Designing 3D printable Eco-Concrete by utilizing biodegradable rheology modifiers.

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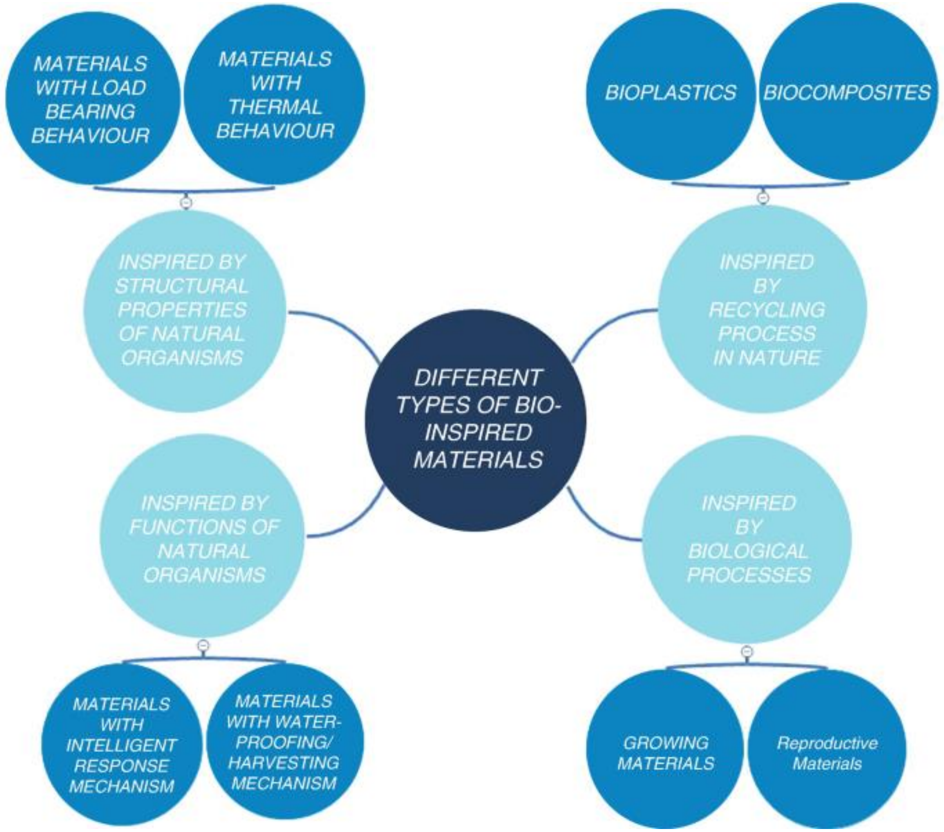
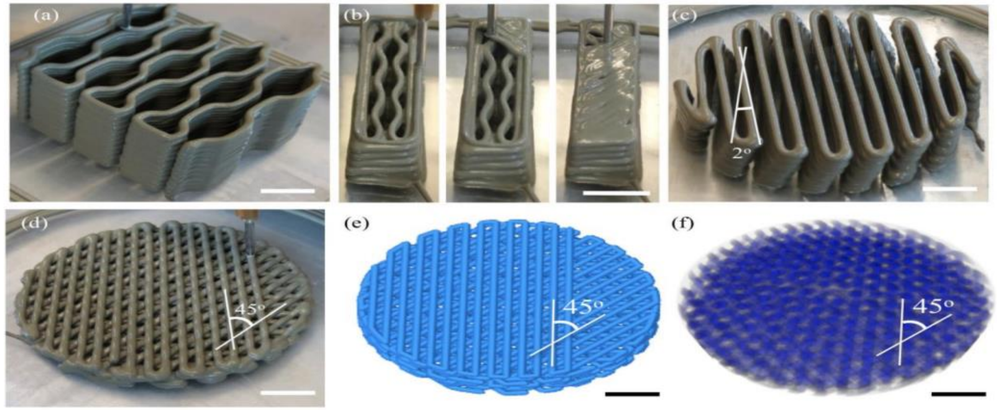
Outline

1. Problem Statement and Objective
2. Viscosity Modifying Admixtures
3. Materials and Methods
4. Preliminary Experimental Investigation
5. Optimization (Response Surface Methodology)
6. Printability Evaluation
7. Conclusions and Future Work

"Bio-inspired materials harness the power of nature's design to create innovative and sustainable solutions for modern challenges."



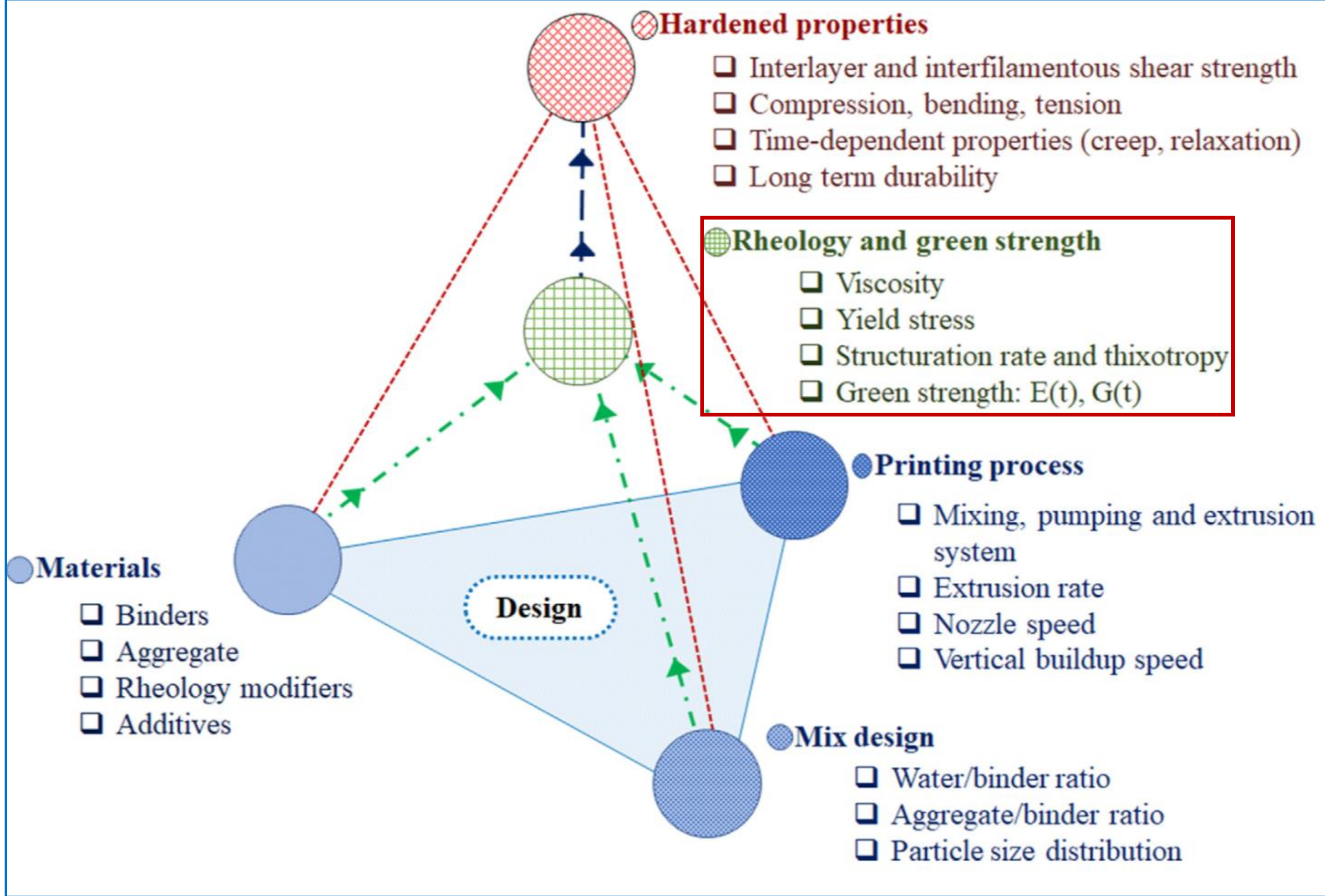
Imani, M., Donn, M., Balador, Z. (2019). Bio-inspired Materials: Contribution of Biology to Energy Efficiency of Buildings. In: Martínez, L., Kharissova, O., Kharisov, B. (eds) Handbook of Ecomaterials. Springer, Cham.



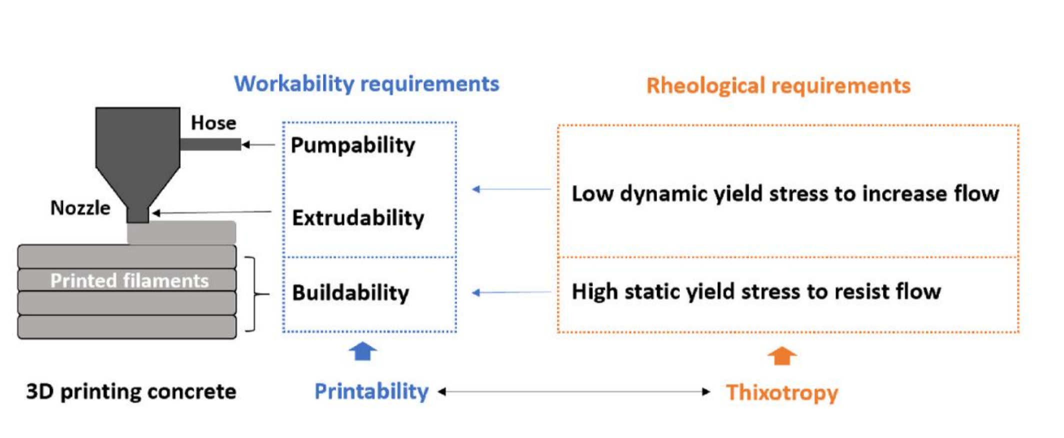
Moini, M., Olek, J., Youngblood, J. P., Magee, B., & Zavattieri, P. D. (2018). Additive manufacturing and performance of architectured cement-based materials. Advanced Materials, 30(43), 1802123.

3D printed soil structures developed by University of Virginia researchers.

Why Rheology is Critical in 3D Concrete Printing?



Murcia, D. H., Genedy, M., & Taha, M. R. (2020). Examining the significance of infill printing pattern on the anisotropy of 3D printed concrete. Construction and Building Materials, 262, 120559.

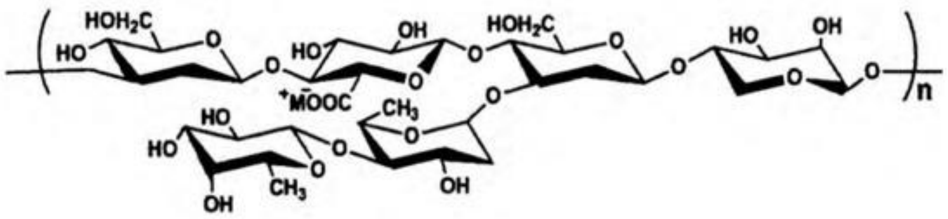


Zhang, C., Nerella, V. N., Krishna, A., Wang, S., Zhang, Y., Mechtcherine, V., & Banthia, N. (2021). Mix design concepts for 3D printable concrete: A review. Cement and Concrete Composites, 122, 104155.

Buildable ⟵ - - - - - - - ⟶ Extrudable

Viscosity modifying admixtures are widely used as rheology modifiers in concrete.

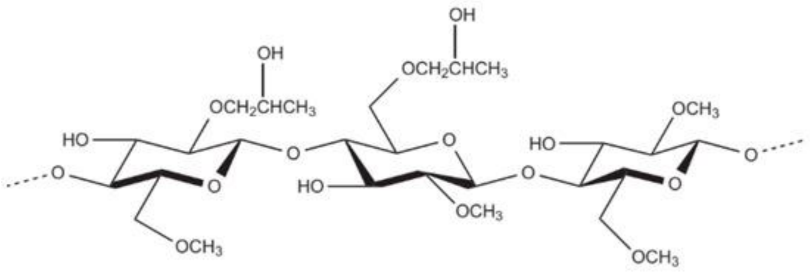
Natural Polymers



Starch
- Corn Starch
- Cassava Starch
- Potato Starch

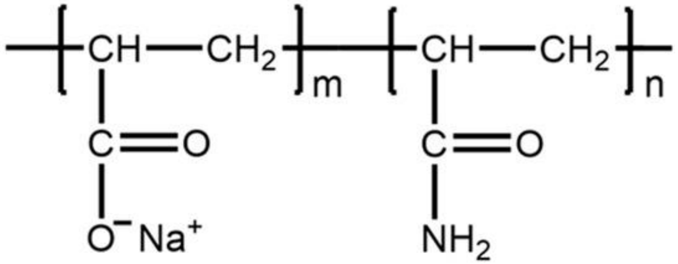
Bio-gums
- Xanthan Gum
- Diutan Gum
- Welan Gum

Semi-synthetic Polymers



Cellulose Ethers
- Methylcellulose
- Hydroxyethyl Cellulose
- Carboxymethyl cellulose

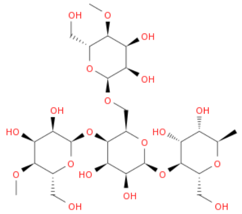
Synthetic Polymers



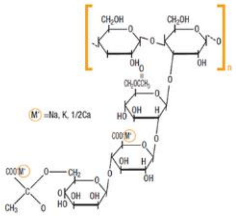
Synthetic polymers
- Polyvinyl Alcohol
- Polyethylene Oxide
- Polyacrylate

Bio-degradable VMAs were utilized in this study.

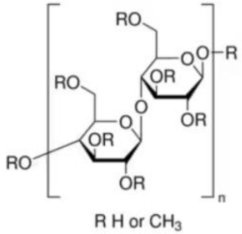
Starch



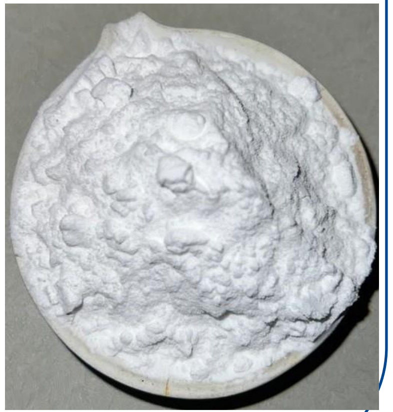
Bio-gums



Cellulose Ethers



Starch
- Corn Starch (Capsul)
- Corn Starch (Ultratex)



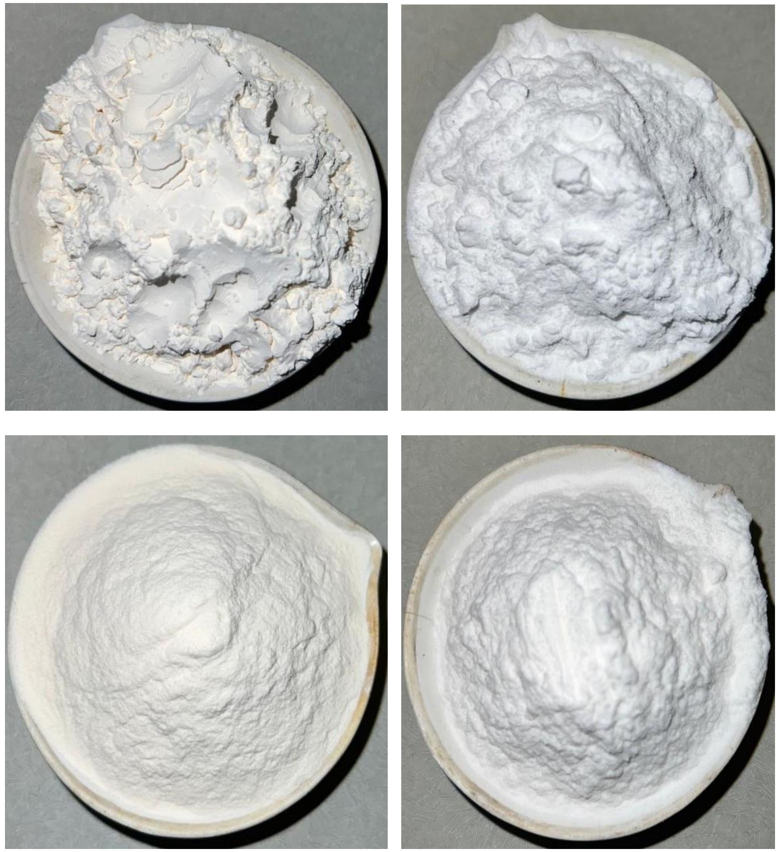
Bio-gums
- Xanthan Gum

Cellulose Ethers
- Methylcellulose

Mix Proportions

Mix	Cement	VMA (%)	W/B	Sand	Adjusted W/B
VMA-0.5	0.50	0.5	0.34	0.33	Vary for each VMA type
VMA-1	0.50	1	0.34	0.33	
VMA-1.5	0.50	1.5	0.34	0.33	
VMA-2	0.50	2	0.34	0.33	

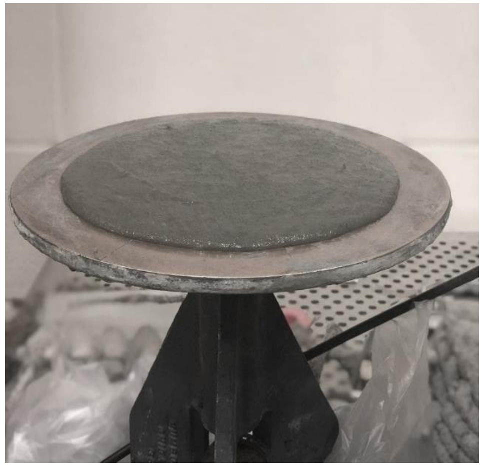
VMA (%): weight % of cement content

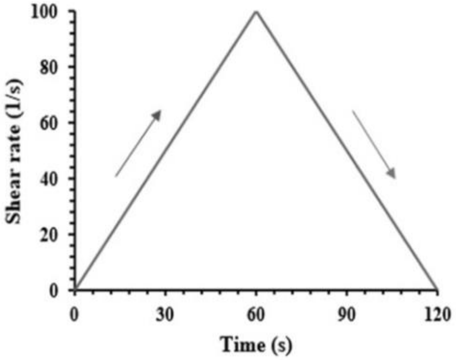


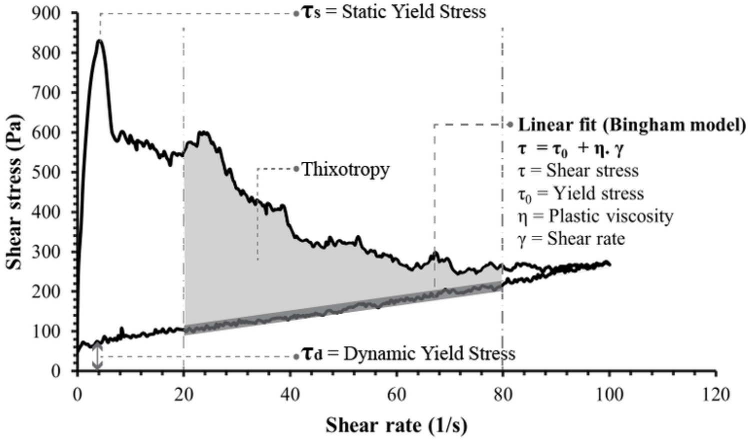
Flowability and rheology tests were done as preliminary experimentations.

Flowability

Rheology







Corn Starch (Capsul) improved the flowability but plastic viscosity and dynamic yield stress were quite low for 3D printing.

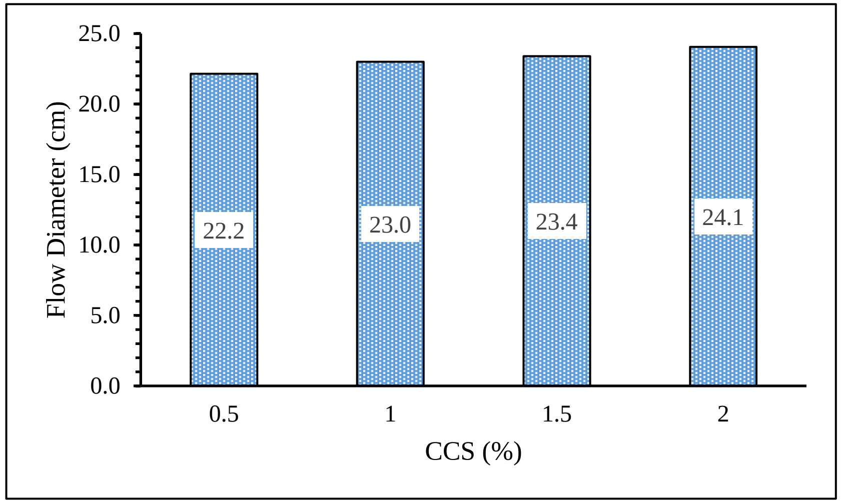
Water Demand : Low (✓)

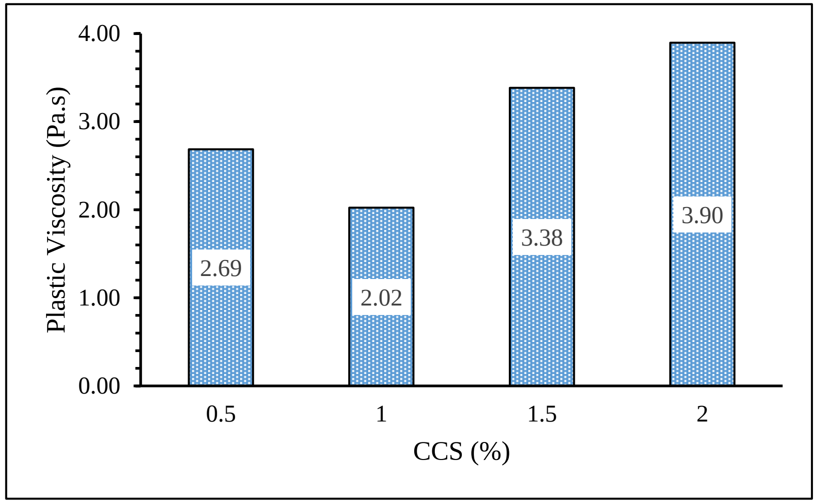
Flowability : Improved (✓)

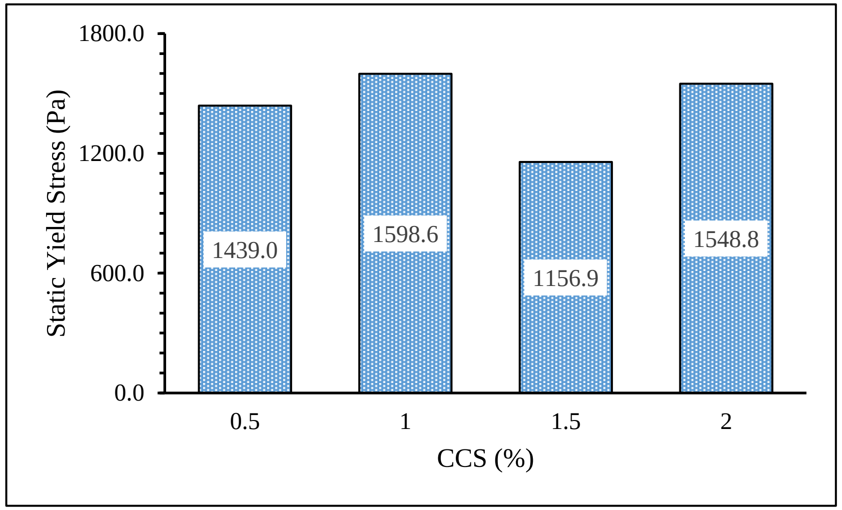
Plastic Viscosity : Low (✗)

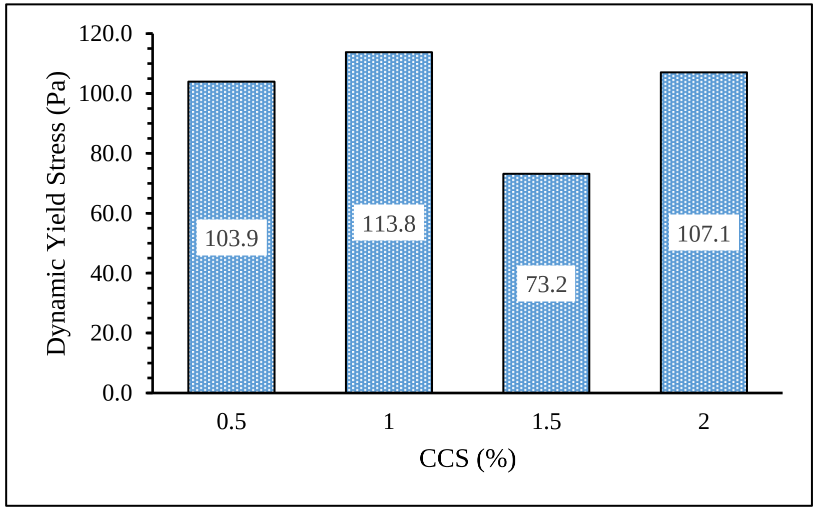
Dynamic Yield Stress : Low (✗)

Static Yield Stress : Satisfactory









Corn Starch (Ultratex) improved the static yield stress but plastic viscosity and dynamic yield stress were quite low for 3D printing. Also water demand was very high comparatively.

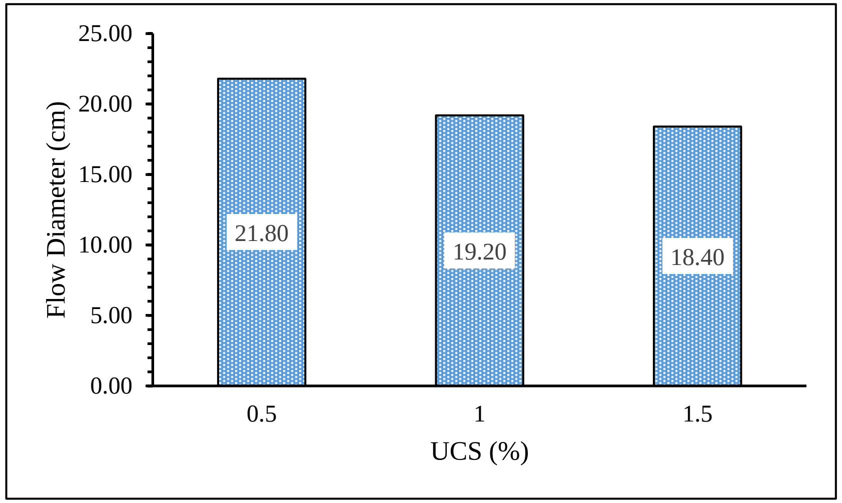
Water Demand : High (✗)

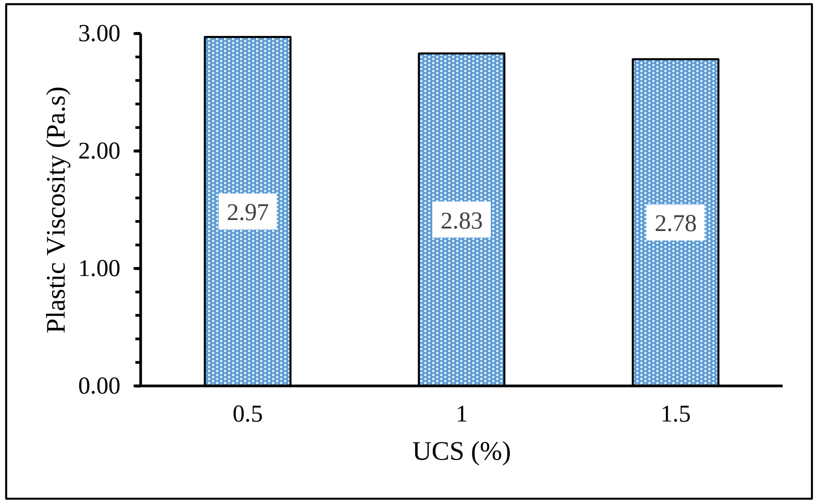
Flowability : Reduced (✗)

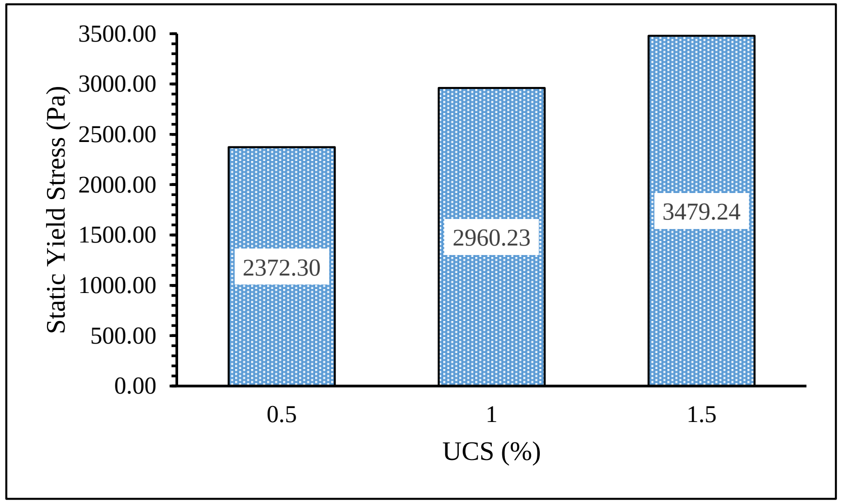
Plastic Viscosity : Low (✗)

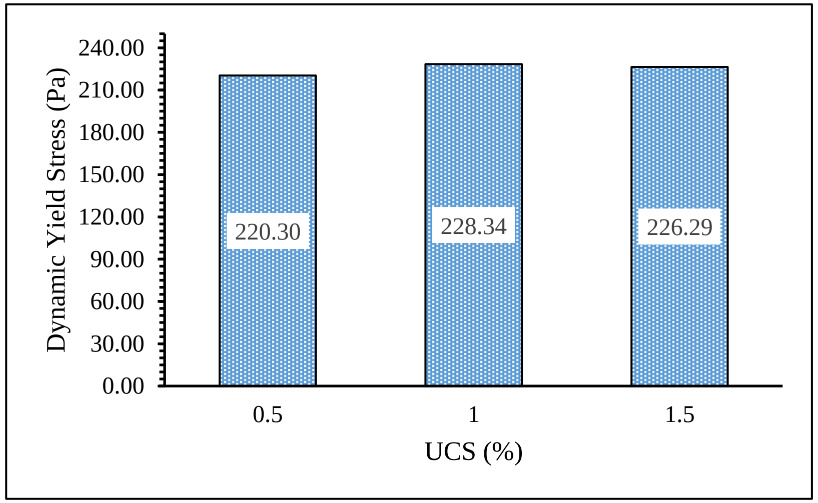
Dynamic Yield Stress : Low (✗)

Static Yield Stress : Improved (✓)









Methylcellulose (MC): Although the rheological parameters were in satisfactory range for printability the mixes were super viscous to work with.

Water Demand : Less (✓)

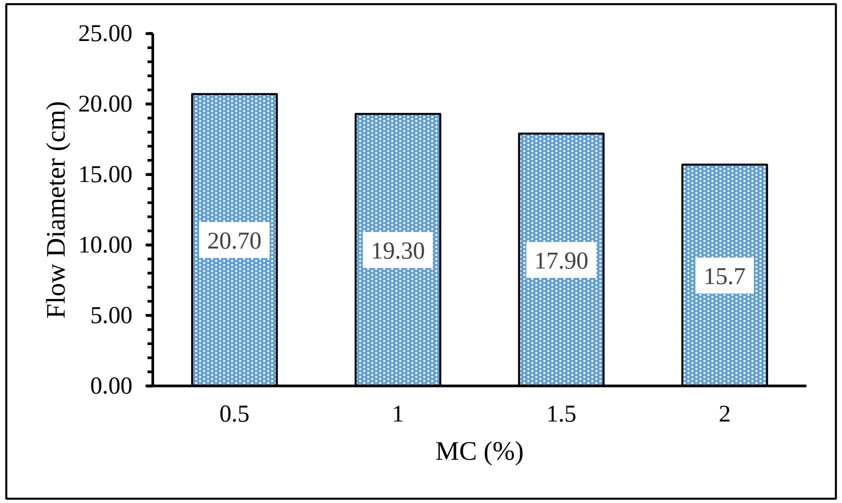
Flowability : Reduced (✗)

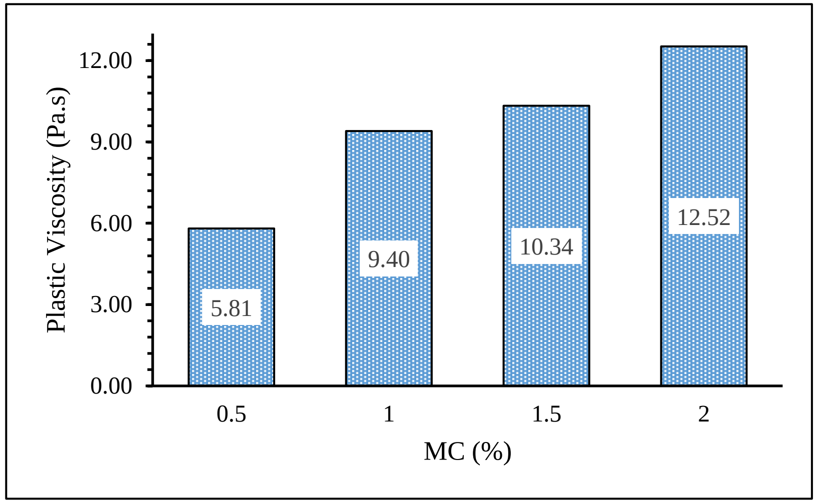
Plastic Viscosity : Improved (✓)

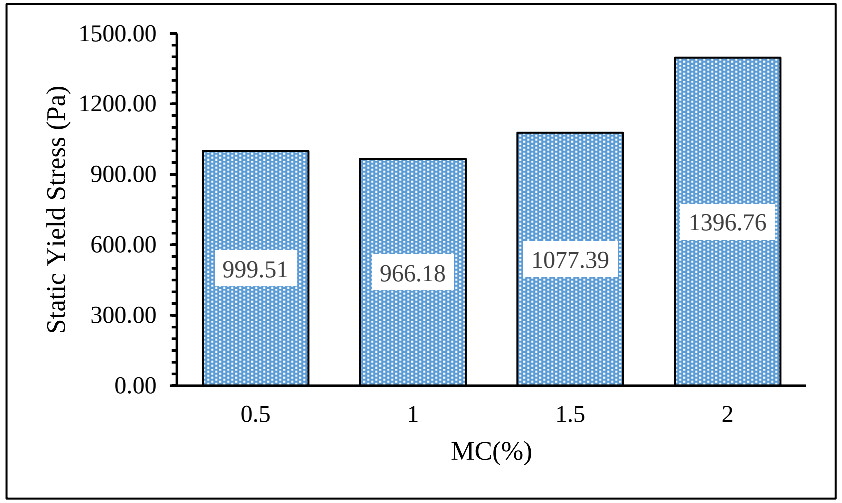
Dynamic Yield Stress : Satisfactory

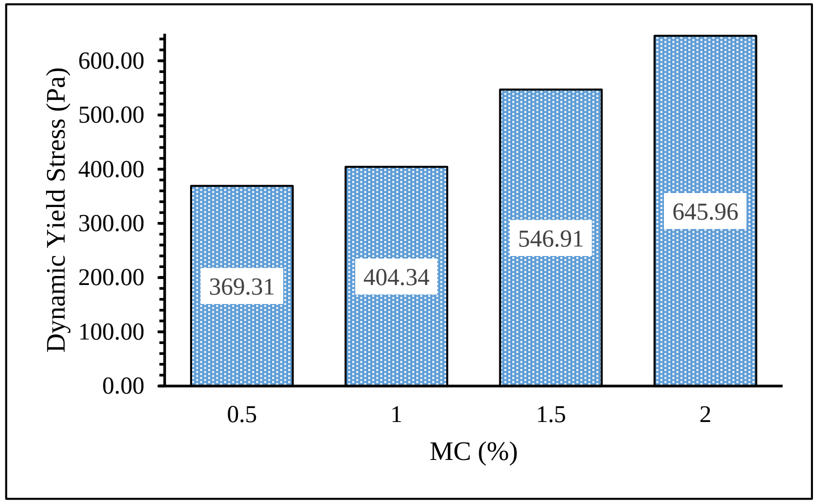
Static Yield Stress : Satisfactory

Mix at MC content of more than 1% was very viscous and not easy to work with.









Xanthan Gum (XG) improved the static yield stress but plastic viscosity and dynamic yield stress were quite low for 3D printing. Also water demand was very high comparatively.

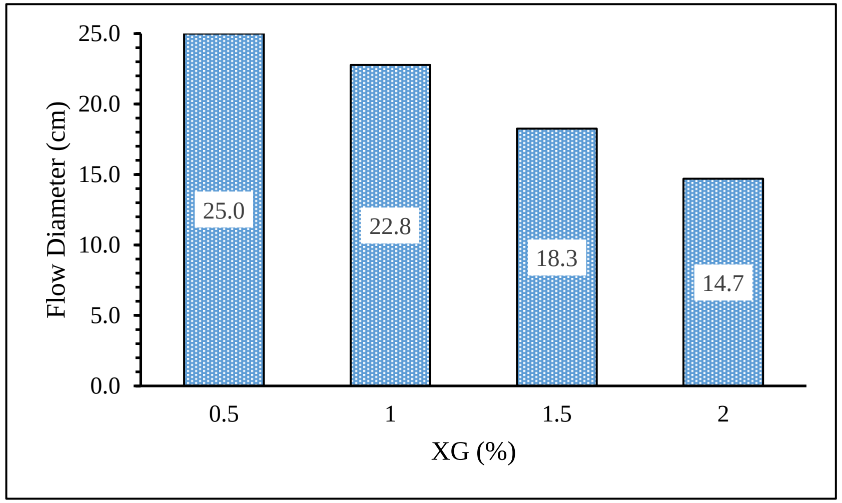
Water Demand : High (✗)

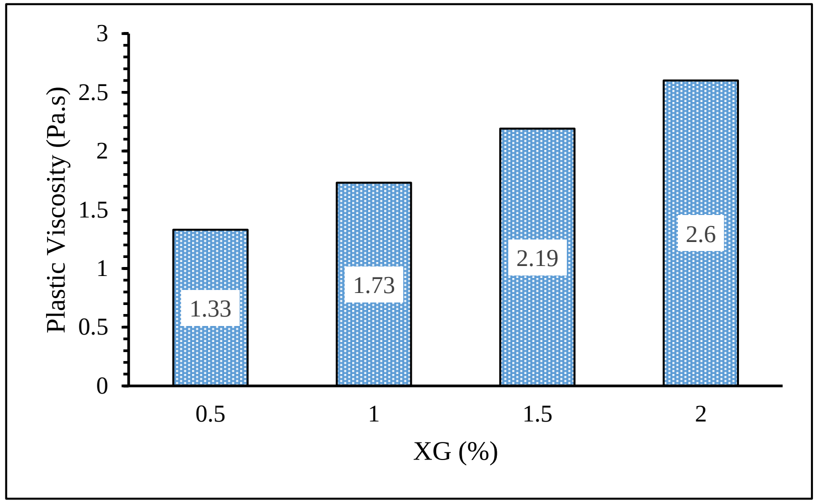
Flowability : Reduced (✗)

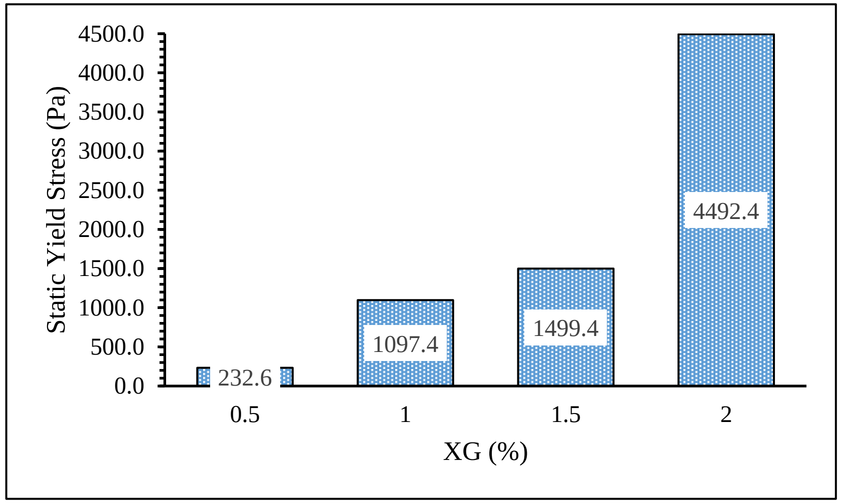
Plastic Viscosity : Reduced (✗)

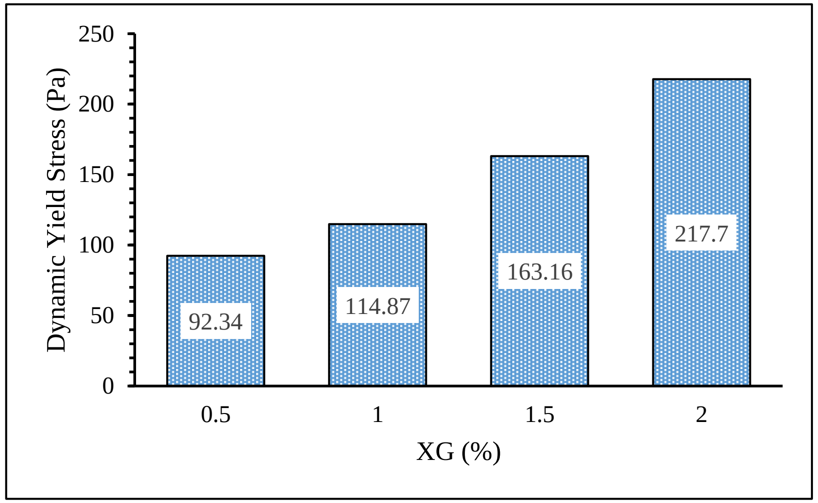
Dynamic Yield Stress : Low (✗)

Static Yield Stress : Improved (✓)

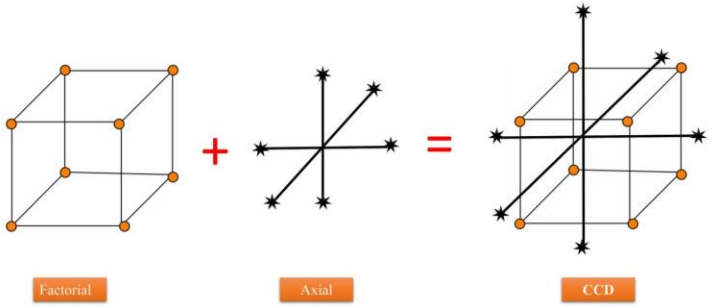


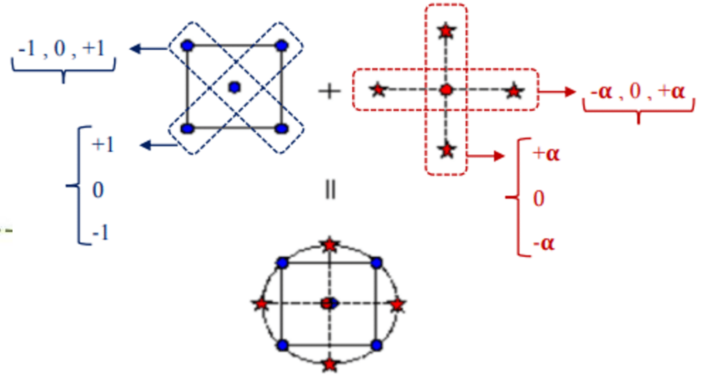


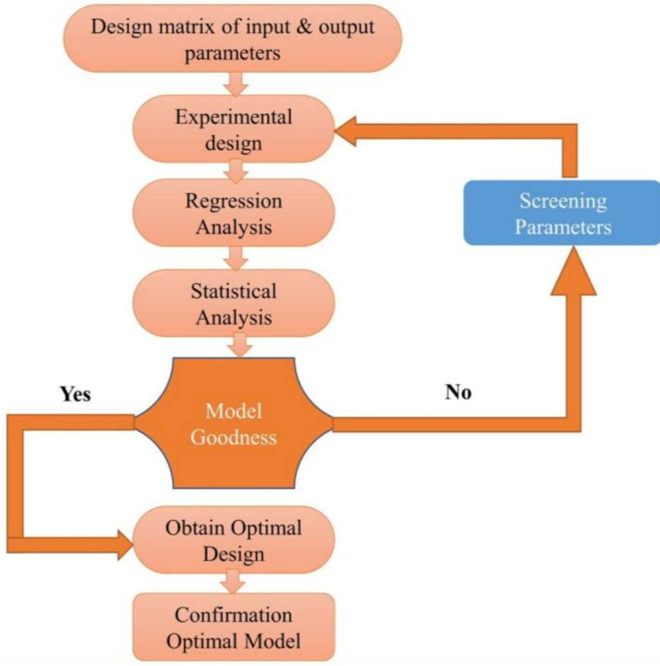


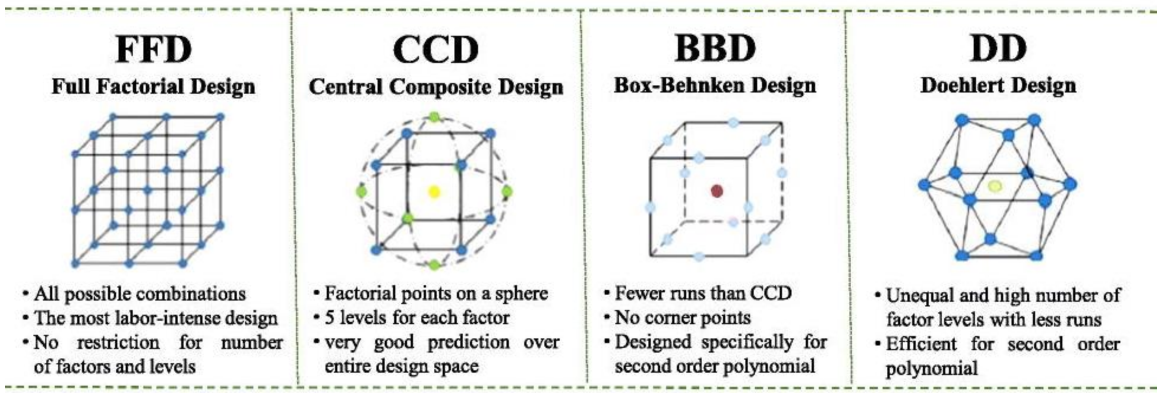


Response Surface Methodology was employed using design expert software to do the optimization.





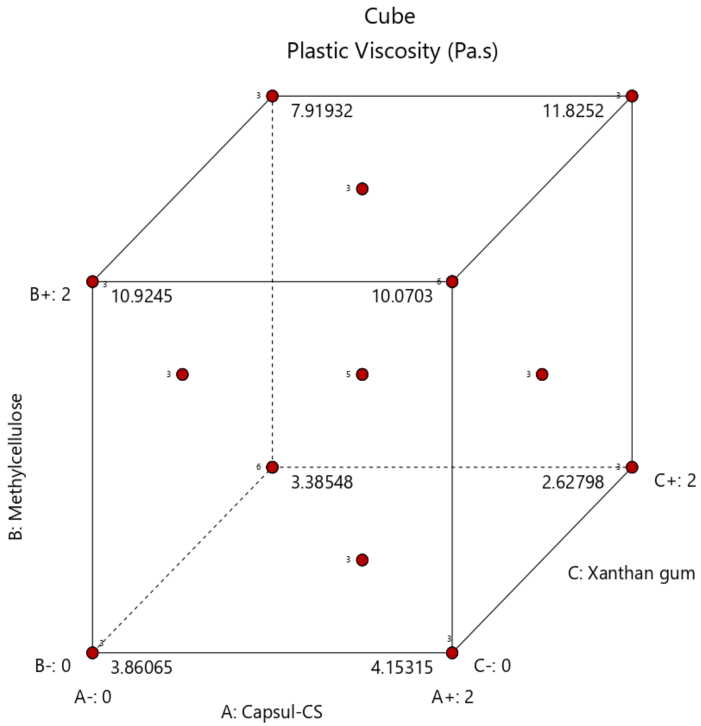


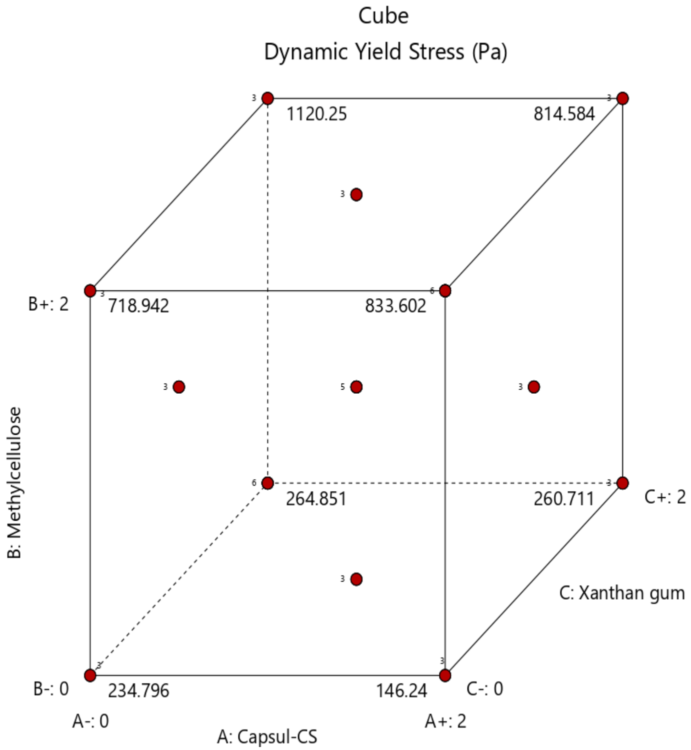


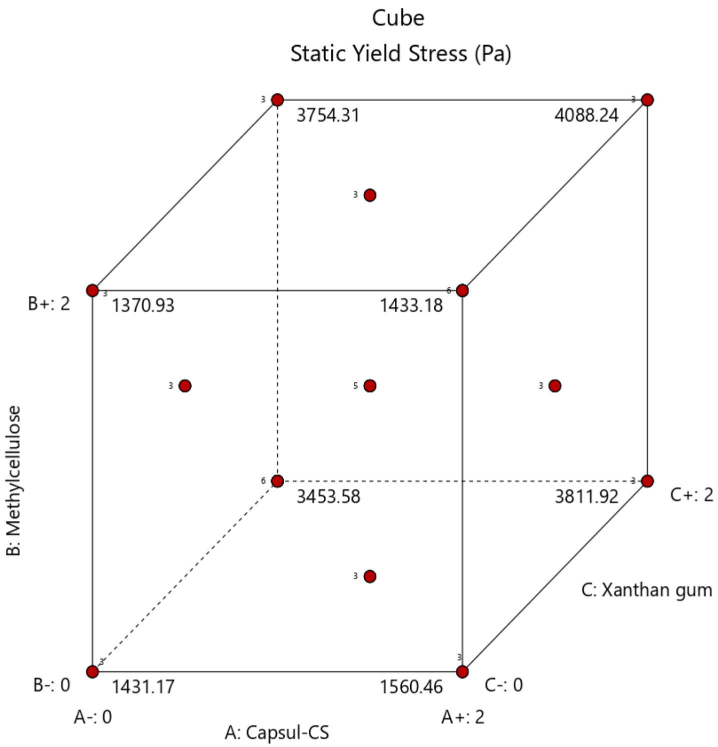
Total 47 experimentations were run to collect the data of three responses defined in preliminary stage of design of experiments.

Run	Factor 1 A:Capsul-CS	Factor 2 B:Methylcellulose	Factor 3 C:Xanthan gum	Response 1 Plastic Viscosity Pa.s	Response 2 Dynamic Yield S... Pa	Response 3 Static Yield Stress Pa
1	0	2	2	9.06	1188.9	3758.8
2	0	0	2	2.09	239.97	2888.57
3	0	2	0	9.39	922.69	1330.66
4	0	1	1	4.97	638.55	2493.59
5	1	2	1	5.19	1026.2	2304.6
6	0	0	2	2.08	228.68	3037.01
7	2	2	2	8.46	1136.8	4524.7
8	1	1	0	9	516.58	2296.5
9	0	2	2	7.74	1131	3429.05
10	1	0	1	13.92	812.89	3550.68
11	0	1	1	14.95	751.63	3372.37
12	2	2	0	10.3	654.01	1218.68
13	0	2	2	7.64	1148.2	4217.03
14	2	0	0	3.89	76.61	1151.65
15	1	0	1	2.07	269.61	2144.24
16	1	1	0	8.81	376.53	1268.06
17	2	2	0	10.45	1123.5	2060.11
18	2	0	0	3.7	89.31	1686.56
19	1	1	2	7.22	649.56	3913.78
20	1	1	1	7.61	654.86	2529.43
21	1	1	1	9.15	490.29	2847.69
22	1	2	1	7.21	670.5	1951.42
23	0	2	0	12.2	598.76	1399.31
24	2	2	2	16.39	639.8	4029.67
25	0	2	0	12.06	673.06	1331.22
26	2	0	2	2.2	235.28	3021.12
27	0	0	0	2.53	185.72	1160.85
28	2	0	2	2.24	253.66	4037.8
29	1	0	1	2.35	286.44	2616.07
30	1	1	0	9.27	505.13	1396.02
31	2	1	1	6.23	481.52	1656.84
32	1	1	2	8.7	392.2	3351.49
33	1	2	1	8.14	775.25	1760.23
34	0	0	0	2.8	171.76	1238.76
35	2	0	2	2.47	245.41	4535.51
36	1	1	1	6.52	626.88	3319.28
37	2	1	1	4.6	603.91	2602.79
38	0	0	0	2.67	176.45	1195.56
39	1	1	1	4.88	643.07	2451.46
40	2	2	2	14.11	827.51	4515.74
41	1	1	2	9.5	472.89	3905.26
42	2	0	0	4.09	155.34	1808.28
43	2	1	1	4.57	658.97	2995.63
44	2	2	0	13.14	813.98	1632.58
45	0	0	2	2.21	225.12	3930.41
46	0	1	1	4.75	778.99	3380.21
47	1	1	1	8.23	525.23	3278.27

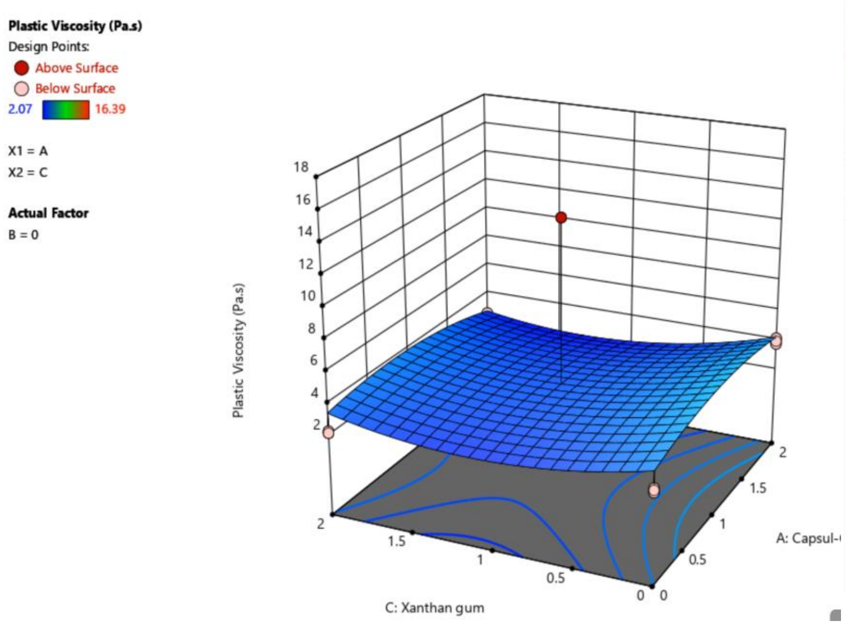
In trinary mixes MC has considerable effect on plastic viscosity and dynamic yield stress; however, XG has significant effect on static yield stress.

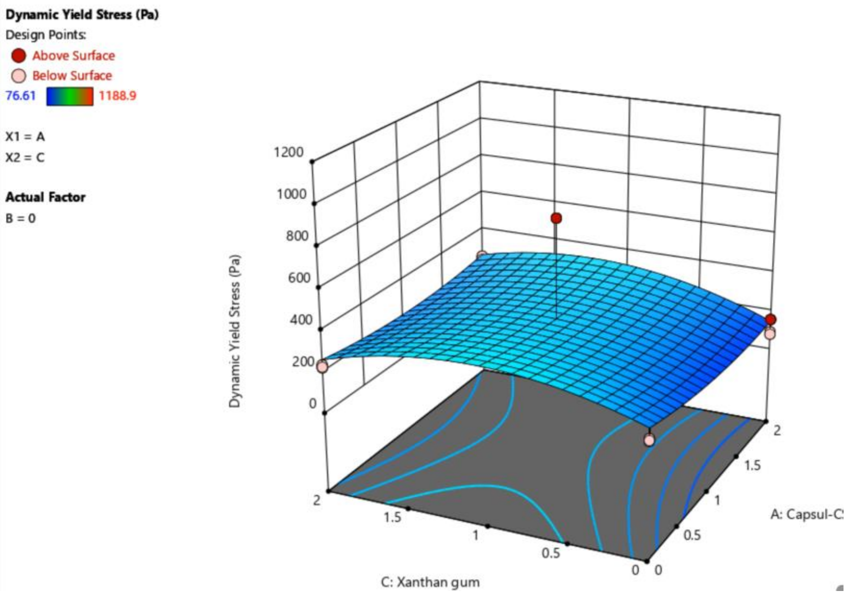


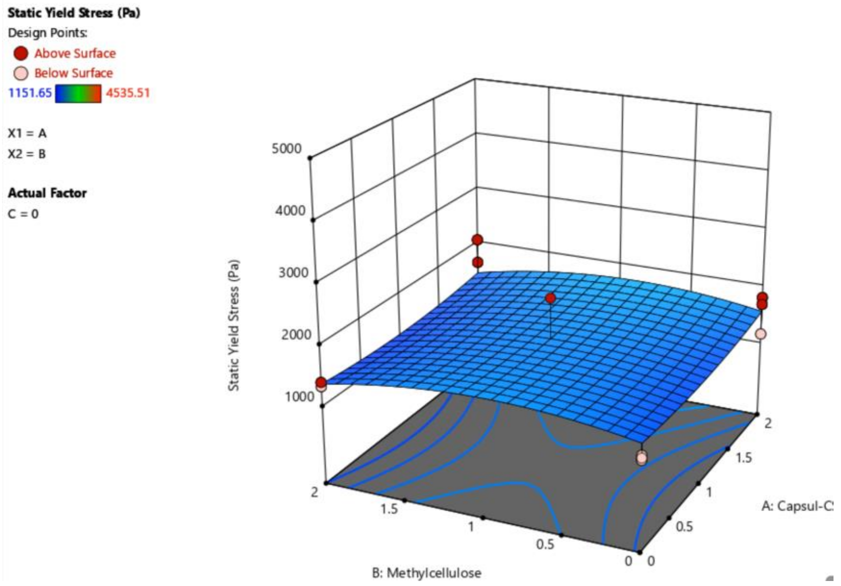




Interaction of all three rheology modifiers in the trinary mixes.

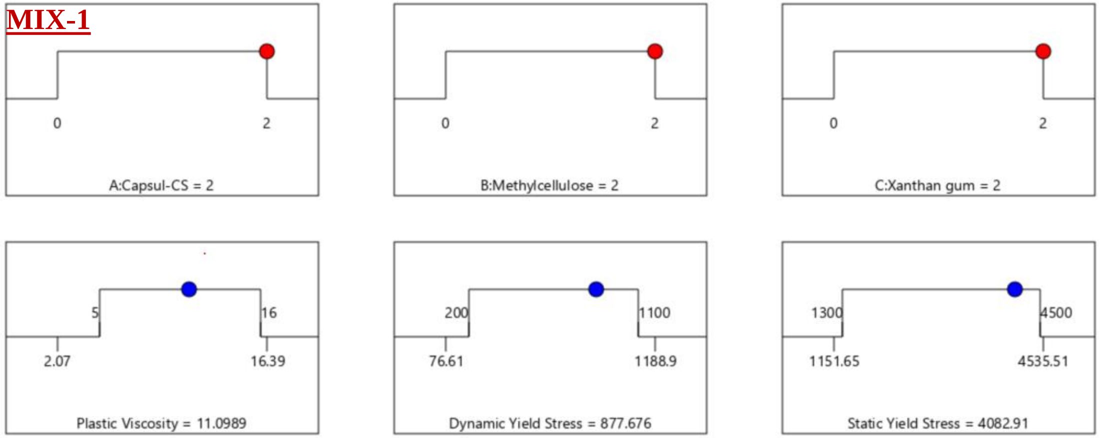




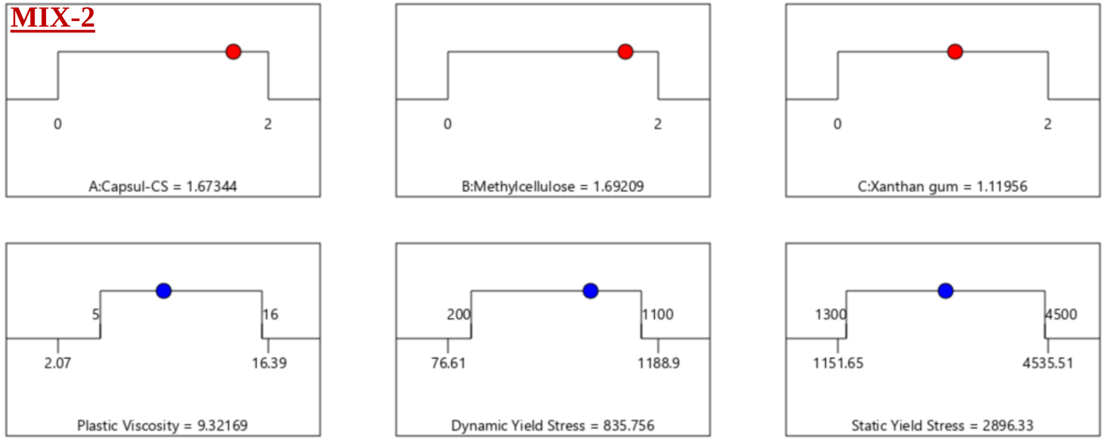


The optimization suggested around 100 different combinations out of which four mixes were selected for printability evaluation.

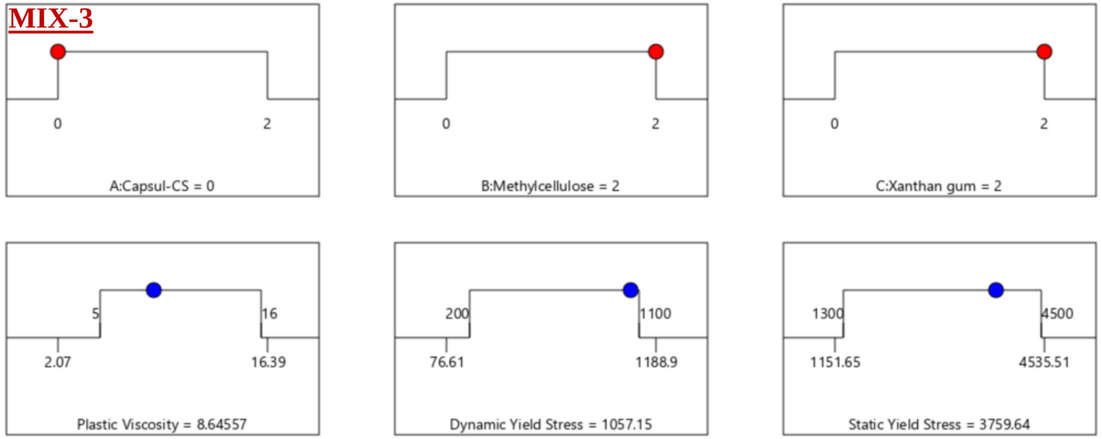
MIX-1



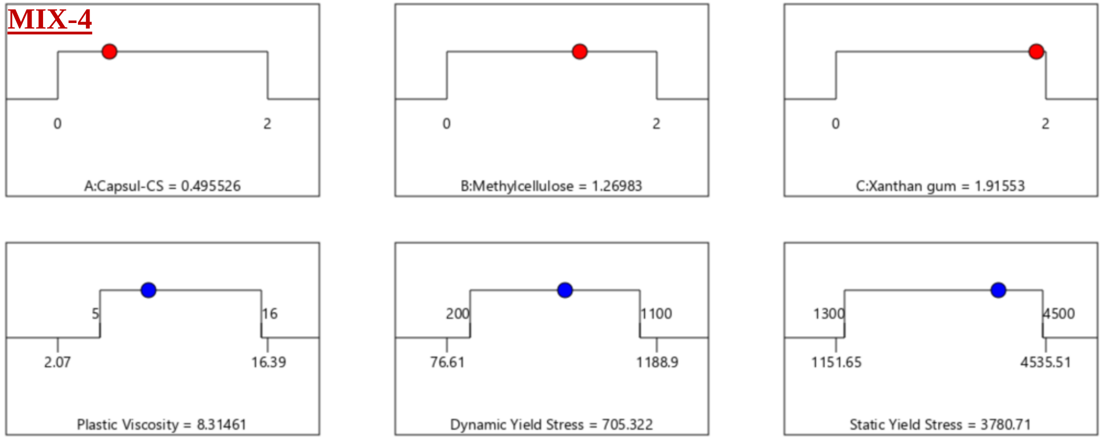
MIX-2



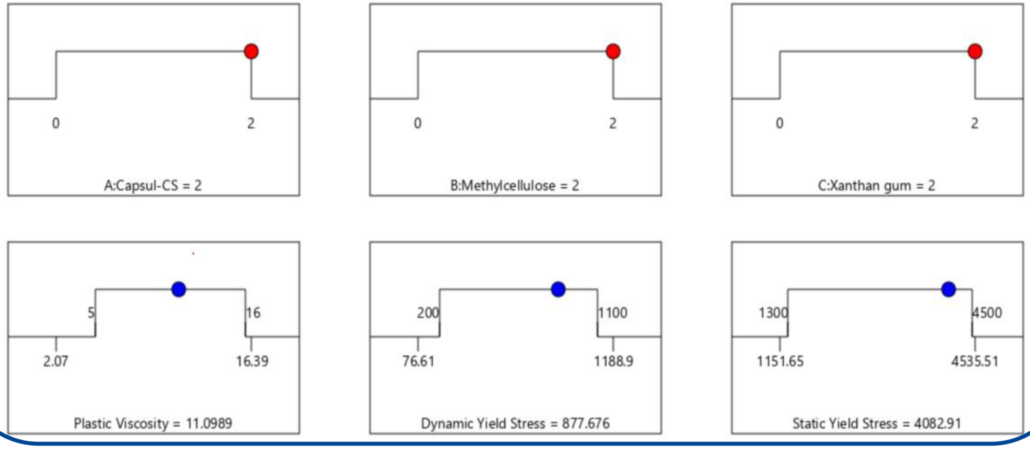
MIX-3

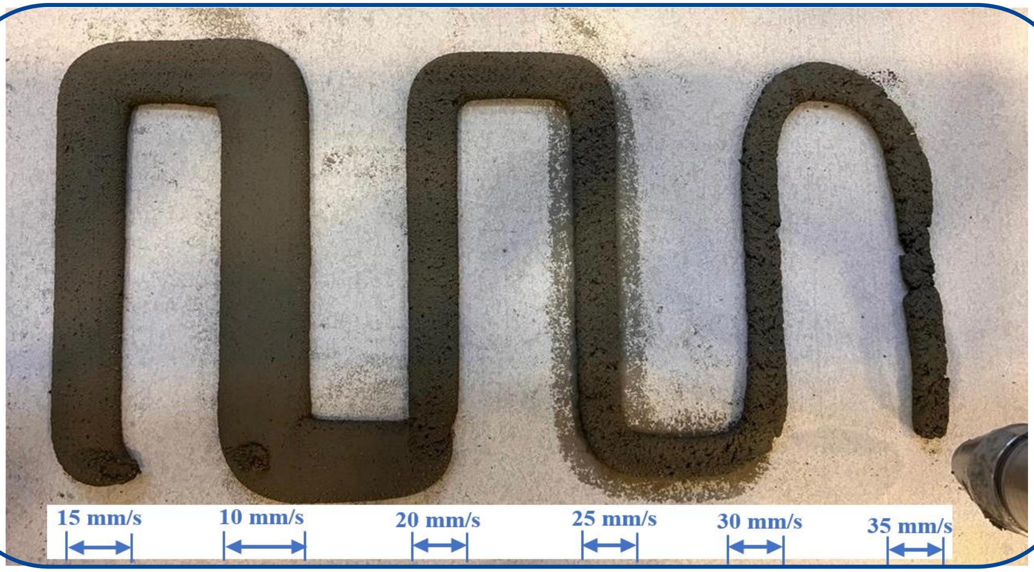


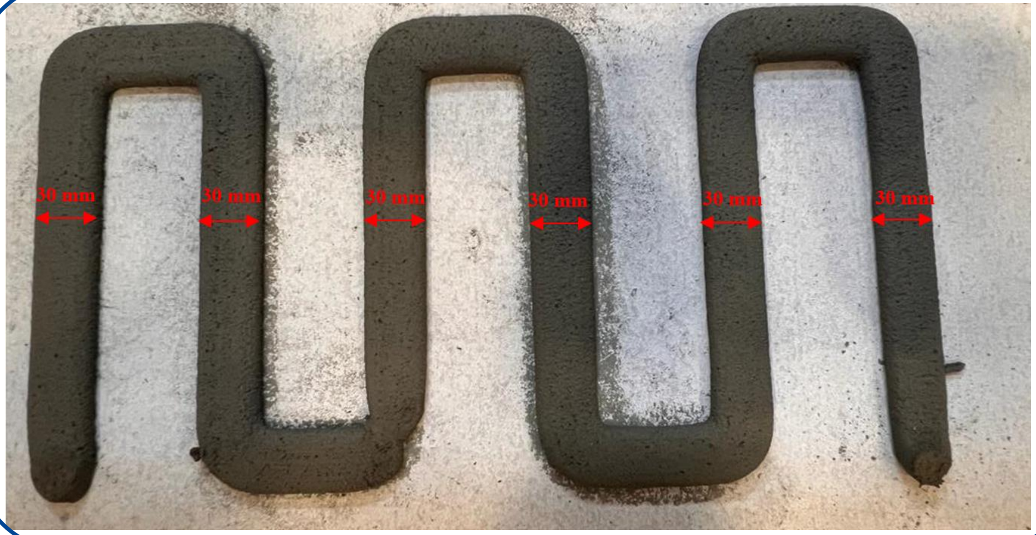
MIX-4



MIX-1: Extrudability







ACI Concrete Convention

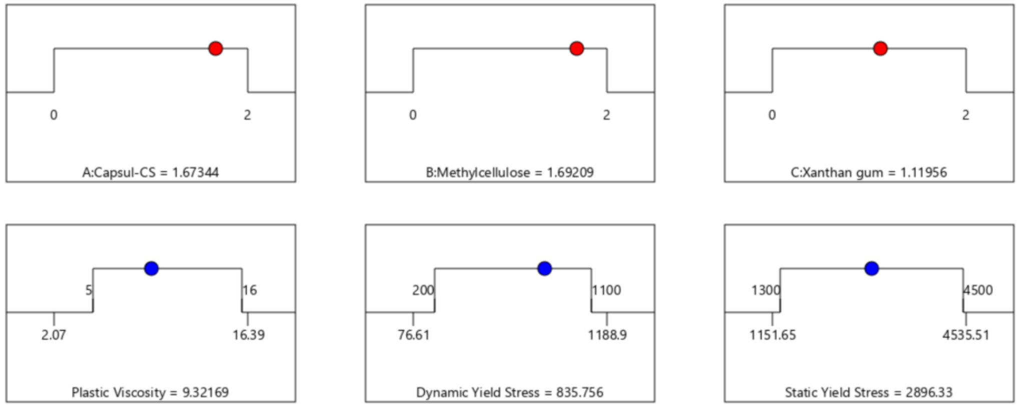
MIX-1: Buildability

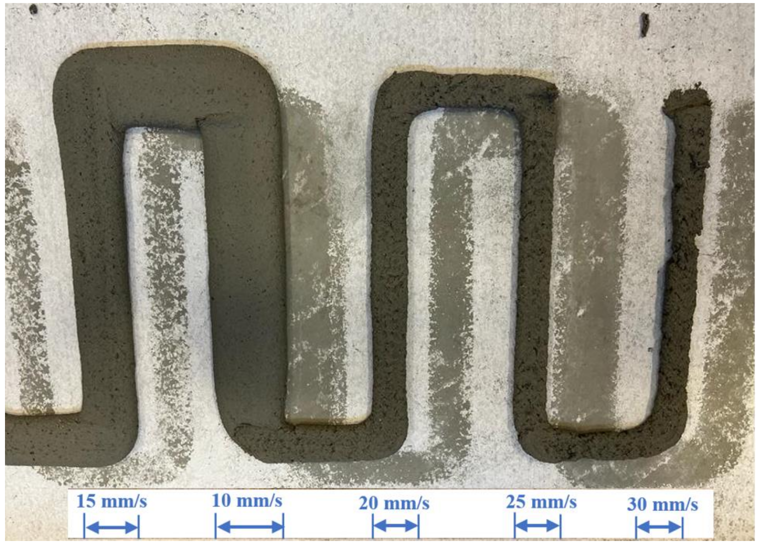
Height Measurement after 10 layers

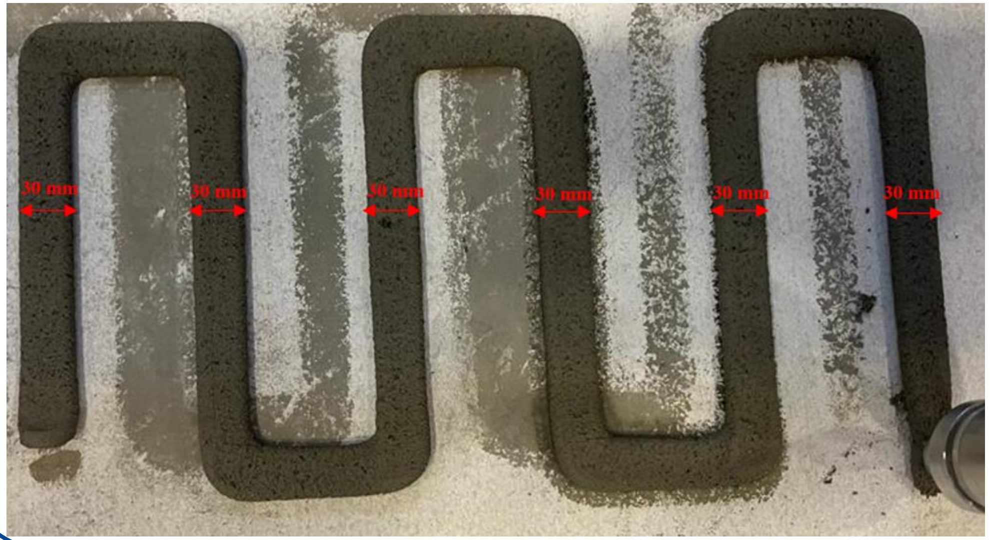
Shape Retention

Height Measurement after 20 layers

MIX-2: Extrudability







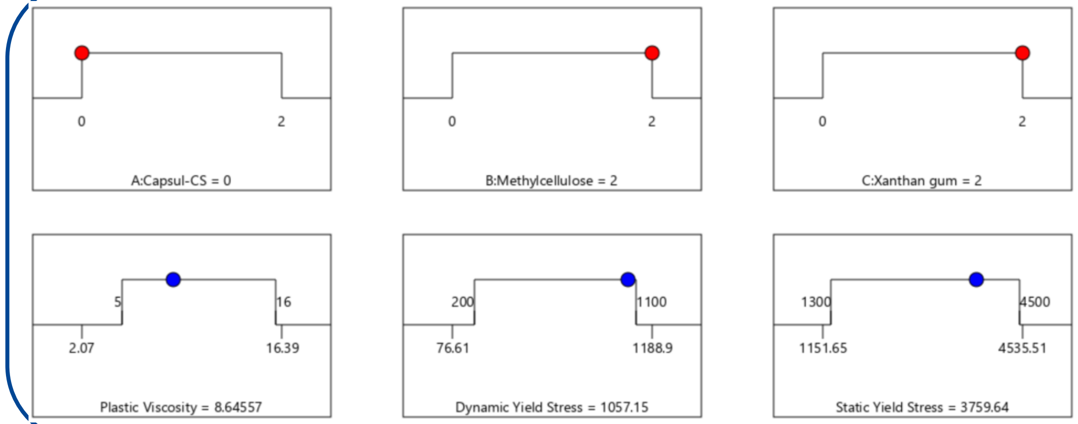
MIX-2: Buildability (The comparatively lower static yield stress resulted a collapse after 15th layer)

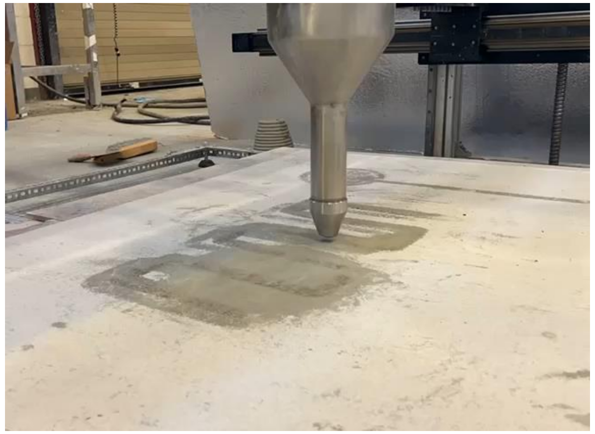
Height Measurement after 10 layers

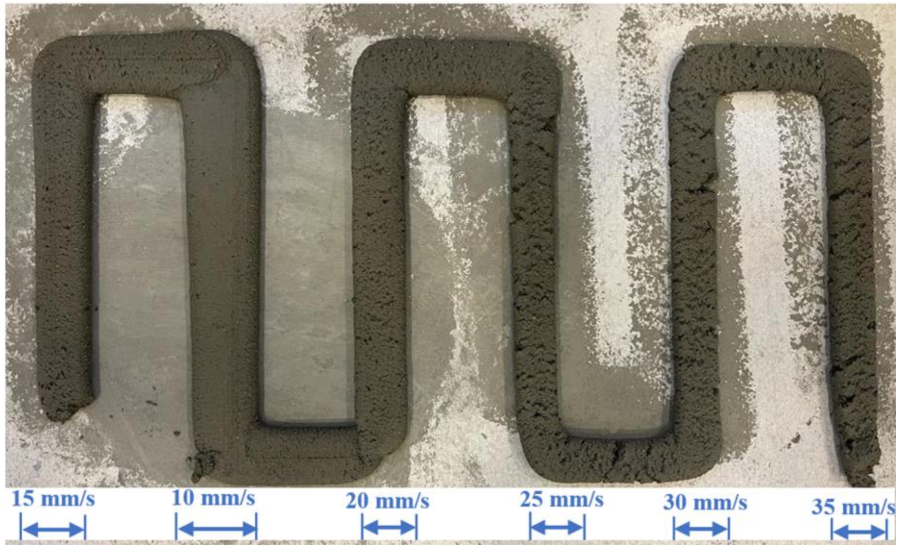
Shape Retention

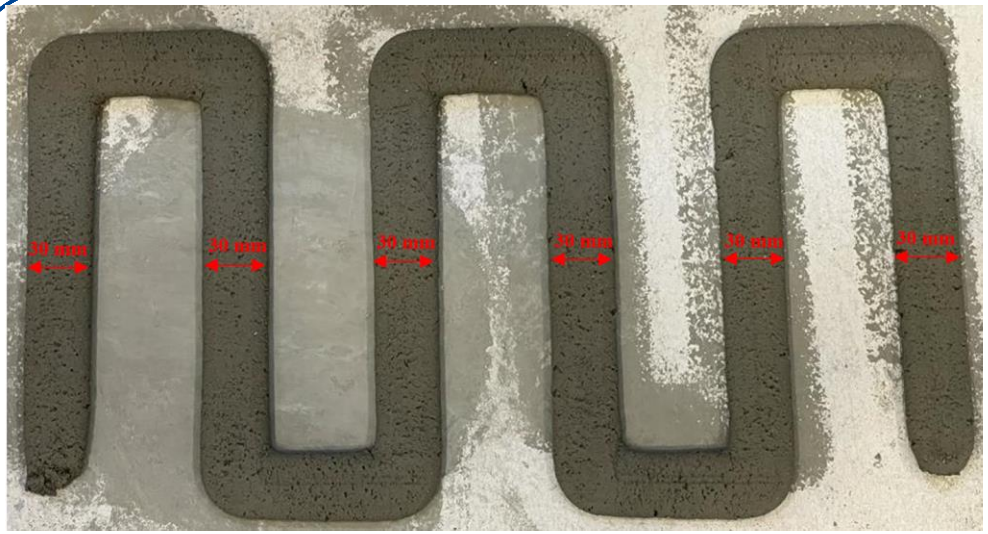
Height Measurement after 15 layers

MIX-3: Extrudability









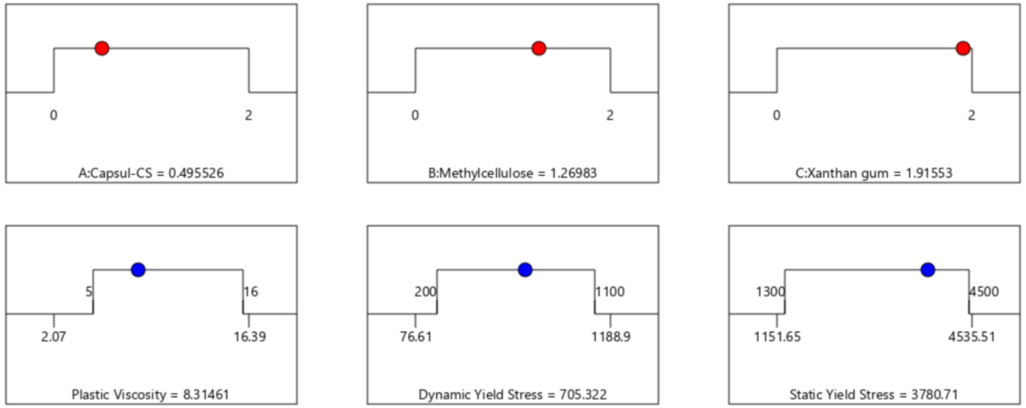
MIX-3: Buildability

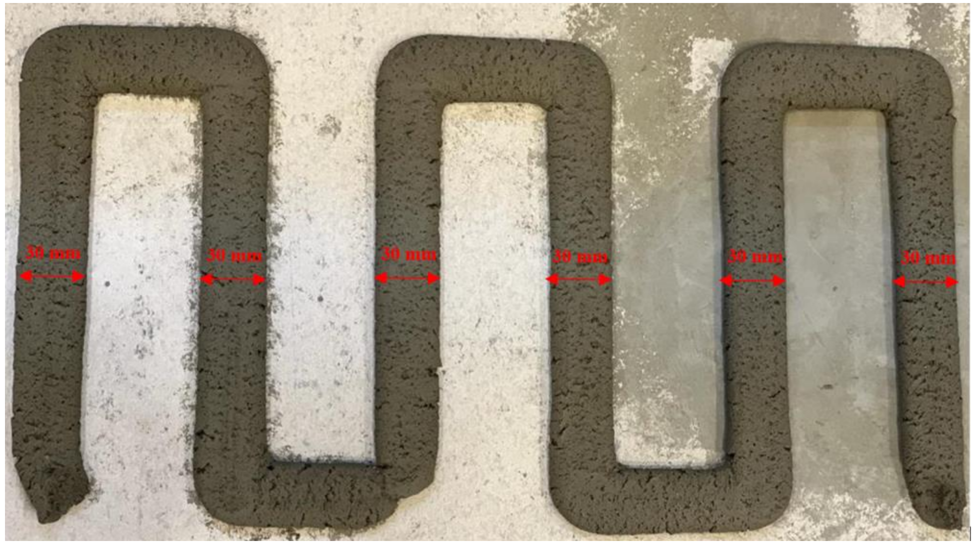
Height Measurement after 10 layers

Shape Retention

Height Measurement after 21 layers

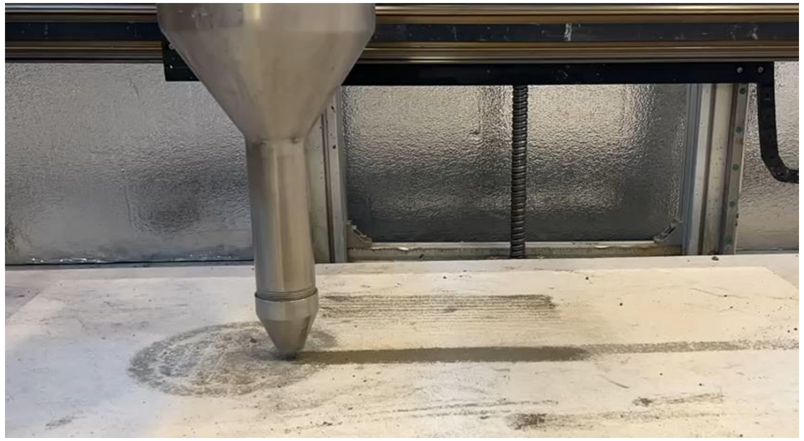
MIX-4: Extrudability





MIX-4: Buildability

Height Measurement after 10 layers



Shape Retention

Height Measurement after 23 layers

Summary:

Mix #	Flowability (cm)	Extrudability	Buildability (Stacked Layers)	Shape Retention	Printing Speed (mm/s)	Extrusion Speed (round/s)
1	11.8	✓	20	✓	15	0.15
2	13	✓	15	✓	20	0.15
3	12.97	✓	21	✓	15	0.15
4	13	Surface Cracks	23	✓	15	0.15

Conclusions

- The individual addition of VMAs leads to some negative impacts on several rheological parameters.

- The response surface methodology is an effective tool to get the optimized mixes.

- The inclusion of different VMAs in binary and trinary optimized the several rheological requirements (Plastic viscosity, dynamic yield stress and static yield stress)

- The mix-1 containing 2% of corn starch, methylcellulose, and xanthan gum and mix-3 containing 2% of methylcellulose, and xanthan gum displayed better printing quality in terms of buildability, shape retention, and extrudability.

- Corn starch, Xanthan gum, and Methylcellulose are quite effective bio-degradable rheology modifiers to utilize in 3D concrete printing applications. The plastic viscosity, dynamic yield stress and static yield stress were found in the ranges of 5-16 Pa.s, 200-1100 Pa, 1300-4500 Pa, respectively.

Future Work

- Evaluating the Green strength of optimized mixes
  - Direct Shear Test
  - Unconfined Compressive Strength Test
- Investigate the effect of adding VMA's on hydration kinetics of the mixes → Calorimetry
- Evaluating the effect of VMA's addition on hardened state strength → Compressive Strength (28 days)

THANK YOU!

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Tran-SET
Transportation Consortium of South-Central States

BASF
The Chemical Company

GCC

Cargill

Working Mechanism of VMA