

CELLULOSE & LIGNIN IN ADDITIVE MANUFACTURING

Potential and challenges in the fabrication of structural nodes for free-form building envelope structures

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MSc Graduation Thesis Final Presentation

Mentors

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BACKGROUND

OBJECTIVE

RESEARCH

MATERIAL EXPLORATION

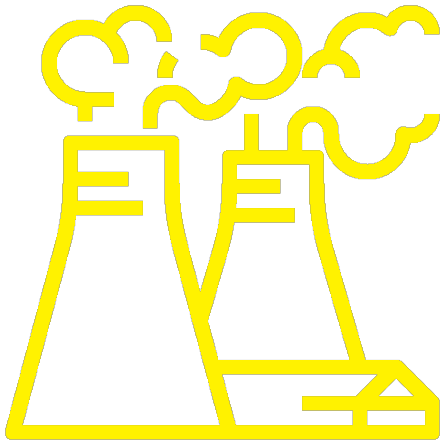
PRINTABILITY EXPLORATION

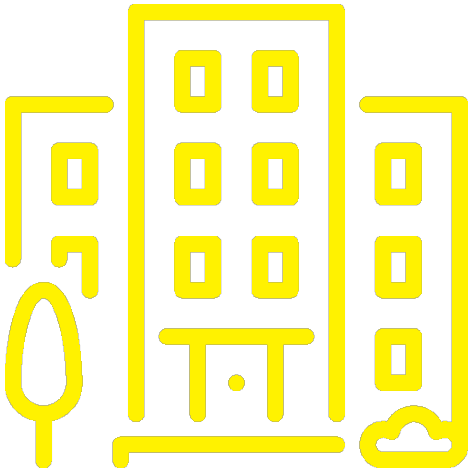
PROPERTIES EXPLORATION

DESIGN & PROTOTYPING

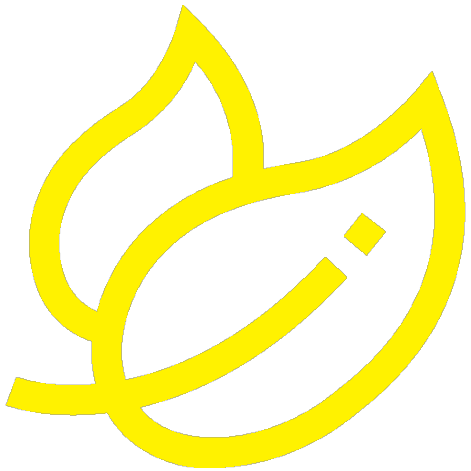
CONCLUSIONS

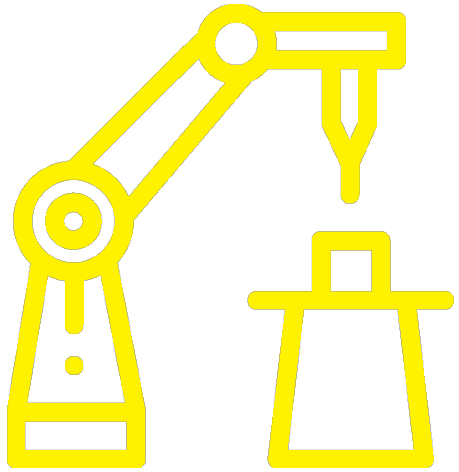
PROBLEM STATEMENT



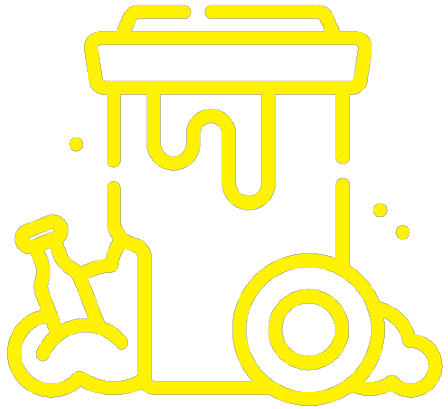


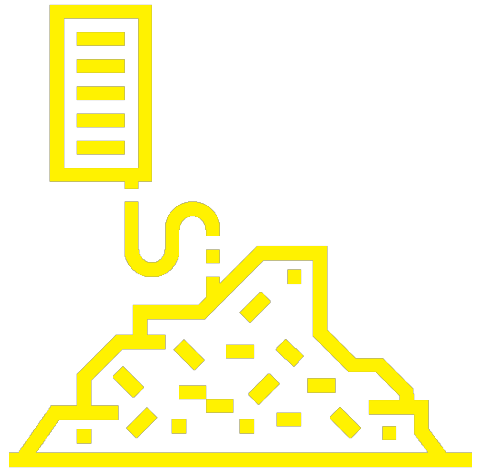
Construction industry & building stock account for 39% of all greenhouse gases emissions





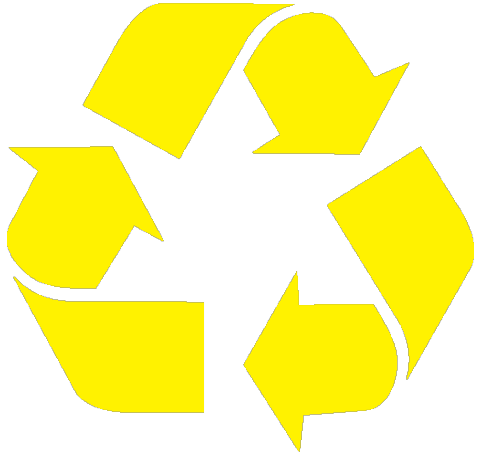
AM is the most efficient fabrication process however the options of bio-based feedstock are limited



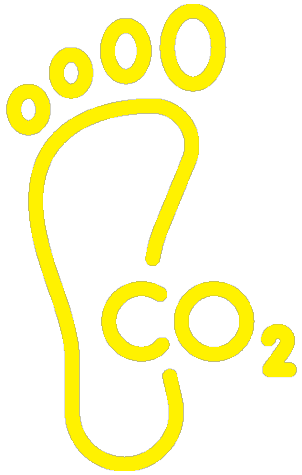


Wood, paper and agricultural residues rich in lignocellulosic fibres wasted

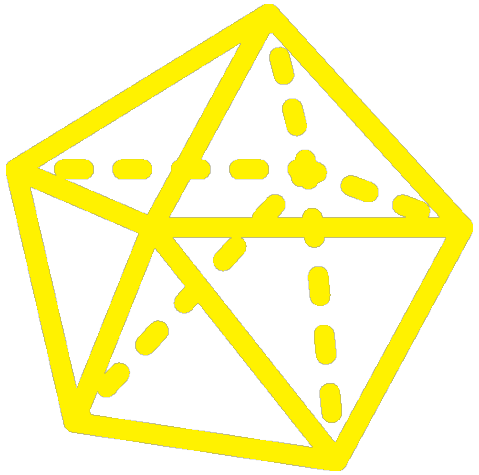
DESIGN VISION



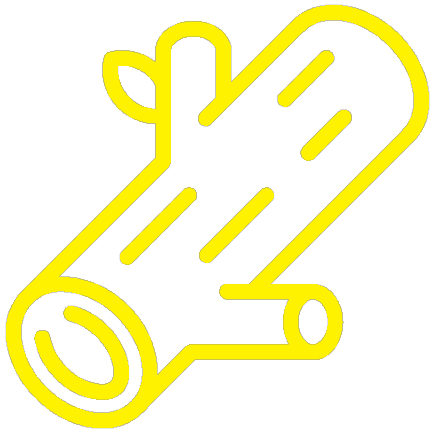
Recycle and upcycle natural residue in the building industry



Reduce the carbon footprint of the building industry



AM and natural materials to fabricate complex geometries



Wood in AM and to efficiently fabricate complex geometries

BACKGROUND

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RESEARCH

MATERIAL EXPLORATION

PRINTABILITY EXPLORATION

PROPERTIES EXPLORATION

DESIGN & PROTOTYPING

CONCLUSIONS







AIM



RESEARCH QUESTION

What are the **potential** and **challenges** of a material made of cellulose and lignin as feedstock for additive manufacturing processes in the fabrication of structural nodes for free-form structures?


ANSWER


ANSWER

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WOOD IN AM



CELLULOSE & RESIN STRUCTURAL WALL
WOULD WOOD – RISE, SWEDEN



WOOD FLOUR & METHYLCELLULOSE
UMEA - SWEDEN



SAWDUST & BIO-EXPOXY
FORUST - USA



WOOD FLOUR & PLA
UNIVERSITY OF MAINE - USA

CELLULOSE & LIGNIN IN AM



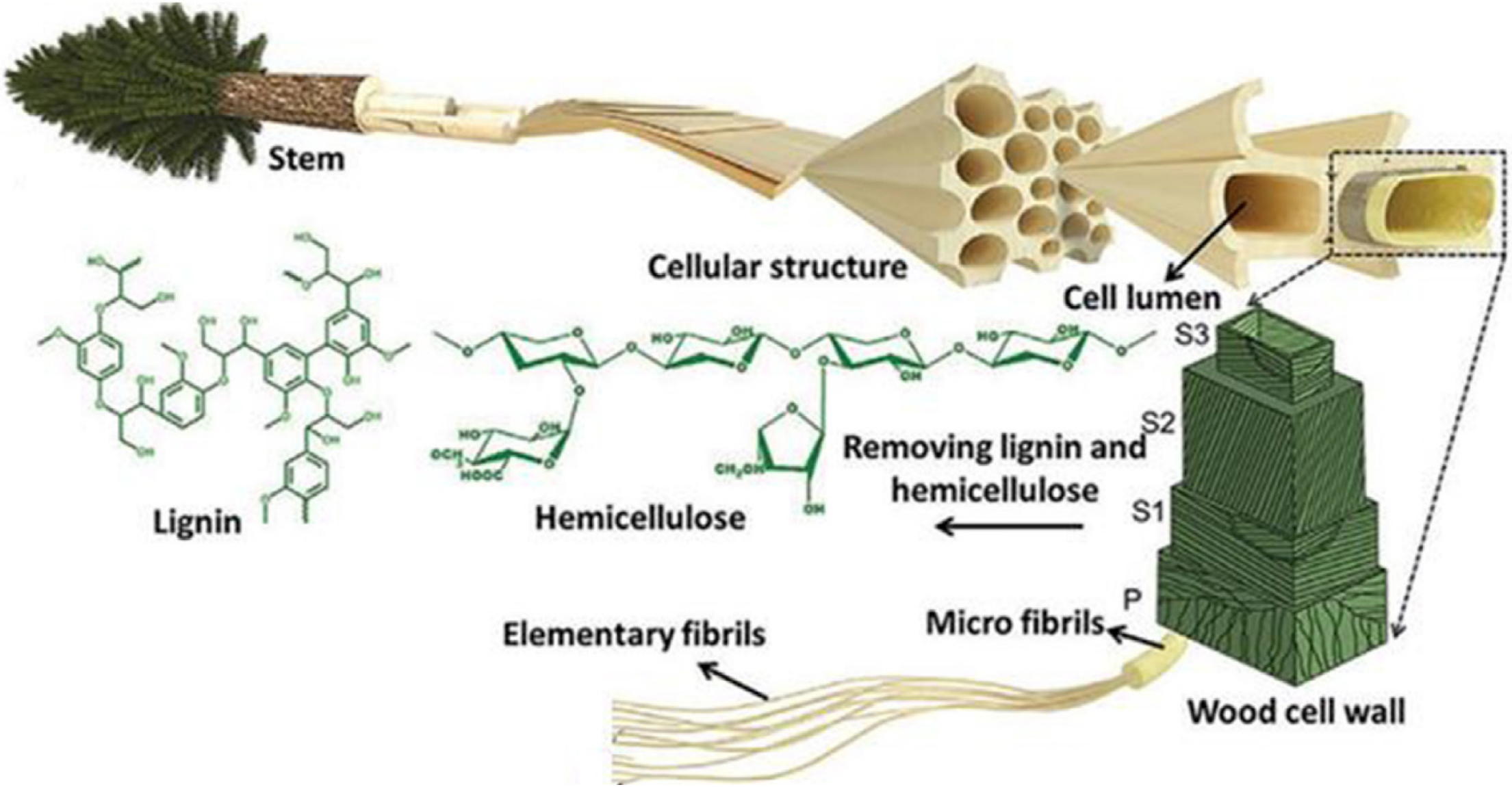




LIGNOCELLULOSIC POLYMERS



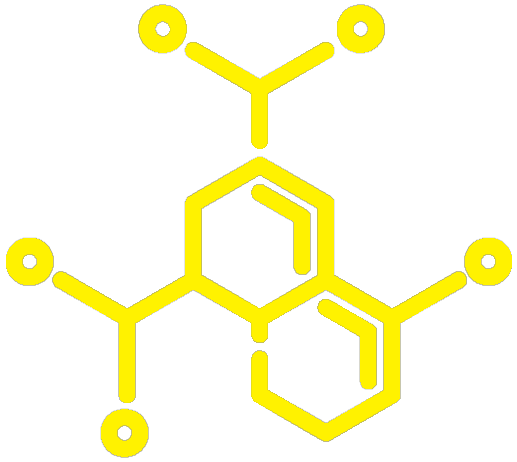
LIGNOCELLULOSIC POLYMERS



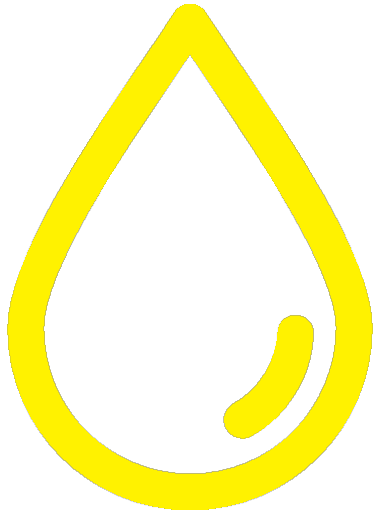
CELLULOSE



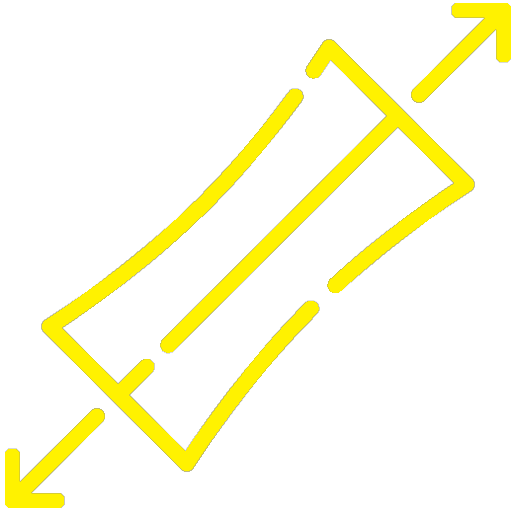
CELLULOSE



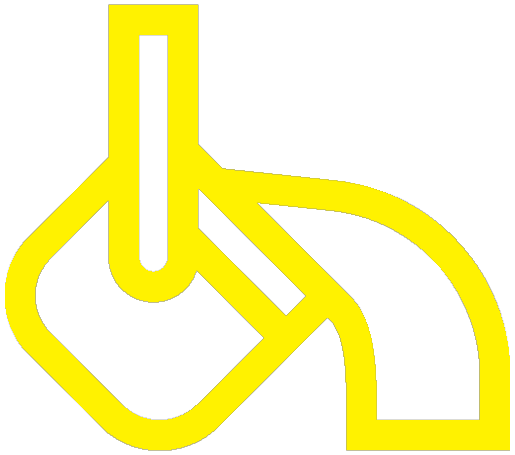
Most abundant polymer in nature



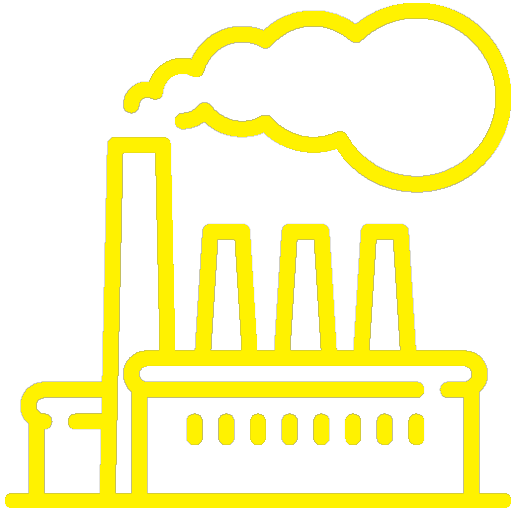
Hygroscopic behaviour



High tensile strength



Degradation before melting above 300C

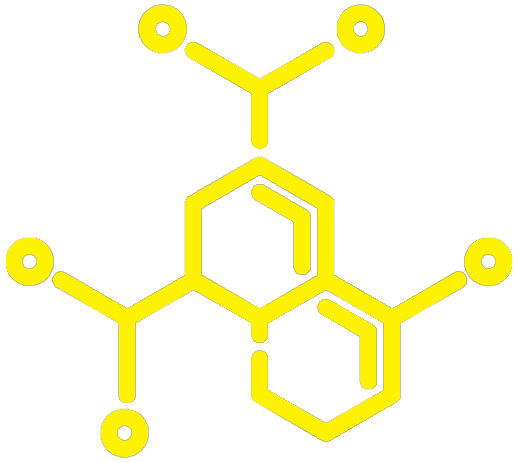


Kraft production process

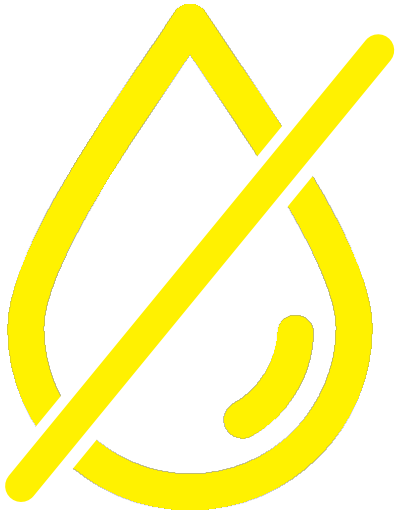
LIGNIN



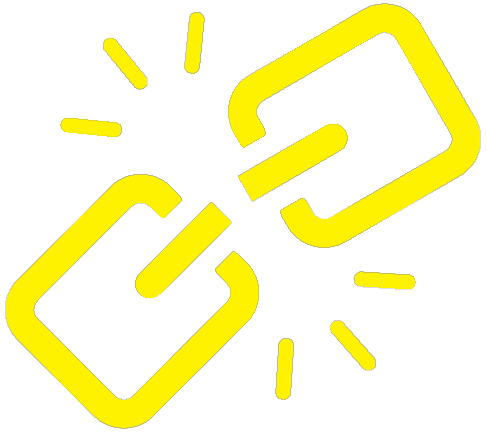
LIGNIN



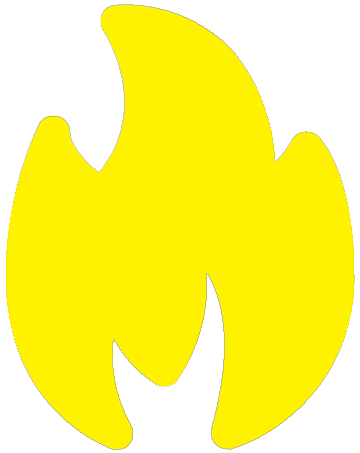
Second most abundant polymer in nature



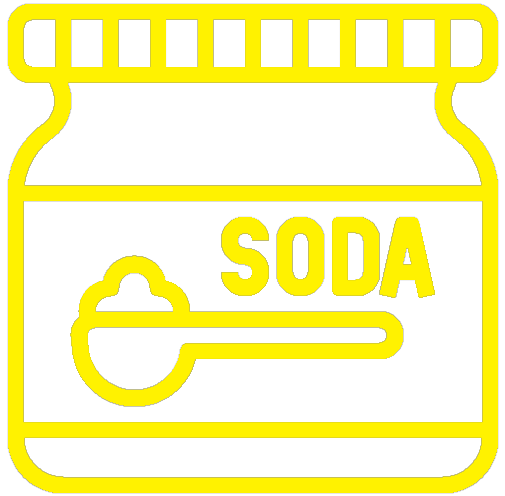
Hydrophobic behaviour



Brittle



Quick degradation (char) above 225C



Soda type

BINDERS



ACETONE



XANTHAN GUM



METHYLCELLULOSE



DMSO



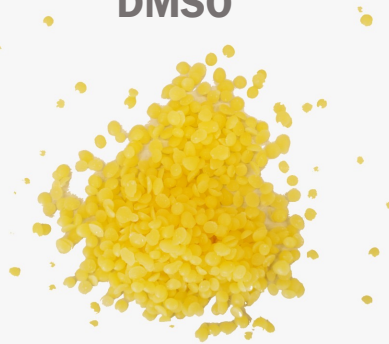
GLYCERINE



CORN STARCH



ALGINATE



BEESWAX



BONE GLUE



WOOD GLUE



BAKING SODA



SUNFLOWER OIL

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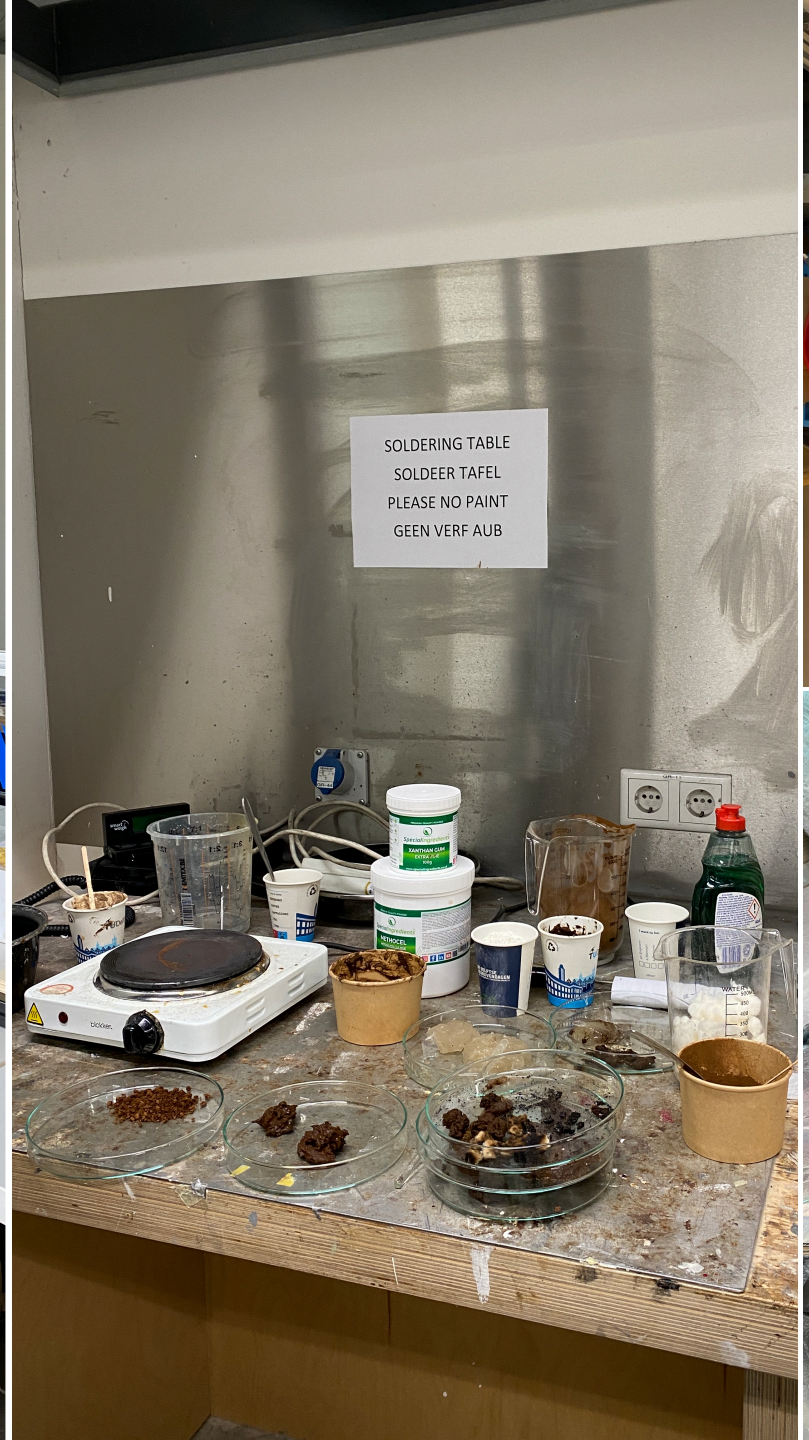
CONCLUSIONS




SOLDERING TABLE
SOLDEER TAFEL
PLEASE NO PAINT
GEEN VERF AUB


WORKSTATION



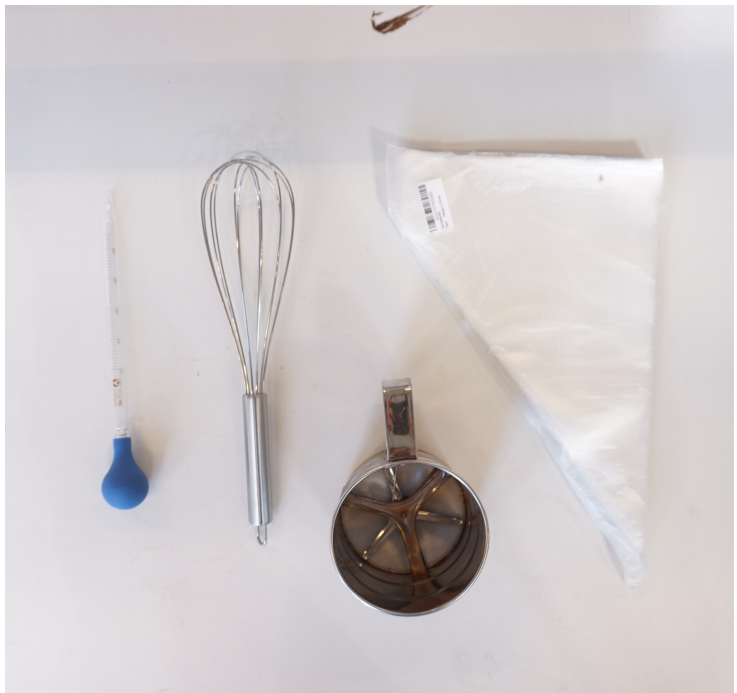
EQUIPMENT













MATERIALS



ACETONE



XANTHAN GUM



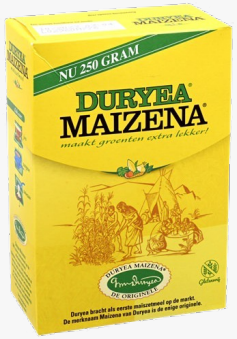
METHYLCELLULOSE



DMSO



GLYCERINE



CORN STARCH



ALGINATE



BEESWAX



BONE GLUE



WOOD GLUE

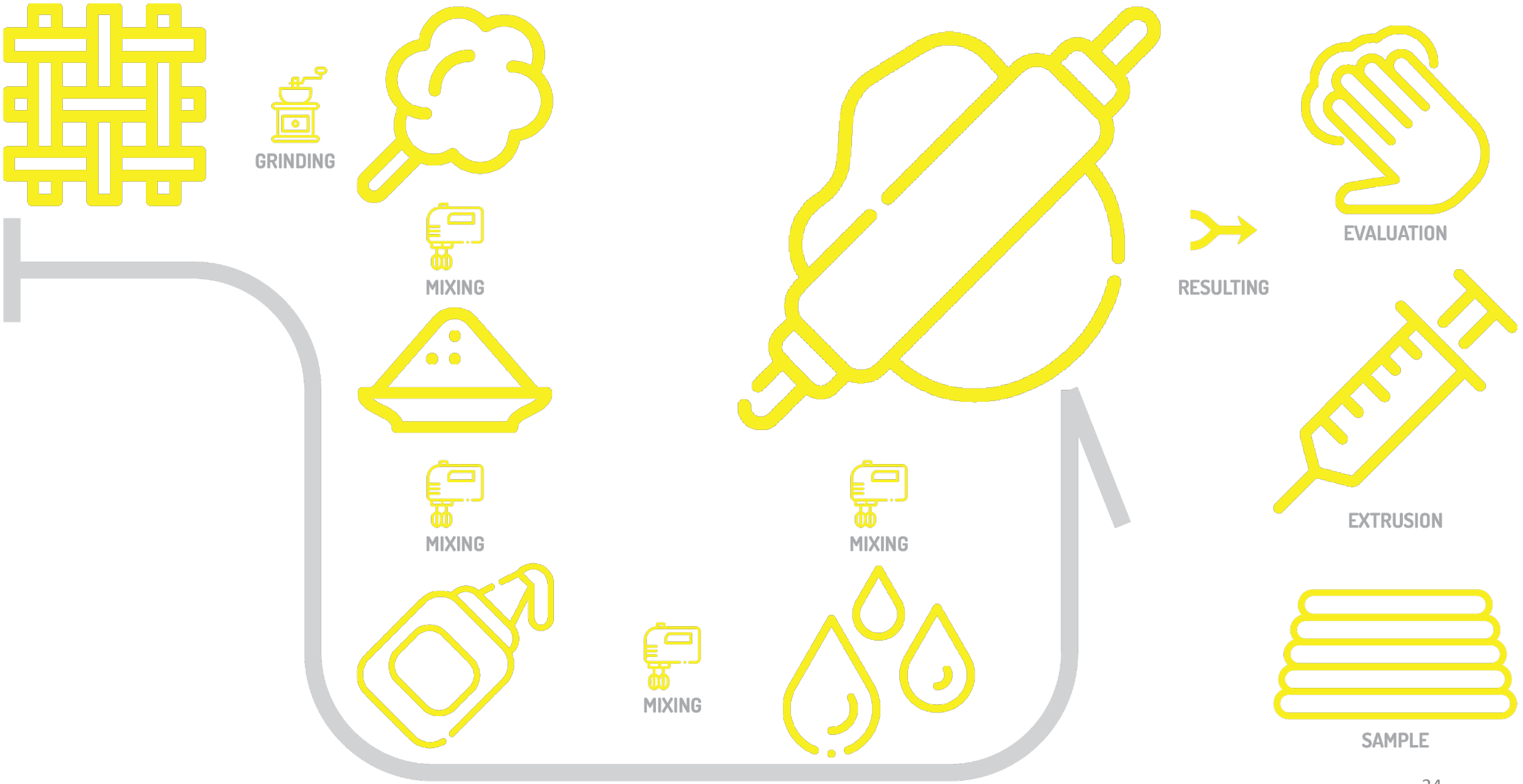


BAKING SODA



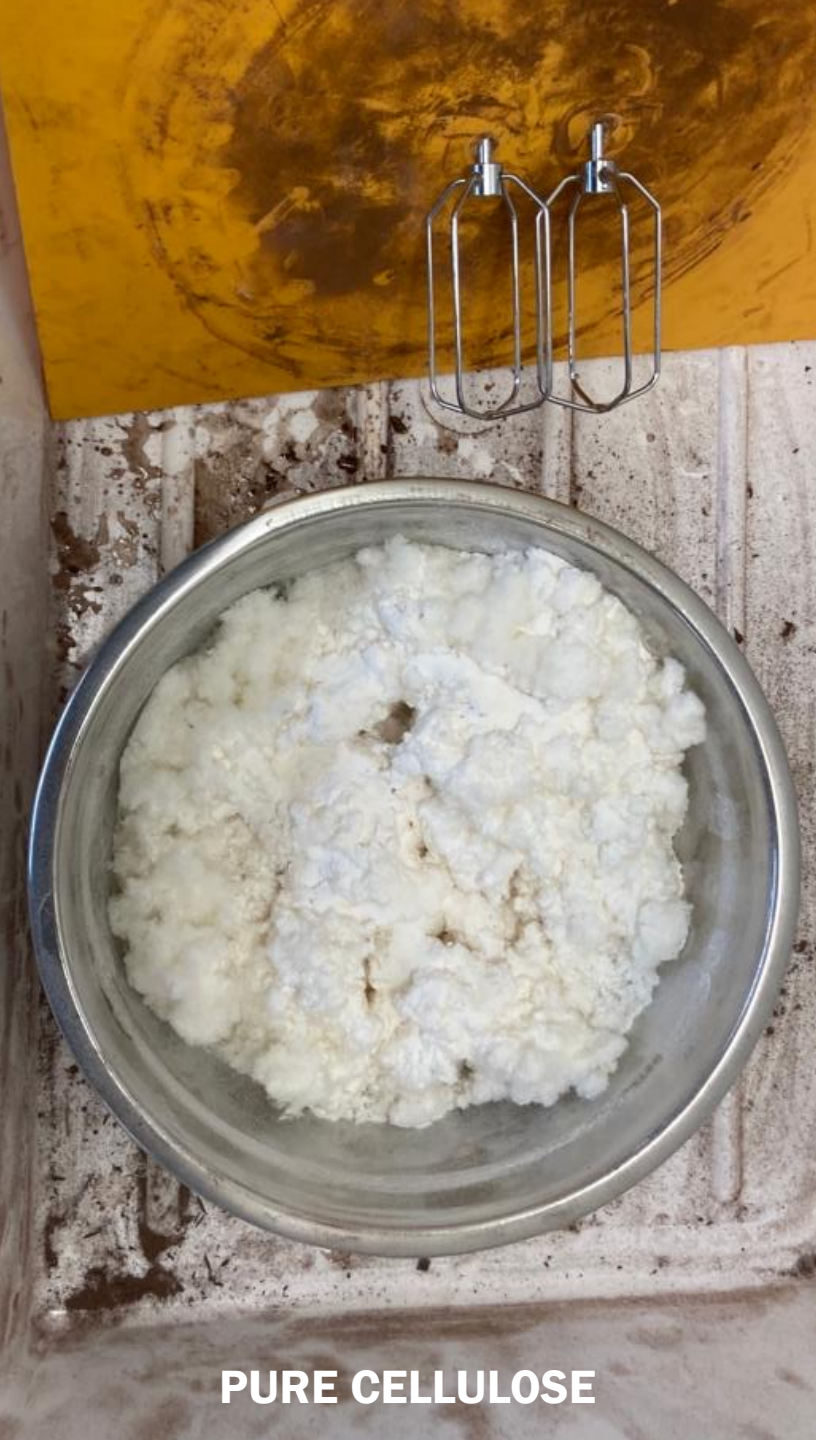
SUNFLOWER OIL

MIXING WORKFLOW



WORKFLOW

MIXING PROCESS



PURE CELLULOSE

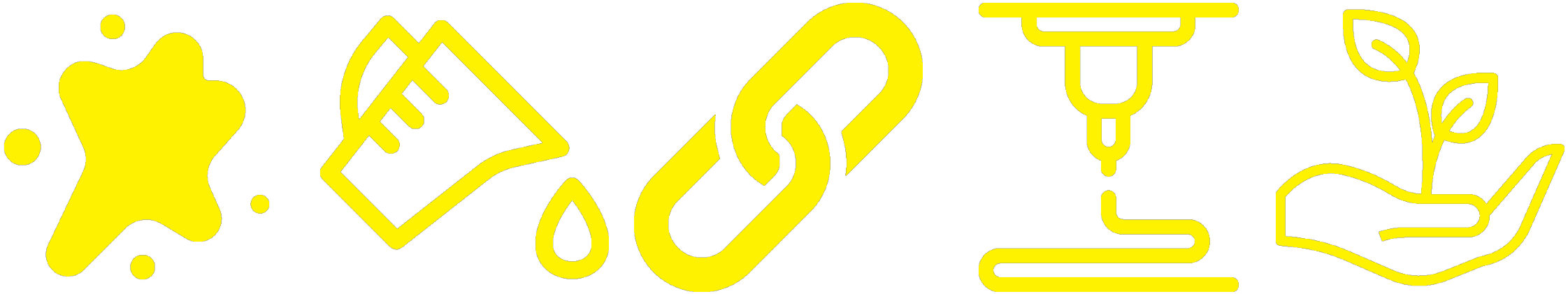


CELLULOSE, LIGNIN & BINDER

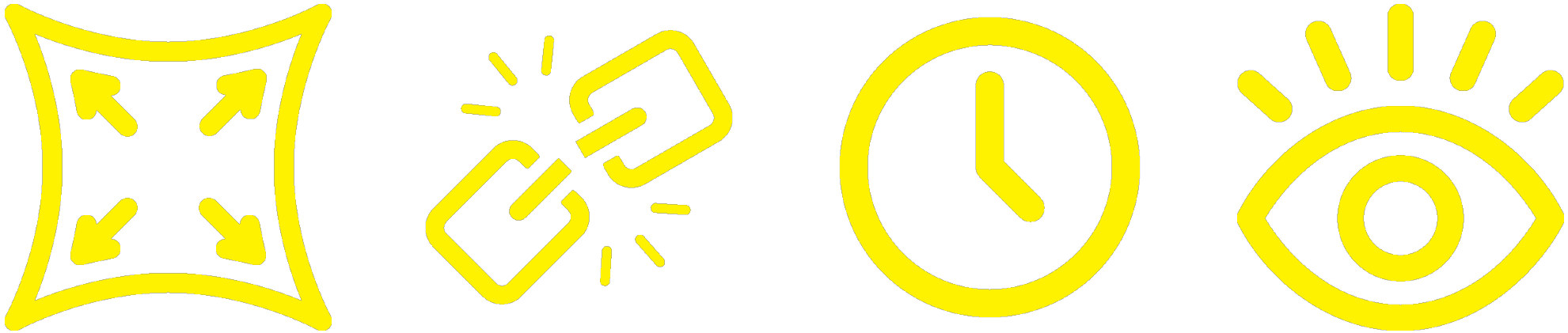


PASTE

EVALUATION CRITERIA

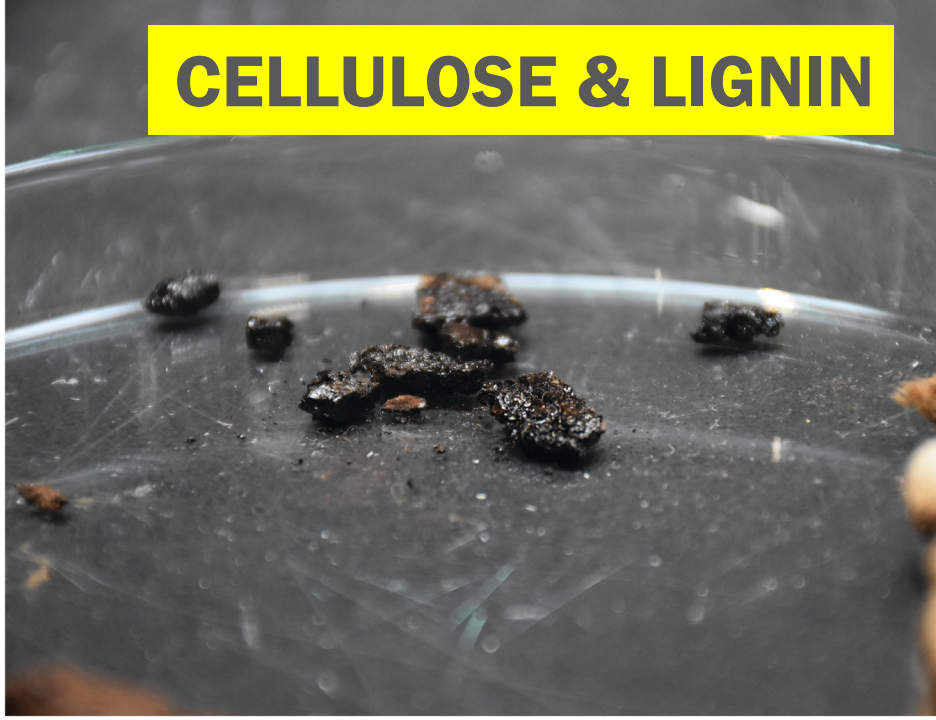


HOMOGENEITY VISCOSITY ADHERENCE EXTRUDABILITY BIO-BASED



SHRINKAGE BRITTLENESS CURING TIME AESTHETICS




CELLULOSE & LIGNIN












XANTHAN GUM






METHYLCELLULOSE



METHYLCELLULOSE




DMSO



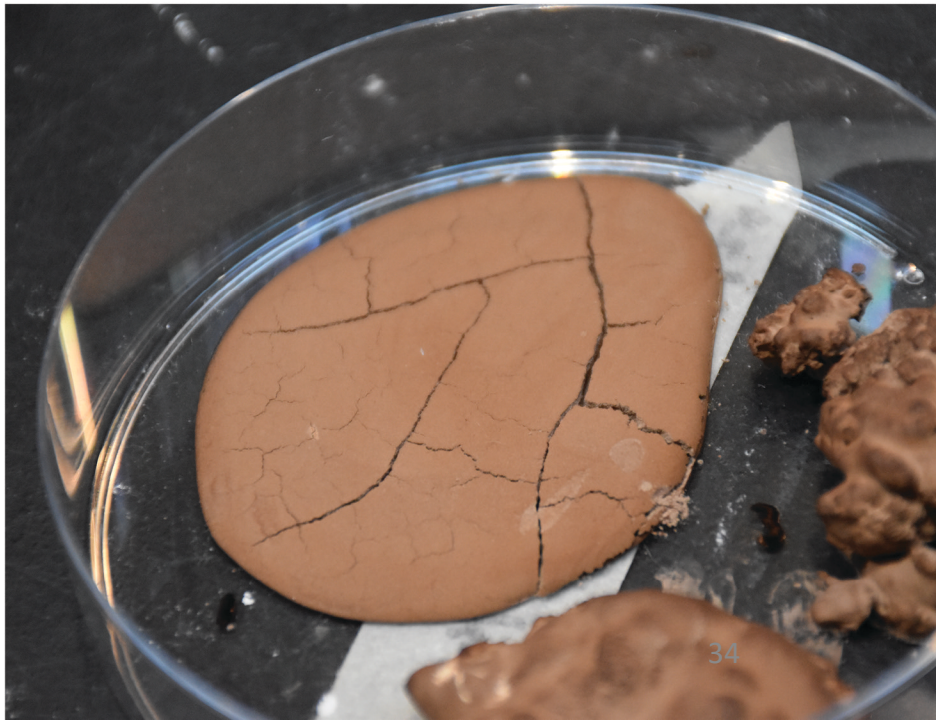



GLYCERINE



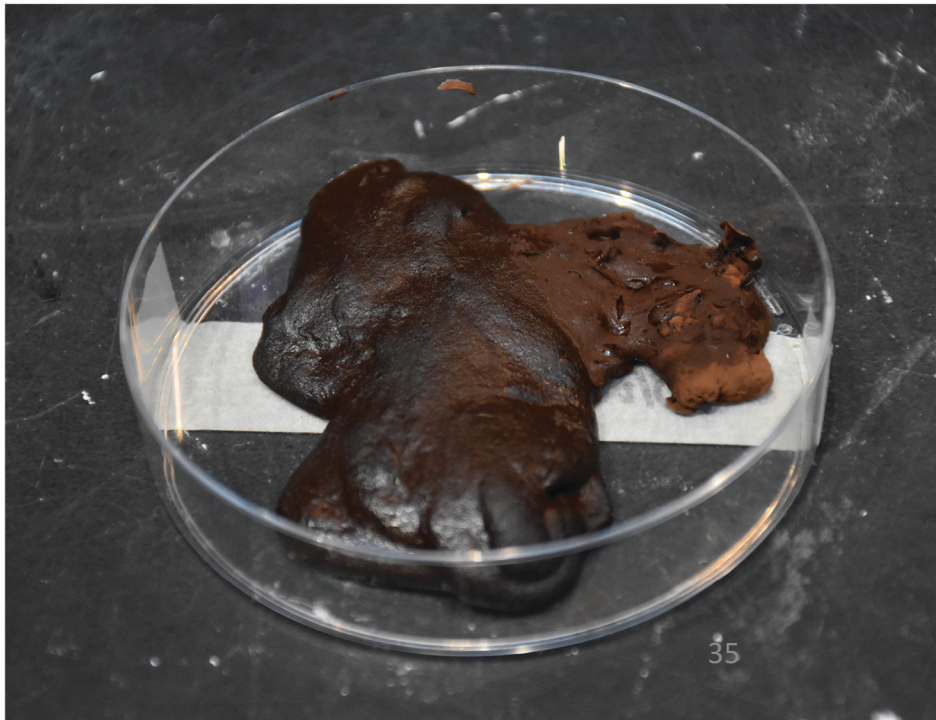



CORN STARCH






ALGINATE





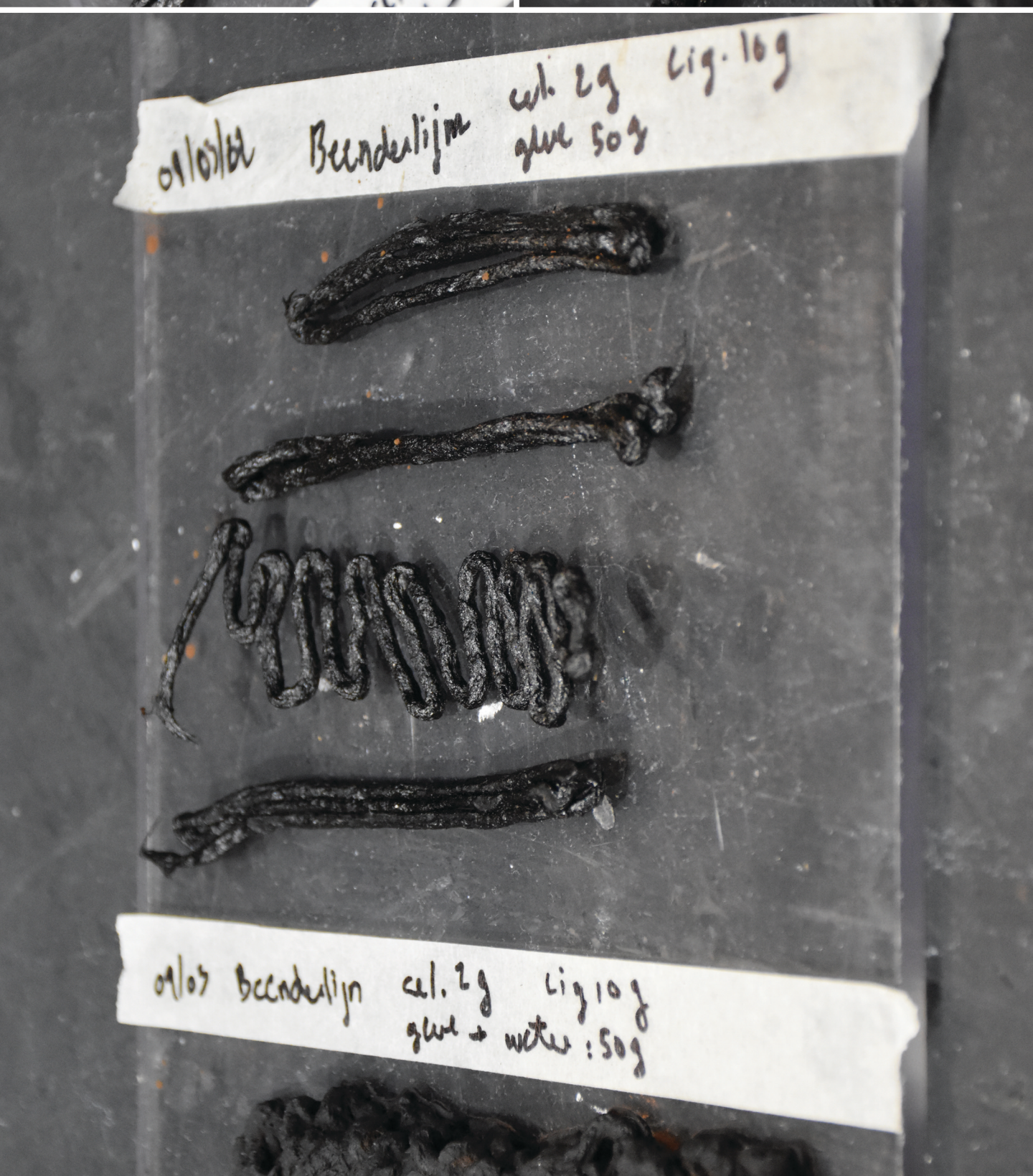

BEESWAX



BONE GLUE




Beendelijm cal. 2g
glue 50g


01/03/22 Beendelijm cal. 2g Lig. 10g
glue 50g
01/03 Beendelijm cal. 2g Lig 10g
glue + water : 50g

WOOD GLUE




BAKING SODA






SUNFLOWER OIL



RESULTS & COMPARISON

	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASED	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETICS	TOTAL
MIX 1 I ACETONE	1	1	1	1	-1	0	1	1	-1	2
MIX 2 I XANTHAN	-1	-1	-1	-1	1	0	0	-1	-1	-5
MIX 3 I MC	1	1	1	1	1	-1	0	1	1	6
MIX 4 I DMSO	1	1	1	1	1	0	0	-1	0	4
MIX 5 I GLYCERINE	-1	-1	-1	-1	1	0	0	-1	0	-4
MIX 6 I CORN STARCH	0	-1	-1	-1	1	0	-1	0	1	-2
MIX 7 I ALGINATE	-1	-1	-1	-1	1	0	0	0	0	-3
MIX 8 I BEE WAX	-1	-1	-1	-1	0	0	-1	1	-1	-5
MIX 9 I BONE GLUE	1	1	1	0	1	-1	0	0	-1	2
MIX 10 I WOOD GLUE	1	1	1	1	-1	0	1	0	1	5
MIX 11 I OIL	1	-1	-1	1	-1	0	0	-1	1	-1
MIX 12 I BS	-1	0	-1	-1	0	0	1	1	0	-1



PHASE 3 - ACETONE



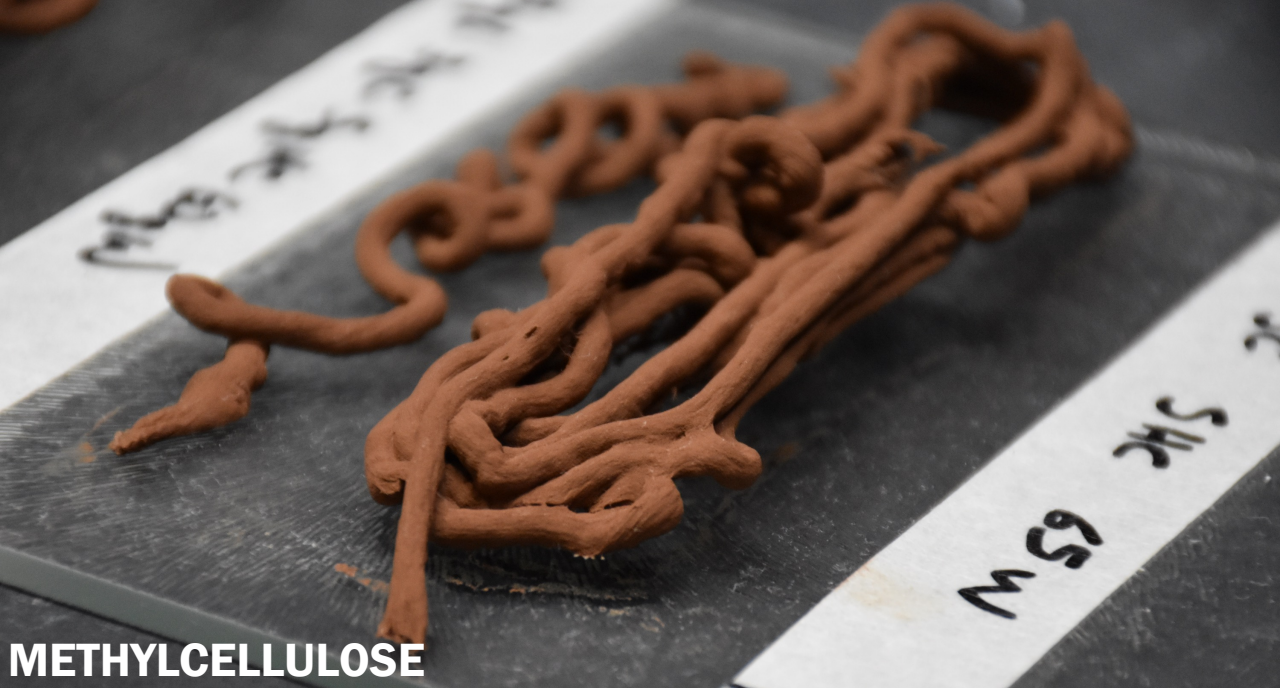


PHASE 3 - METHYLCELLULOSE








METHYLCELLULOSE


PROMISING MIXES
WOOD GLUE


ACETONE


DMSO

RECIPES

ACETONE MIX RECIPE

	QUANTITIES USED	WT %
LIGNIN	60g	58.25%
CELLULOSE	5g	4.85%
WATER	10g	9.71%
ACETONE	28g	27.19%



METHYLCELLULOSE MIX RECIPE

	QUANTITIES USED	WT %
LIGNIN	30g	29.13%
CELLULOSE	3g	2.91%
WATER	65g	63.11%
METHYLCELLULOSE	5g	4.85%



DMSO MIX RECIPE

	QUANTITIES USED	WT %
LIGNIN	35g	50.72%
CELLULOSE	4g	5.80%
WATER	10g	14.49%
DMSO	20g	28..99%



WOOD GLUE MIX RECIPE

	QUANTITIES USED	WT %
LIGNIN	10g	24.39%
CELLULOSE	1g	2.44%
WATER	-	-
WOOD GLUE	30g	73.17%




SELECTED MIX

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MATERIAL EXPLORATION

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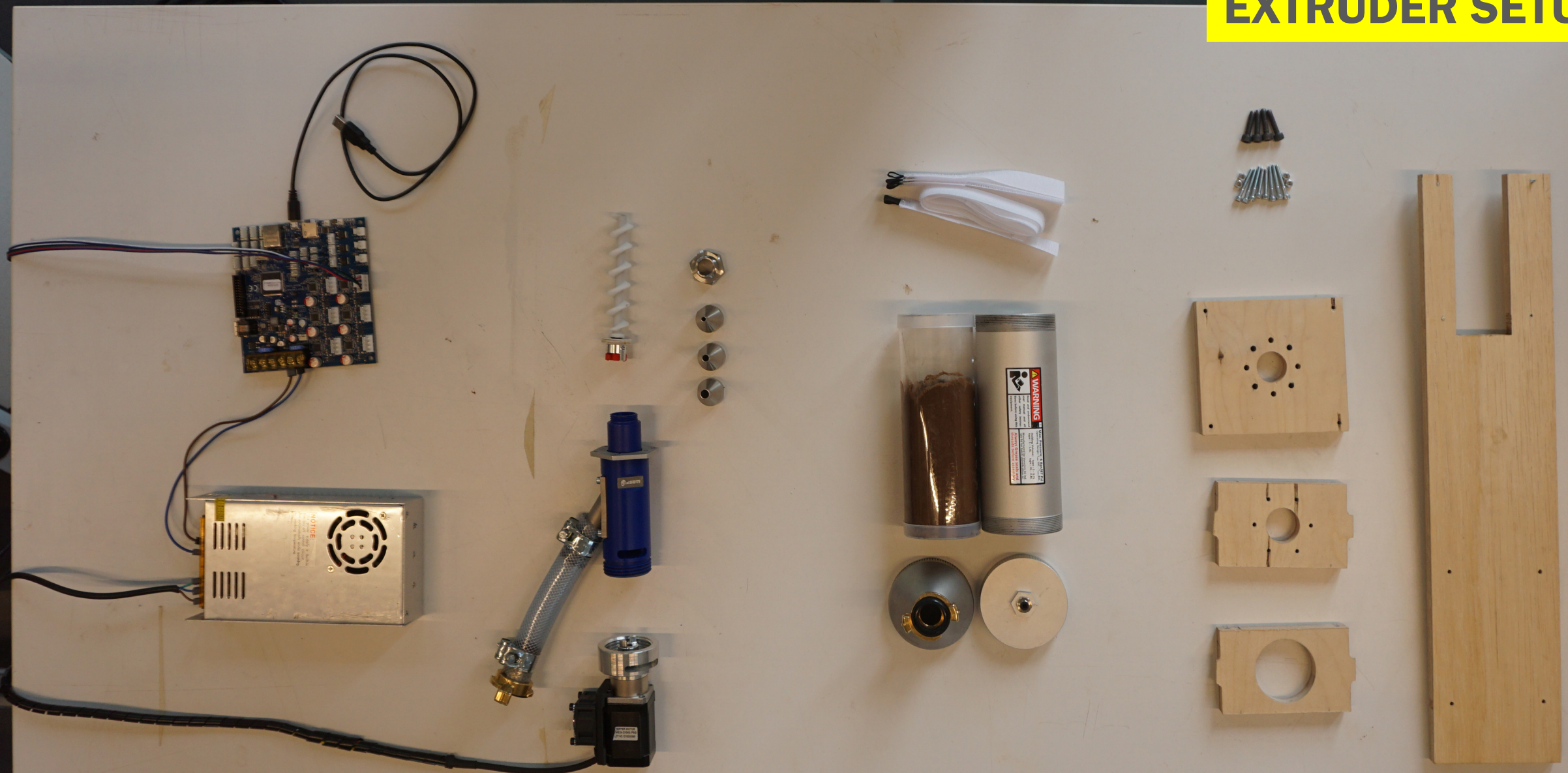
EXTRUDER SETUP

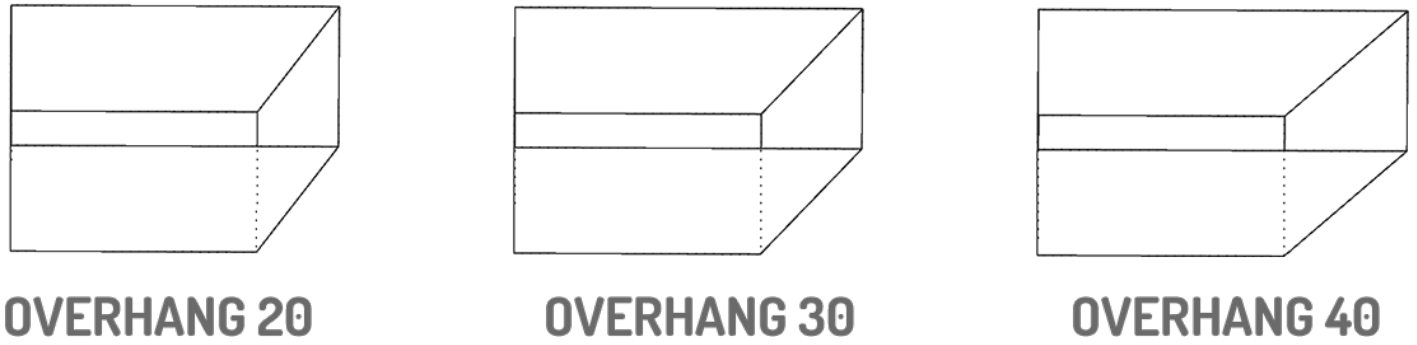


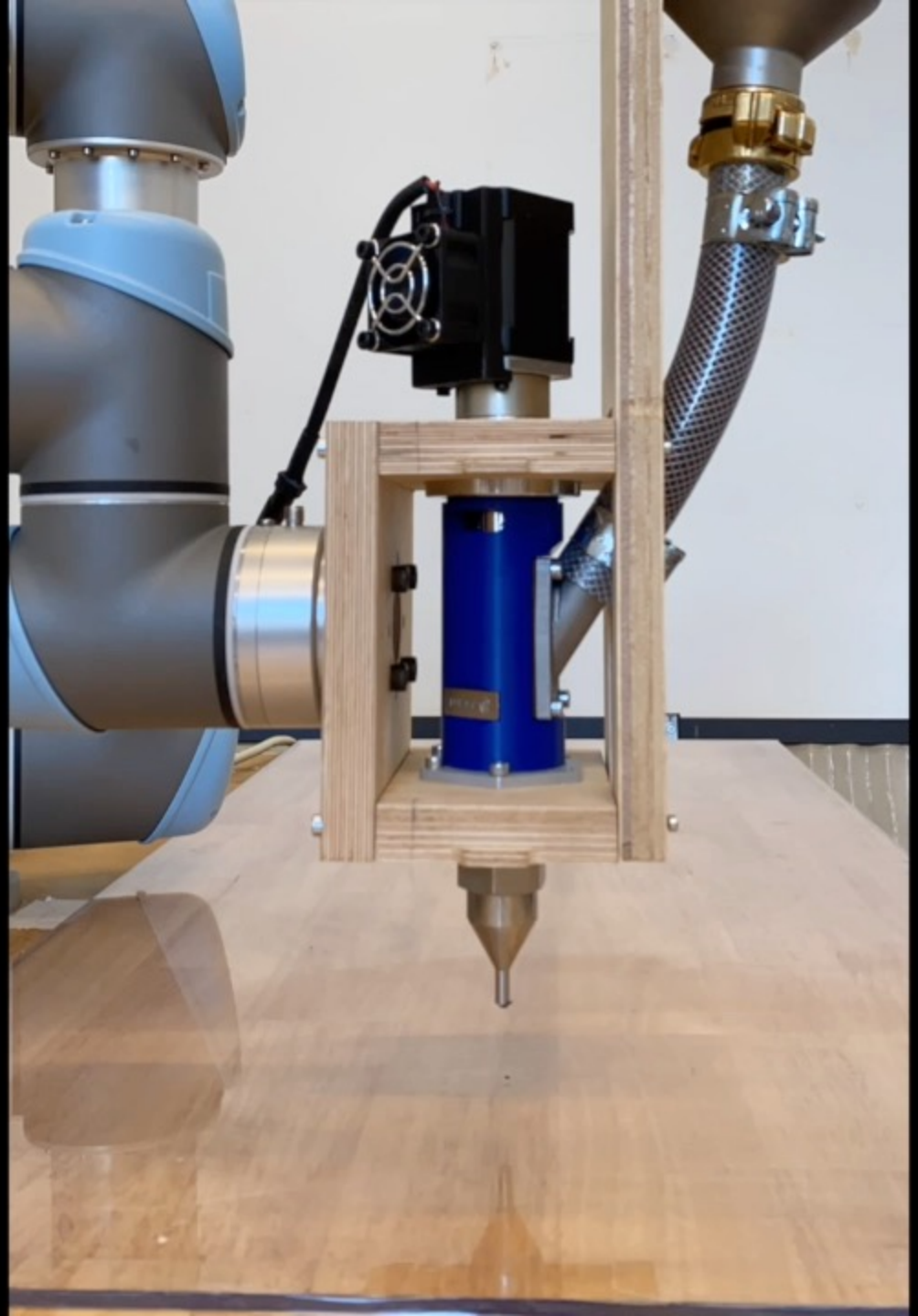
ROBOTIC ARM SETUP

PRINTING TESTS









GEOMETRY


GEOMETRY





OVERLAPPING

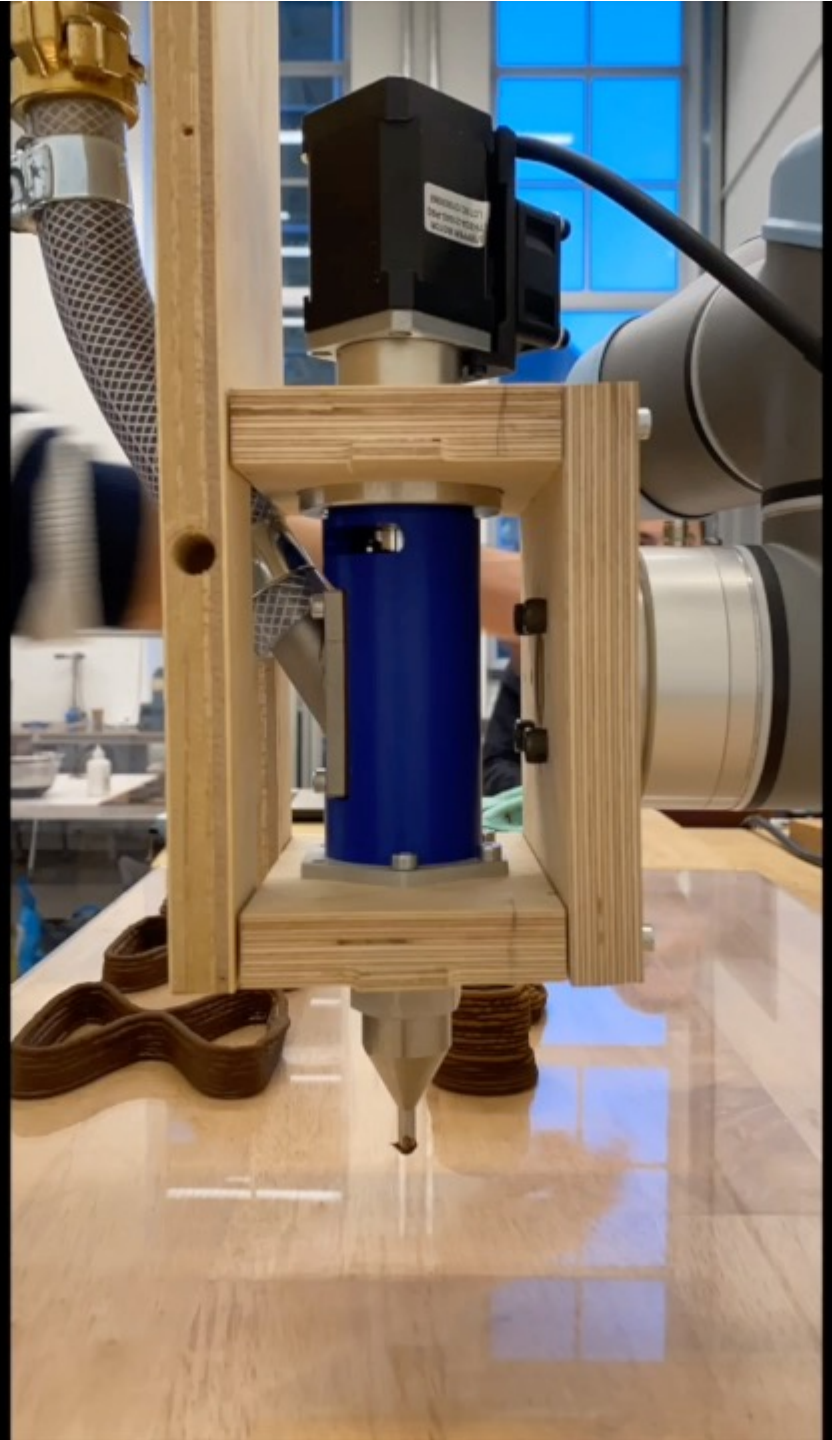

OVERLAPPING







GEOMETRY & OVERLAPPING



OVERHANG








OVERHANG





CHALLENGE

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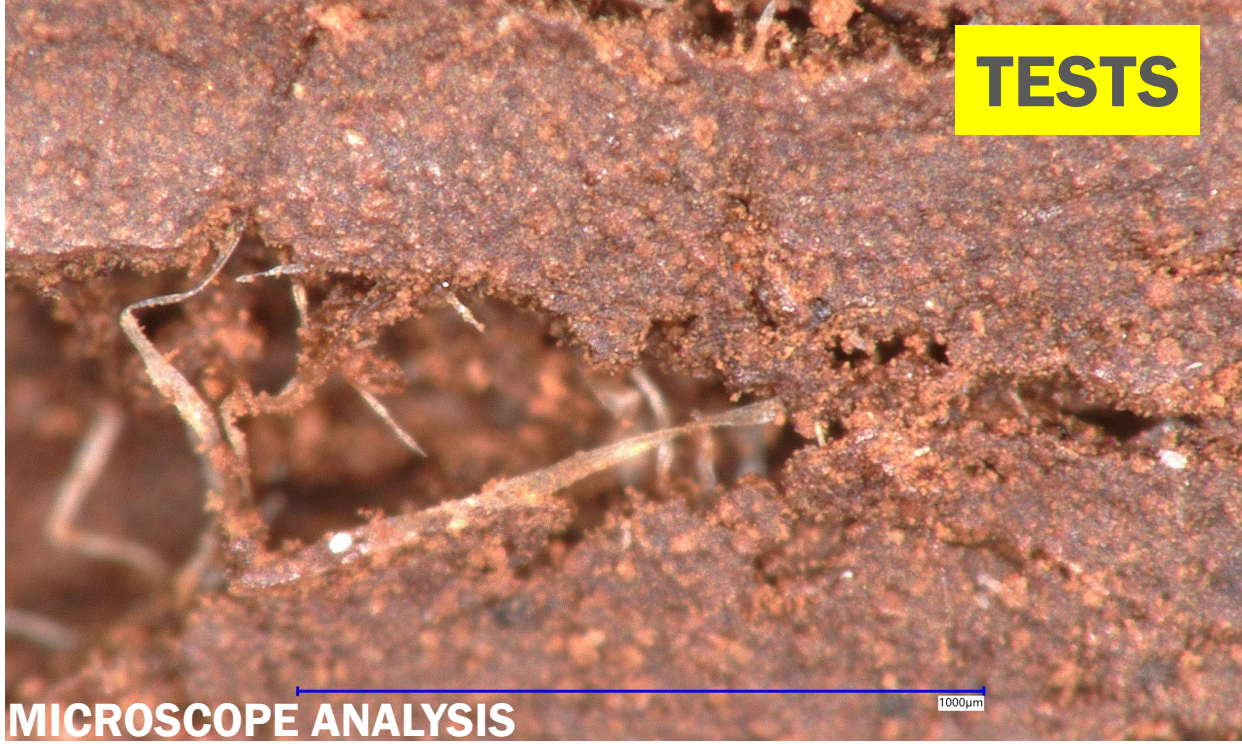
METHYLCELLULOSE MIX

TESTS



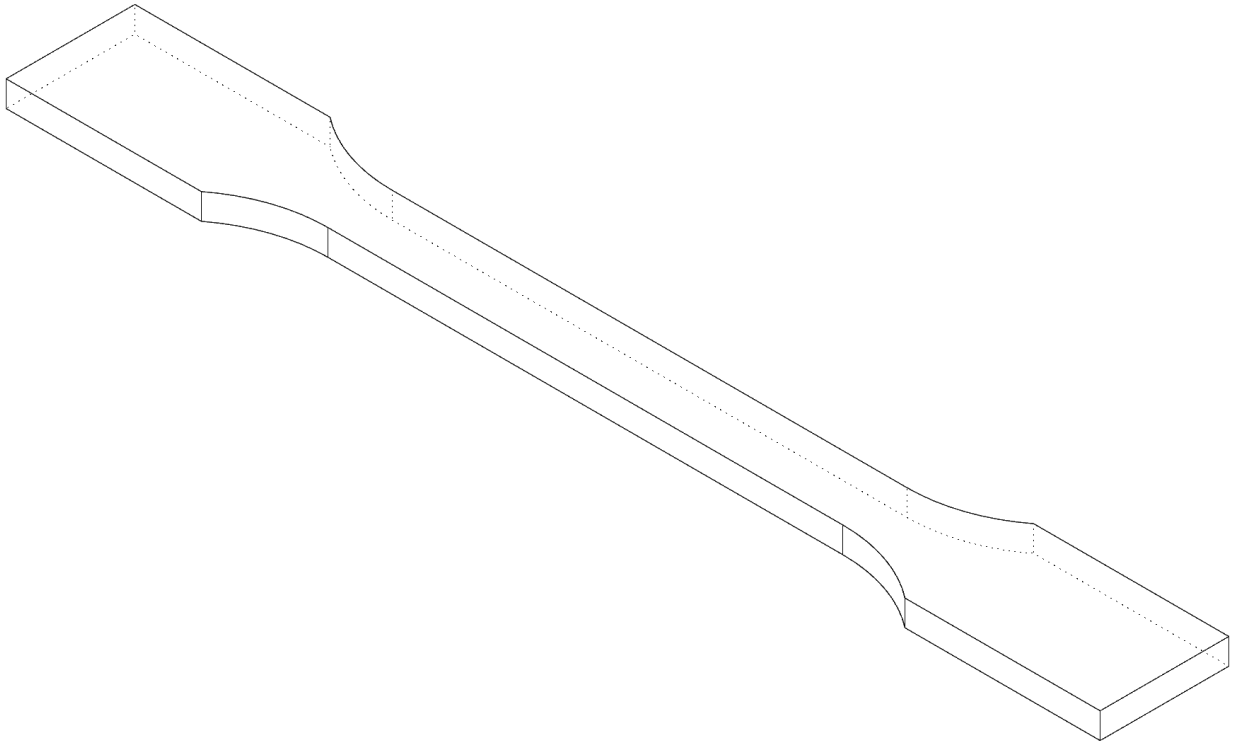
MICROSCOPE ANALYSIS



WATER ABSORPTION

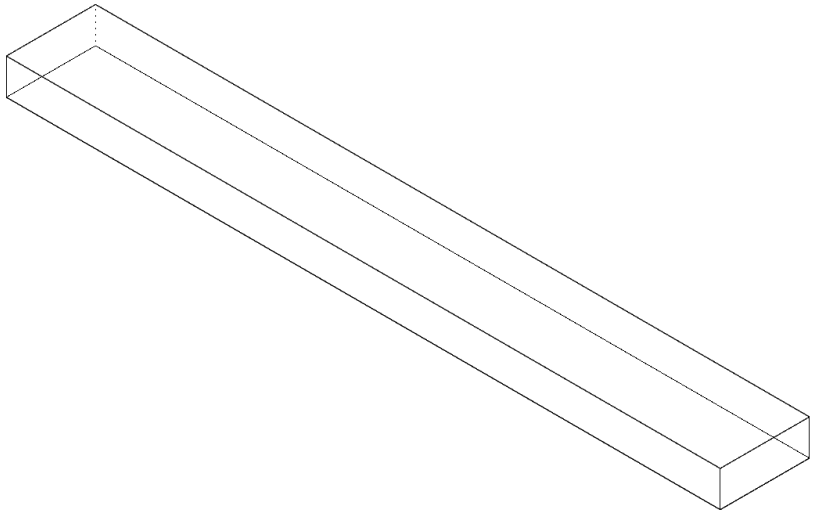
TENSILE & 3-POINT BENDING

SPECIMENS



Dumbbell Type – TENSILE TEST

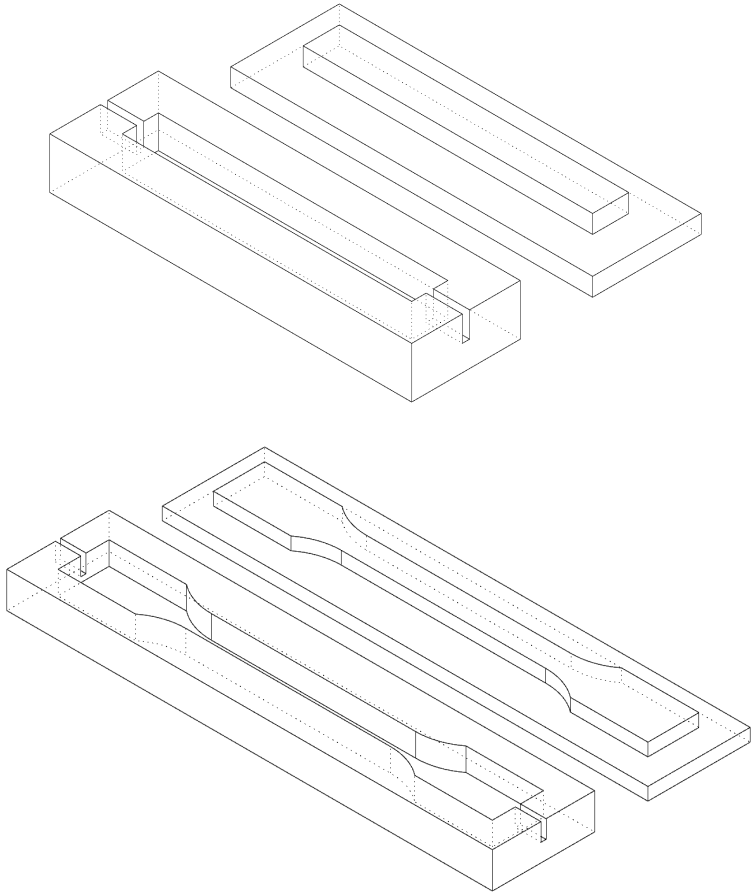
Overall Dimensions | 210x22x4mm
Test Area (gauge) | 80x10x4mm



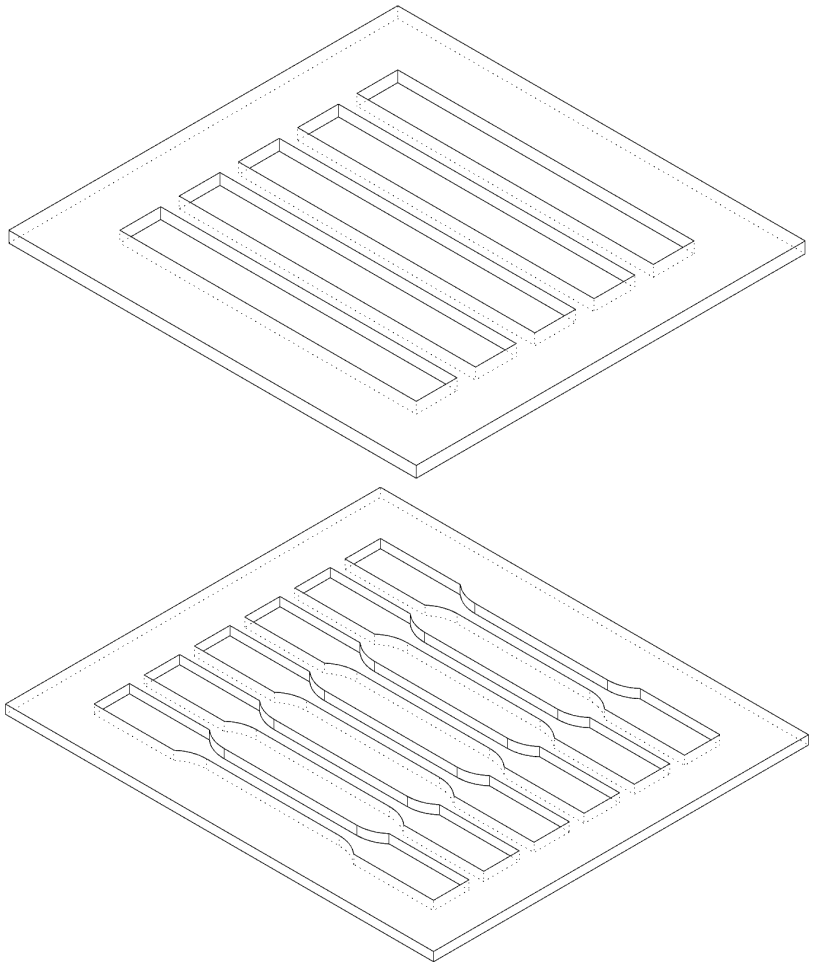
Beam Type – BENDING TEST

Overall Dimensions | 150x20x4mm
Test Area | 80x20x4mm

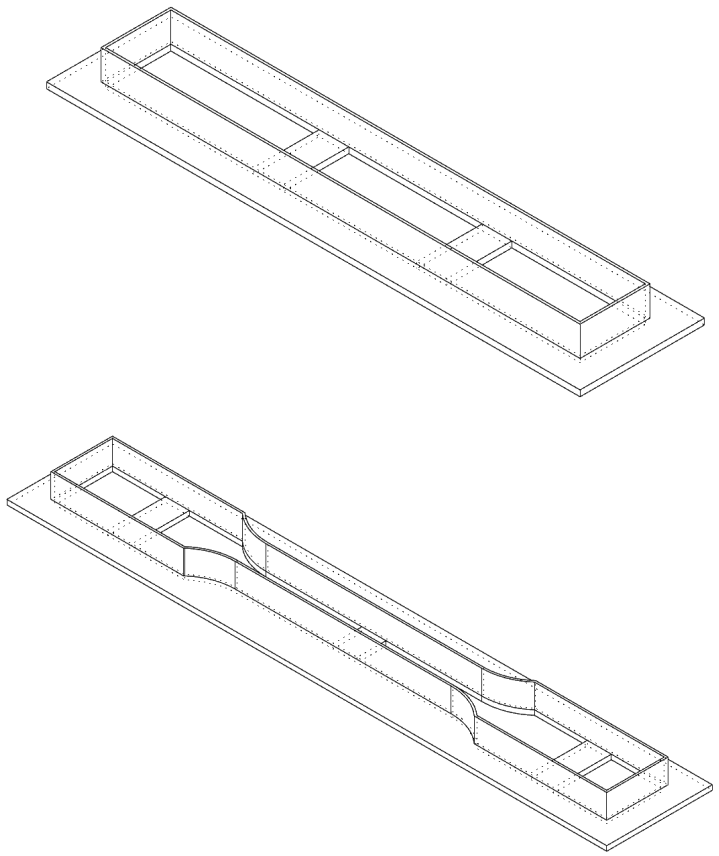
MOULD



Specimens Mould - v1
Compression Mould

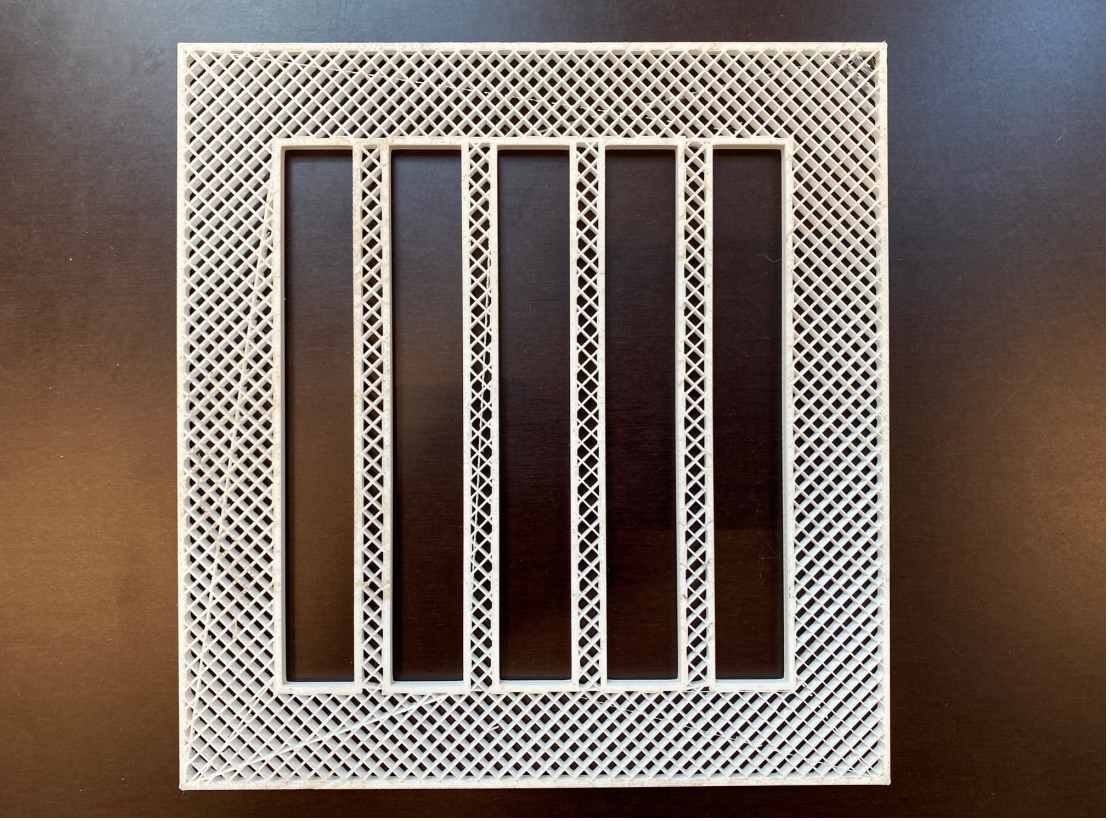


Specimens Mould – v2
Cut-Out

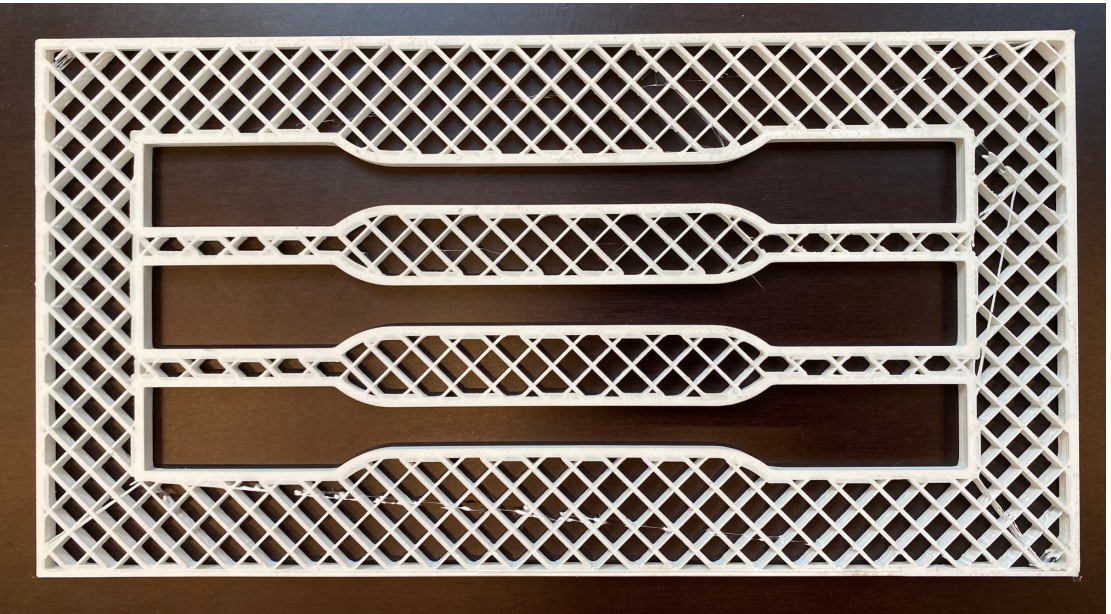


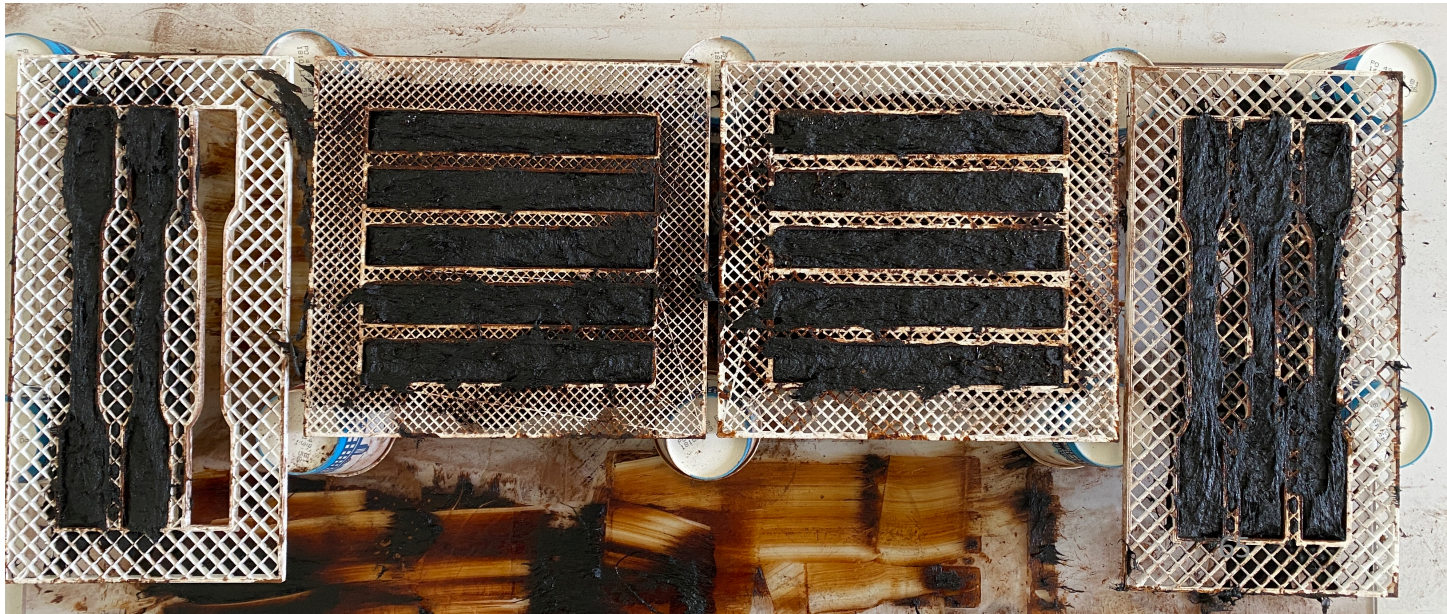
Specimens Mould – v3
Cutter


PRODUCTION




PRODUCTION



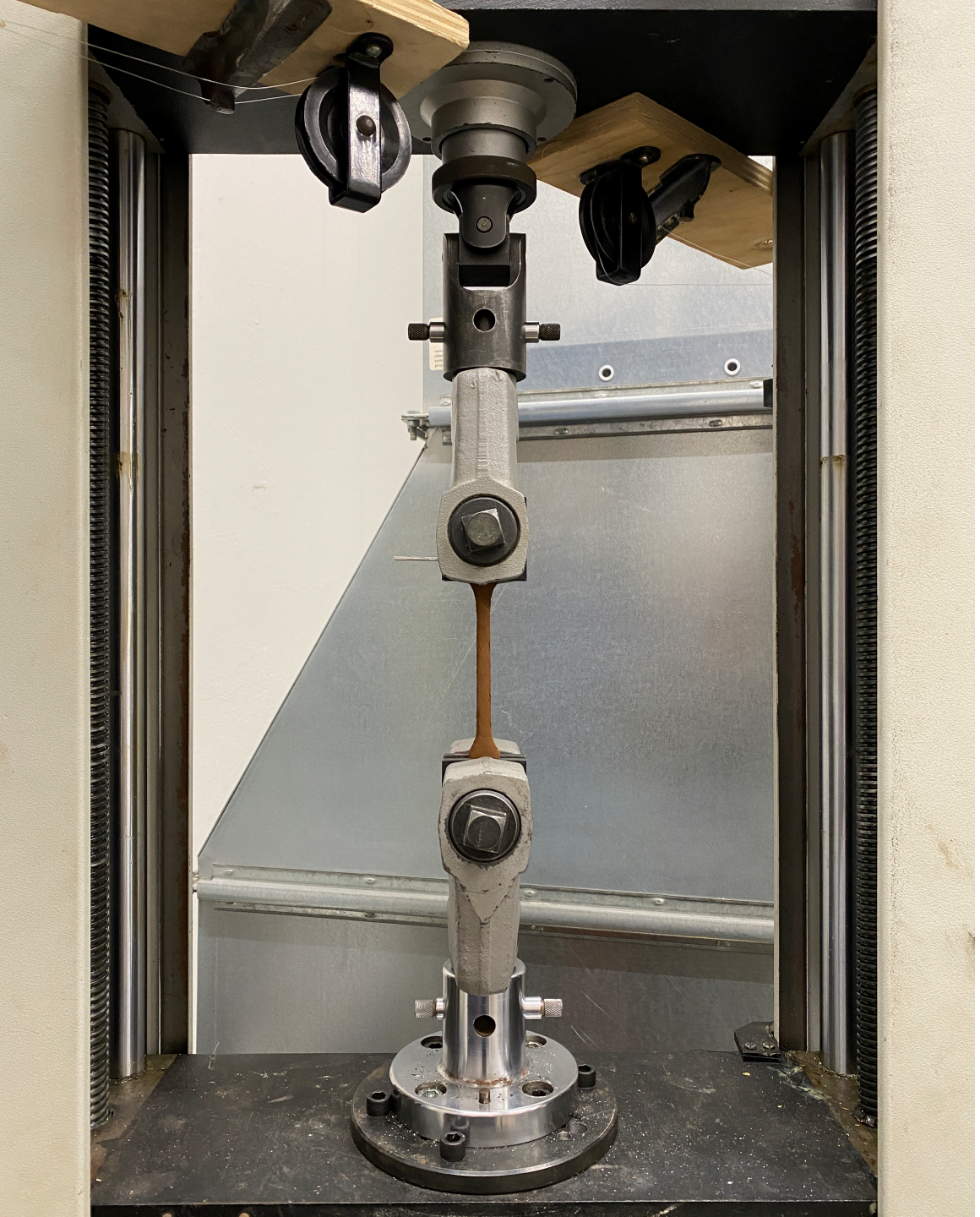


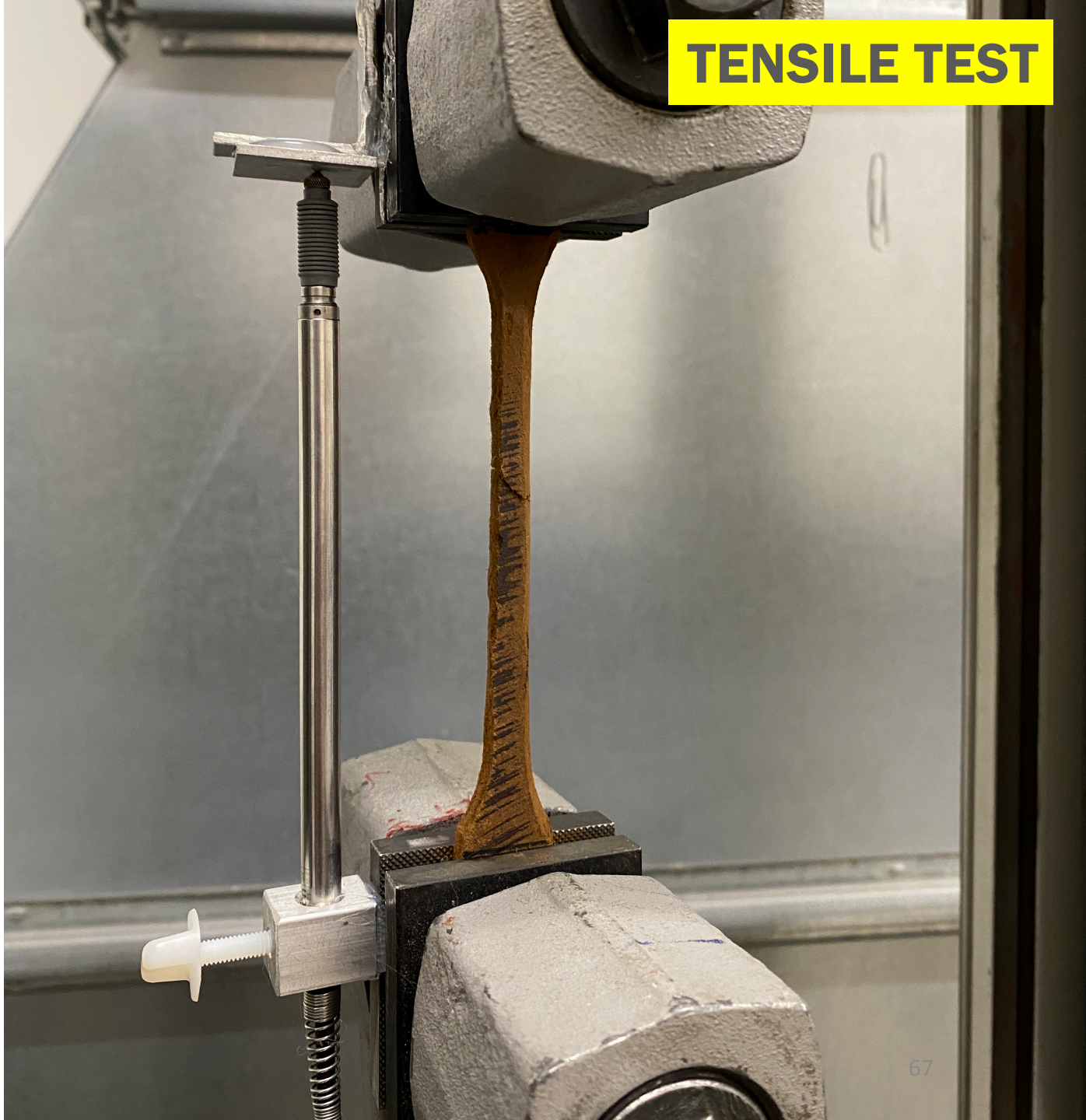



DEFORMATION








TENSILE TEST


TENSILE TEST

TENSILE TEST OUTCOME




DMSO FAIL

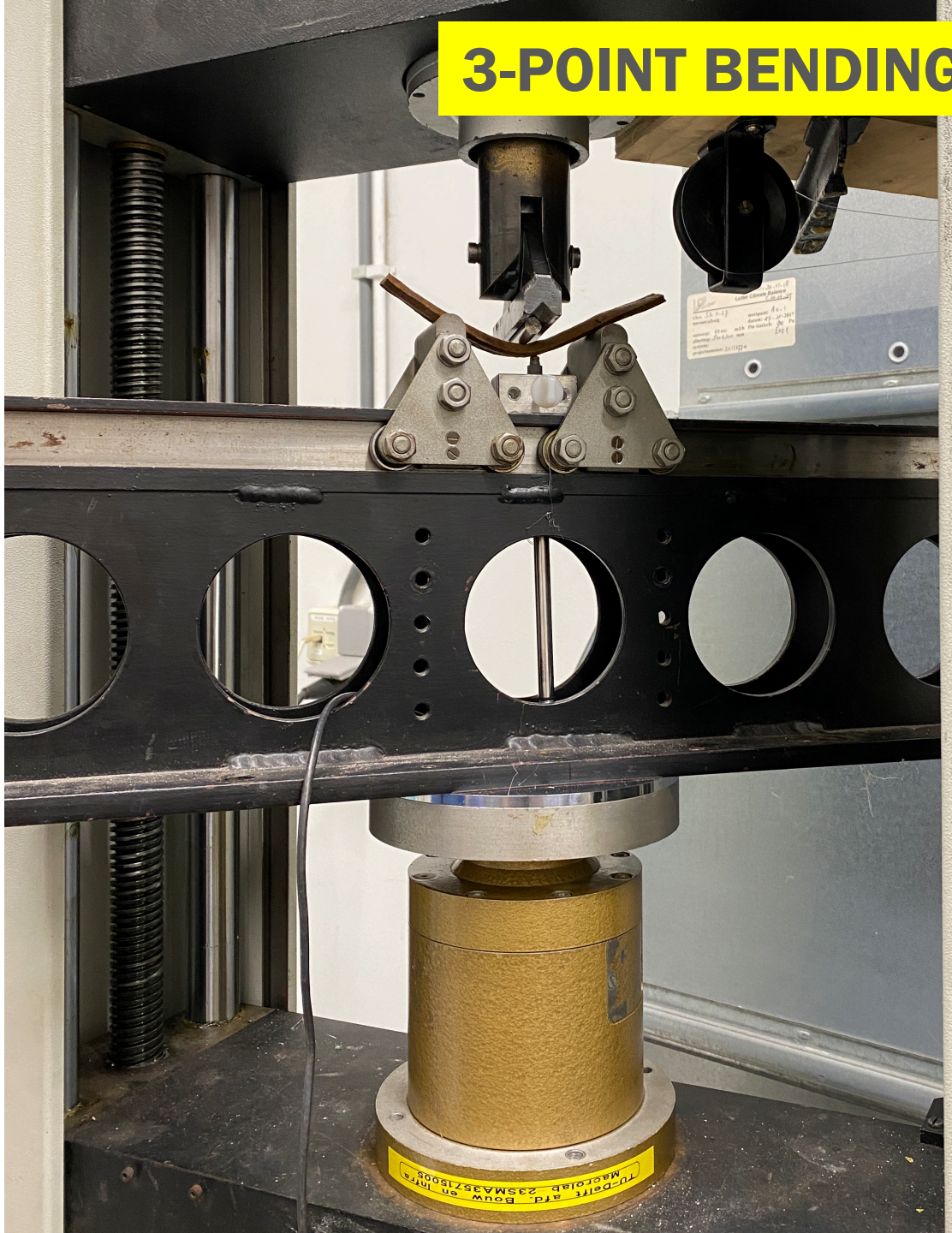
TENSILE PROPERTIES

TENSILE PROPERTIES COMPARISON

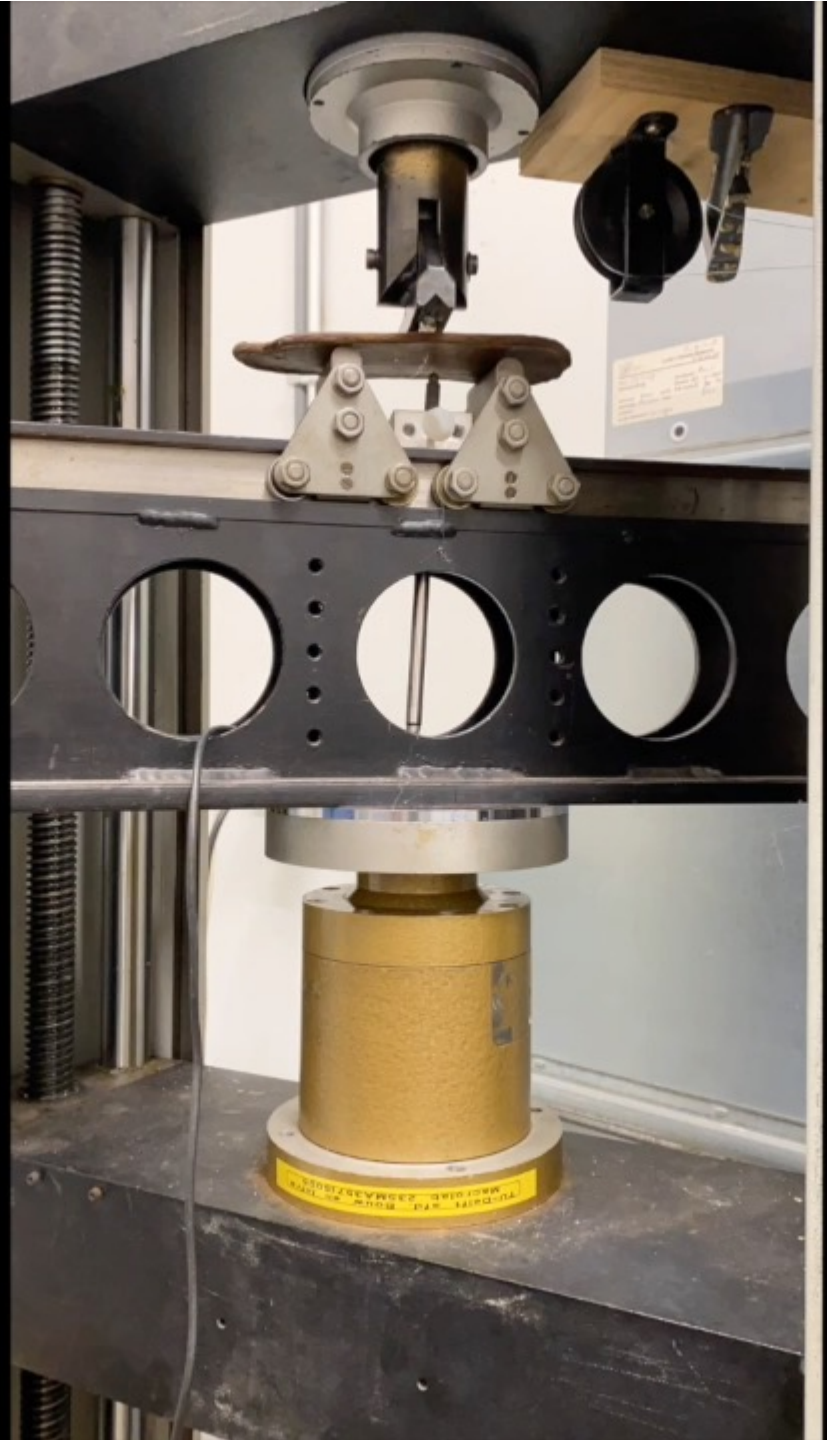
	YIELD STRENGTH	MODULUS ELASTICITY (TENSION)
METHYLCELLULOSE MIX	3.21 - 4.06 MPa	0.33 - 0.56 GPa
WOOD GLUE MIX	3.58 - 4.81 MPa	0.30 - 0.77 GPa
ACETONE MIX	0.81 - 1.51 MPa	0.11 - 0.20 GPa

3-POINT BENDING TEST





3-POINT BENDING TEST



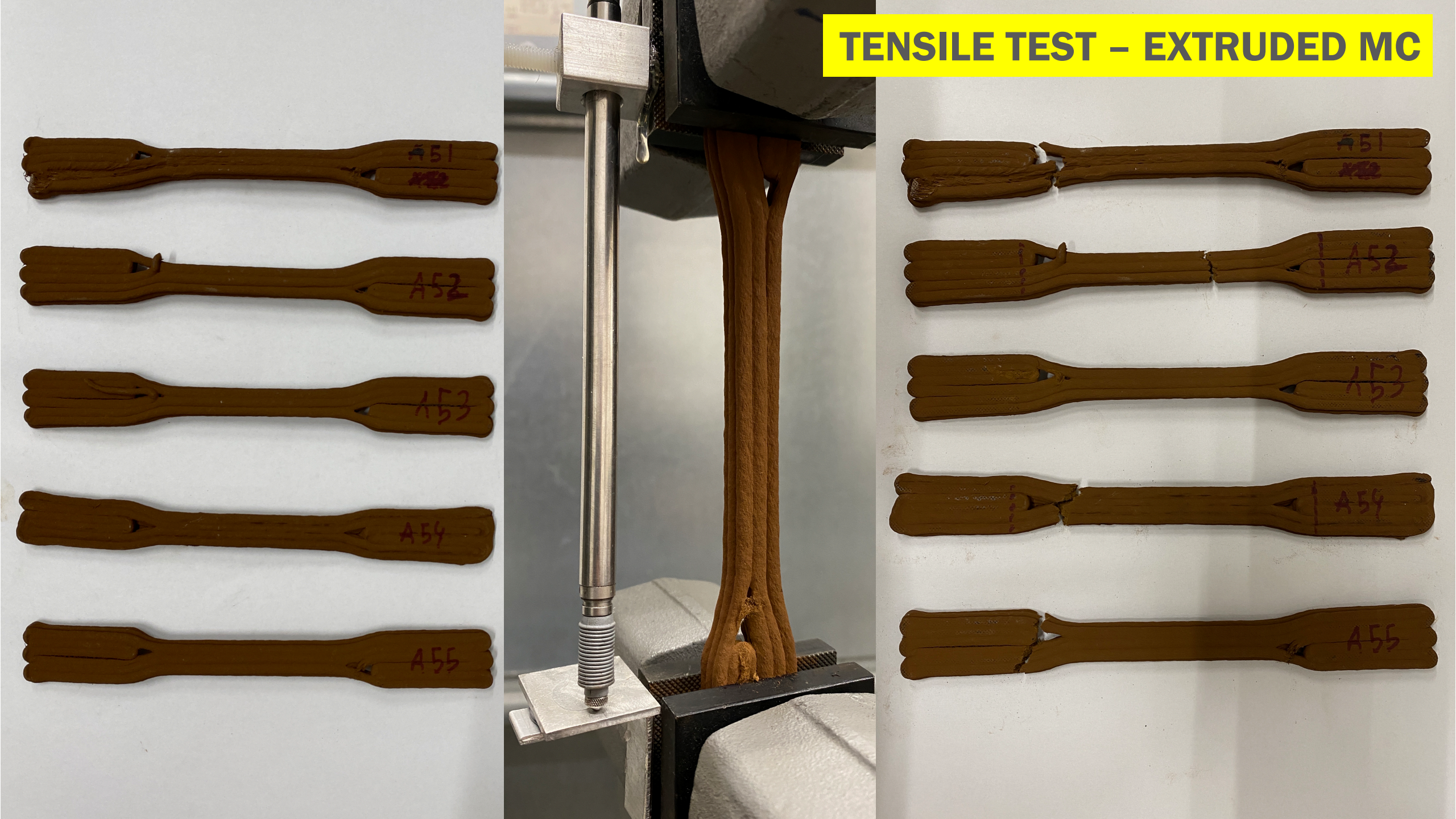
3-POINT BENDING TEST OUTCOME



FLEXURAL PROPERTIES

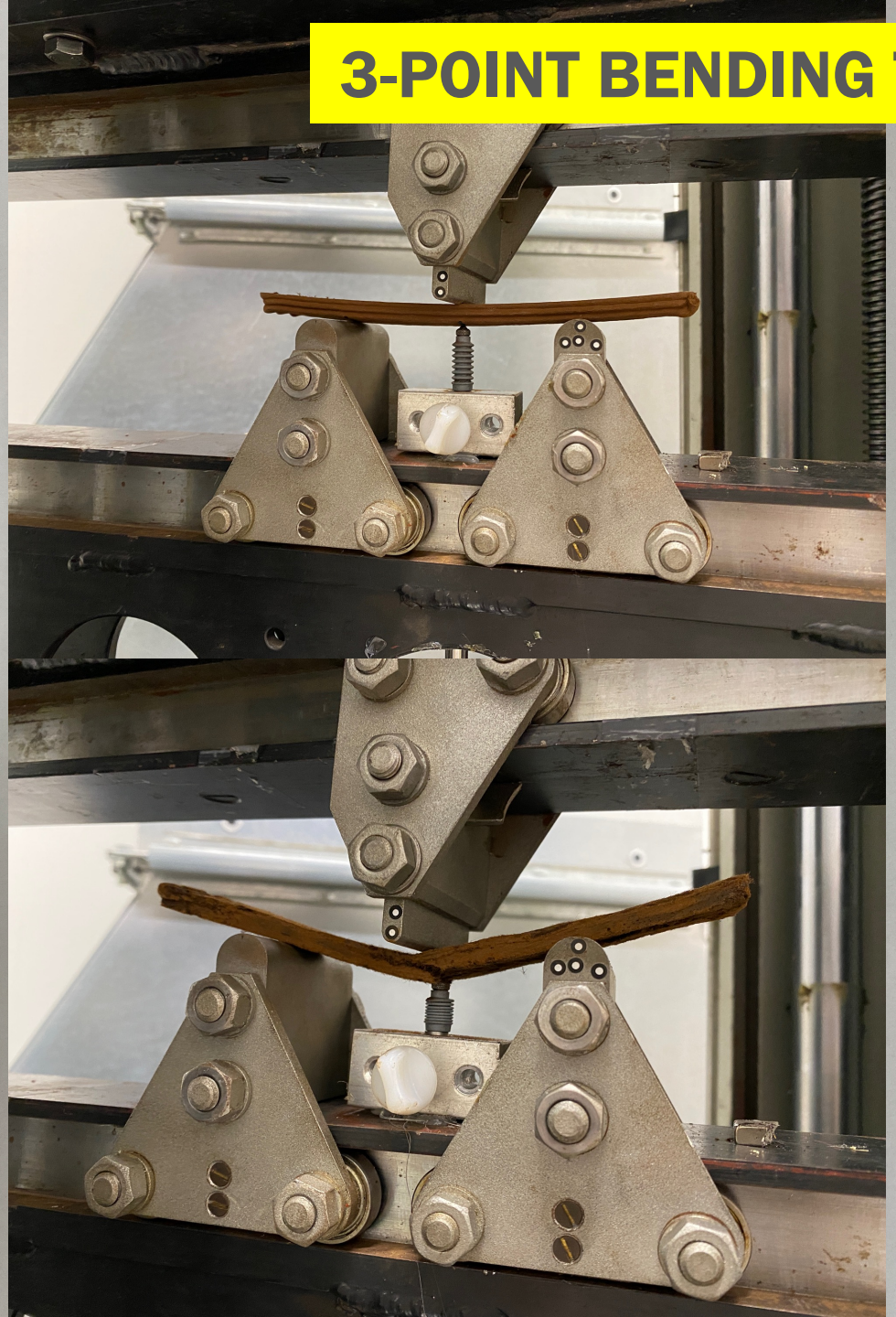
FLEXURAL PROPERTIES COMPARISON		
	FLEXURAL STRENGTH	MODULUS ELASTICITY (BENDING)
METHYLCELLULOSE MIX	8.59 - 10.60 MPa	0.67 - 1.05 GPa
WOOD GLUE MIX	20.67 - 28.89 MPa	0.64 - 0.90 GPa
ACETONE MIX	4.77 - 9.74 MPa	0.15 - 0.37 GPa

TENSILE TEST – EXTRUDED MC



3-POINT BENDING TEST – EXTRUDED MC

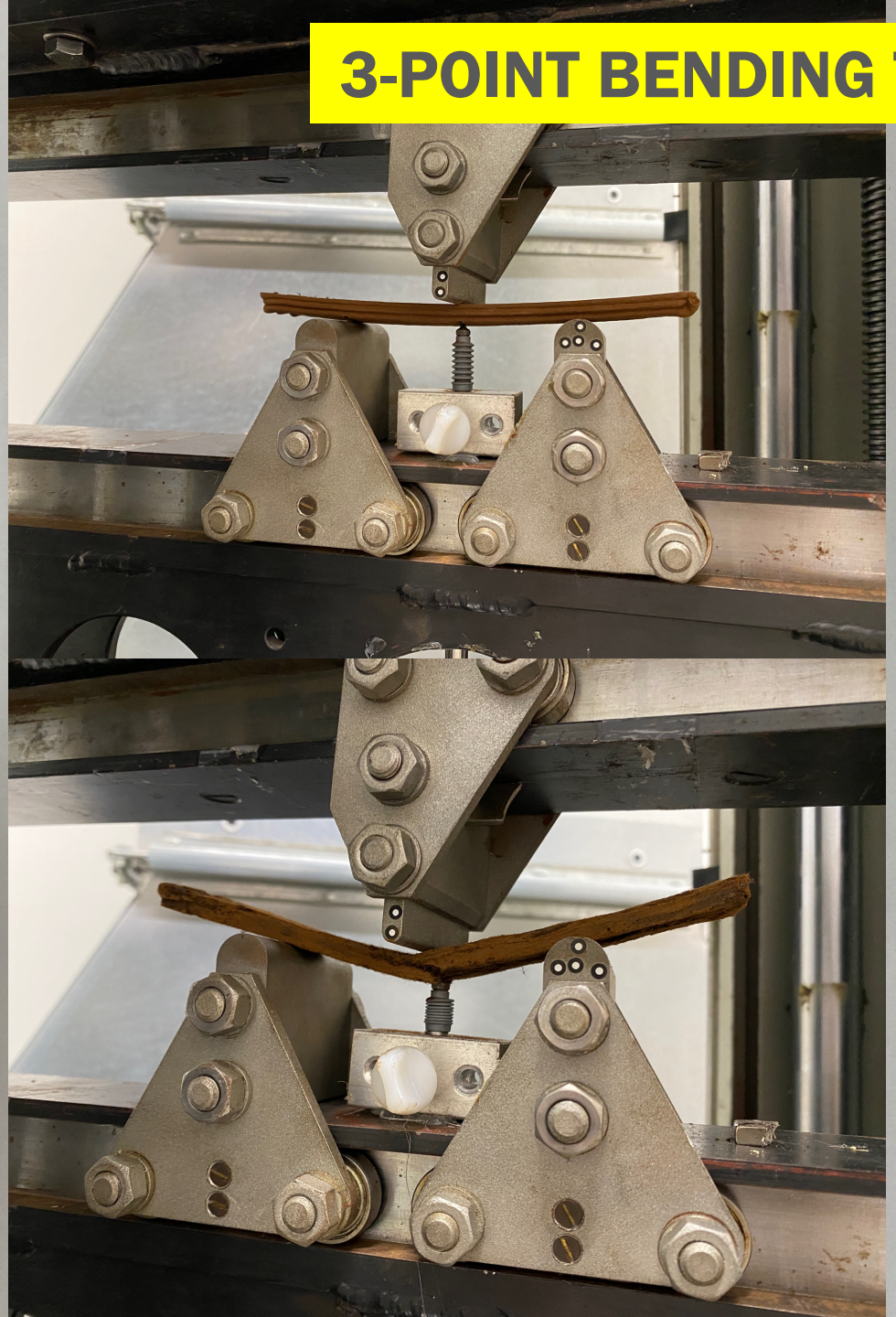






3-POINT BENDING TEST – EXTRUDED MC







MOULDED vs. EXTRUDED

MECHANICAL PROPERTIES COMPARISON – MOULDED vs. EXTRUDED				
	FLEXURAL STRENGHT	MODULUS ELASTICITY (BENDING)	YIELD STRENGHT	MODULUS ELASTICITY (TENSION)
METHYLCELLULOSE MIX – MOULDED	8.59 – 10.60 MPa	0.67 – 1.05 GPa	3.21 – 4.06 MPa	0.33 – 0.56 GPa
METHYLCELLULOSE MIX – EXTRUDED	8.48 – 9.55 MPa	0.60 – 0.64 GPa	2.38 – 3.10 MPa	0.40 – 0.52 GPa

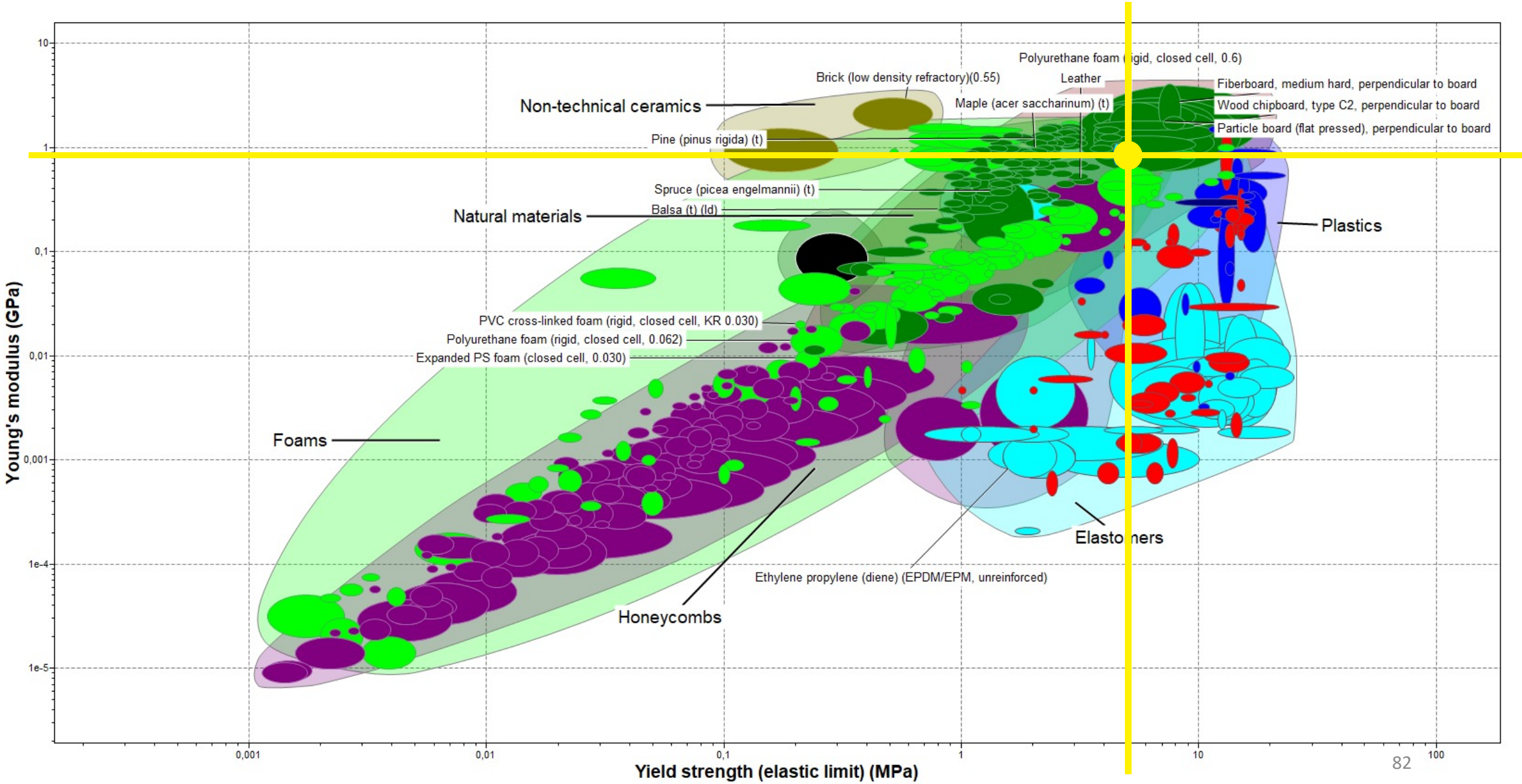
MECHANICAL PROPERTIES COMPARISON

	FLEXURAL STRENGHT	MODULUS ELASTICITY (BENDING)	YIELD STRENGHT	MODULUS ELASTICITY (TENSION)	REFERENCE
BEECH, AMERICAN	-	9.5 GPa	86.2 MPa	-	(USDA Forest Service, 2010)
OAK, OVERCUP	-	9.8 GPa	77.9 MPa	-	(USDA Forest Service, 2010)
PINE, EASTERN WHITE	-	8.5 GPa	73.1 MPa	-	(USDA Forest Service, 2010)
SPRUCE, ENGELMANN	-	8.9 GPa	84.8 MPa	-	(USDA Forest Service, 2010)
PARTICLEBOARD	-	2.8 - 4.1 GPa	15 - 24 MPa	-	(USDA Forest Service, 2010)
MDF	-	3.6 GPa	36 MPa	-	(USDA Forest Service, 2010)
OSB	-	4.4 - 6.3 GPa	22 - 35MPa	-	(USDA Forest Service, 2010)
PLYWOOD	-	7 - 8.6 GPa	34 - 43 MPa	-	(USDA Forest Service, 2010)
GLULAM	-	9 - 14.5 GPa	29 - 63 MPa	-	(USDA Forest Service, 2010)
PLA + WOOD POWDER	-	3 GPa	30 MPa	-	(Gardner et al., 2019)
PLA + LIGNIN (40WT%)	-	1.93 GPa	29.25 MPa	-	(Tanase-Opedal et al., 2019)
WOOD POWDER + GLUE	-	3 - 3.94 GPa	30 - 57 MPa	-	(Das et al., 2021a)
TECNARO ARBOBLEND	-	4.3 GPa	58 MPa	-	(www.albis.com)
FLAM!	-	0.26 GPa	6.12 MPa	-	(Sanandiya et al., 2018)
METHYLCELLULOSE MIX	8.59 - 10.60 MPa	0.67 - 1.05 GPa	3.21 - 4.06 MPa	0.33 - 0.56 GPa	(own work)
WOOD GLUE MIX	20.67 - 28.89 MPa	0.64 - 0.90 GPa	3.58 - 4.81 MPa	0.30 - 0.77 GPa	(own work)
ACETONE MIX	4.77 - 9.74 MPa	0.15 - 0.37 GPa	0.81 - 1.51 MPa	0.11 - 0.20 GPa	(own work)

MECHANICAL PROPERTIES COMPARISON

	E	σ_{ys}
OAK	9.8 GPa	77.9 MPa
MDF	3.6 GPa	36 MPa
Tecnaro Arboblend	4.3 GPa	58 MPa
FLAM	0.26 GPa	6.12 MPa
Methylcellulose	0.67-1.05 GPa	3.21-4.06 MPa

METHYLCELLULOSE vs. OTHER MATERIALS

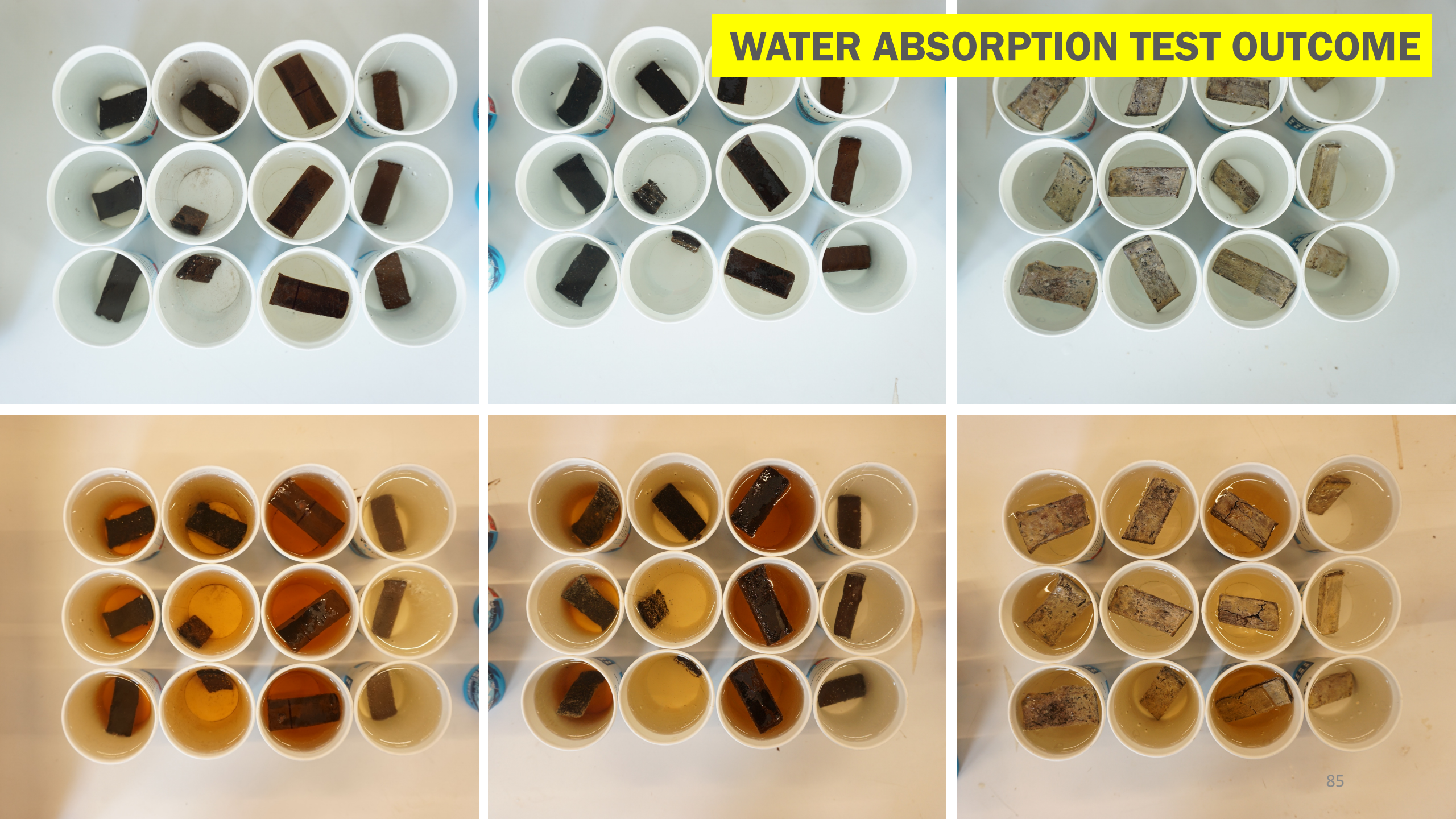


PIC OF RIGID FOAM, FLAM

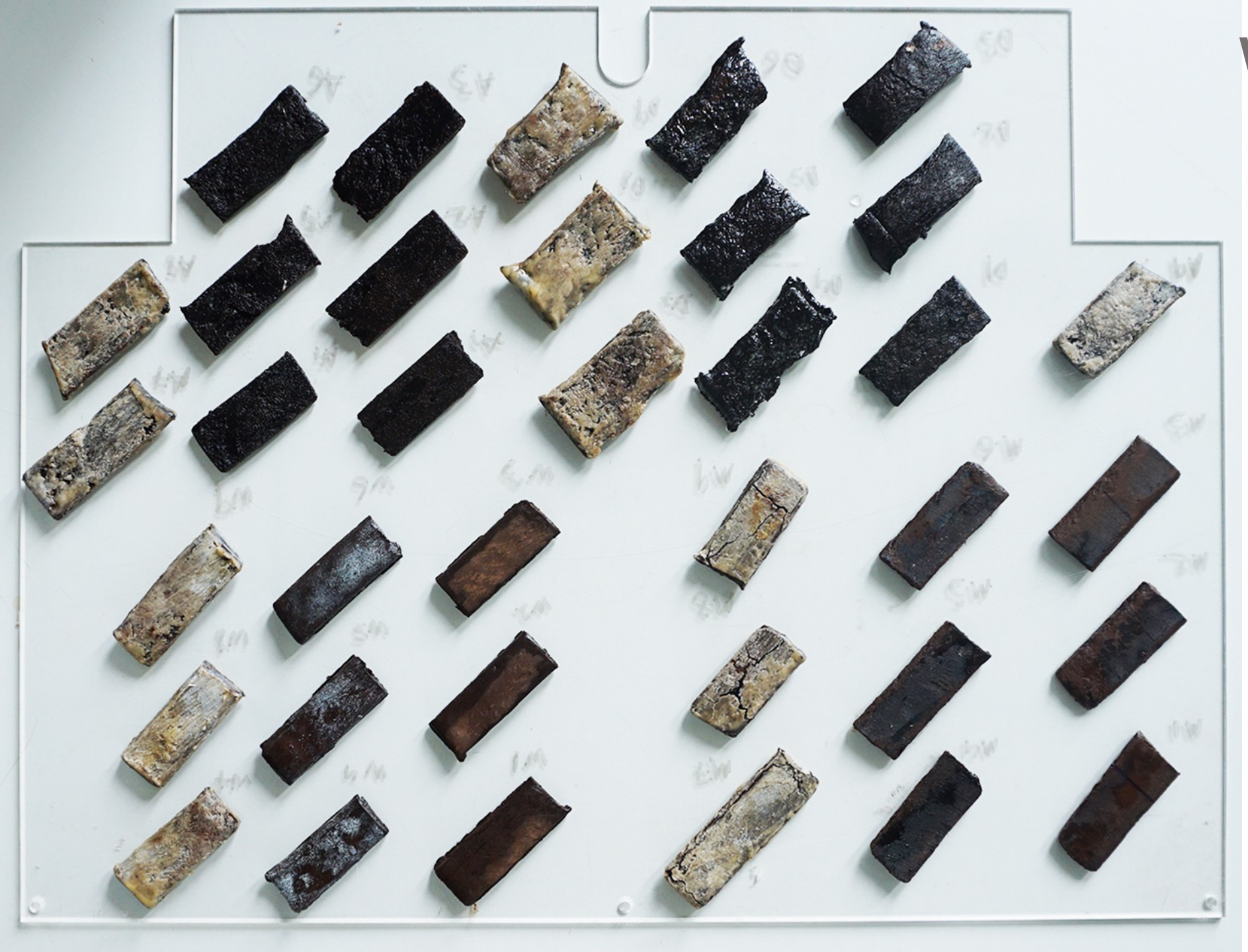
WATER ABSORPTION TEST



WATER ABSORPTION TEST OUTCOME



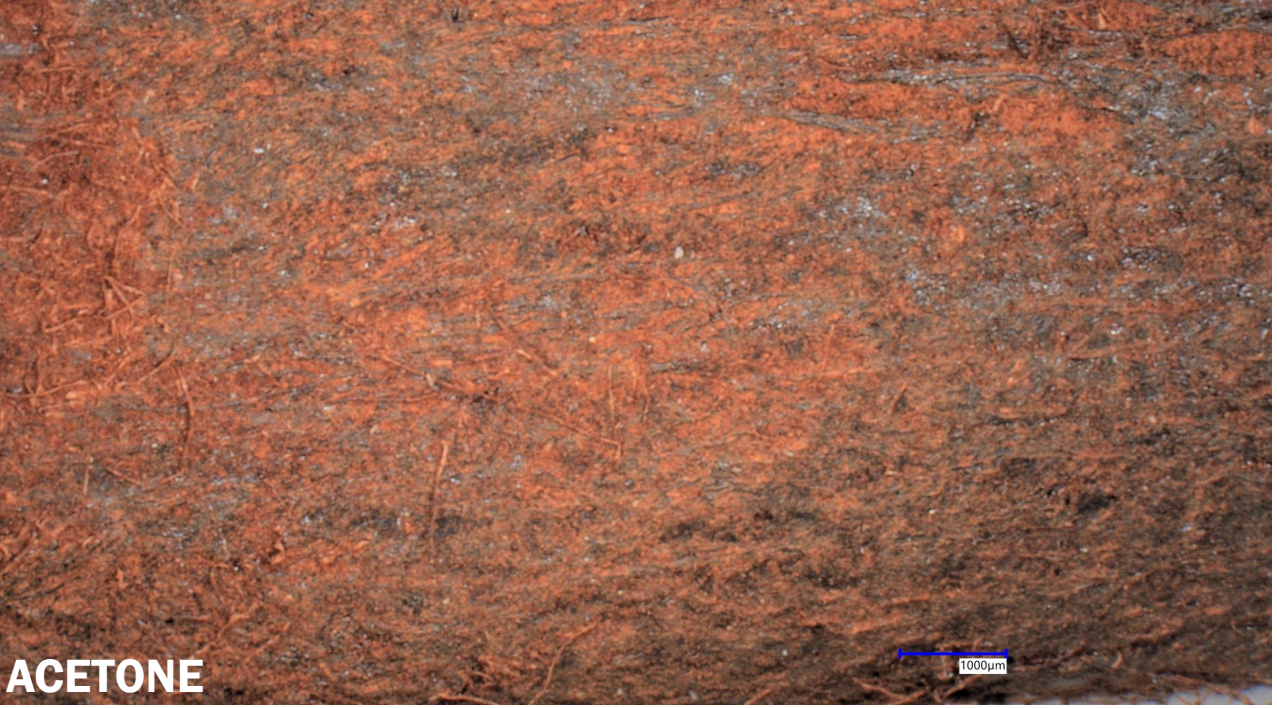
WATER RETENTION

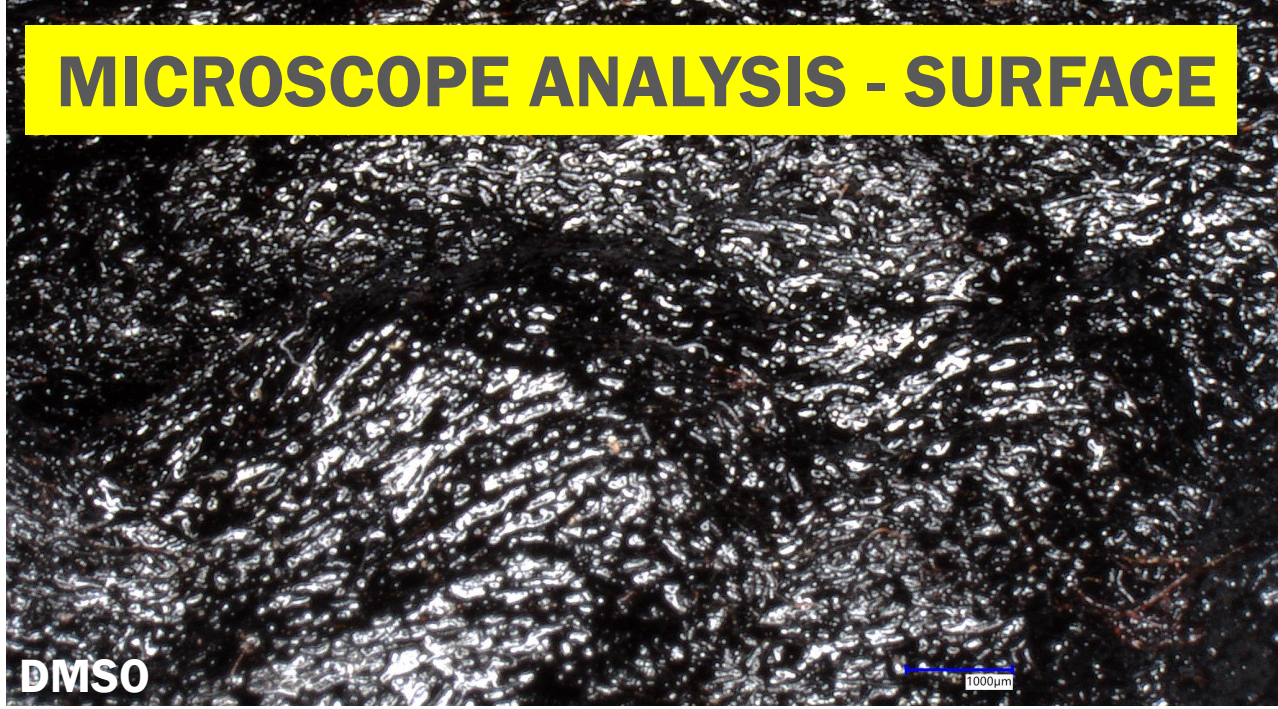


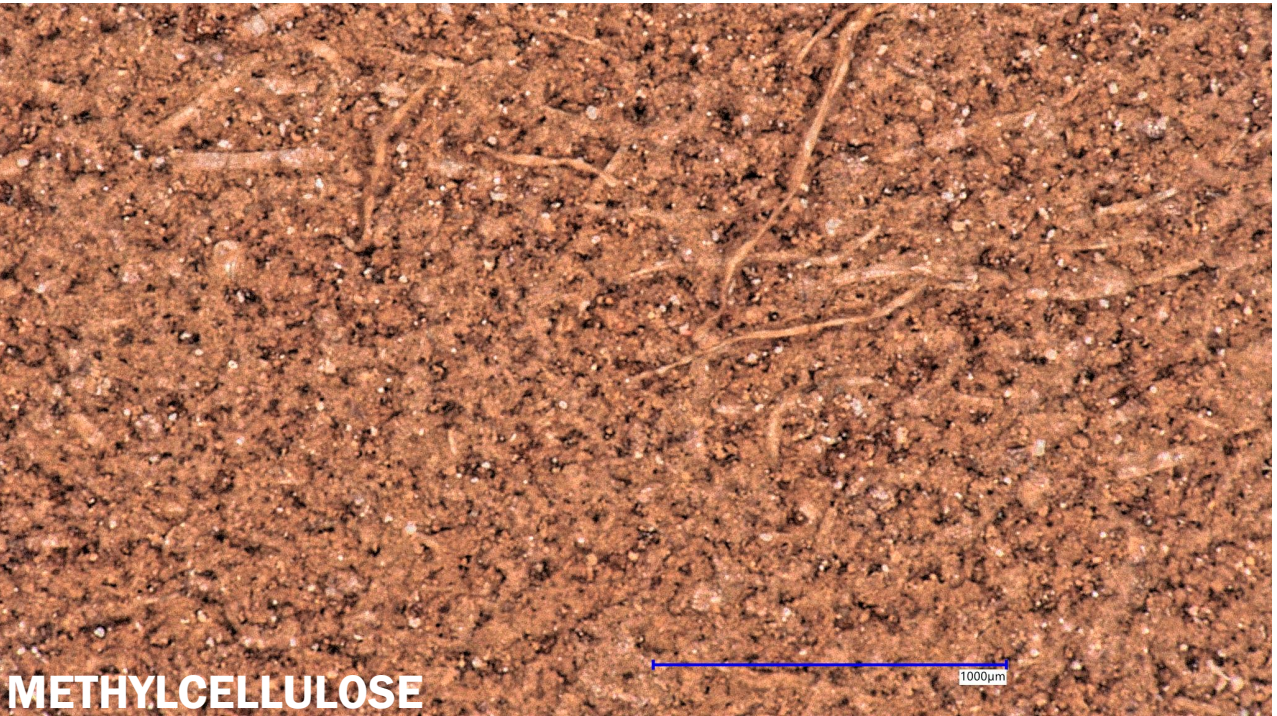
WATER ABSORPTION PROPERTIES COMPARISON

	No Coating	Linseed Oil
Wood Glue	10%	8%
Acetone	25%	20%
DMSO	28%	30%
Methylcellulose	135%	70%
Pine Heartwood	100%	84%

MICROSCOPE ANALYSIS - SURFACE

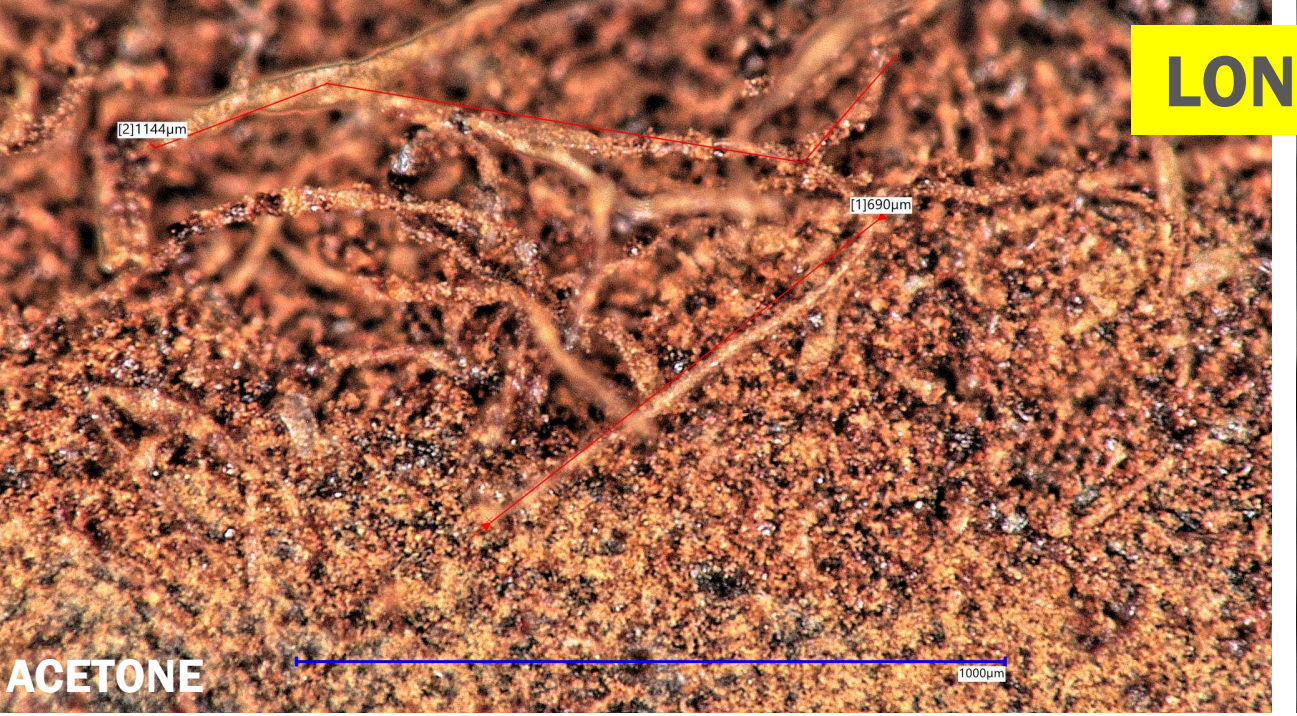


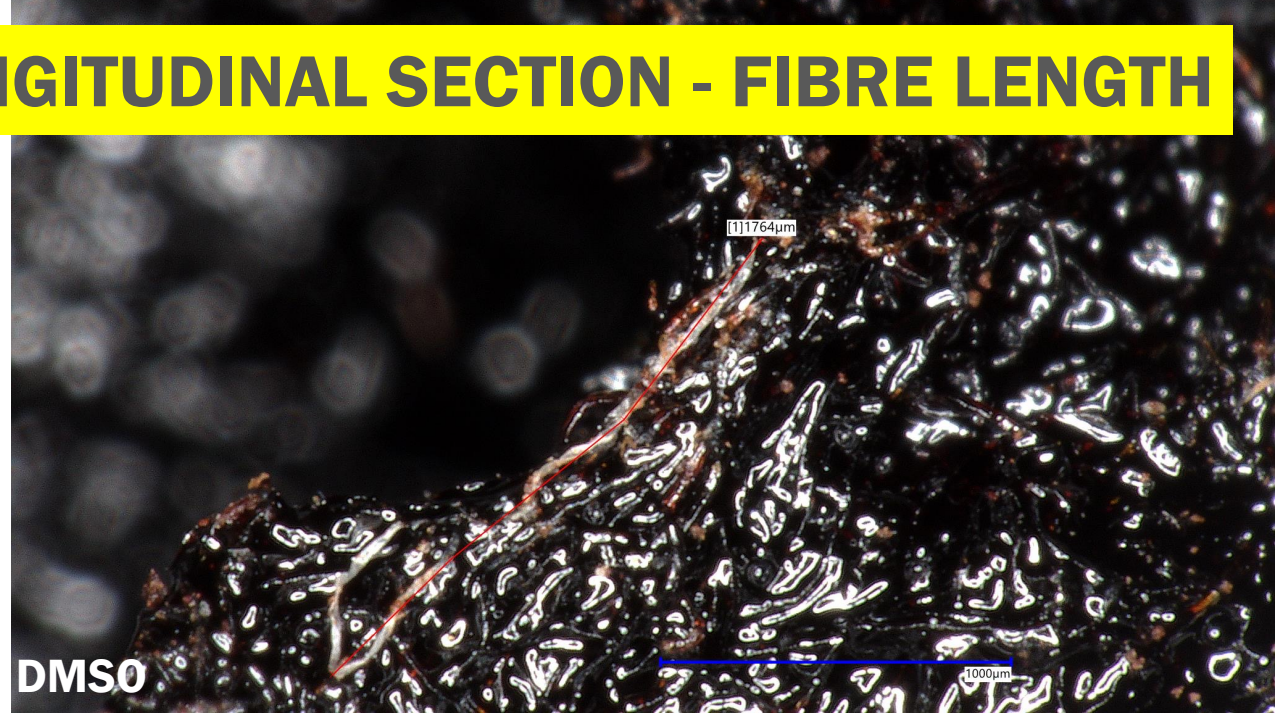






LONGITUDINAL SECTION - FIBRE LENGTH



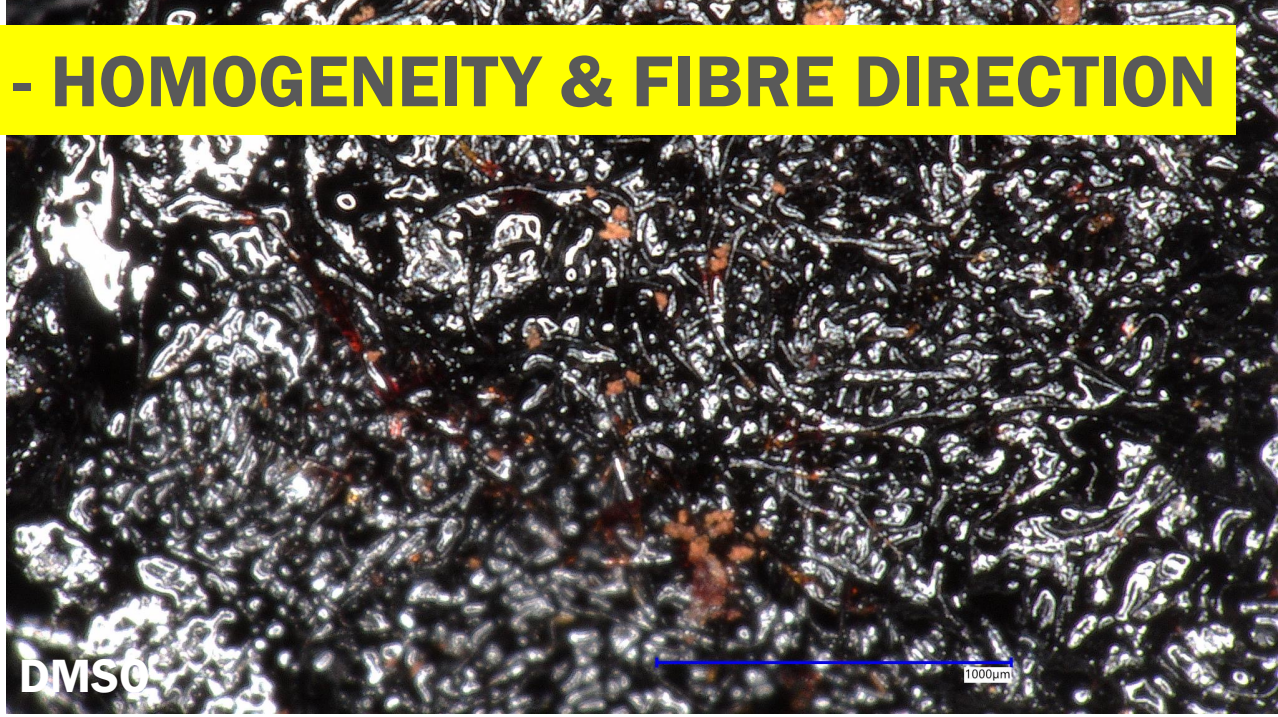




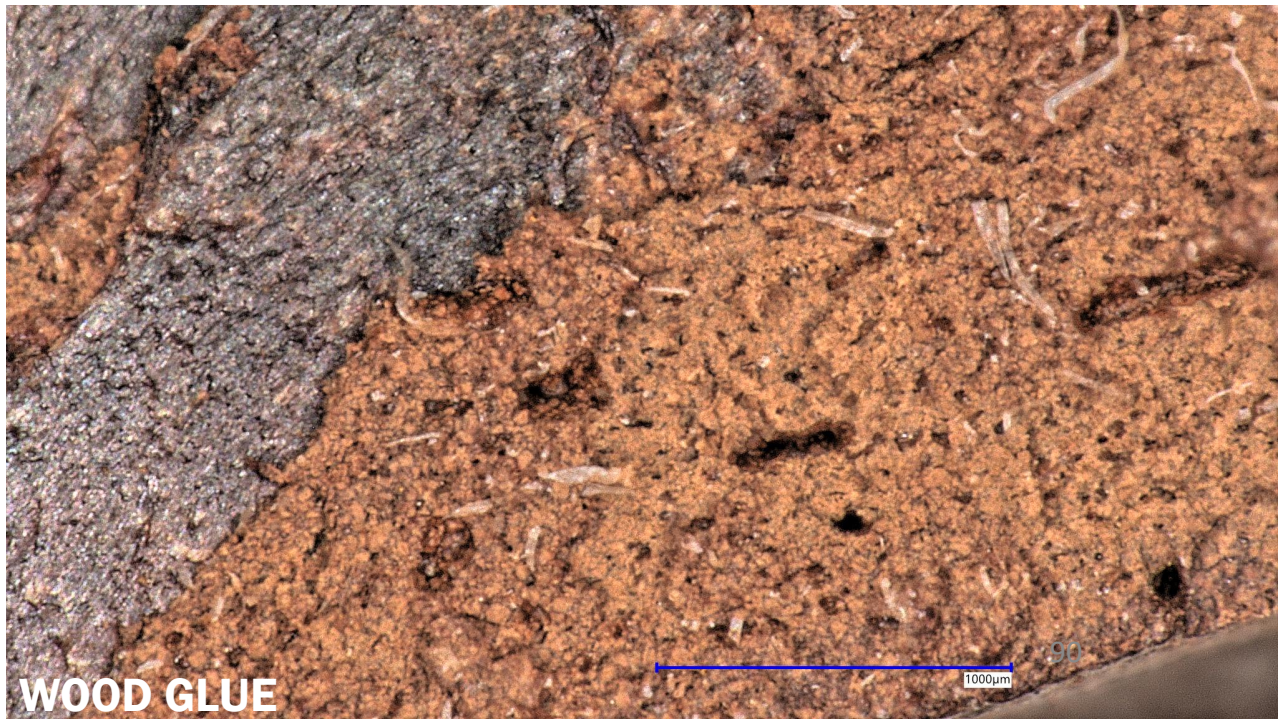


CROSS SECTION - HOMOGENEITY & FIBRE DIRECTION









BACKGROUND

OBJECTIVE

RESEARCH

MATERIAL EXPLORATION

PRINTABILITY EXPLORATION

PROPERTIES EXPLORATION

DESIGN & PROTOTYPING

CONCLUSIONS

DESIGN CONSTRAINTS

OVERHANG CORNERS WEIGHT GEOMETRY PROPERTIES

MATERIAL ENHANCEMENT

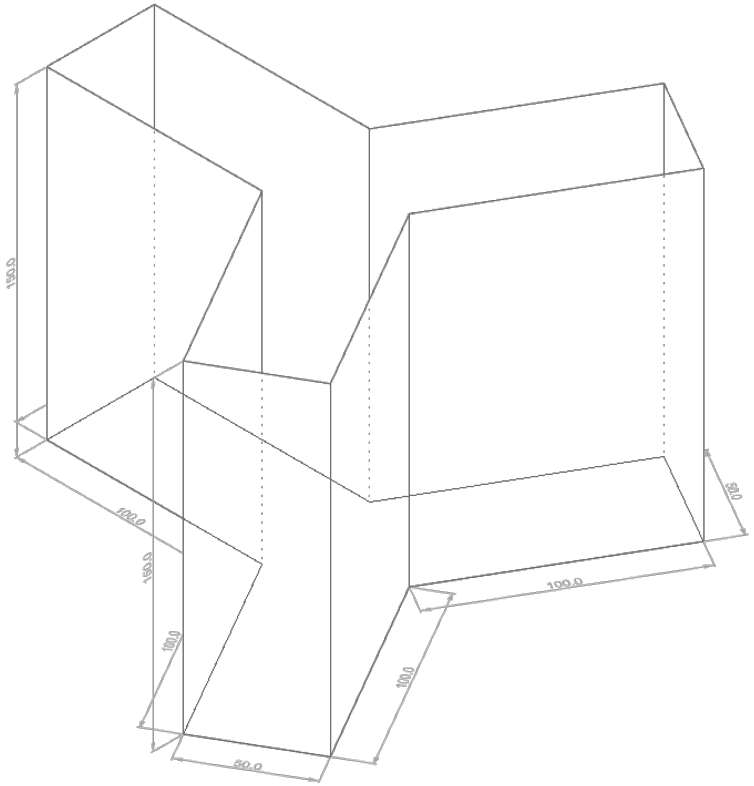


FLAX

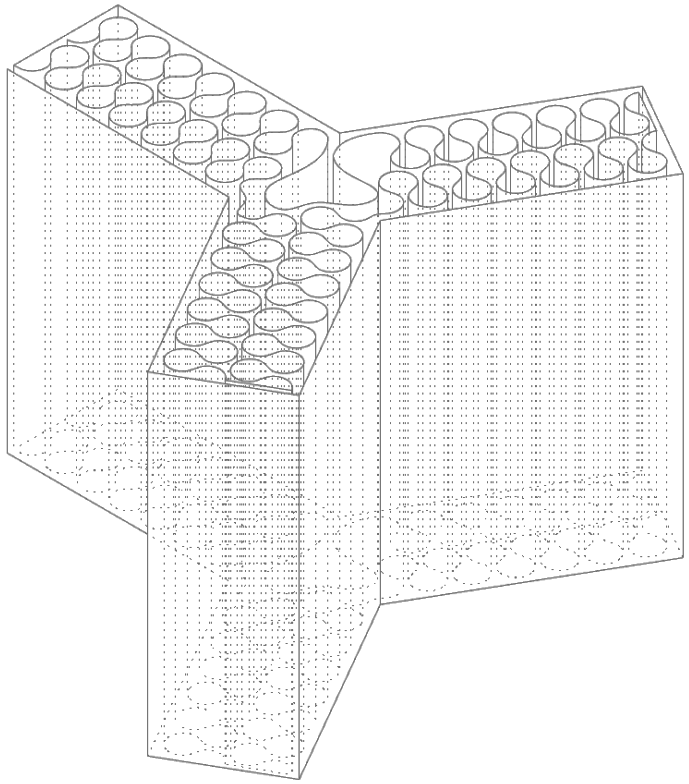


BENTONITE

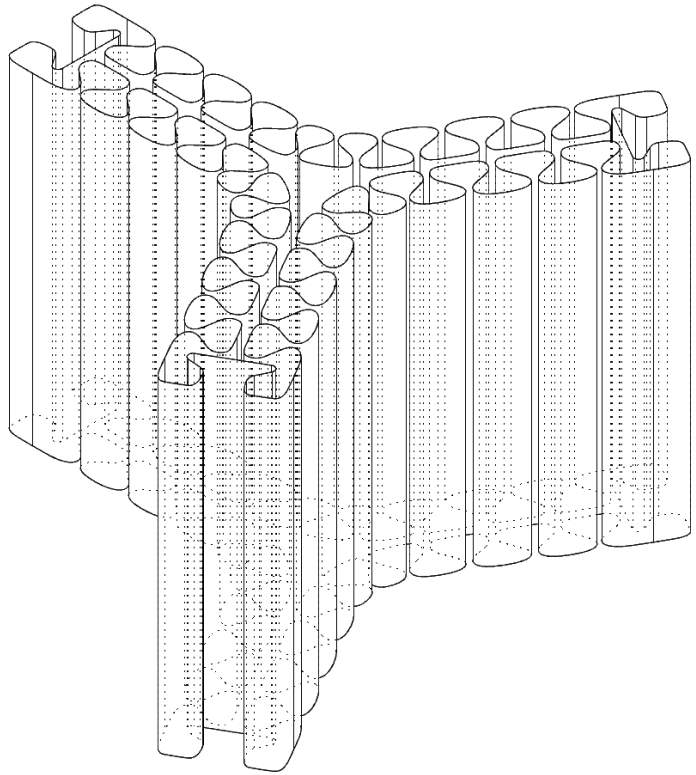
DESIGN EVOLUTION



Outline



Outline & Curvilinear Infill



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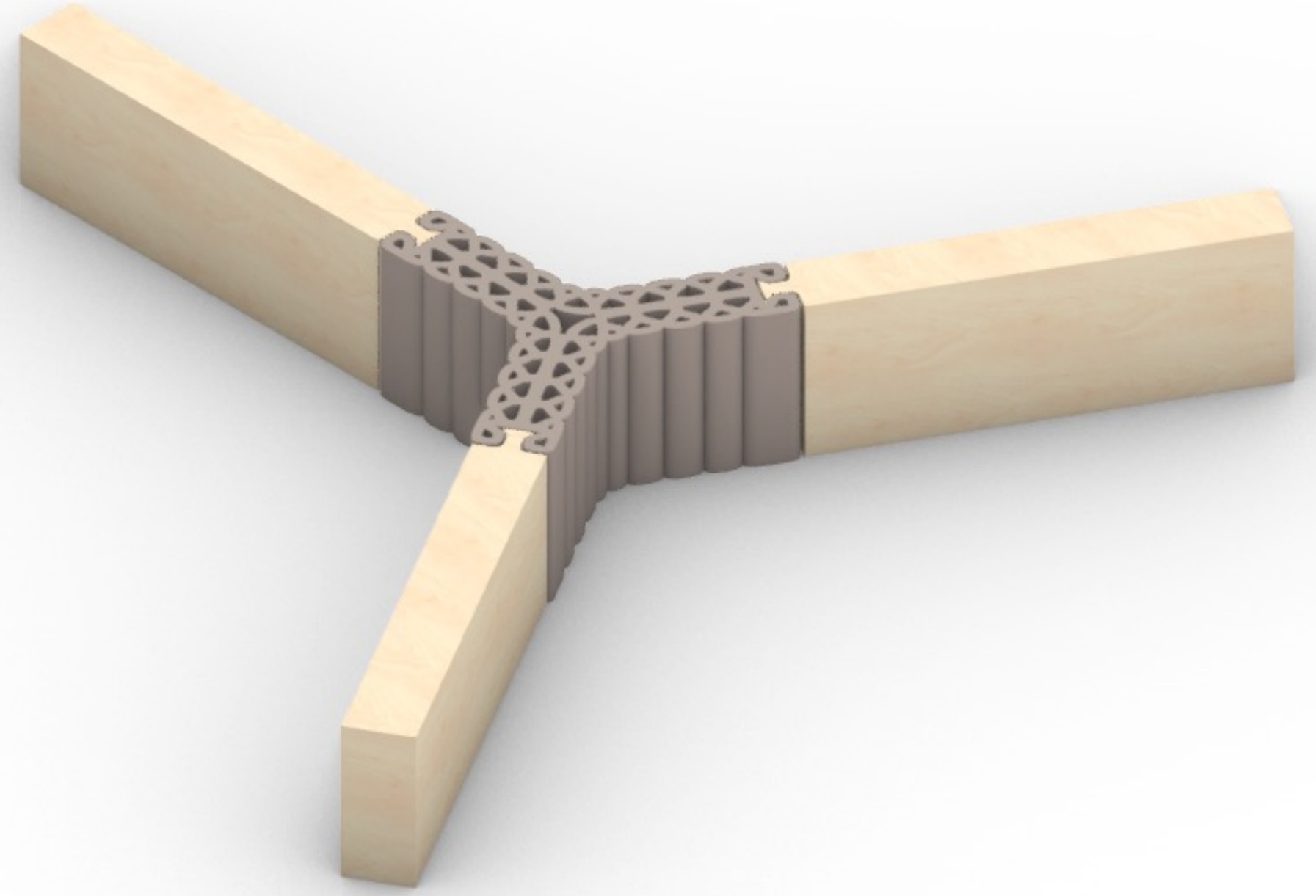
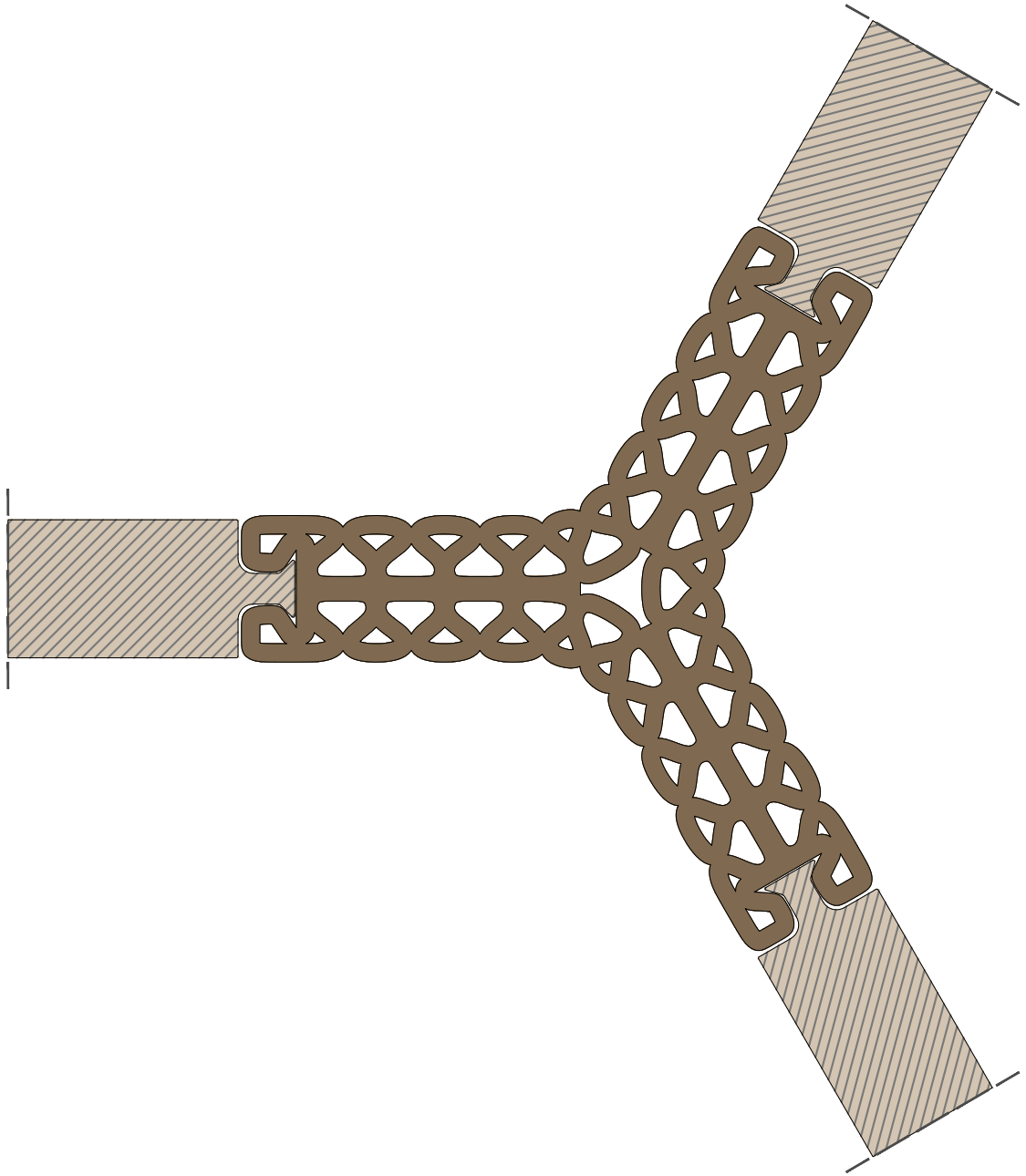
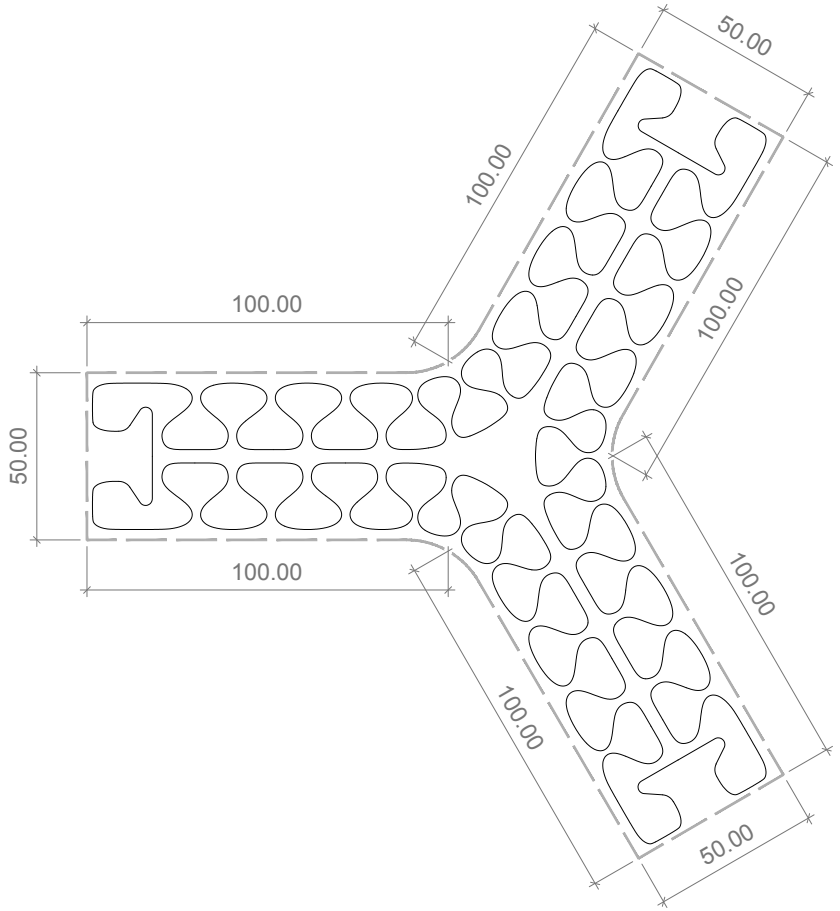
DESIGN OUTCOME



NODE TOP VIEW & TOOL PATH





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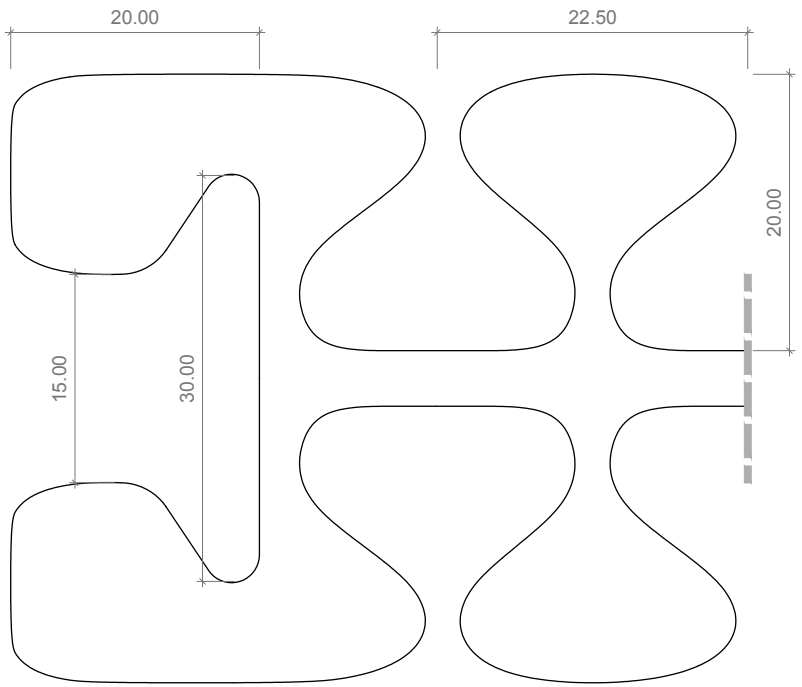
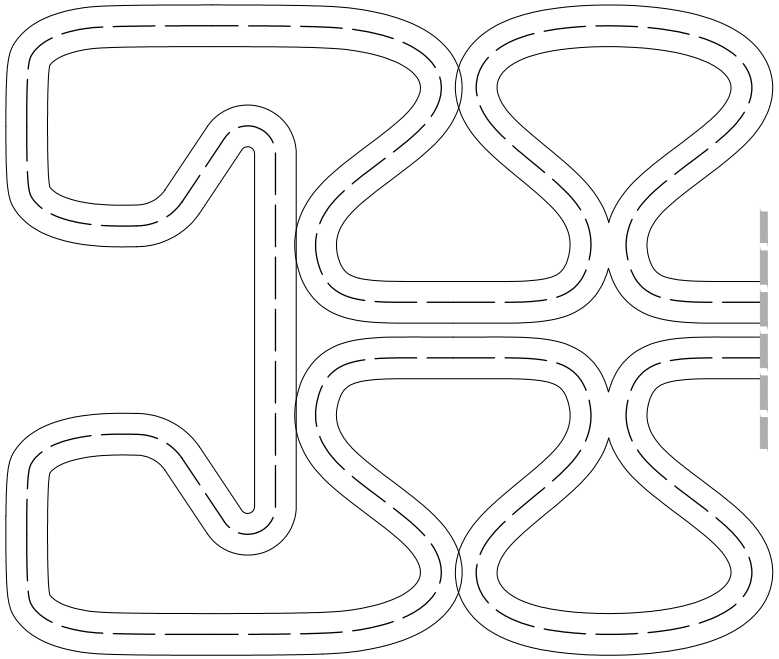
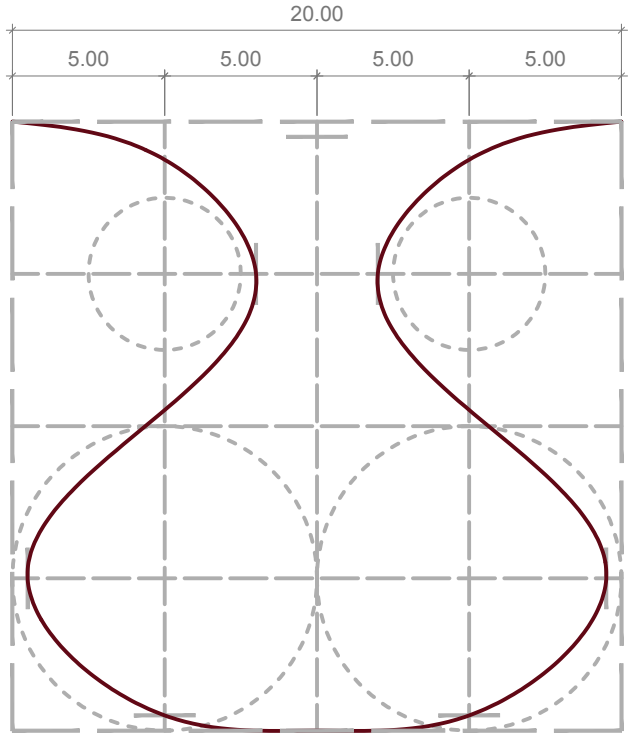
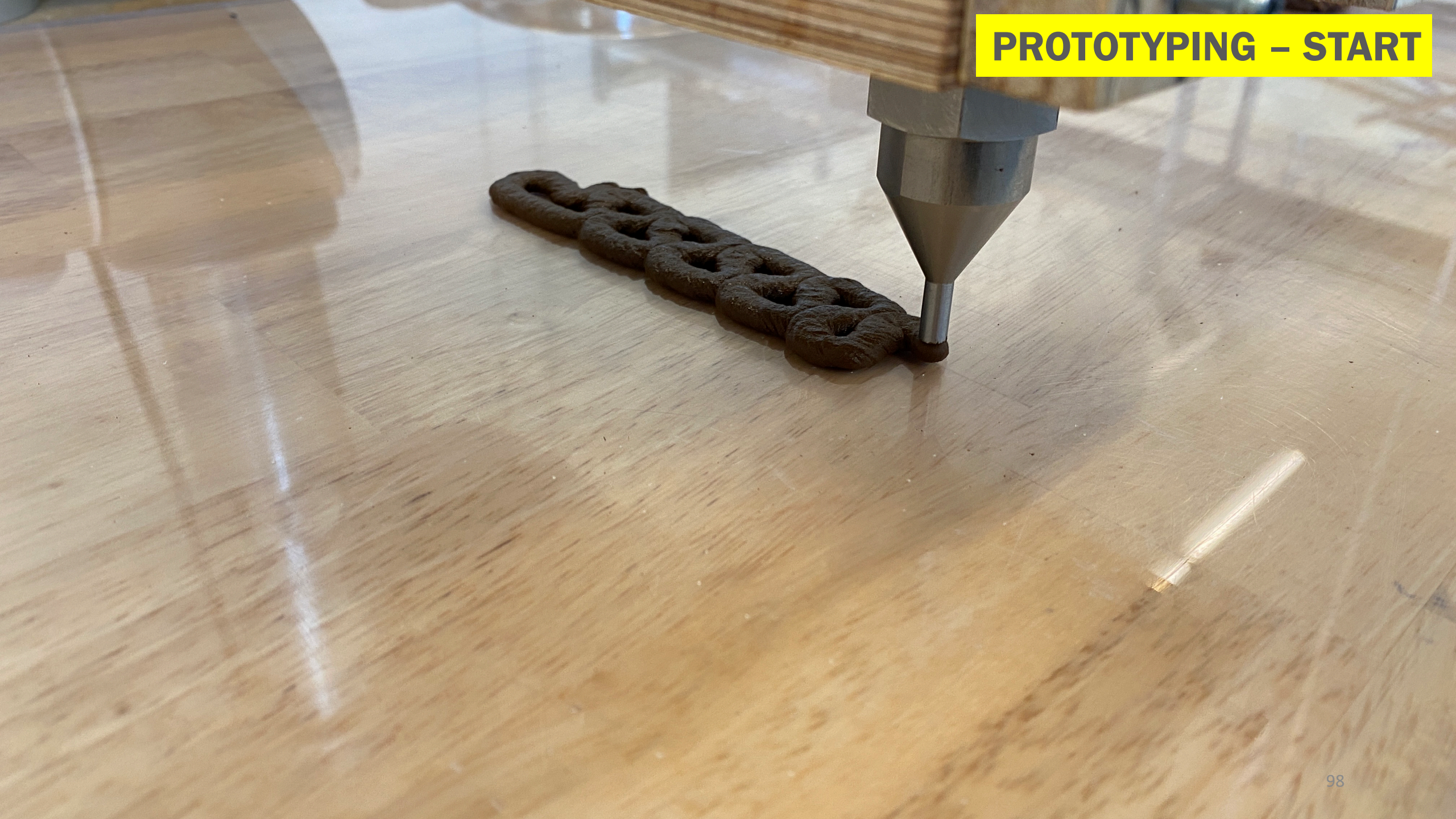
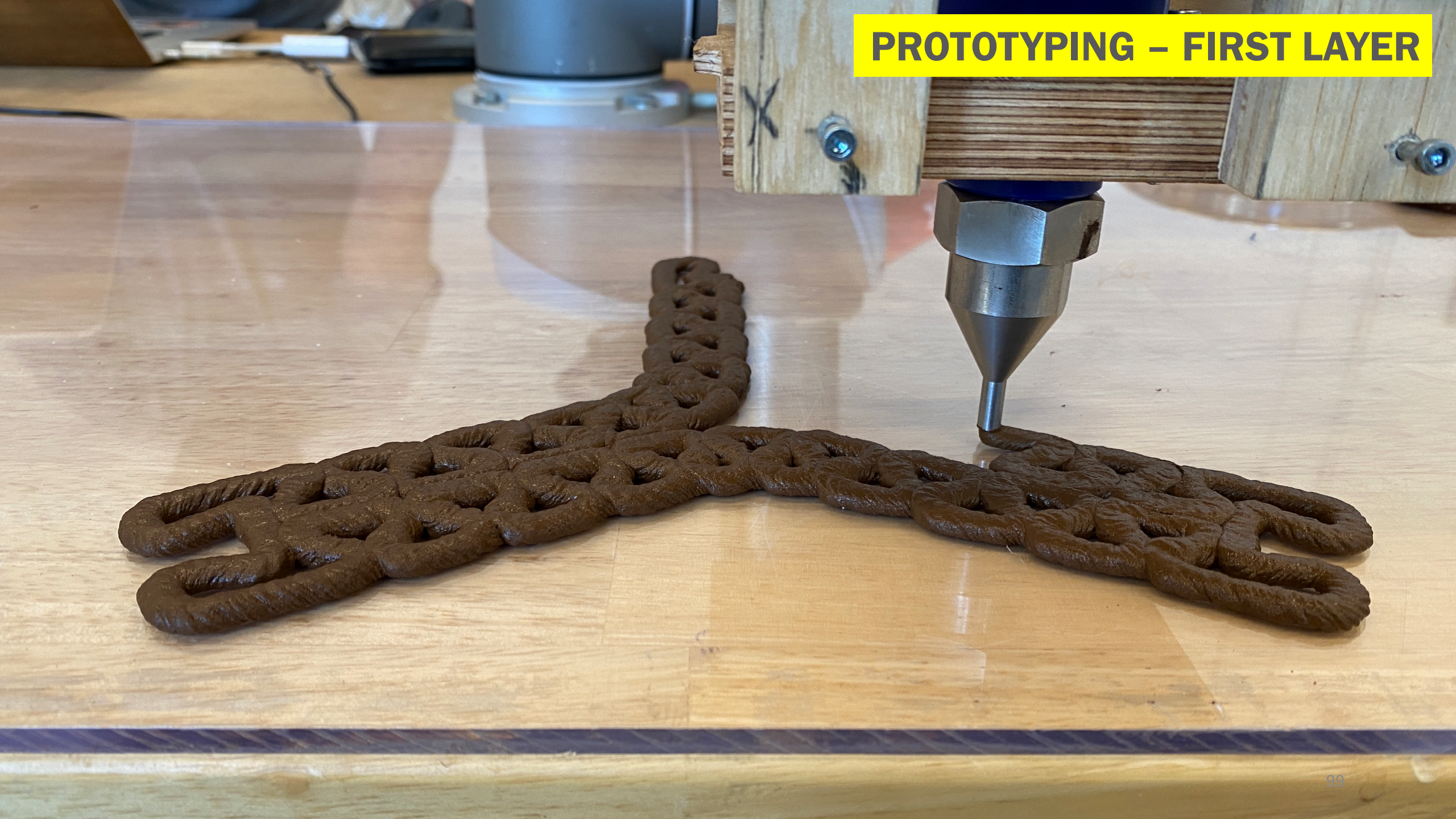




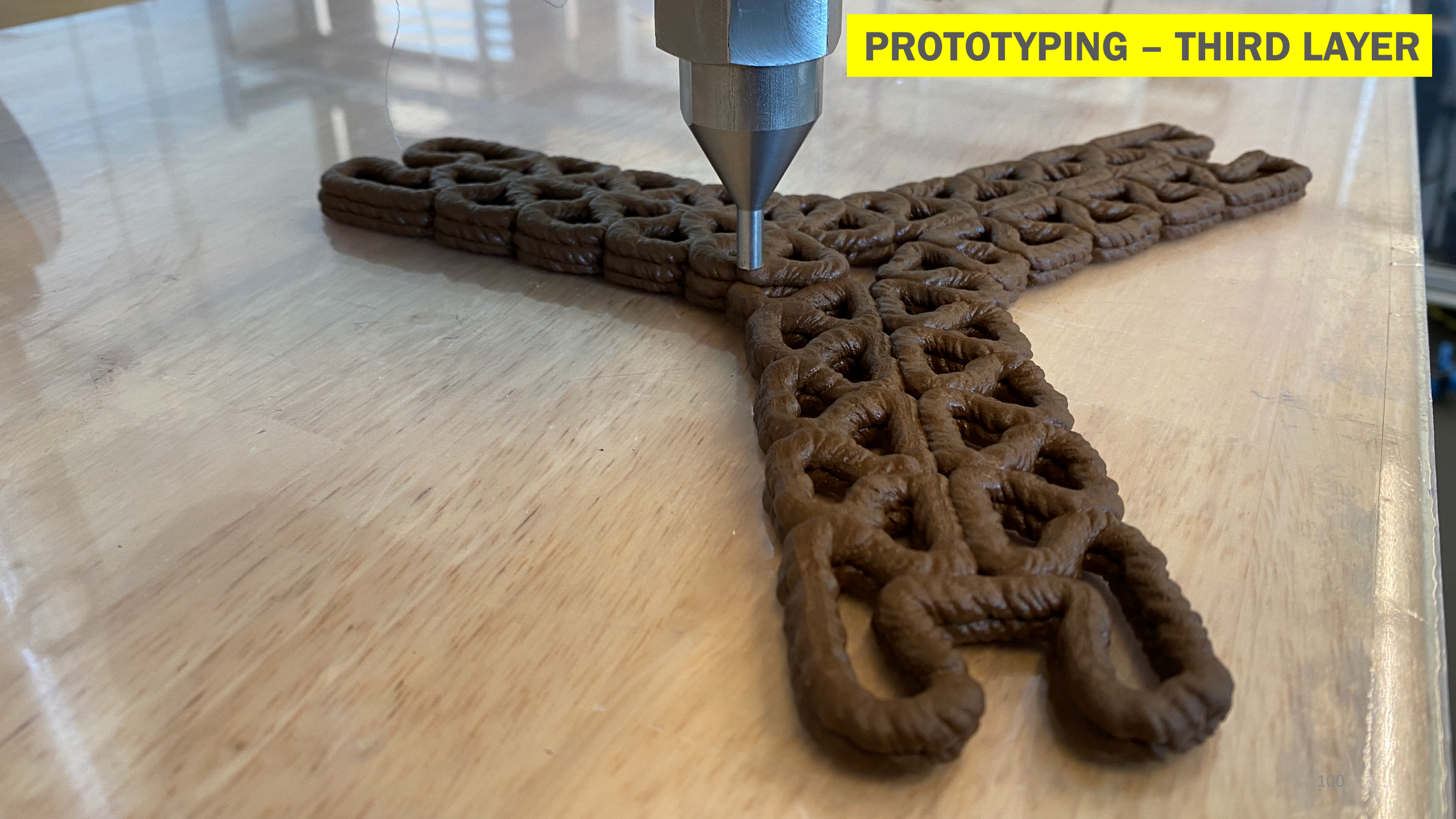



PROTOTYPING – START

PROTOTYPING – FIRST LAYER



PROTOTYPING – THIRD LAYER




FABRICATION

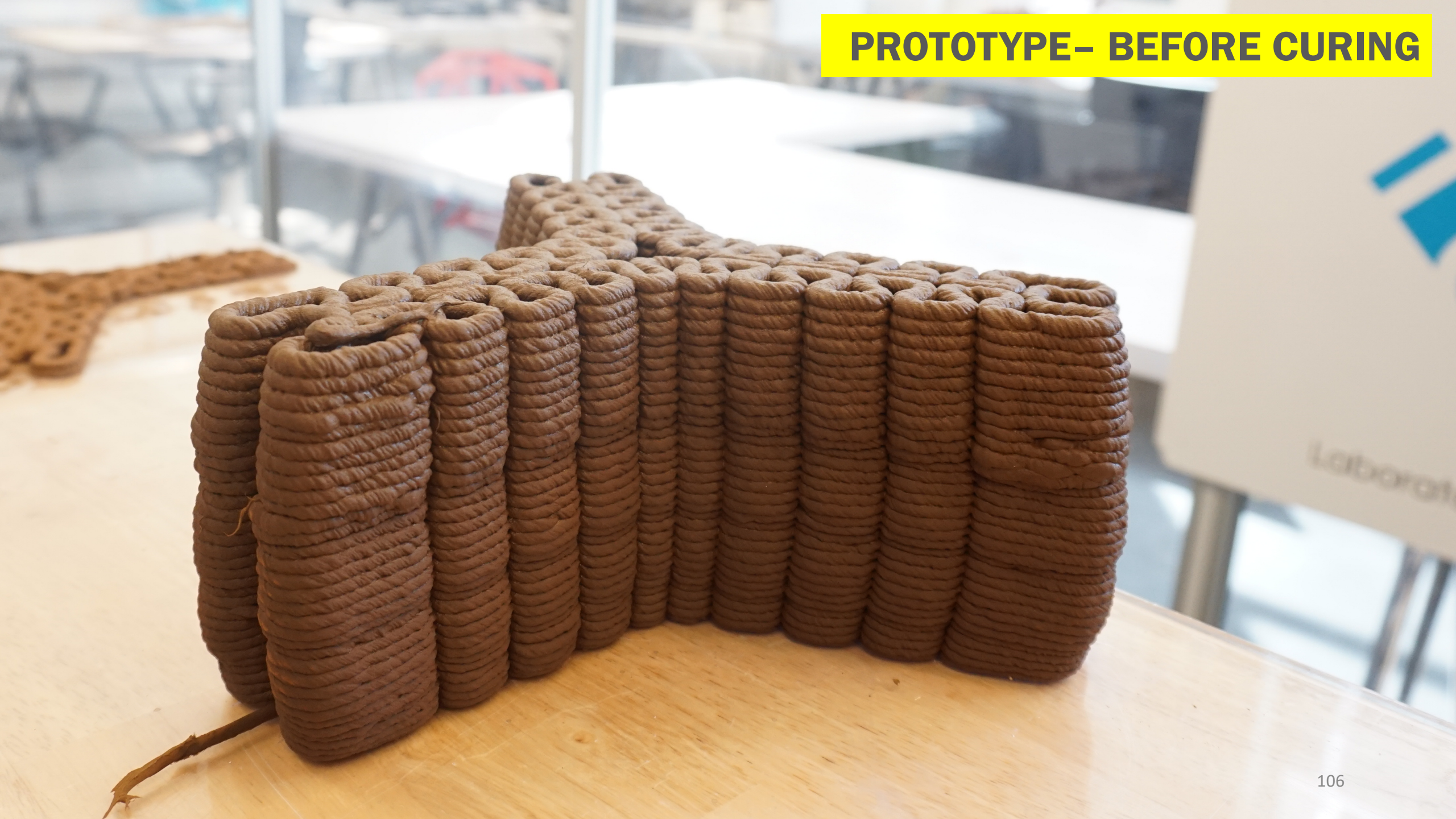

FABRICATION

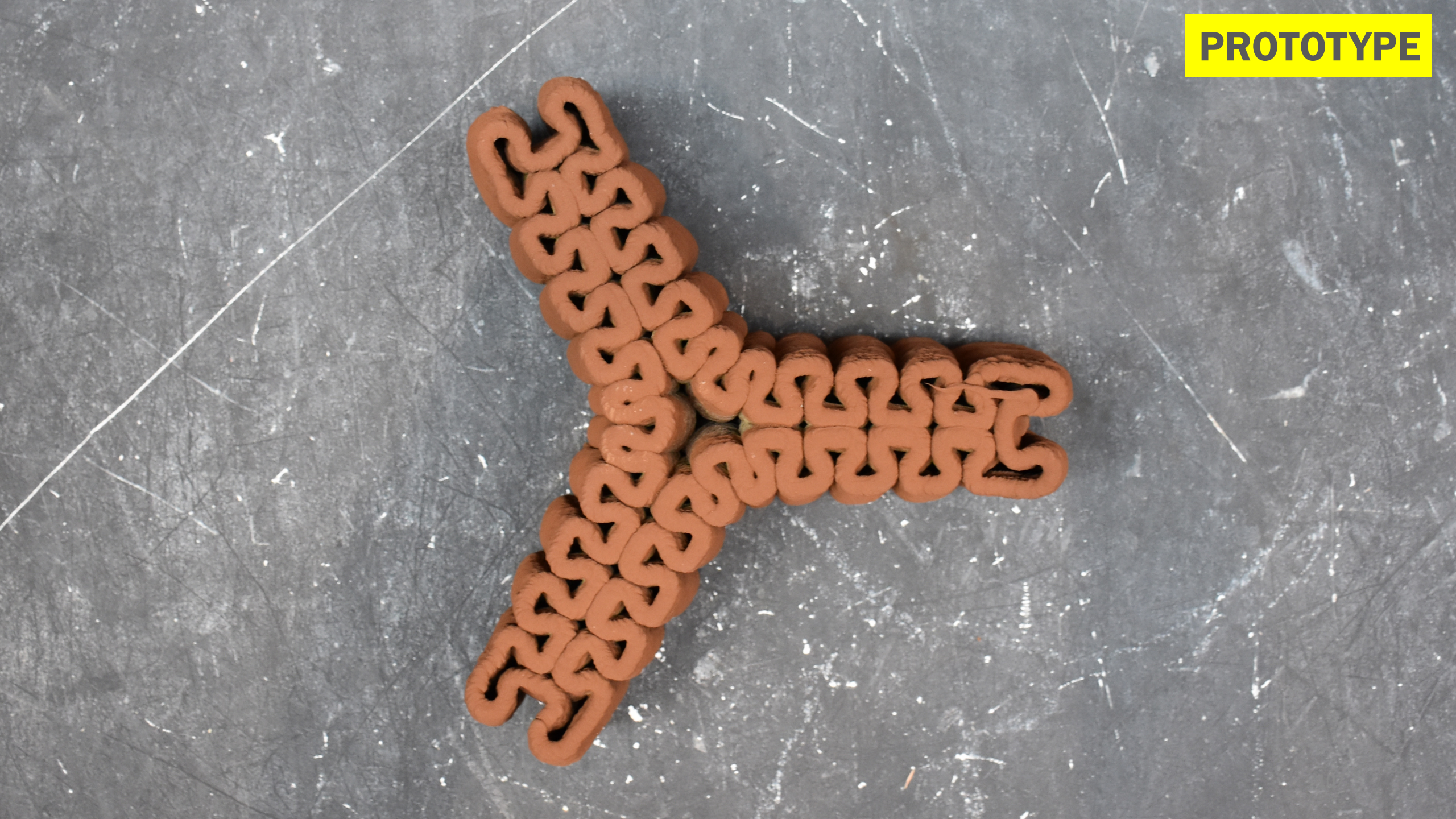

FABRICATION

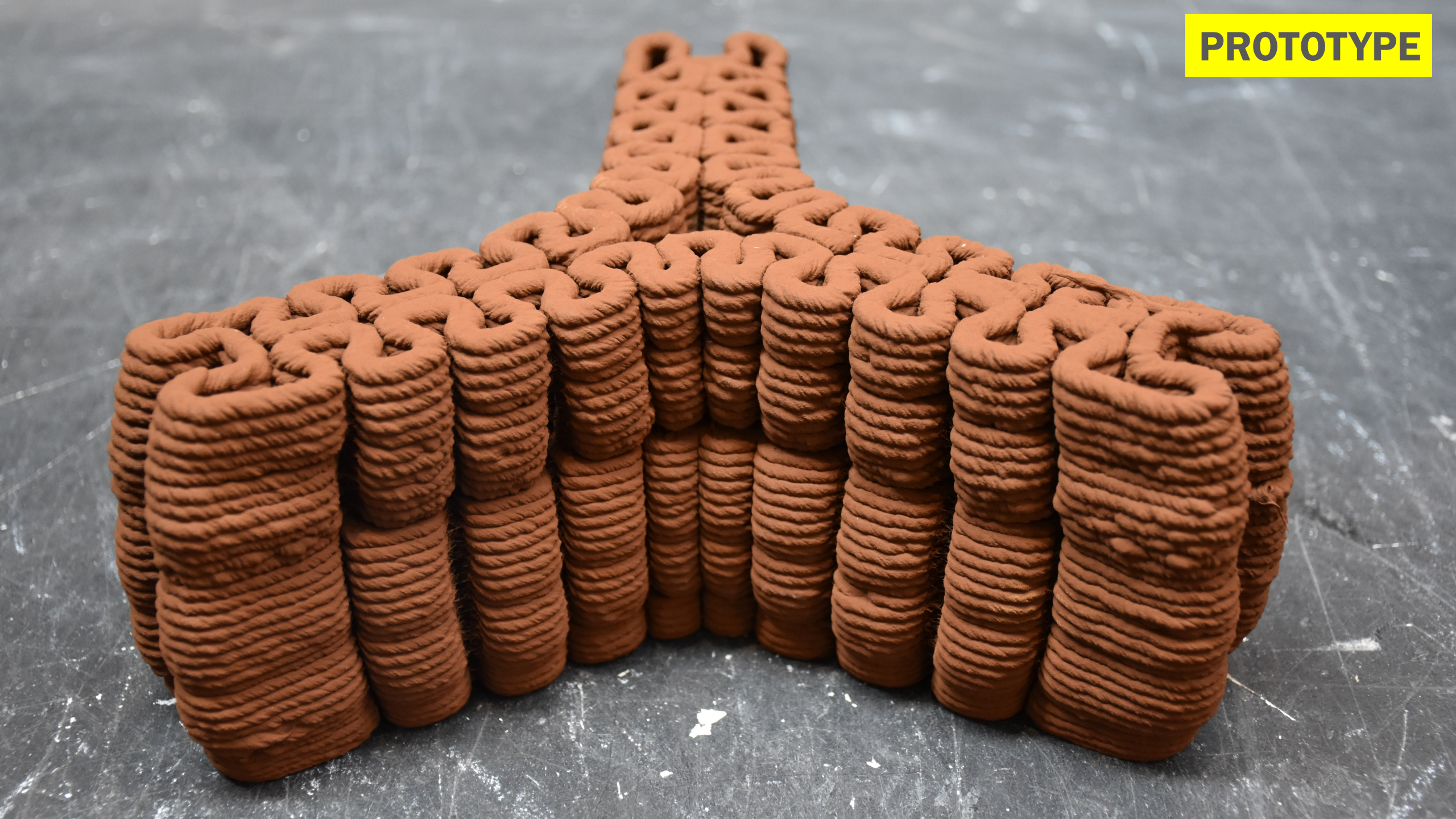

FABRICATION


PROTOTYPE

PROTOTYPE– BEFORE CURING




PROTOTYPE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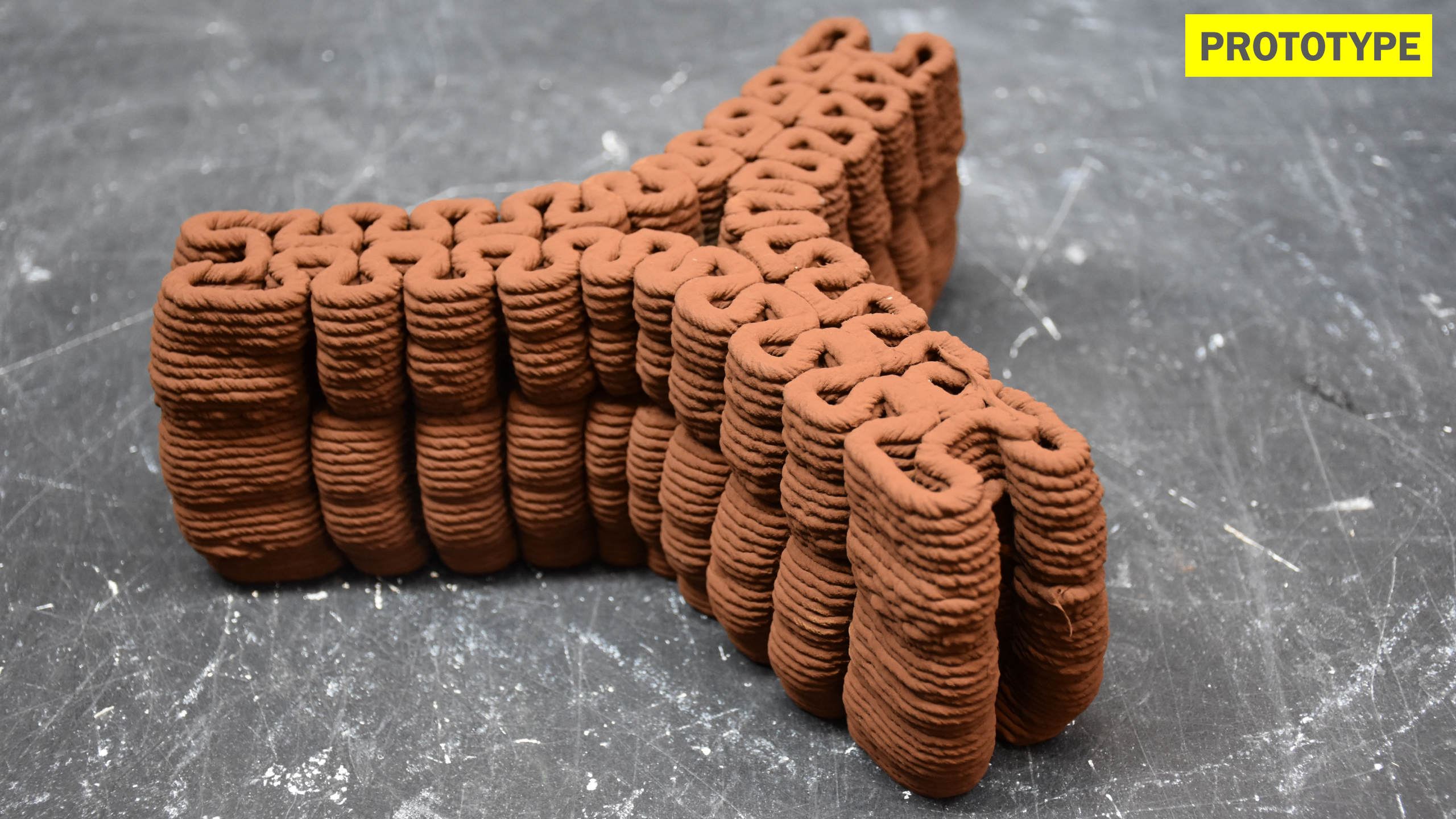
PROTOTYPE


PROTOTYPE


PROTOTYPE


PROTOTYPE

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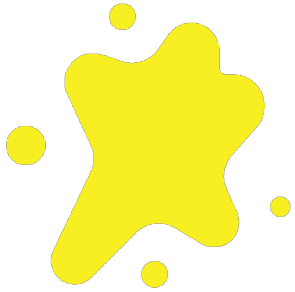
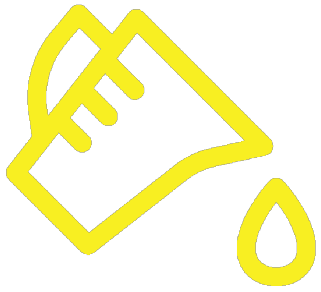
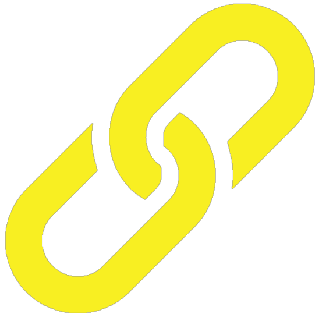
POTENTIAL



HOMOGENEITY



VISCOSITY

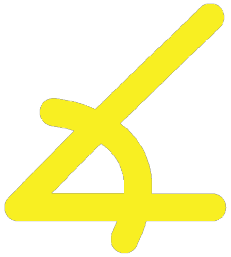


ADHERENCE

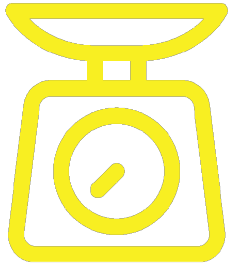
CHALLENGES



OVERHANG



CORNERS



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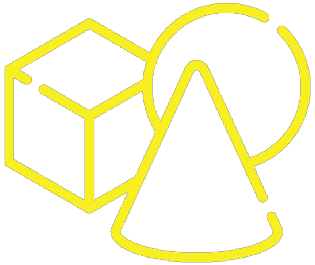
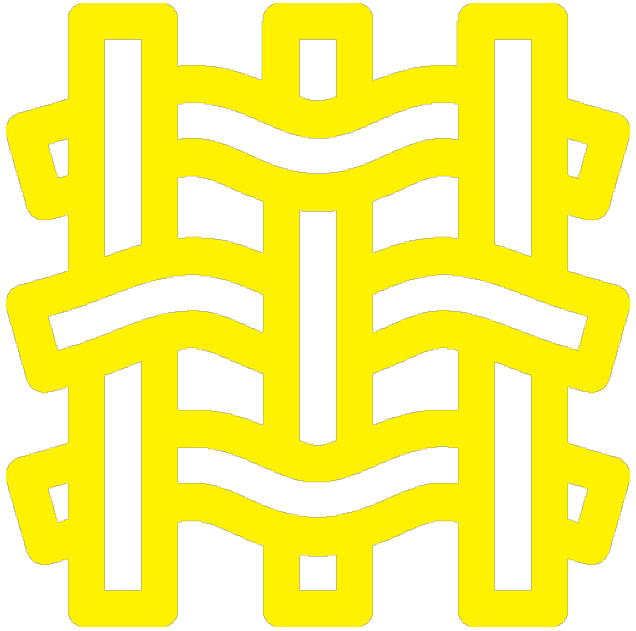
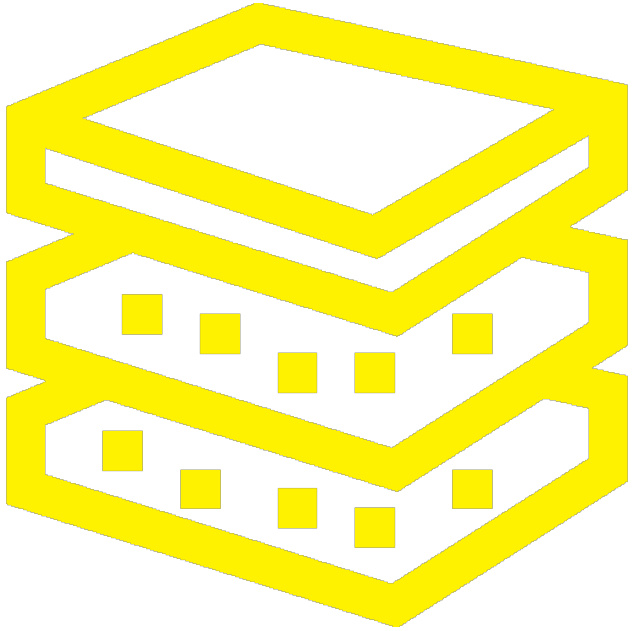


GEOMETRY

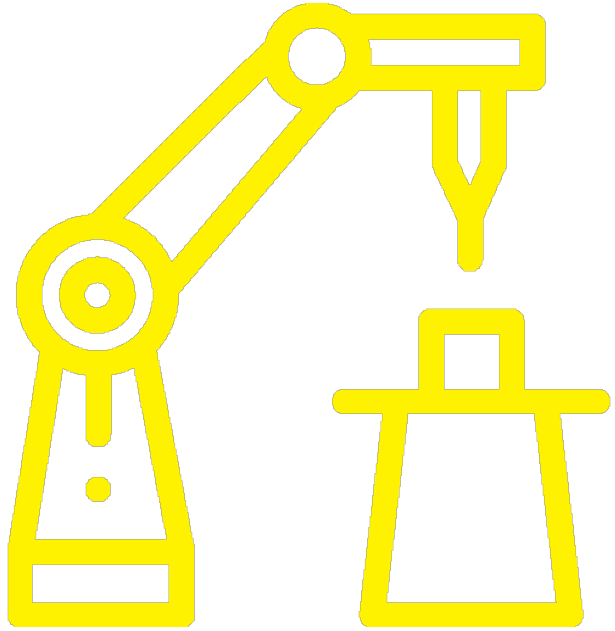
FUTURE RESEARCH



Additional Fibre Reinforcement
Structural Properties



Material Characterization
Composition & Properties



Fabrication Processes
Hot / Pellets

GRADUATION

Material development targeting digital fabrication and additive manufacturing

More research by design than design by research, exploration phases were the most fruitful

Material and fabrication more valuables than a design lacking foundation

External and inter-faculty collaboration fundamental for the research development

SOCIETY

Solid result at identifying the potential and challenges of a new feedstock

Full innovation achieved – bio-based feedstock development and proof of concept produced

Natural material potentially sourced from waste, reducing the construction industry CO2 footprint

“Liquid wood” made from waste breaks the paradigms of building industry materials



THANK YOU

QUESTIONS?