

**GEOPOLYMER-CAMP 2024**

# Numerical Optimization of 3D Printing Parameters for Geopolymer-Based Composites

**ABRAR GASMI<sup>1</sup>**

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<sup>2</sup> Institut Géopolymère, France



# OVERVIEW



CONTEXT & REVIEW



MATERIAL CHARACTERIZATION



RHEOLOGICAL CHARACTERIZATION



ROBOCASTING PROCESS DEVELOPMENT



NUMERICAL SIMULATION OF AM



INDICATORS & OUTLOOK

# CONTEXT & REVIEW



# CONTEXT

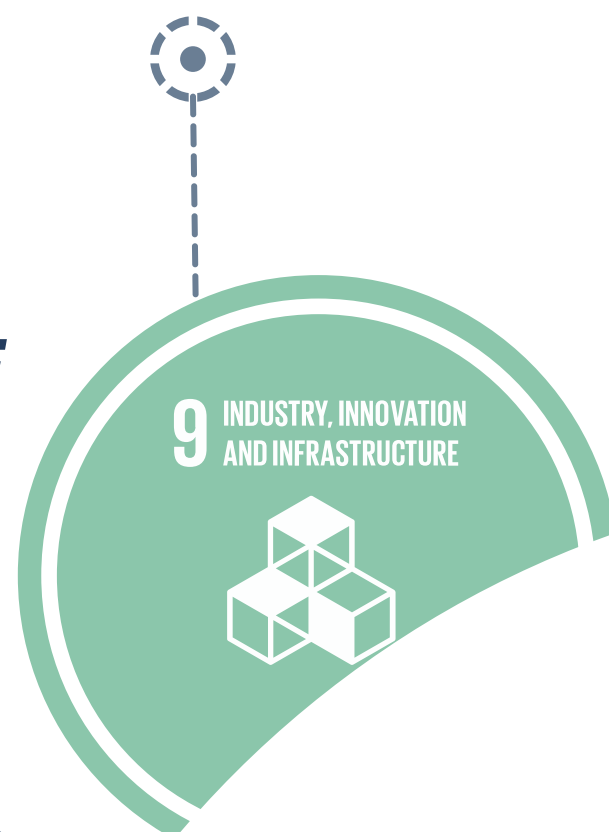
## ***ECO-RESPONSIBLE PRODUCTION?***



# CONTEXT

**MANUFACTURING  
PROCESS ?**

**ECO-RESPONSIBLE  
PRODUCTION?**



**SUSTAINABLE  
DEVELOPMENT  
GOALS**

# CONTEXT

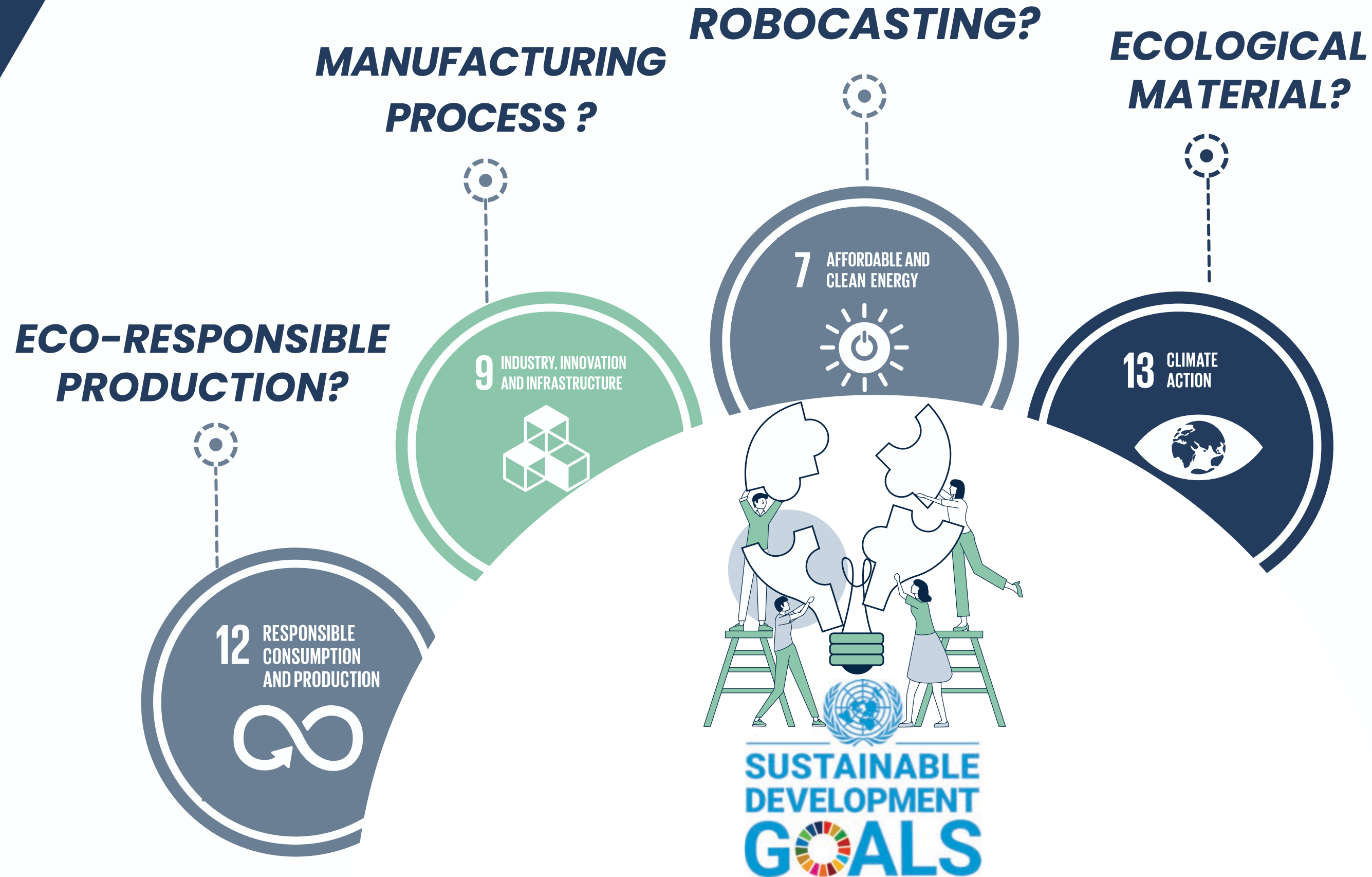
**MANUFACTURING  
PROCESS ?**

**ROBOCASTING?**

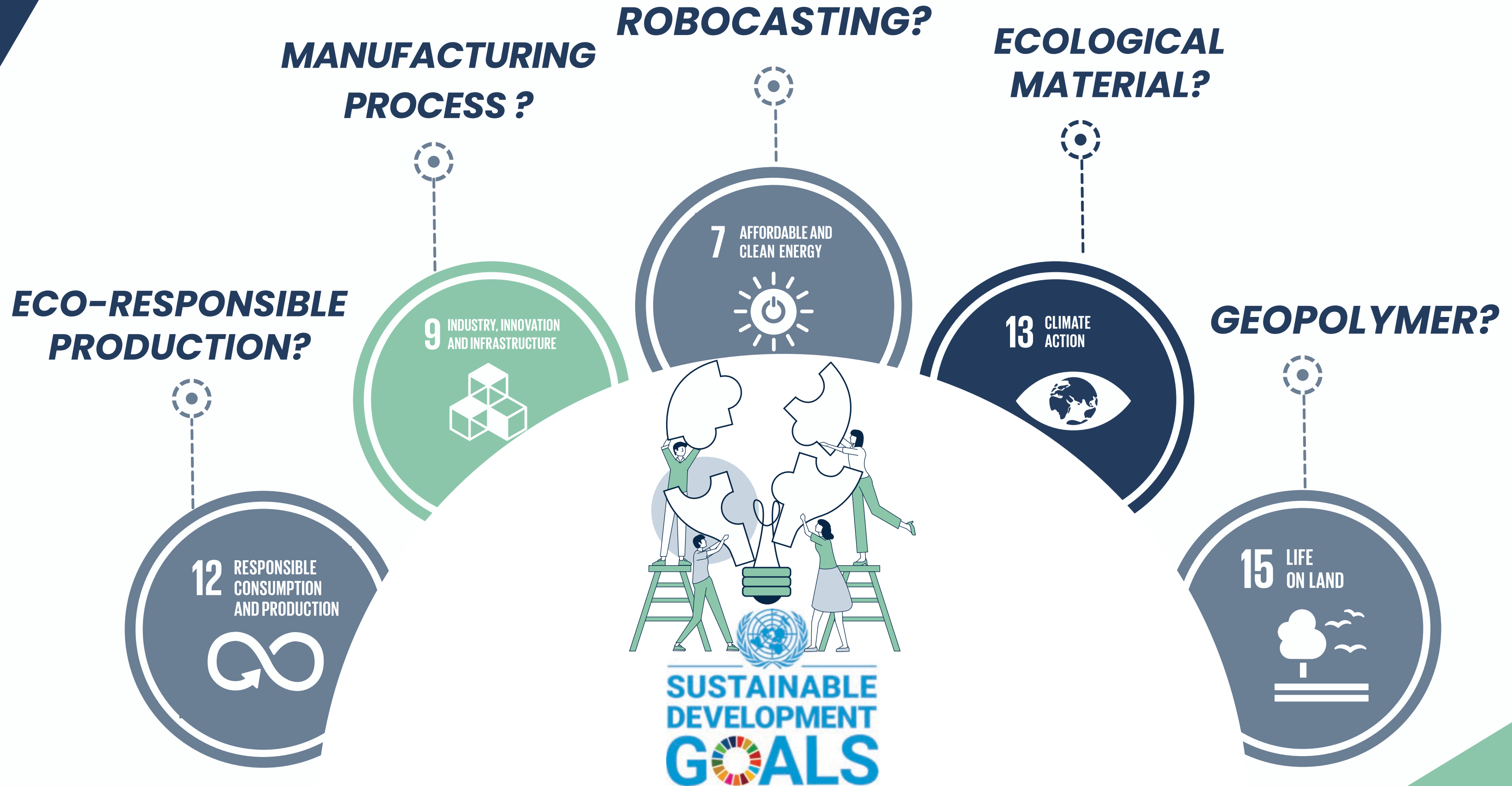
**ECO-RESPONSIBLE  
PRODUCTION?**



# CONTEXT

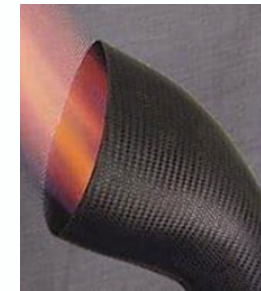


# CONTEXT



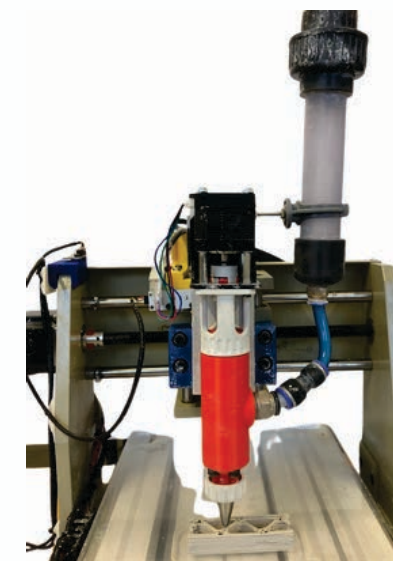


# CHALLENGES



## **GEOFAB**

**Physical and chemical properties tailored for catalysis and forming applications.**

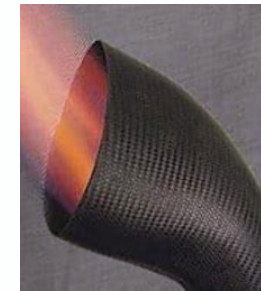


# CHALLENGES



## **RHEOLOGICAL PROPERTIES**

Achieving the ideal viscosity and thixotropy of the formula for 3D Printing.



## **GEOFAB**

Physical and chemical properties tailored for catalysis and forming applications.



# CHALLENGES



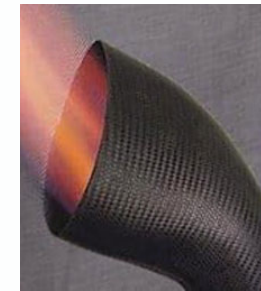
## **RHEOLOGICAL PROPERTIES**

Achieving the ideal viscosity and thixotropy of the formula for 3D Printing.



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Physical and chemical properties tailored for catalysis and forming applications.



## **PRINTER COMPATIBILITY**

Adapting the Formula to the 3D printer's extrusion system.

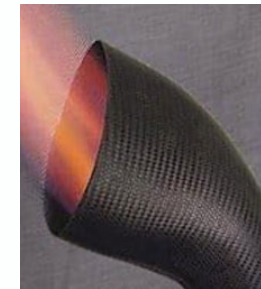


# CHALLENGES



## **RHEOLOGICAL PROPERTIES**

Achieving the ideal viscosity and thixotropy of the formula for 3D Printing.



## **GEOFAB**

Physical and chemical properties tailored for catalysis and forming applications.



## **POST-PROCESSING**

Addressing post-processing steps to enhance the final properties.



## **PRINTER COMPATIBILITY**

Adapting the Formula to the 3D printer's extrusion system.

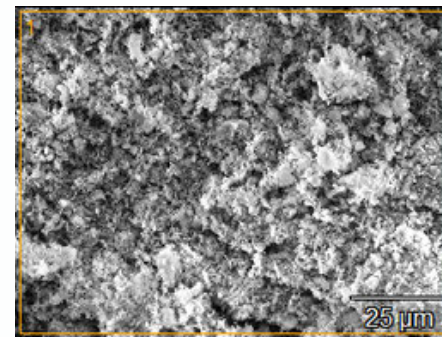
# MATERIAL CHARACTERIZATION



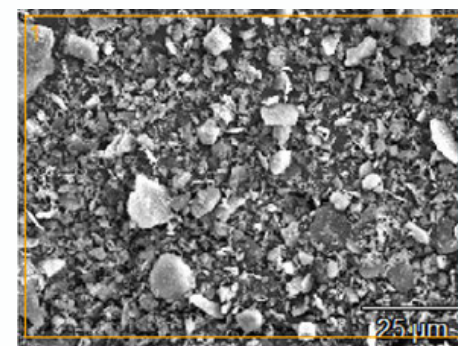
# MATERIAL CHARACTERIZATION

## Metakaolin Selection

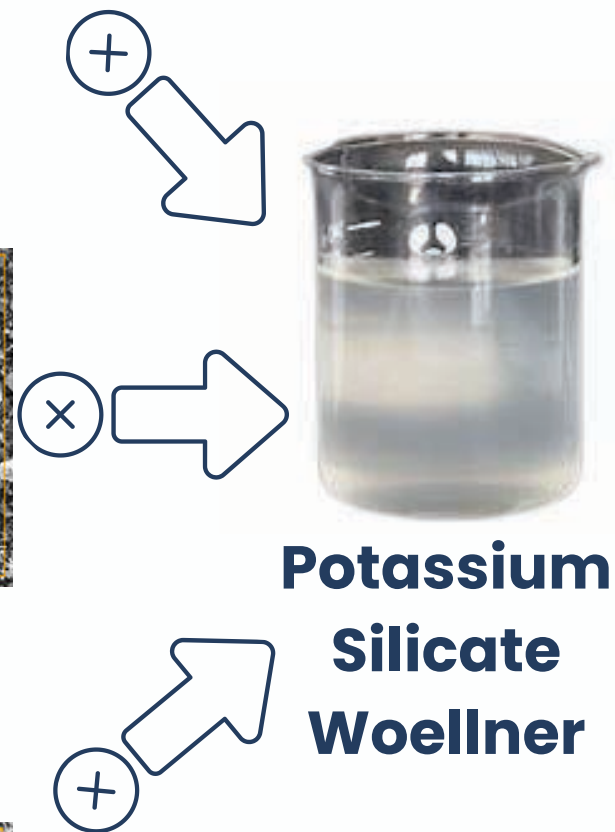
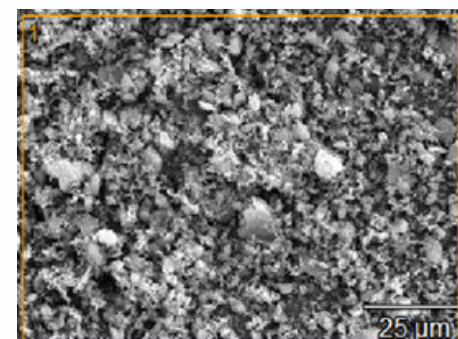
Tempozz M88  
d50=3 $\mu$ m



Metamax  
d50=4 $\mu$ m



M1200s  
d50=2 $\mu$ m

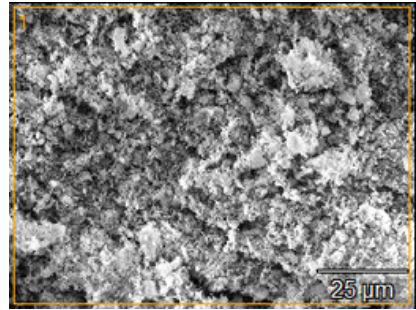


Potassium  
Silicate  
Woellner

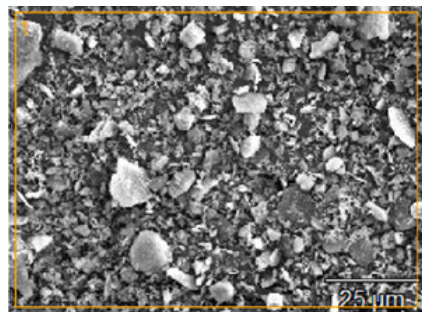
## Fillers Selection

### Metakaolin Selection

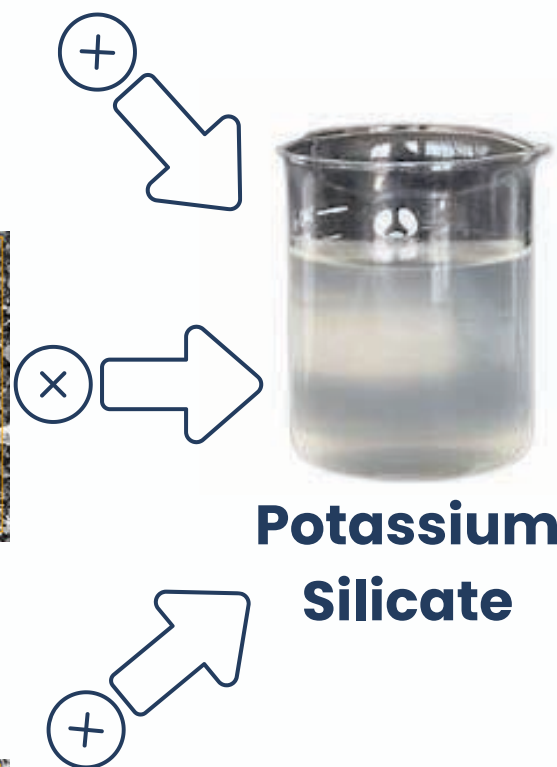
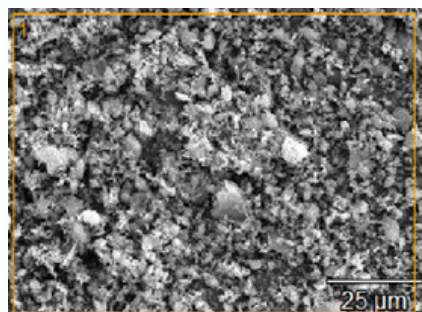
Tempozz M88  
d50=3µm



Metamax  
d50=4µm

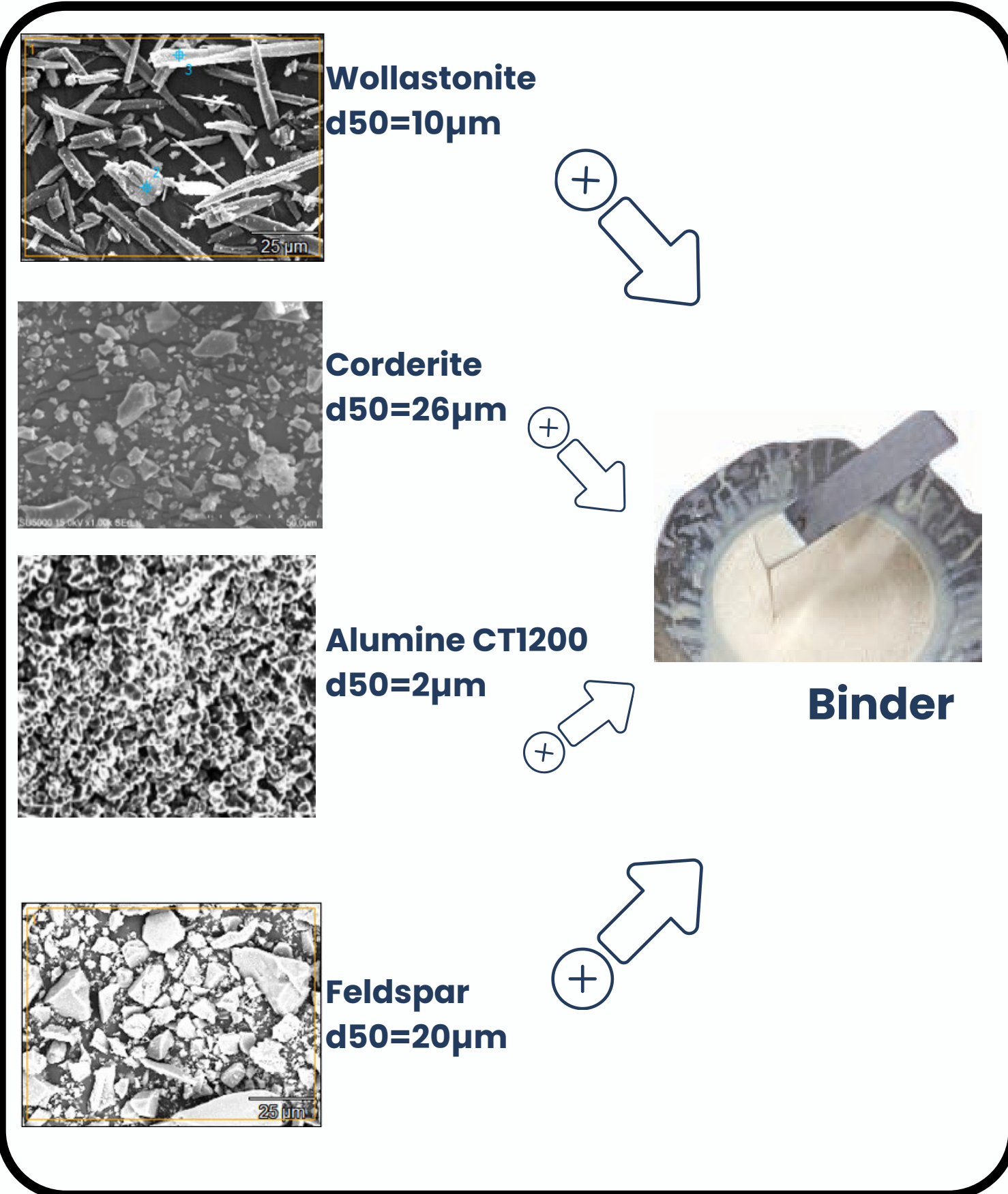


M1200s  
d50=2µm



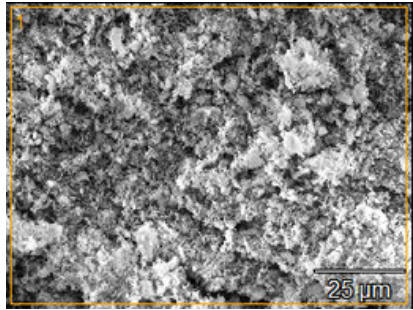
Potassium Silicate

NEXT >>

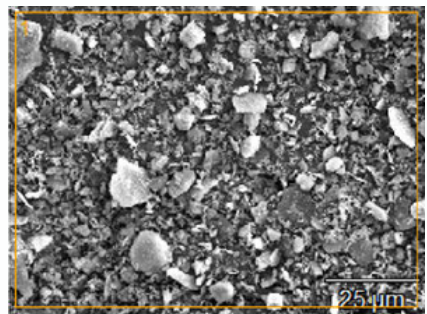


## Metakaolin Selection

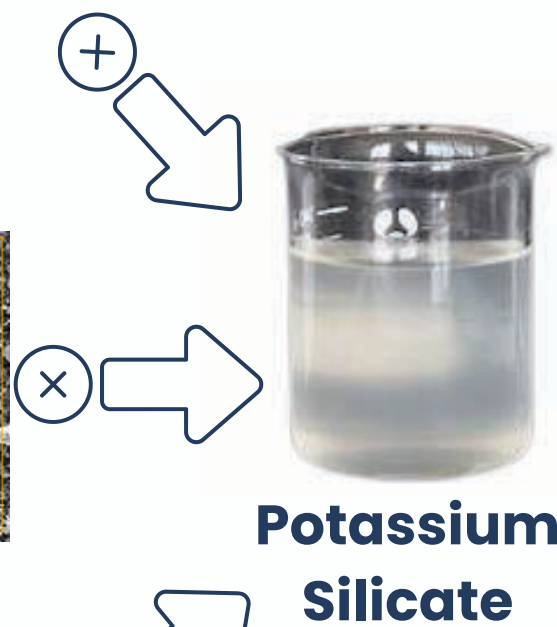
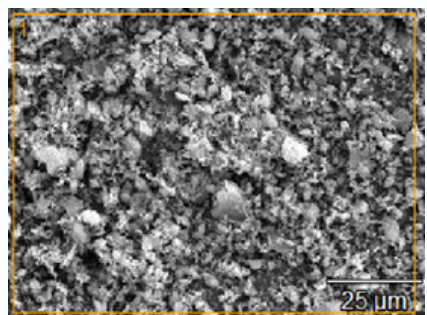
Tempozz M88  
d50=3µm



Metamax  
d50=4µm



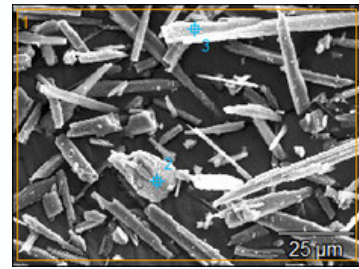
M1200s  
d50=2µm



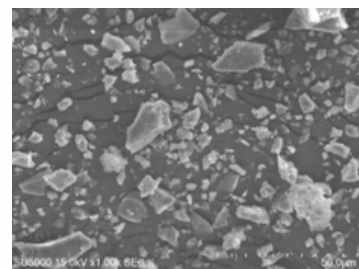
Potassium  
Silicate



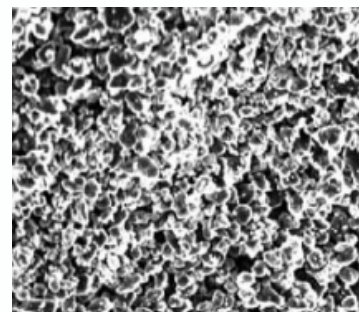
## Fillers Selection



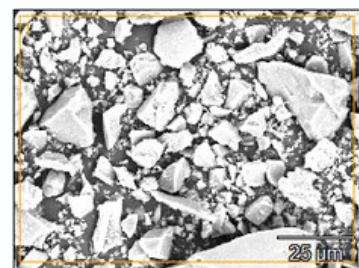
Wollastonite  
d50=10µm



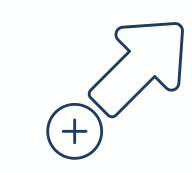
Corderite  
d50=26µm



Alumine CT1200  
d50=2µm



Feldspar  
d50=20µm

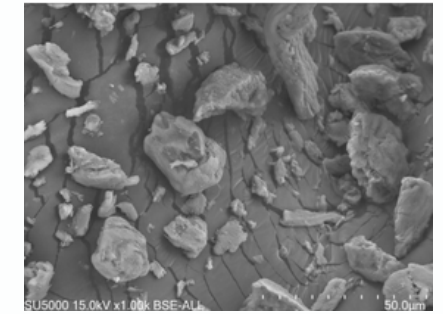


Binder

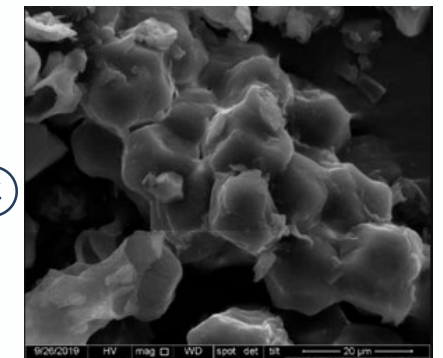


## Additive Selection

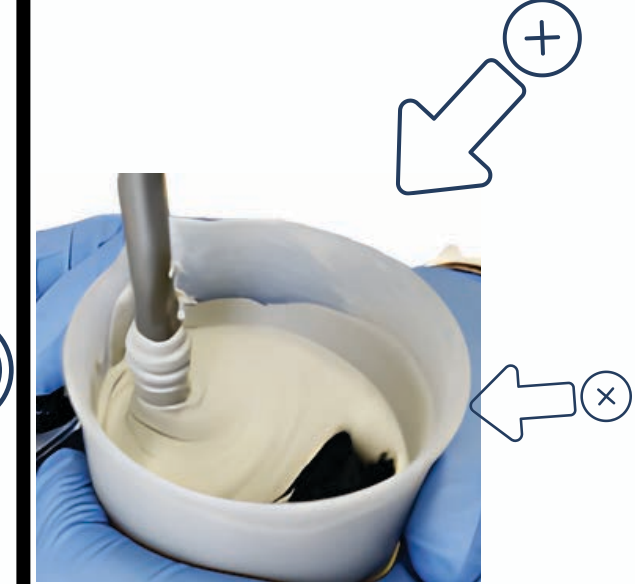
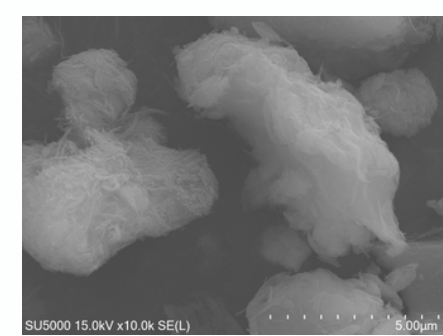
Xanthan Gum  
d50=25µm



PEG4000  
d50=28.8µm



Sepiolite  
d50=4.49µm



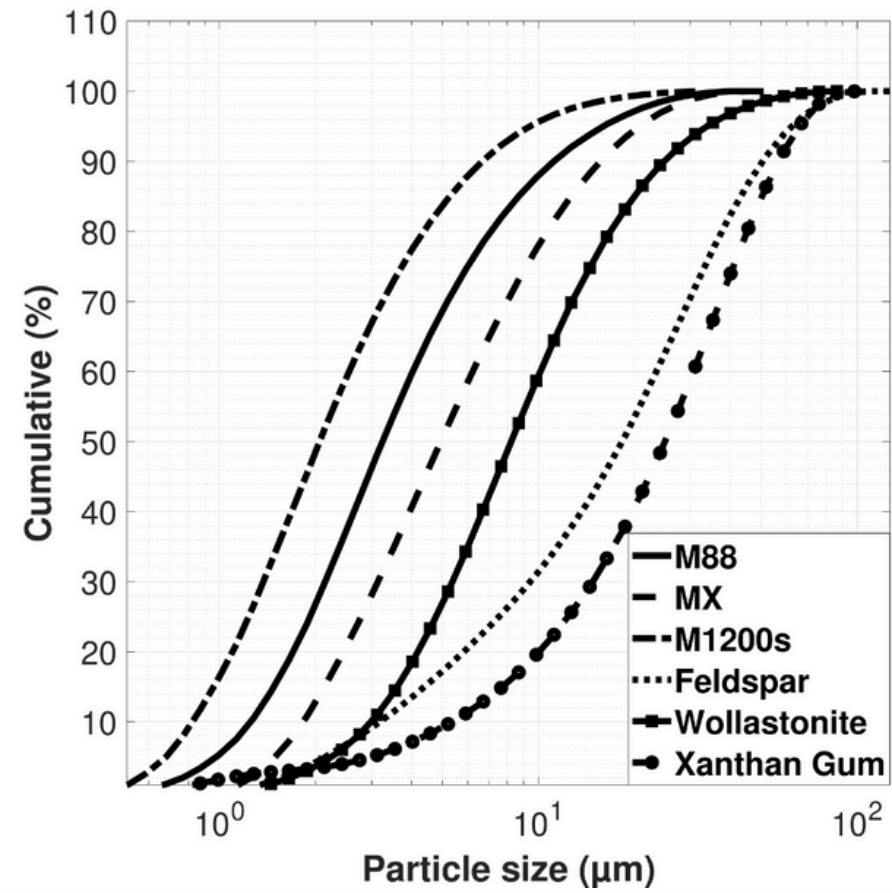


# RHEOLOGICAL CHARACTERIZATION



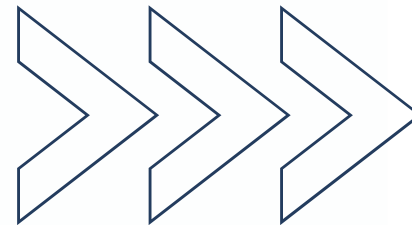
# BINDERS CHARACTERIZATION

Particle size distribution of raw materials

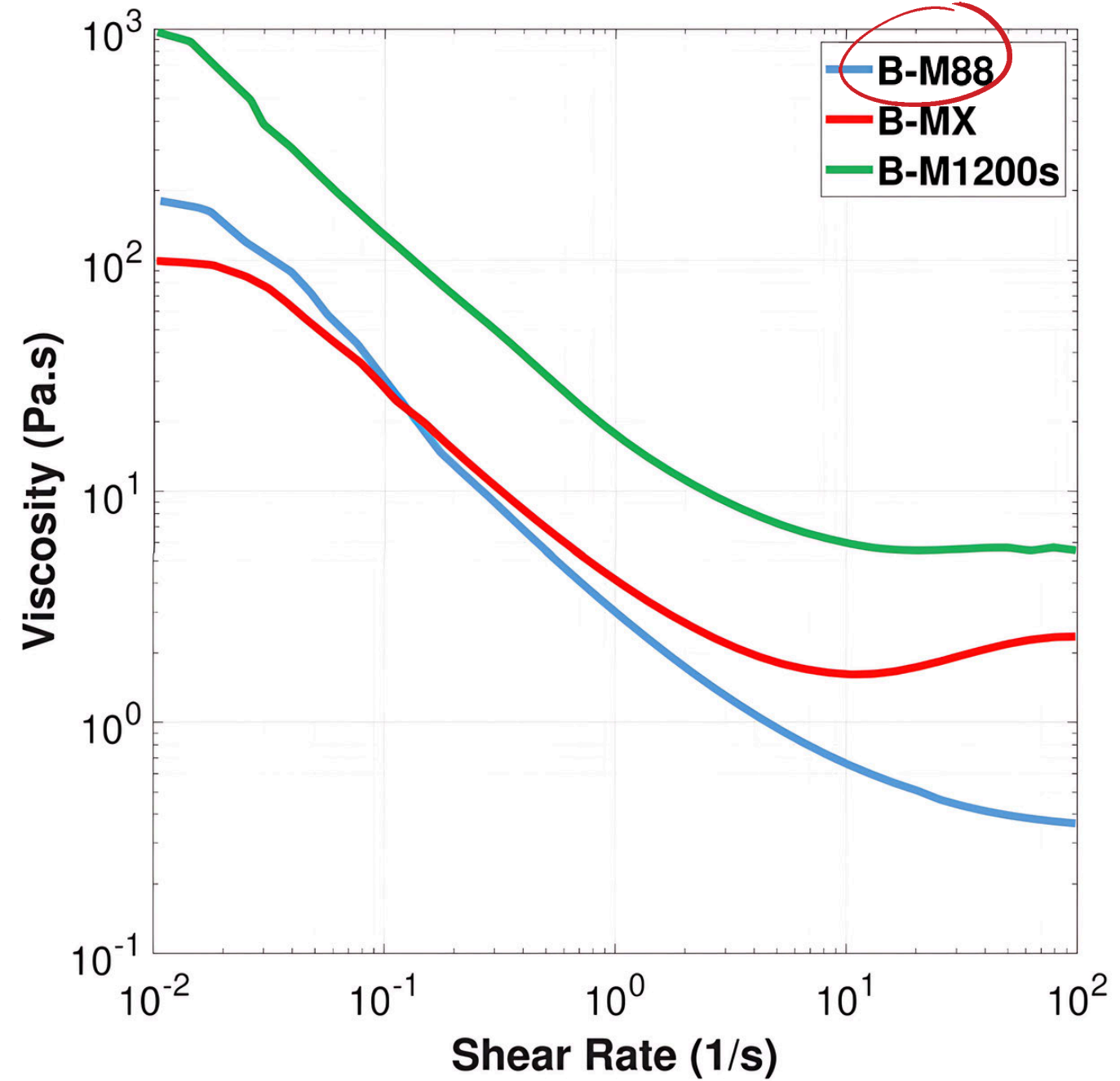


Specific Surface Area

Metakaolin	Specific Surface Area (m <sup>2</sup> /g)
M1200s	29.673
Tempozz M88	25.104
Metamax	22.864



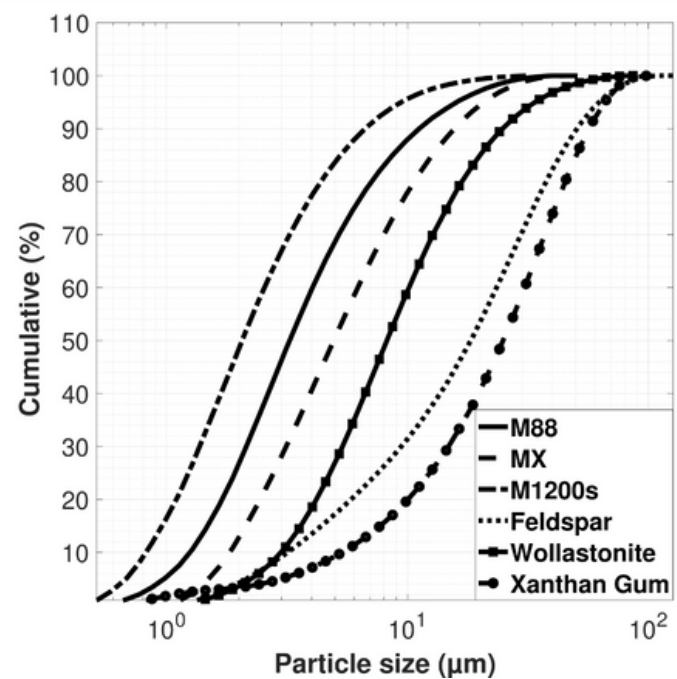
Viscosity Test



• More fillers = less shrinkage

# BINDERS CHARACTERIZATION

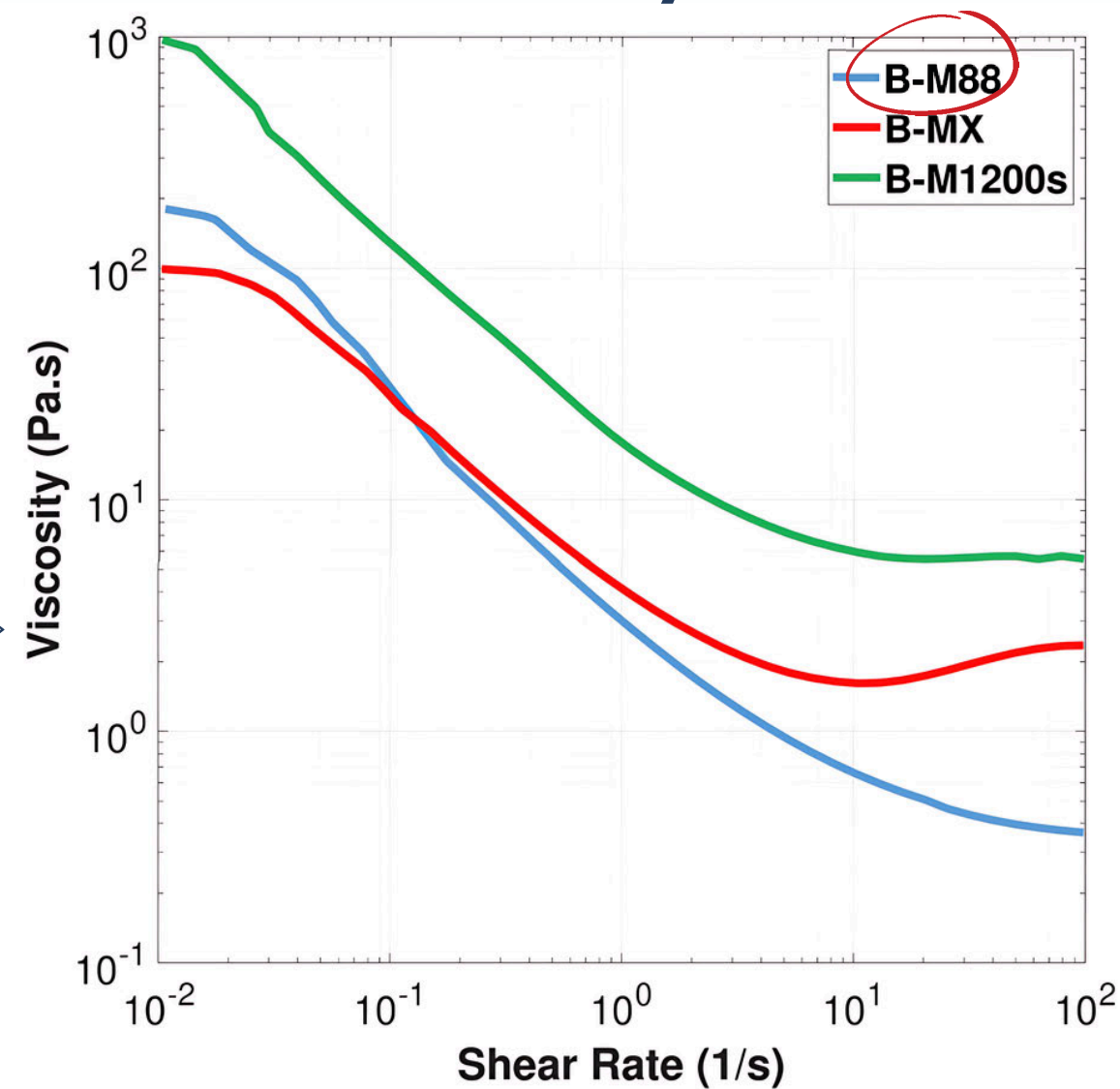
Particle size distribution of raw materials



Specific Surface Area

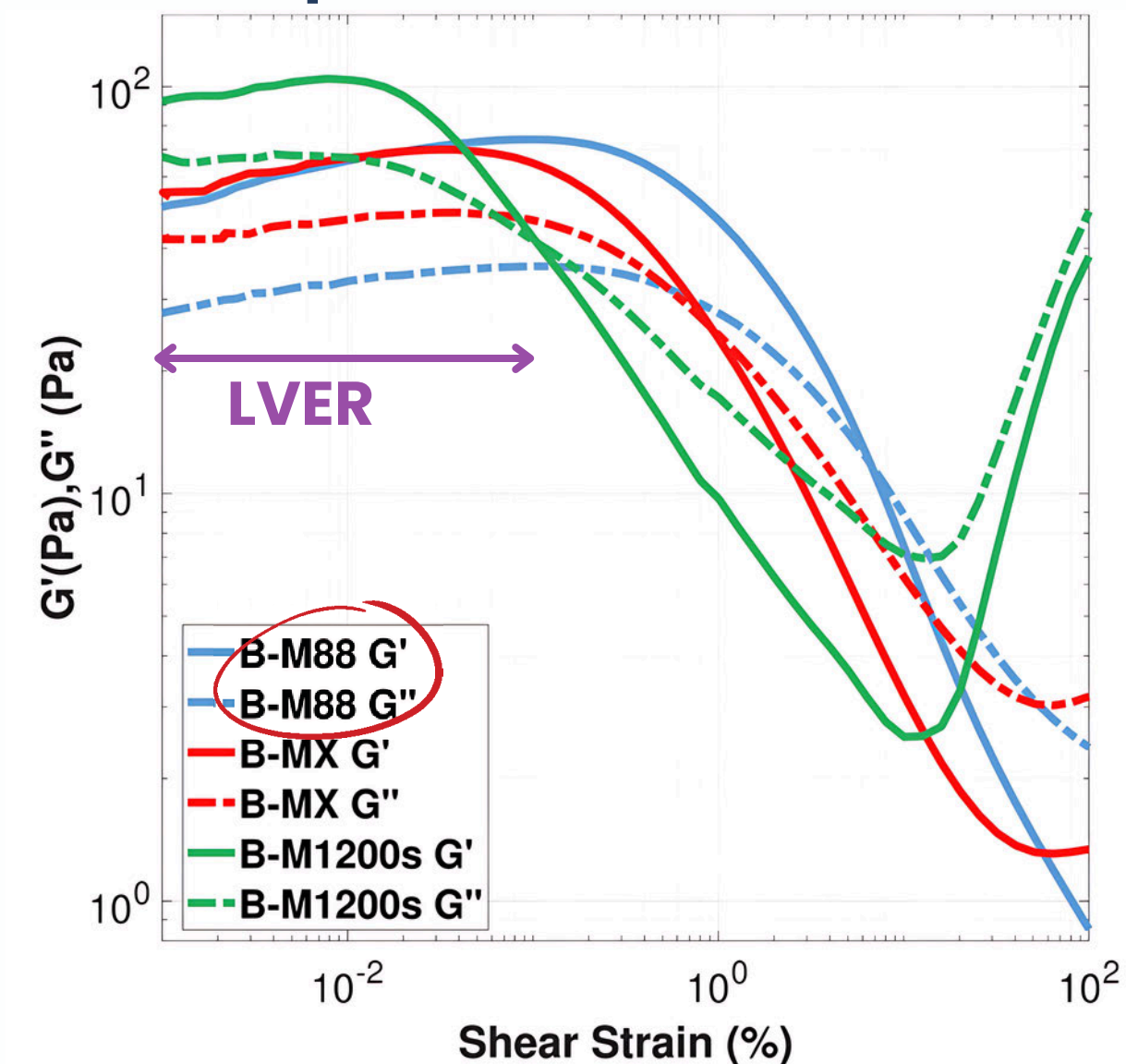
Metakaolin	Specific Surface Area (m <sup>2</sup> /g)
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## Viscosity Test



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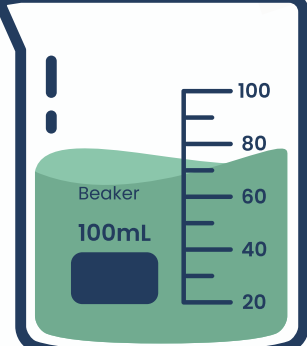

## Amplitude Oscillation Test



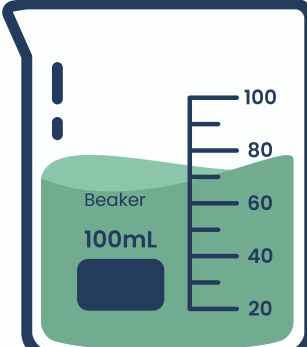

• Greater LVER

# FORMULA OPTIMIZATION

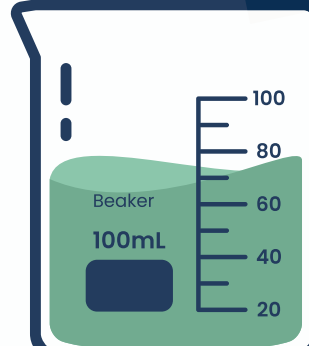

## FILLERS



**40% fillers**  
**GP-F**  
**100% Feldspar**


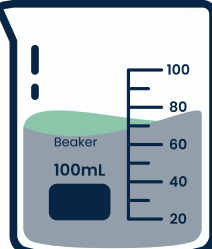


**40% Fillers**  
**GP-FW**  
**80% Feldspar**  
**20% Wollastonite**


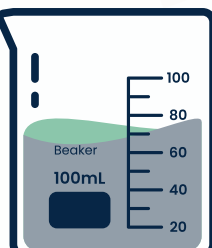


**55% Fillers**  
**GP-FWMax**  
**80% Feldspar**  
**20% Wollastonite**

# FORMULA OPTIMIZATION


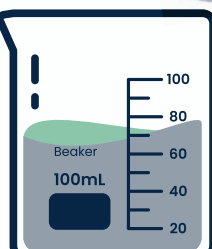



**40% fillers**  
**GP-F**  
**100% Feldspar**

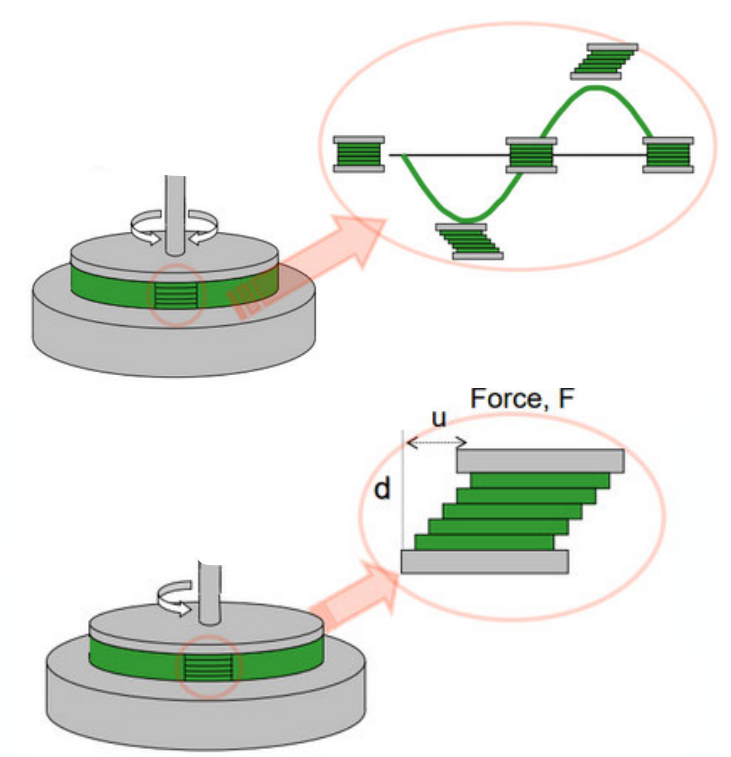



**40% Fillers**  
**GP-FW**  
**80%Feldspar**  
**20% Wollastonite**

NEXT >>


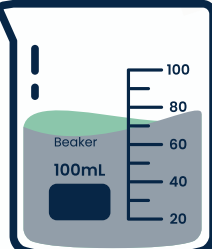
**55% Fillers**  
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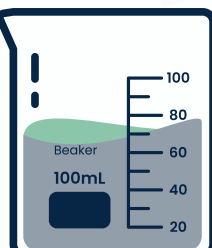
Rheology

# FORMULA OPTIMIZATION


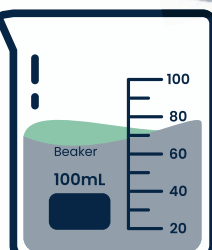
## ADDITIVES

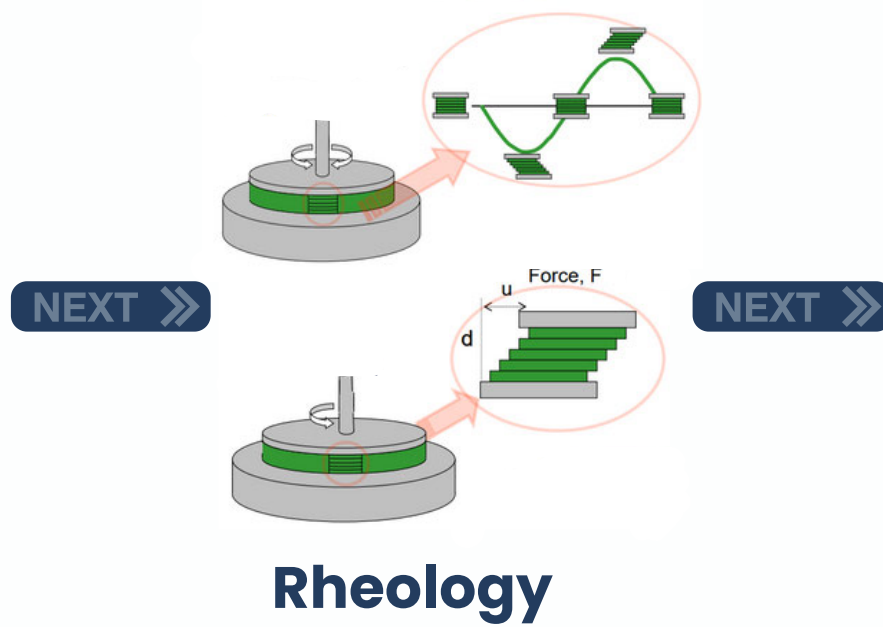
**40% fillers**  
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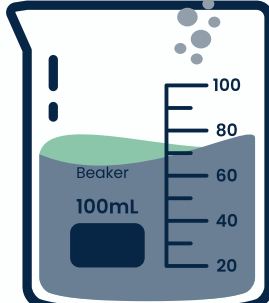



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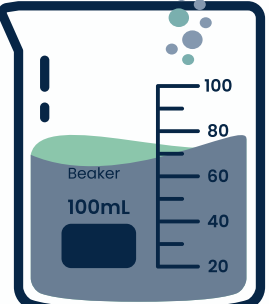




**0.35wt% Xanthan Gum**


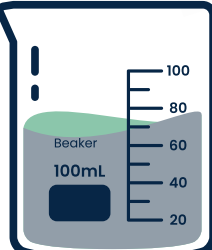



**3wt% Sepiolite**


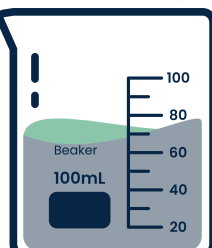



**2wt% PEG4000**


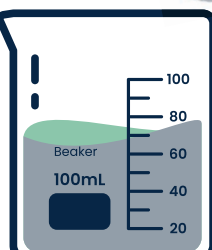
# FORMULA OPTIMIZATION

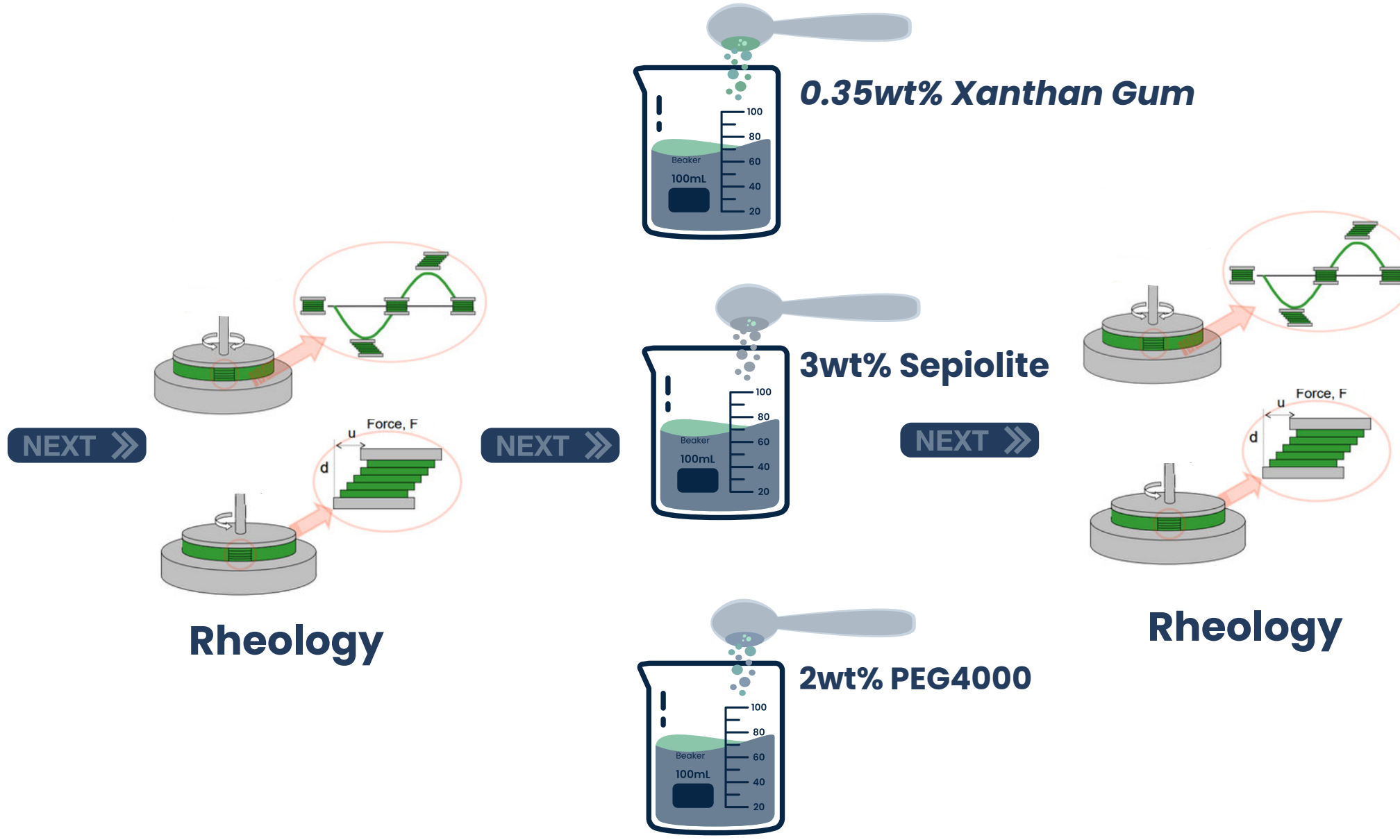
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**100% Feldspar**

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# FORMULA OPTIMIZATION

## FILLERS

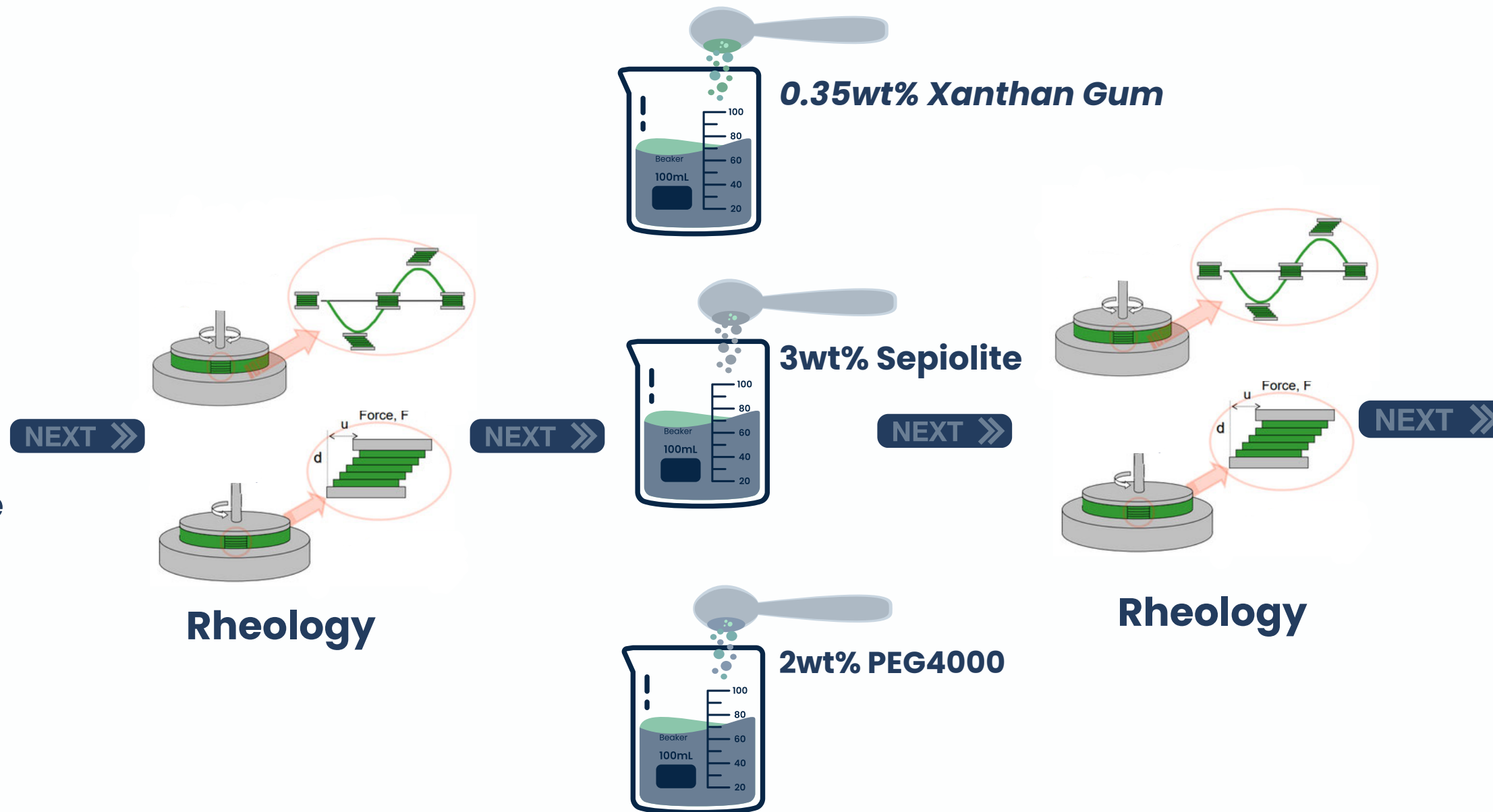
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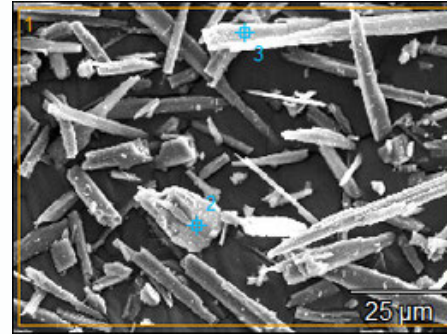


**3D Printing**

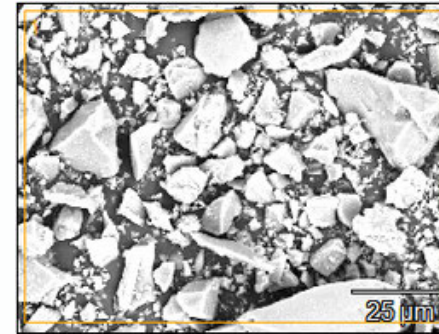


# RHEOLOGY - FILLERS

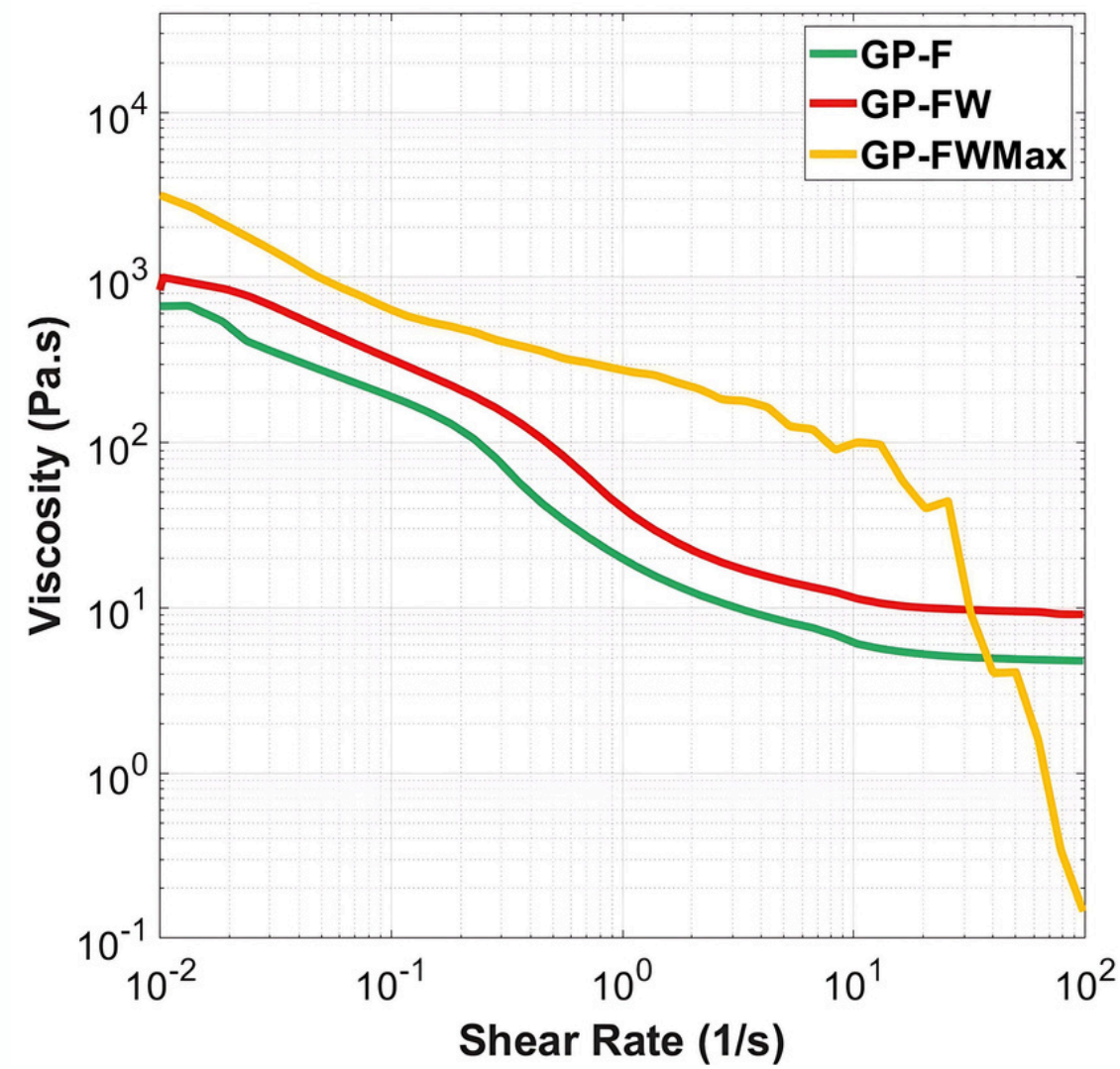
MEB Wollastonite



MEB Feldspar

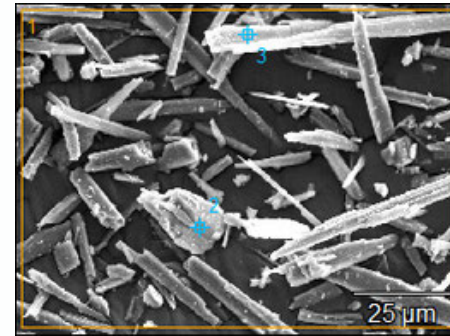


Viscosity Test

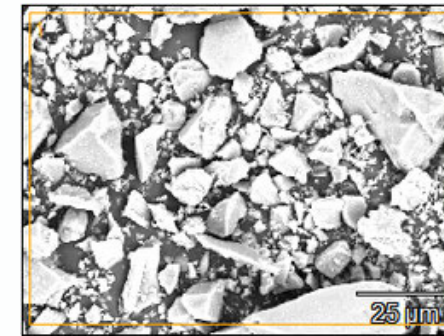


# RHEOLOGY - FILLERS

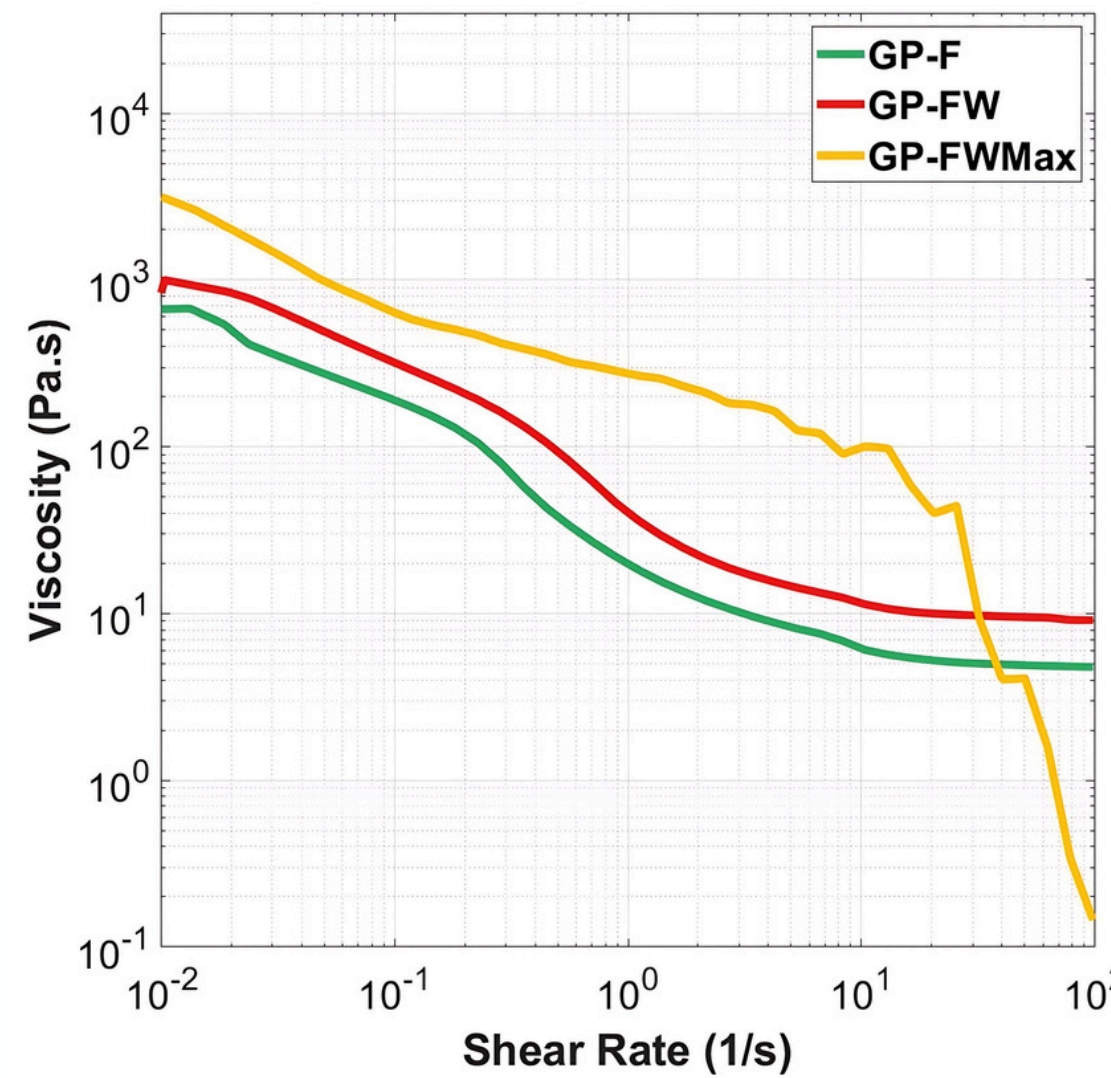
MEB Wollastonite



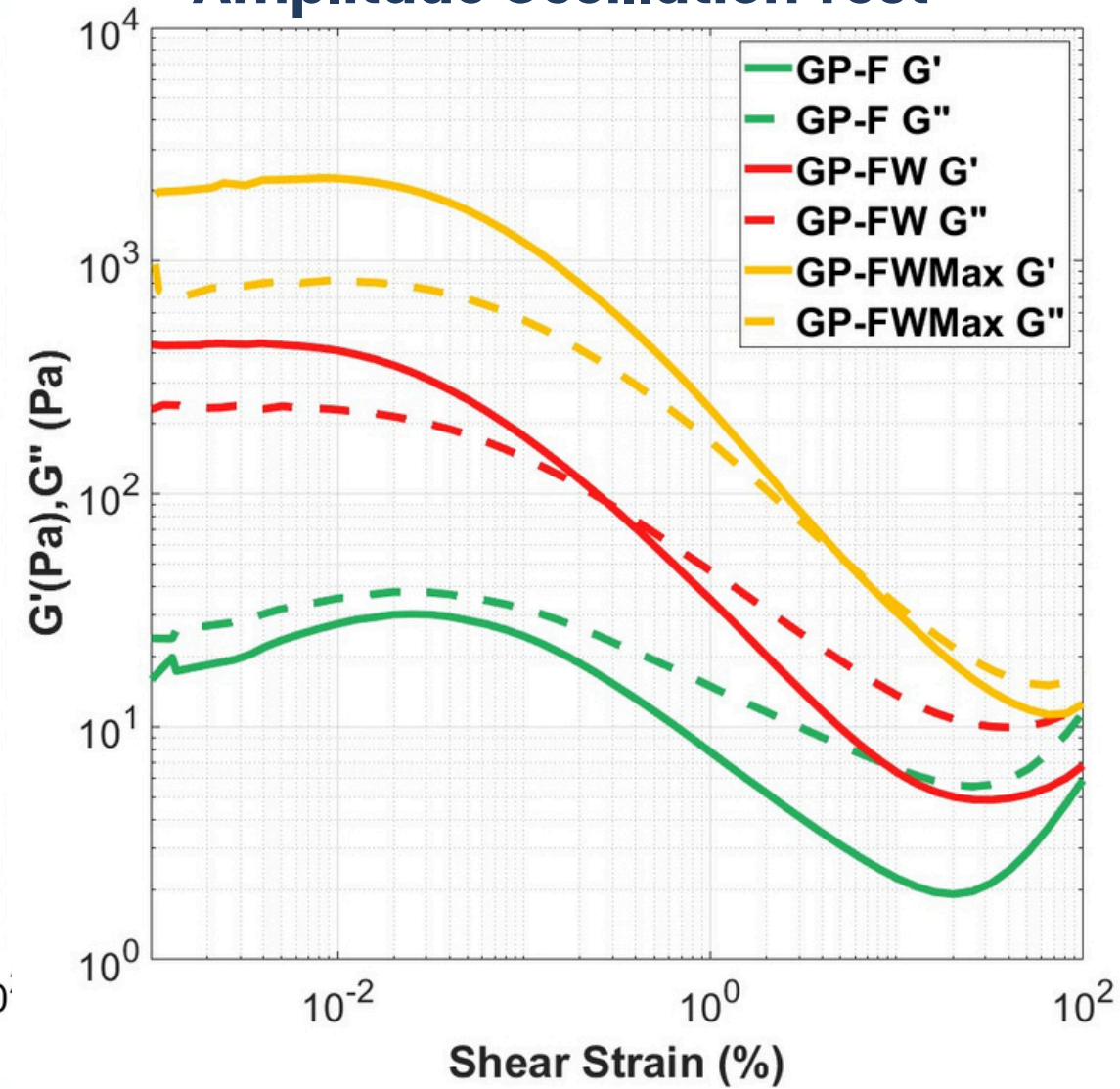
MEB Feldspar



Viscosity Test

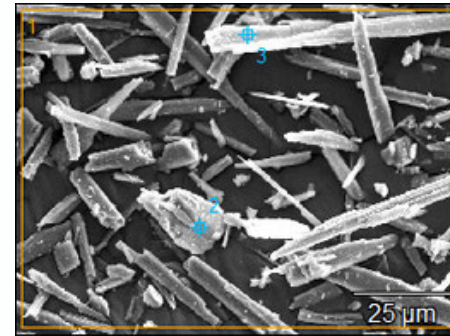


Amplitude Oscillation Test

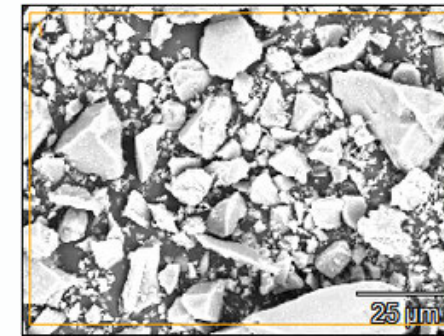


# RHEOLOGY - FILLERS

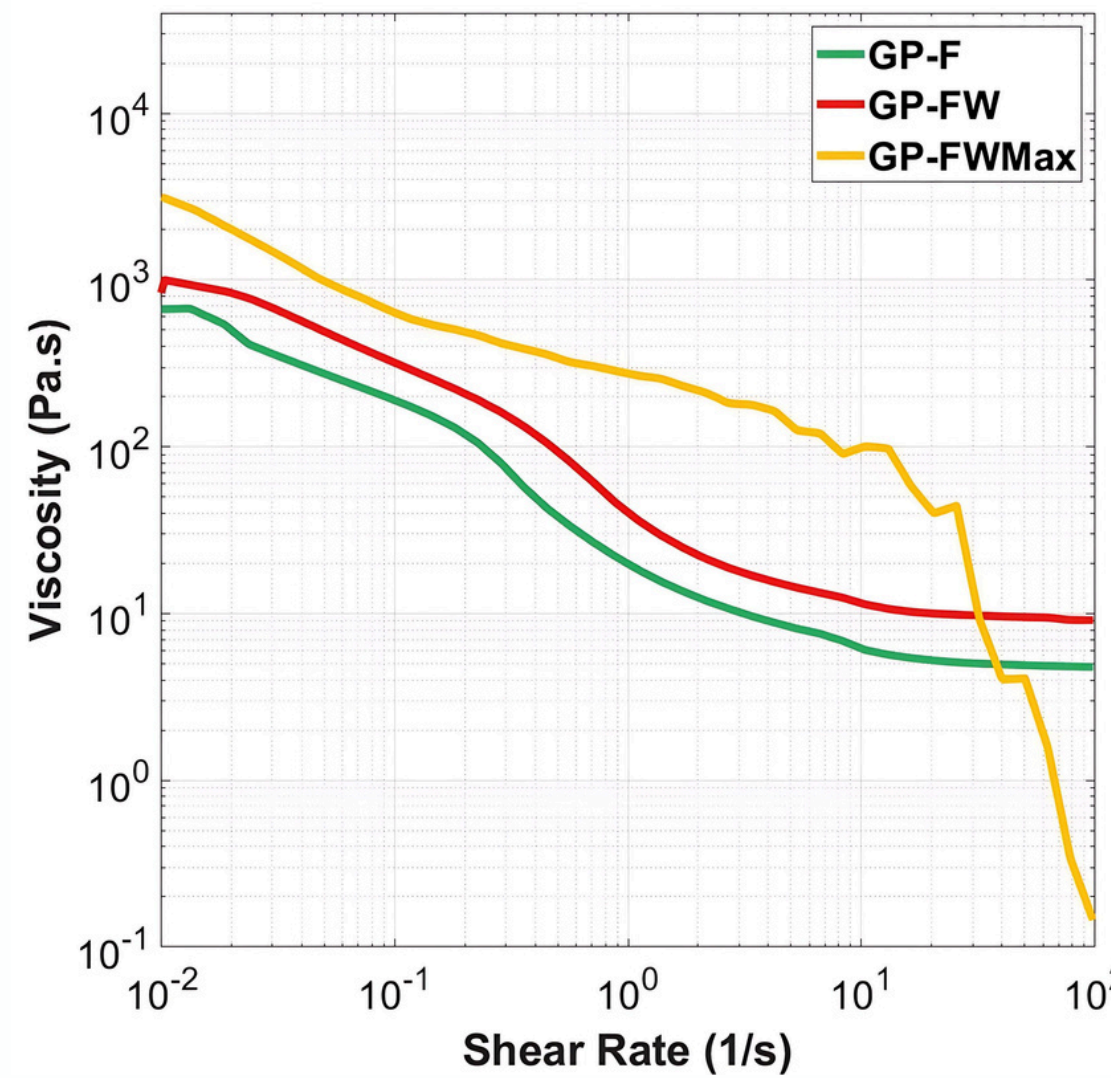
MEB Wollastonite



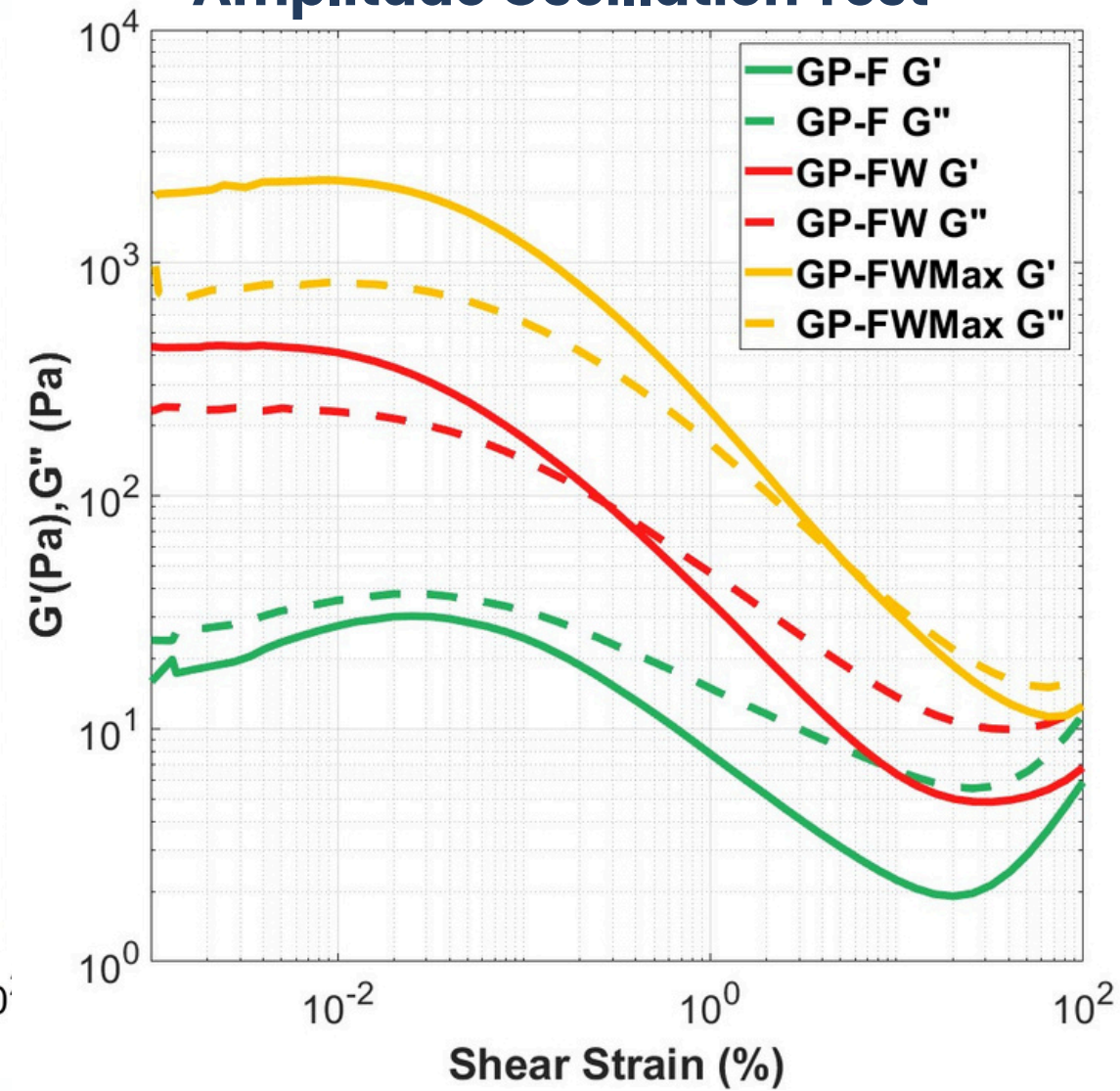
MEB Feldspar



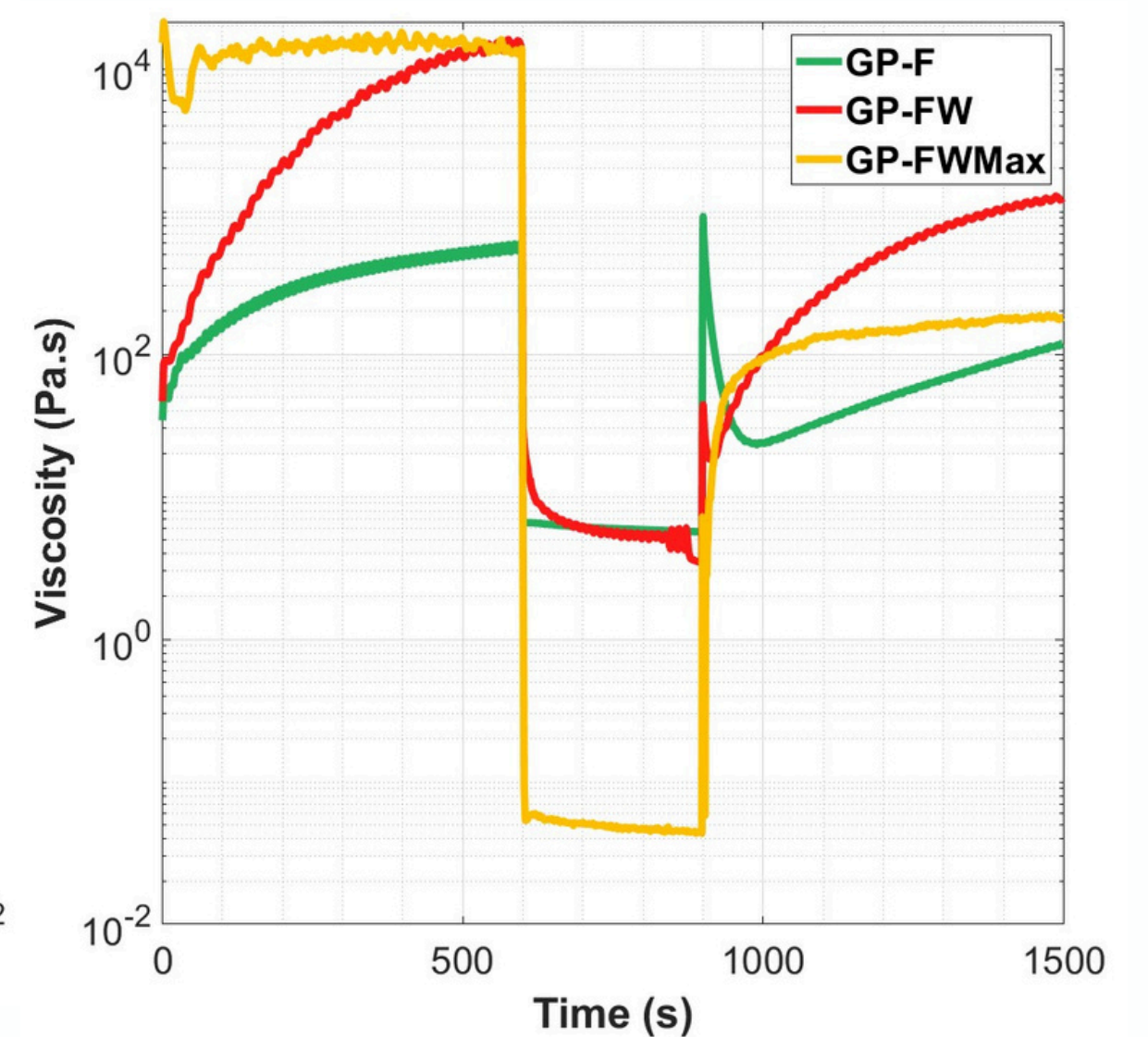
Viscosity Test



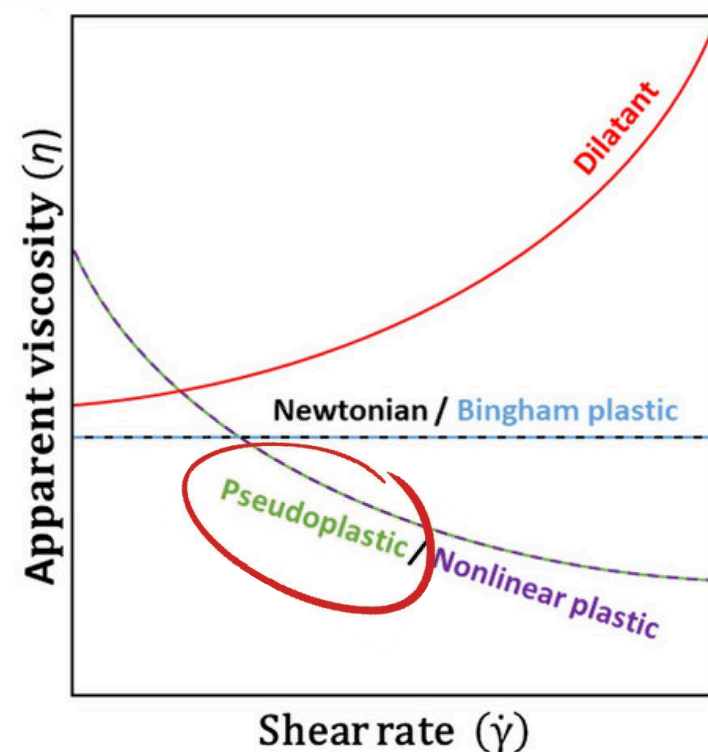
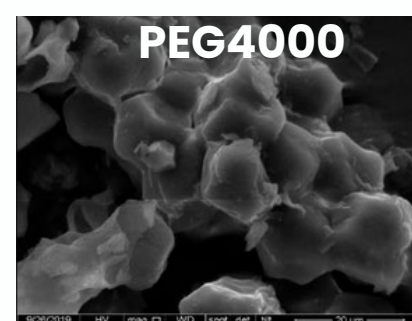
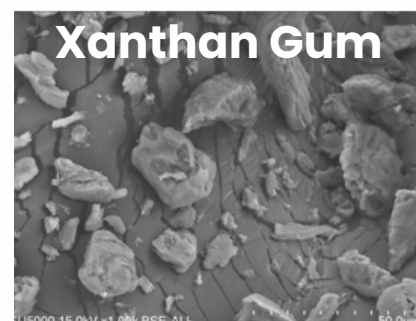
Amplitude Oscillation Test



Thixotropy Test

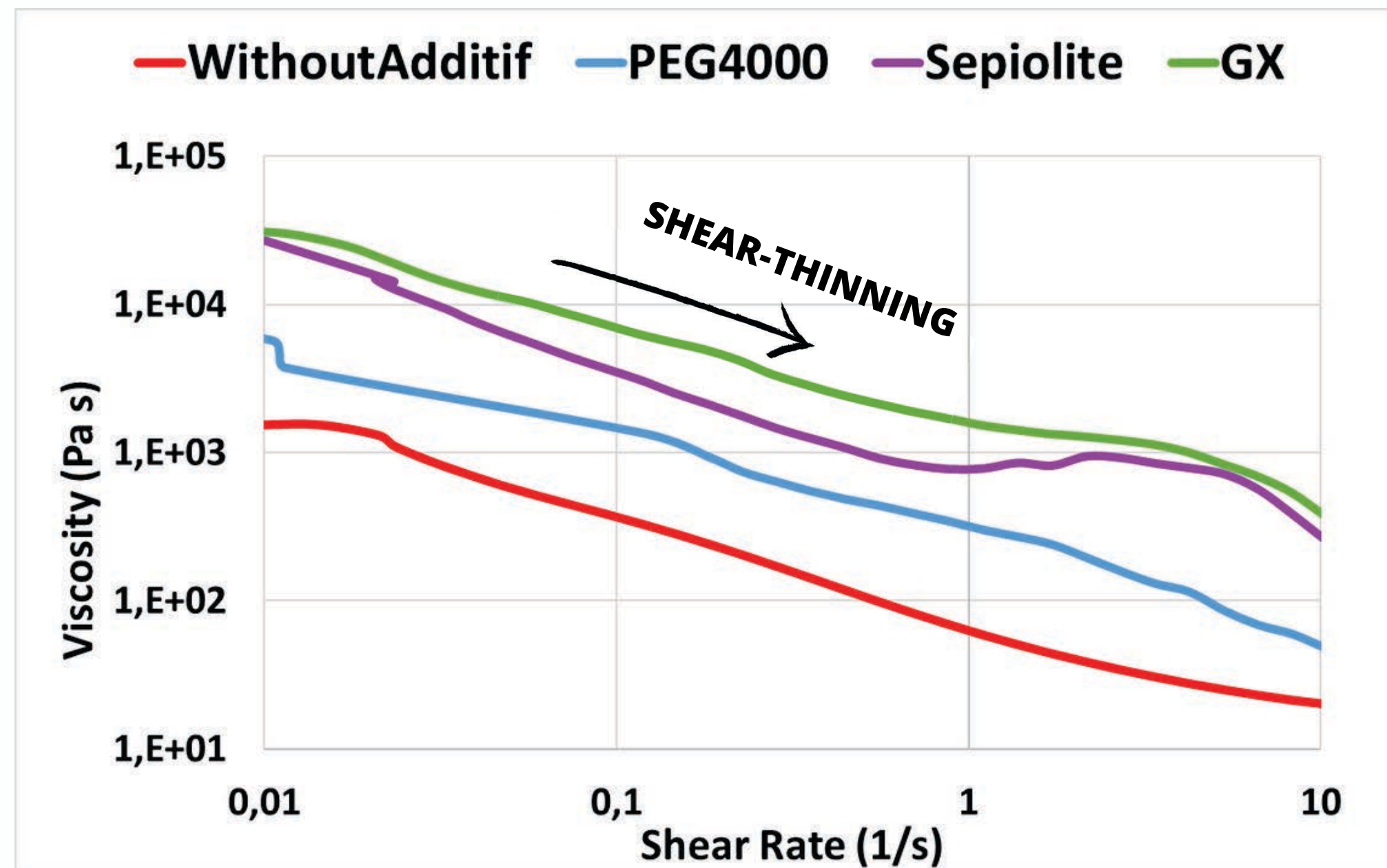
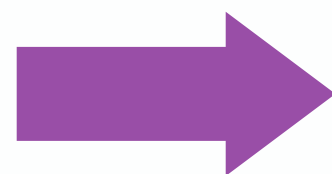


# RHEOLOGY - ADDITIVES



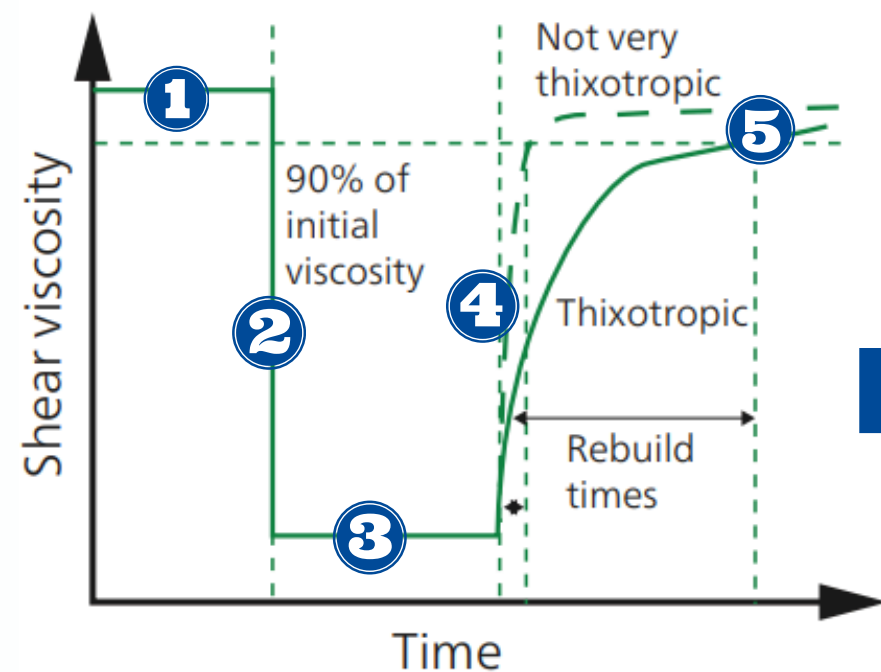
**Viscosity behavior**

**POWER LAW**  
 $\eta = K (\dot{\gamma})^{n-1}$   
 $n < 0.6$  : Subtle Shear-Thinning  
 $n < 0.2$  : Highly Pronounced Shear-Thinning

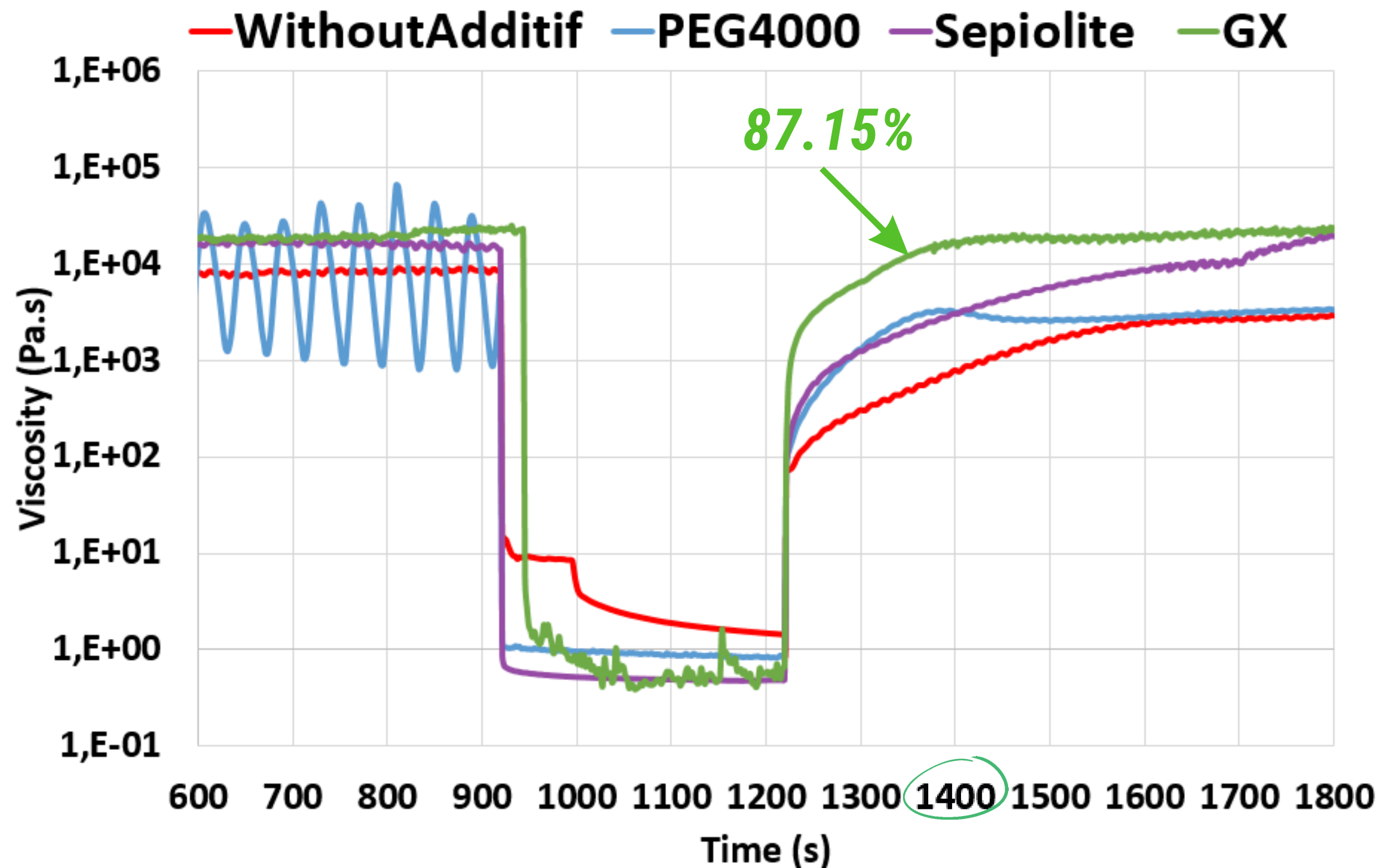


**Viscosity behavior of geopolymer formula with different additives**

# RHEOLOGY - ADDITIVES



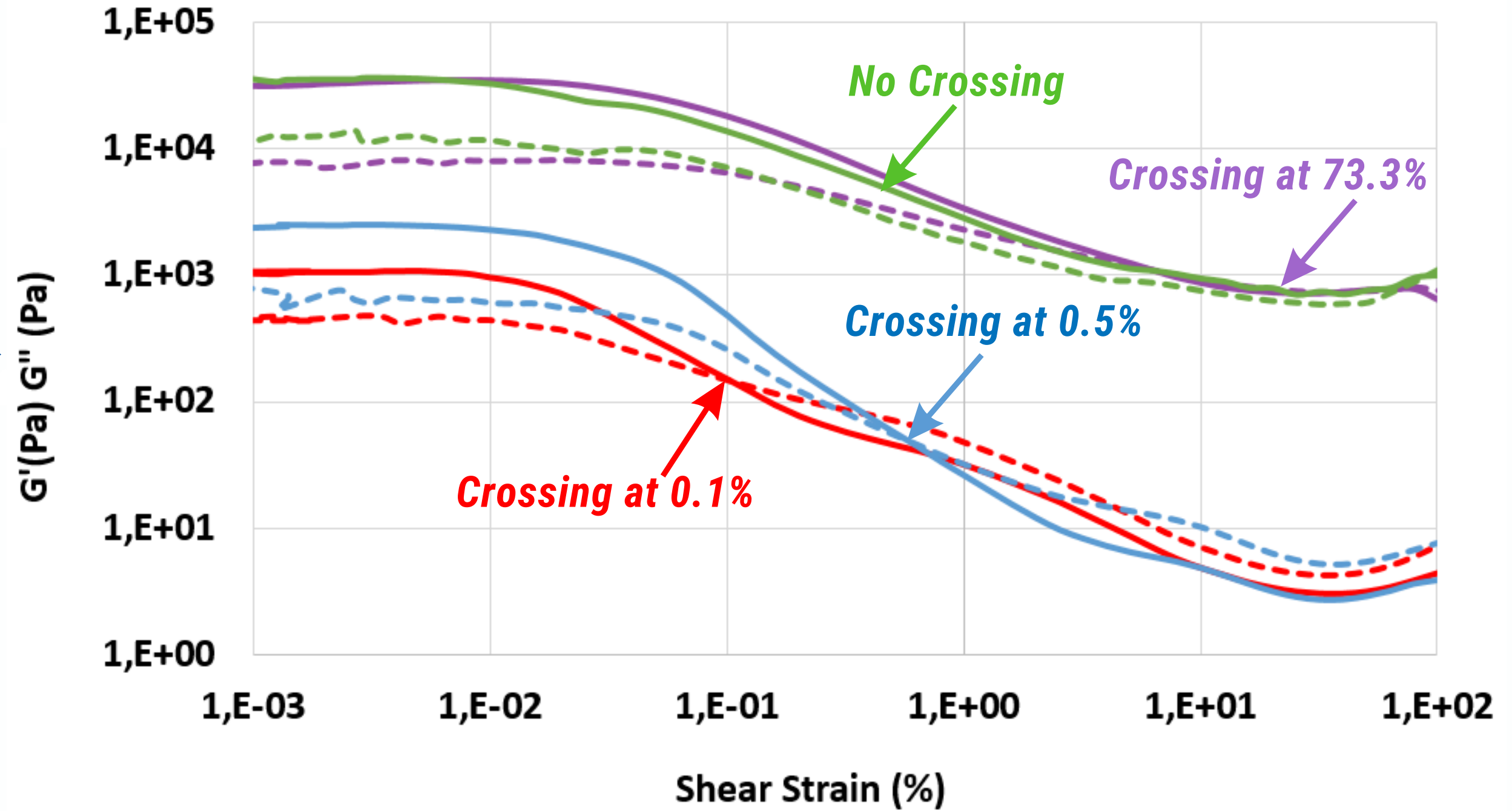
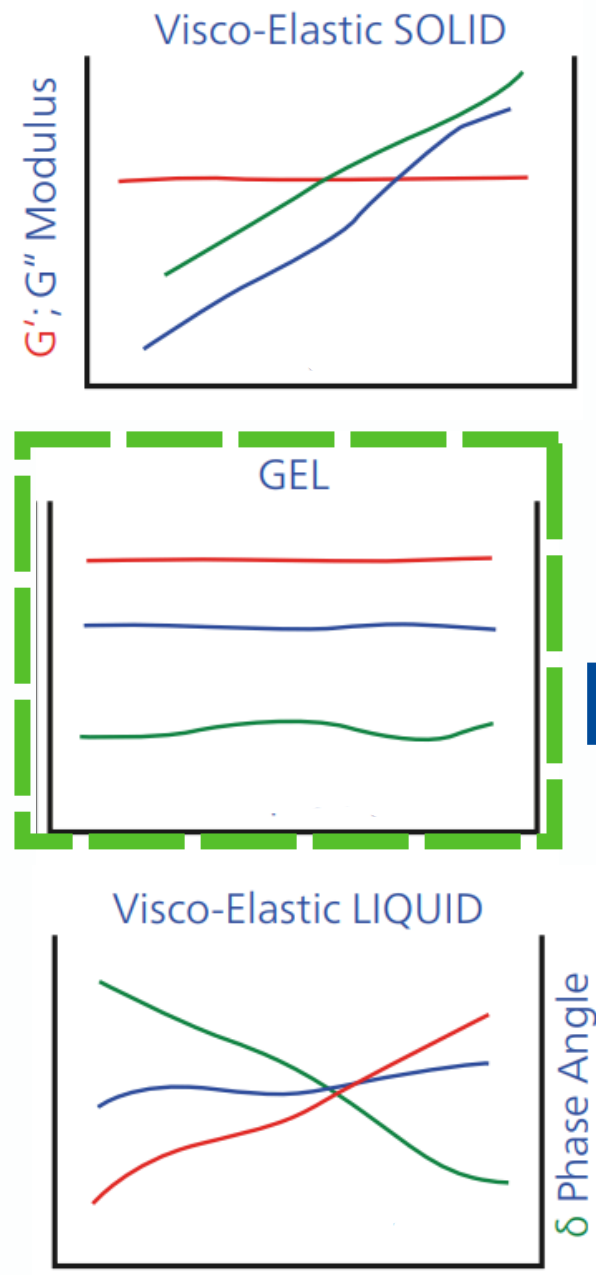
**Step shear rate test for thixotropy for non-thixotropic and thixotropic fluids**



**Three step Shear Rate Test**

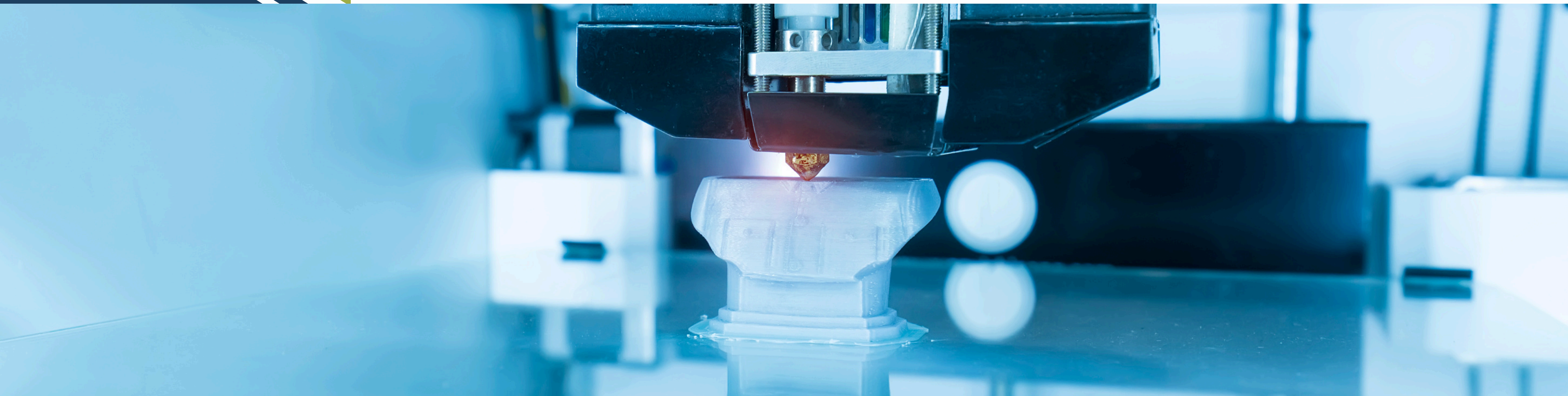
# RHEOLOGY - ADDITIVES

— Without Additif G'    - - - Without Additif G''    — PEG G'    - - - PEG G''  
— Sepiolite G'    - - - Sepiolite G''    — GX G'    - - - GX G''

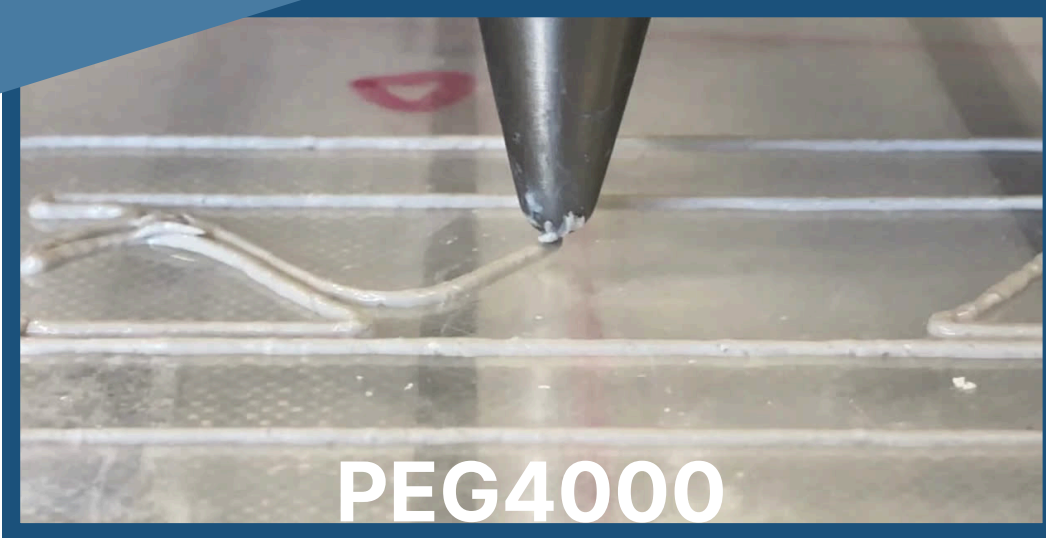


Storage modulus (G') Loss modulus (G'')

# ROBOCASTING PROCESS DEVELOPMENT



# ADDITIVES PRINTABILITY

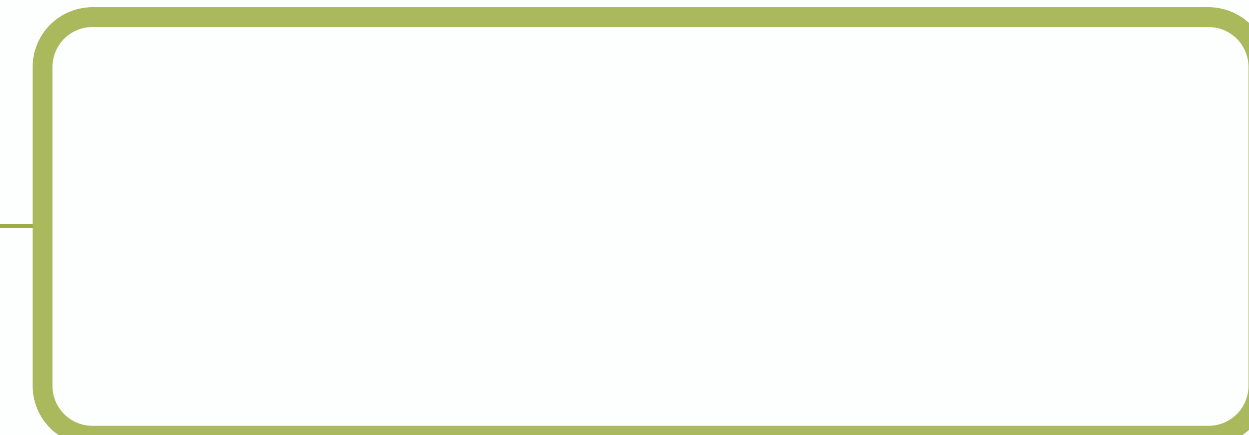
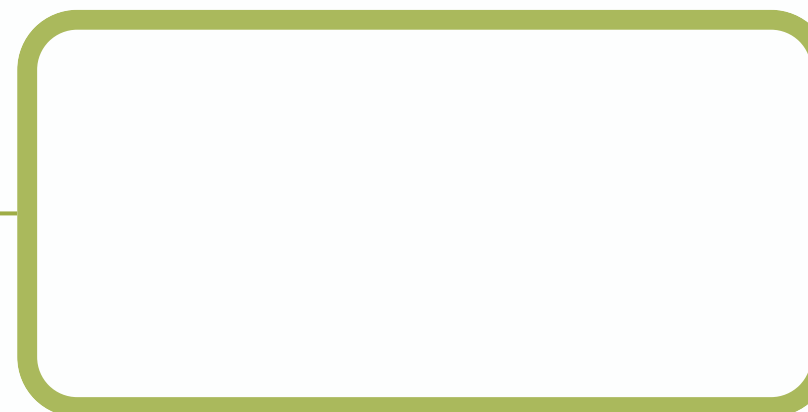
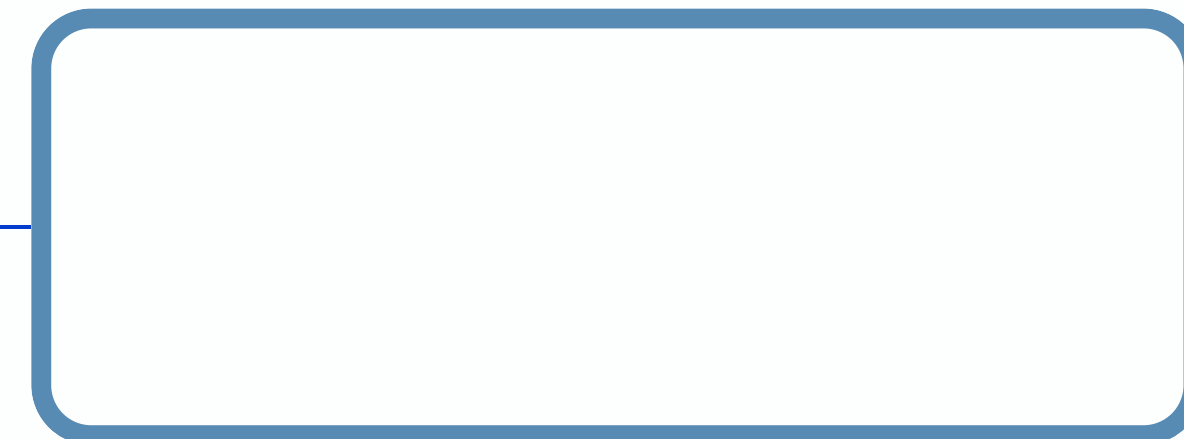
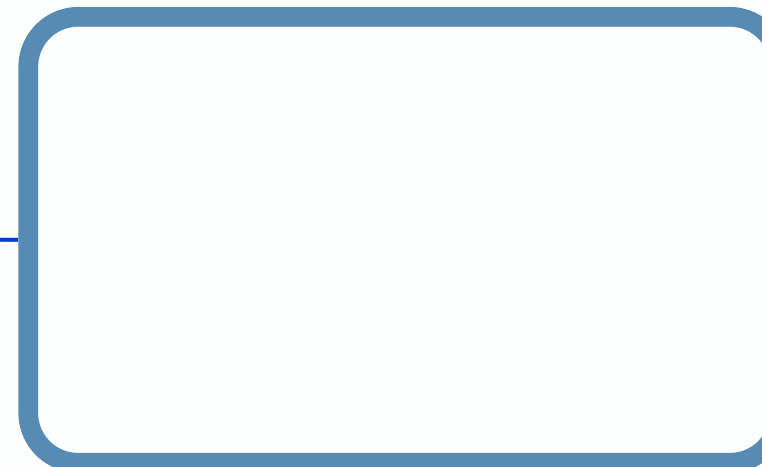


## RHEOLOGY

Viscosity = 5740Pa.s  
Recovery rate = 45.11%  
Yield Stress = 55.02%

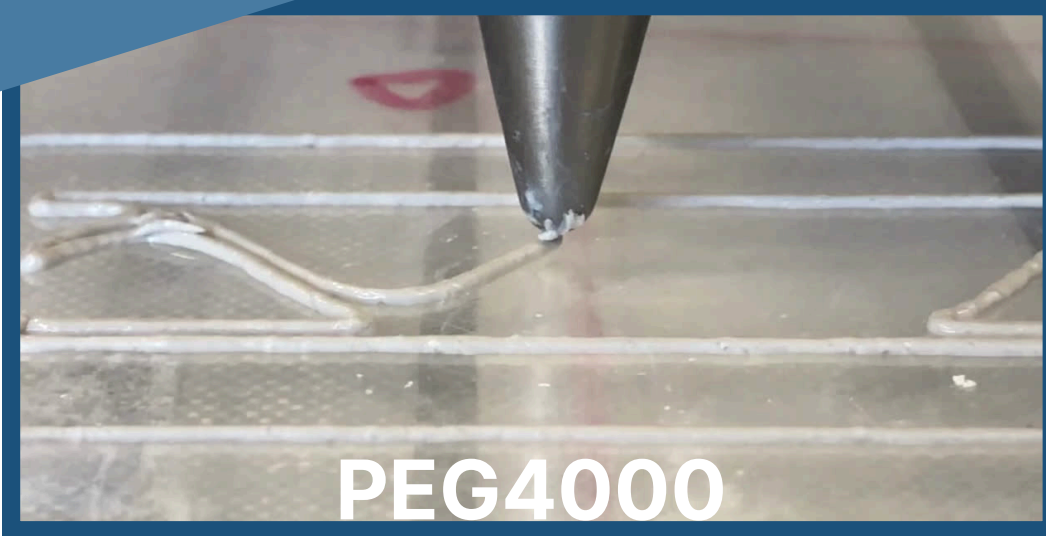
## 3D PRINTING

Extrusion Speed= 80step/mm.  
Limited print flow control.  
Significant sagging.  
Less Precision.





# ADDITIVES PRINTABILITY



## RHEOLOGY

Viscosity = 5740Pa.s  
 Recovery rate = 45.11%  
 Yield Stress = 55.02%

## 3D PRINTING

Extrusion Speed= 80step/mm.  
 Limited print flow control.  
 Significant sagging.  
 Less Precision.



Viscosity = 29740Pa.s  
 Recovery rate = 85.77%  
 Yield Stress = 722Pa

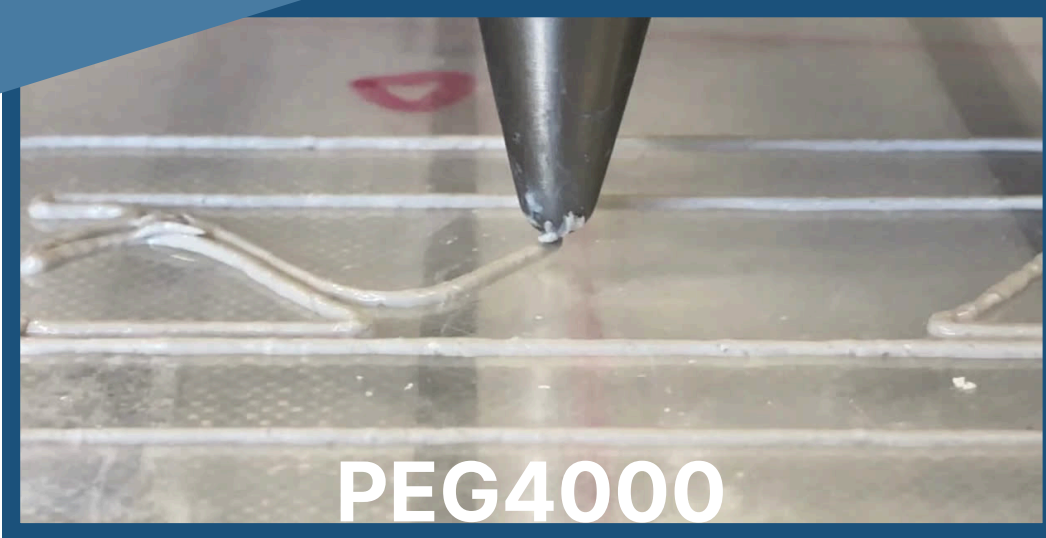
Extrusion Speed= 120step/mm.  
 Uneven Extrusion.  
 Premature Gelling.  
 Bridging Effect.



(Empty box)

(Empty box)

# ADDITIVES PRINTABILITY



## RHEOLOGY

Viscosity = 5740Pa.s  
 Recovery rate = 45.11%  
 Yield Stress = 55.02%

## 3D PRINTING

Extrusion Speed= 80step/mm.  
 Limited print flow control.  
 Significant sagging.  
 Less Precision.



Viscosity = 29740Pa.s  
 Recovery rate = 85.77%  
 Yield Stress = 722Pa

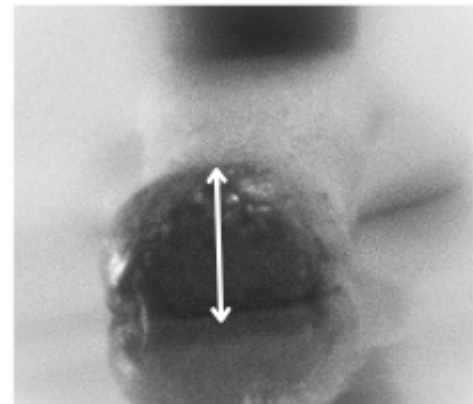
Extrusion Speed= 120step/mm.  
 Uneven Extrusion.  
 Premature Gelling.  
 Bridging Effect.



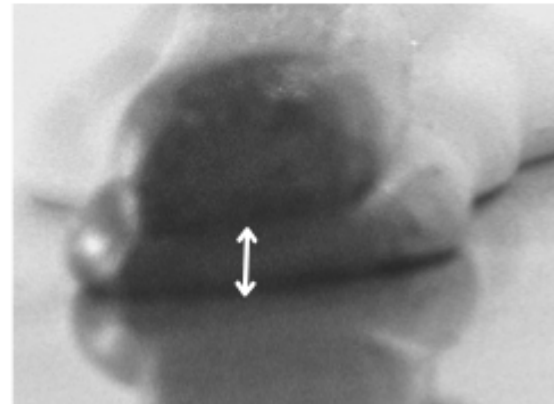
Viscosity = 31120Pa.s  
 Recovery rate =87.15%  
 Yield Stress = None

Extrusion Speed= 120step/mm.  
 Layer Visibility.  
 Premature Gelling.

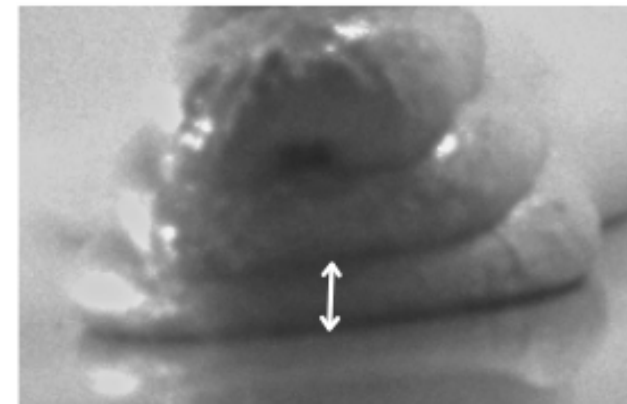
# GP-FWGX PRINTABILITY



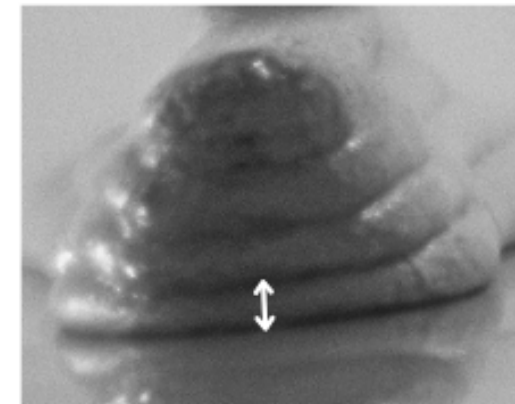
1st Layer Deposition



2nd Layer Deposition



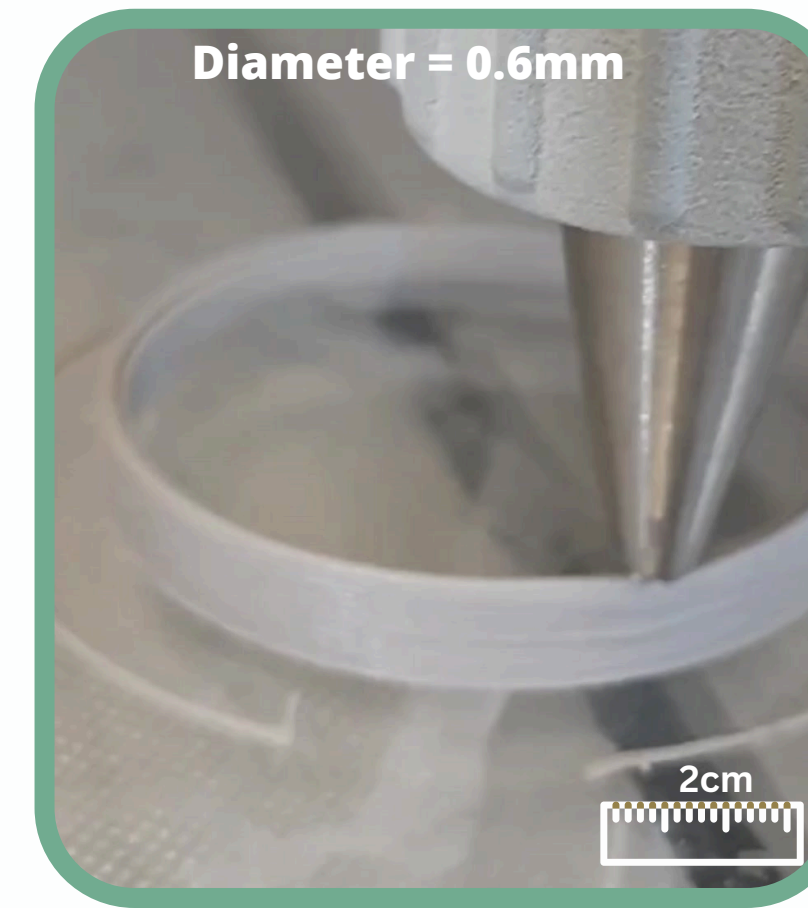
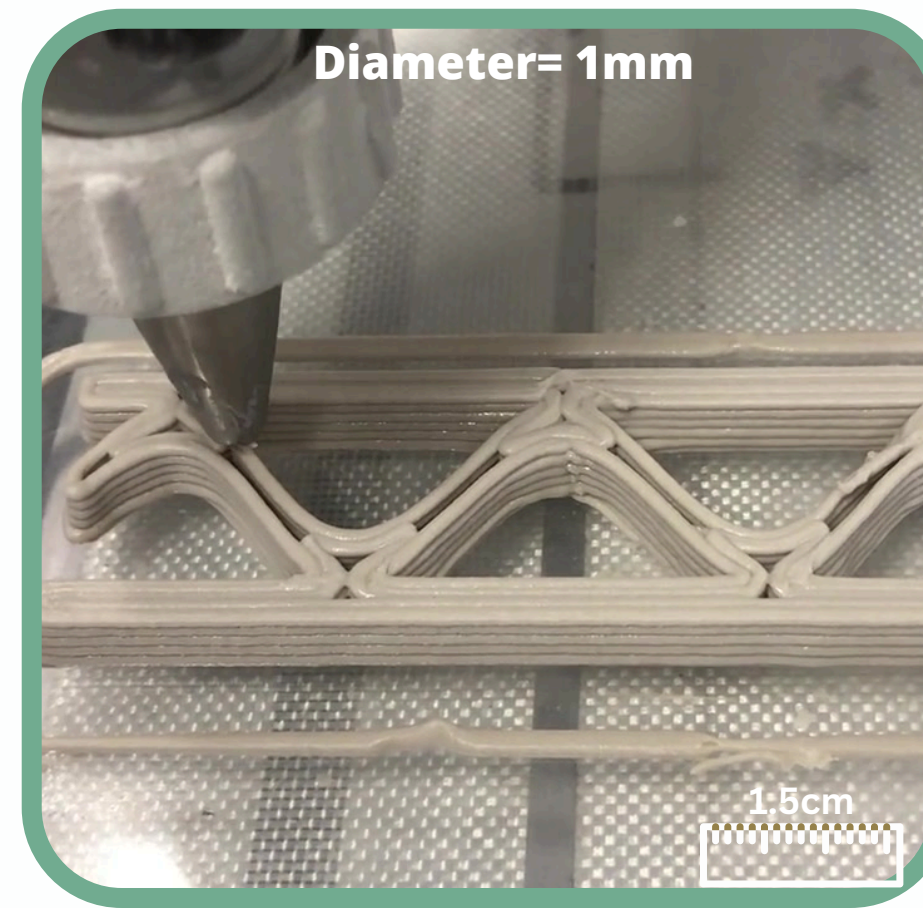
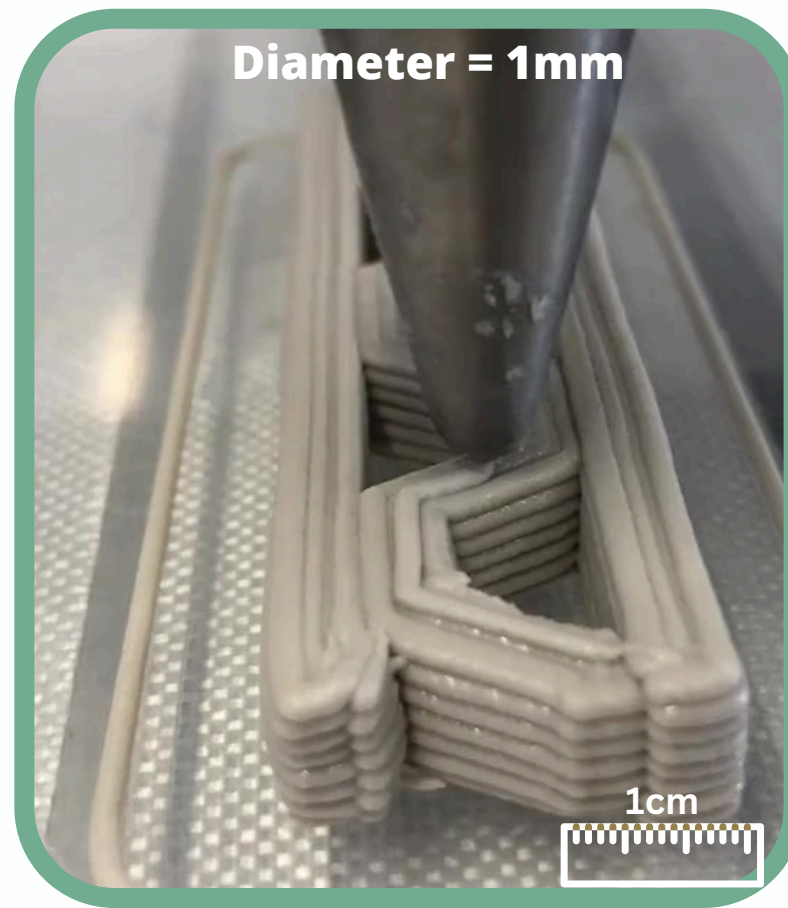
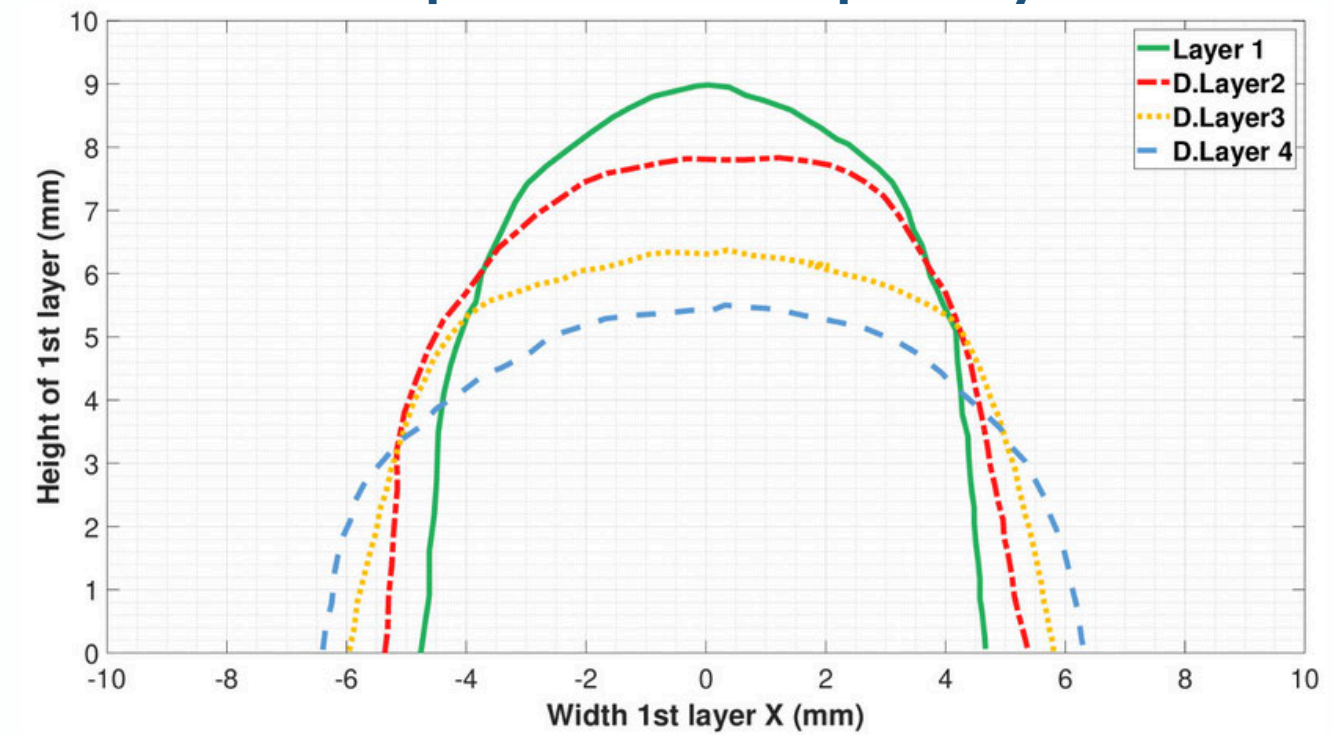
3rd Layer Deposition



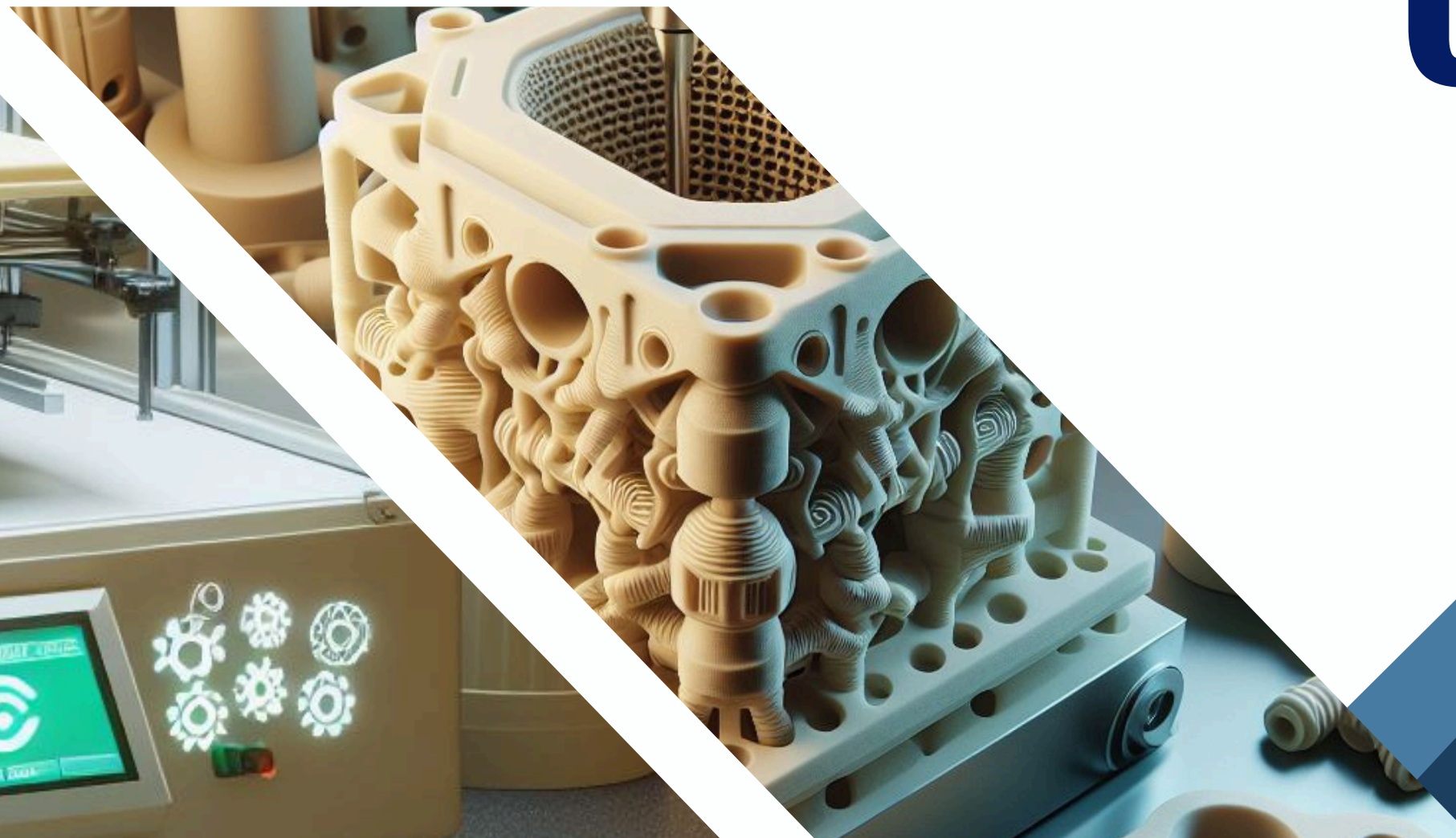
4th Layer Deposition

Evolution of the 1st layer

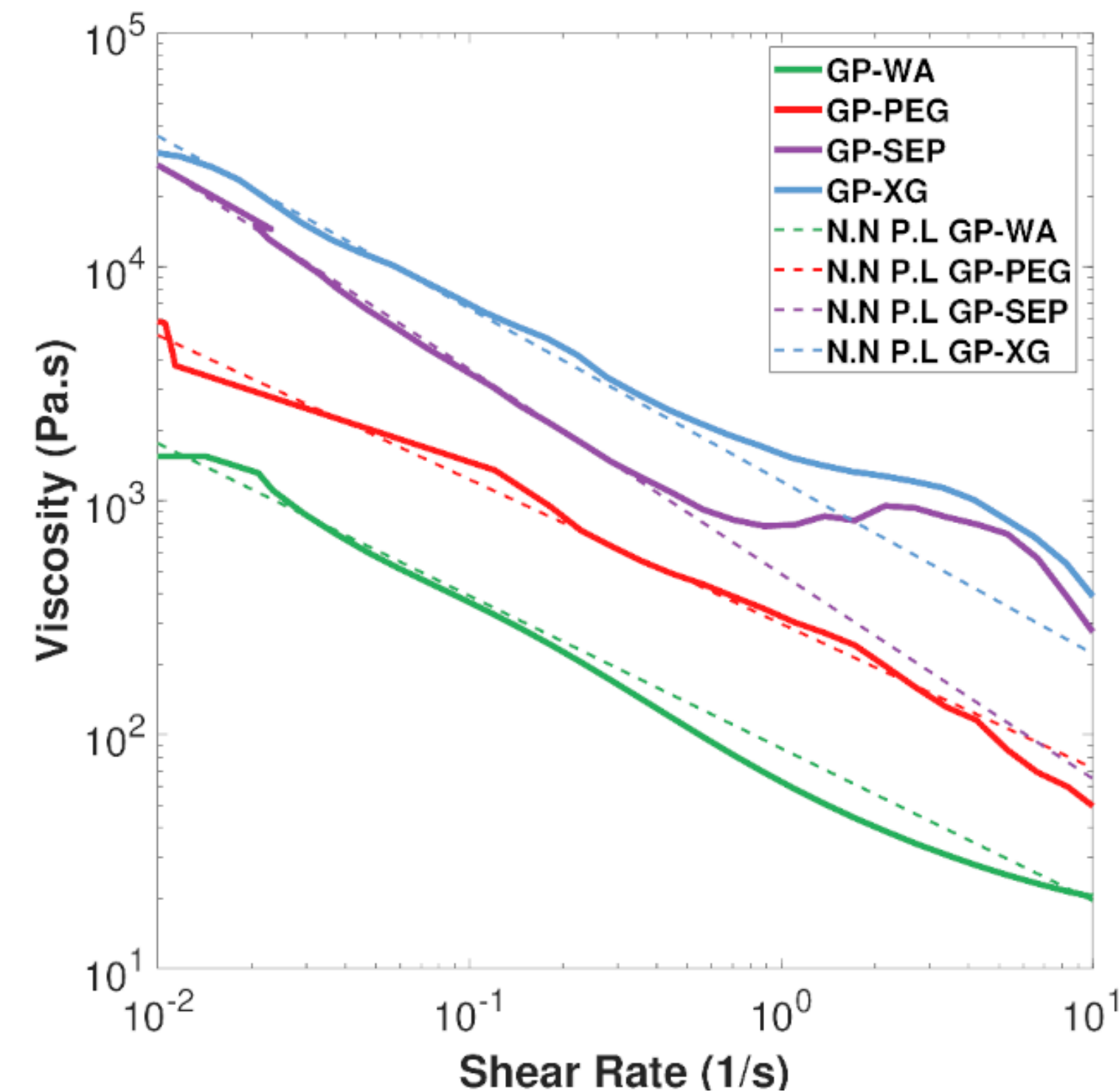
Shape of the first layer as a function of the deposition of subsequent layers



# NUMERICAL SIMULATION OF AM



# IDENTIFICATION OF THE RHEOLOGICAL LAW



## NON NEWTONIEN POWER LAW

$$\eta = \max(\min(K \dot{\gamma}^n, \eta_{max}), \eta_{min})$$

GP-Formula	K (Pa.s)	n	min (Pa.s)	max (Pa.s)	$R^2$
GP-WA	87.526	0.348	20.02	1544	0.976
GP-PEG	298.195	0.383	47.55	6940	0.981
GP-SEP	486.871	0.125	255.4	27300	0.994
GP-XG	1214	0.262	8.836	48400	0.945

## Non newtonien Power Law parameters

$\eta$  Viscosity

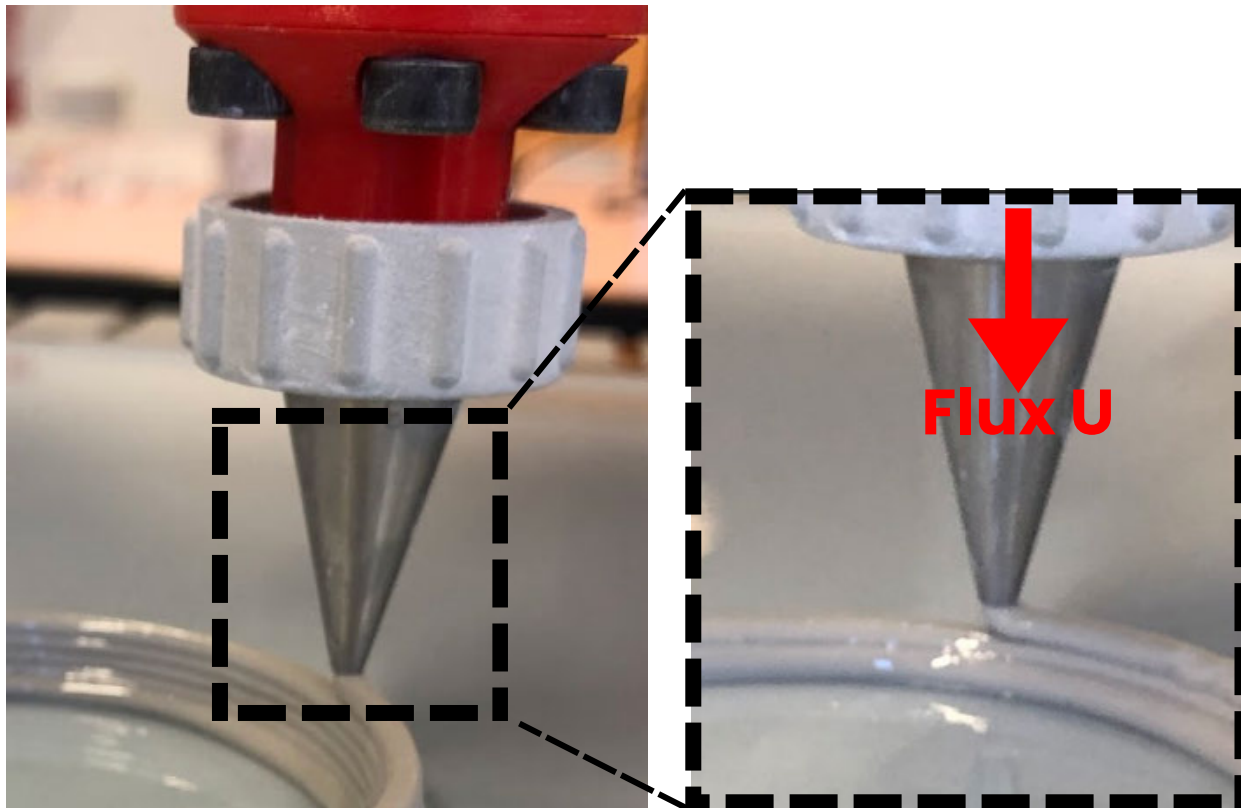
$n$  Flow behavior index

$K$  Consistency index

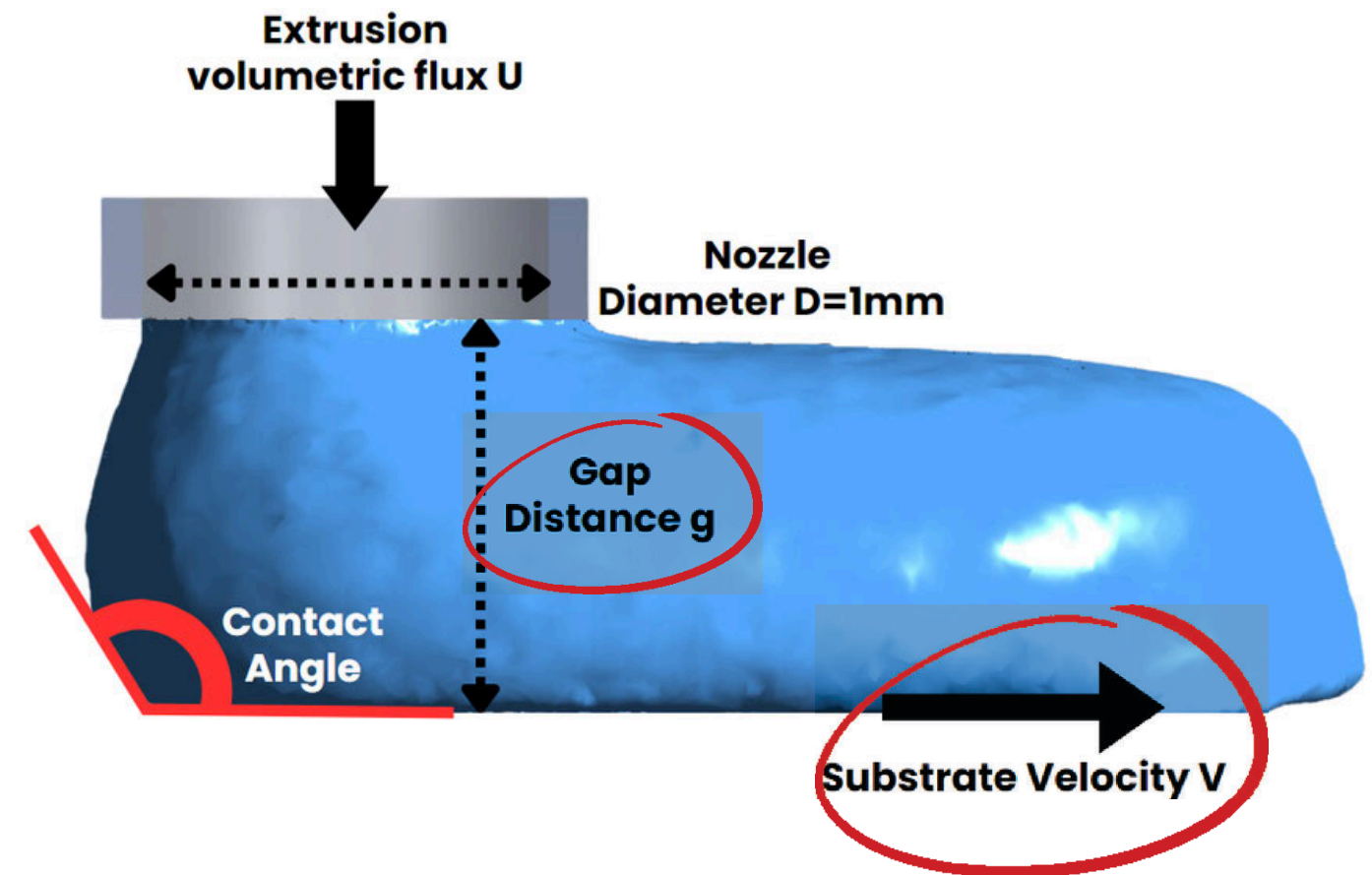
$\dot{\gamma}$  Shear rate

# COMPUTATIONAL FLUID DYNAMICS MODEL

## Real Strand Deposition

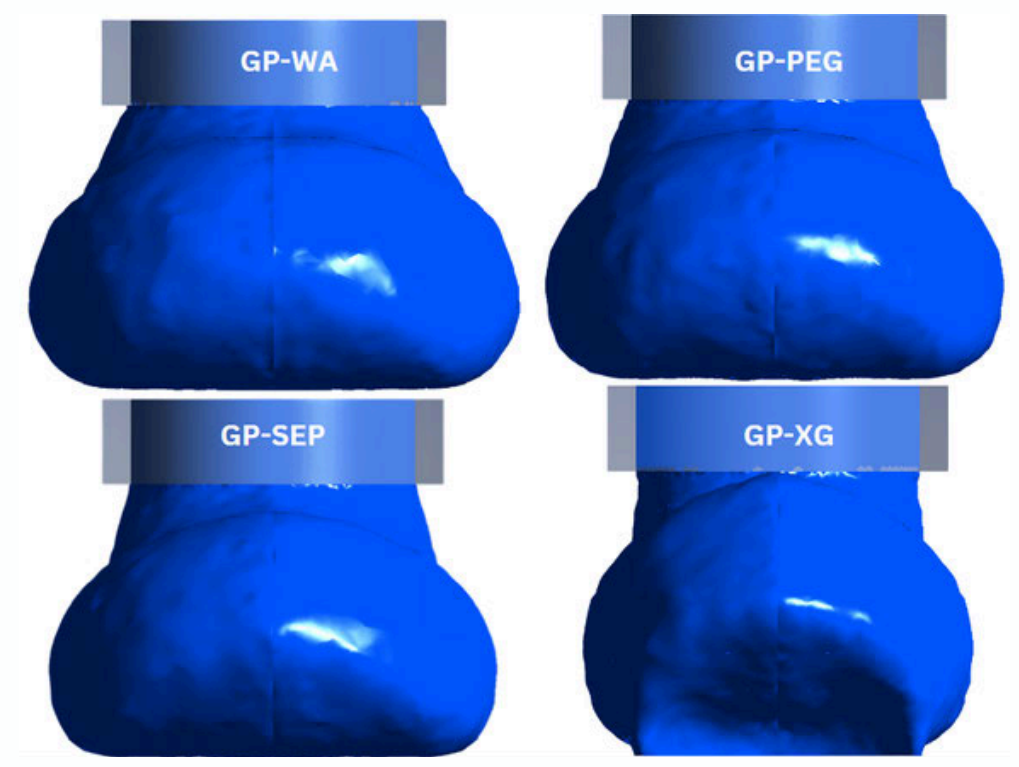


## Boundary Conditions Strand Deposition

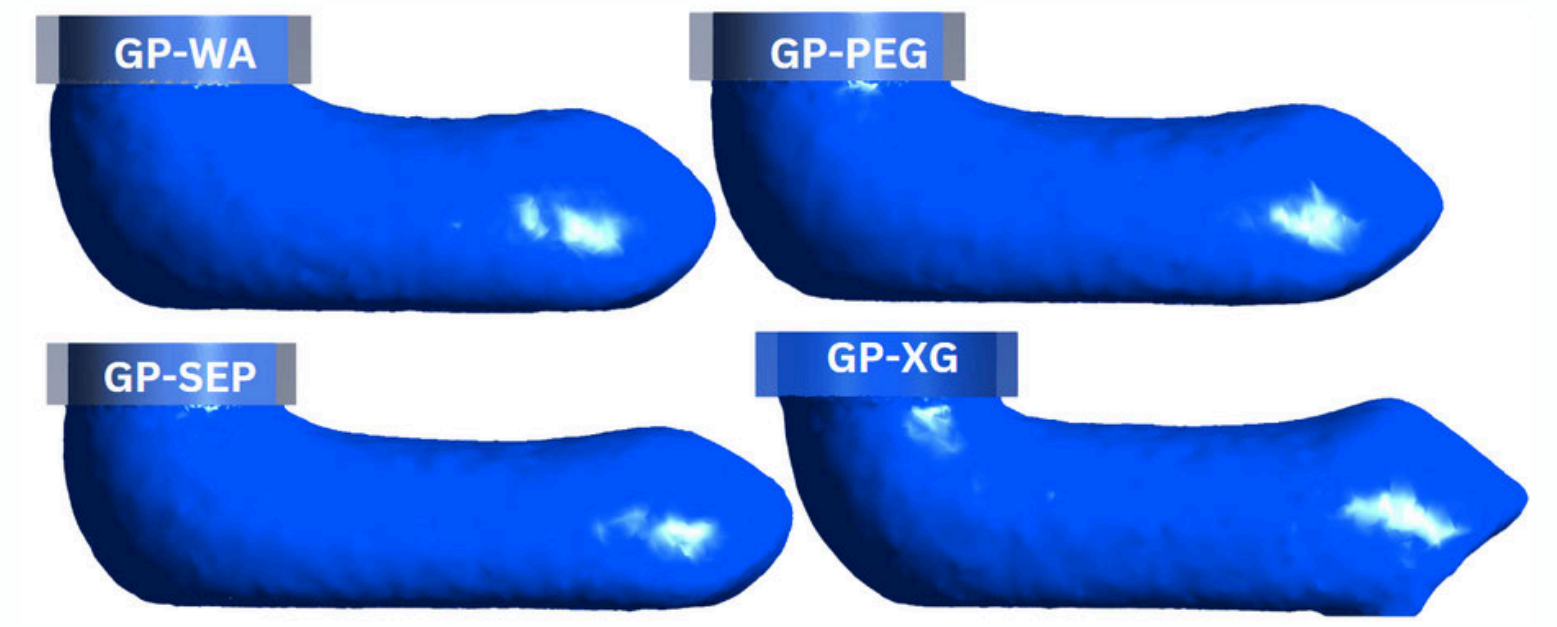


# EFFECT OF THE VISCOSITY ON STRAND DEPOSITION

$v/u=1$

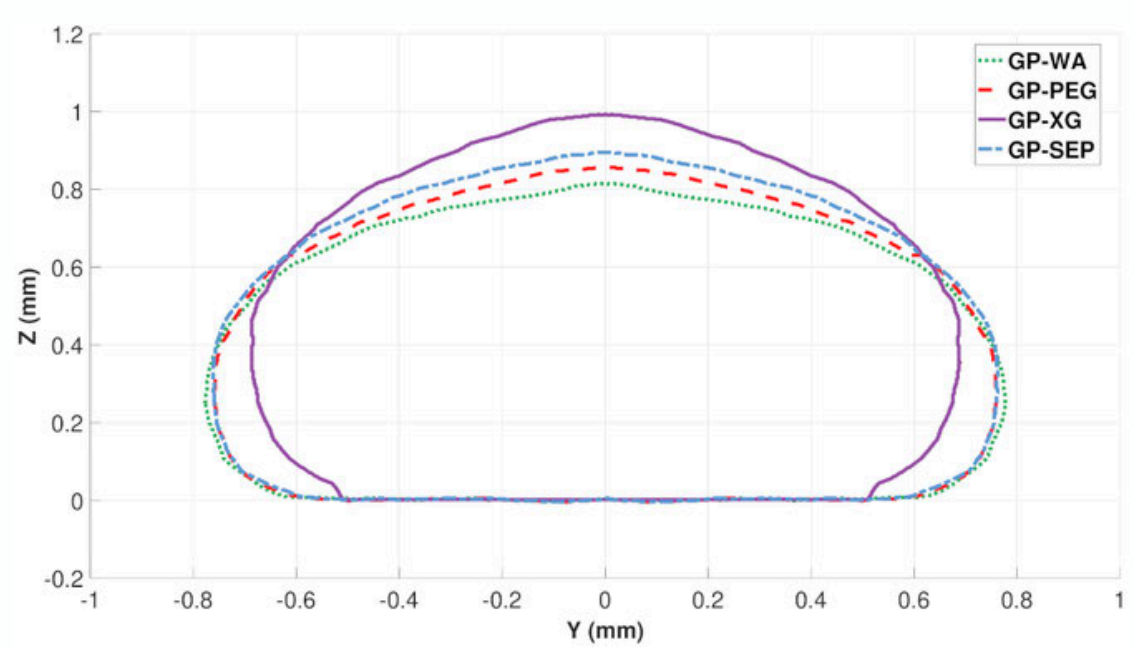


$g/D=1$

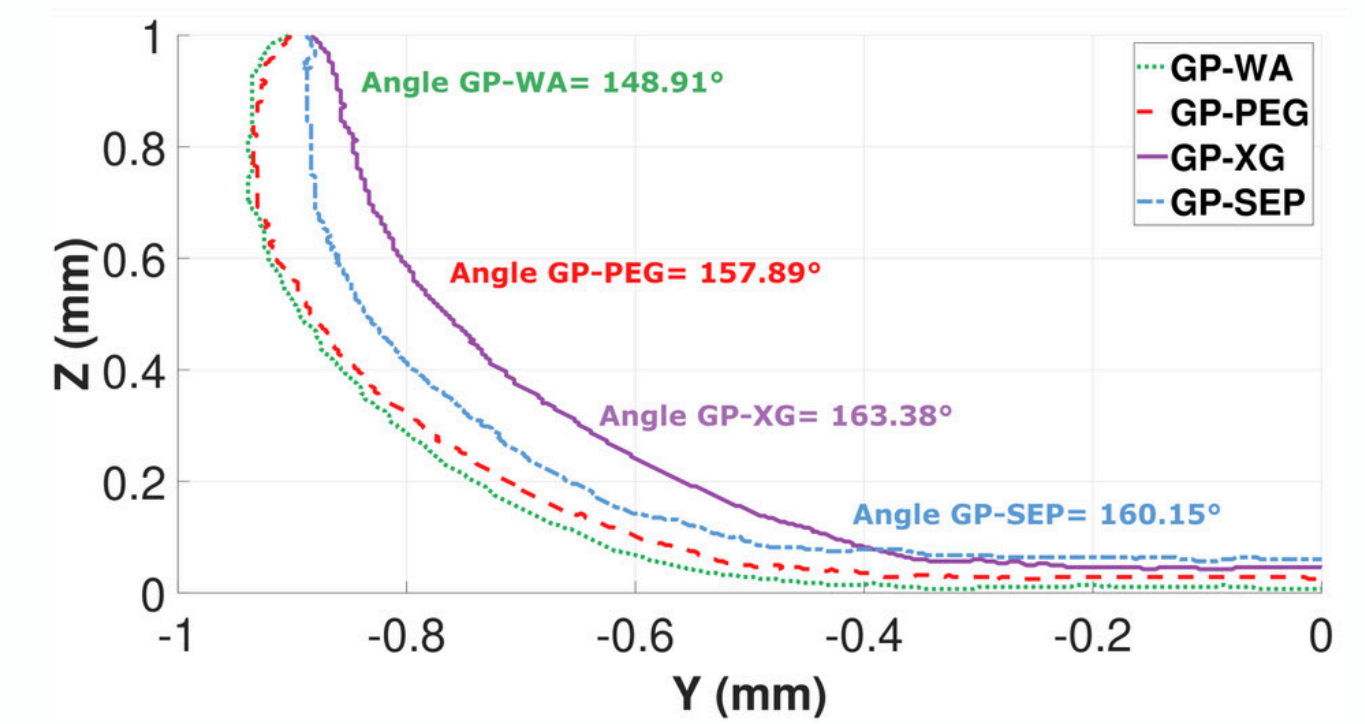


3D strands for different GP

3D strands for different GP



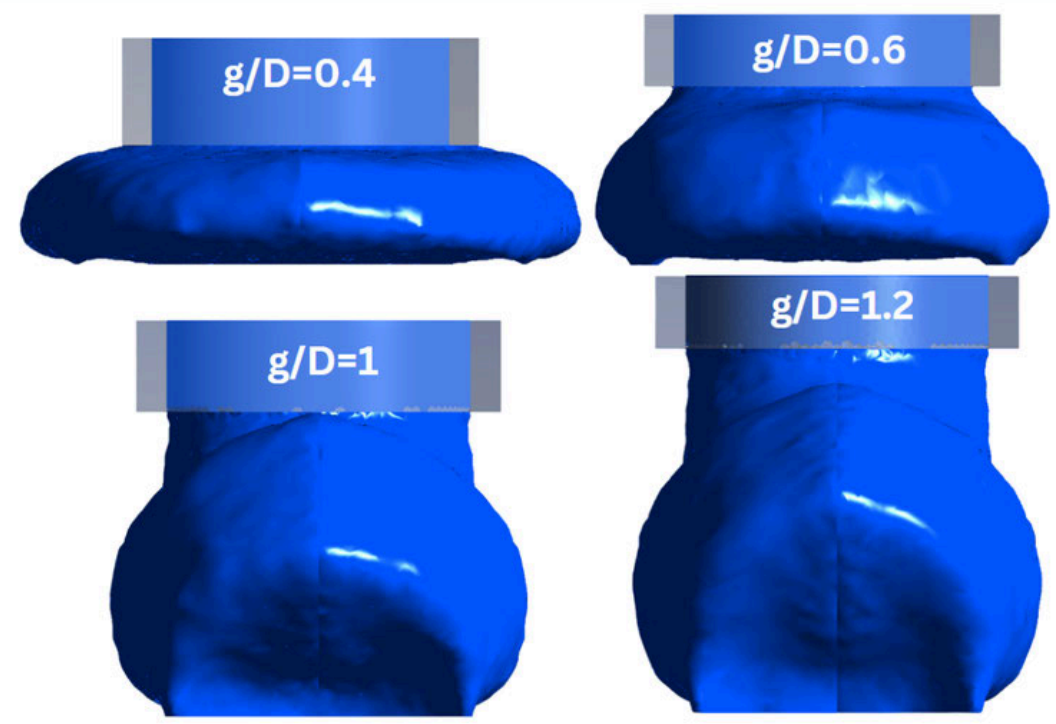
Front view profiles



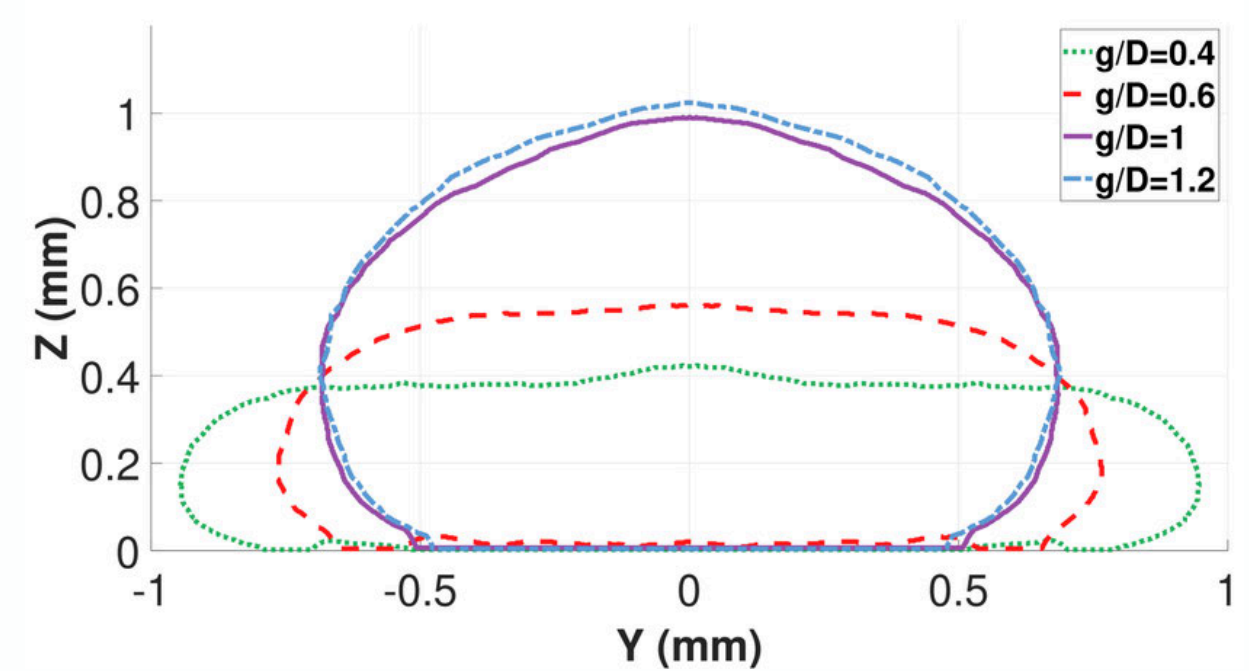
Side view profiles

# EFFECT OF THE GAP ON STRAND DEPOSITION

**V/U=1**

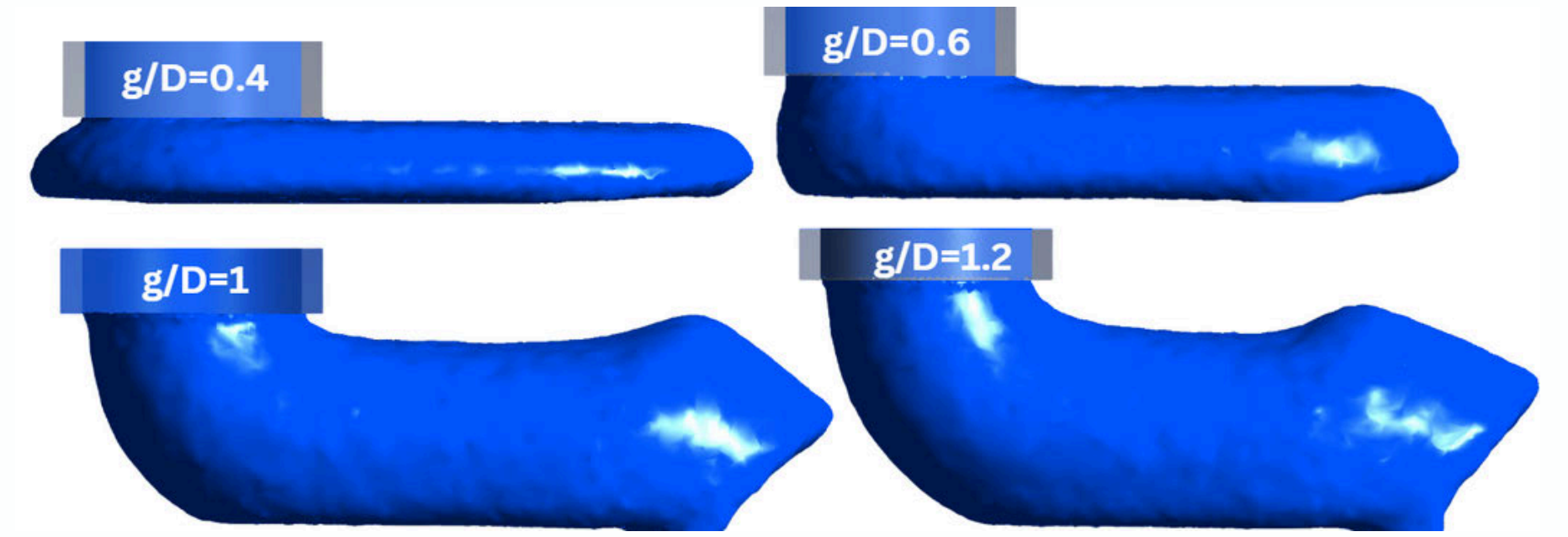


**3D strands for different GP**

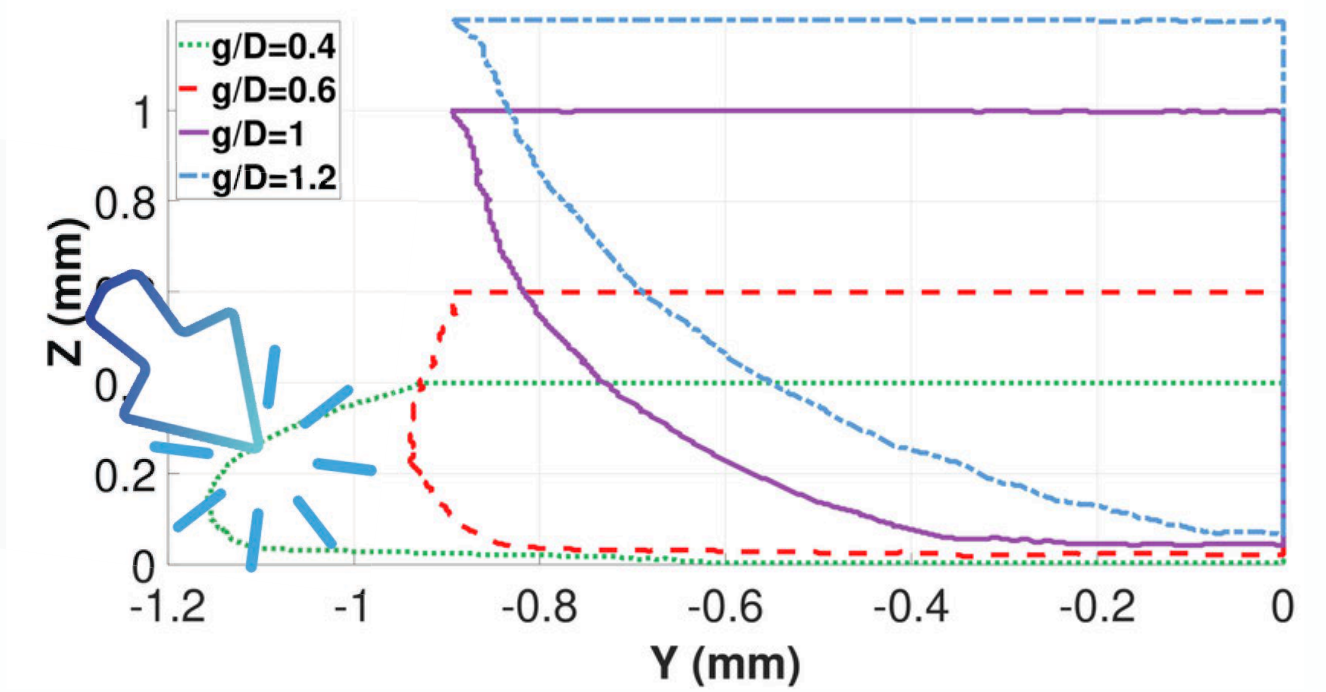


**Front view profiles**

**GP-XG**



**3D strands for different GP**



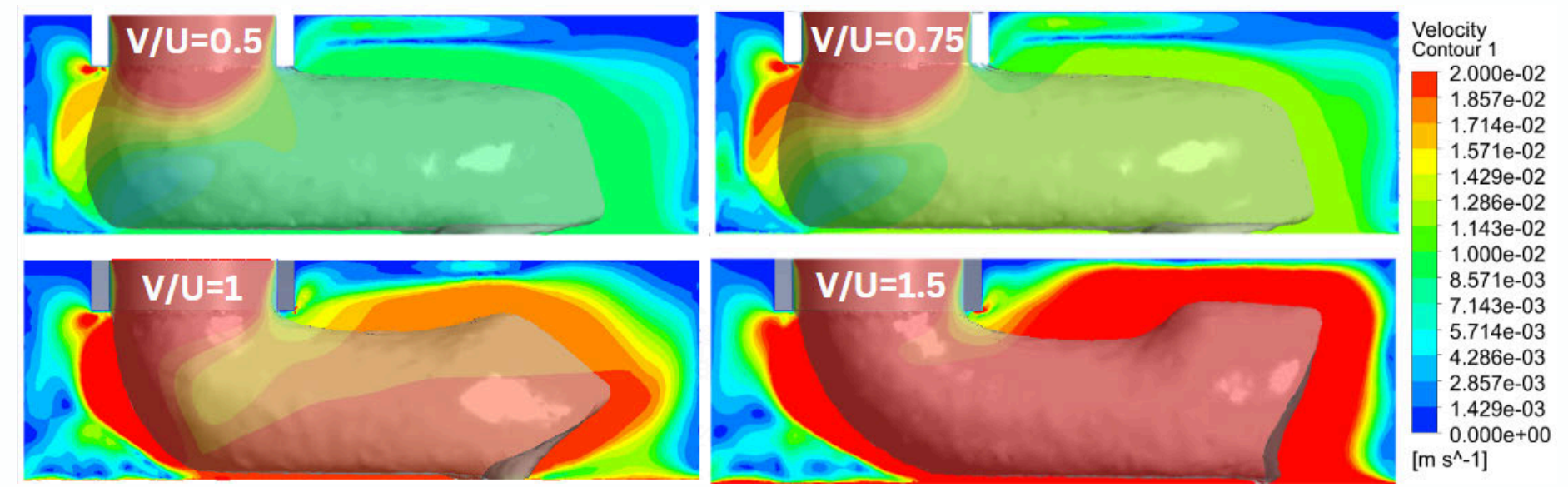
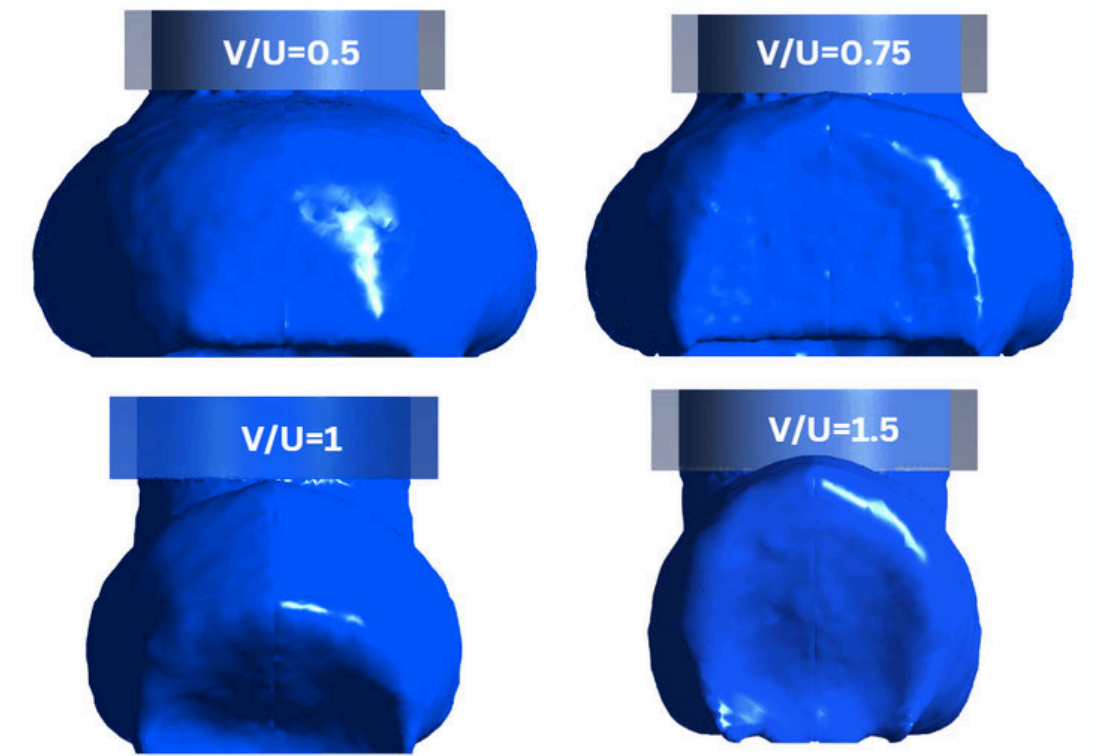
**Side view profiles**



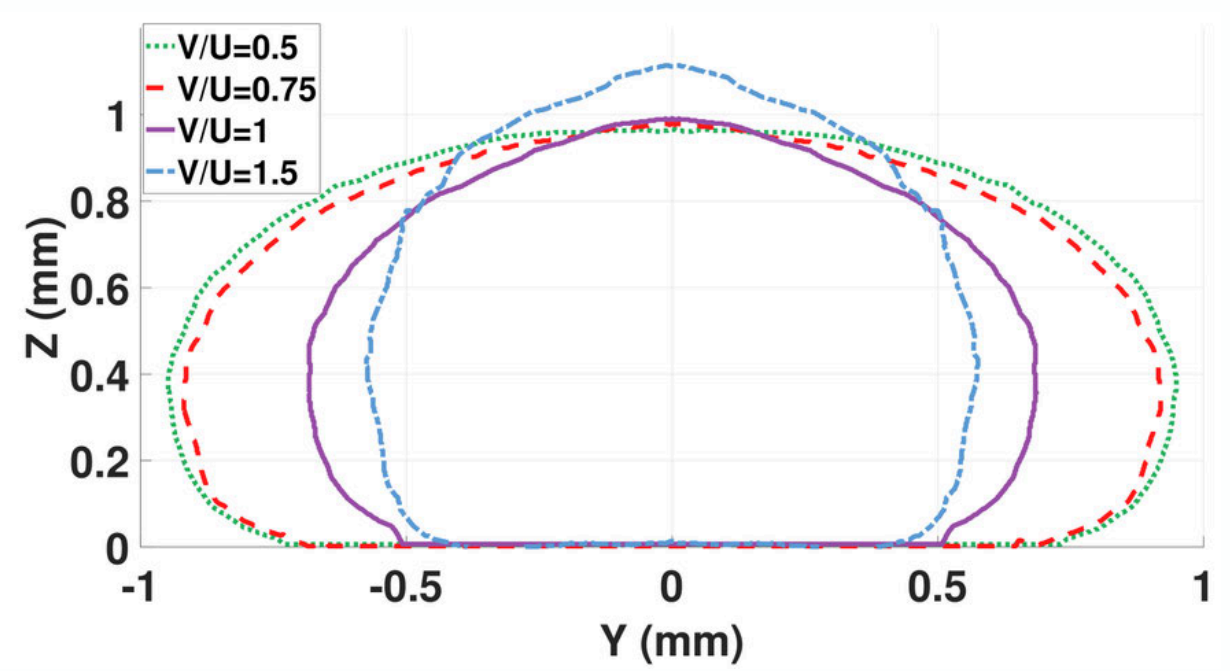
# EFFECT OF THE VELOCITY ON STRAND DEPOSITION

$g/D=1$

GP-XG

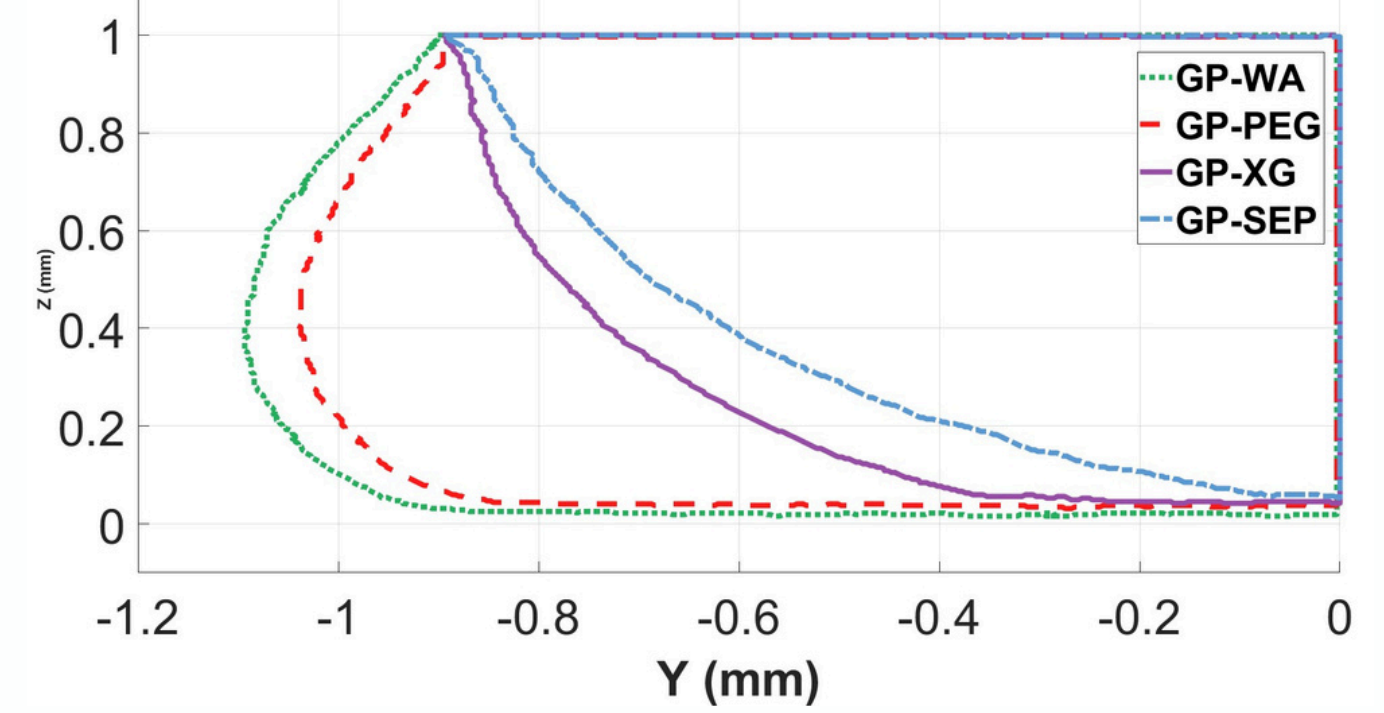


3D strands for different GP



Front view profiles

3D strands for different GP



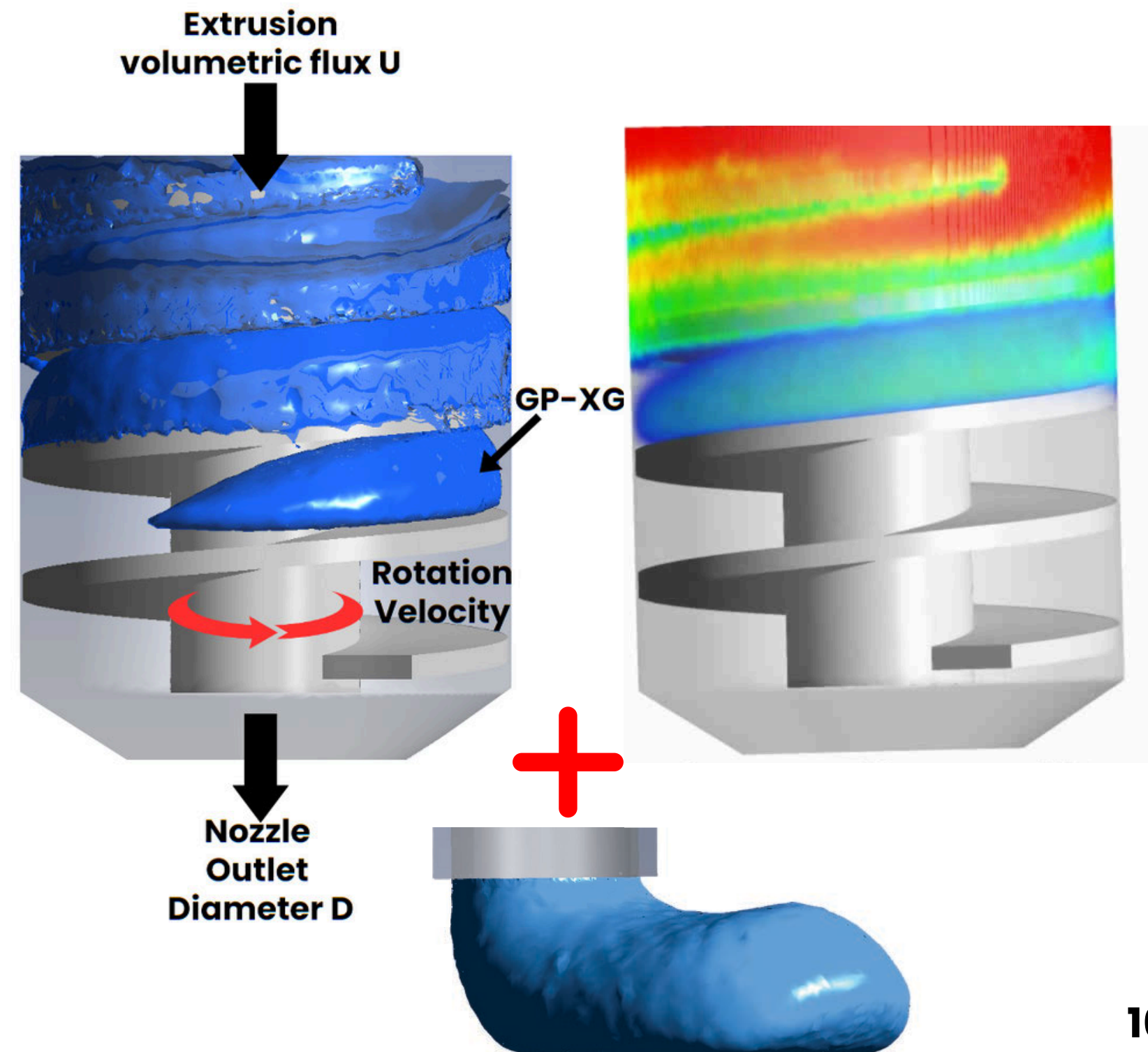
Side view profiles

# COMPUTATIONAL FLUID DYNAMICS MODEL

## Real Screw System



## Boundary Conditions Screw system





# PERSPECTIVES



# PERSPECTIVES

## 01

### NUMERICAL MODELING

Prediction through simulation of a multilayer and complex Model.

## 02

### 3D PRINTER

Real-time 3D printing machine autocorrection via sensors.

## 03

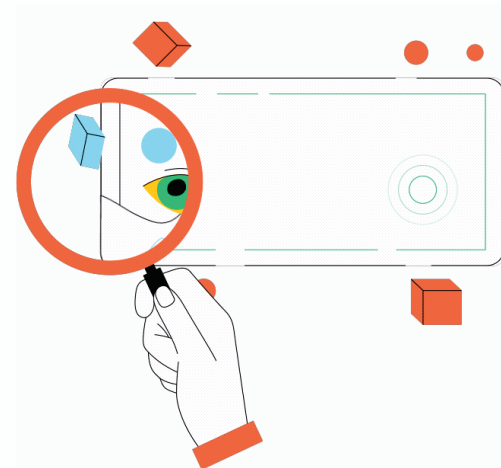
### HIGH TEMPERATURE

Apply the developed process to manufacture parts for the Geofab application.

## 04

### MACHINE LEARNING

Implementation of a machine learning approach for the rheological analysis.





# Thank you!

Questions ?

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