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SCHOOL OF ENGINEERING AND DIGITAL SCIENCES

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Skoltech
Skolkovo Institute of Science and Technology

Computational Materials Science Seminar (CMS)

Computational Materials Science and Engineering of Concrete: Computational rheology and pumping of concrete

Yanwei Wang

Laboratory of Computational Materials Science
Center for Energy and Advanced Materials Science, National Laboratory Astana (NLA)

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November 10, 2022, Astana

Warm-up Questions

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What is the most consumed substance in the world?

What is the second most consumed substance in the world?

What is the most consumed man-made material in the world?

Warm-up Questions

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Hoover Dam (Since 1936)

Three Gorges Dam(Since 2003)

https://www.britannica.com/topic/Hoover-Dam#/media/1/271416/213566
https://www.britannica.com/topic/Three-Gorges-Dam#/media/1/593760/113950 (Access Date: November 10, 2022)

Warm-up Questions

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What is the most consumed substance in the world?

Water

What is the second most consumed substance in the world?

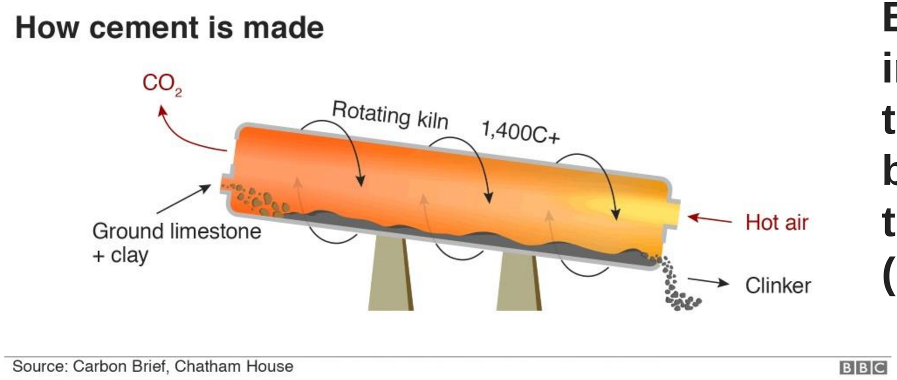
Concrete

What is the most consumed man-made material in the world?

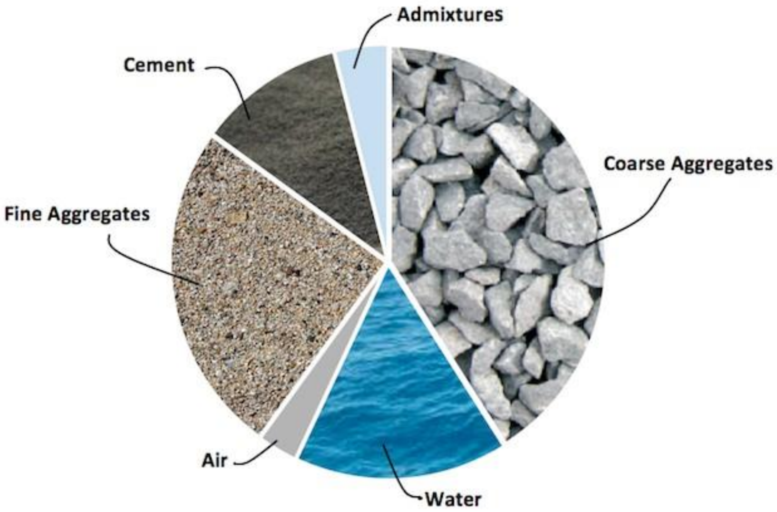
Concrete

Worldwide, over ten billion tons of concrete are being produced each year.

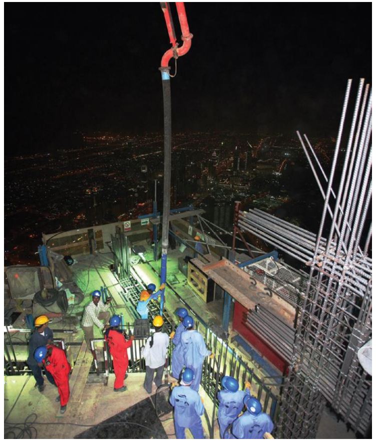

Urbanization
Transportation
圣彼得堡
莫斯科
喀山
奥伦堡
霍尔果斯
乌鲁木齐
兰州
郑州
连云港
Clean Energy
Environment



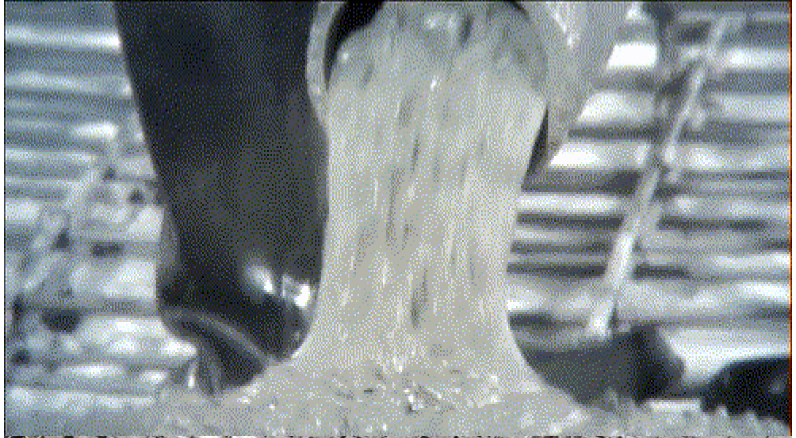
Burj Khalifa in Dubai, the tallest building in the world (since 2010)

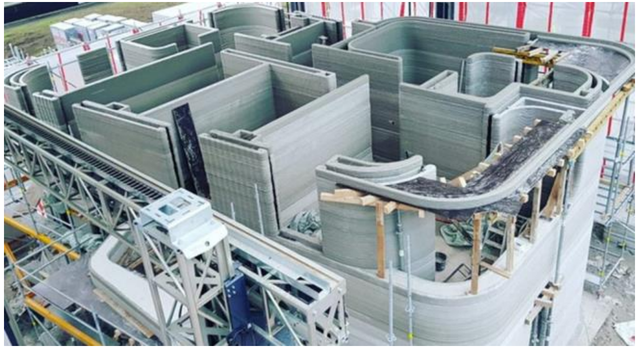


https://www.giatecscientific.com/education/concrete-mix-design-just-got-easier/



Aldred, J. (2010, May). Burj Khalifa–a new high for high-performance concrete. In Proceedings of the Institution of Civil Engineers-Civil Engineering (Vol. 163, No. 2, pp. 66-73). Thomas Telford Ltd.





Pumping of Concrete

3D Concrete Pumping

Burj Khalifa set new standards for reinforced-concrete construction, but there is no room for complacency in future projects.

Aldred, J. (2010, May). Burj Khalifa–a new high for high-performance concrete. In Proceedings of the Institution of Civil Engineers-Civil Engineering (Vol. 163, No. 2, pp. 66-73). Thomas Telford Ltd.

Materials Science and Engineering of Concrete

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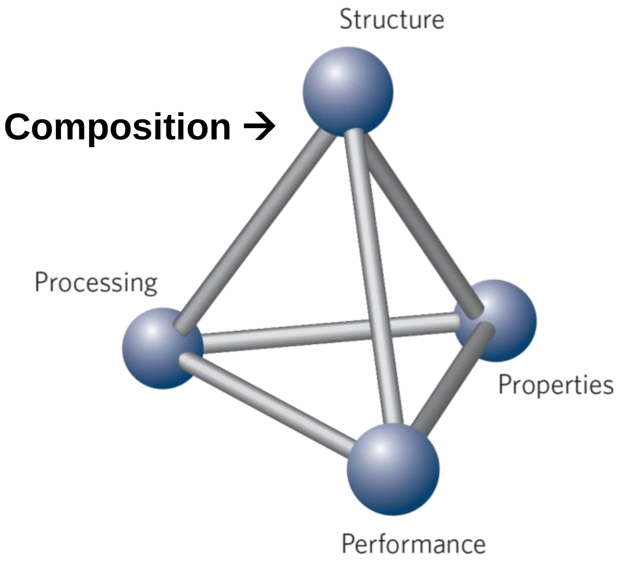
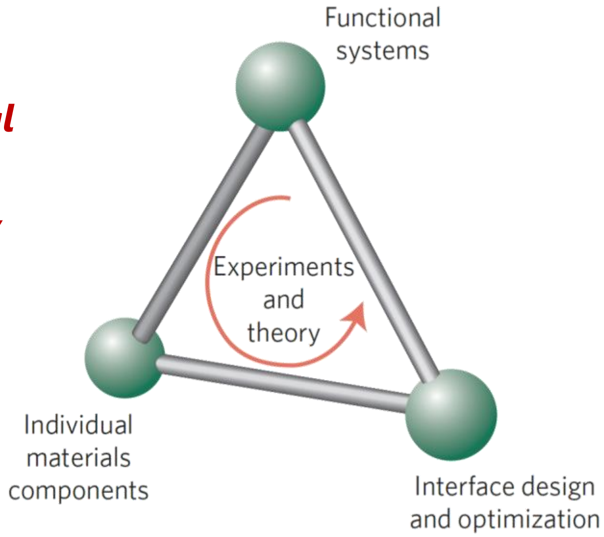
The traditional materials science tetrahedron



"System-level planning of theoretical and experimental efforts is increasingly important for the development of modern materials science."

The emerging systems materials engineering triangle

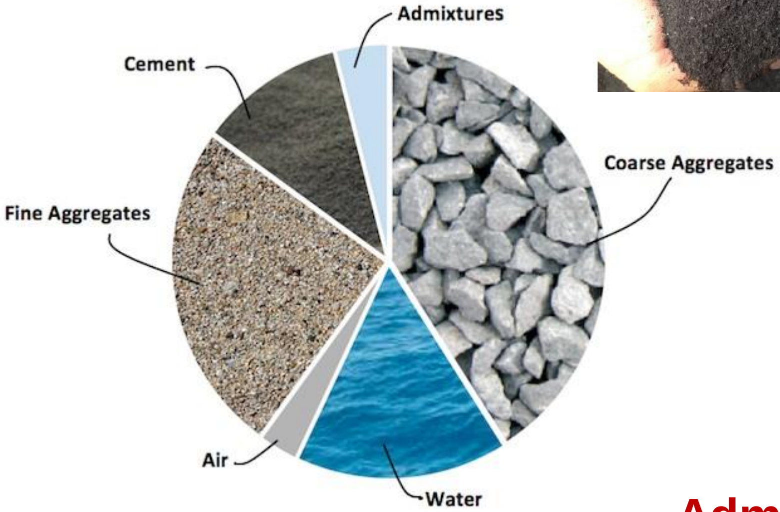


Yang, P., & Tarascon, J. M. (2012). Towards systems materials engineering. Nature materials, 11(7), 560-563.

Materials Science and Engineering of Concrete

Admixtures

- Mineral admixtures
- Chemical admixtures



Admixtures in concrete are like spices in food.

Computational Materials Science and Engineering of Concrete

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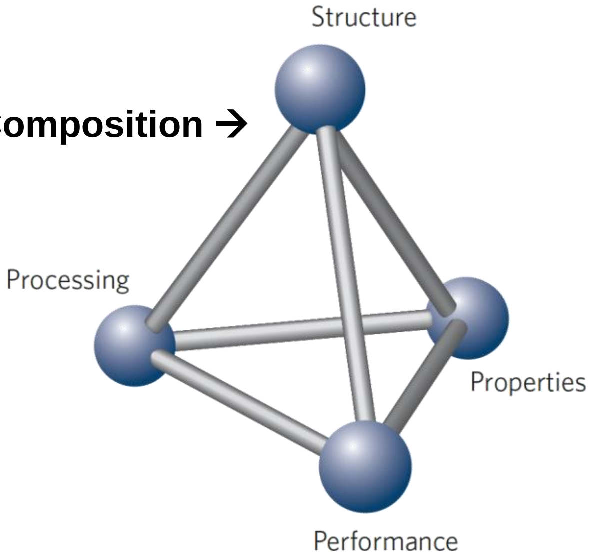
The traditional materials science tetrahedron

Composition →



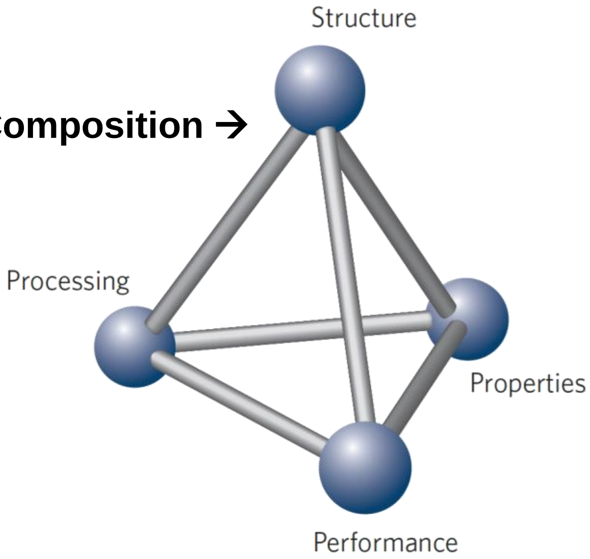
Selected Topics for Computational Studies

- Design of chemical admixtures
- Mix design
- Composition → Processing → Structure → Properties→ Performance (PSPP) relationships
- Influences of temperature, humidity, and other environmental factors
- Improvement of concrete processability (workability)
- Improvement of concrete durability
- Life Cycle Assessments (LCA)
- Service life prediction

Computational Materials Science and Engineering of Concrete

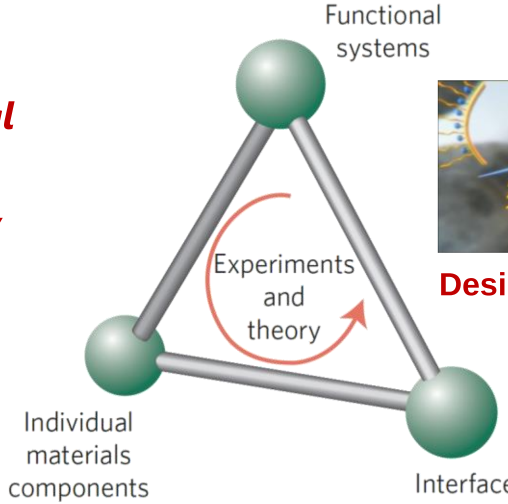
The traditional materials science tetrahedron

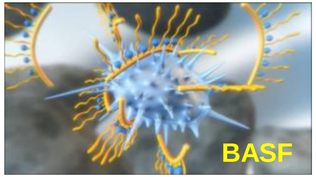
Composition →



"System-level planning of theoretical and experimental efforts is increasingly important for the development of modern materials science."

The emerging systems materials engineering triangle



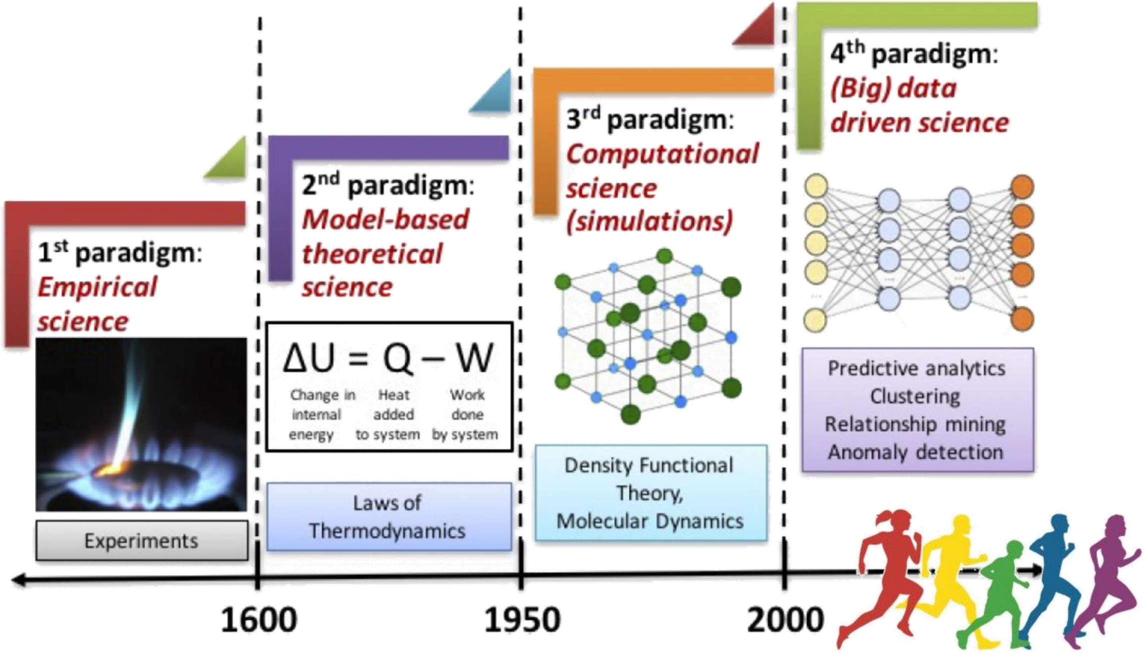


Design of interfaces

Yang, P., & Tarascon, J. M. (2012). Towards systems materials engineering. Nature materials, 11(7), 560-563.

Computational Materials Science and Engineering of Concrete

The four paradigms of science: empirical, theoretical, computational, and data-driven



Agrawal, A., & Choudhary, A. (2016). Perspective: Materials informatics and big data: Realization of the "fourth paradigm" of science in materials science. Apl Materials, 4(5), 053208.

https://doi.org/10.1063/1.4946894

Computational Materials Science and Engineering of Concrete

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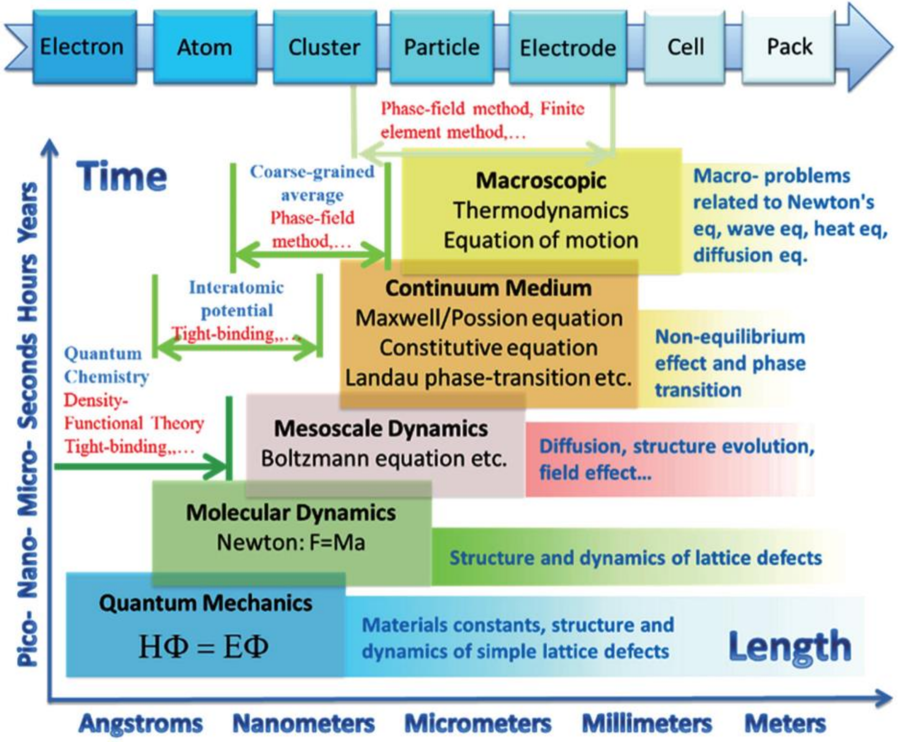
Multi-scale & Multi-physics-based Modelling

Shi et al. (2015). Multi-scale computation methods: Their applications in lithium-ion battery research and development. Chinese Physics B, 25(1), 018212.



https://doi.org/10.1088/1674-1056/25/1/018212

Computational Rheology of Concrete

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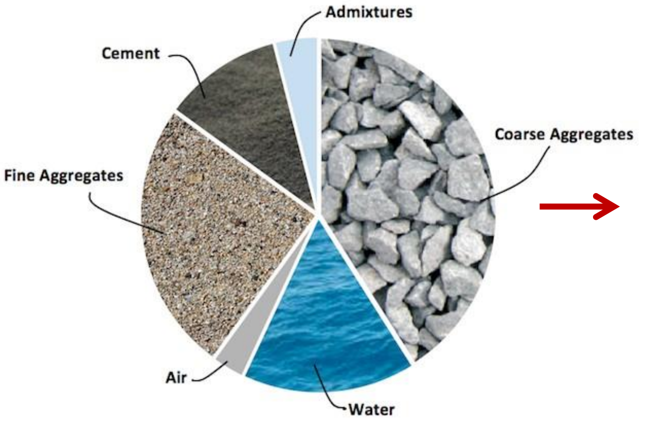
Rheology
rheo: ‘flow’; -logy: 'study of'

Wikipedia:
- Rheology is the study of the flow of matter
- Rheology deals with the deformation and flow of materials

Given composition, can we compute the rheological properties of concrete?



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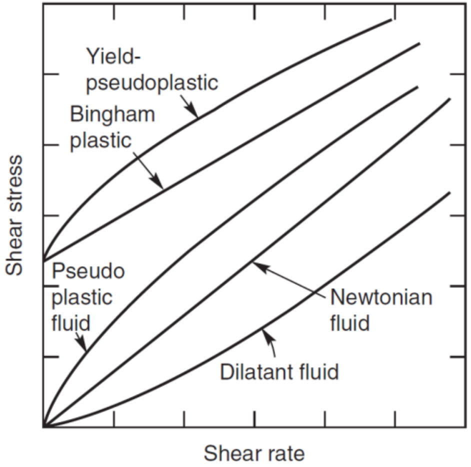

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Rheology of Concrete

Rheology
rheo: ‘flow’; -logy: 'study of'

Wikipedia:
- Rheology is the study of the flow of matter
- Rheology deals with the deformation and flow of materials

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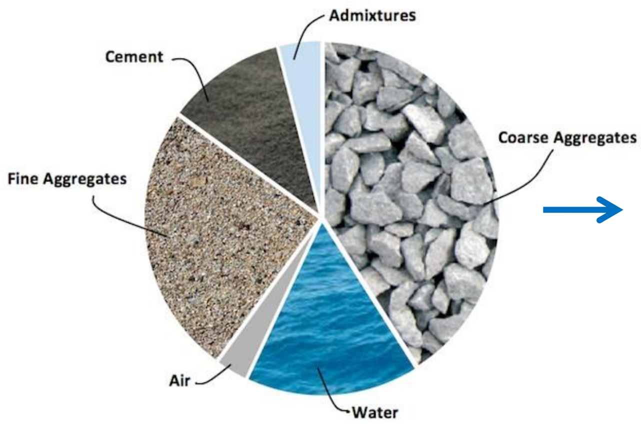

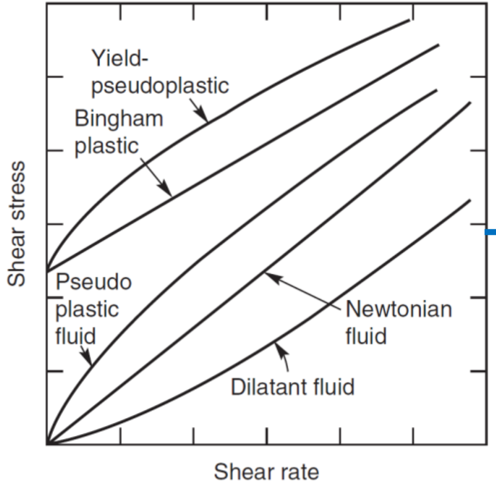

Rheology of Concrete

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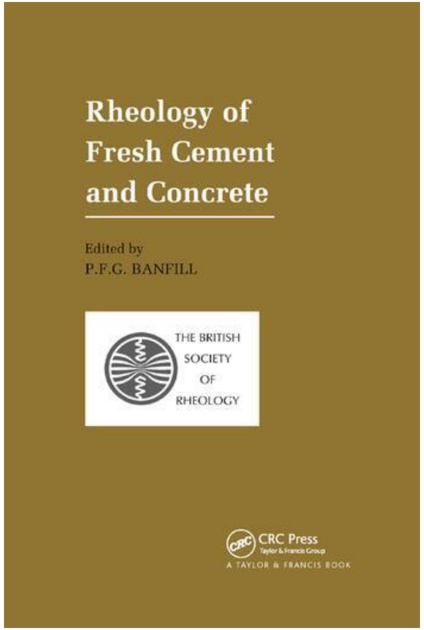
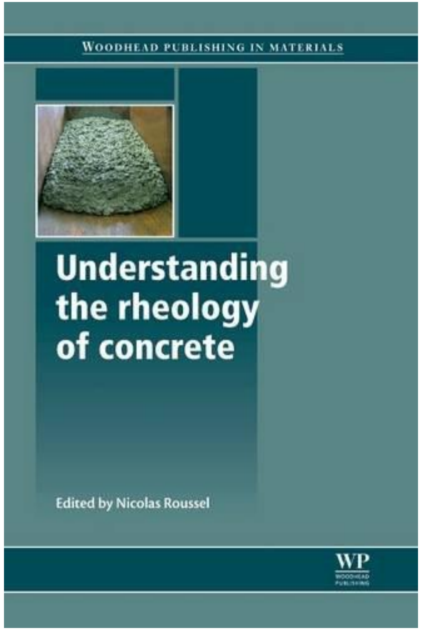
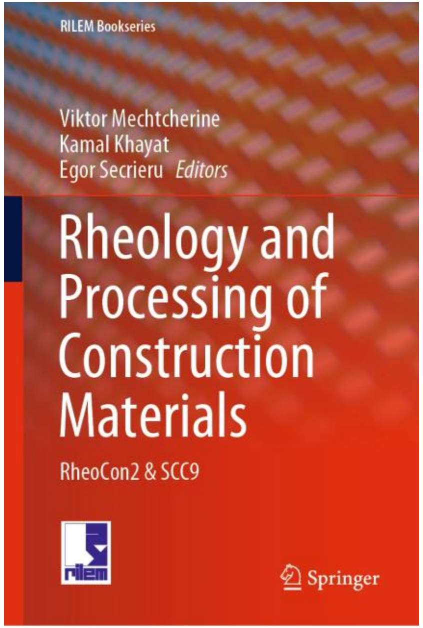


Rheology of Fresh Cement and Concrete, Edited By P.F.G. Banfill, 1990



Understanding the Rheology of Concrete, Edited by Nicolas Roussel, 2016



Rheology and Processing of Construction Materials, RheoCon2 & SCC9, Edited by Viktor Mechtcherine, Kamal Khayat, Egor Secrieru, 2020

Rheology of Fresh Cement-Based Materials Fundamentals, Measurements, and Applications.

By Qiang Yuan, Caijun Shi, Dengwu Jiao. 2023

Rheology of Concrete

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Cement and Concrete Research 41 (2011) 1279–1288

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Rheology as a tool in concrete science: The use of rheographs and workability boxes

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[b] ICI Rheocenter, Innovation Center Iceland, Keldnaholti, IS-112 Reykjavik, Iceland

A R T I C L E I N F O

Article history:
Received 14 August 2010
Accepted 12 January 2011

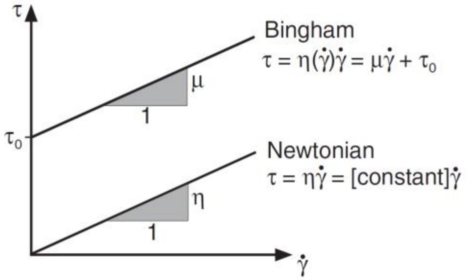
Keywords:
Rheograph
Workability box (A)
Fresh concrete (A)
Rheology (A)

A B S T R A C T

Rheology can supply valuable and practical information regarding the properties of fresh concrete, how to reach an optimization of the product and how to attain it by the use of rheograph. Otherwise, the optimization is largely based on feeling. The rheograph reveals in a systematical way the effects of diverse changes on the rheological behavior of the cement based suspension and thus is a convenient and essential tool to compare different concrete types and examine the behavior relative to changed quantities of constituents. Effects of many admixtures as well as the basic constituents of fresh concrete have been revealed in rheographs. In principle the effect of two or more constituents can be added in a rheograph to estimate the combined effect, which constitutes a so-called vectorized-rheograph approach.
Different applications and types of concrete like slipform, underwater, and high strength, are described by workability boxes. New rheograph with boxes for various types of self compacting concrete is proposed.

Bingham Model

- **Yield stress: τ_0**
- **Plastic viscosity: μ**



Rheology of Concrete: Rheograph

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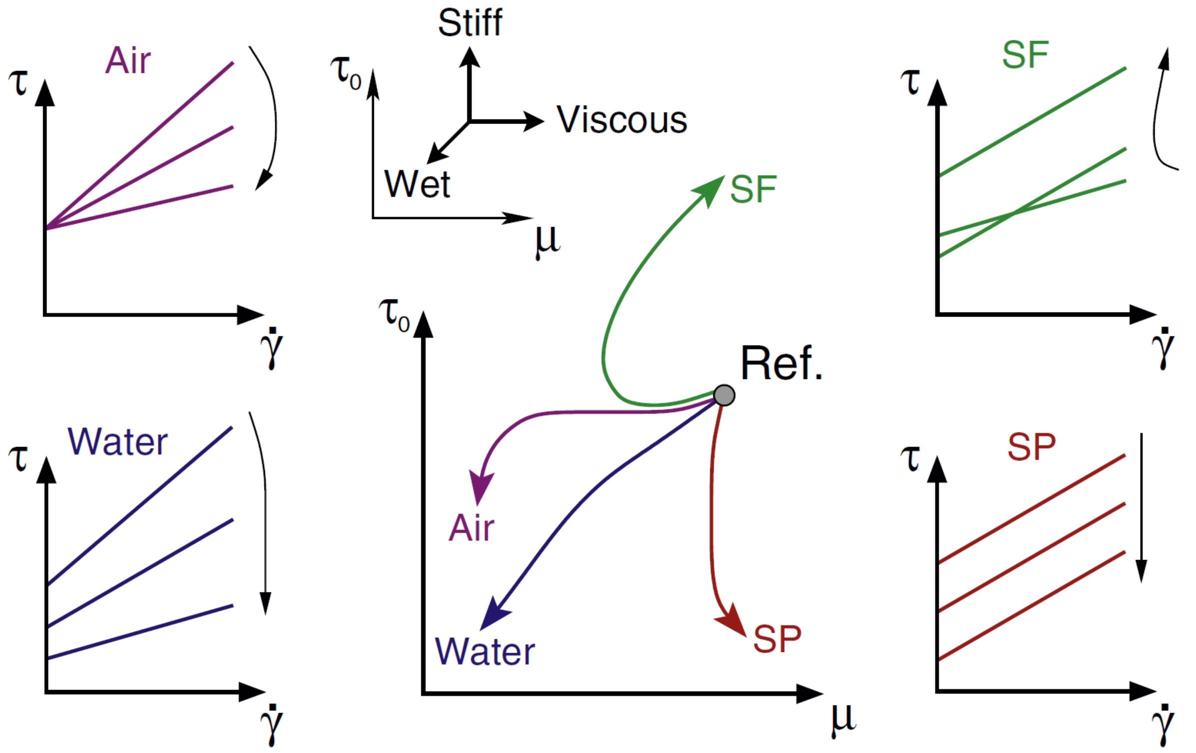
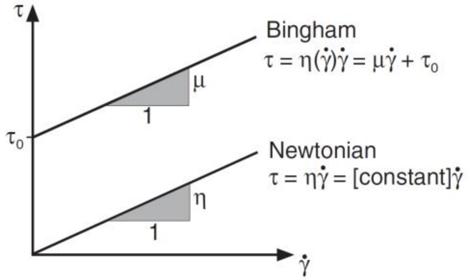
O.H. Wallevik, J.E. Wallevik / *Cement and Concrete Research* 41 (2011) 1279–1288

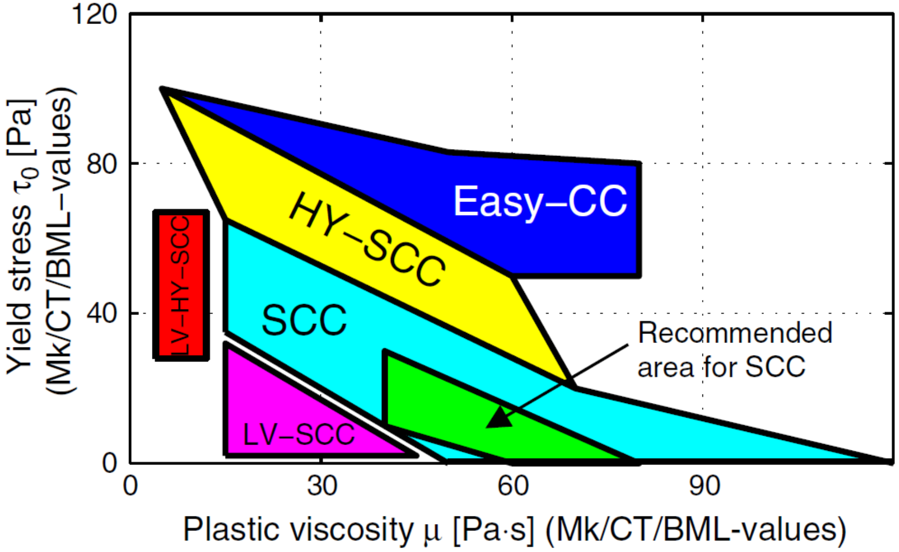


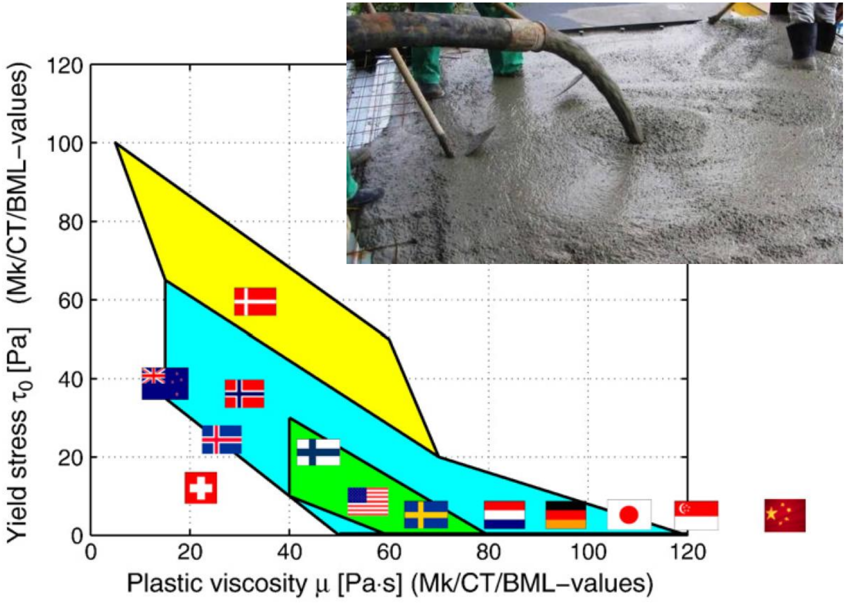
Bingham Model

- Yield stress: τ_0
- Plastic viscosity: μ



Rheology of Concrete: Rheograph





CVC = Conventional vibrated concrete; SCC = Self-Compacting Concrete (Self-consolidating concrete);

Easy-CC = East compacting concrete; HY-SCC = High yield SCC; LV-SCC = Low-viscous SCC

LV-HY-SCC = Low-viscous high-yield SCC

Rheology of Concrete

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Why is fresh **self-compacting concrete shear thickening**?

D Feys, R Verhoeven, G De Schutter - **Cement** and **concrete** Research, 2009 - Elsevier

… Results on **cement** pastes prove that the grain inertia theory is not the main … of **shear thickening** in **self-compacting concrete**. The influence of several parameters on the **shear thickening** …

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Fresh **self compacting concrete**, a **shear thickening** material

D Feys, R Verhoeven, G De Schutter - **Cement** and **Concrete** Research, 2008 - Elsevier

… of **concrete** have been investigated thoroughly, resulting in a simple description, in steady state, by means of the Bingham model. **Self compacting concrete** … – or **shear thickening** – in the …

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… type **self-compacting concrete** in a wide-gap concentric cylinder rheometer: Part II. Influence of mineral additions and chemical admixtures on the **shear thickening** …

G Heirman, R Hendrickx, L Vandewalle… - **Cement** and **Concrete** …, 2009 - Elsevier

… the **shear thickening** effect … **shear thickening**. The limestone, quartzite and fly ash addition used in this research project, respectively increase, unalter and decrease the **shear thickening** …

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Extension of the Poiseuille formula for **shear-thickening** materials and application to **Self-Compacting Concrete**

D Feys, R Verhoeven, G De Schutter - Applied Rheology, 2008 - degruyter.com

… derivation of the Poiseuille formula for **shearthickening** liquids with a yield stress, like SCC. … be verified further in this paper whether they are valid in case of **SelfCompacting Concrete**. …

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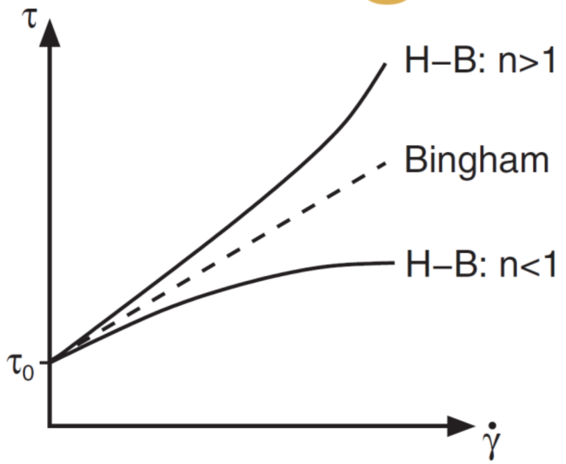


Bingham Model (1917)

$$\begin{cases} \tau = \tau_0 + \mu_p \dot{\gamma} & \text{for } \tau > \tau_0 \\ \dot{\gamma} = 0 & \text{for } \tau \le \tau_0 \end{cases}$$

Herschel–Bulkley Model (1926)

$$\begin{cases} \tau = \tau_0 + K \dot{\gamma}^n & \text{for } \tau > \tau_0 \\ \dot{\gamma} = 0 & \text{for } \tau \le \tau_0 \end{cases}$$

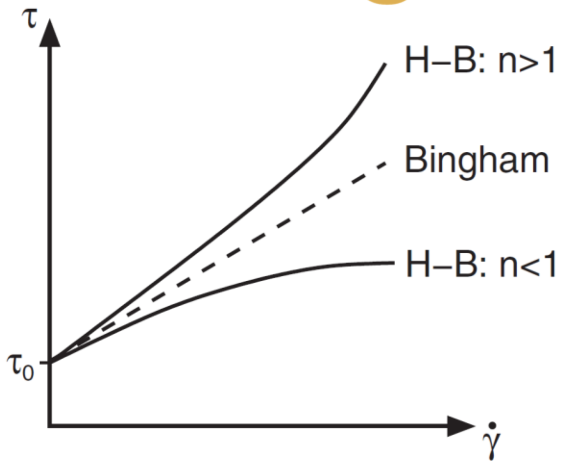
Rheology of Concrete

Modified Bingham Model (Yahia2001, Feys2007)

$$\begin{cases} \tau = \tau_0 + \mu_p \dot{\gamma} + A_2 \dot{\gamma}^2 & \text{for } \tau > \tau_0 \\ \dot{\gamma} = 0 & \text{for } \tau \leq \tau_0 \end{cases}$$

"Generalized Bingham" Model: A four-parameter model (Our work; Under review)

$$\begin{cases} \tau = \tau_0 + \mu_p \dot{\gamma} + K \dot{\gamma}^n & \text{for } \tau > \tau_0 \\ \dot{\gamma} = 0 & \text{for } \tau \leq \tau_0 \end{cases}$$



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Herschel–Bulkley Model (1926)

$$\begin{cases} \tau = \tau_0 + K \dot{\gamma}^n & \text{for } \tau > \tau_0 \\ \dot{\gamma} = 0 & \text{for } \tau \leq \tau_0 \end{cases}$$

Zhaidarbek, Balnur and Tleubek, Aruzhan and Berdibek, Galymbek and Wang, Yanwei, Analytical Predictions of Concrete Pumping: Extending the Khatib-Khayat Model to Herschel-Bulkley and Modified Bingham Fluids. Available at SSRN: https://ssrn.com/abstract=4188701 or http://dx.doi.org/10.2139/ssrn.4188701

Rheology of Concrete

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Wang et al. In Preparation (2022)

Table 1. Some special cases of the generalized Bingham model proposed by Zhaidarbek *et al.* [32]. The constitutive equation corresponds to $\tau \geq \tau_0$.

Fluid type	Constitutive model	Rheological parameters			
		τ_0	μ_p	K	n
Newtonian	$\tau = \mu\dot{\gamma}$	0	μ	0	0
Power-law [36,37]	$\tau = K\dot{\gamma}^n$	0	0	K	n
Sisko [38]	$\tau = \mu_p\dot{\gamma} + K\dot{\gamma}^n$	0	μ_p	K	n
Bingham	$\tau = \tau_0 + \mu_p\dot{\gamma}$	τ_0	μ_p	0	0
Casson	$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\mu_p\dot{\gamma}}$	τ_0	μ_p	$2\sqrt{\tau_0\mu_p}$	$1/2$
Herschel–Bulkley	$\tau = \tau_0 + K\dot{\gamma}^n$	τ_0	0	K	n
modified Bingham	$\tau_0 + \mu_p\dot{\gamma} + A_2\dot{\gamma}^2$	τ_0	μ_p	A_2	2
Caggioni *et al.* [33]	$\tau = \tau_0 + \mu_p\dot{\gamma} + K\dot{\gamma}^{1/2}$	τ_0	μ_p	K	$1/2$

Rheology of Concrete

Wang et al. In Preparation (2022)

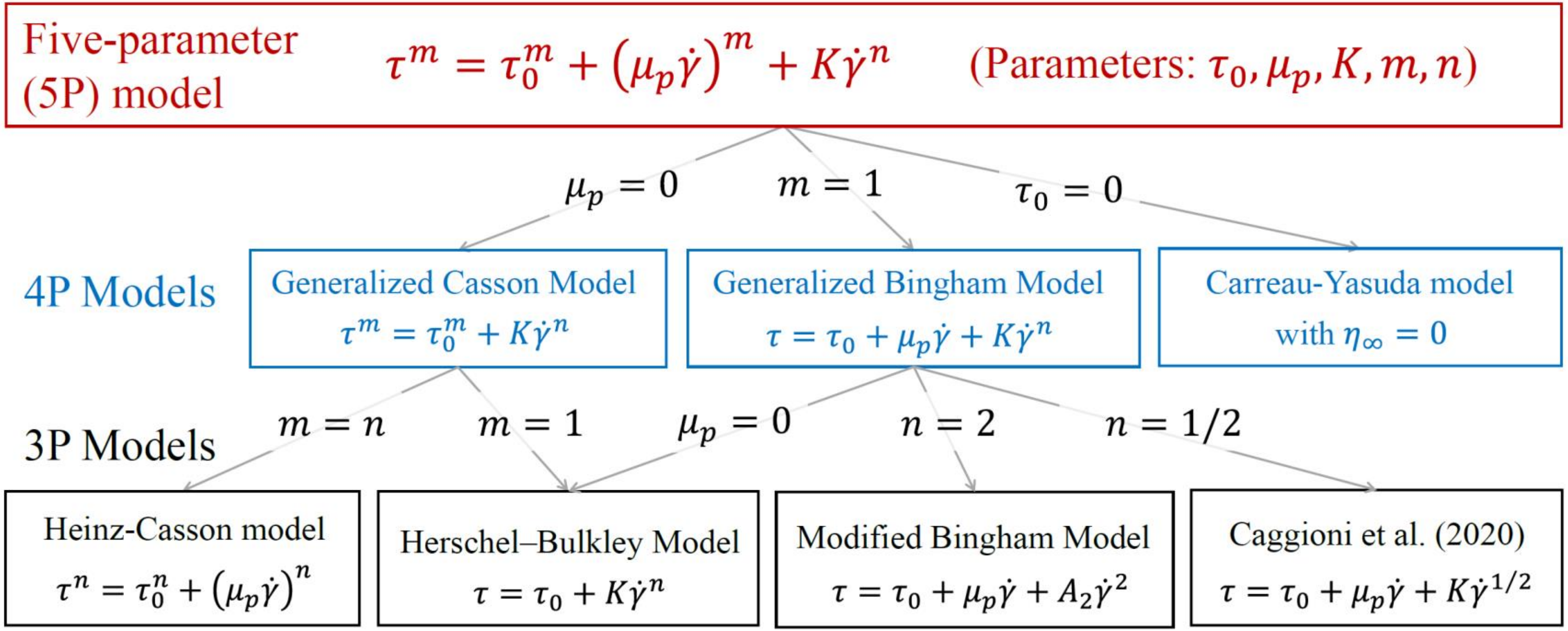
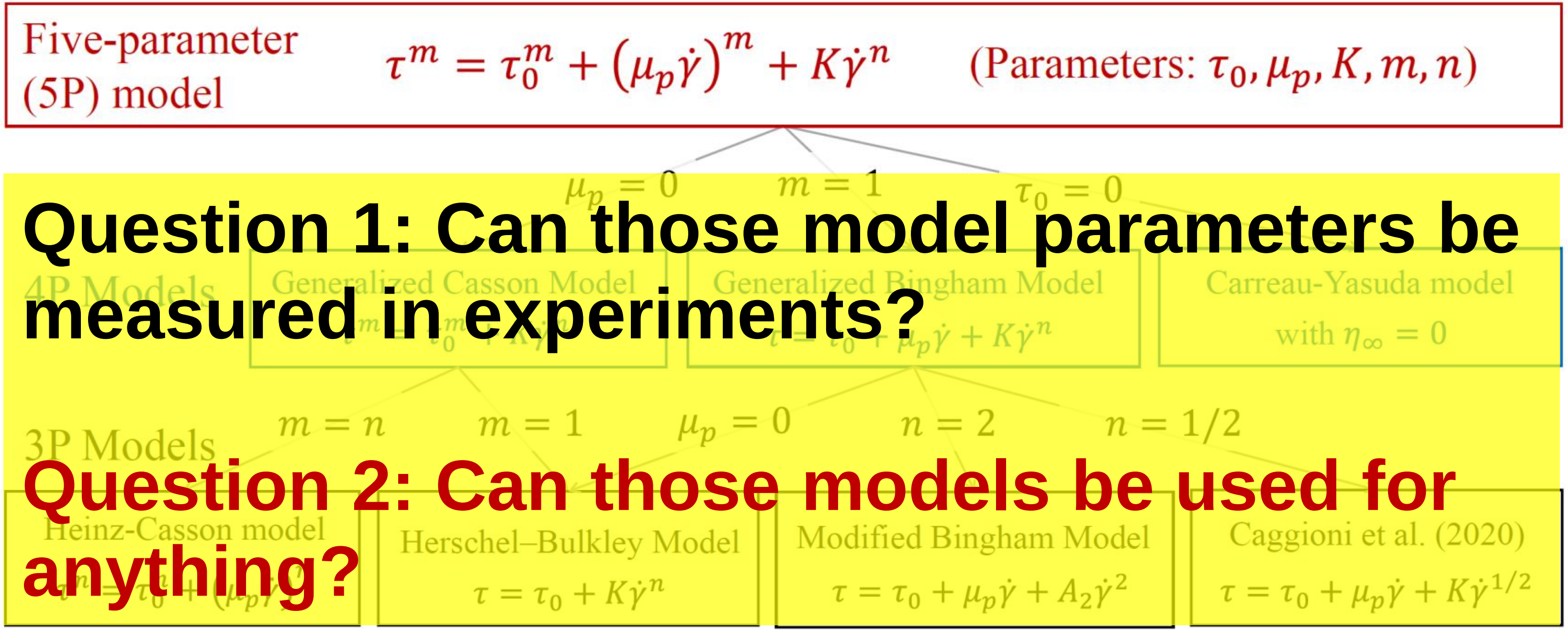


Figure 1. Schematic representation of the relations between the different rheological models investigated in this work.

Rheology of Concrete

Wang et al. In Preparation (2022)



Question 1: Can those model parameters be measured in experiments?

Question 2: Can those models be used for anything?

Figure 1. Schematic representation of the relations between the different rheological models investigated in this work.

Pumping of Concrete

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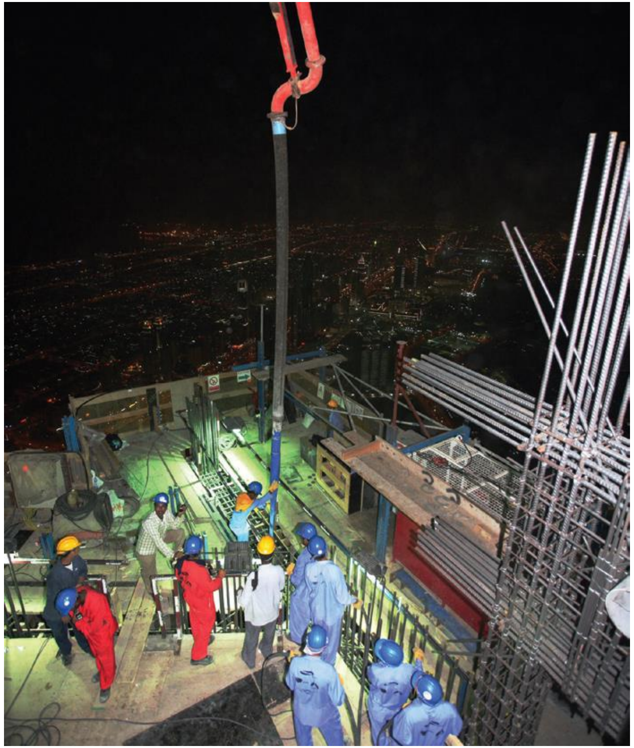
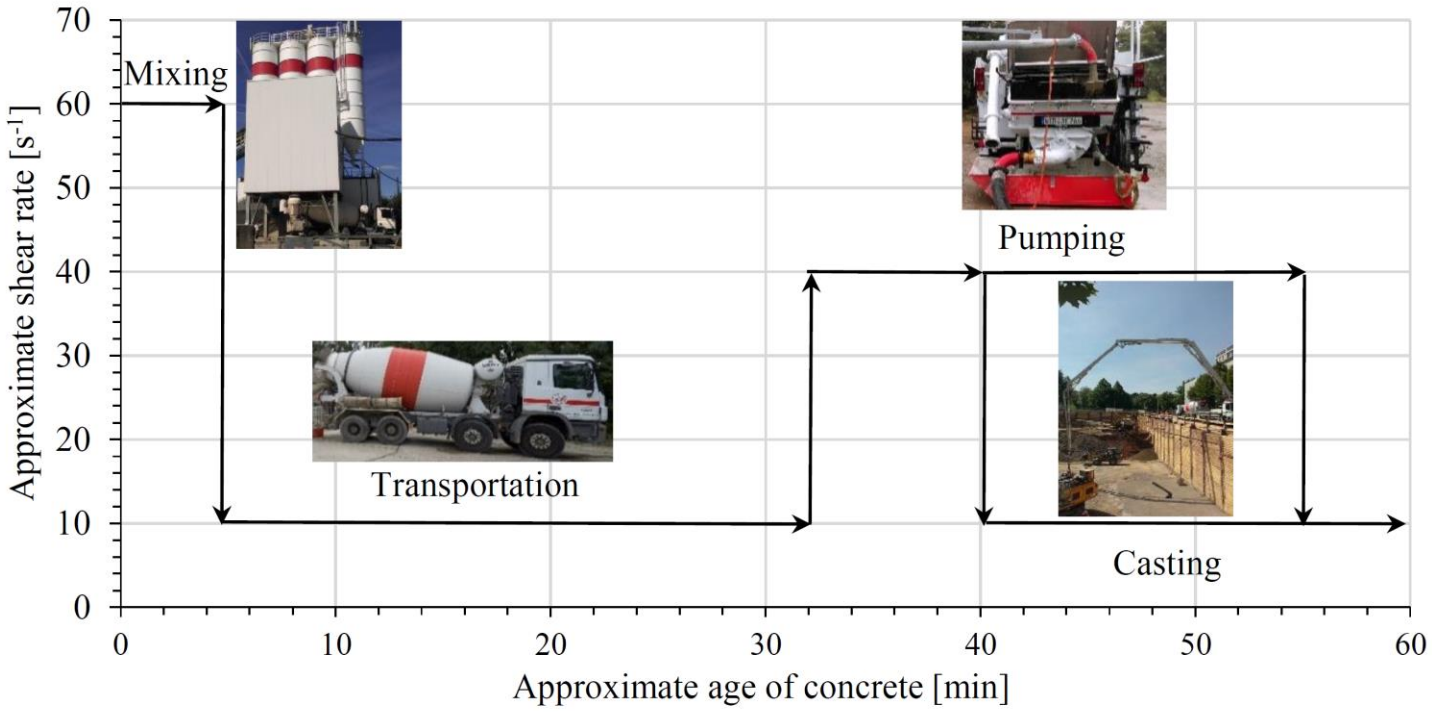


Aldred, J. (2010, May). Burj Khalifa–a new high for high-performance concrete. In Proceedings of the Institution of Civil Engineers-Civil Engineering (Vol. 163, No. 2, pp. 66-73). Thomas Telford Ltd.

Pumping of Concrete



Secrieru, Egor. (2018). Pumping behaviour of modern concretes–Characterisation and prediction (Doctoral dissertation, Technische Universität Dresden). http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-234912

Pumping of Concrete

RILEM Technical Letters (2016) 1: 76 – 80
DOI: http://dx.doi.org/10.21809/rilemtechlett.2016.15

RILEM technical letters

Prof. Dr. Ir. Geert DE SCHUTTER

Dimitri Feys

Pumping of Fresh Concrete: Insights and Challenges

Geert De Schutter [a*], Dimitri Feys [b]

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[b] Department of Civil, Architectural and Environmental Engineering, Missouri University of Science and Technology, MO, United States

Received: 22 September 2016 / Accepted: 10 November 2016 / Published online: 25 November 2016

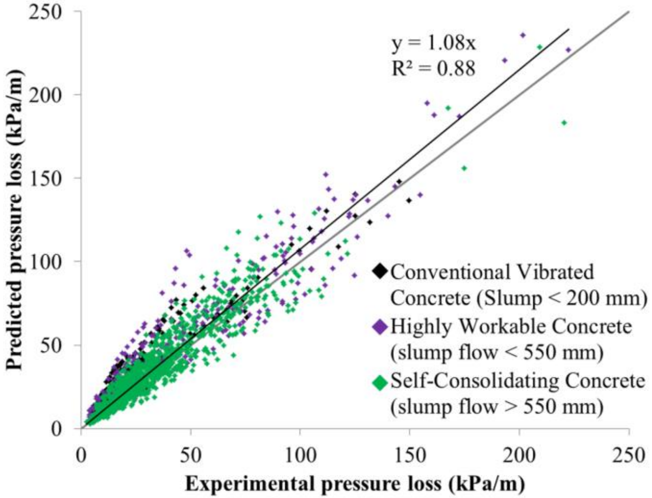

Figure 1. Pumping pressure is well predicted based on Kaplan's model [14], based on tribology and rheology measurements on different types of concrete. Figure modified from [24].

Challenges

(1) Formation of *lubrication layer* in high-performance concrete
(2) Test methods for evaluation of pumpability of fresh concrete
(3) Bends and reducers
(4) Changes in concrete properties due to pumping
(5) Active control

Pumping of Concrete

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Cement and Concrete Research 154 (2022) 106720

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

Pumping of concrete: Understanding a common placement method with lots of challenges

Dimitri Feys [a,*], Geert De Schutter [b], Shirin Fataei [c], Nicos S. Martys [d], Viktor Mechtcherine [c]

[a] *Department of Civil, Architectural, and Environmental Engineering, Missouri University of Science and Technology, 1401 N. Pine Street, Rolla, MO 65409, United States*
[b] *Magnel-Vandepitte Laboratory, Department of Structural Engineering and Building Materials, Ghent University, Ghent, Belgium*
[c] *Institute of Construction Materials, Technische Universität Dresden, Georg-Schumann-Straße 07, 01087 Dresden, Germany*
[d] *Materials and Structural Systems Division, National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899, United States*

A R T I C L E I N F O

Keywords:
Pumping
Concrete
Lubrication layer
Rheology
Numerical simulation

A B S T R A C T

Several million cubic meters of concrete are pumped daily, as this technique permits fas
Fundamental research has been performed and practical guidelines have been devel
knowledge of concrete behavior in pipes. However, the pumping process and concrete
understood. This paper gives an overview of the current knowledge of concrete pumpin
physics governing the flow of concrete in pipes are introduced. A series of experimental
izing concrete flow behavior near a smooth wall to predict pressure-flow rate relationsh
lowed by recent developments in the use of numerical simulations of concrete behavior in pipes. The influence of the pumping process on concrete rheology and air-void system is reviewed, and the first developments in active rheology control for concrete pumping are introduced. The last section of this paper gives an overview of open research questions and challenges.

D. Feys et al.

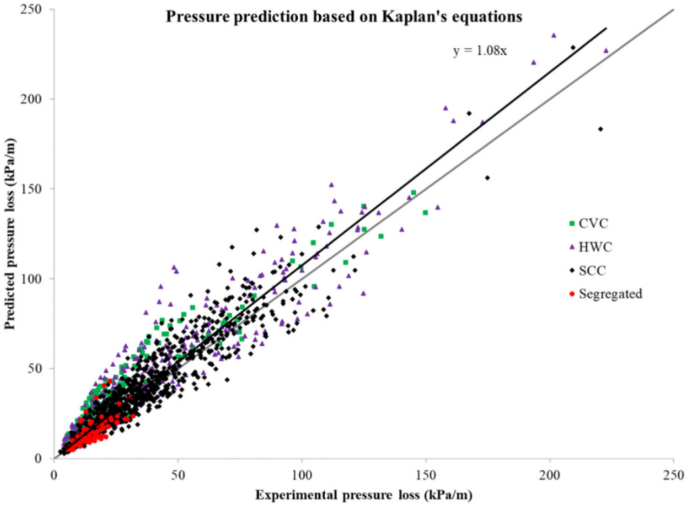


Fig. 6. Validation of Kaplan's equations predicting pumping pressure [26,36], based on interface and bulk concrete rheology, pipe radius and flow rate. Measurements are performed on pumpable concrete mixtures with varying consistencies (CVC = conventional vibrated concrete, SCC = self-consolidating concrete, HWC = highly workable concrete with consistency between CVC and SCC). Figure adapted from [52].

Formation of Lubrication Layer

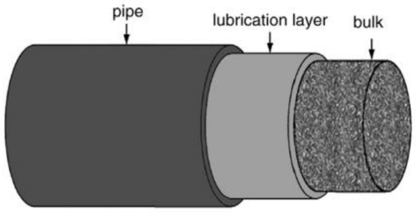
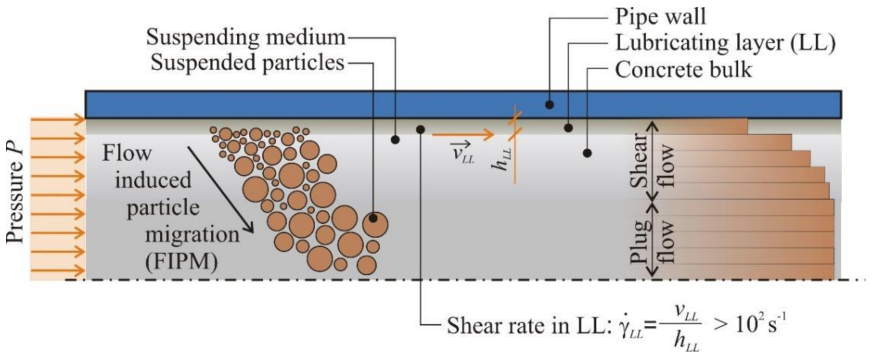
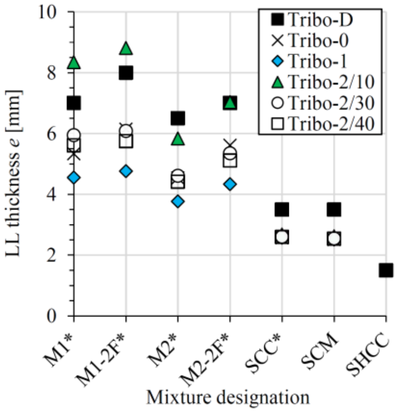
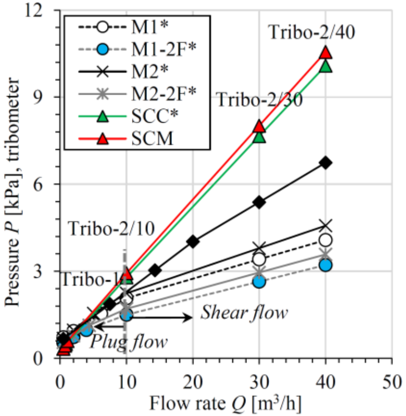
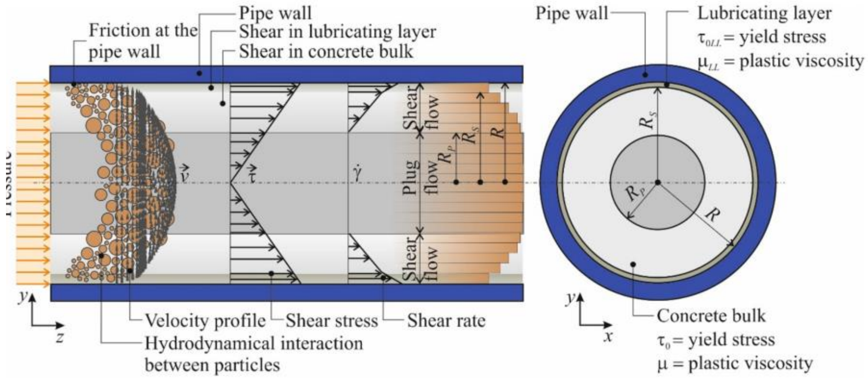


Fig. 1. Schematic pattern of concrete flow in the pipe.



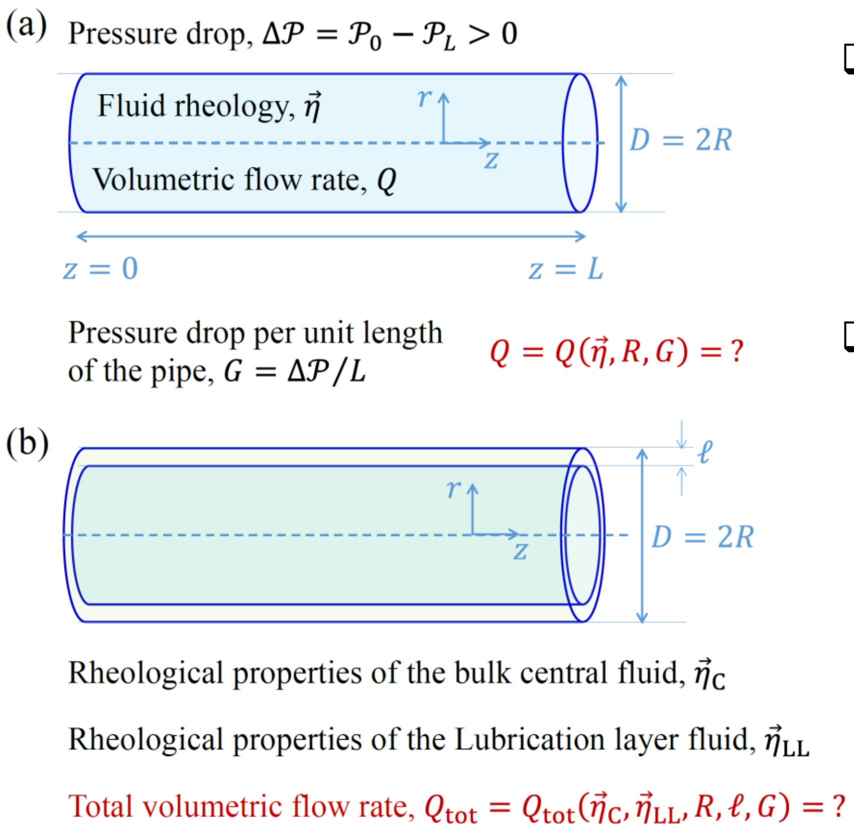






Choi, M., Roussel, N., Kim, Y., & Kim, J. (2013). Lubrication layer properties during concrete pumping. Cement and Concrete Research, 45, 69-78; Secrieru, Egor. (2018). Pumping behaviour of modern concretes–Characterisation and prediction (Doctoral dissertation, Technische Universität Dresden). http://nbn-resolving.de/urn:nbn:de:bsz:14-qucosa-234912

Analytical Predictions of Concrete Pumping



- Solving the Hagen–Poiseuille flow (laminar flow in a pipe) using rheological parameters ($\vec{\eta}$) of bulk concrete will **over-estimate** the needed pressure for a given flow rate.

- Kaplan *et al.* [ACI Materials Journal 2005] considered the formation of a **lubrication layer (LL)** and introduced a **slip-velocity** between bulk concrete and the pipe wall. The Bingham model is used for bulk concrete. The slip-velocity approach corresponds to an infinitely thin LL ($\ell/R \to 0$)

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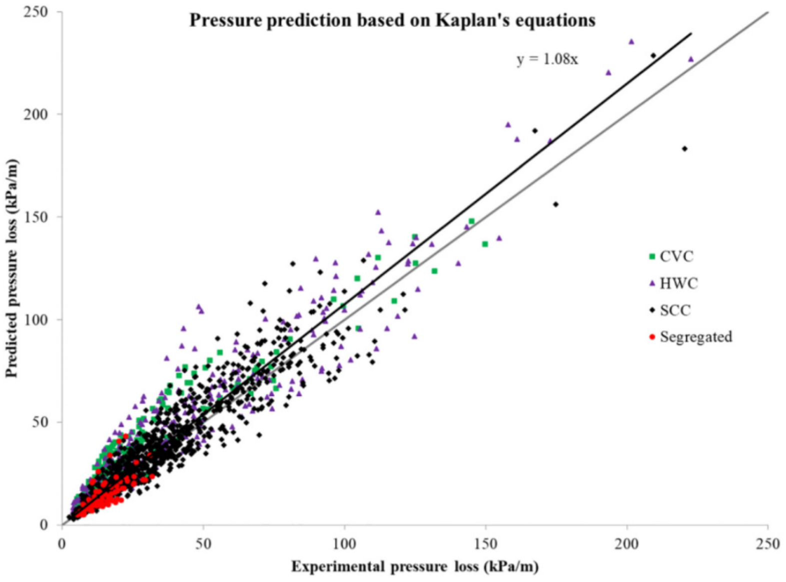
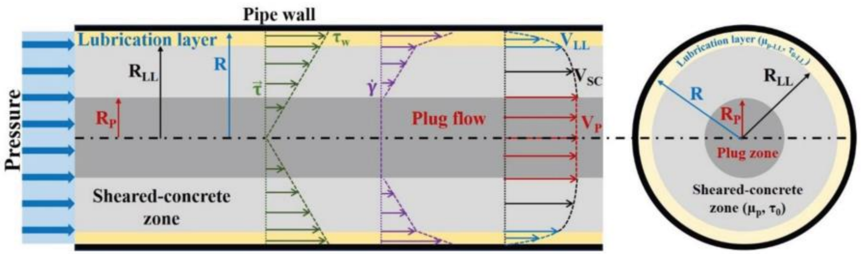


Fig. 6. Validation of Kaplan's equations predicting pumping pressure [26,36], based on interface and bulk concrete rheology, pipe radius and flow rate. Measurements are performed on pumpable concrete mixtures with varying consistencies (CVC = conventional vibrated concrete, SCC = self-consolidating concrete, HWC = highly workable concrete with consistency between CVC and SCC). Figure adapted from [52].

- Rami Khatib and Kamal H. Khayat [ACI Materials Journal 2021] relaxed the assumption of an infinitely thin LL ($\ell/R \rightarrow 0$) and developed a **two-fluid model**, where both the LL fluid and the bulk concrete are described by **the Bingham model**.



Tavangar, T., Hosseinpoor, M., Yahia, A., & Khayat, K. H. (2021). Computational Investigation of Concrete Pipe Flow: Critical Review. ACI Materials Journal, 118(6).

Analytical Predictions of Concrete Pumping

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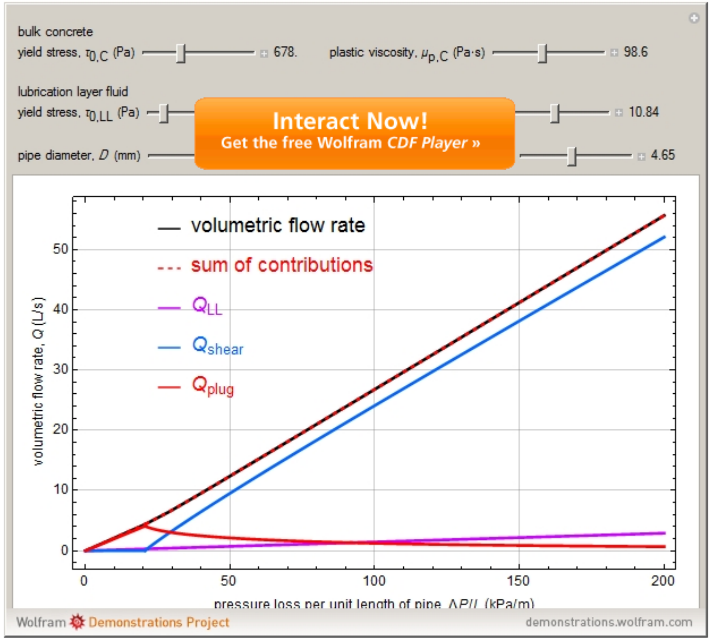
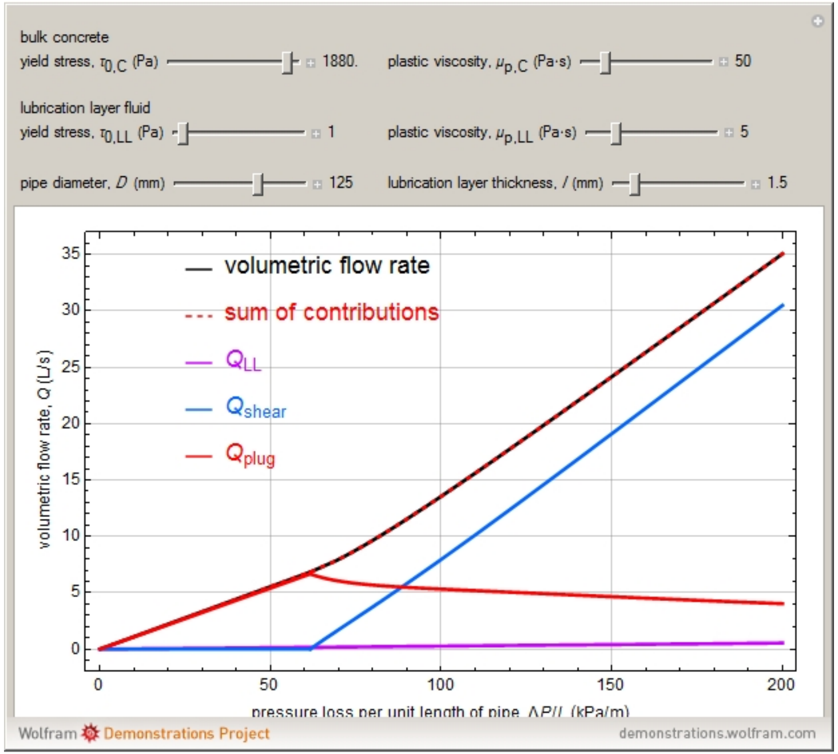
Khatib-Khayat Model for Pumping Flowable Concrete





Balnur Zhaidarbek and Yanwei Wang. http://demonstrations.wolfram.com/KhatibKhayatModelForPumpingFlowableConcrete/. Wolfram Demonstrations Project (August 2022)

Rheology of Concrete

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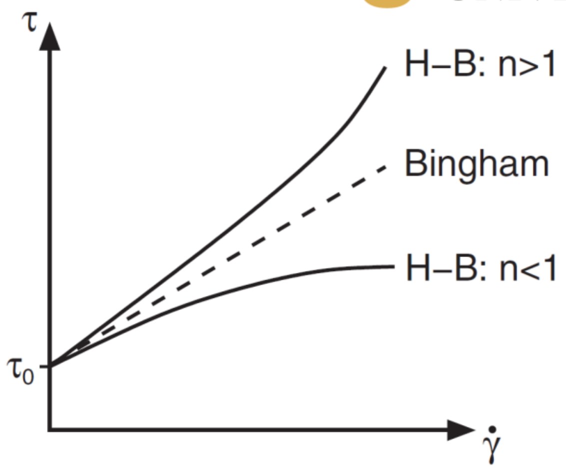
Why is fresh **self-compacting concrete shear thickening**?
D Feys, R Verhoeven, G De Schutter - **Cement** and **concrete** Research, 2009 - Elsevier
… Results on **cement** pastes prove that the grain inertia theory is not the main … of **shear thickening** in **self-compacting concrete**. The influence of several parameters on the **shear thickening** …
Save Cite Cited by 222 Related articles All 7 versions Web of Science: 144

Fresh **self compacting concrete**, a **shear thickening** material
D Feys, R Verhoeven, G De Schutter - **Cement** and **Concrete** Research, 2008 - Elsevier
… of **concrete** have been investigated thoroughly, resulting in a simple description, in steady state, by means of the Bingham model. **Self compacting concrete** … – or **shear thickening** – in the …
Save Cite Cited by 220 Related articles All 8 versions Web of Science: 132

… type **self-compacting concrete** in a wide-gap concentric cylinder rheometer: Part II. Influence of mineral additions and chemical admixtures on the **shear thickening** …
G Heirman, R Hendrickx, L Vandewalle… - **Cement** and **Concrete** …, 2009 - Elsevier
… the **shear thickening** effect … **shear thickening**. The limestone, quartzite and fly ash addition used in this research project, respectively increase, unalter and decrease the **shear thickening** …
Save Cite Cited by 60 Related articles All 9 versions Web of Science: 40

Extension of the Poiseuille formula for **shear-thickening** materials and application to **Self-Compacting Concrete**
D Feys, R Verhoeven, G De Schutter - Applied Rheology, 2008 - degruyter.com
… derivation of the Poiseuille formula for **shearthickening** liquids with a yield stress, like SCC. … be verified further in this paper whether they are valid in case of **SelfCompacting Concrete**. …
Save Cite Cited by 26 Related articles All 7 versions Web of Science: 21



Bingham Model (1917)

$$\begin{cases} \tau = \tau_0 + \mu_p \dot{\gamma} & \text{for } \tau > \tau_0 \\ \dot{\gamma} = 0 & \text{for } \tau \leq \tau_0 \end{cases}$$

Herschel–Bulkley Model (1926)

$$\begin{cases} \tau = \tau_0 + K \dot{\gamma}^n & \text{for } \tau > \tau_0 \\ \dot{\gamma} = 0 & \text{for } \tau \leq \tau_0 \end{cases}$$

Rheology of Concrete

Wang et al. In Preparation (2022)

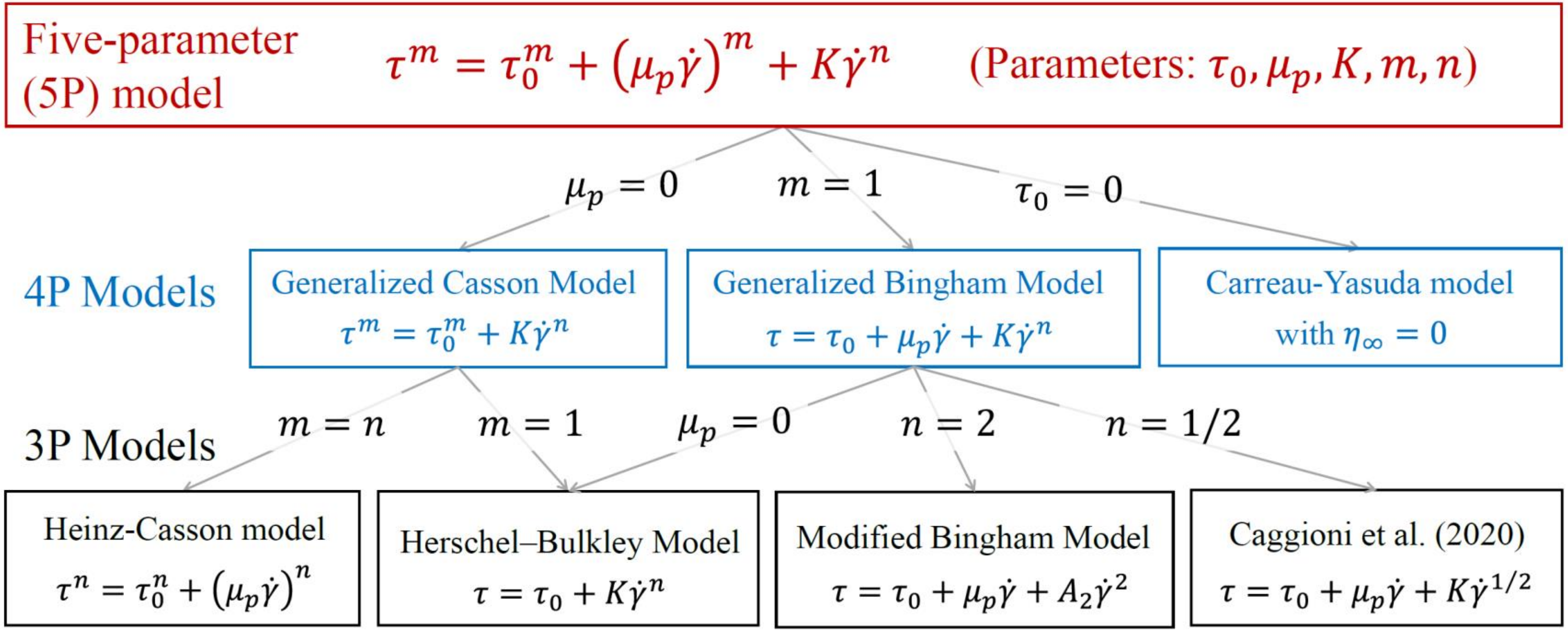
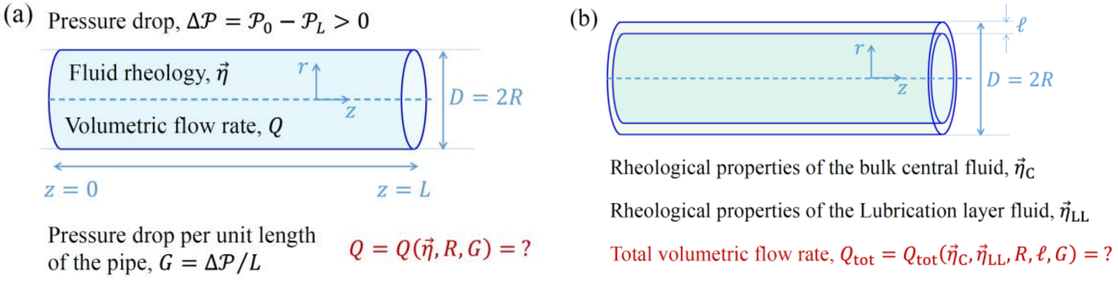


Figure 1. Schematic representation of the relations between the different rheological models investigated in this work.

Analytical Predictions of Concrete Pumping



Inputs
- ❑ Pressure drop per unit length: $G = \Delta\mathcal{P}/L$
- ❑ Pipe radius (or diameter, D): $R = D/2$
- ❑ Fluid rheology: $\vec{\eta} = \{\tau_0, \mu_p, K, m, n\}$

→

Nondimensionalization

Base units:
- Pipe radius: R
- Wall shear stress: τ_{wall}
- Wall shear rate: $\dot{\gamma}_{wall}$

↓

Inputs in dimensionless form
- ❑ Pressure drop per unit length: $\tilde{G} = 2$
- ❑ Pipe radius: $R = 1$
- ❑ Fluid rheology: $\vec{\eta} = \{\tilde{\tau}_0, \tilde{\mu}_p, \tilde{K}, m, n\}$

←

Outputs
- ❑ Flow rate as a function of the inputs

$$\tilde{u}_{avg} = \frac{1}{3}[1 - A_3(\tilde{\tau}_0, \tilde{\mu}_p, \tilde{K}, m, n)]$$

$$Q = \pi R^3 \dot{\gamma}_{wall} \tilde{u}_{avg}$$

Inputs
- ❑ Pressure drop per unit length: $G = \Delta\mathcal{P}/L$
- ❑ Pipe radius (or diameter, D): $R = D/2$
- ❑ Lubrication layer (LL) thickness, ℓ
- ❑ Rheological parameters of bulk central fluid: $\vec{\eta}_C$
- ❑ Rheological parameters of the LL fluid, $\vec{\eta}_{LL}$

↓

Contributions to the flow rate

$Q_1 = Q_{HP}(\vec{\eta}_{LL}, R, G)$

$Q_2 = Q_{HP}(\vec{\eta}_{LL}, R - \ell, G)$

$Q_3 = Q_{HP}(\vec{\eta}_C, R - \ell, G)$

↓

$r_{plug} < R - \ell$

- **False** → $Q = Q_1 - Q_2$ (CVC)
- **True** → $Q = Q_1 - Q_2 + Q_3$ (SCC)

Wang et al. In Preparation (2022)

Analytical Predictions of Concrete Pumping

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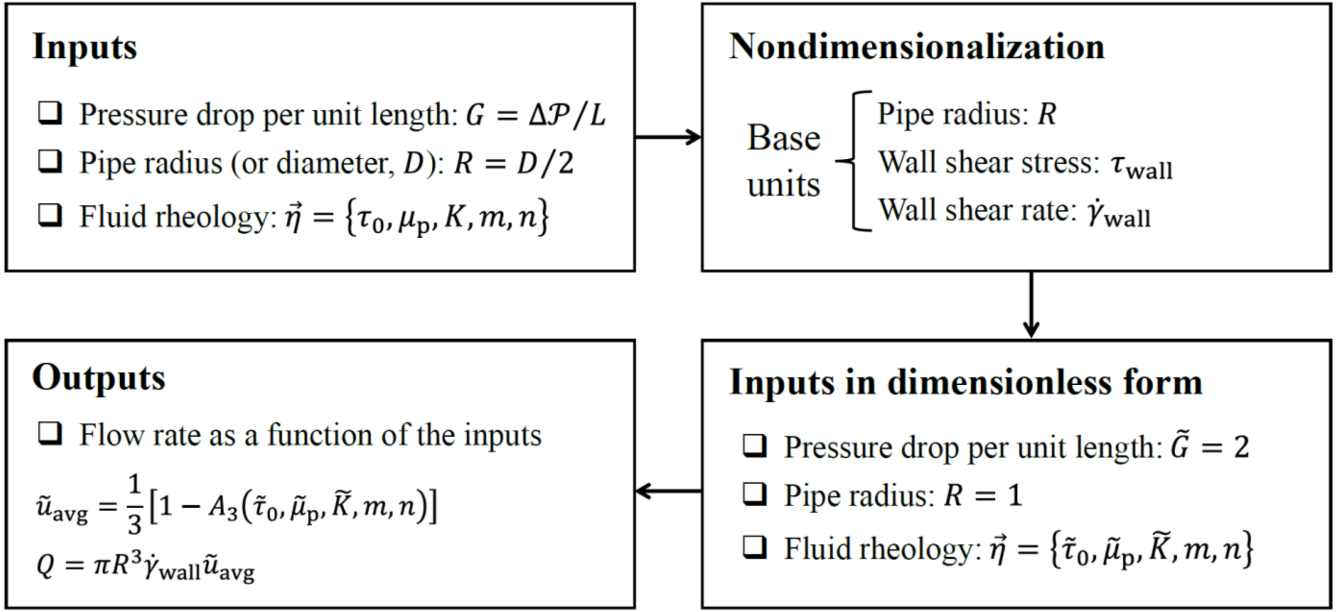
Given a complex generalized Newtonian model, how do we obtain the flow rate – pressure drop relation in Hagen–Poiseuille flow?



Wang, Y. (2022). Steady isothermal flow of a Carreau–Yasuda model fluid in a straight circular tube. Journal of Non-Newtonian Fluid Mechanics, 310, [104937]. https://doi.org/10.1016/j.jnnfm.2022.104937

Analytical Predictions of Concrete Pumping

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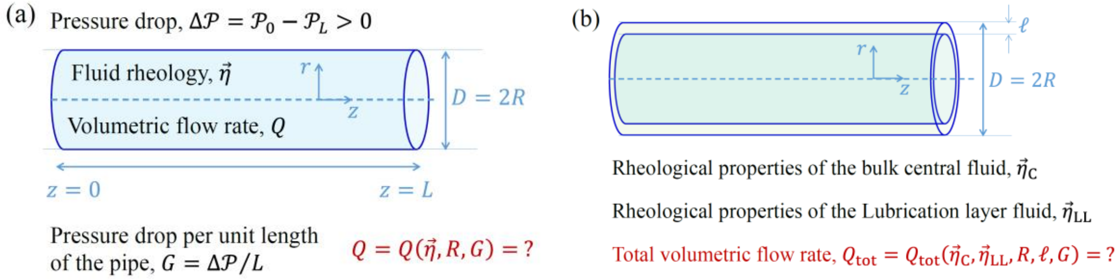
How to prove our approach for obtaining the flow rate – pressure drop relation in Hagen–Poiseuille flow of two-fluids?



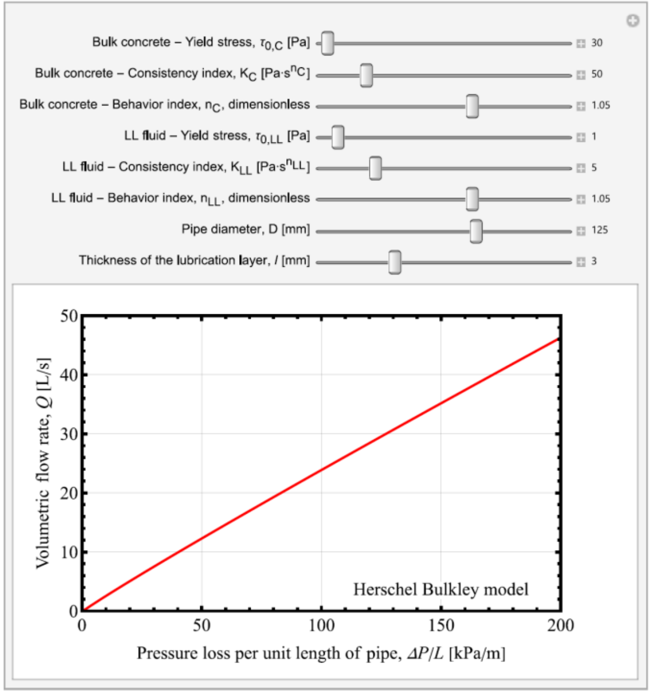
CVC $$Q = Q_{\mathrm{HP}}(\vec{\eta}_{\mathrm{LL}}, R, G) - Q_{\mathrm{HP}}(\vec{\eta}_{\mathrm{LL}}, R-\ell, G)$$

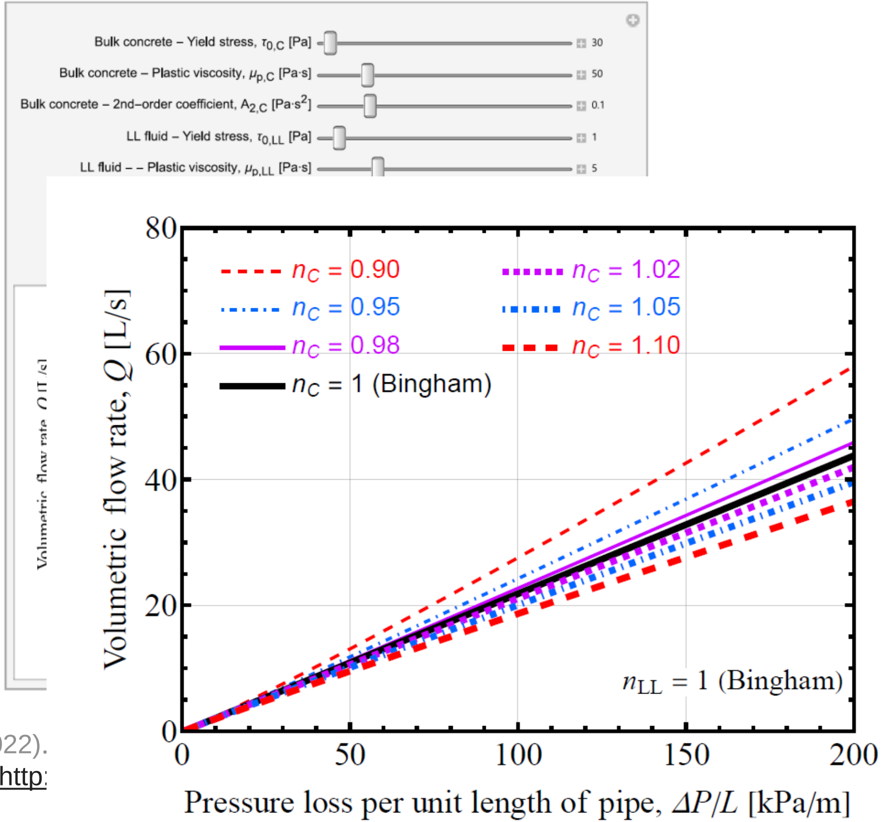
SCC $$Q = Q_{\mathrm{HP}}(\vec{\eta}_{\mathrm{LL}}, R, G) - Q_{\mathrm{HP}}(\vec{\eta}_{\mathrm{LL}}, R-\ell, G) + Q_{\mathrm{HP}}(\vec{\eta}_{\mathrm{C}}, R-\ell, G)$$

Zhaidarbek, B., Tleubek, A., Berdibek, G., & Wang, Y. (2022). Analytical Predictions of Concrete Pumping: Extending the Khatib-Khayat Model to Herschel-Bulkley and Modified Bingham Fluids. Elsevier. http://dx.doi.org/10.2139/ssrn.4188701 **Under Review**

Analytical Predictions of Concrete Pumping: Extending the Khatib-Khayat Model to Herschel-Bulkley and Modified Bingham Fluids

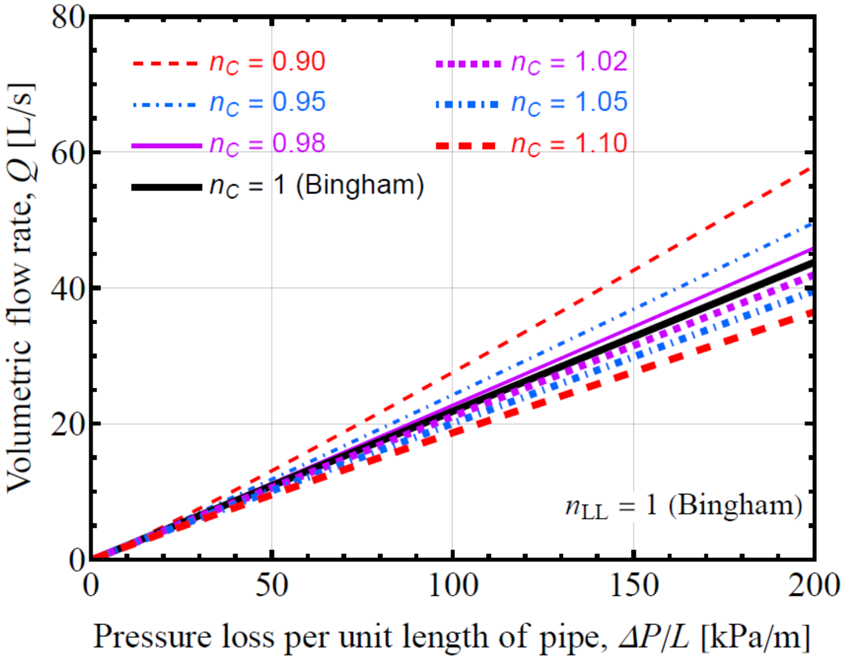
Balnur Zhaidarbek, Aruzhan Tleubek, Galymbek Berdibek, Yanwei Wang

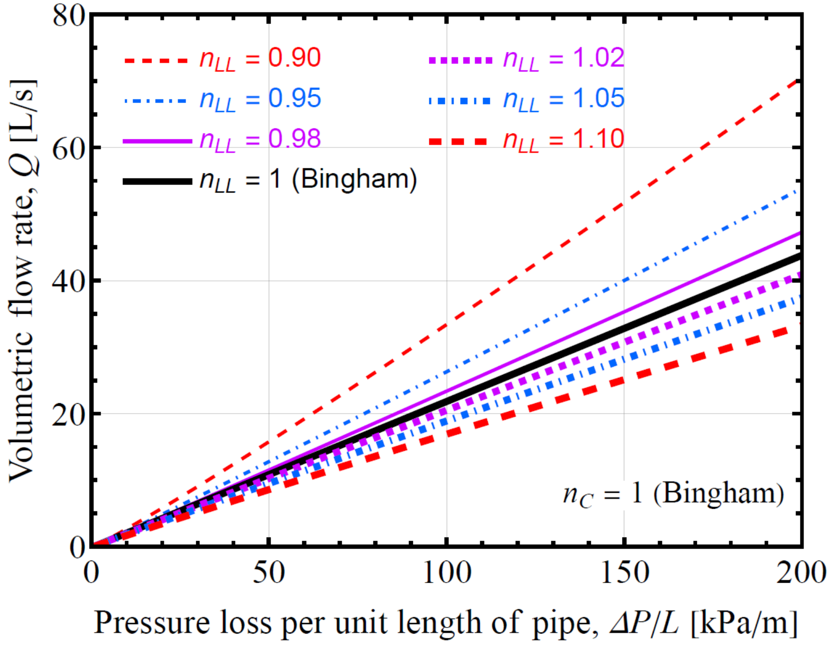




Zhaidarbek, B., Tleubek, A., Berdibek, G., & Wang, Y. (2022). … at Model to
Herschel-Bulkley and Modified Bingham Fluids. Elsevier. http:

Analytical Predictions of Concrete Pumping





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- Members of the RILEM Technical Committee – PCC: Pumping of Concrete
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- Students involved in this research: Balnur Zhaidarbek, Aruzhan Tleubek, Galymbek Berdibek

Comments and suggestions are very welcome.

https://research.nu.edu.kz/en/persons/yanwei-wang

Thank you for your attention.