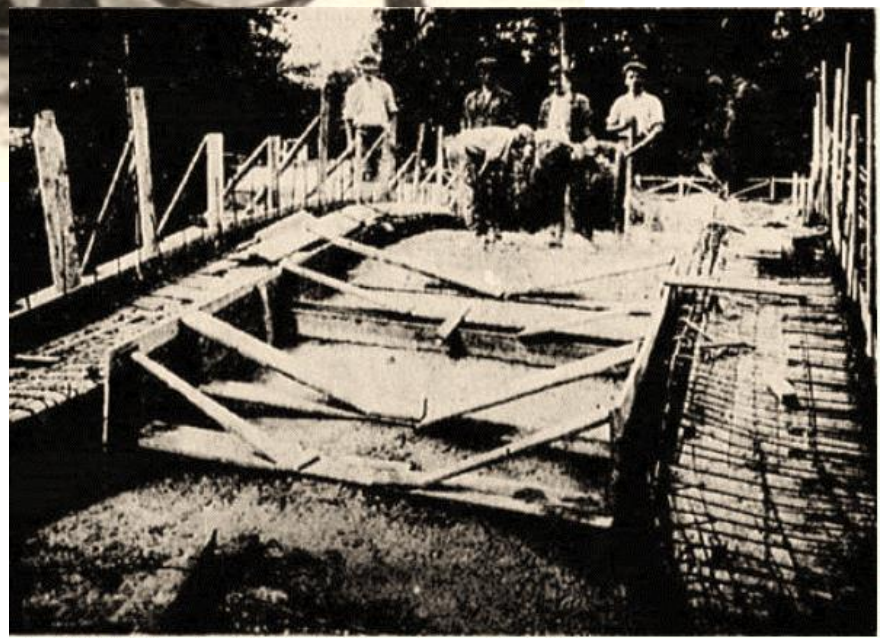
V. Ramey, N. Francis, 2009. "A Century of Work and Leisure," American Economic Journal: Macroeconomics, American Economic Association, vol. 1(2), pages 189-224

Average labor productivity in the US (2005 $)

Sources: Employment in thousands of workers 14 and older for 1900–1947 from *Historical Statistics of the United States, Colonial Times to 1970*, pp. 126–127; workers 16 and older for 1948 onward from FRED database, Federal Reserve Bank of St. Louis, *research.stlouisfed.org/fred2/series/CE16OV*. Average labor productivity is output divided by employment, where output is from Fig. 1.1.

Concrete production techniques are in this trend



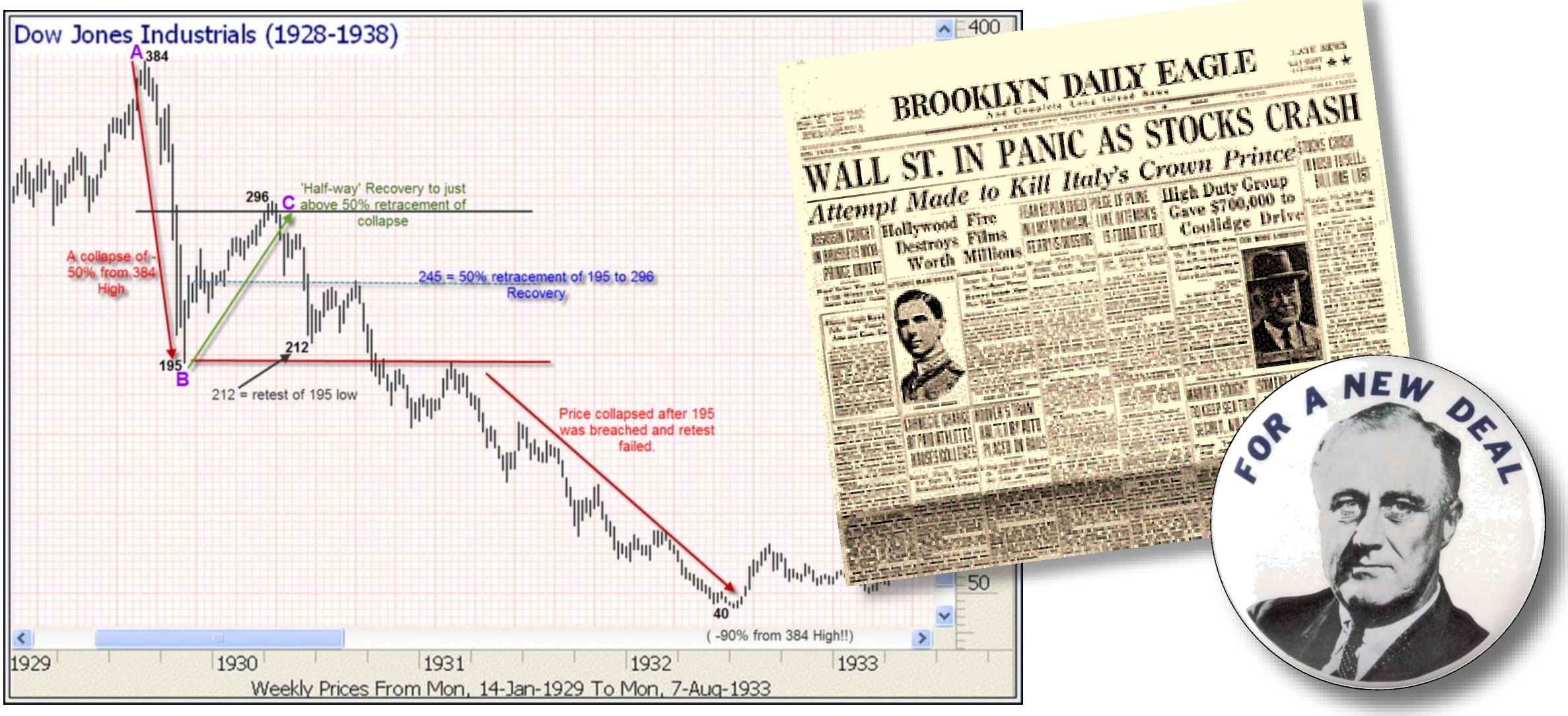


1913

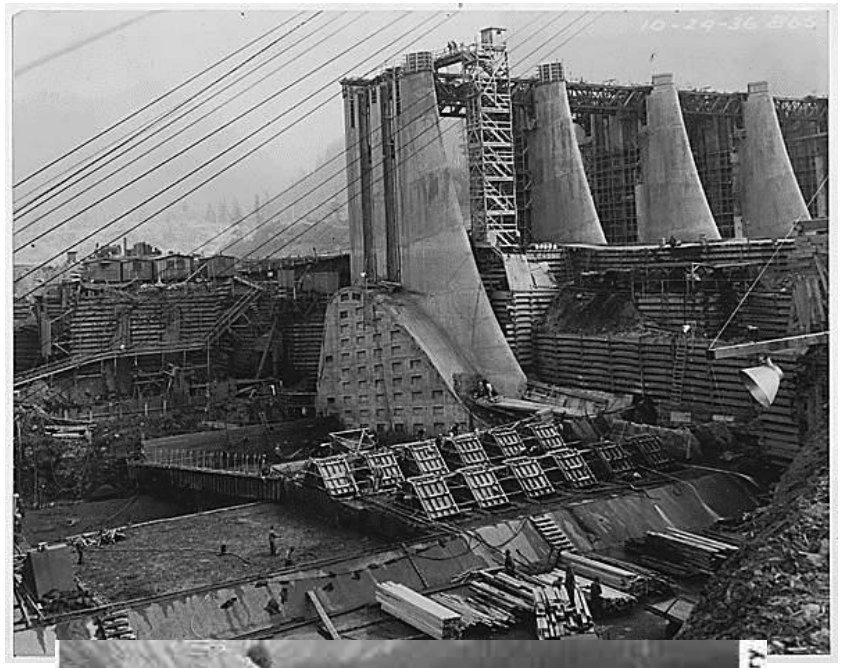
2018

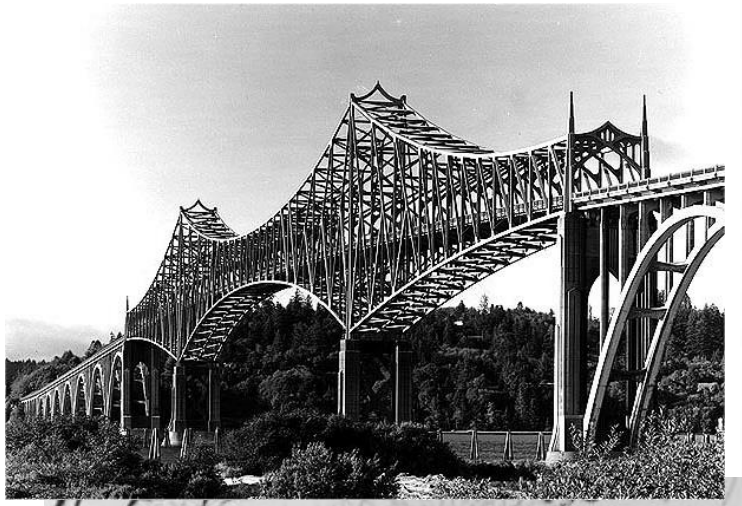
2. Rheology and Concrete industry developement

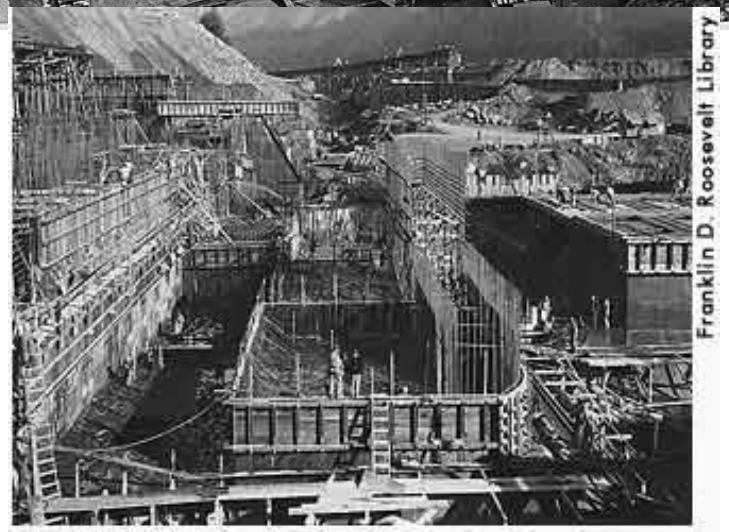
1929 Financial Crisis and massive Investment



Strong public civil works policy







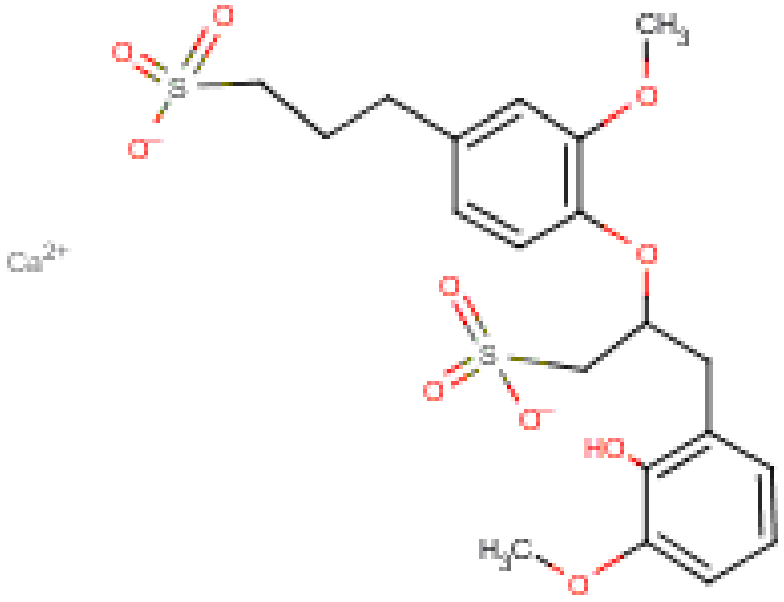
Franklin D. Roosevelt Library

PWA Project - Bonneville Power and Navigation Dam on the Columbia River, Oregon, 1936

Evolution of concrete fluidity

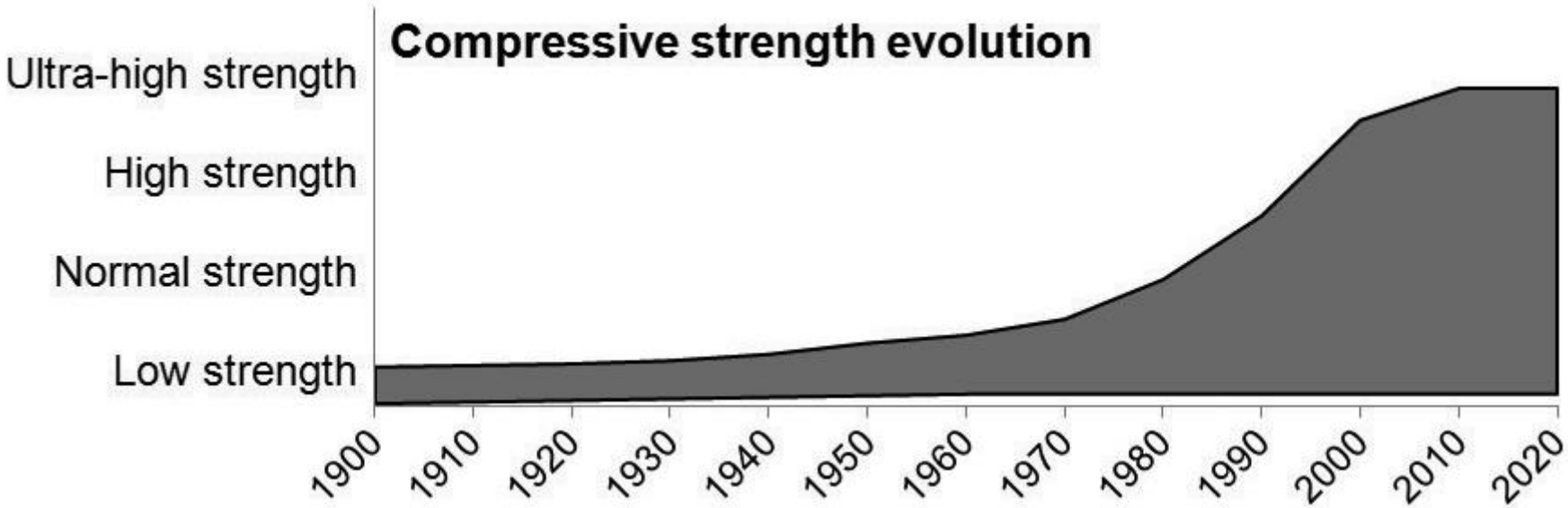
Wide road network building (motorways)

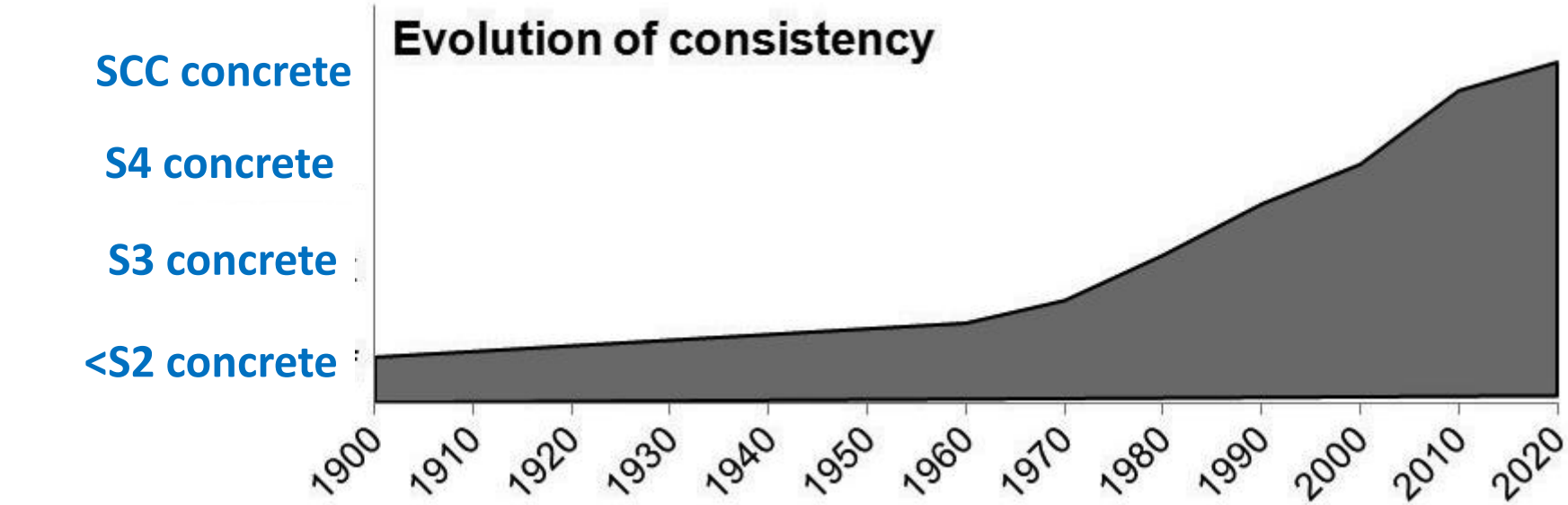
Mainly concrete built



Calcium Lignosulfonate

1930s: The introduction of Lignosulfonates as color dispersant led to the first step of fluid concrete eveloution


Compressive strength evolution
Ultra-high strength
High strength
Normal strength
Low strength
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020


Evolution of consistency
SCC concrete
S4 concrete
S3 concrete
<S2 concrete
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020

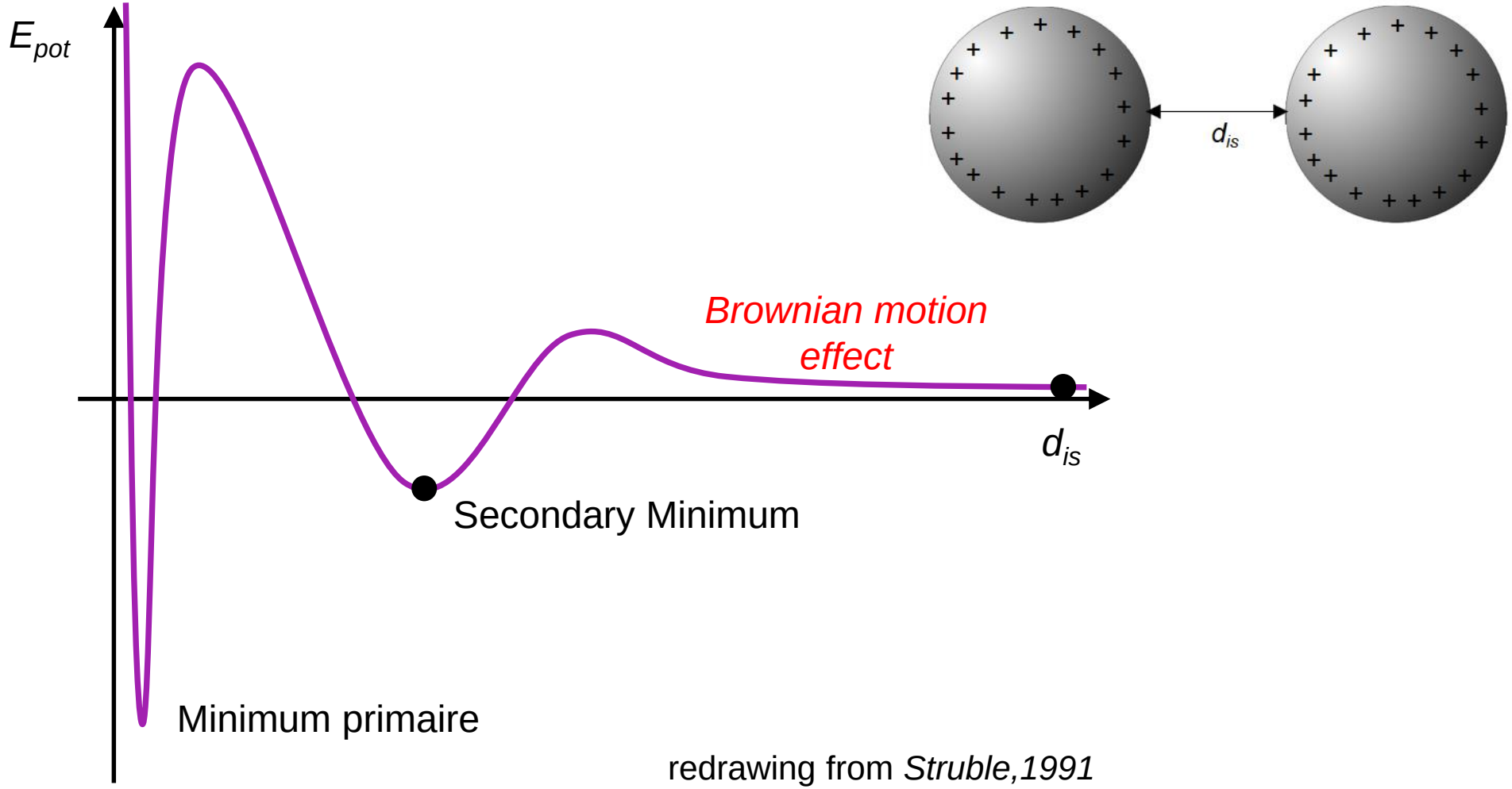
3. Rheological models for concrete

Rheological models: an increasing complexity

Bingham [14, 98]	$\tau = \tau_o + \mu\dot{\gamma}$;	1916
Herschel-Bulkley [129]	$\tau = \tau_o + A\dot{\gamma}^B$;	1928
Robertson-Stiff [130]	$\tau = A(\dot{\gamma} + B)^C$;	
Modified Bingham [131]	$\tau = \tau_o + \mu\dot{\gamma} + B\dot{\gamma}^2$;	
Casson [132]	$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu\dot{\gamma}}$;	1959
De Kee [131]	$\tau = \tau_o + \mu\dot{\gamma}e^{-A\dot{\gamma}}$;	
Vom Berg [134]	$\tau = \tau_o + A\sinh^{-1}(B\dot{\gamma})$	1979
Quemada [133]	$\tau = \left(\frac{1+\sqrt{(A\gamma)}}{B+C\sqrt{(A\gamma)}}\right)^2 \dot{\gamma}$	1984
Yahia and Khayat [131]	$\tau = \tau_0 + 2\sqrt{\tau_0\mu\dot{\gamma}e^{-A\gamma}}$	2001

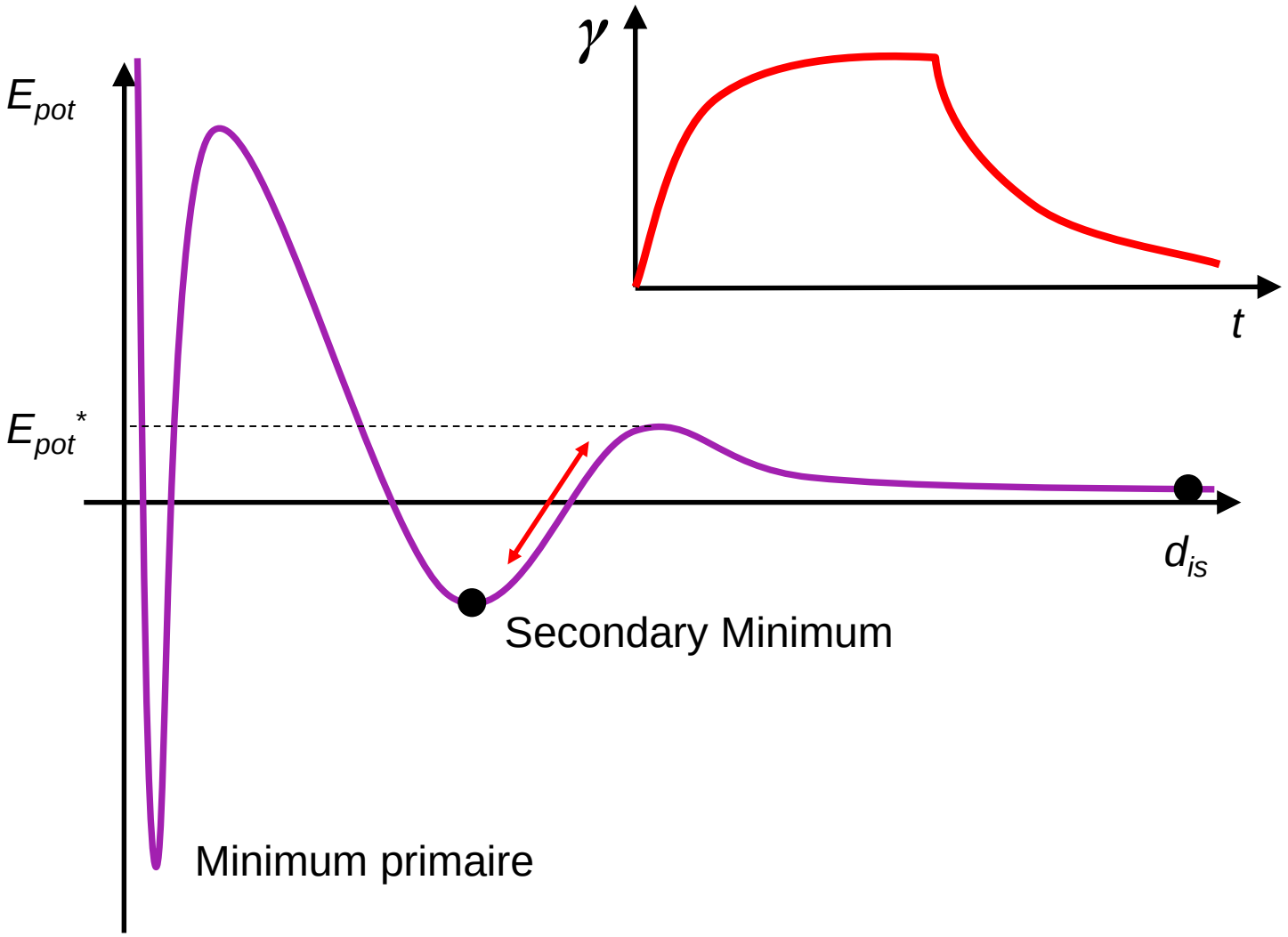
Which is the 'right' model?

The eneregy landscape between two cement particles



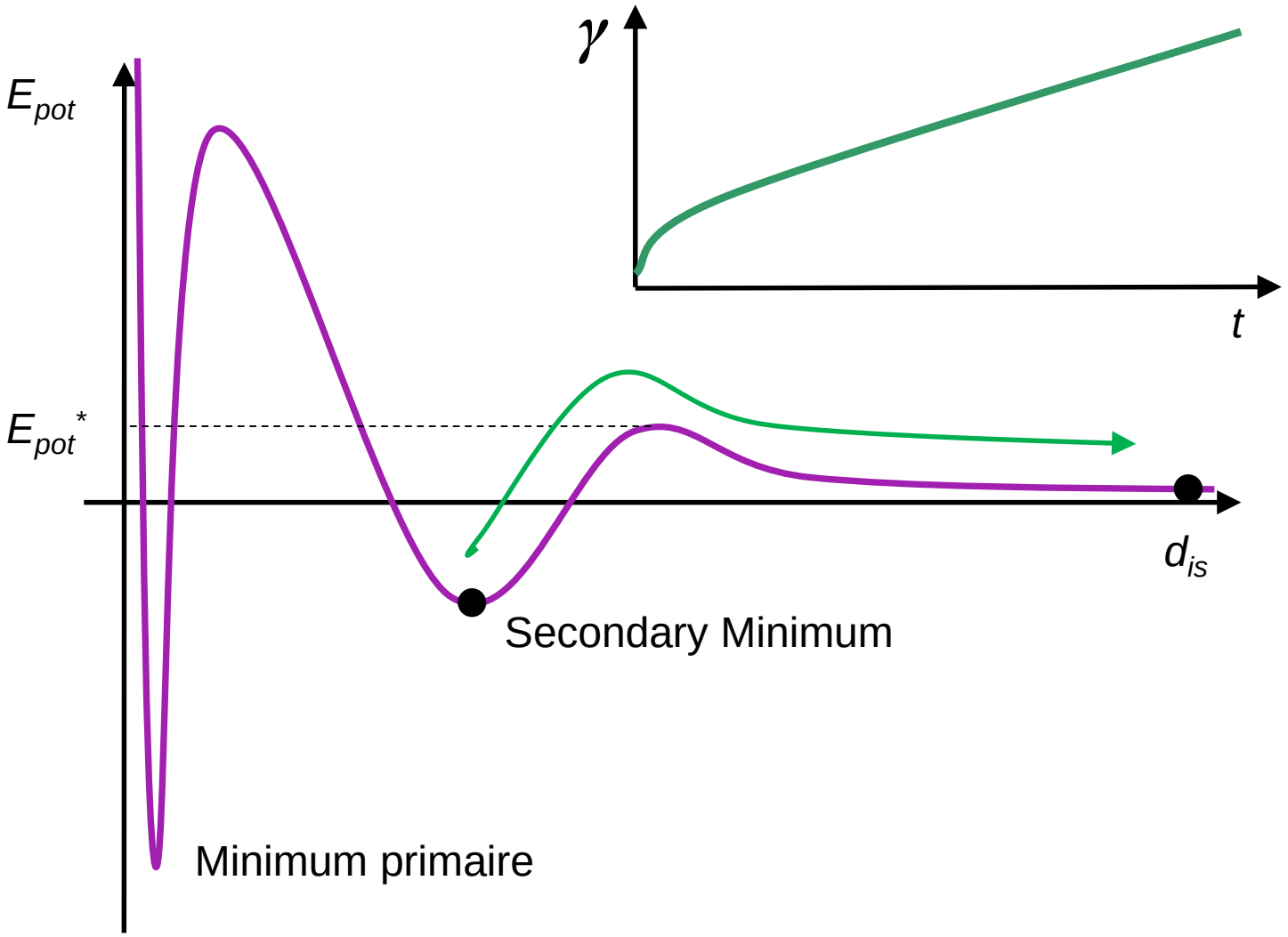
redrawing from *Struble,1991*

What are the accessible physical phenomena?



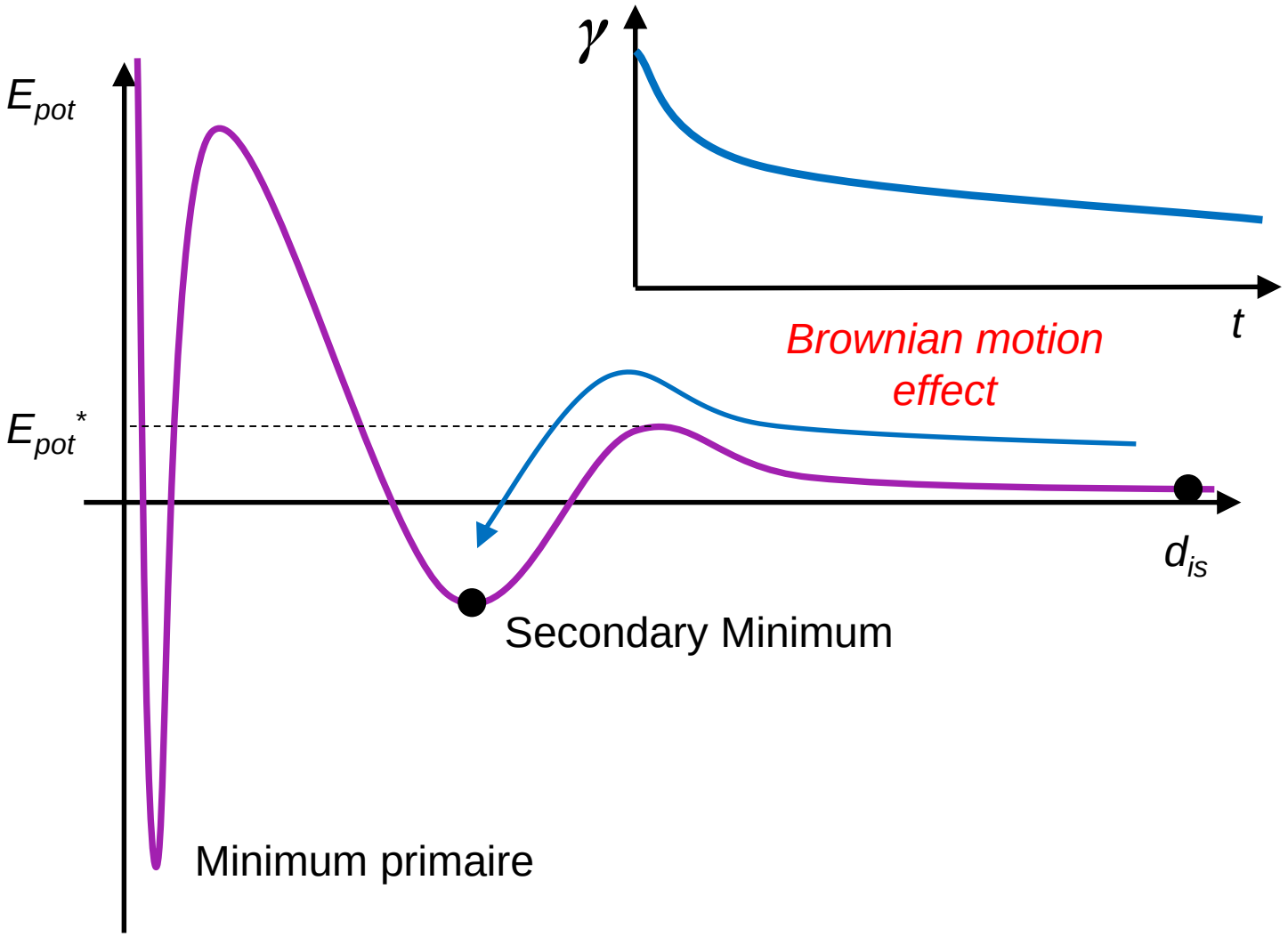
Elastic margin
(below yield stress)

What are the accessible physical phenomena?



Viscous flow
(over yield stress)

What are the accessible physical phenomena?



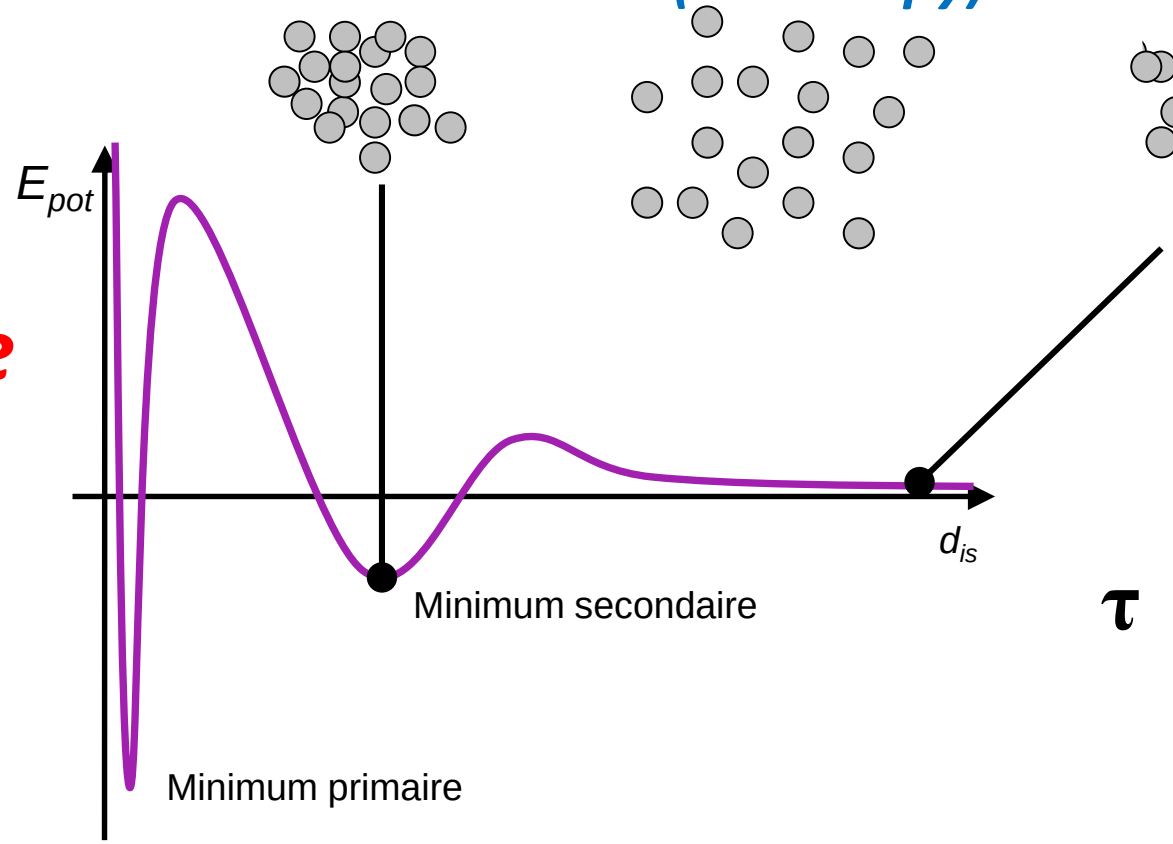
Rebuilding at rest (thixotropy)

What are the accessible physical phenomena?

Maximal aggregation state

Transition State (thixotropy)

Minimal aggregation state

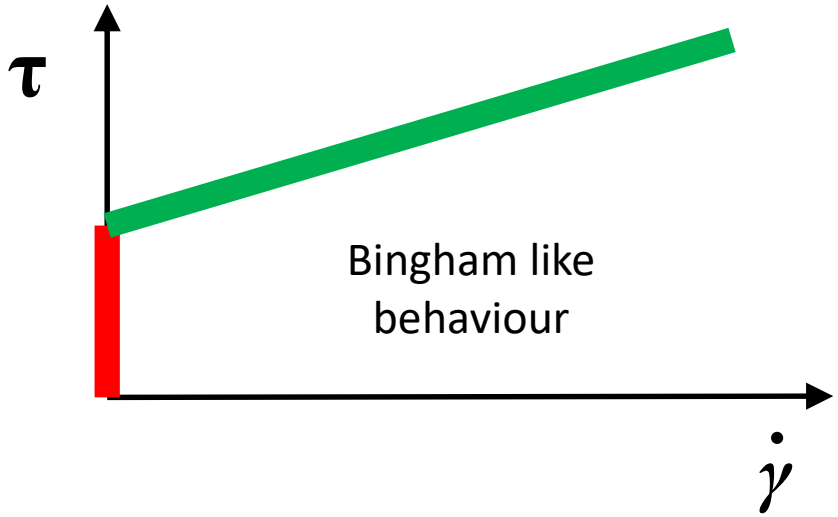


Rest state

S=1

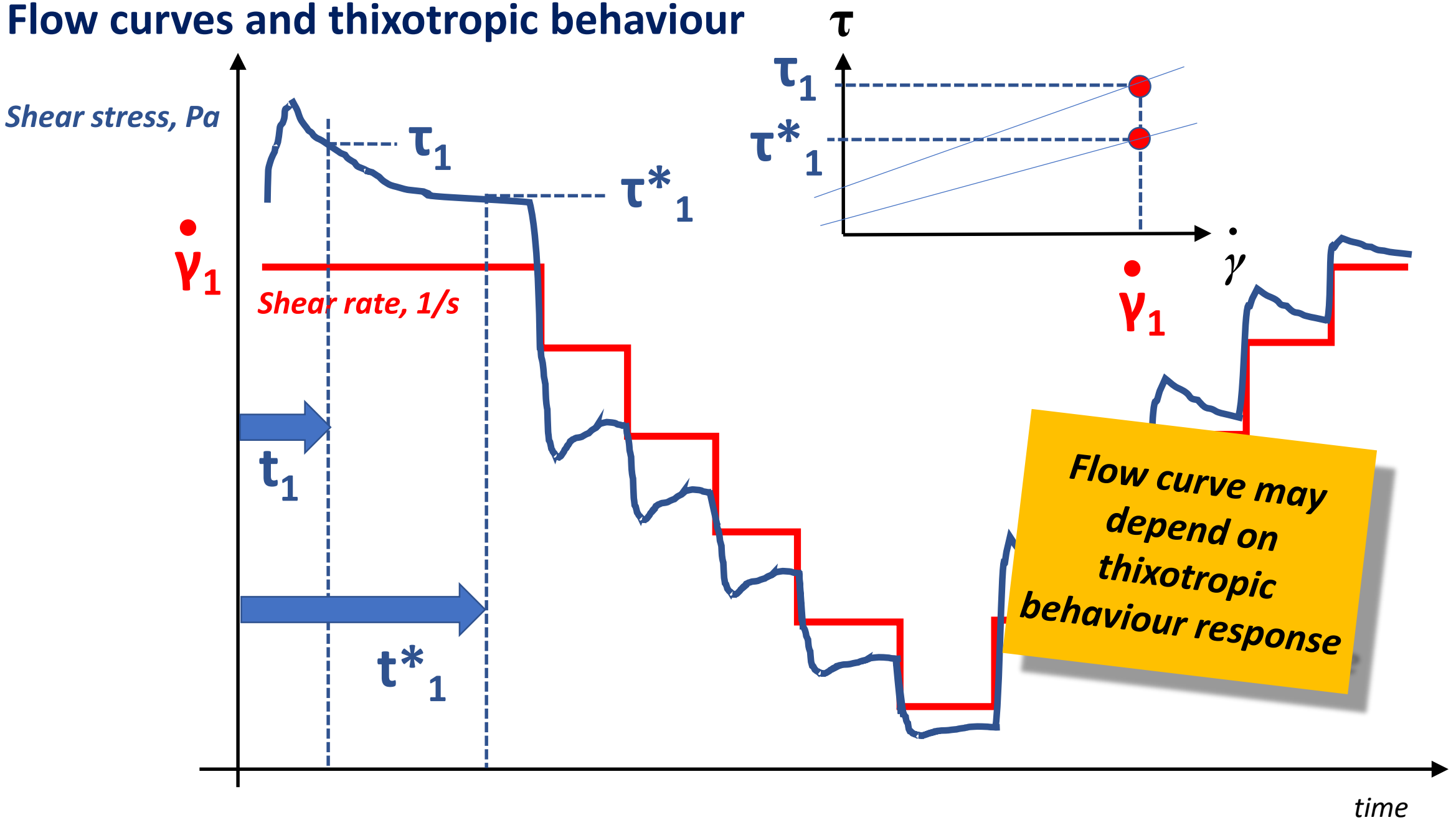
Shear state

S=0

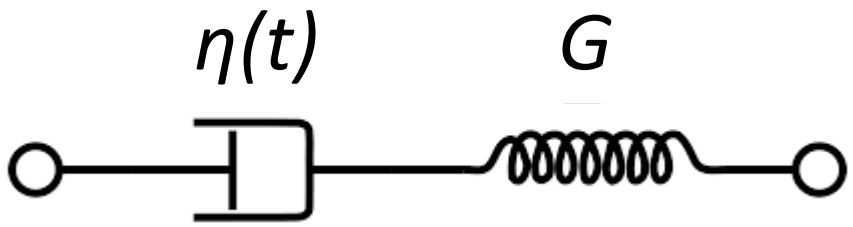


S = structural parameter according to Quemada

Flow curves and thixotropic behaviour

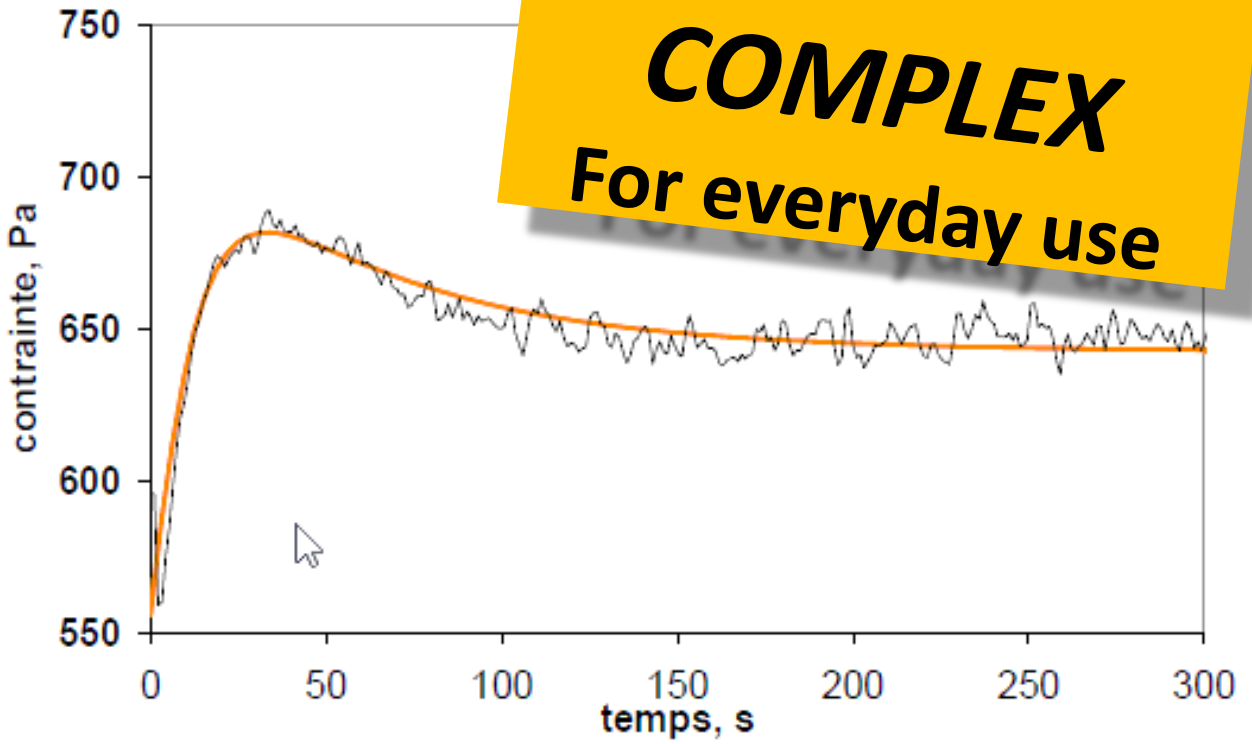


Complex model may describe these phenomena



Maxwell thixoelastic (Quemada)

VERY COMPLEX
For everyday use



$$\frac{1}{G(t)}\frac{d\sigma}{dt}+\frac{\sigma}{\eta(t)}=\dot{\gamma}(t)$$

Flocuation kynetics

$$\frac{dS}{dt}=k_a(1-S)+k_dS$$

$$\eta(S)=\frac{\eta_\infty}{[1-(1-\chi)S(t)]^2} \qquad \chi=\left(\frac{\eta_\infty}{\eta_0}\right)^{1/2}$$

Memory function

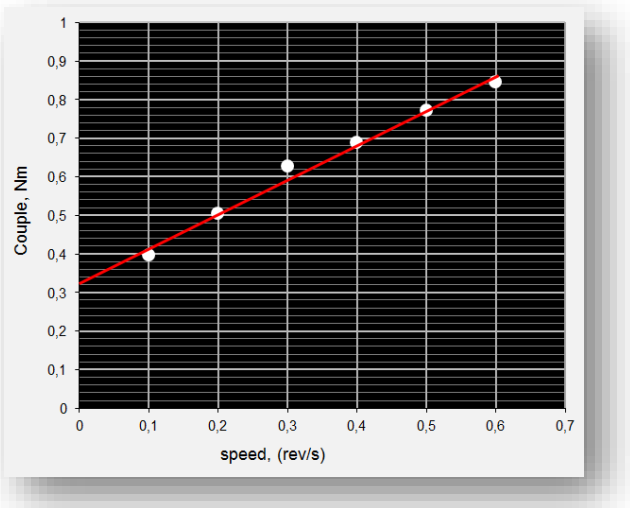
$$F(t,t')\equiv\int_{t'}^{t}\frac{G(t'')}{\eta(t'')}dt''=G\int_{t'}^{t}\frac{[1-(1-\chi)S(t)]^2}{\eta_\infty}dt''$$

Share stress as time function

$$\sigma(t)=\sigma(0)\ \mathrm{e}^{-F(t,0)}+\int_0^t G(t')\ \mathrm{e}^{-F(t,t')}\dot{\gamma}(t')dt'$$

F. Fabbris, W. De Carvalho, Le comportement rhéologique de la pâte de ciment et sa comparaison avec celui du béton :techniques de mesure et analogies d'échelle. 44 GFR 2008

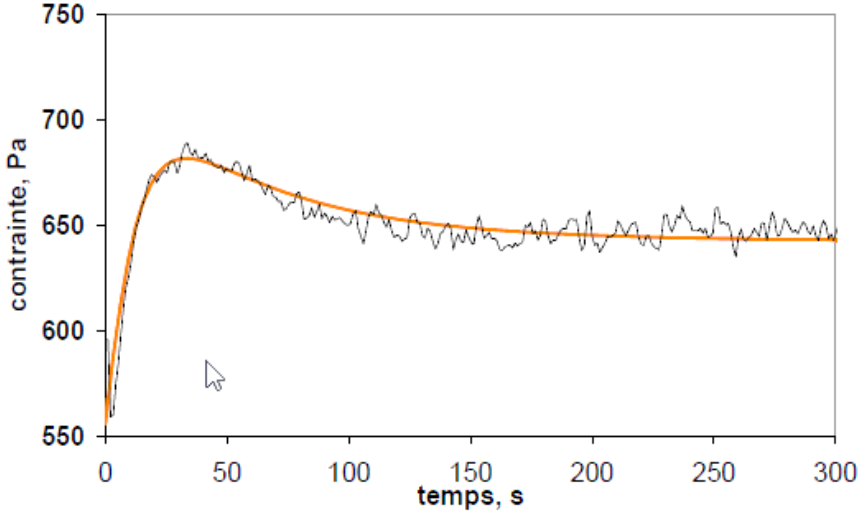
Model choice is to fit to specific needs



Bingham like

- Simple and with few parameters
- Easy technical exchange (universally known)
- Fast data treatement

- Hides time depending phenomena (thixotropy and viscoelasticity)
- May be affected by measurement parametrization
- Insufficient for whole fluid description



Quemada like

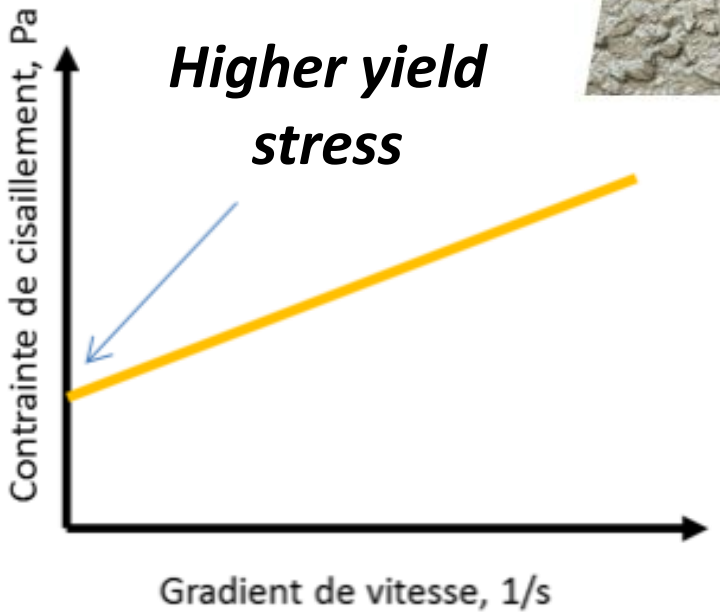
- Accurate description of time dependency
- Brings back to Bingham model
- Describes detailed aspects of industrial process

- Many parameters (some not directly measurable)
- Long data treatement
- Difficult to rely to practical parameters
- Not universally known

For industrial application universality, ease of use and wide share are key

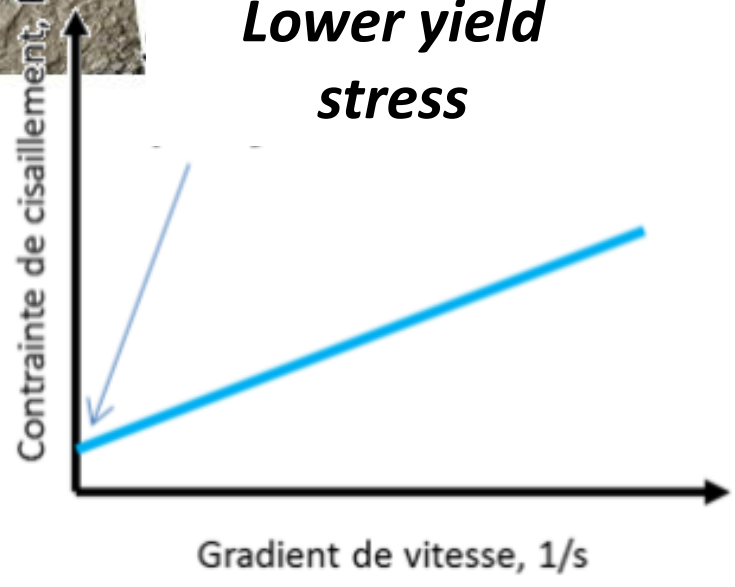
Link between everyday, filed experience and modelization

Higher yield stress

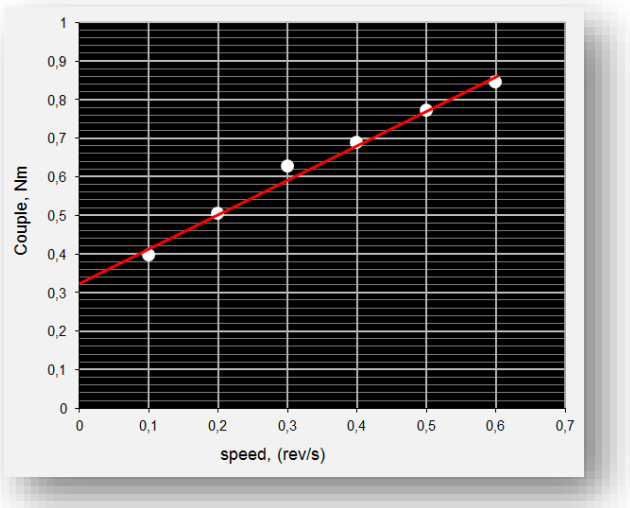


Easy understating is key for everyday use

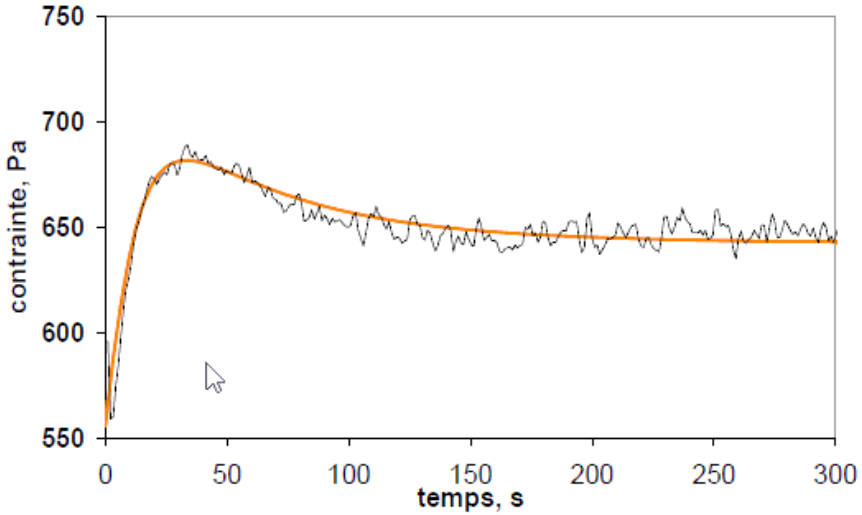
Lower yield stress



Model choice is to fit to specific needs



Bingham like



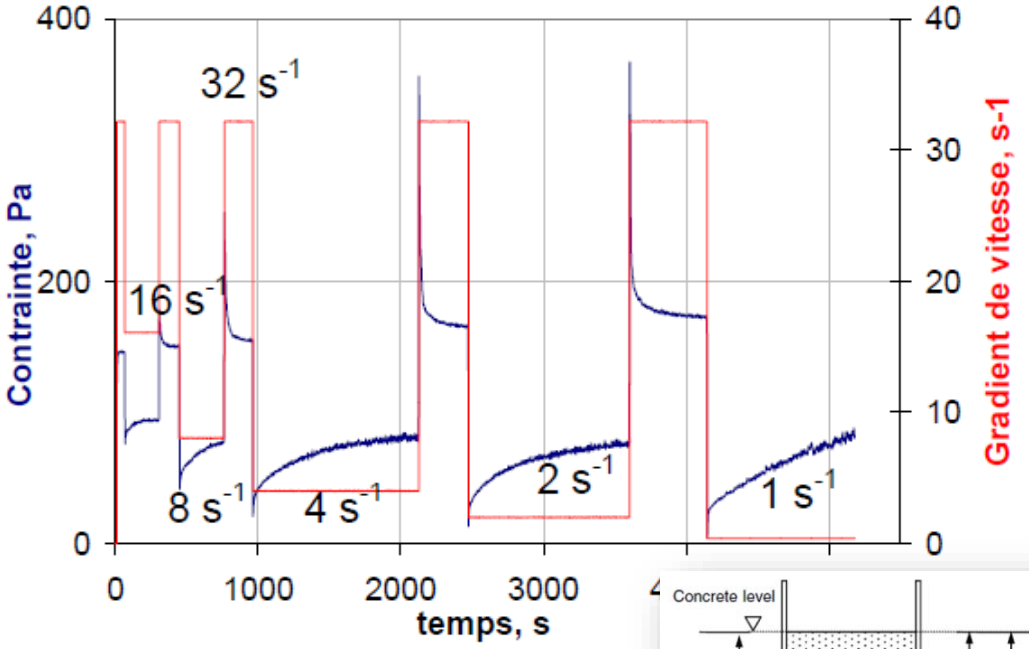
Quemada like

Mass databases, Continuous monitoring, Everyday activity

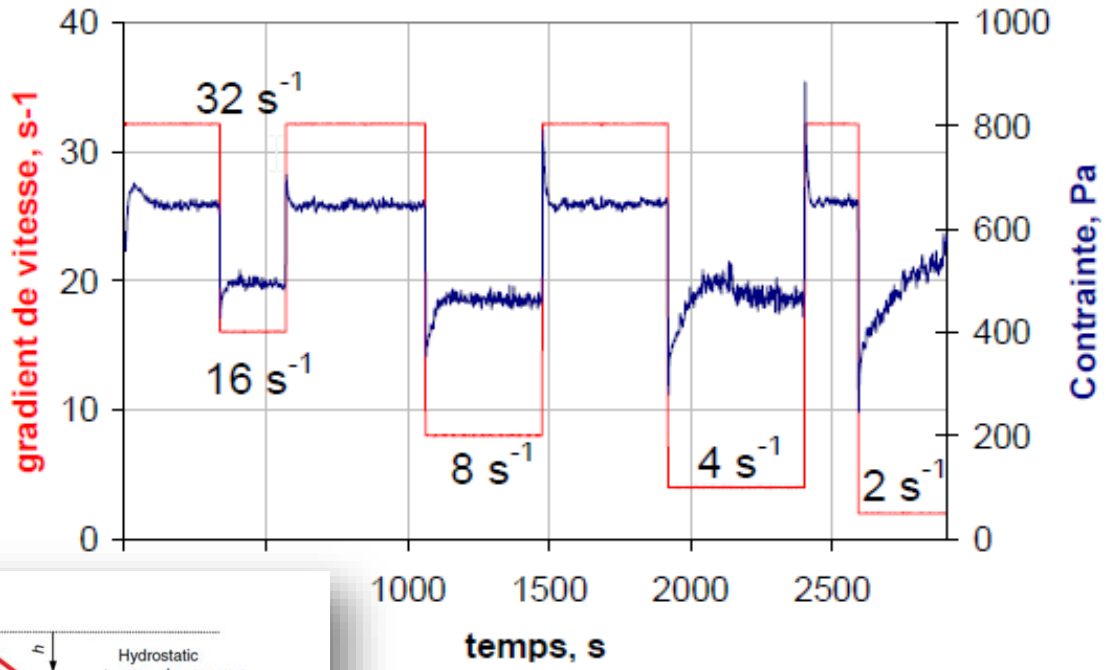
Specific technical issues, Developement, Fine analysis

An exemple of application: thixoelastic fit for formwork pressure reduction

Classical viscoelastic concrete



Thixoelastic concrete



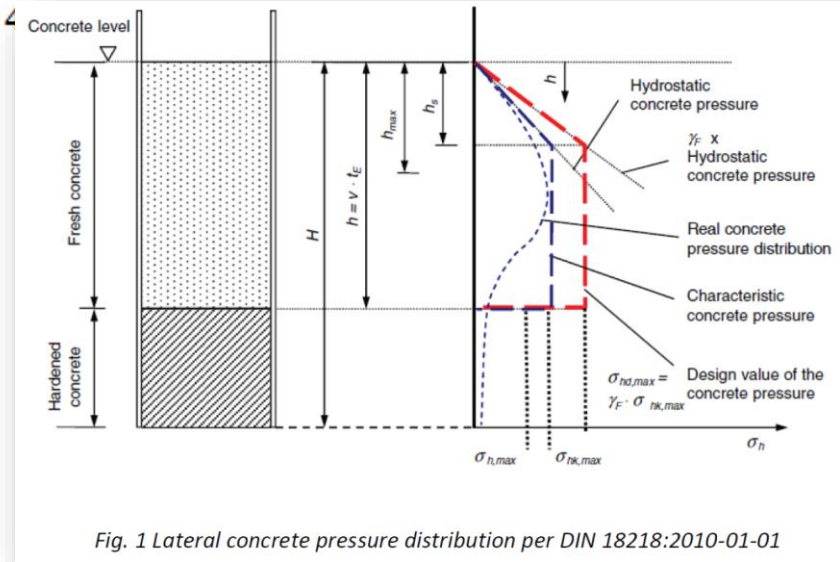


Fig. 1 Lateral concrete pressure distribution per DIN 18218:2010-01-01

KERN TunnelTechnik,
The crucial role played by the concrete in the formwork design, 2017

4. Contribution of concrete rheology on technical and Quality issues

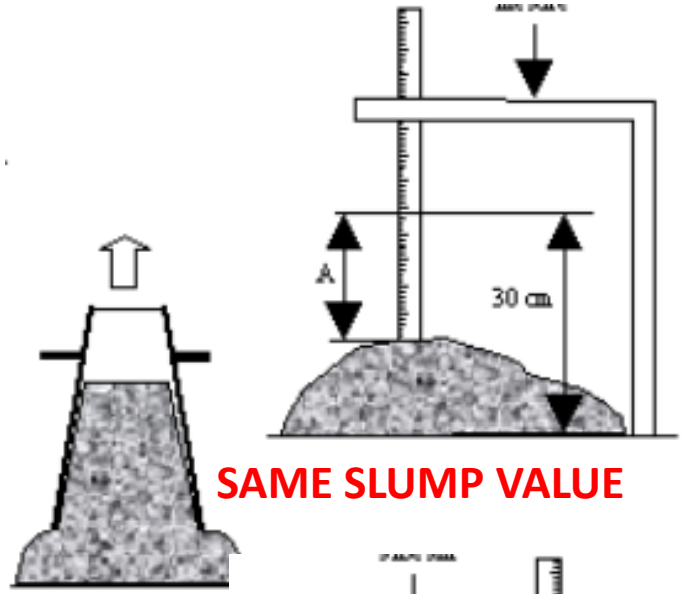
Rheology brings information that is not available with technological tests

Qualitative, on yard estimate

« Sticky »,
« slow »,
« gluing »
« stable »

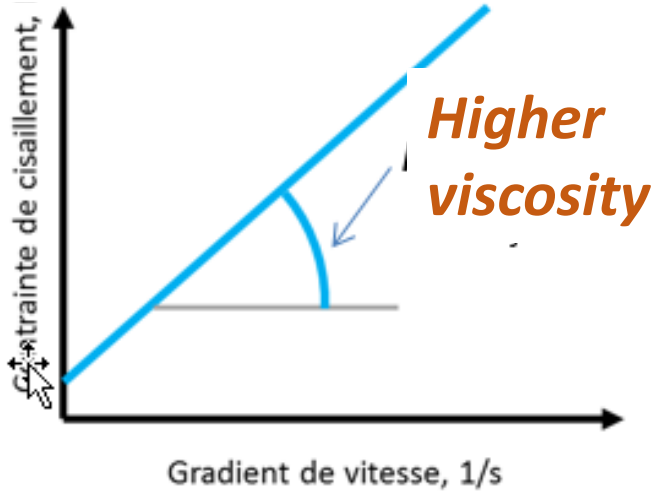
« Fast »,
« sporty »,
« light»
« unstable »

Technological test



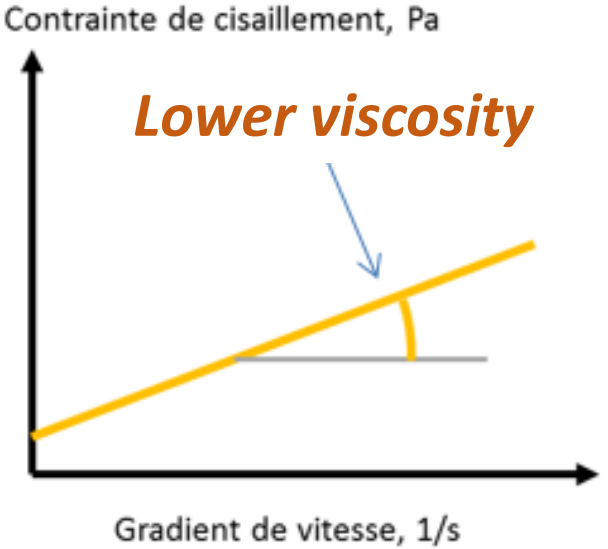
SAME SLUMP VALUE

Quantitative information



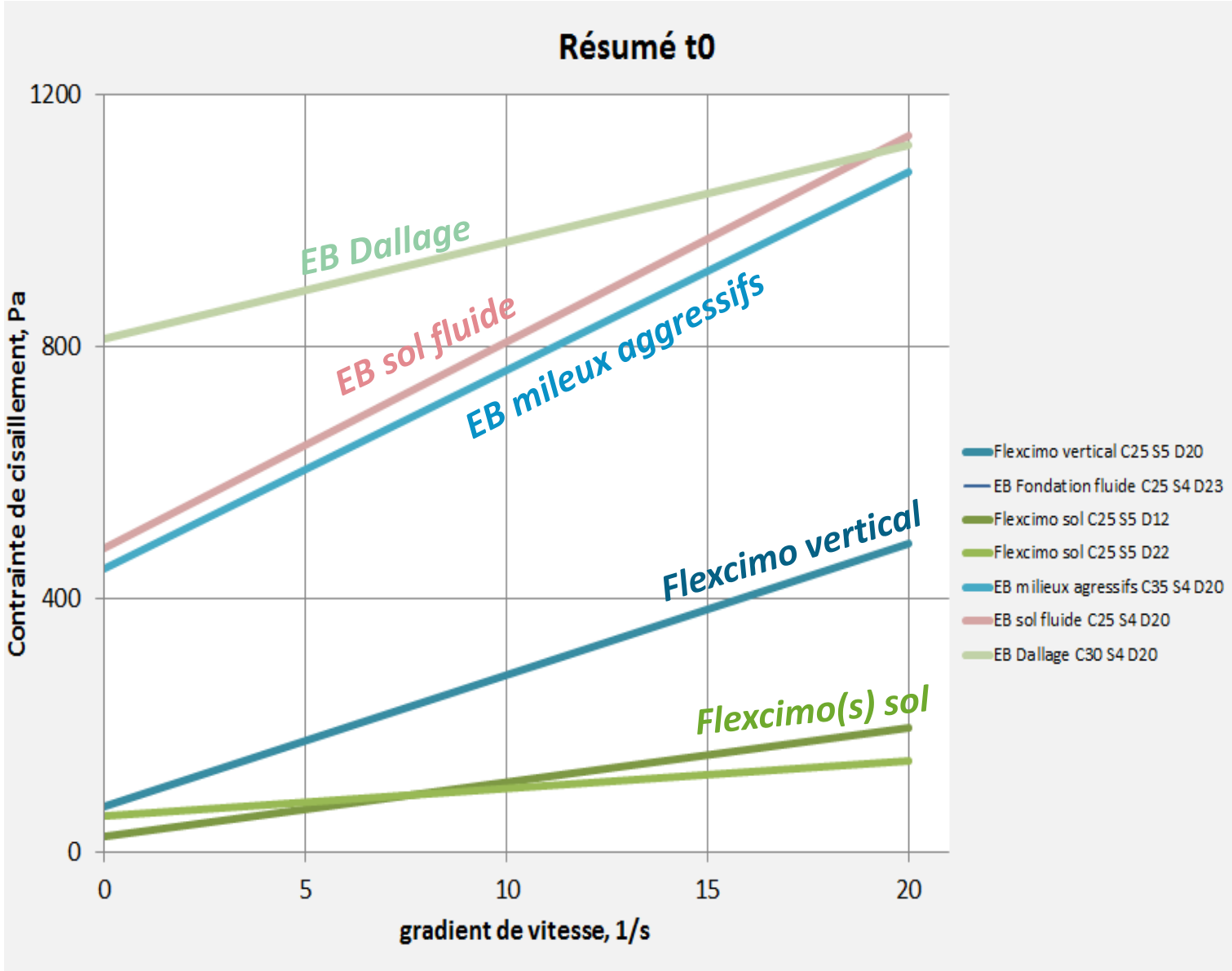
Higher viscosity

Same yield stress



Lower viscosity

Rheological curves Database let to asses reference behaviour



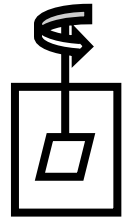
> Correlation between application and typical rheological curve

80

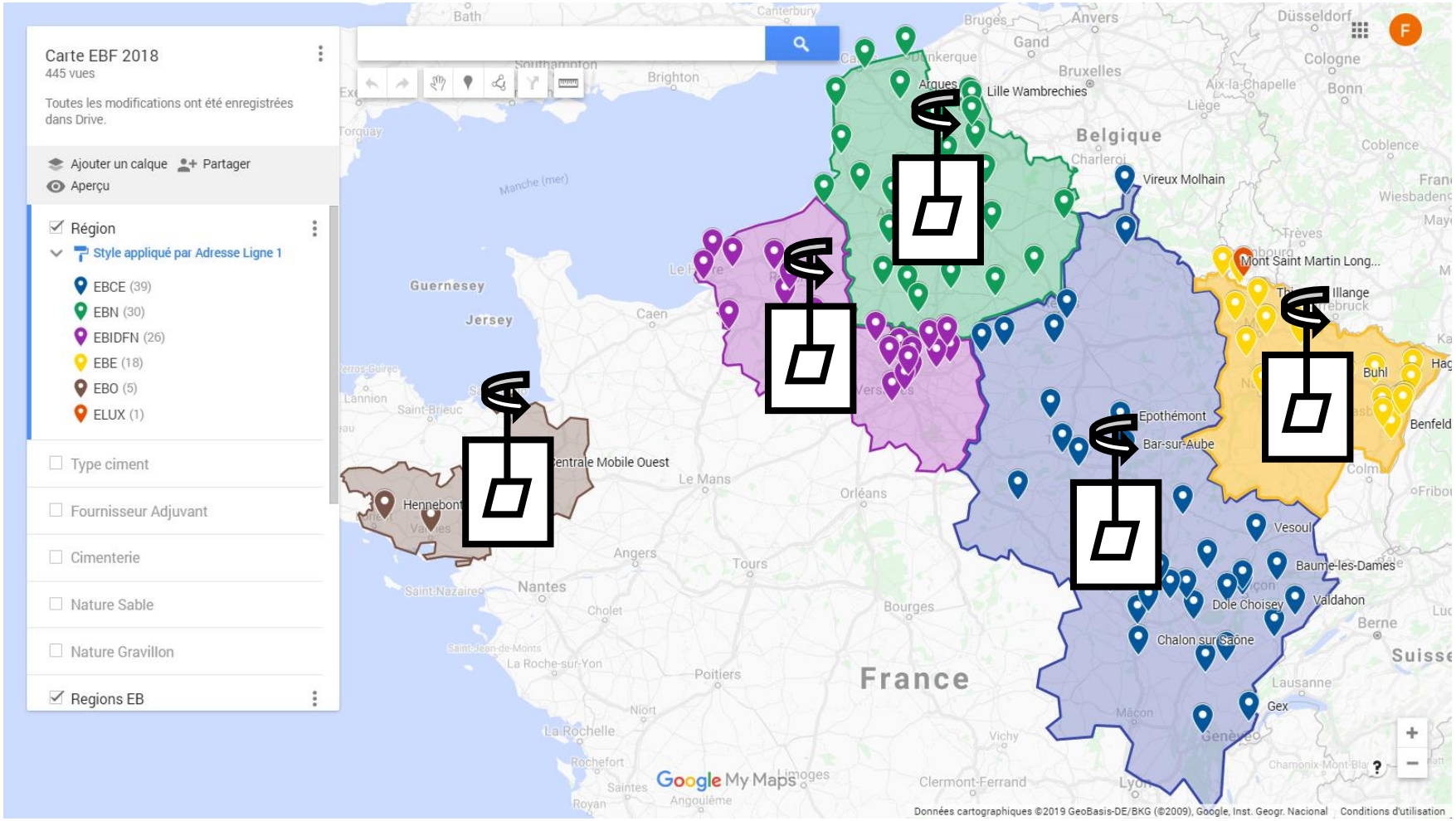
S4 concrete formulation Lab and Yard rheograms

Data sharing and network access

- 6 ICAR type rheometers
- Connected database
- Online and offline
- access



= 1 ICAR rheometer



Data sharing and network access

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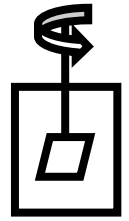

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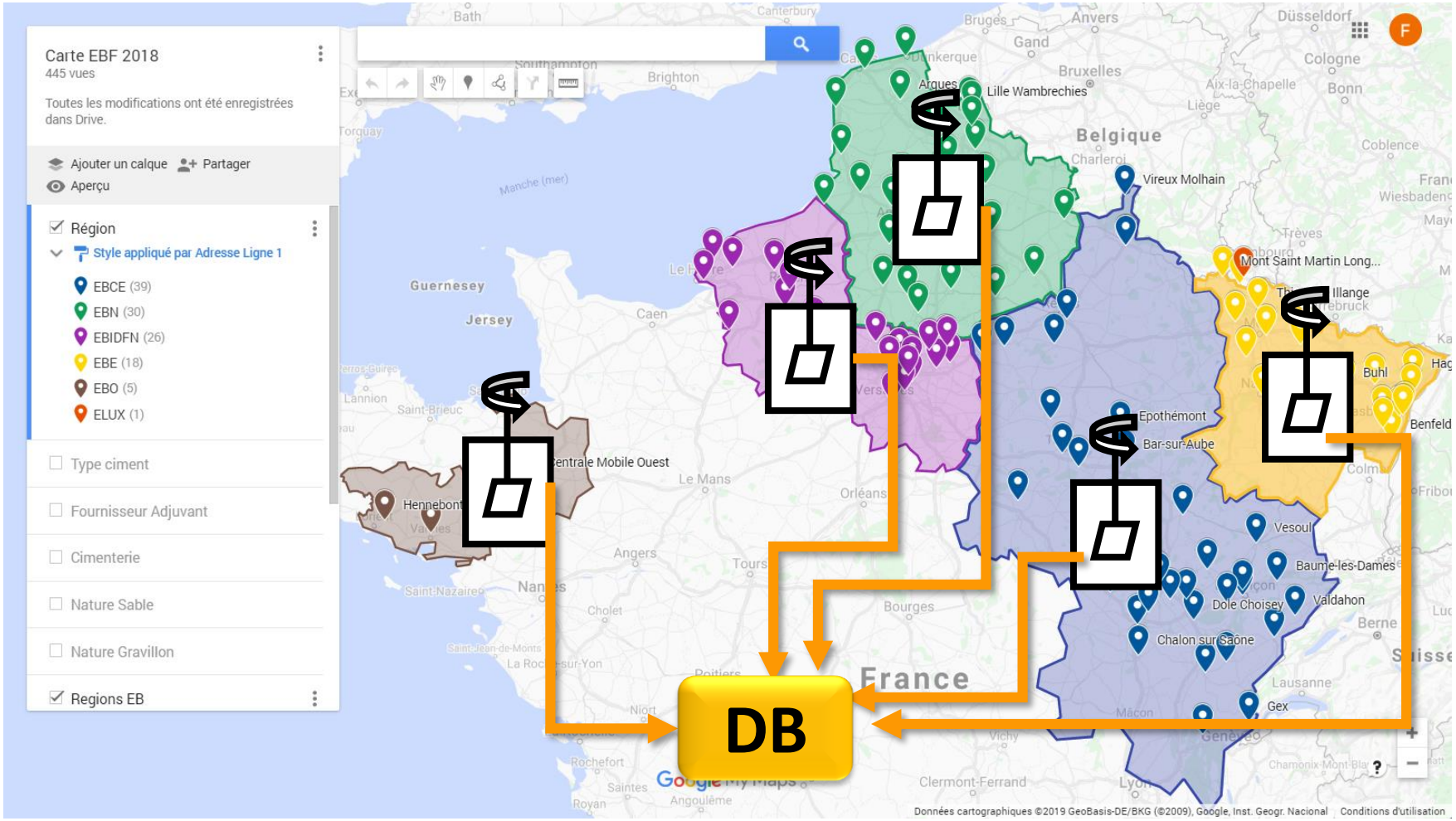
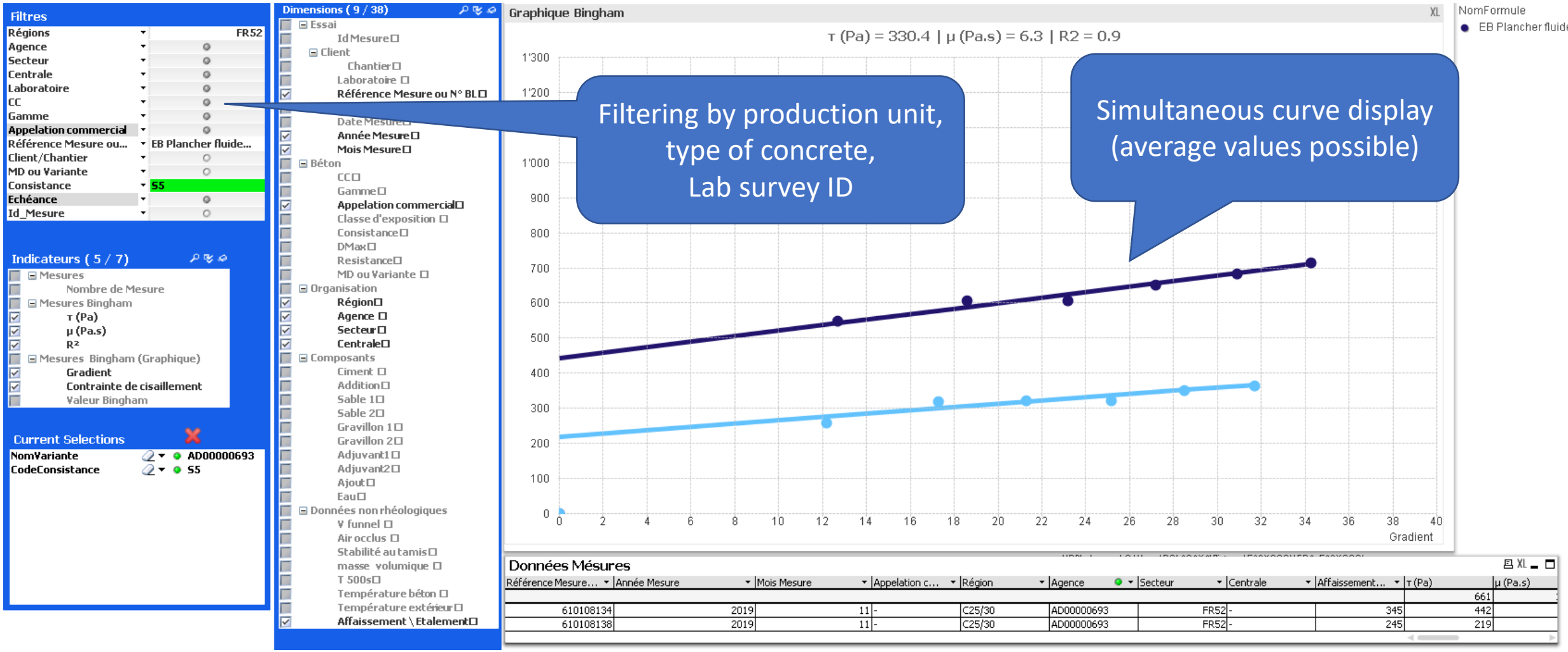
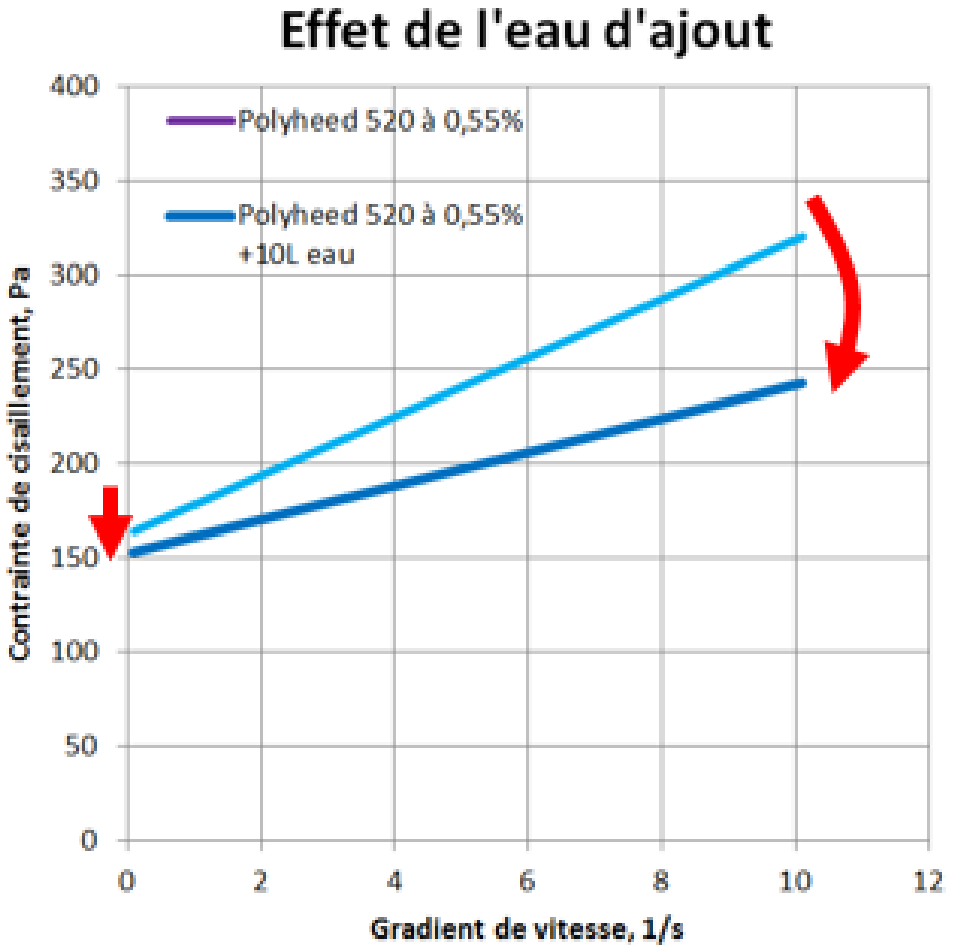


Data sharing and network access



Rheological curves Database let to study formulation effect

Exemple :

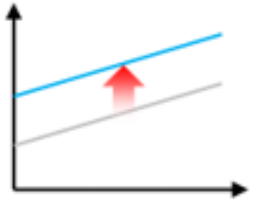
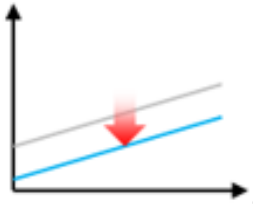


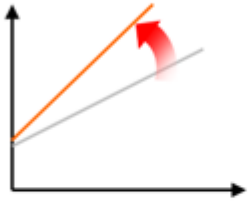
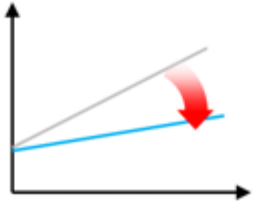
	Ref.	+10 L/m³
Floxw, mm	200	230
	+15%	
Yield Stress, Pa	160	150
	-6%	
Viscosity, Pa·s	16	9
	-43%	

L'effet principale de l'ajout d'eau est la baisse de la viscosité. Le seuil diminue en moindre mesure

Rheological curves Database let to form a parameter/effect table

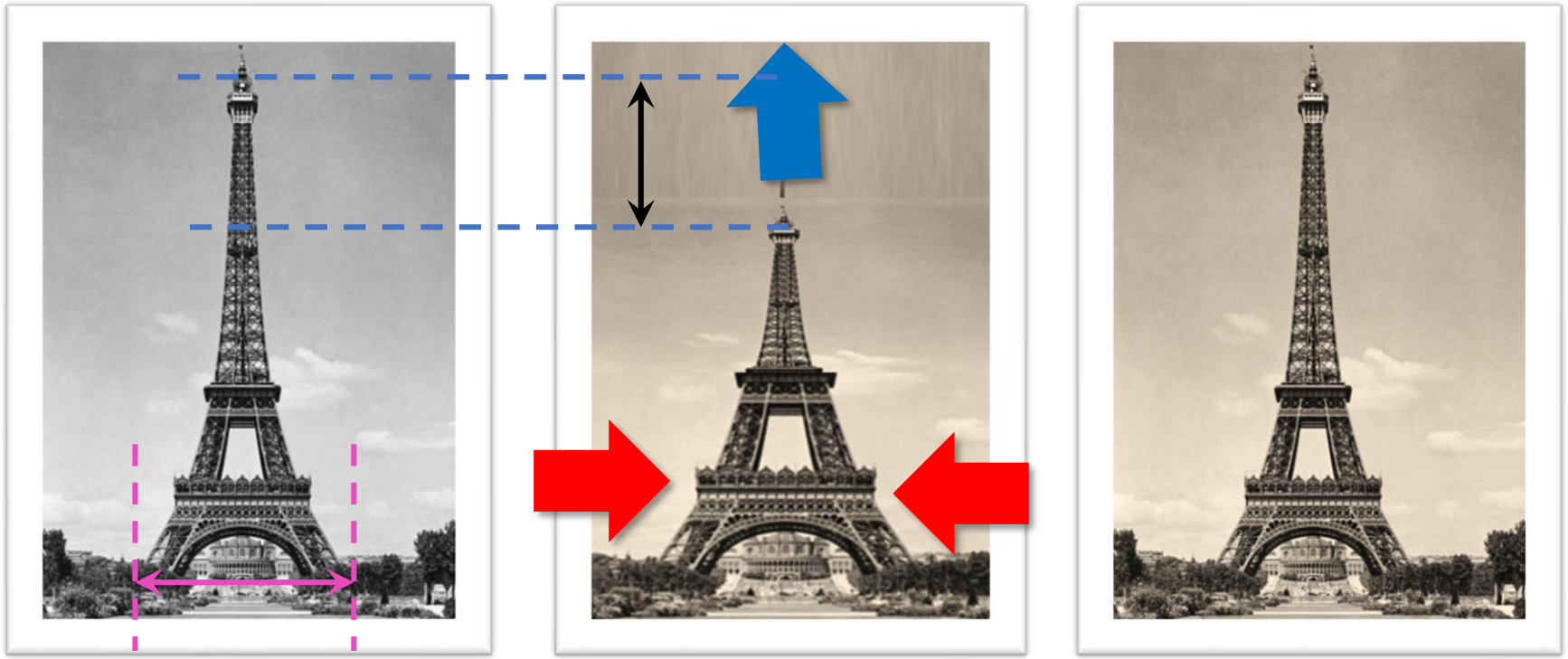
Variation	Yield stress effect	Viscosity effect
W/C ratio increase	↘	↘↘
Paste volume increase	↘	↘
Parameter 1	↗↗↗	-
Parameter 2	↗	↗↗
Parameter 3	-	↘
Parameter 4	↘↘	-
Para		

Targeted variation	Parameter modification
To **increase Yield stress** (by decreasing impact effect) 	- Parameter 1 - Parameter 2 - Parameter 6 - ....
To **lower Yield stress** (by decreasing impact effect) 	- Parameter 4 - Parameter 5 - Parameter 0 .... -

Targeted Variation	Parameter modification
To **Increase viscosity** (by decreasing impact effect) 	- Parameter 3 - Parameter 5 - Parameter 1 - ....
To **Decrease viscosity** (by decreasing impact effect) 	- Parameter 2 - Parameter 7 - Parameter 6 .... -

Rheological “footprint” approach

1. Feature a rheological behavoiur **considered as a « reference »**
2. **Quantify the gap** when a parameter is changing;
3. **Correct the gap by formulation** adjustments in order to **find the targeted behaviour**



Rheological curves Database let to assess reference behaviour

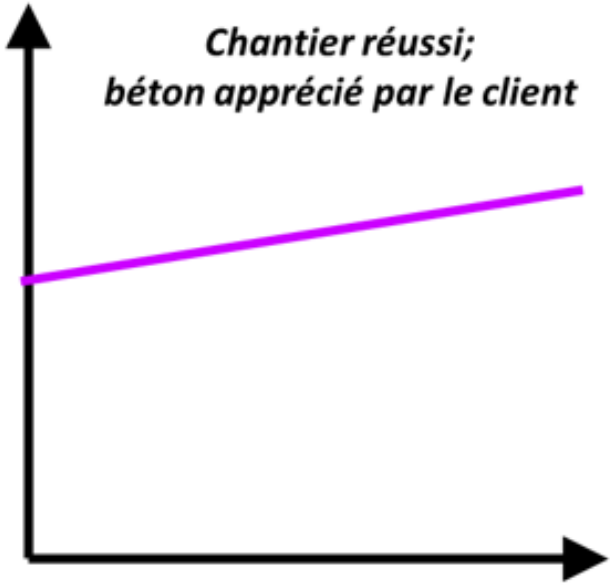
Identical
SPECIFICATIONS

Production Unit A

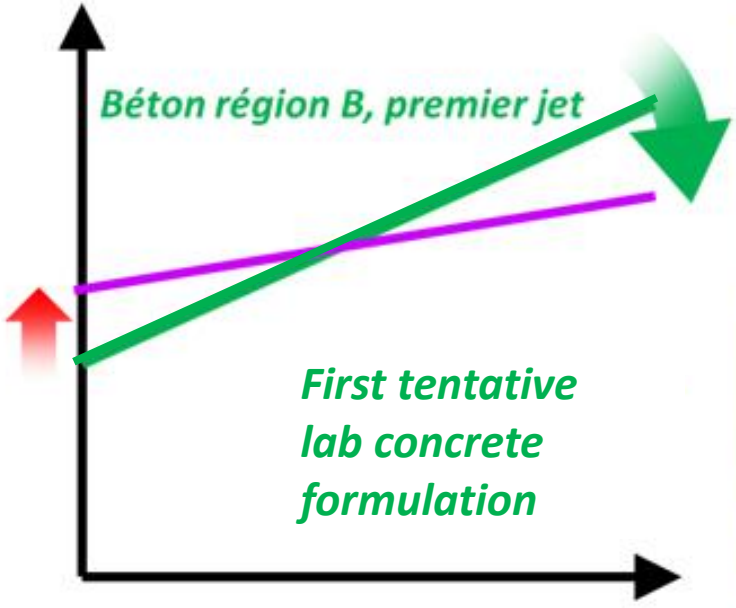
Production Unit B

Industrial application exemple

Civil work region A



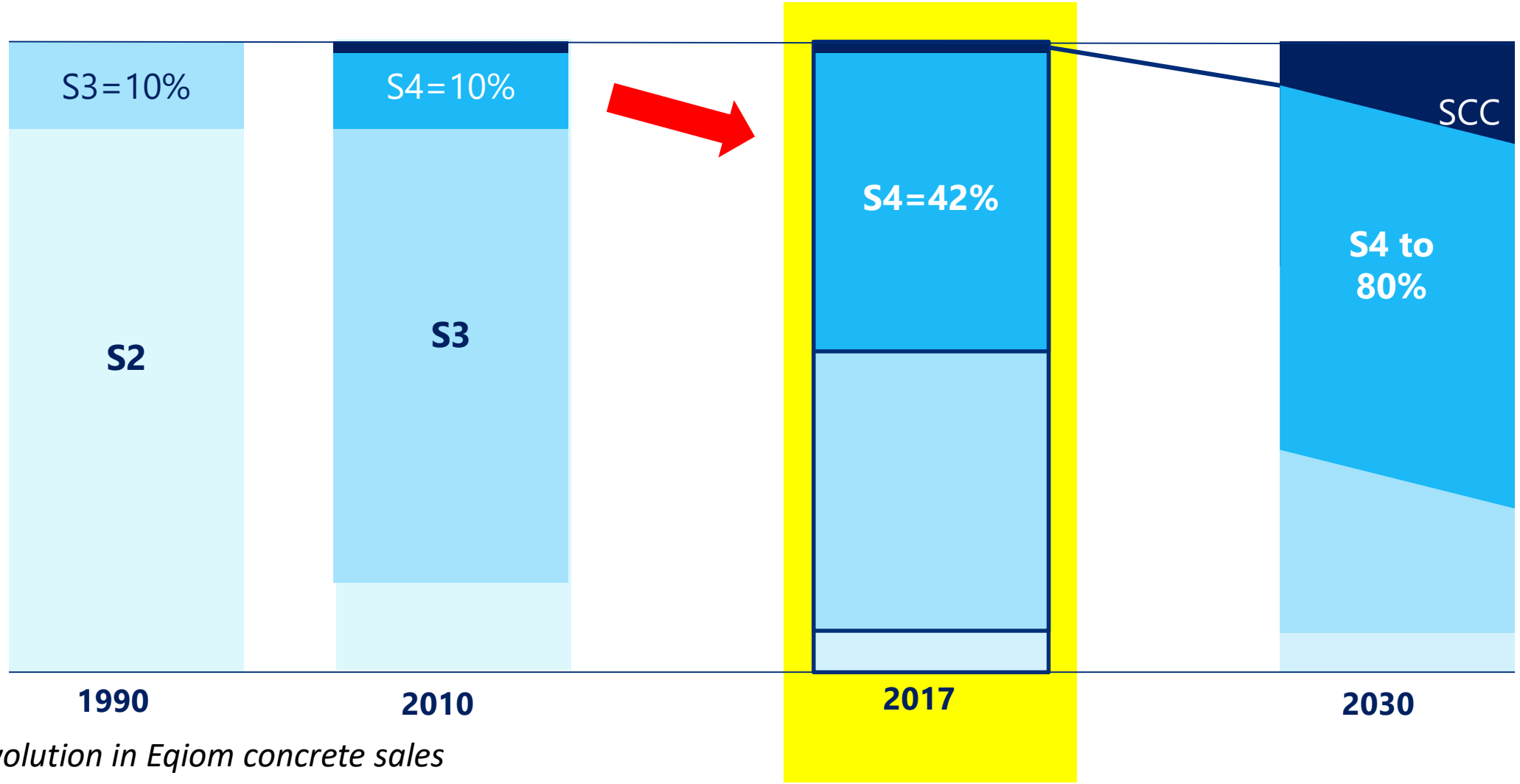
Technical success, Concrete fit for application



Civil work region B

« S4 attitude »

Rheological know how let to improve fluid concrete sales share



Fluidity evolution in Eqiom concrete sales

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Thank you for your attention!