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Pumping shotcrete: past knowledge applied for modern shotcrete mix design

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Shotcrete for Underground Support XIV

Nong Nouch Garden, Pattaya, Thailand

19 November 2019

Pumping for Wet-Mix Shotcrete

CRIB
Centre de recherche sur les infrastructures en béton

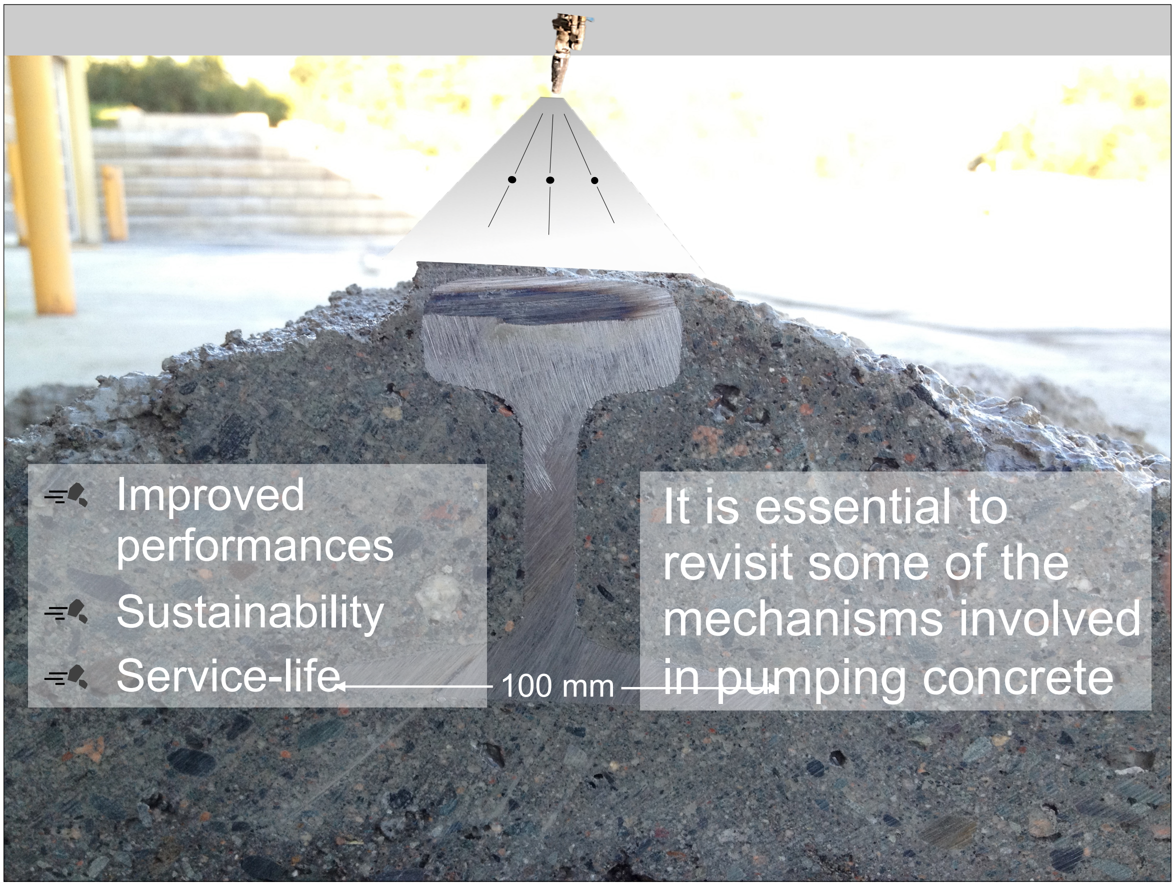
Photo credit : Coastal Gunite

Context & Background

Background

- Wet-mix shotcrete has been around for more than 50 years
- Modern shotcretes:
  - Improved performances
  - Sustainability
  - Service-life

However, *pumping constraints* are <u>always</u> present! 😈



- Improved performances
- Sustainability
- Service-life

It is essential to revisit some of the mechanisms involved in pumping concrete

Pumping Basics

… or how to get gravel through a pipe!

Pumping Concrete

- *Pumpability* (definition)

  « The ability of confined concrete to <u>flow</u> under pressure while <u>maintaining</u> its initial properties »

- … which leads to 2 "types" of studies:
  - *Stability* under pressure
  - *Mobility* under pressure

Pumping Concrete

- *Mobility*: Ede (1967) observed that concrete flow in a pipe respected the laws of hydraulics
  - Flow is independent of pressure
  - Head loss is linear
- Flow *vs* friction

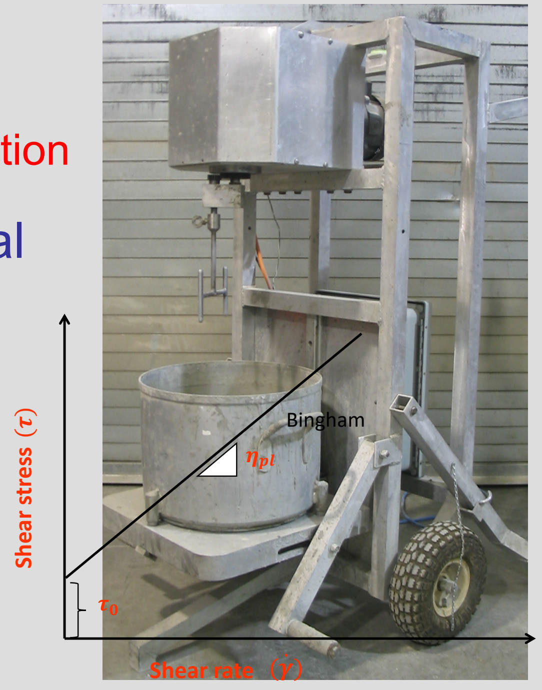
  Several studies are available, but results vary considerably:
  - Often, only the slump is considered omitting the viscosity
  - Friction is rarely considered

Slump & Viscosity ?

- Rheology
  - Study of fluids in motion
- Bingham rheological model

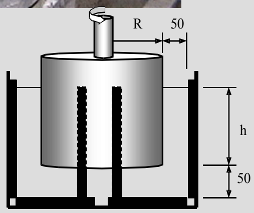
$$\tau = \tau_0 + \eta_{pl}\,\dot{\gamma}$$

  - Yield stress (τ_0)
  - Plastic viscosity (η_{pl})



Friction in the pipe ?

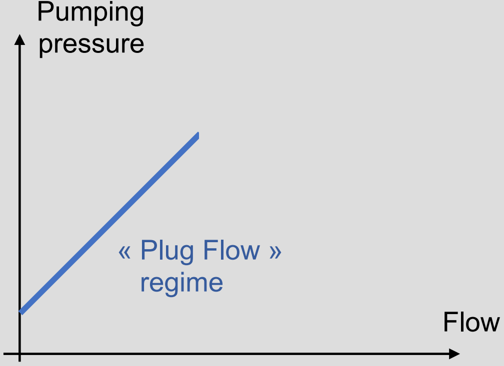
- Tribology: Study of the interaction of *surfaces in relative motion*

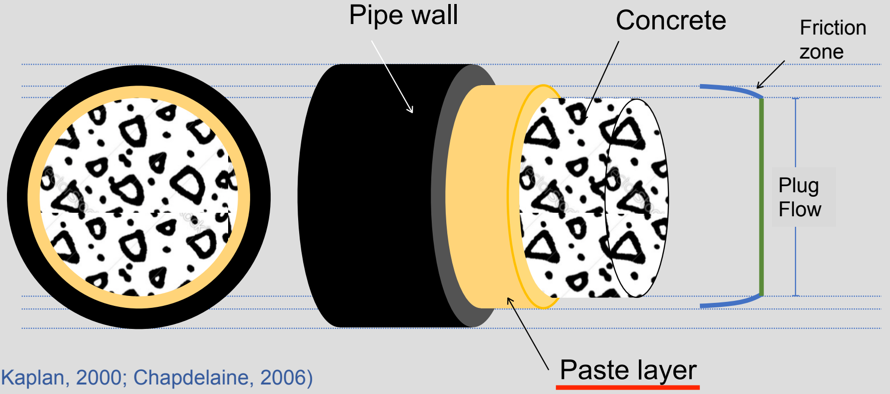


Chapdelaine, 2006

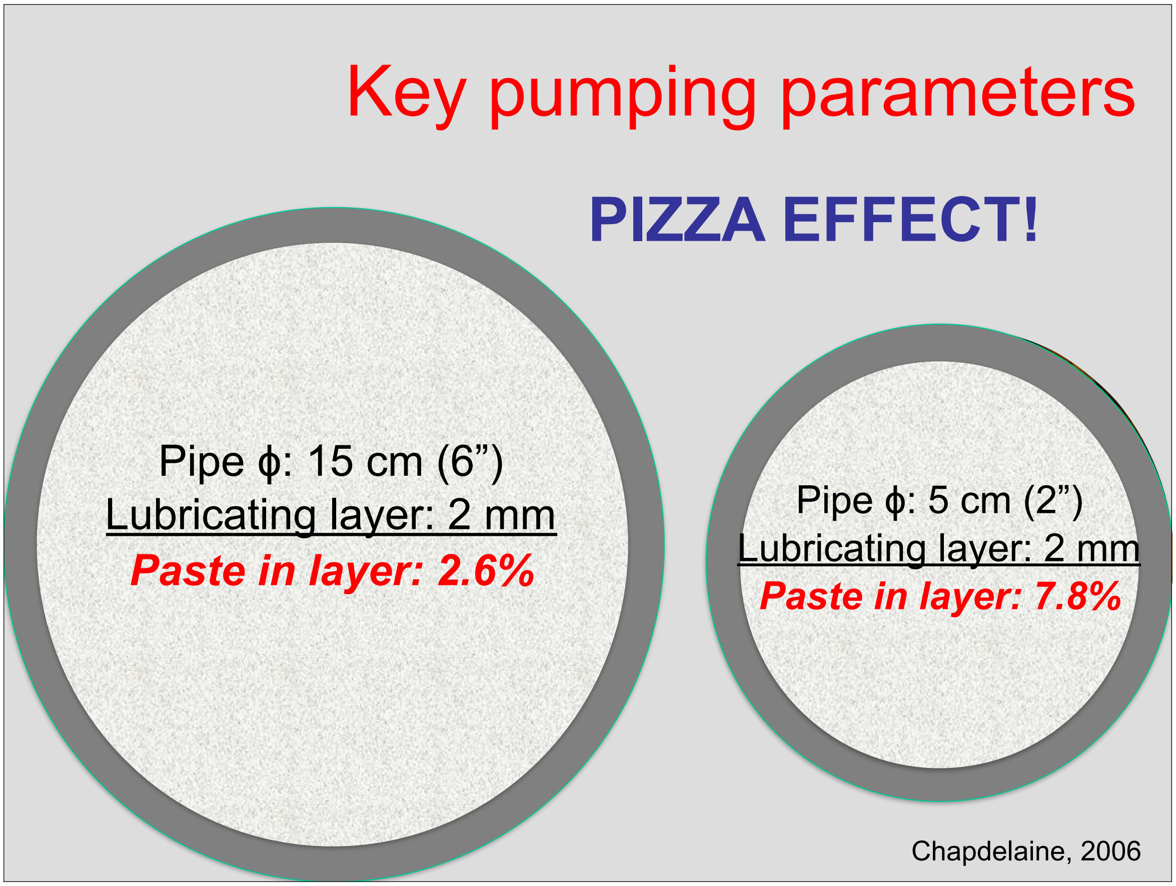
Behavior

- Bilinear model
  - Low velocity → tribology
    - *Interface properties*
  - Higher velocity → rheology & tribology
    - *Interface & flow properties*





(Kaplan, 2000; Chapdelaine, 2006)



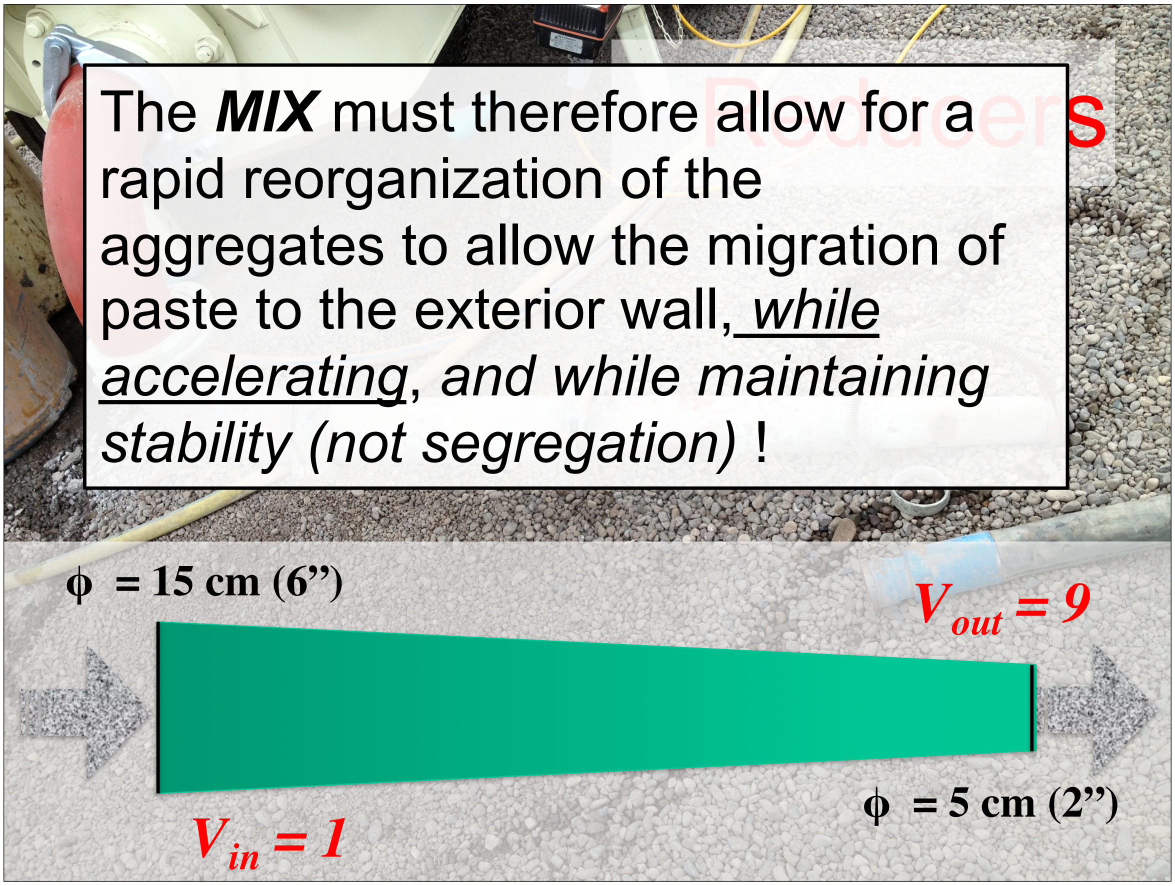
Key pumping parameters

PIZZA EFFECT!

Pipe ϕ: 15 cm (6")
Lubricating layer: 2 mm
Paste in layer: 2.6%

Pipe ϕ: 5 cm (2")
Lubricating layer: 2 mm
Paste in layer: 7.8%

Chapdelaine, 2006



Reducers

The ***MIX*** must therefore allow for a rapid reorganization of the aggregates to allow the migration of paste to the exterior wall, *<u>while accelerating</u>, and while maintaining stability (not segregation)* !

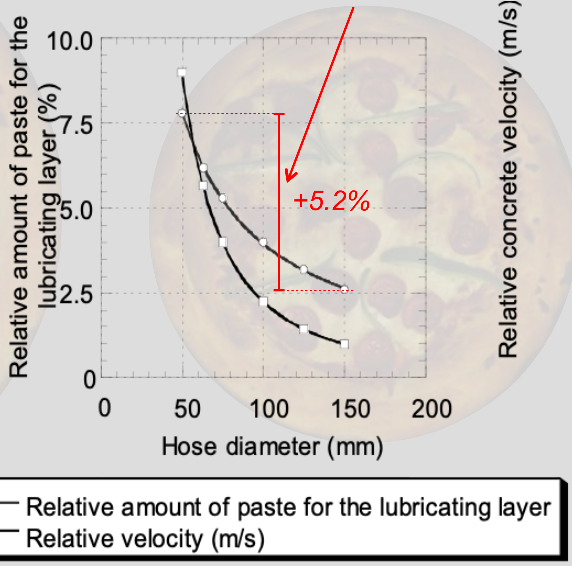
Key Pumping Parameters

- Effects of reducers
  - Increases concrete velocity
  - Increases relative amount of paste to maintain lubricating layer

For comparison:

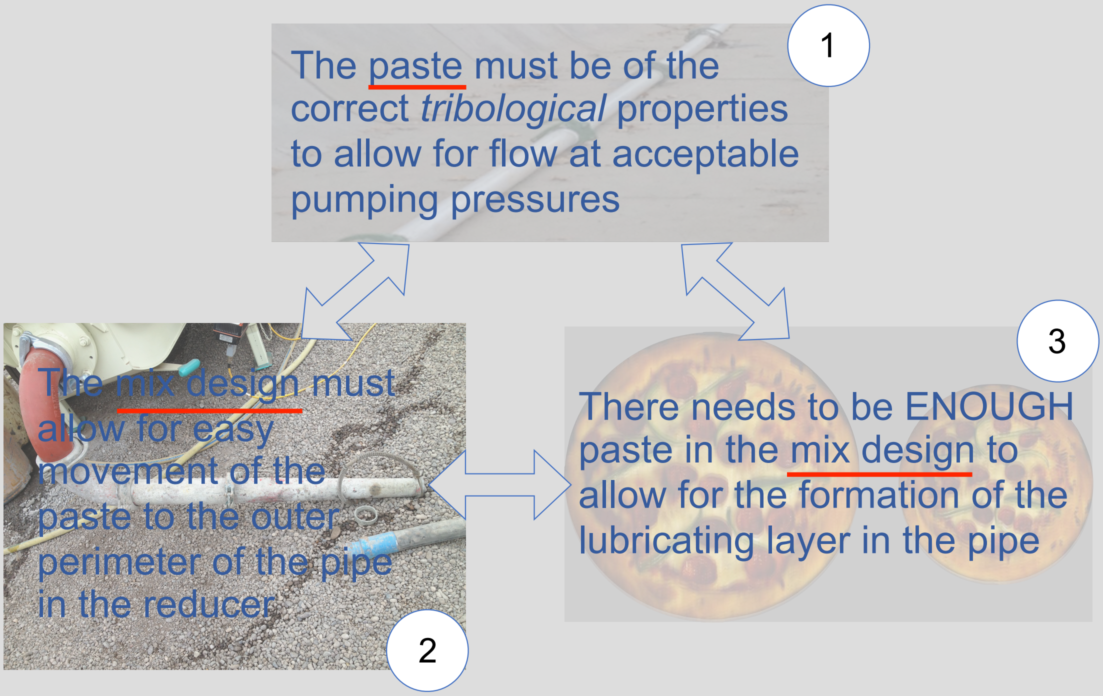
- +25 kg/m^3 of cement is equivalent to ≈ <u>+1%</u> paste
- changing 20% of cement to fly ash is equivalent to ≈ <u>+1%</u> paste

Extra volume of paste for small line pumping !



Chapdelaine, 2006

Key Pumping Parameter: PASTE



The paste must be of the correct *tribological* properties to allow for flow at acceptable pumping pressures

The mix design must allow for easy movement of the paste to the outer perimeter of the pipe in the reducer

There needs to be ENOUGH paste in the mix design to allow for the formation of the lubricating layer in the pipe

Mix Design Basics

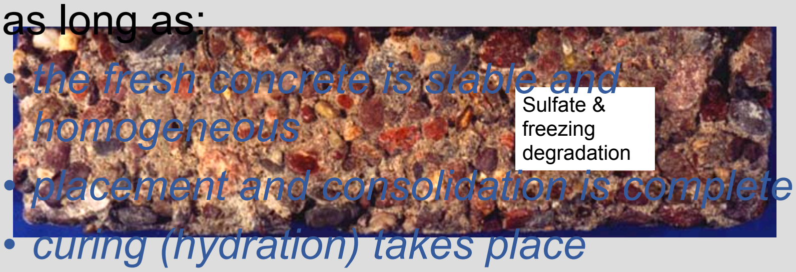
… more water, less cement, or the other way around!

Strength & Durability

- The single most important factor *for strength and durability* is the water/cement ratio!!

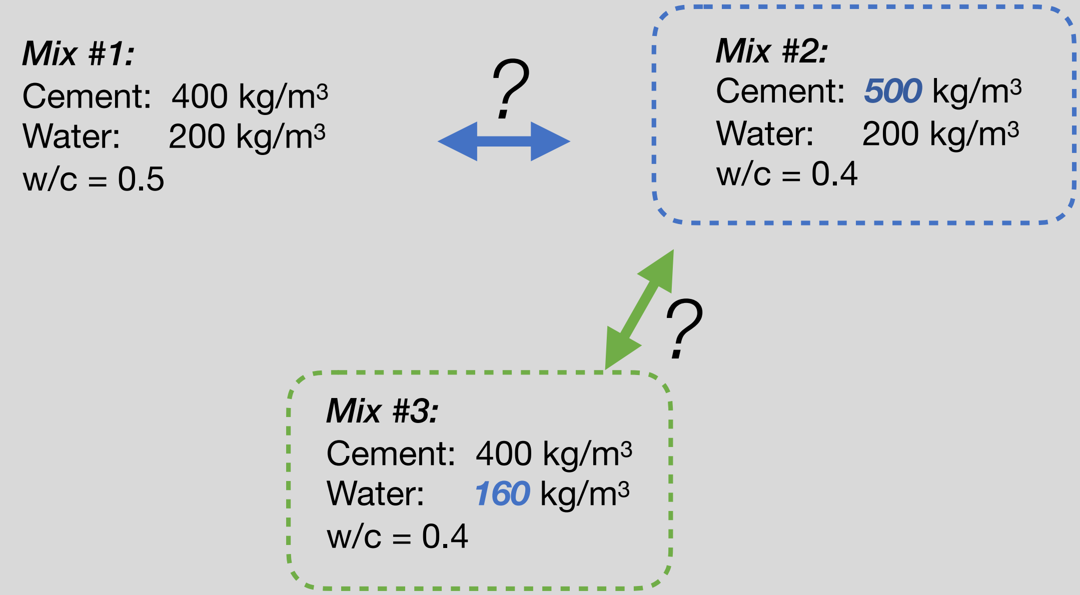
➡ *… because w/c controls the porosity*

as long as:



- *the fresh concrete is stable and homogeneous*
- *placement and consolidation is complete*
- *curing (hydration) takes place*

Question: which one has the highest compressive strength



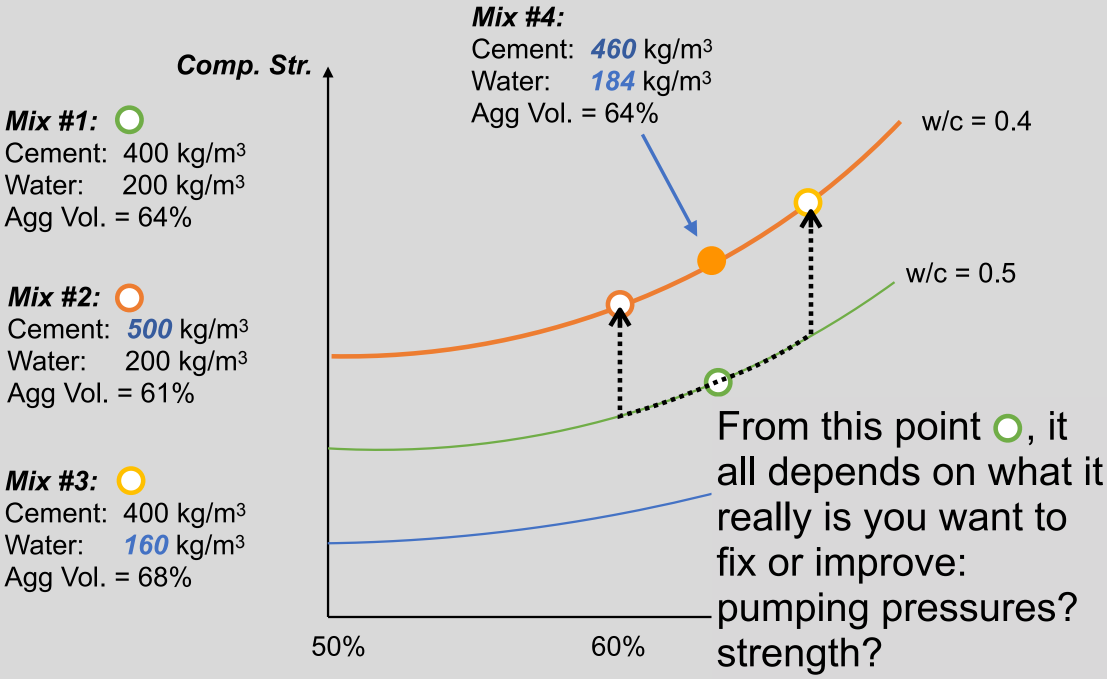
Mix #1:
Cement: 400 kg/m^3
Water: 200 kg/m^3
w/c = 0.5

?

Mix #2:
Cement: ***500*** kg/m^3
Water: 200 kg/m^3
w/c = 0.4

?

Mix #3:
Cement: 400 kg/m^3
Water: ***160*** kg/m^3
w/c = 0.4



Mix #1: ○
Cement: 400 kg/m^3
Water: 200 kg/m^3
Agg Vol. = 64%

Mix #2: ○
Cement: ***500*** kg/m^3
Water: 200 kg/m^3
Agg Vol. = 61%

Mix #3: ○
Cement: 400 kg/m^3
Water: ***160*** kg/m^3
Agg Vol. = 68%

Mix #4:
Cement: ***460*** kg/m^3
Water: ***184*** kg/m^3
Agg Vol. = 64%

From this point ○, it all depends on what it really is you want to fix or improve: pumping pressures? strength?

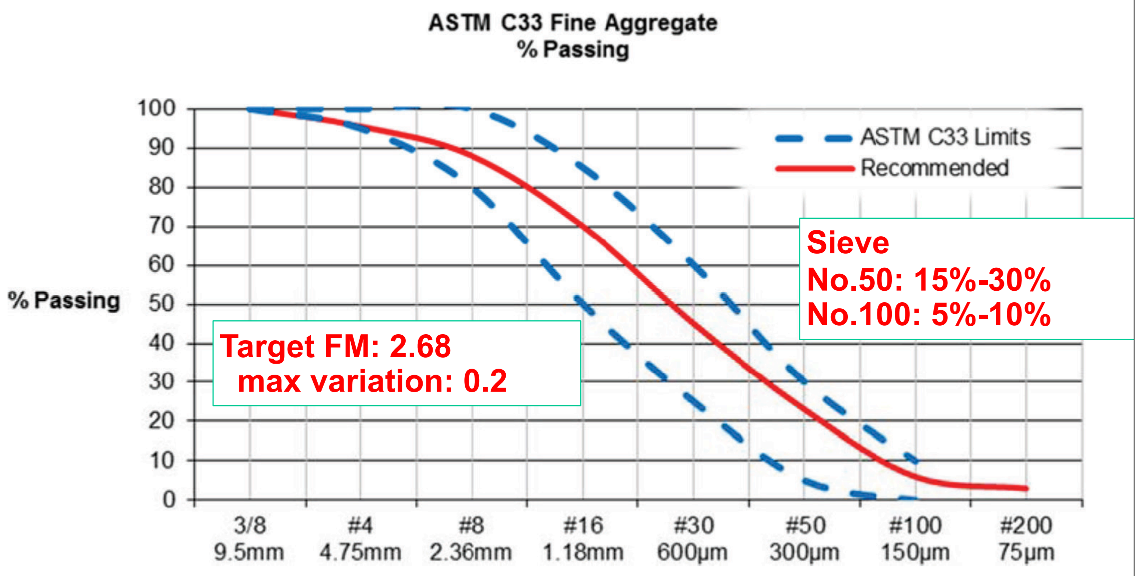
Stock et al, 1979

How to *“Mix design for the **PUMP**” – ACI 304.2R*

- *Select* a w/c based on exposure conditions AND compressive strength (< value)
- *Based* on aggregate* size, air content and *target* slump , *choose* water content and *calculate* cement content
  - *TARGET SLUMP: 5-15 cm – 2”-6”*
- …

* gradation per ASTM C33 *and more*

Sand gradation



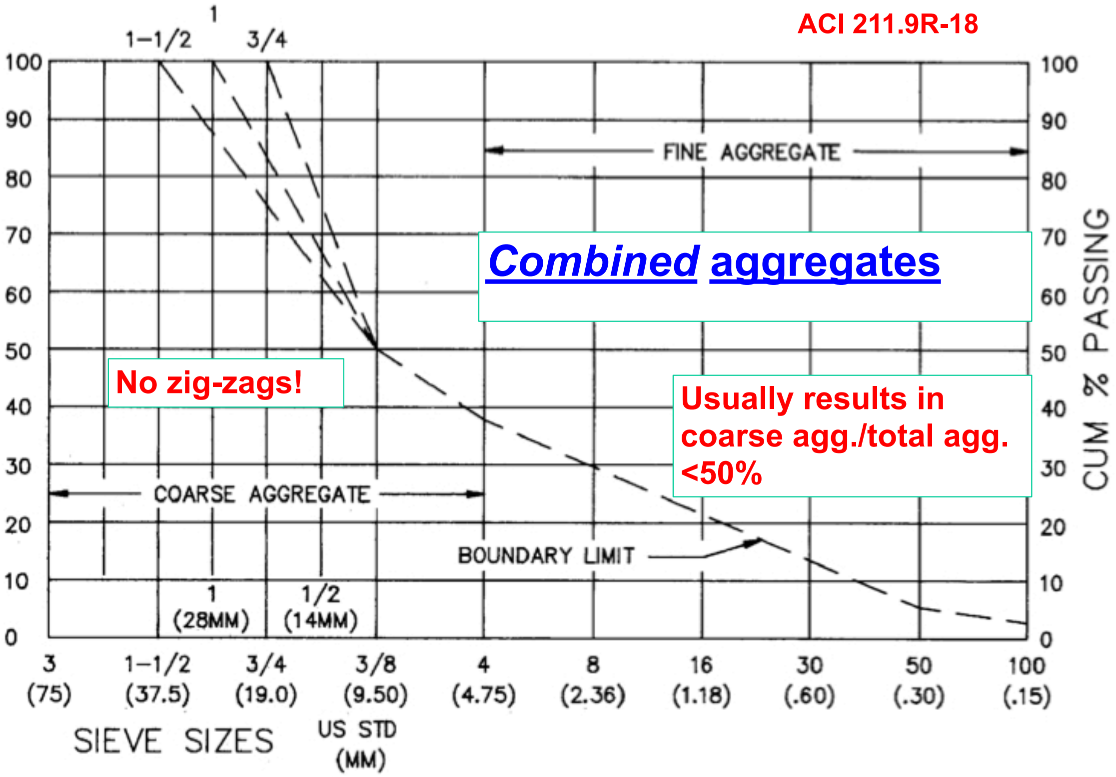
Sieve
No.50: 15%-30%
No.100: 5%-10%

Target FM: 2.68
max variation: 0.2

ACI 211.9R-18

ACI 211.9R-18

Combined aggregates



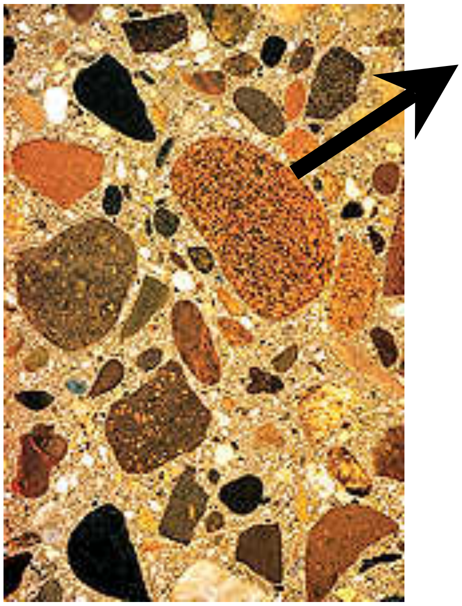
No zig-zags!

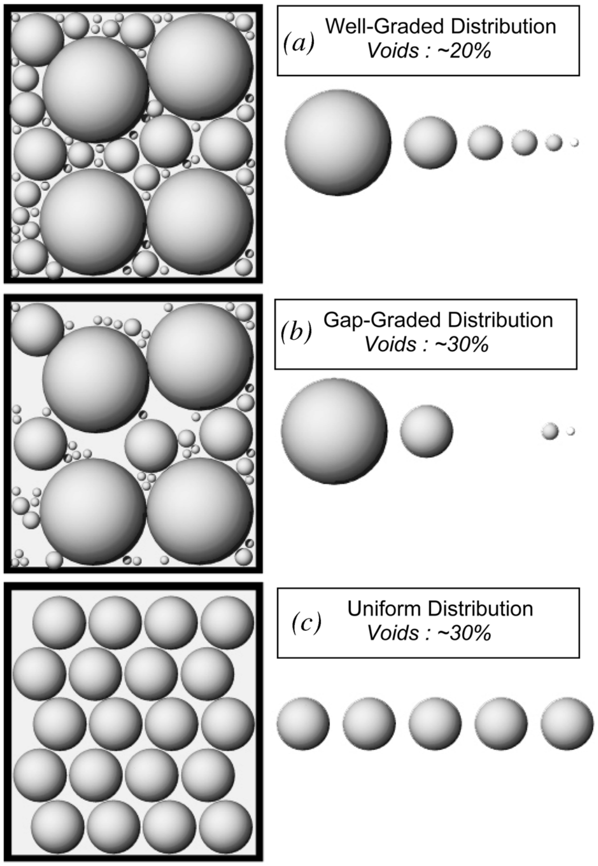
Usually results in coarse agg./total agg. <50%

Fig. 12—Analysis worksheet (courtesy Morgen Manufacturing Co., Yankton, SD)

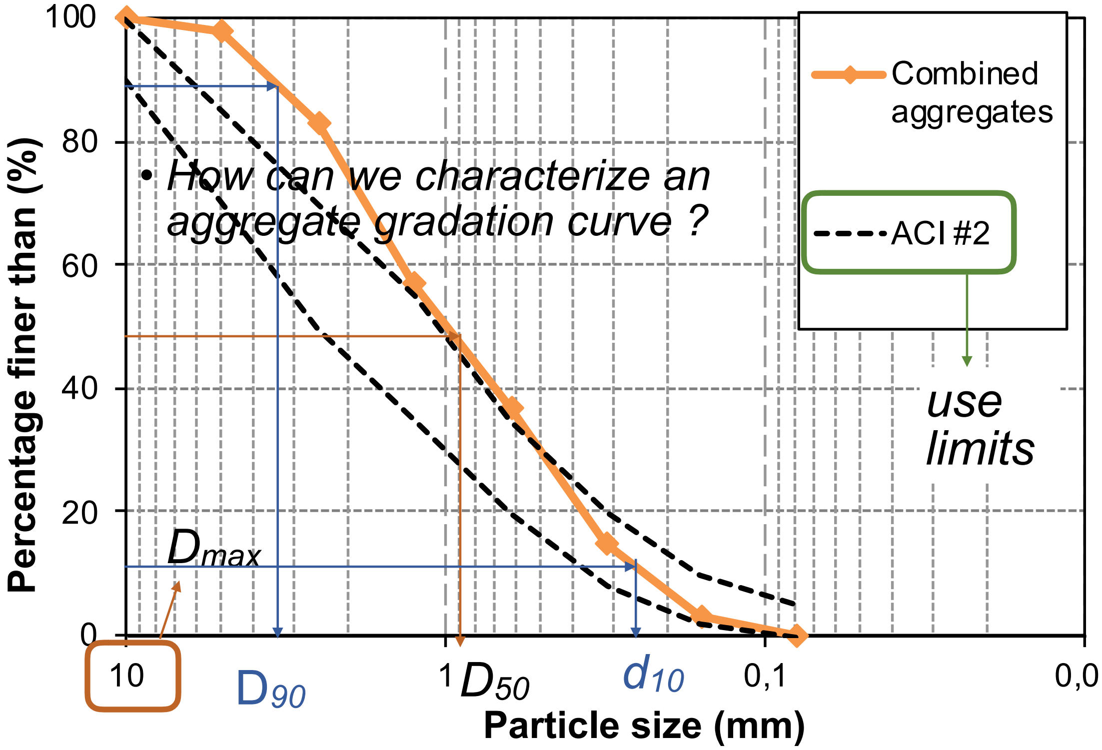
Why care so much about the aggregate?

Aggregates – Gradation





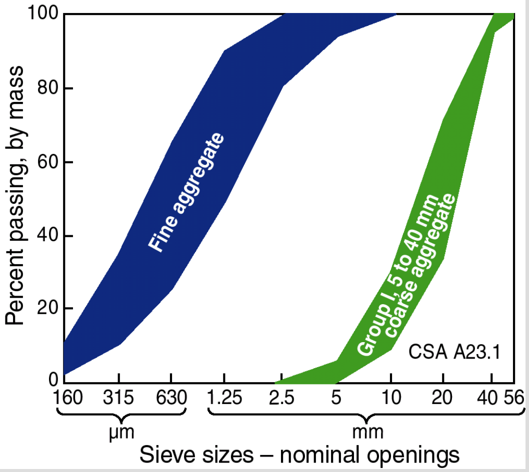
Aggregate Gradation



- *How can we characterize an aggregate gradation curve ?*

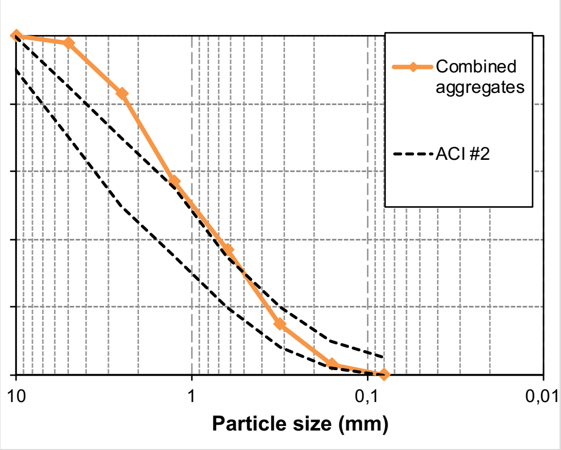
Characterizing an aggregate gradation curve ?

- It is *NOT* a simple question !
- A lot of what we know is based on *experience!*
- In concrete technology, usually:
  - maximum size *and* limits



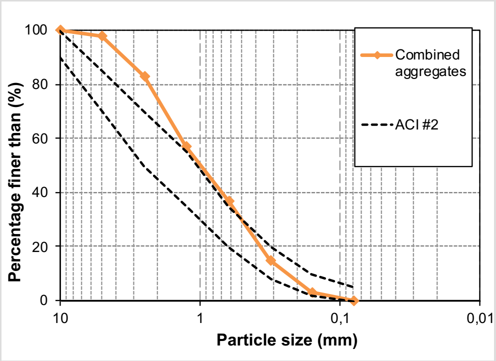
Characterizing an aggregate gradation curve ?

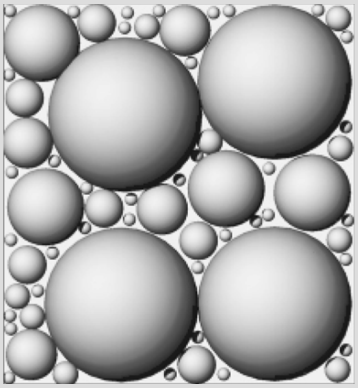
- *Maximum size*: usually based on the application
- *Limits*: good start, but it can lead to problems difficult to explain:
  - combined *vs* individual agg.
  - zig-zags



Earlier Observations

- For pumping, we need a carefully selected ***aggregate skeleton***





How can we analyse the *aggregate gradation* to inform us on the the *packing* of the aggregate in the mix?

Characterizing of gradation:
packing of the aggregate skeleton

- …

- Use of different *theoretical* approaches to obtain the *optimized* gradation:
  - Fuller's Curve:

$$cpft = \left(\frac{d}{D}\right)^{\frac{1}{2}}$$

  - General power law:

$$cpft = \left(\frac{d}{D}\right)^{n}$$

  - and many more (deLarrard, Dreux, etc.)

Characterizing of gradation:
packing of the aggregate skeleton

- …

- my favorite so far:
    - Dinger-Funk

$$cpft = \left(\frac{d^n - D_s^n}{D_L^n - D_s^n} \right)$$

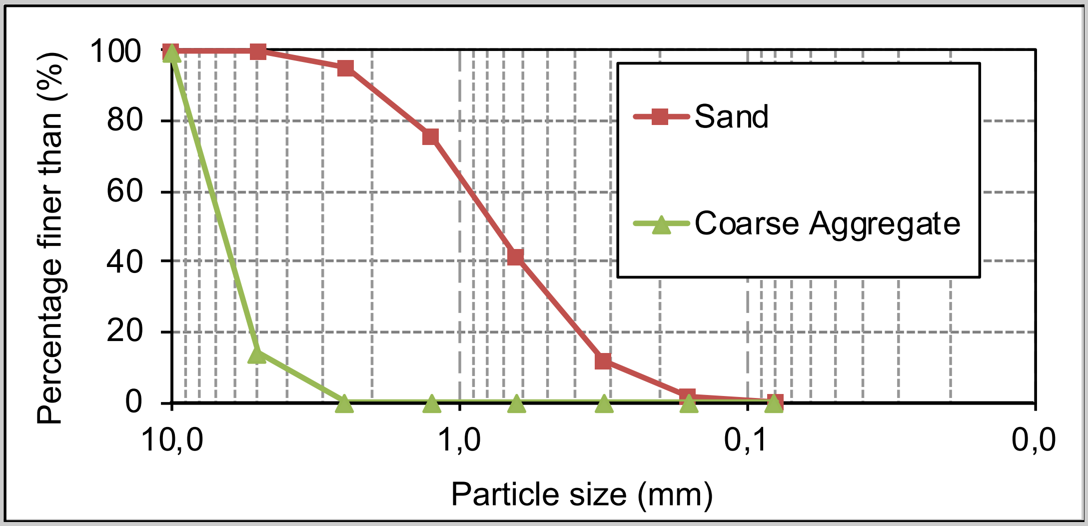
D_S and D_L are the smallest and largest size,

in theory, optimal packing density is at n=0.36,
but a lower value is preferable to a higher one

Funk, J.E., Dinger, D.R. (1994) Predictive Process Control of Crowded Particulate Suspensions Publishers, K. A. (ed.), Norwell, Massachusetts.

Case #2

… my best attempts at improving pump-ability

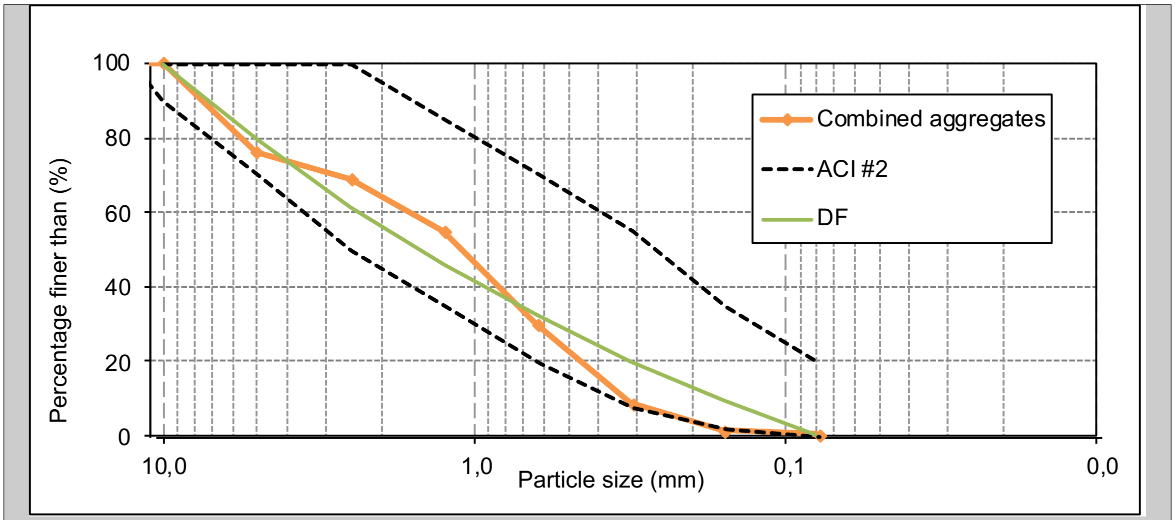


Typical mix design:

- 450 kg/m³ binder; w/b of 0.42, 5% air
- roughly 1620 kg/m³ of combined aggregate
  - 1175 kg/m³ sand
  - 445 kg/m³ of 10 mm agg.

Blockage after a few pump strokes

Wet-Mix

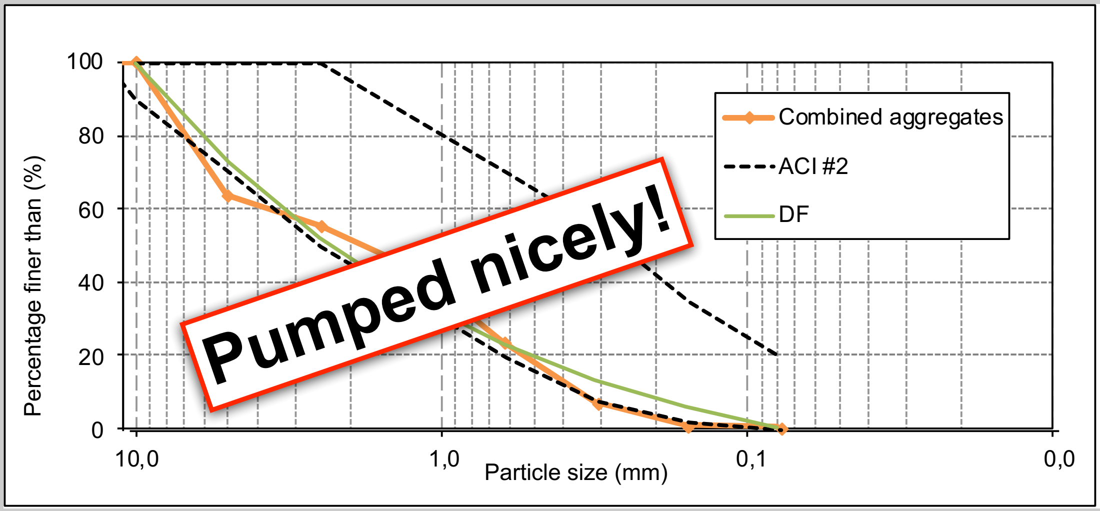


Combined aggregates:

72.5% Sand & 27.5% C. Agg.

- inside ACI#2, but barely
- the DF best-fit gives n = 0.187

Wet-Mix
A



Wet-Mix #B

Combined aggregates:

58% Sand & 42% C. Agg.

- outside ACI#2 !!
- the DF best-fit gives n = 0.37

	#A	**#B**	
Sieve No.30	29,8		***Target***
Sieve No.50	8,8	7,1	*15% - 30%*
Sieve No.100	1,3	1,0	*5%-10%*
Sieve No.200	0,4		-

In practice…

- It is often difficult to *completely* change the aggregate source
  - follow the rules
  - and make sure there is enough paste

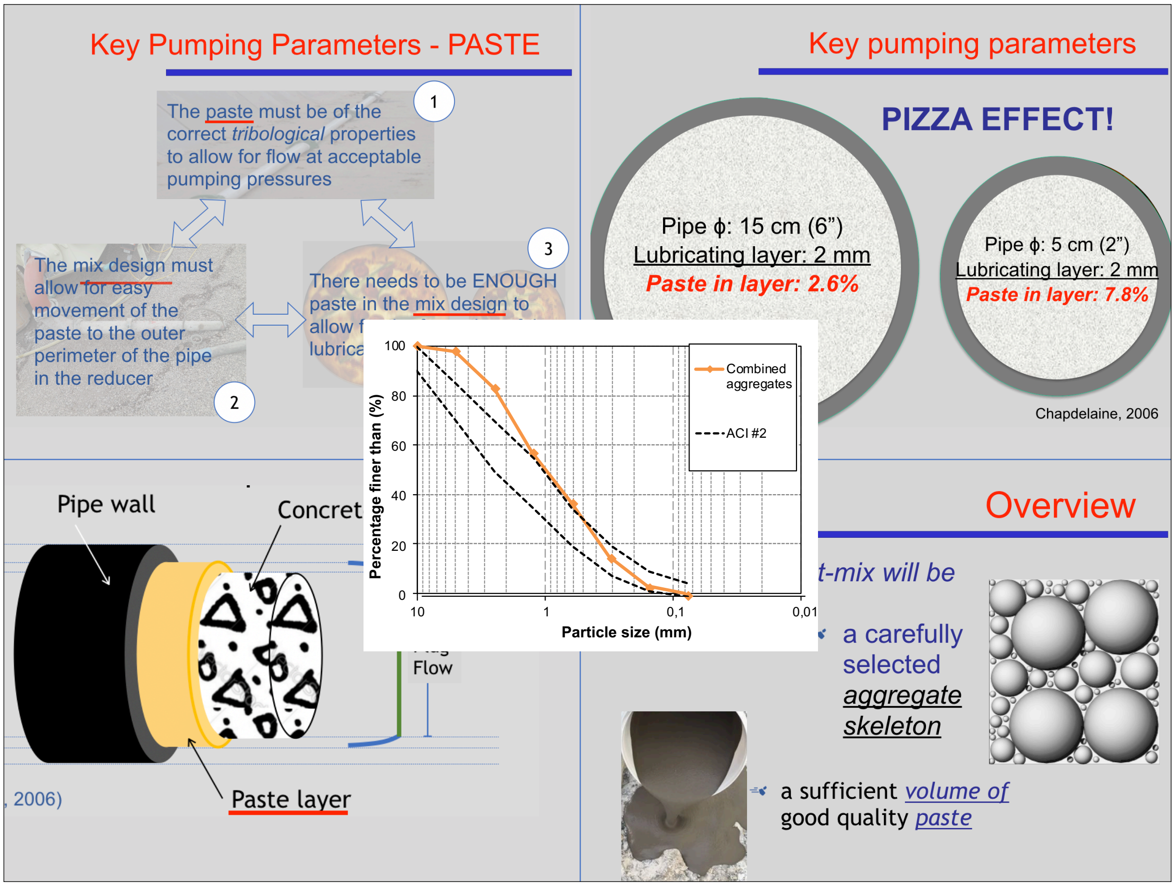
	Target
Sieve No.50	*15% - 30%*
Sieve No.100	*5%-10%*
Sieve No.200	*(2% - 5%)*

- If the combined aggregates can be optimized to Dinger-Funk:
  - save on binder & start making really good shotcrete!

Interesting "Quotes" (211.9R-18)

- "For gradation purposes, the fine and coarse aggregate should be considered as one…"
- "The use of extra quantities of cementitious materials as the only means to correct pumping difficulties is short-sighted and uneconomical. Correcting any deficiencies in the aggregate gradation is more important."

Concluding Remarks



Key Pumping Parameters - PASTE

The paste must be of the correct *tribological* properties to allow for flow at acceptable pumping pressures ①

The mix design must allow for easy movement of the paste to the outer perimeter of the pipe in the reducer ②

There needs to be ENOUGH paste in the mix design to allow f lubrica ③

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Chapdelaine, 2006

Overview

t-mix will be

- a carefully selected *aggregate skeleton*
- a sufficient *volume of* good quality *paste*

Contributors

Thank you !

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Photo credit : King Shotcrete Solutions

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