Using vibration to control the rheology of concrete for 3D printing

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Mixture design for concrete 3D printing

Selecting Proportions for Normal-Density and High-Density Concrete—Guide

Reported by ACI Committee 211

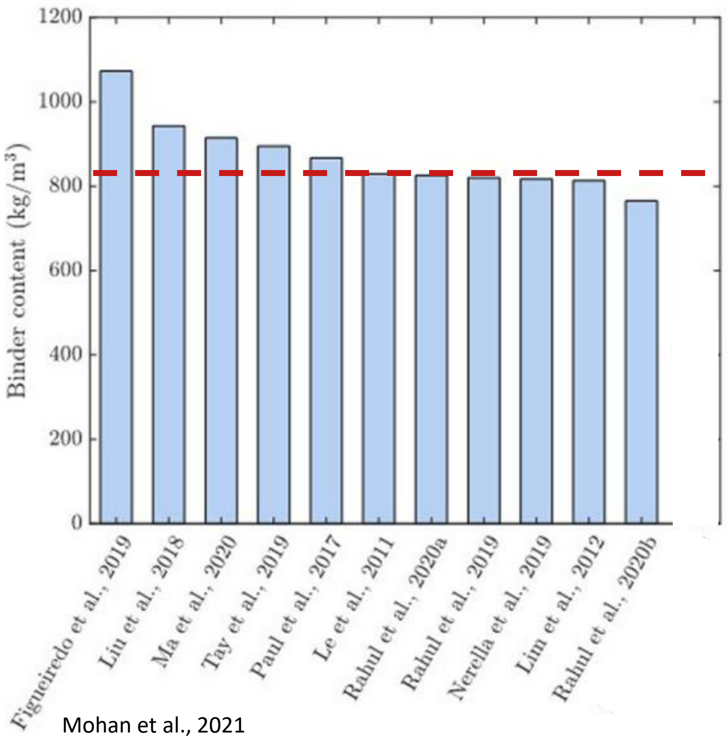
3D printable concrete needs to have yield strength that is:

Low enough to allow flow through the nozzle,

<u>BUT</u>

High enough to withstand its own weight and the weight of additional layers once printed

Mixture design for concrete 3D printing



Mohan et al., 2021

Mixture design for concrete 3D printing

Table 8—Effect of additional constituents on various fresh properties (Kosmatka and Wilson 2016)

Property	Cement	*w/cm*	Water	Air	Fly ash	Slag cement	Silica fume
Water demand	↑	↓	N/A	↓	↓	↓	↑
Workability	↑	↑	↑	↑	↑	↑	↓
Air content	↓	↓	↓	N/A	↓	↔	↓
Bleeding and segregation	↓	↑	↑	↓	↓	↕	↓
Finishability	↕	↕	↕	↑	↑	↑	↓
Time of setting	↓	↑	↑	↔	↑	↑	↔
Heat of hydration	↑	↓	↓	↔	↓	↔	↑
Strength	↑	↓	↓	↓	↑	↑	↑
Permeability	↓	↑	↑	↔	↓	↓	↓
Cracking	↑	↑	↑	↓	↓	↑	↑

Note: ↑ Increases; ↓ Decreases; ↕ Increases or decreases; ↔ Neutral.

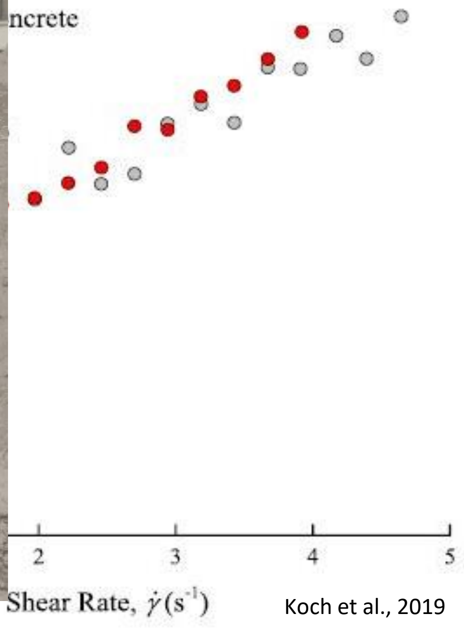
ACI 211.1-22

Rheology of concrete under vibration

Yield stress seemingly
eliminated at low she

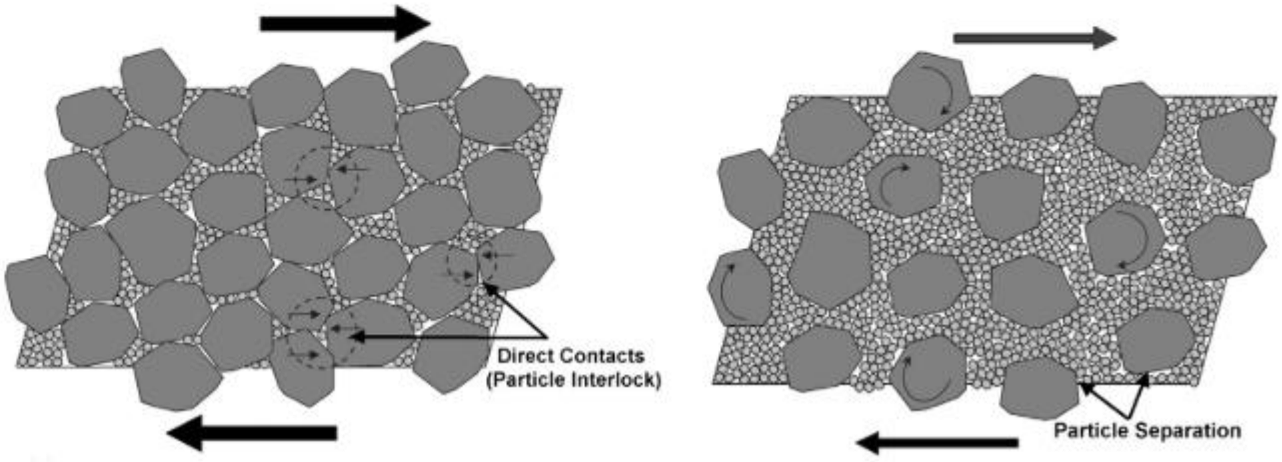
Response to vibration
instantaneous and re

Granular Fluids



Koch et al., 2019

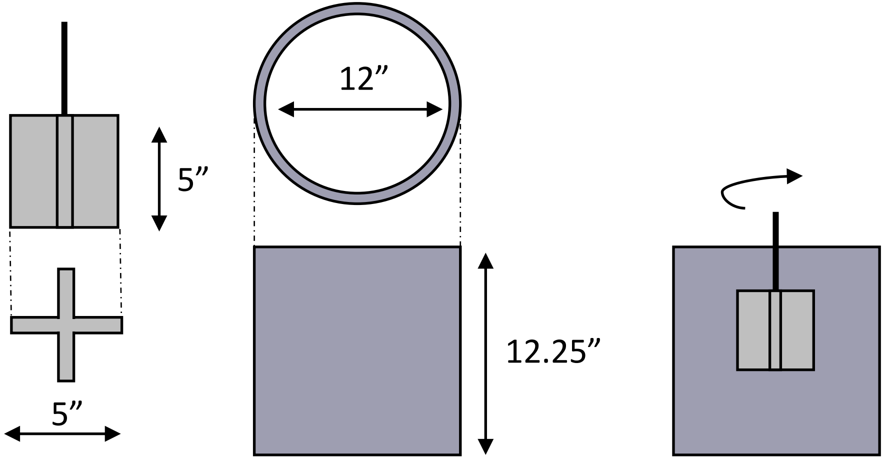
Rheology of concrete under vibration



Hanotin et al., 2015 Mehdipour et al., 2018

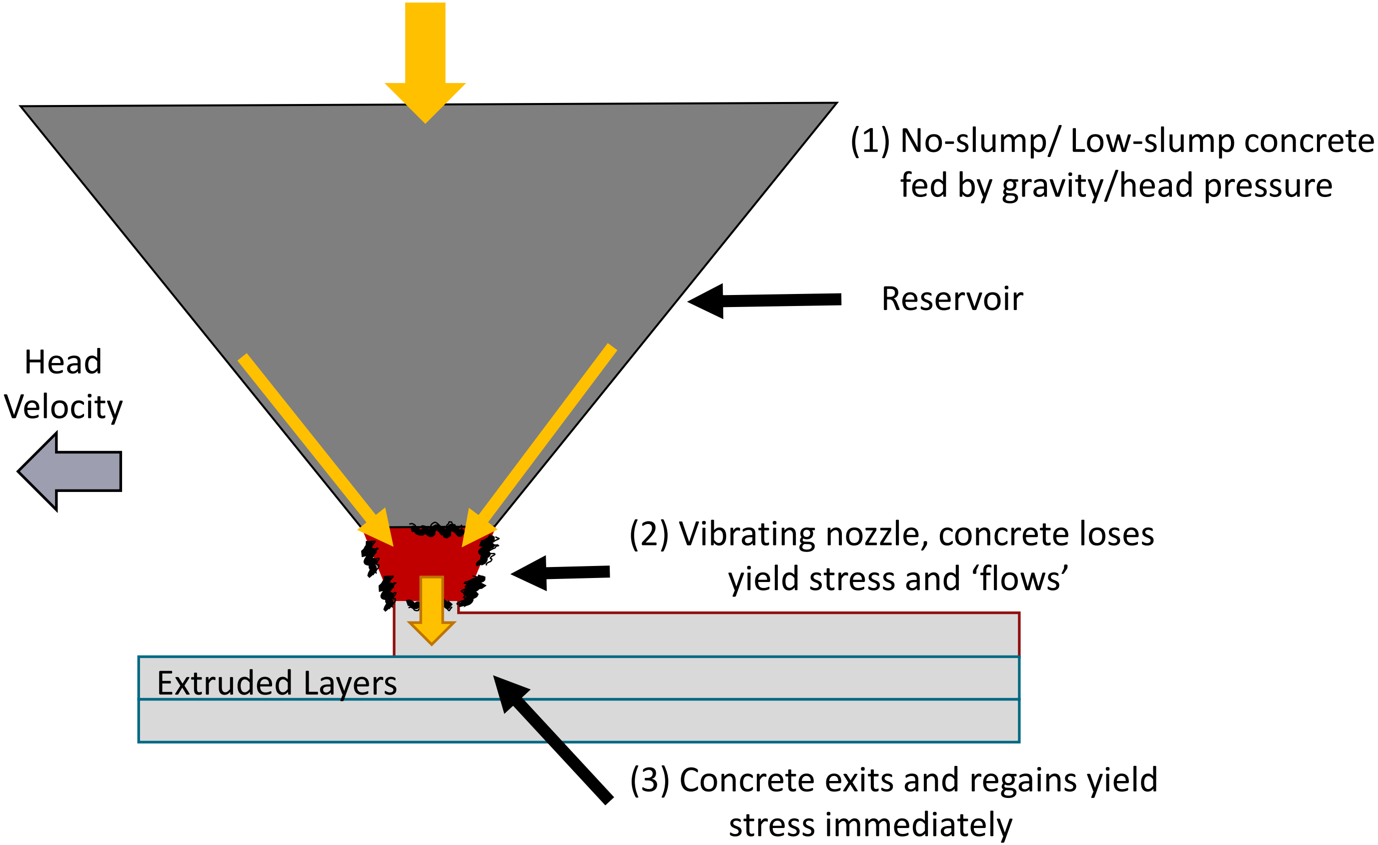
Measuring rheology during vibration

International Center for Aggregate Research (ICAR) concrete rheometer was modified to reliably measure yield stress during vibration.

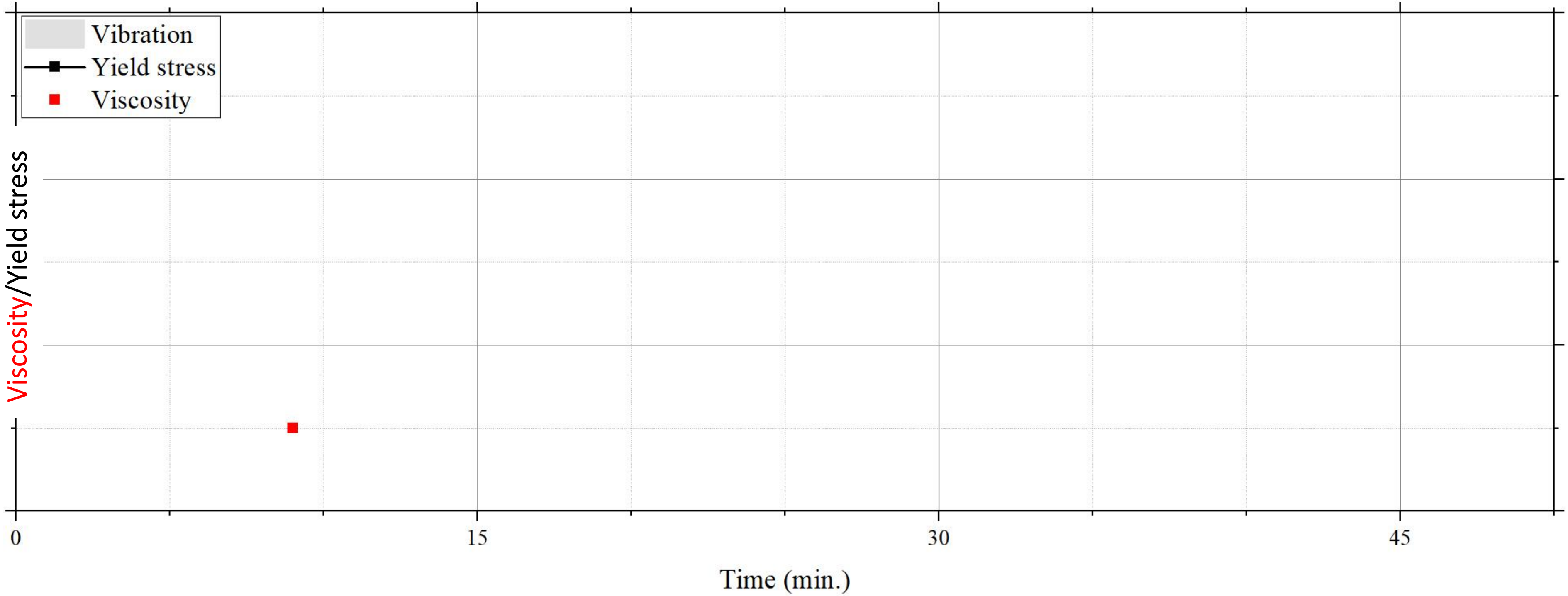


Vibration table – 60 Hz, 0.001 m max. amplitude

Schematic of proposed concrete 3D printer

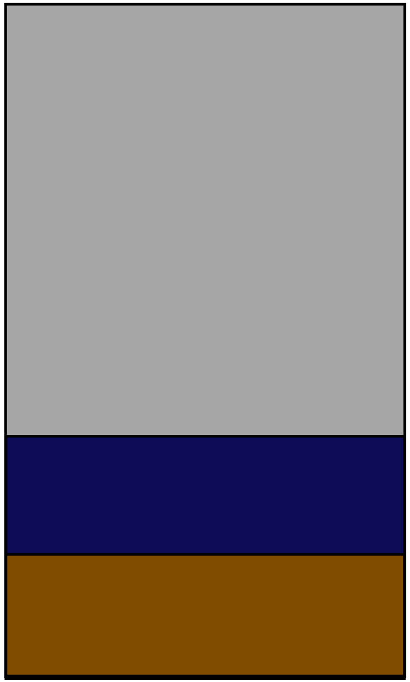


Experimental protocol

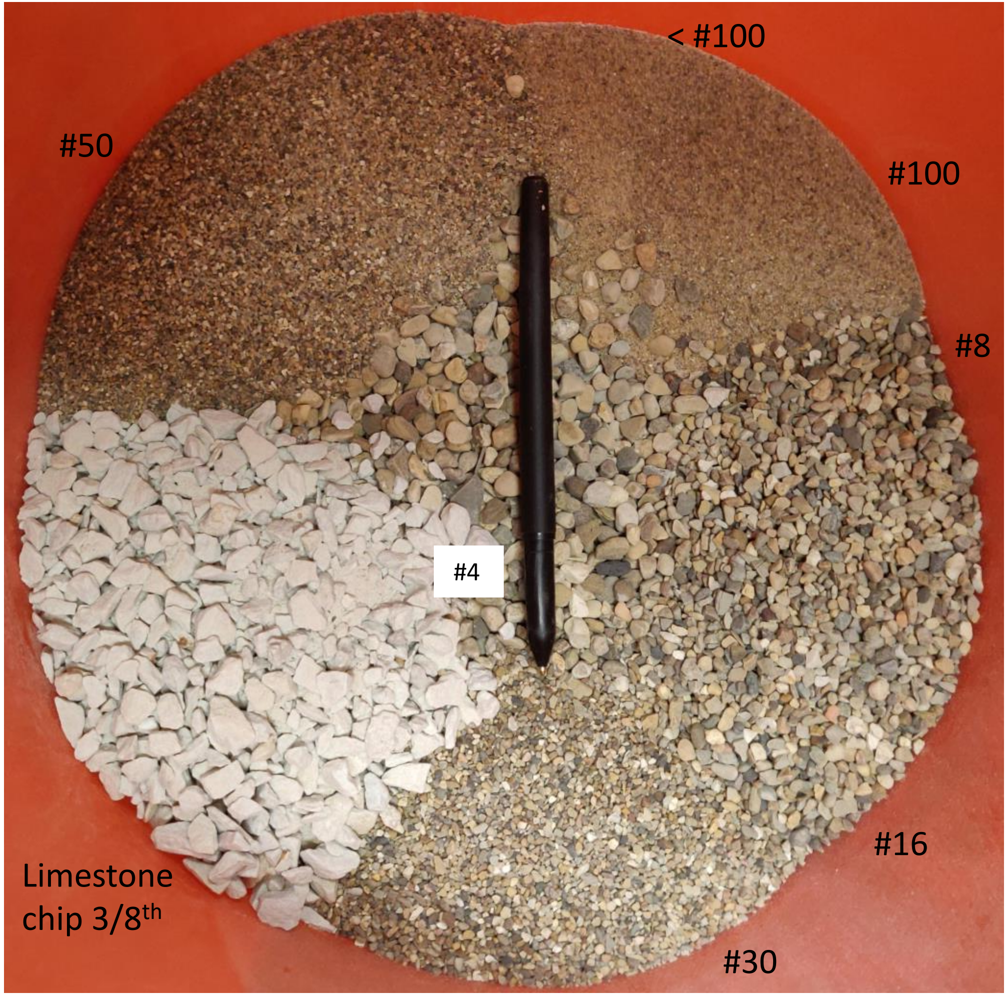


Nomenclature

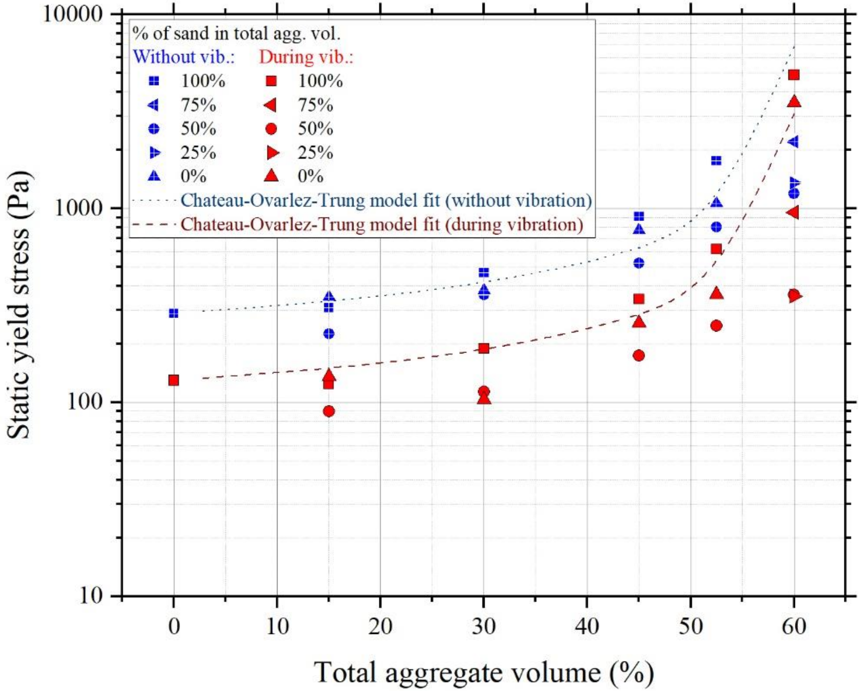
W0.400-P70-S15



- Paste volume assumes 3% volume of air
- Coarse – 3/8˝ limestone chip


< #100
#50
#100
#8
#4
#16
Limestone chip 3/8th
#30

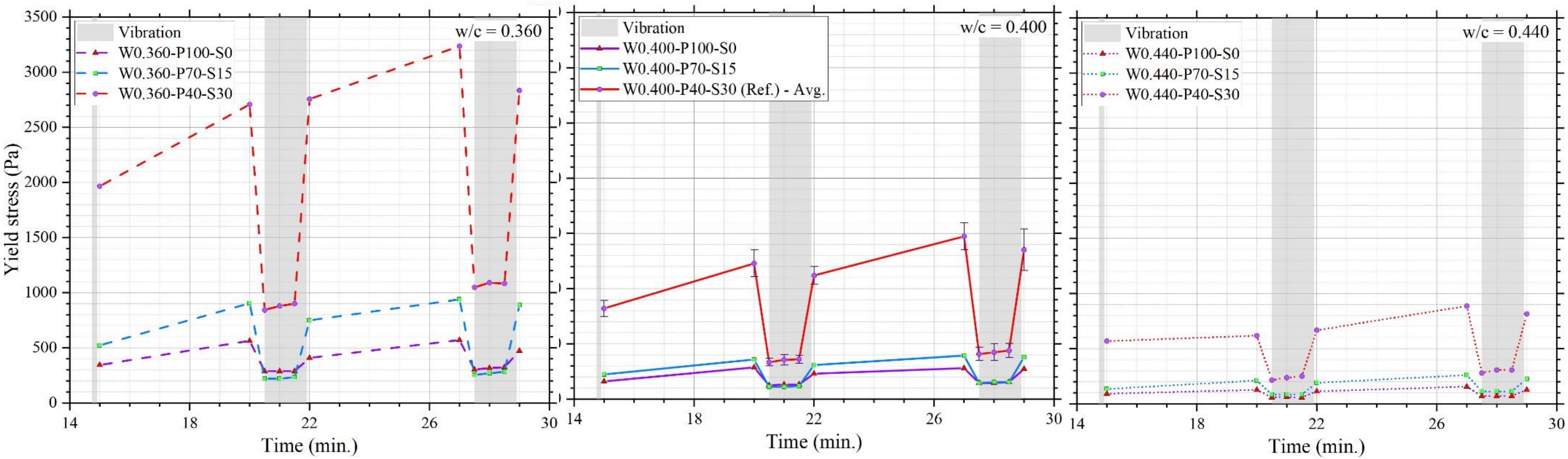
Effect of aggregate content



- At low aggregate content - cement paste rheology
- As aggregate content increases - rheological properties of the concrete increases exponentially

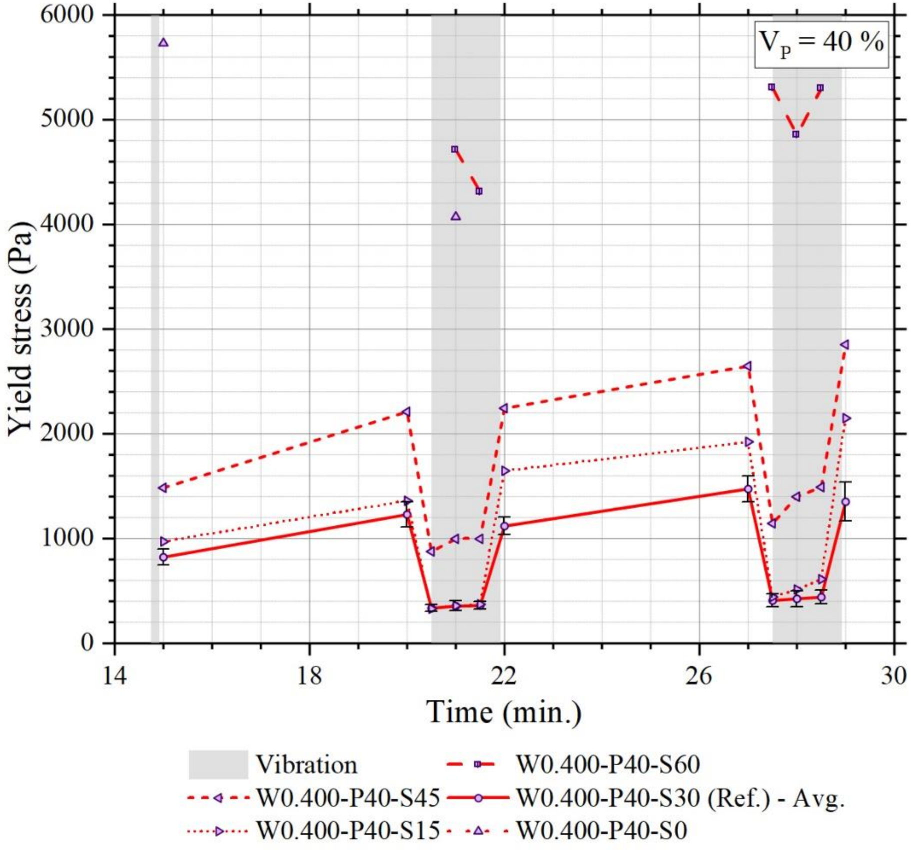
Parameter	Sensitive to
Yield stress	V_{Agg}
Yield stress during vibration	V_{Agg}

Effect of w/c

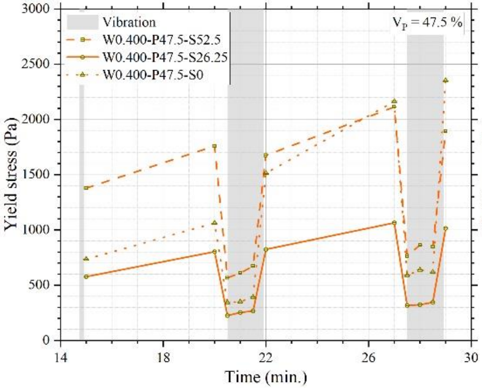

Vibration
W0.360-P100-S0
W0.360-P70-S15
W0.360-P40-S30
w/c = 0.360
Yield stress (Pa)
3500
3000
2500
2000
1500
1000
500
0
14
18
22
26
30
Time (min.)
Vibration
W0.400-P100-S0
W0.400-P70-S15
W0.400-P40-S30 (Ref.) - Avg.
w/c = 0.400
14
18
22
26
30
Time (min.)
Vibration
W0.440-P100-S0
W0.440-P70-S15
W0.440-P40-S30
w/c = 0.440
14
18
22
26
30
Time (min.)

Parameter	Sensitive to	
Yield stress	V_{Agg}	$\frac{1}{w/c}$
Yield stress during vibration	V_{Agg}	$\frac{1}{w/c}$

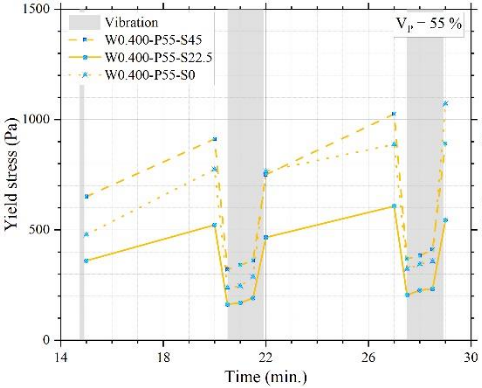
Effect of sand : chip ratio



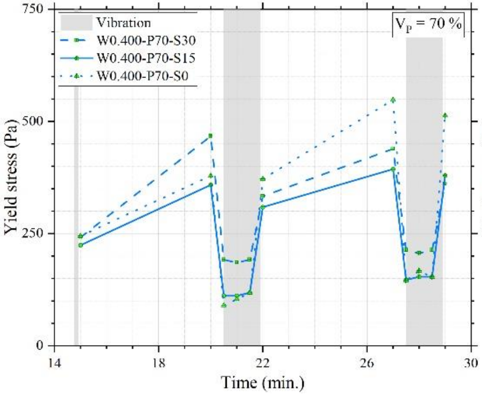
V_P 47.5 %



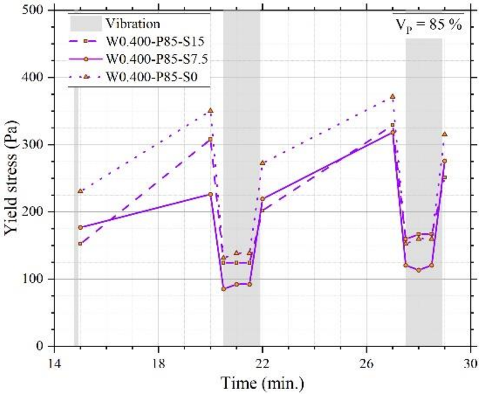
V_P 55 %



V_P 70 %



V_P 85 %

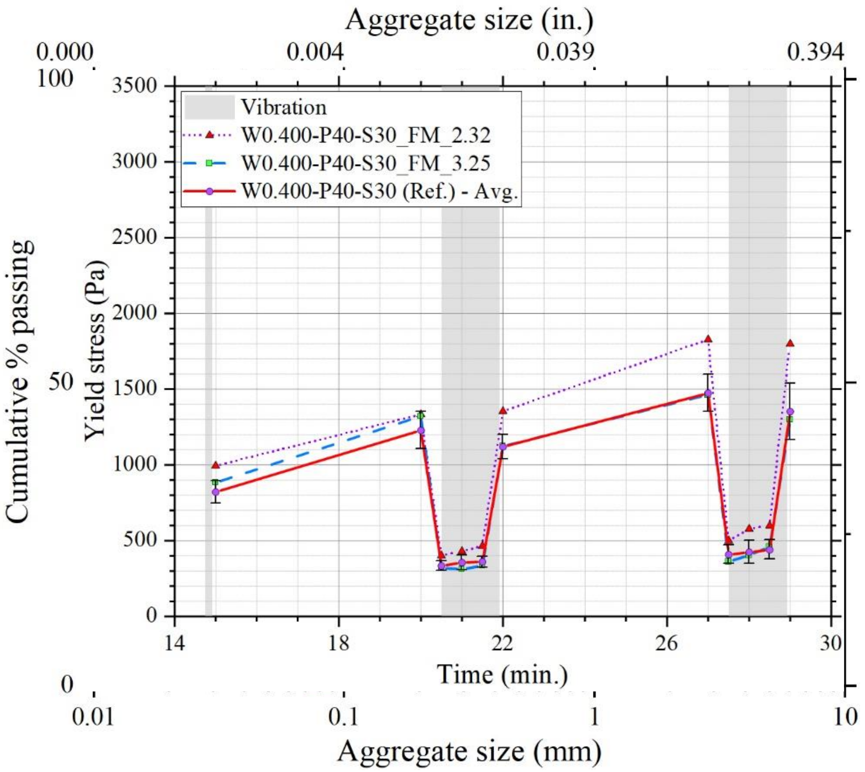


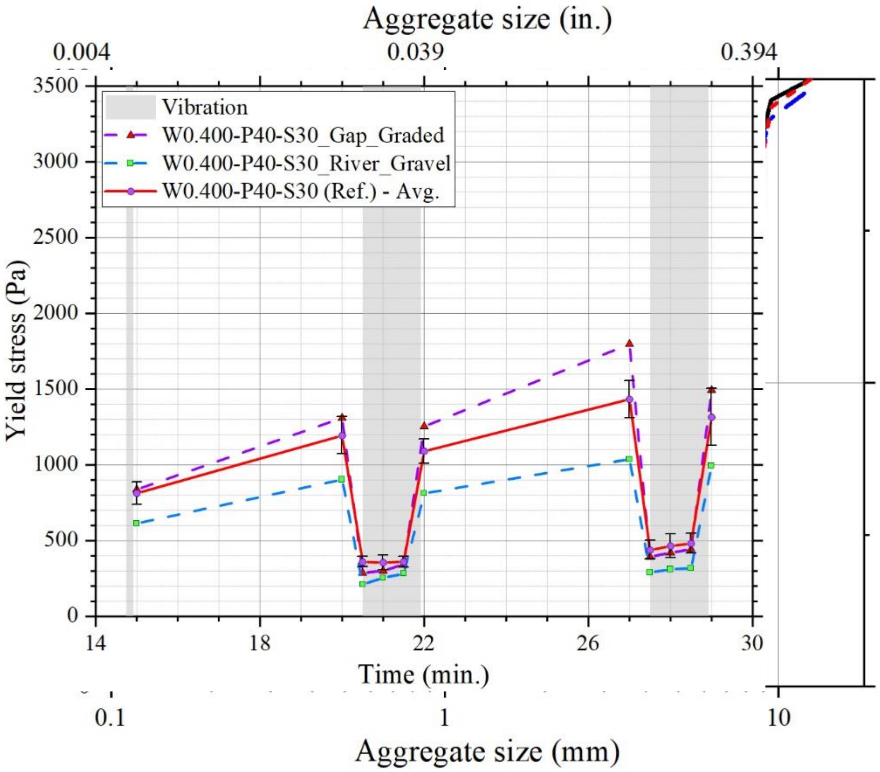
Sand:Chip (%)

Yield stress - 100:0 > 0:100 > 50:50

Parameter	Sensitive to		
Yield stress	V_{Agg}	$\frac{1}{w/c}$	Sand : Chip
Yield stress during vibration	V_{Agg}	$\frac{1}{w/c}$	Sand : Chip

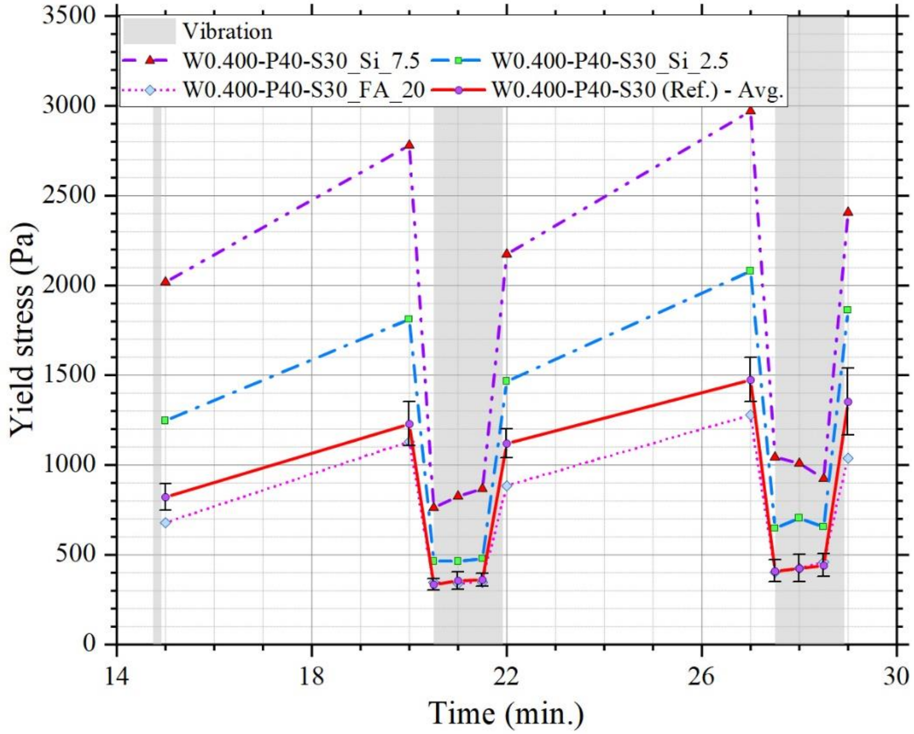
Effect of changing aggregate





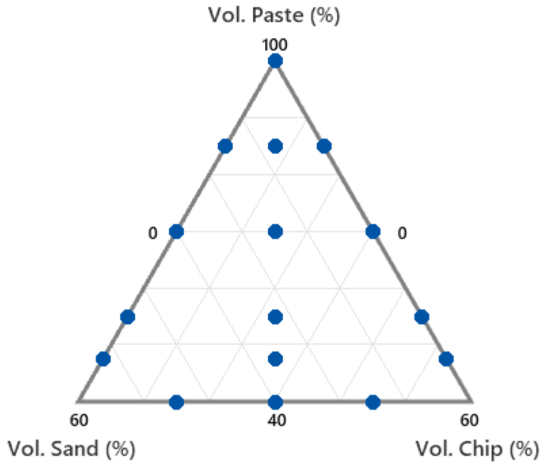
Parameter	Sensitive to			
Yield stress	V_{Agg}	$\frac{1}{w/c}$	Sand : Chip	Aggregate Gradation, Type
Yield stress during vibration	V_{Agg}	$\frac{1}{w/c}$	Sand : Chip	

Effect of changing paste



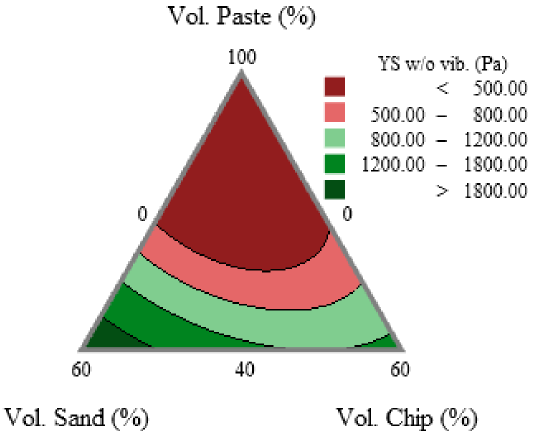
Parameter	Sensitive to				
Yield stress	V_{Agg}	$\frac{1}{w/c}$	Sand : Chip	Aggregate Gradation, Type	Paste
Yield stress during vibration	V_{Agg}	$\frac{1}{w/c}$	Sand : Chip		Paste

Statistical modeling

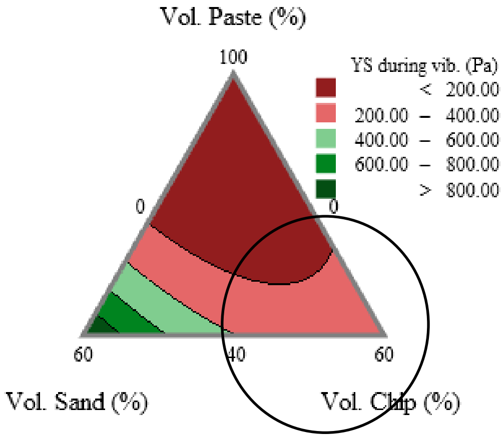


Special cubic canonical model

$$\eta = \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \sum_{j=i+1}^{3} \beta_{ij} X_i X_j + \sum_{i=1}^{3} \sum_{j=i+1}^{3} \sum_{k=i+2}^{3} \beta_{ijk} X_i X_j X_k$$

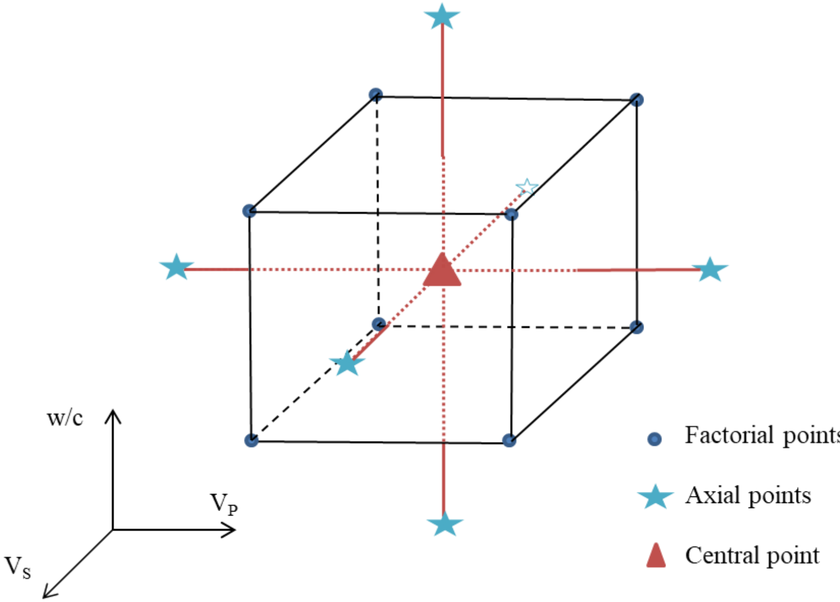


Yield stress



Yield stress during vib.

Prediction of concrete rheology during vibration



2^n

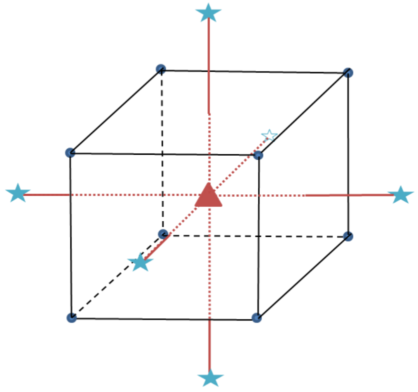
$2n \ at \ \alpha = (2^n)^{\frac{1}{4}}$

Input variable, X_i	Range
Volume of paste, V_P (%)	30.00 – 50.00
Volume of sand, V_S (%)	20.00 – 40.00
Water to cement ratio, w/c	0.360 – 0.440

Box-Wilson central composite design (CCD)

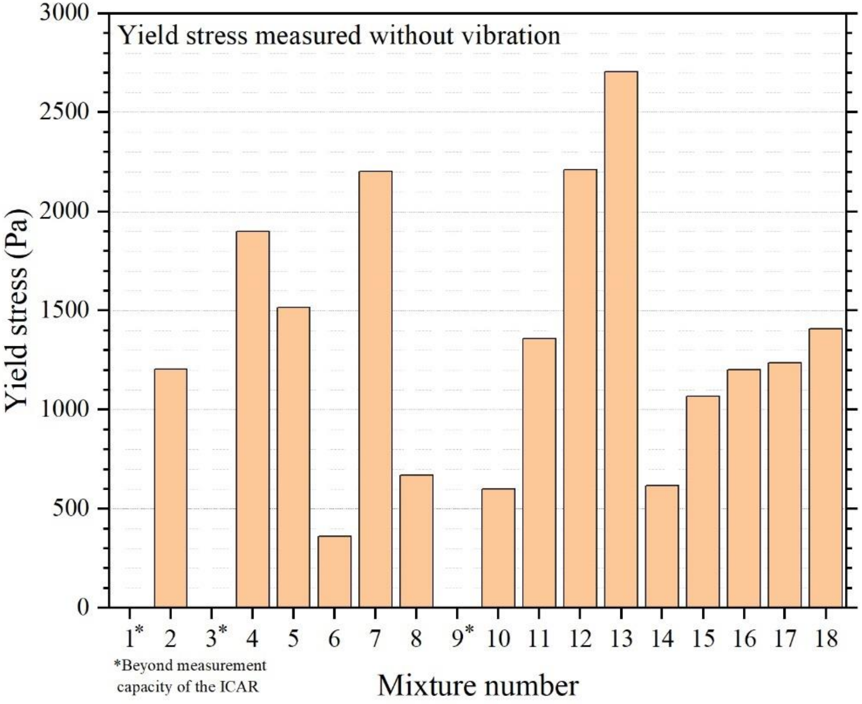
Prediction of concrete rheology during vibration

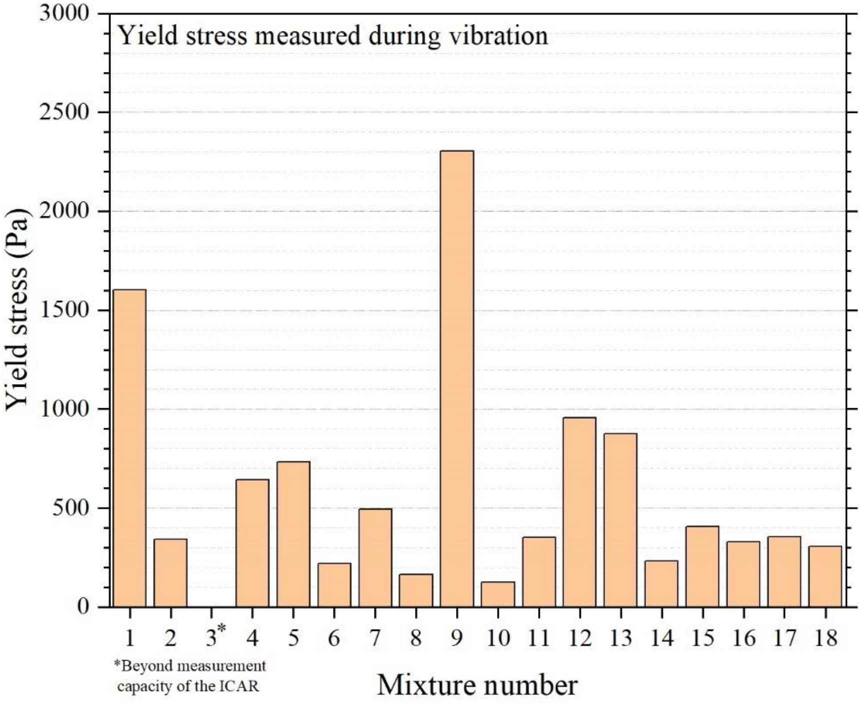
Input variable	Range	Coded level				
		-α	-1	0	+1	+α
Volume of paste, V_P (%)	30.00 – 50.00	30.00	34.05	40.00	45.95	50.00
Volume of sand, V_S (%)	20.00 – 40.00	20.00	24.05	30.00	35.95	40.00
Water to cement ratio, w/c	0.360 – 0.440	0.360	0.376	0.400	0.424	0.440



Mixture number	Type of point	Factor levels					
		Coded			Experimental		
		V_P	V_S	w/c	V_P (%)	V_S (%)	w/c
1	Factorial	-1	-1	-1	34.05	24.05	0.376
2		+1	-1	-1	45.95	24.05	0.376
3		-1	+1	-1	34.05	35.95	0.376
4		+1	+1	-1	45.95	35.95	0.376
5		-1	-1	+1	34.05	24.05	0.424
6		+1	-1	+1	45.95	24.05	0.424
7		-1	+1	+1	34.05	35.95	0.424
8		+1	+1	+1	45.95	35.95	0.424
9	Axial	-1.68	0	0	30.00	30.00	0.400
10		+1.68	0	0	50.00	30.00	0.400
11		0	-1.68	0	40.00	20.00	0.400
12		0	+1.68	0	40.00	40.00	0.400
13		0	0	-1.68	40.00	30.00	0.360
14		0	0	+1.68	40.00	30.00	0.440
15	Central	0	0	0	40.00	30.00	0.400
16		0	0	0	40.00	30.00	0.400
17		0	0	0	40.00	30.00	0.400
18		0	0	0	40.00	30.00	0.400

Model inputs





Prediction of concrete rheology during vibration

$$\eta = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X_i^2 + \sum_{i=1}^{n} \sum_{j=i+1}^{n} \beta_{ij} X_i X_j$$

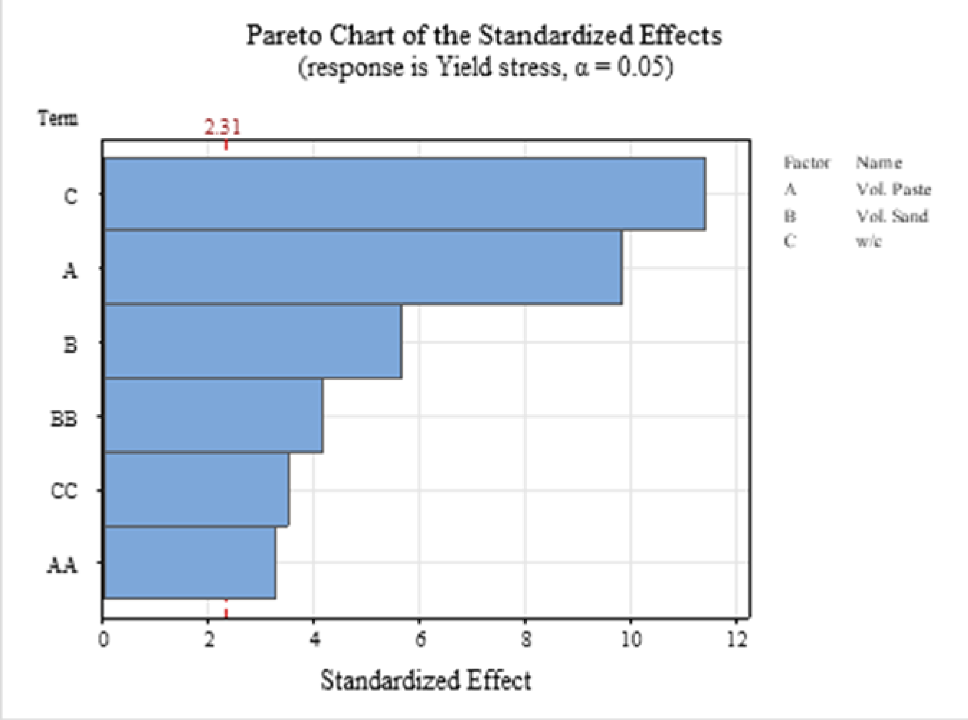
η – Response
X – Input variable

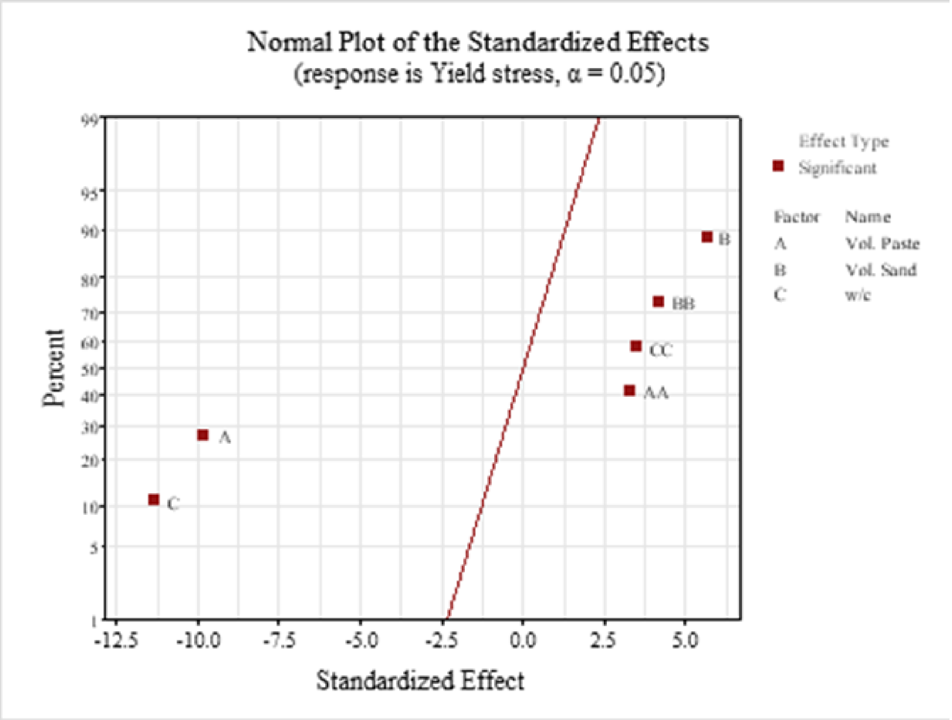
Modeled response equations

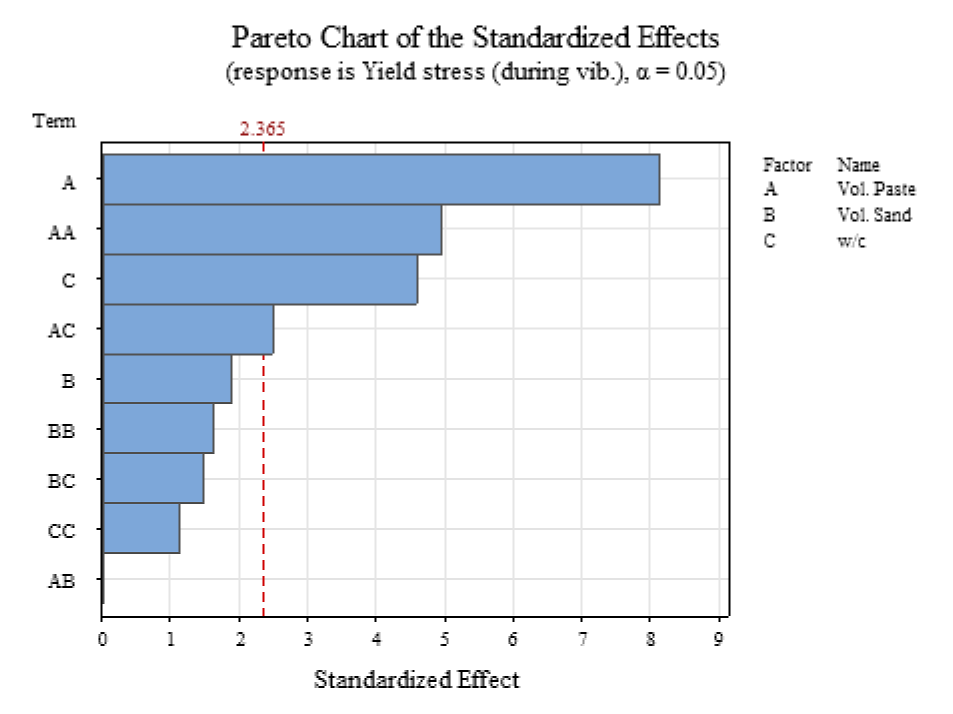
Response	Adj. R^2 (%)			
	Linear	Linear + Square	Linear + interaction	Full quadratic
YS	81.95	**94.50**	76.14	92.06
YS_Vib.	58.02	78.23	53.21	**85.17**
Visc.	35.47	37.74	88.24	**91.52**
Visc._Vib.	16.00	0.00	87.71	**87.80**

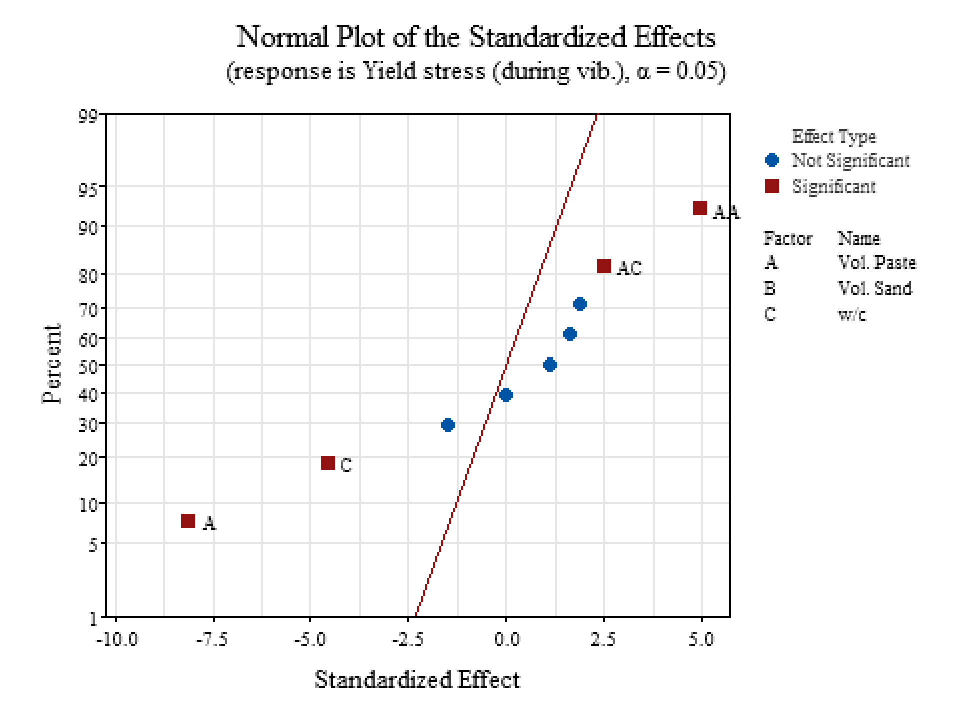
Modeled response equations

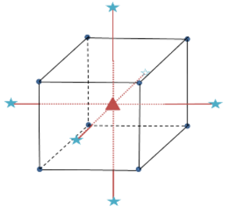
Response	Units	Equation	Adj. R^2 (%)
Yield stress	Pa	Yield stress = 72874 $- 617\ V_P - 116.1\ V_S - 254240\ w/c$ $+ 6.23\ V_P^2 + 2.509\ V_S^2 + 287590\ w/c^2$	94.50
Yield stress (during vibration)	Pa	Yield stress (during Vib.) = 58800 $- 1457\ V_P + 315\ Vs - 149733\ w/c$ $+ 9.05\ V_P^2 + 1.351\ V_S^2 + 126668\ w/c^2$ $- 0.00\ V_P \times V_S + 1606\ V_P \times w/c - 950\ Vs \times w/c$	85.17
Viscosity	Pa.s	Viscosity = -476 $- 3.1\ V_P + 3.94\ Vs + 2669\ w/c$ $+ 0.1074\ V_P^2 + 0.0113\ V_S^2 - 660\ w/c^2$ $+ 0.1762\ V_P \times V_S - 31.0\ V_P \times w/c - 30.4\ Vs \times w/c$	91.52
Viscosity (during vibration)	Pa.s	Viscosity (during vib.) = -868 $+ 25.04\ V_P - 18.04\ Vs + 3614\ w/c$ $- 0.0299\ V_P^2 - 0.013\ V_S^2 - 3149\ w/c^2$ $+ 0.0515\ V_P \times V_S - 61.8\ V_P \times w/c + 40.1\ Vs \times w/c$	87.80


Pareto Chart of the Standardized Effects
(response is Yield stress, α = 0.05)
Term
2.31
C
A
B
BB
CC
AA
0
2
4
6
8
10
12
Standardized Effect
Factor Name
A Vol. Paste
B Vol. Sand
C w/c

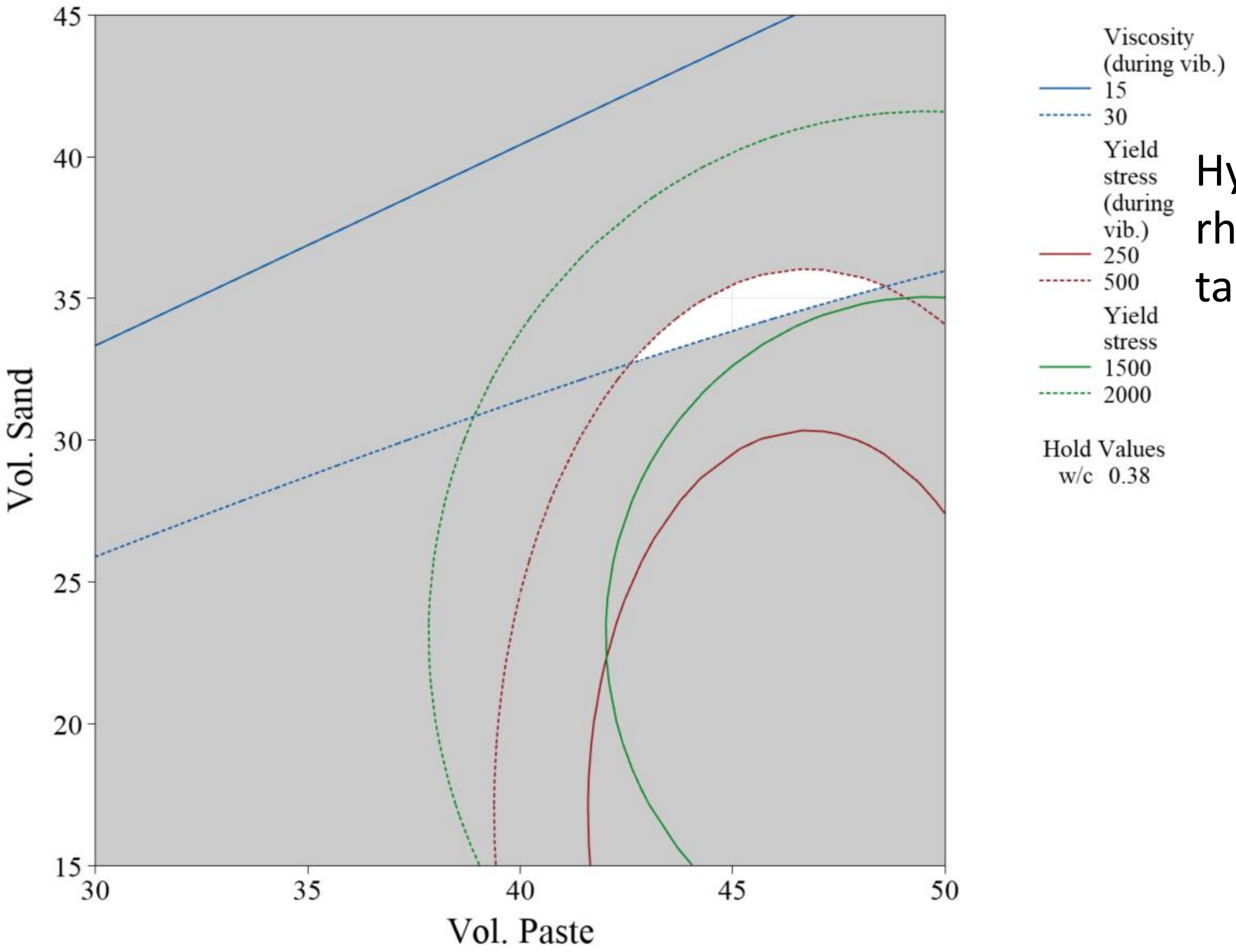

Normal Plot of the Standardized Effects
(response is Yield stress, α = 0.05)
Percent
99
95
90
80
70
60
50
40
30
20
10
5
1
-12.5
-10.0
-7.5
-5.0
-2.5
0.0
2.5
5.0
Standardized Effect
B
BB
CC
AA
A
C
Effect Type
Significant
Factor Name
A Vol. Paste
B Vol. Sand
C w/c


Pareto Chart of the Standardized Effects
(response is Yield stress (during vib.), α = 0.05)
Term
2.365
A
AA
C
AC
B
BB
BC
CC
AB
0
1
2
3
4
5
6
7
8
9
Standardized Effect
Factor
Name
A
Vol. Paste
B
Vol. Sand
C
w/c


Normal Plot of the Standardized Effects
(response is Yield stress (during vib.), α = 0.05)
99
95
90
80
70
60
50
40
30
20
10
5
1
Percent
-10.0
-7.5
-5.0
-2.5
0.0
2.5
5.0
Standardized Effect
AA
AC
C
A
Effect Type
Not Significant
Significant
Factor
Name
A
Vol. Paste
B
Vol. Sand
C
w/c



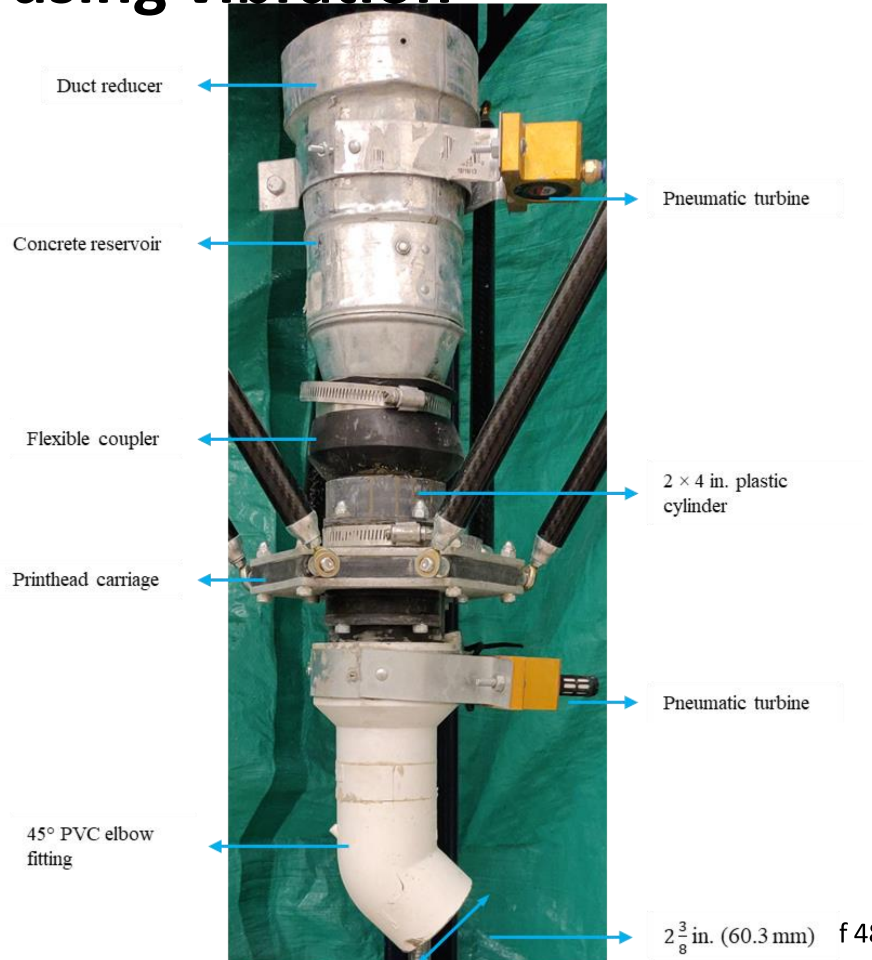
Response	Statistically significant term, ranked		
	1	2	3
Yield Stress	$\frac{1}{\mathrm{w/c}}$	$\frac{1}{V_P}$	V_S
Vib. Yield Stress	$\frac{1}{V_P}$	(V_P^2)	$\frac{1}{\mathrm{w/c}}$
Viscosity	$(V_P \times V_S)$	$\frac{1}{V_P}$	$\frac{1}{V_S}$
Vib. Viscosity	$\frac{1}{V_P \times \mathrm{w/c}}$	$\frac{1}{V_S}$	$\frac{1}{\mathrm{w/c}}$



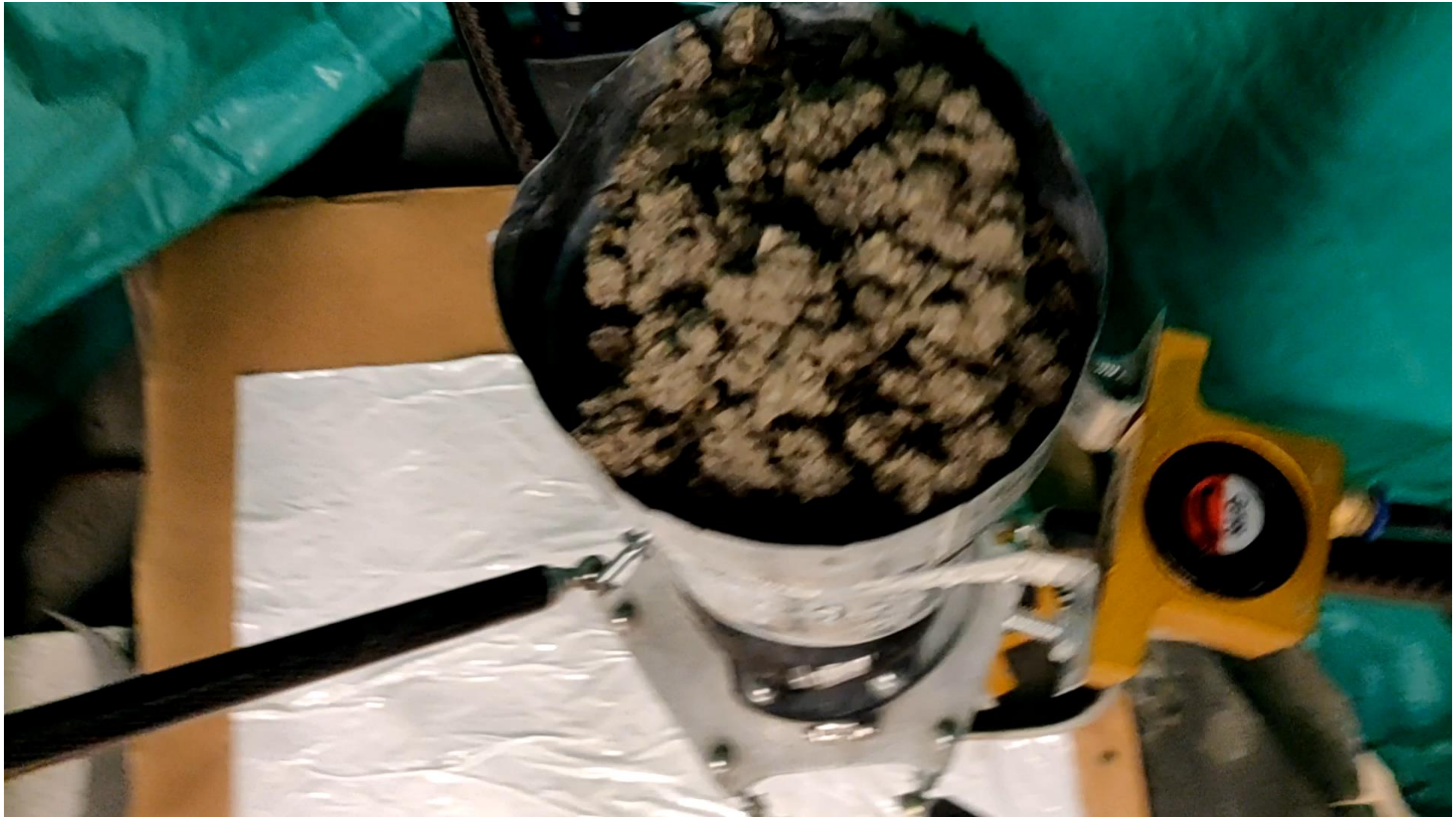
Hypothetical rheological targets

Prototype concrete 3D printer using vibration

Delta 3D printer with a modified nozzle

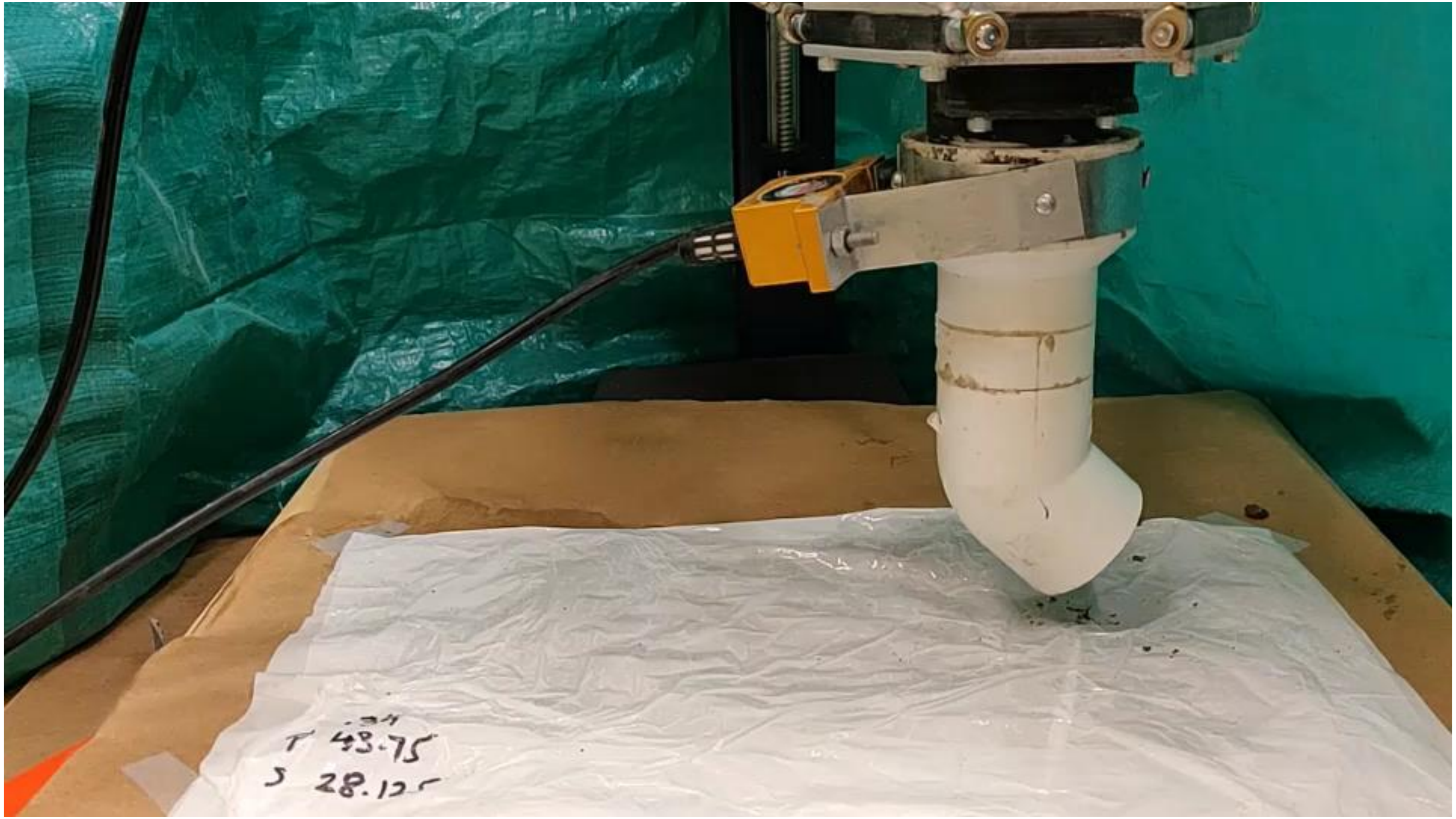


3D printing with vibration



3D printing with vibration

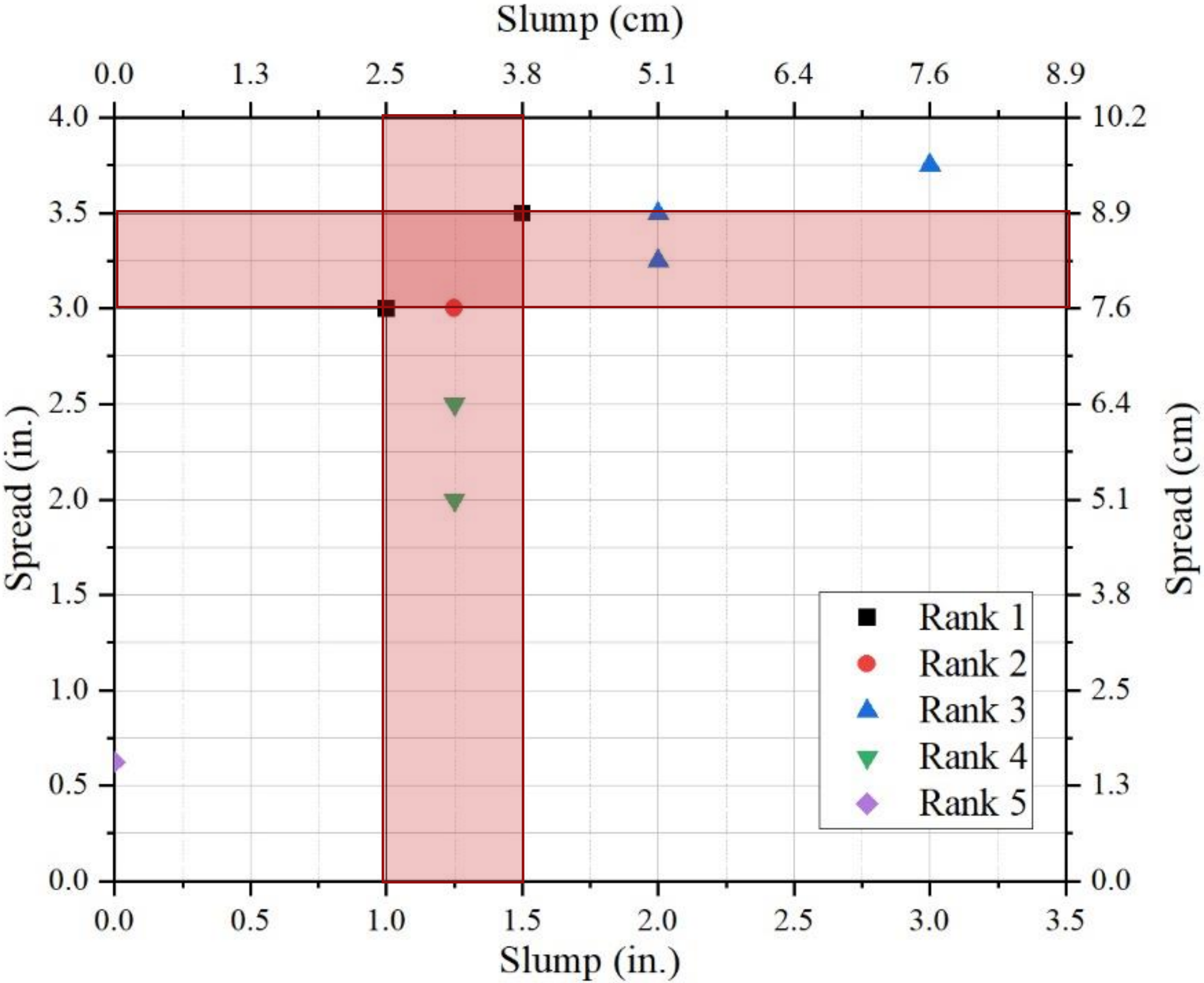
W0.34-P43.75-S28.125

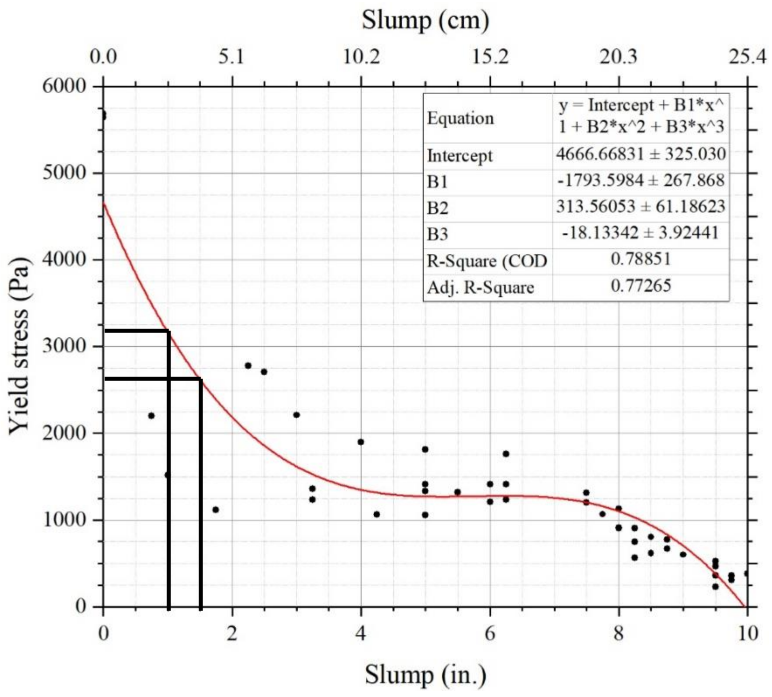


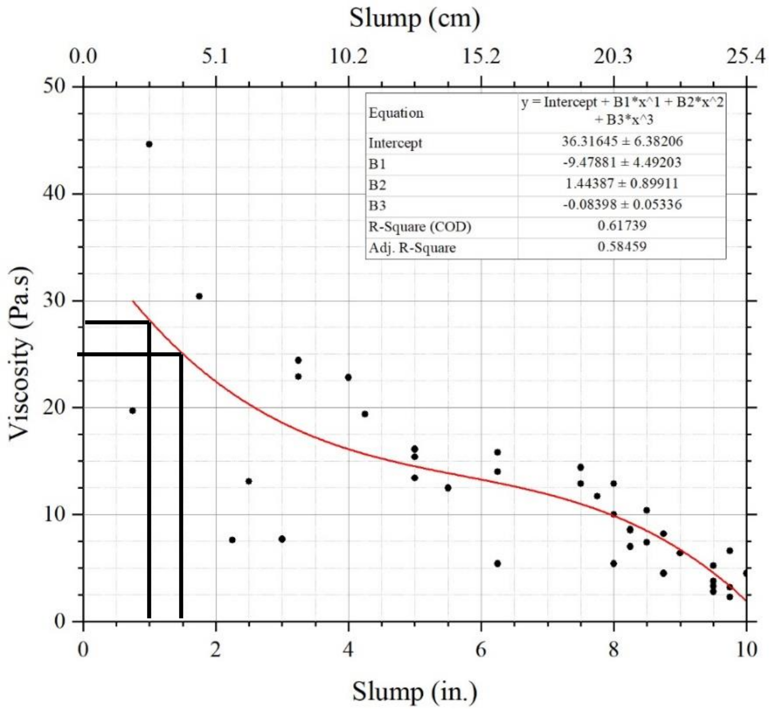
	P40-S30	P43.75-S28.125	P47.5-S26.25
W0.36			
W0.34			
W0.32			

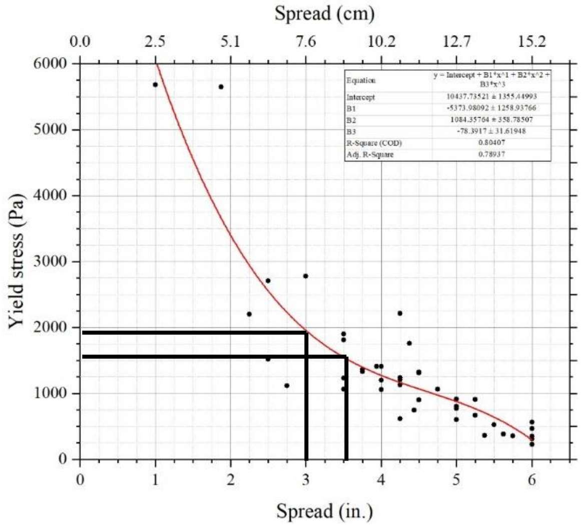
Measuring rheology without a rheometer?

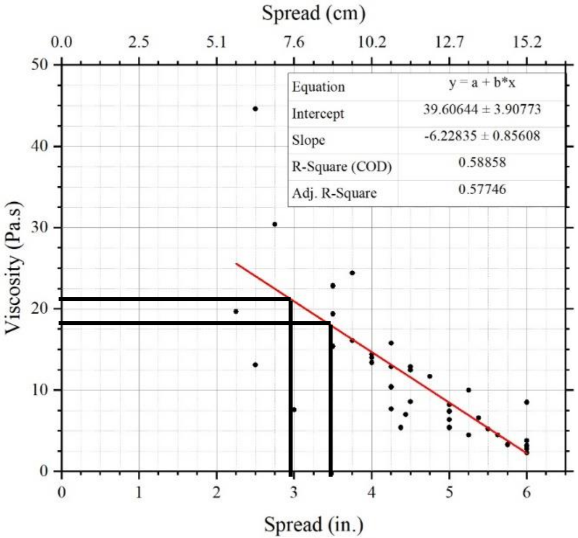
- 3D printable concrete mixtures have low or no slumps
- Regression analysis from Slump (ASTM C143) and Flow table (ASTM C1437)

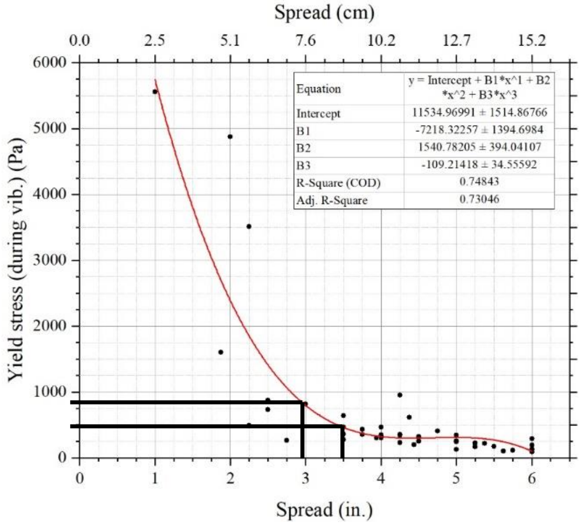

Slump (cm)
0.0
1.3
2.5
3.8
5.1
6.4
7.6
8.9
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Spread (in.)
10.2
8.9
7.6
6.4
5.1
3.8
2.5
1.3
0.0
Spread (cm)
Rank 1
Rank 2
Rank 3
Rank 4
Rank 5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Slump (in.)

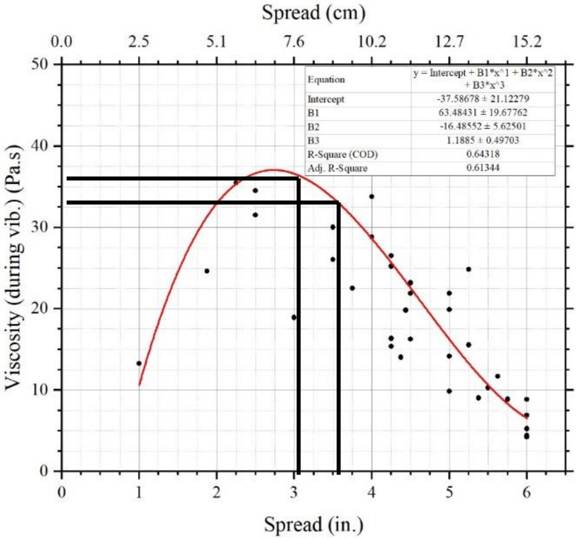

Slump (cm)
Yield stress (Pa)
Slump (in.)
Equation
y = Intercept + B1*x^1 + B2*x^2 + B3*x^3
Intercept 4666.66831 ± 325.030
B1 -1793.5984 ± 267.868
B2 313.56053 ± 61.18623
B3 -18.13342 ± 3.92441
R-Square (COD 0.78851
Adj. R-Square 0.77265


Slump (cm)
Viscosity (Pa.s)
Slump (in.)
Equation
y = Intercept + B1*x^1 + B2*x^2 + B3*x^3
Intercept 36.31645 ± 6.38206
B1 -9.47881 ± 4.49203
B2 1.44387 ± 0.89911
B3 -0.08398 ± 0.05336
R-Square (COD) 0.61739
Adj. R-Square 0.58459









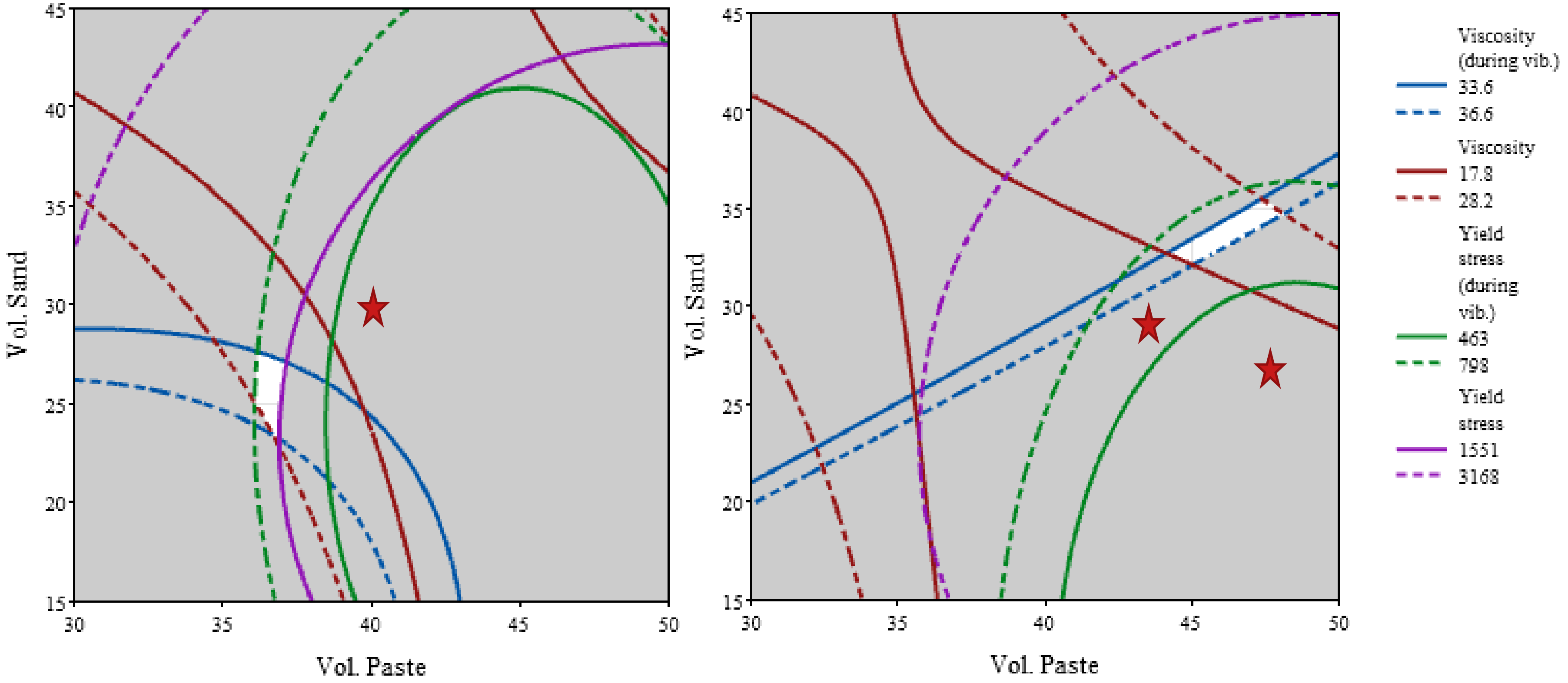
Yield stress:
1551 to 3168 Pa

Yield stress (during vib.)
463 to 798 Pa

Viscosity:
17.8 to 28.2 Pa.s

Viscosity (during vib.):
33.6 to 36.6 Pa.s

Targeted rheology with CCD model



w/c 0.40

w/c 0.36

Conclusions

- Effect of vibration on the rheology of concrete is immediate and reversible
- As aggregate content increases, the yield strength of the concrete increases considerably
- CCD can be used to effectively model rheological properties of concrete to develop equations to target specific rheological numbers
- To predict the performance of 3D printable concrete, we can potentially estimate the rheological parameters using established concrete testing methods such as slump or mortar flow

Parameter	Sensitive to				
Yield stress	V_{Agg}	$\frac{1}{w/c}$	Sand : Chip	Aggregate Gradation, Type	Paste
Viscosity	V_{Agg}	$\frac{1}{w/c}$	V_{Chip}		
Yield stress during vibration	V_{Agg}	$\frac{1}{w/c}$	Sand : Chip	Paste	$\frac{1}{\text{Vib. Acceleration}}$
Viscosity during vibration	V_{Agg}	$\frac{1}{w/c}$	V_{Chip}		

Thank you!

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- K. Pattaje Sooryanarayana, K. A. Hawkins, P. Stynoski, and D. A. Lange, "Controlling Three-Dimensional-Printable Concrete with Vibration," Mater. J., vol. 118, no. 6, pp. 353–358, Nov. 2021.

- K. Pattaje Sooryanarayana, P. Stynoski, and D. Lange, "Effect of Vibration on the Rheology of Concrete for 3D Printing," in RILEM Bookseries, vol. 28, Springer, 2020, pp. 353–359.