Re-P-Tile

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Problem

Consumers / Contributors

Global waste generation

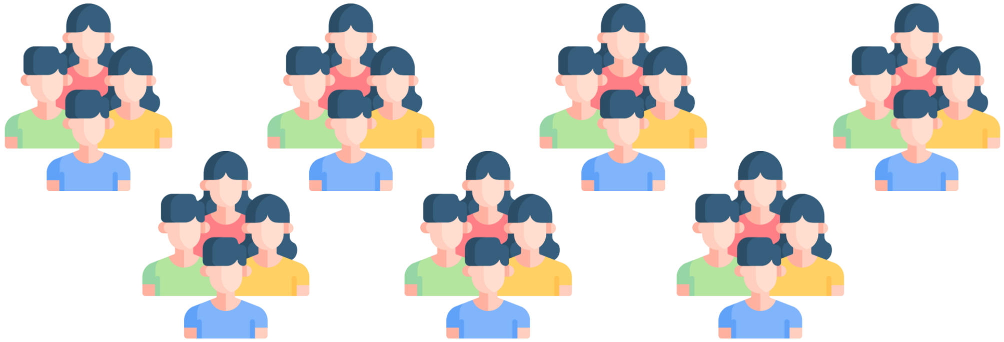
Source : Icons from Flaticon

Problem

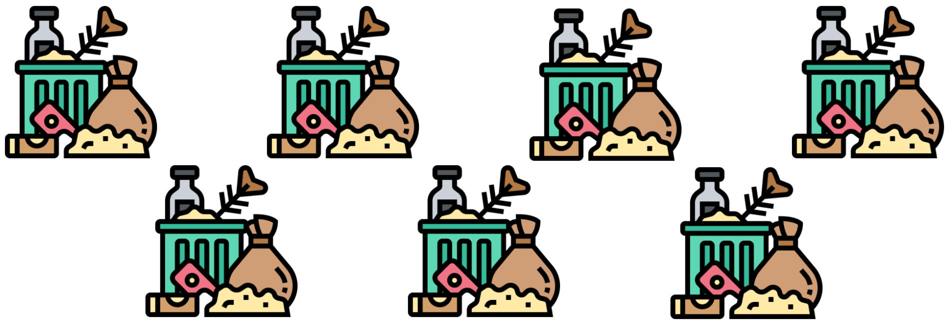
Consumers / Contributors

Global waste generation

Increase in population



Increase in waste generation



Source : Icons from Flaticon

Problem

Global waste generation

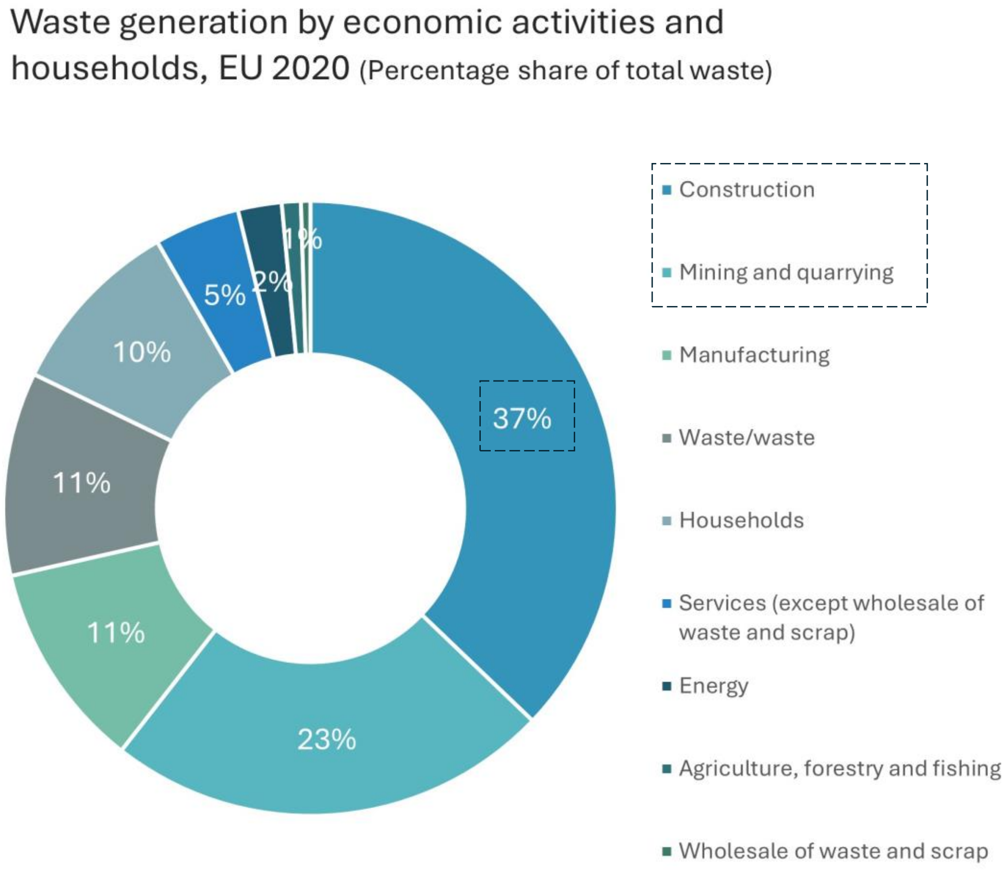
UN environment programme

Global Waste Management Outlook 2024

Every year across the globe more than
Two Billion Tonnes
of municipal solid waste is generated.

Problem

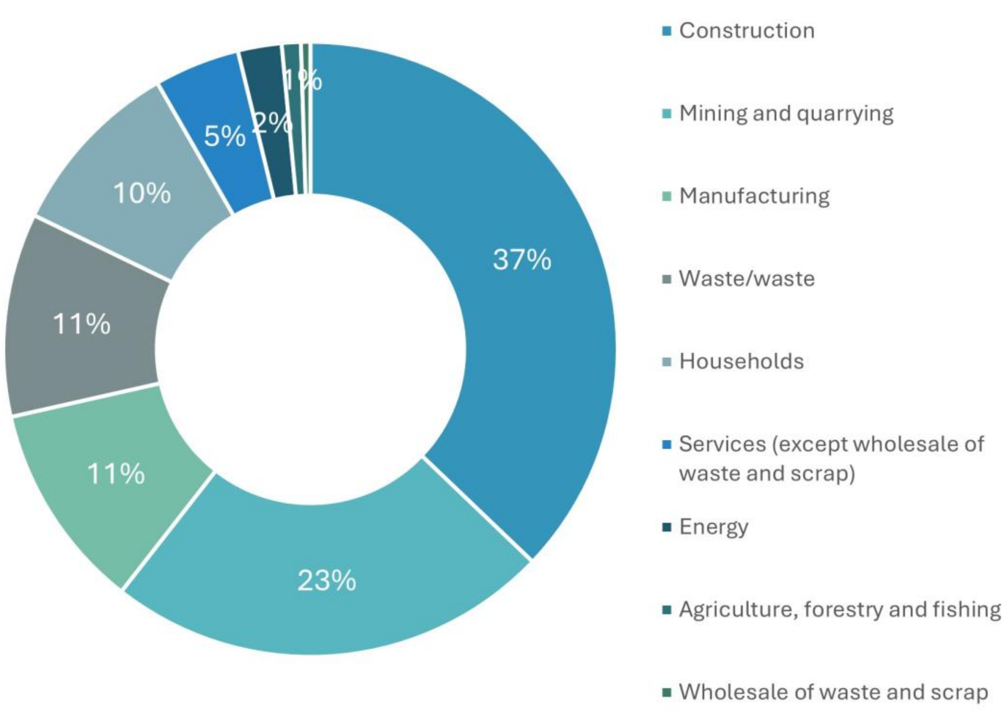
Global waste generation



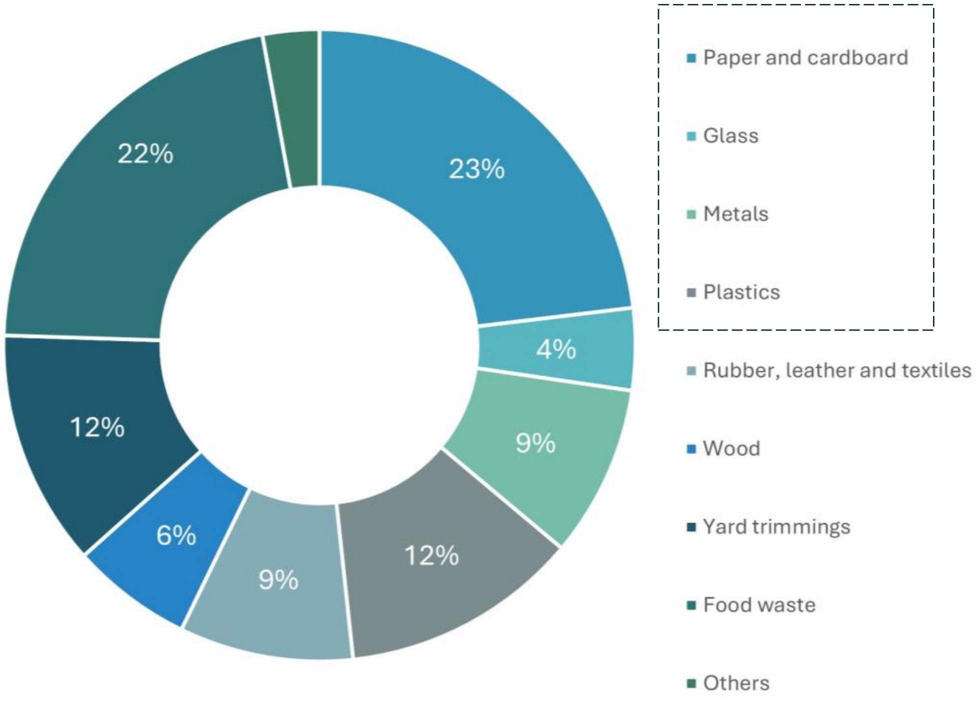
Source : Eurostat

Problem

Waste generation by economic activities and households, EU 2020 (Percentage share of total waste)



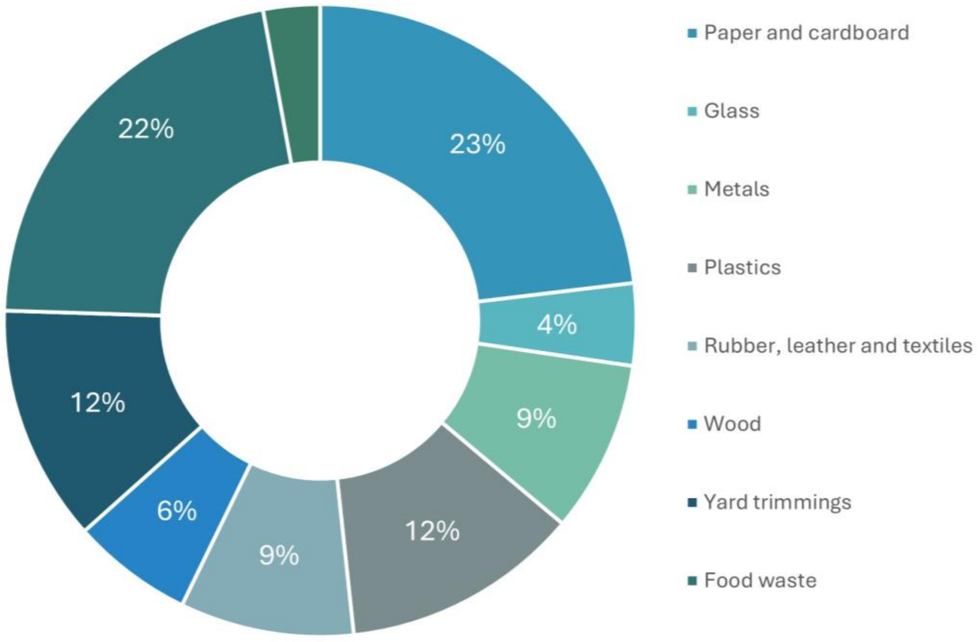
Waste generation by category in solid municipal waste, EU 2020 (Percentage share of total solid municipal waste generated)

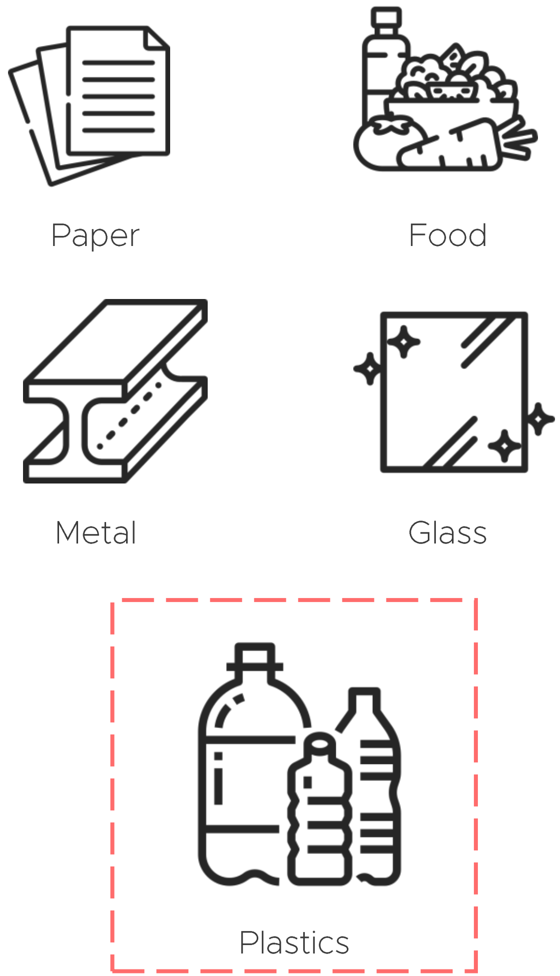


Source : Eurostat

Problem

Waste generation by category in solid municipal waste, EU 2020 (Percentage share of total solid municipal waste generated)





Plastic – as a material

Plastics

replaced →

Source : Icons from Flaticon

Plastic – as a material

Plastics

Material properties

- Low cost
- Light weight
- Low maintenance
- Chemical and water resistant
- Electrical and heat insulation
- Dimensional stability

Benefit to price paid

Application in built environment

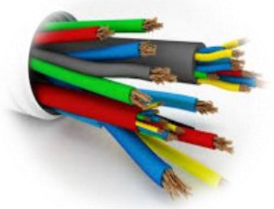

Cladding tiles


Roofing tiles


Doors and windows


Sanitary pipes


Insulation


Cables

Source : Icons from Flaticon

Plastic – as a material

Plastics

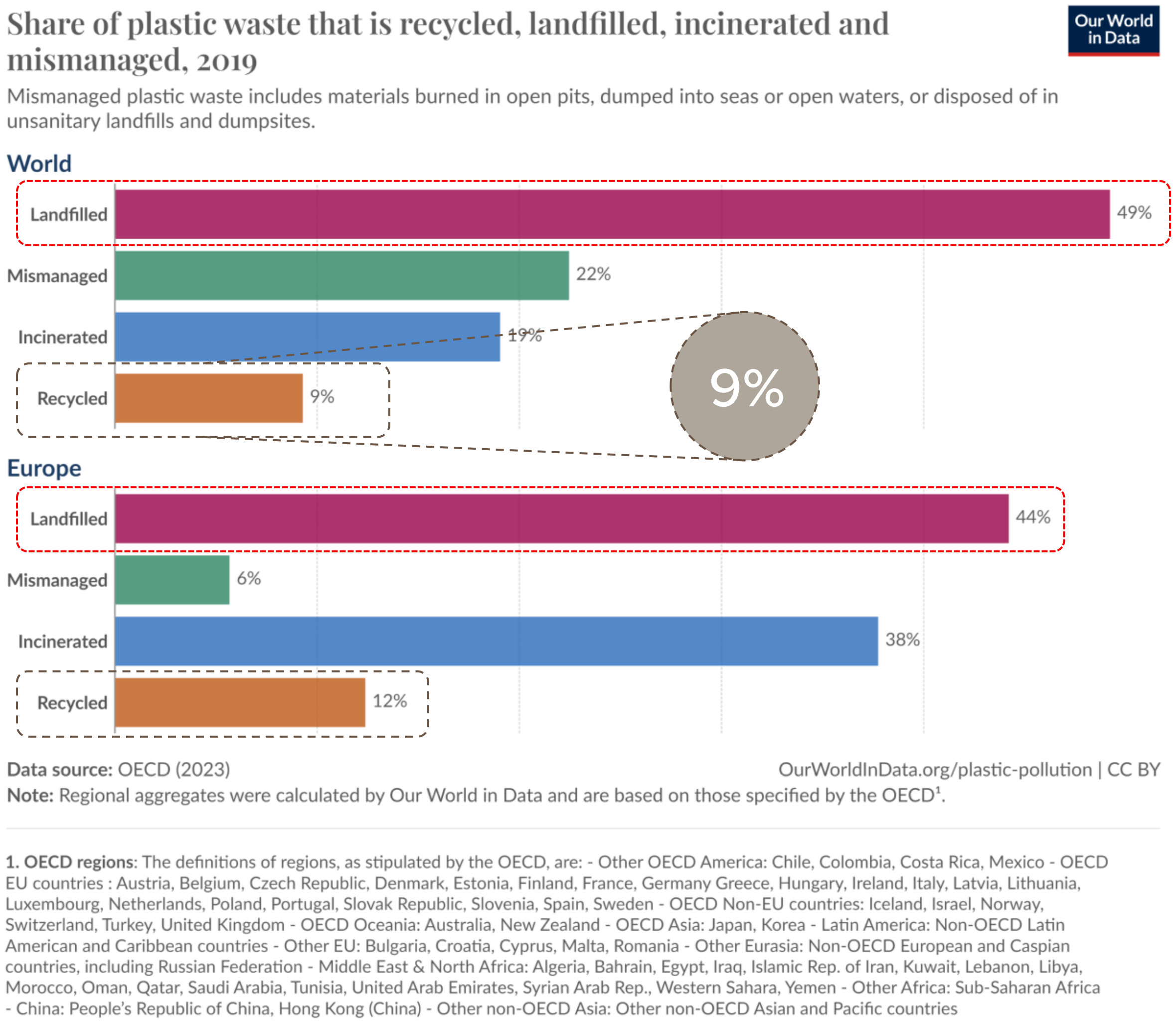
2020

420 million tonnes

→

2040

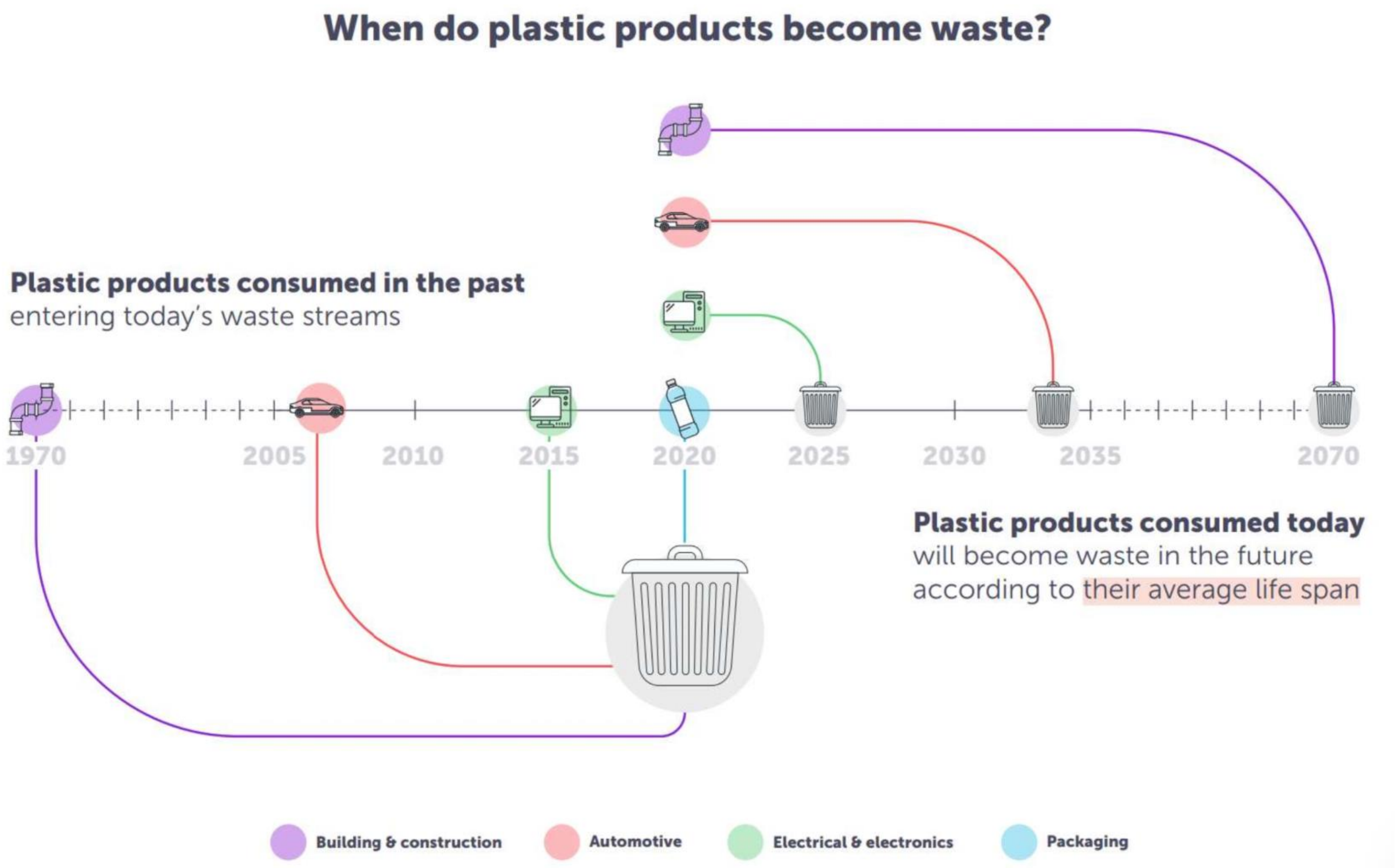
780 million tonnes



Source : Our world in Data

Landfills : We are running out of Space ! ! !

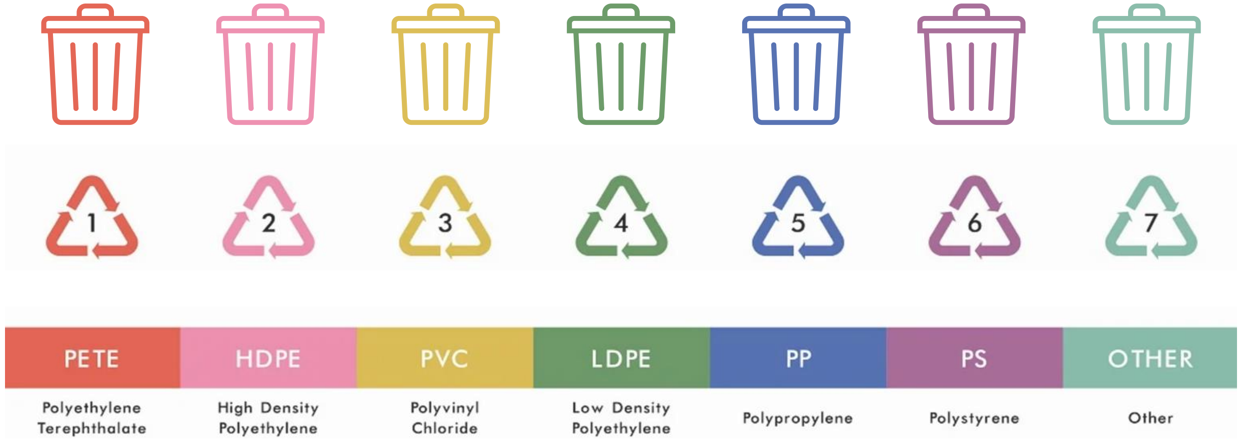
Why is there an urgent need to solve this?



Source : Plastic Europe report 2022

Plastic recycling

Plastic identification



Challenges

Each plastic resin has to be processed separately

↓

Need for manual sorting of plastic resin

↓

- Need of high infrastructure
- Labour intensive process
- Material degradation

} High cost of recycling

Plastic resin selection

Criteria for resin selection

1. Cost of virgin material
2. Density of the material
3. Mechanical properties – Tensile strength, compressive strength and bending strength
4. Thermal properties – Thermal resistivity, melting point and glass transition temperature
5. Durability properties – UV radiation and flammability

	Plastic classification and properties *(Properties represent material data without any contamination)*	Price	Physical properties	Mechanical properties			Thermal and combustion properties			Durability		Optical properties	Usage in construction industry - examples of projects / products			
			Density	Tensile strength	Compressive strength	Bending strength	Thermal resistivity	Melting point	Glass temperature	UV radiation	Flammability	Transparency	Superstructure	Enclosure	Interiors	Services
		Euro/kg	kg/m³	MPa	MPa	MPa	m.°C/W	°C	°C							
	Source of information	[1]														
Engineering plastics	Polyethylene (PE) – LDPE	1.6 - 1.78	917 - 932	13.3 - 26.4	10.8 - 17.4	*10.0-20.0 (*)*	*0.3 - 0.4 (*)*	97.85 - 114.85	105 - 115 (*)	Poor	Highly fammable	Translucent	Vapour barrier and moisture protector	-	Wall finish sheets	-
	Polyethylene (PE) – HDPE	1.23 - 1.27	952 - 965	26 - 31	18.6 - 24.8	*20.0-37.0 (*)*	*0.4 - 0.5 (*)*	129.85 - 136.85	120 - 130 (*)	Fair	Highly fammable	Translucent	beams, columns , truss	-	Wall finish sheets	Water pipes
	Polypropylene (PP)	1.51 - 1.73	895 - 909	26 - 50	23.8 - 25	21.7 - 39.1	5.02 - 5.22	139.85 - 149.85	160 - 170 (*)	Poor	Highly fammable	Translucent	-	PP foam insulation	-	-
	Polyvinyl Chloride (PVC)	2.14 - 2.26	1.29e3 - 1.46e3	38 - 46	37 - 44.3	37.2 - 54.7	4.78 - 6.8	59.85 - 149.85	79.85 - 87.85	Fair	Self - extinguishing	Transparent	Beams and columns	Exterior cladding- composite panels, Roofing material, window frames, doors	Flooring tiles (Vinyl flooring), wall panels - composite panels	Water pipes, drainage pipes, electrical boxes, electrical conduits, ductwork, cable trays
	Polyethylene Terephthalate (PET)	1.26 - 1.82	1.29e3 - 1.39e3	55 - 60	50 - 60	59.3 - 65.4	4.17 - 7.25	260.05	59.85 - 83.85	Fair	Highly flammable	Translucent	-	Exterior cladding- composite panels	-	PET Ducts
	Polystyrene (PS)	1.96 - 2.67	1.04e3 - 1.05e3	35.9 - 51.7	82.7 - 89.6	30.2 - 59	7.14 - 8.33	170 - 280	89.85 - 99.85	Fair	Highly flammable	Opaque	-	Wall and roof insulation, interior doors	-	-
	ABS	2.44 - 2.56	1.03e3 - 1.06e3	37.9 - 51.7	39.2 - 86.2	19.4 - 53.6	3.8 - 3.95	190 - 270	101.85 - 114.85	Poor	Highly flammable	Opaque	Shear walls - High strength ABS	Window frames	-	Drainage pipes
	Polycarbonate (PC)	3.11 - 3.38	1.19e3 - 1.21e3	62.7 - 72.4	69 - 86.2	62 - 73.5	4.59 - 5.18	280 - 320	141.85 -157.85	Fair	Slow burning	Optical quality	Panels - shear walls	Roofing sheet	-	Electrical boxes
	Polyamide (Nylon/PA)	4.08 - 6.02	1.12e3 - 1.15e3	42 - 72	46 - 82	52.5 - 99.5	3.95 - 4.29	219.85 - 259.85	43.85 - 65.85	Fair	Slow burning	Translucent	Beams and columns	-	Carpets	Cable trays
	Polyetheretherketone (PEEK)	75 - 83.1	1.03e3 - 1,32e3	97 - 117	111 - 141	68.3 - 99.8	3.85 - 4.17	321.85 - 345.85	142.85 - 156.85	Excellent	Self - extinguishing	Opaque	-	-	Bearings, connectors	High performance seals, conectors
	Polytetrafluroethylene (PTFE)	11.2 - 14	2.14e3 - 2.2e3	20.7 - 34.5	11.2 - 12.3	15.8 - 26.3	3.83 - 4.13	314.85 - 338.85	116.85 - 129.85	Good	Non-flammable	Translucent	-	Coating	-	chemical-resistant linings for pipes and fittings
	Polymethylmethacrylate (PMMA)	2.21 - 2.97	1.17e3 - 1.2e3	54 - 72	72.4 - 124	72.4 - 131	*0.15 - 0.2 (*)*	*205 - 230 (*)*	99.85 - 109.85	Good	Highly flammable	Optical quality	-	Skylights, daylighting panels	Decorative room dividers	Transparent service panels
	Ethylene tetrafluroetylene (ETFE)	33.9 - 40.8	1.68e3 - 1.72e3	42.7 - 47.1	46.6 - 51.4	36.1 - 39.8	4.03 - 4.37	258.85 - 280.85	77.85 - 92.85	Good	Self- extinguishing	Translucent	-	Inflatable cushions for lightweight structures	Atrium coverings	-

Source : [1 Ansys Granta Edupack [2] – Resin identification codes defined by the european commission (https://en.wikipedia.org/wiki/Recycling_codes) [3] Google search engine

TU Delft Delft University of Technology

Plastic resin selection

- PVC – PolyVinyl Chloride
- PEEK – Polyetheretherketone
- PTFE – Polytetrafluroethylene
- ETFE- Ethylene tetrafluroetylene

Building & construction post consumer plastic waste generation EU 28+2 in 2018 (in thousand tonnes)[31]:

Type of plastic	Total waste generation	Total recovery	Total recovery: Mechanical Recycling (%)	Total recovery: Energy recovery (%)
LDPE	90	70	27	51
HDPE	225	164	24	49
PP	130	95	23	50
PS	30	21	7	64
EPS	140	95	9	59
PVC	910	683	34	41
Miscellaneous	235	172	7.5	65.5
Total	1,760	1,300	25	47.5

Plastic classification and properties (*Properties represent material data without any contamination*)		Price	Physical properties	Mechanical properties			Thermal and combustion properties			Durability		Optical properties	Usage in construction industry - examples of projects / products			
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Delft University of Technology

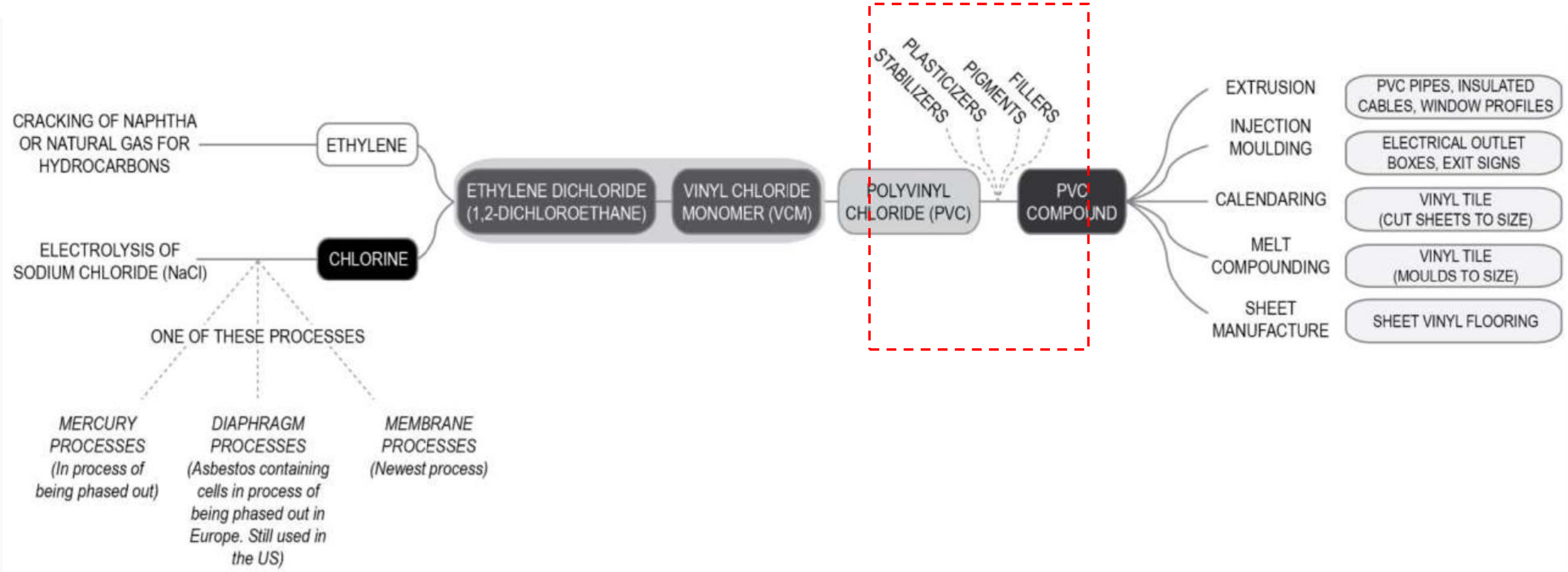
Polyvinyl Chloride (PVC)

Poly-vinyl chloride (PVC)

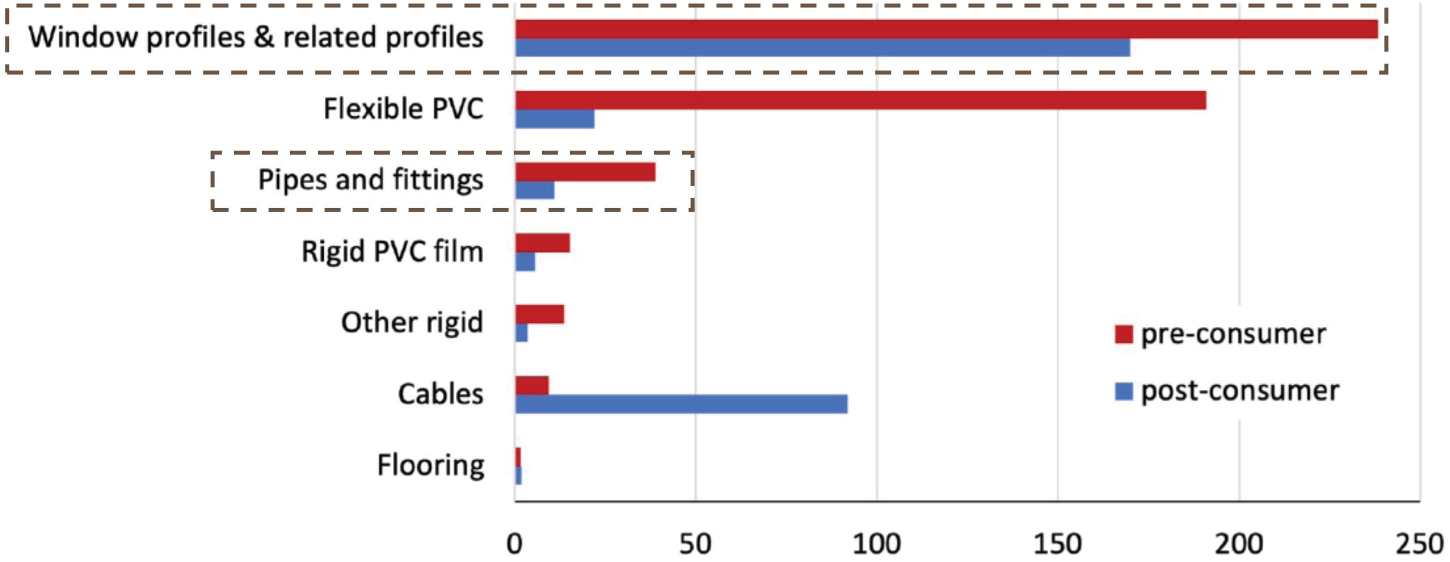
- Very popular thermoplastic
- Very rigid and cannot be use at room temperature therefore always combined with plasticizers, additives for its processing and manufacturing

Additives and reason for inclusion

- Stabilizers – PVC is heat sensitive – Heat stabilizers to protect chemical breakdown under heat
- Plasticizers – for ease of processing
- Fillers – to cut down the cost- mostly calcium carbonate
- Pigments- Colourants



Polyvinyl Chloride (PVC)



Graphical representation of recycled PVC compunds in 2022 (Source: Lahl & Zeschmar-Lahl, 2024)

“How can PVC waste streams originating from windows and pipes be processed to develop sheet material for architectural components??”

Material exploration and experimental validation

Shred Characterisation	To know the composition and thermal behaviour of the shreds
Production tests	Know the feasible method of production
Parameter Optimisation	Optimise the production and composition parameters
Application	Architecture component design

Shred characterisation

- **Shred Characterisation**
- Production tests
- Parameter Optimisation
- Application

FT-IR	LIBS	XRF	DSC
Fourier Transform Infrared Spectroscopy	Laser Induced Breakdown Spectroscopy	X-ray fluorescence	Differential scanning calorimetry

Rapid test (FT-IR, LIBS)

In-detail examination (XRF, DSC)

Shred characterisation

Shred Characterisation

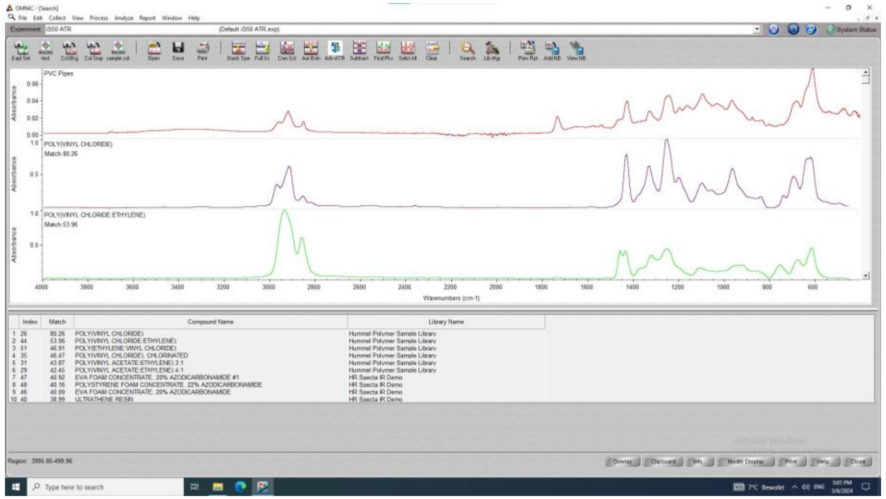
Production tests

Parameter Optimisation

Application

FT-IR	LIBS	XRF	DSC
Fourier Transform Infrared Spectroscopy	Laser Induced Breakdown Spectroscopy	X-ray fluorescence	Differential scanning calorimetry

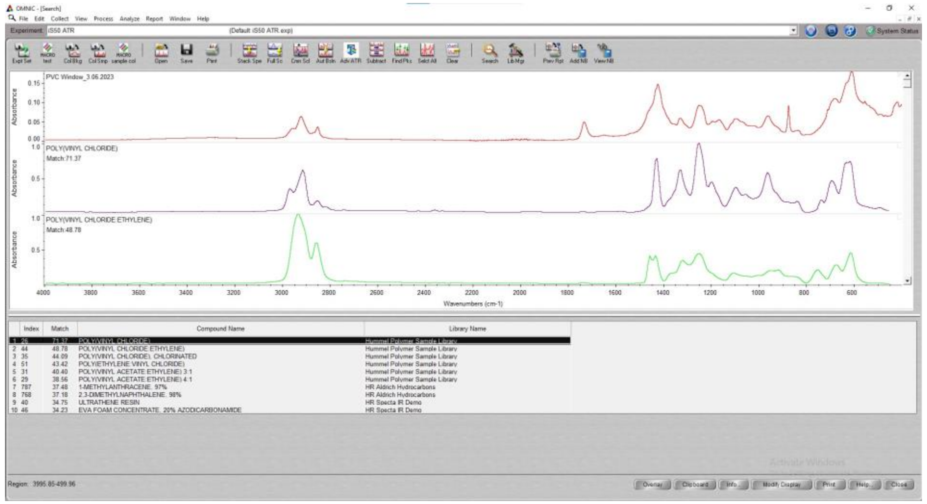
PVC pipes sample



	Index	Match	Compound Name	Library Na
1	26	80.26	POLY(VINYL CHLORIDE)	Hummel Polymer Sample Library
2	44	53.96	POLY(VINYL CHLORIDE:ETHYLENE)	Hummel Polymer Sample Library
3	51	46.91	POLY(ETHYLENE:VINYL CHLORIDE)	Hummel Polymer Sample Library
4	35	46.47	POLY(VINYL CHLORIDE), CHLORINATED	Hummel Polymer Sample Library
5	31	43.87	POLY(VINYL ACETATE:ETHYLENE) 3:1	Hummel Polymer Sample Library
6	29	42.45	POLY(VINYL ACETATE:ETHYLENE) 4:1	Hummel Polymer Sample Library
7	47	40.92	EVA FOAM CONCENTRATE, 20% AZODICARBONAMIDE #1	HR Specta IR Demo
8	48	40.16	POLYSTYRENE FOAM CONCENTRATE, 22% AZODICARBONAMIDE	HR Specta IR Demo
9	46	40.09	EVA FOAM CONCENTRATE, 20% AZODICARBONAMIDE	HR Specta IR Demo
10	40	38.99	ULTRATHENE RESIN	HR Specta IR Demo

80% match with PVC IR database

PVC windows sample



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1	26	71.37	POLY(VINYL CHLORIDE)	Hummel Polymer Sample Library
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3	35	44.09	POLY(VINYL CHLORIDE), CHLORINATED	Hummel Polymer Sample Library
4	51	43.42	POLY(ETHYLENE:VINYL CHLORIDE)	Hummel Polymer Sample Library
5	31	40.40	POLY(VINYL ACETATE:ETHYLENE) 3:1	Hummel Polymer Sample Library
6	29	38.56	POLY(VINYL ACETATE:ETHYLENE) 4:1	Hummel Polymer Sample Library
7	787	37.48	1-METHYLANTHRACENE, 97%	HR Aldrich Hydrocarbons
8	768	37.18	2,3-DIMETHYLNAPHTHALENE, 98%	HR Aldrich Hydrocarbons
9	40	34.75	ULTRATHENE RESIN	HR Specta IR Demo
10	46	34.23	EVA FOAM CONCENTRATE, 20% AZODICARBONAMIDE	HR Specta IR Demo

71.37% match with PVC IR database

Shred characterisation

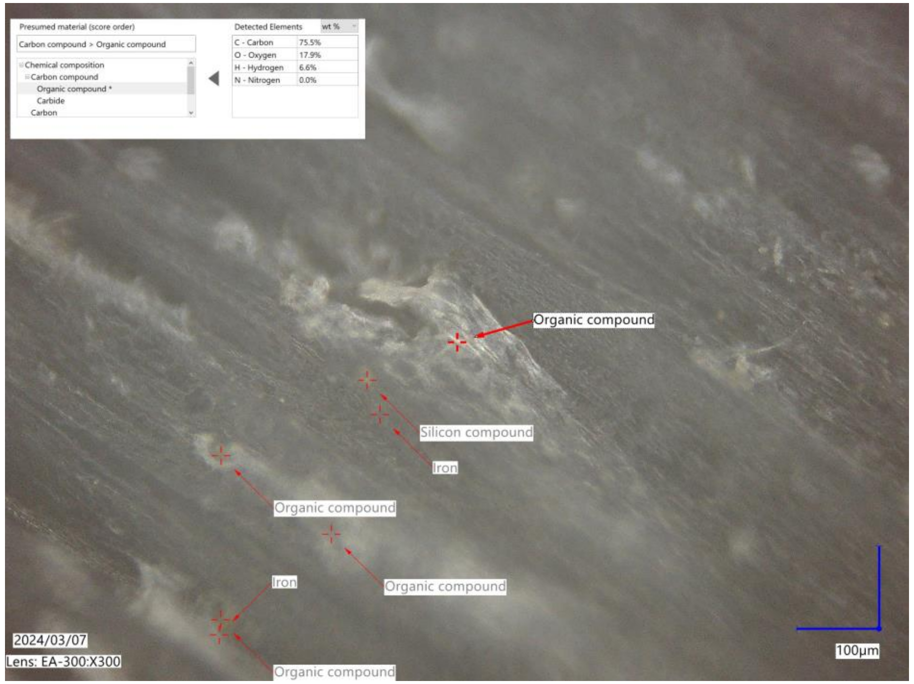
Shred Characterisation

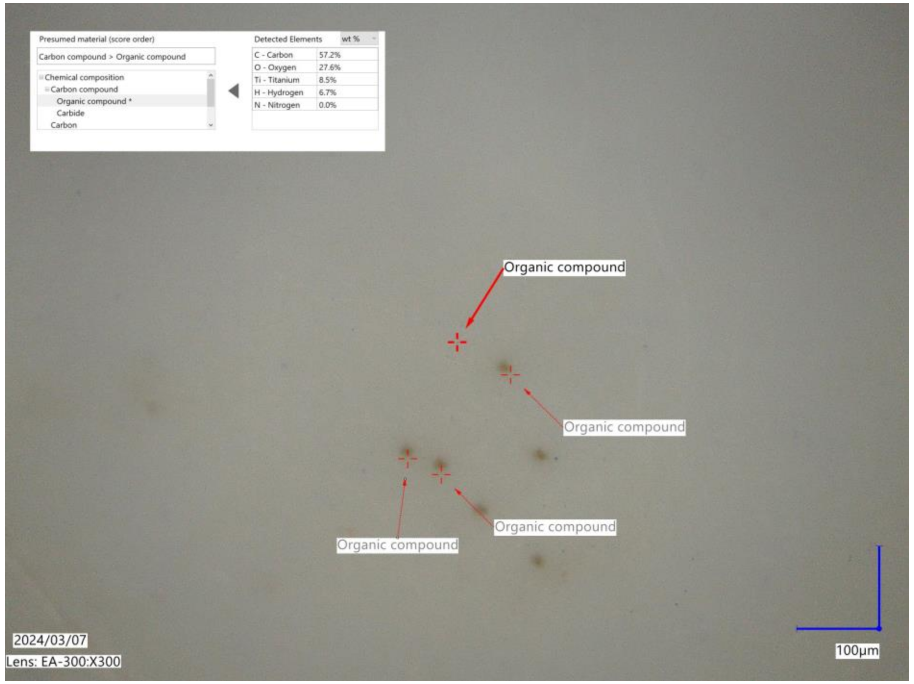
Production tests

Parameter Optimisation

Application

FT-IR	LIBS	XRF	DSC
Fourier Transform Infrared Spectroscopy	Laser Induced Breakdown Spectroscopy	X-ray fluorescence	Differential scanning calorimetry





Could not detect Chlorine and Bromine due to their low molecular weights

Shred characterisation

- **Shred Characterisation**
- Production tests
- Parameter Optimisation
- Application

FT-IR	LIBS	**XRF**	DSC
Fourier Transform Infrared Spectroscopy	Laser Induced Breakdown Spectroscopy	X-ray fluorescence	Differential scanning calorimetry

PVC pipes sample

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Cl	83.489	0.1
2	Ca	13.838	0.1
3	Ti	1.122	0.03
4	Pb	0.602	0.02
5	Si	0.265	0.02
6	Zn	0.219	0.01
7	Al	0.158	0.01
8	Na	0.128	0.01
9	Mg	0.058	0.007
10	Fe	0.055	0.007
11	P	0.034	0.006
12	S	0.018	0.004
13	Sr	0.016	0.004

Presence of lead

PVC windows sample

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	Cl	84.758	0.1
2	Ca	5.822	0.08
3	Ti	5.039	0.07
4	Pb	3.333	0.05
5	Si	0.351	0.02
6	P	0.138	0.01
7	Na	0.128	0.01
8	Al	0.118	0.01
9	Mg	0.111	0.01
10	Zn	0.065	0.008
11	Cd	0.057	0.007
12	S	0.031	0.005
13	Fe	0.03	0.005
14	Sr	0.011	0.003
15	Zr	0.008	0.003

Presence of lead

Shred characterisation

- **Shred Characterisation**
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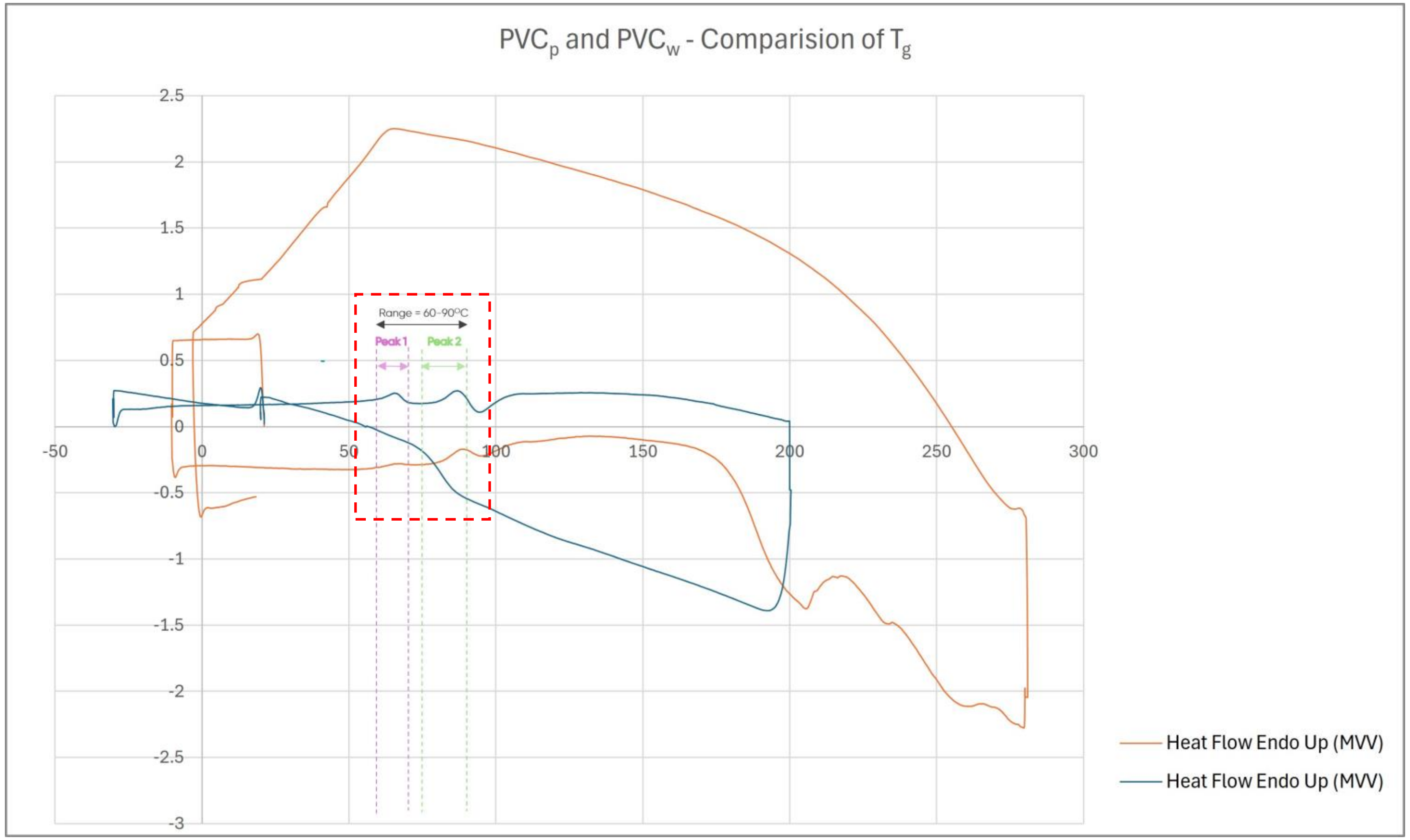
FT-IR	LIBS	XRF	**DSC**
Fourier Transform Infrared Spectroscopy	Laser Induced Breakdown Spectroscopy	X-ray fluorescence	Differential scanning calorimetry



Production tests

Shred Characterisation

Production tests

Parameter Optimisation

Application

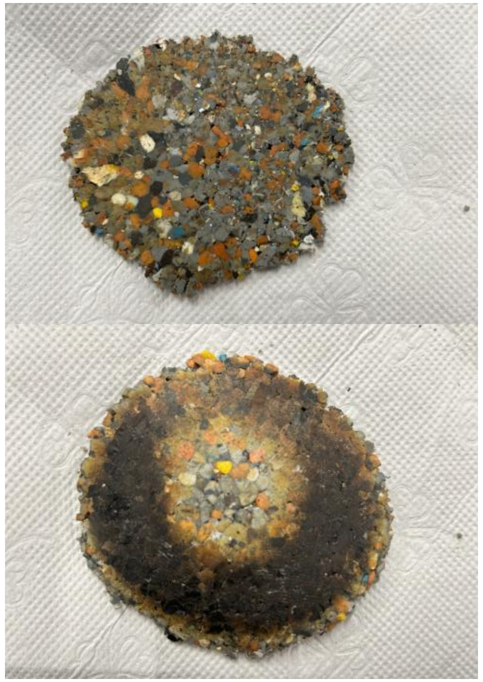
Preliminary test for heating technique

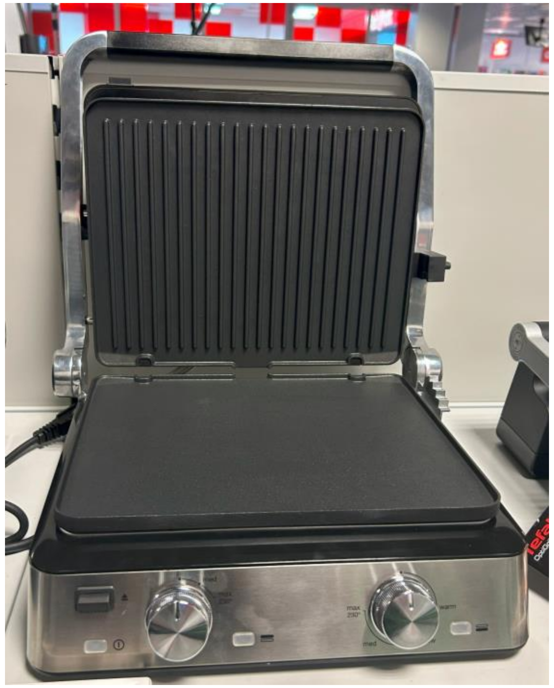
Test using a well-engineered Aluminium mould

Indirect heating using Bain Marie technique

Hot forming using hot plate

Hot forming using grill press





Production tests

Shred Characterisation

Production tests

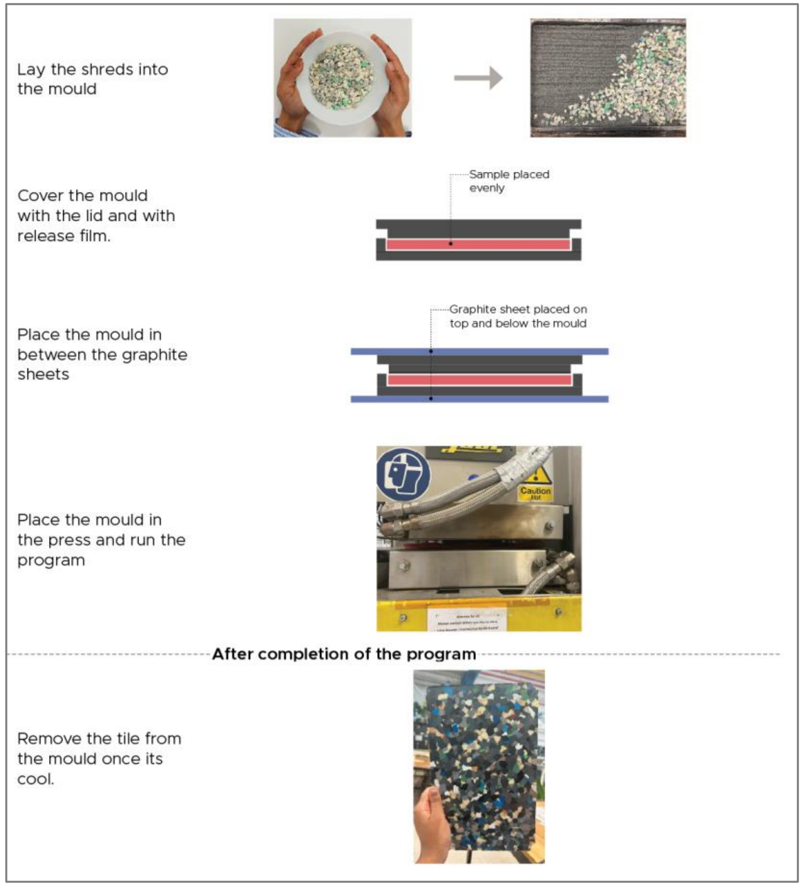
Parameter Optimisation

Application

Preliminary test for heating technique → Test using a well-engineered Aluminium mould

Hot press at Aerospace

Production process



Parameter optimisation and quality control

Shred Characterisation

Production tests

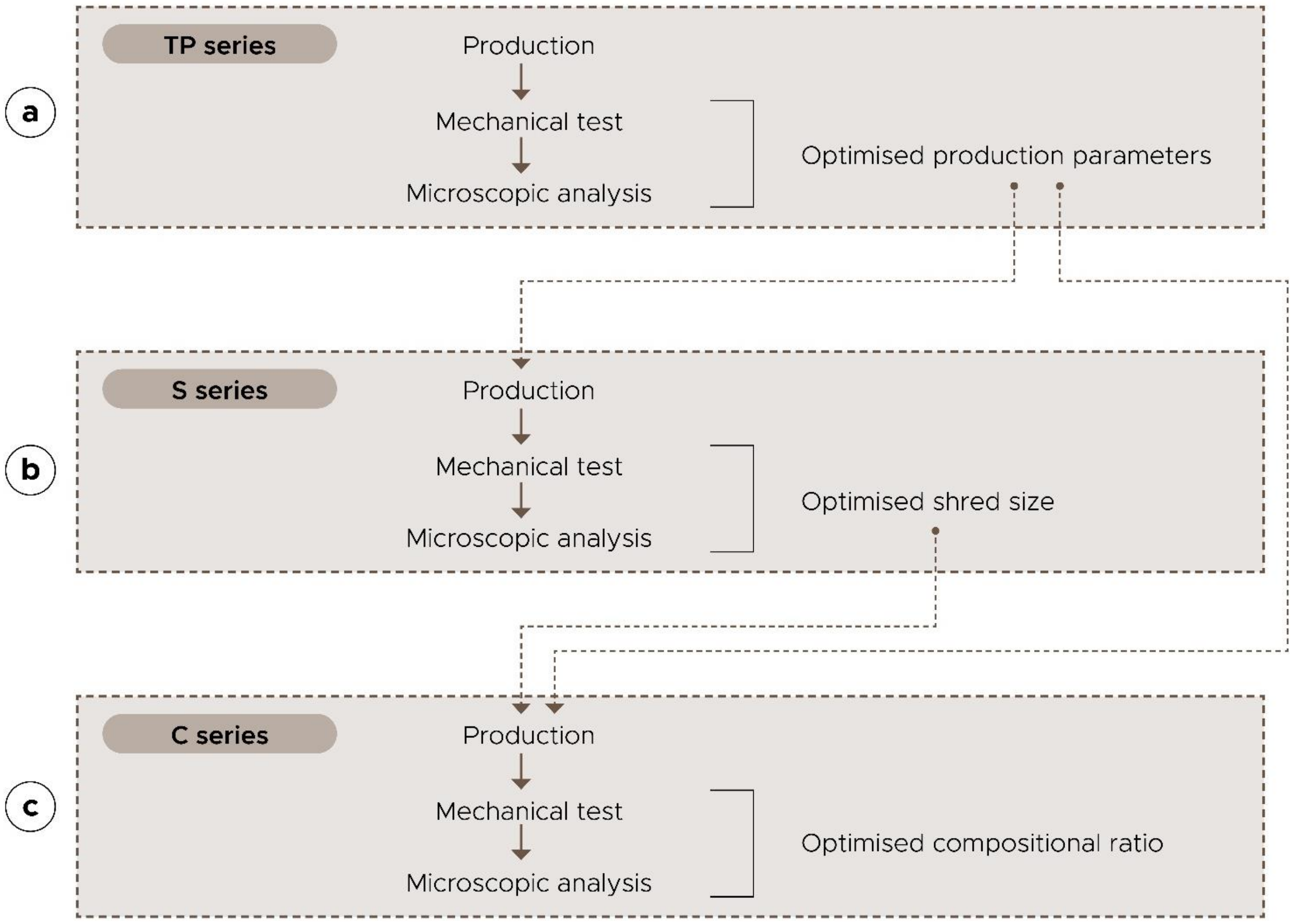
Parameter Optimisation

Application

Pressure, temperature and dwell time

Shred Size

Compositional variation



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Parameter optimisation and quality control

Shred Characterisation

Production tests

Parameter Optimisation

Application

Pressure, temperature and dwell time

Shred Size

Compositional variation

Production plan

Testing parameter	Sample ID	Choice of waste stream	Shred size (mm)	Output thickness (mm)	Temperature (^oC)	Pressure (Bars)	Dwell time (mins)	Evaluation
Temperature and Pressure	S1	3mm PVC_p shred	3	5	180	1	30	Sample TP_f
	S2	3mm PVC_p shred	3	5	180	10	60	
	S3	3mm PVC_p shred	3	5	140	10	60	
	S4	3mm PVC_p shred	3	5	135	10	60	
	S5	3mm PVC_p shred	3	5	130	10	60	
	S6	3mm PVC_p shred	3	5	130	100	60	

Sample results

Sample S1

Sample S2

Sample S3

Sample S4

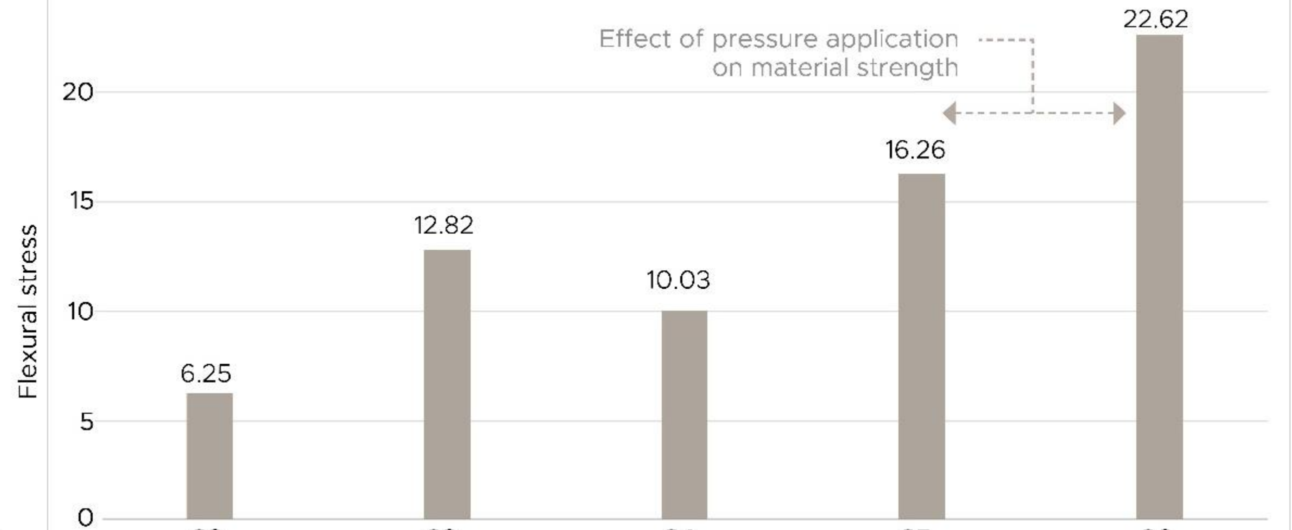
Sample S5

Sample S6

Parameter optimisation and quality control

- Shred Characterisation
- Production tests
- **Parameter Optimisation**
- Application

Pressure, temperature and dwell time | Shred Size | Compositional variation



Sample ID	S2	S3	S4	S5	S6
Shred size	3mm shreds				
Temperature (in°C)	180	140	135	130	
Pressure (in bars)	10				100
Dwell time (in mins)	60				

Parameter optimisation and quality control

Shred Characterisation

Production tests

Parameter Optimisation

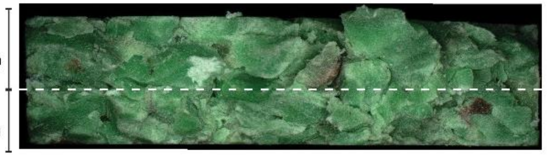
Pressure, temperature and dwell time

Shred Size

Compositional variation

Application

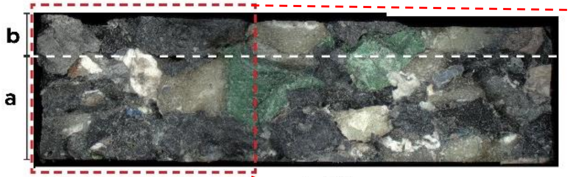
Sample S2



Sample S3

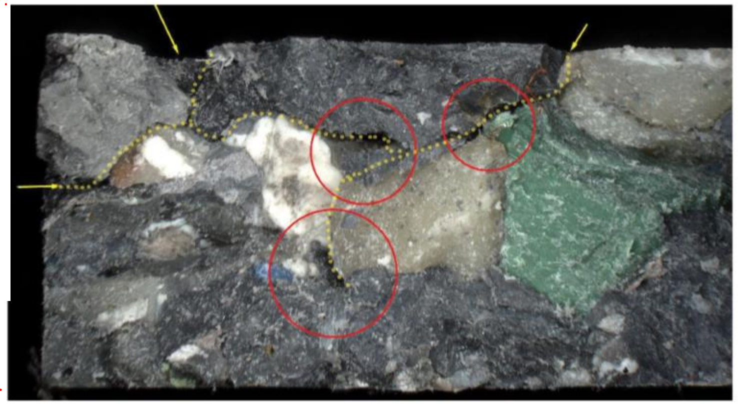
Sample S4

Sample S5



Sample S6

Microscopic view of the fractured surface showing the two zones (Source : Author)
*Legend : **a** - Zone of compaction ; **b** - Zone of shreds with interfacial connections*



Zoomed view of the fractured surface of sample S6 showing loosened interfacial connection in red and cracks leading to surface with yellow (Source : Author)

Parameter optimisation and quality control

Shred Characterisation

Production tests

Parameter Optimisation

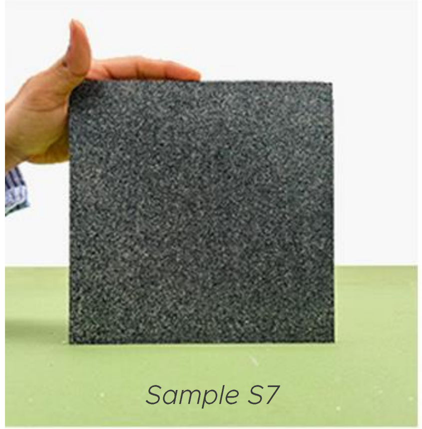
Application

Pressure, temperature and dwell time → Shred Size

Compositional variation

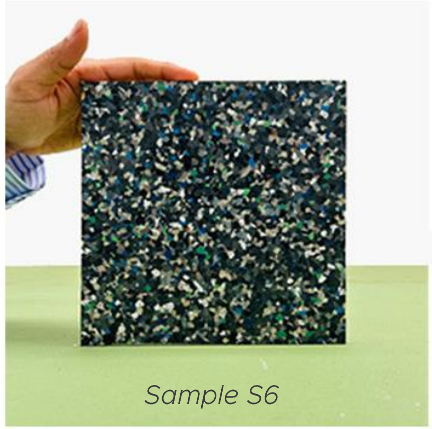
Shred Size:

0.2 µmm powder



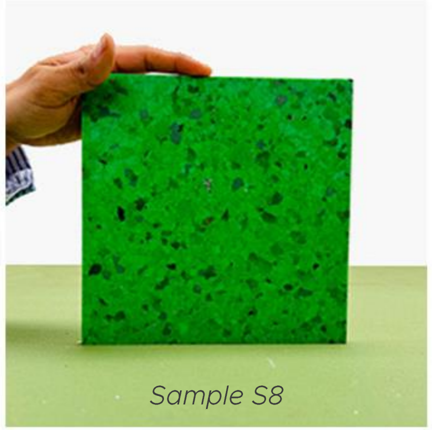
Sample S7

3 mm shred



Sample S6

7 mm shred



Sample S8

10 mm shred

Sample S9

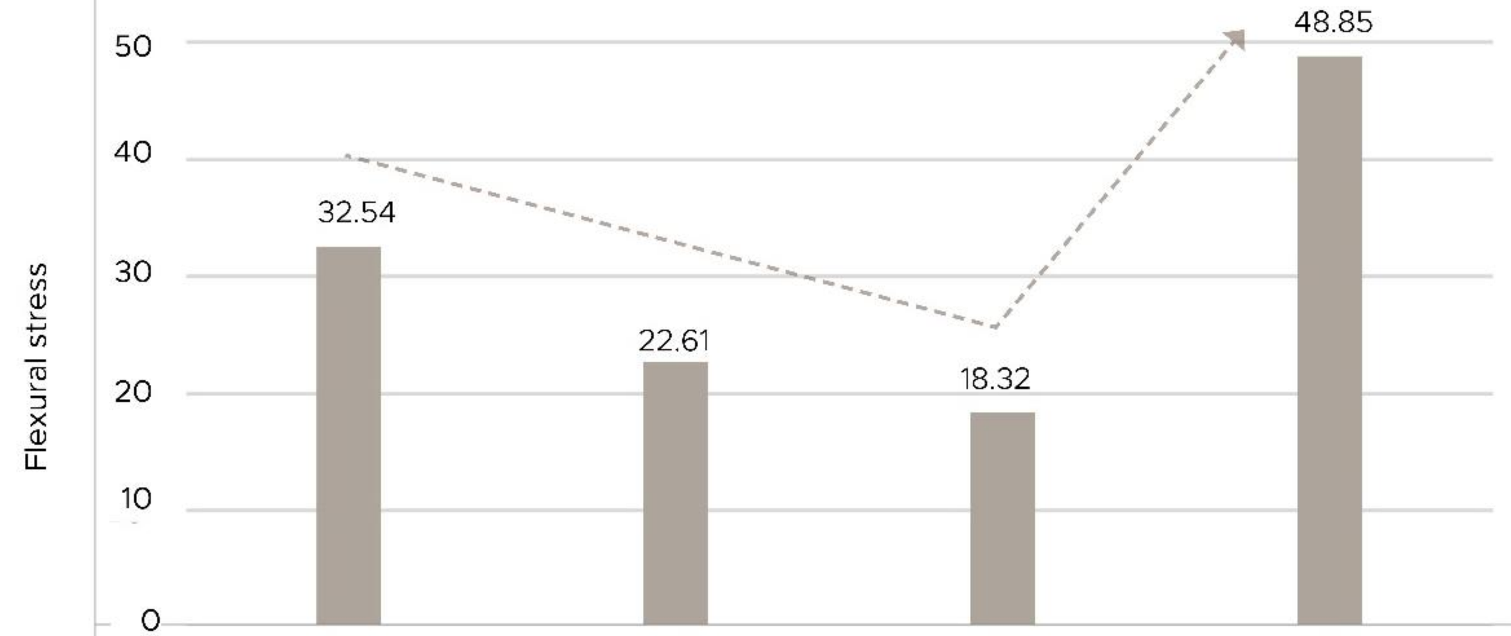
Production plan

Shred size	S7	3mm PVC_p shred	0.2	5	130	100	60	Sample S_f
	S6	3mm PVC_p shred	3	5	130	100	60	
	S8	3mm PVC_p shred	7	5	130	100	60	
	S9	3mm PVC_p shred	10	5	130	100	60	

Parameter optimisation and quality control

- Shred Characterisation
- Production tests
- **Parameter Optimisation**
- Application

Pressure, temperature and dwell time → **Shred Size** | Compositional variation



Sample ID	S7	S6	S8	S9
Shred size	0.2 mm powder	3 mm powder	7 mm powder	10 mm powder
Temperature	130°C			
Pressure	100 bars			

Parameter optimisation and quality control

Shred Characterisation

Production tests

Parameter Optimisation

Application

Pressure, temperature and dwell time

Shred Size

Compositional variation

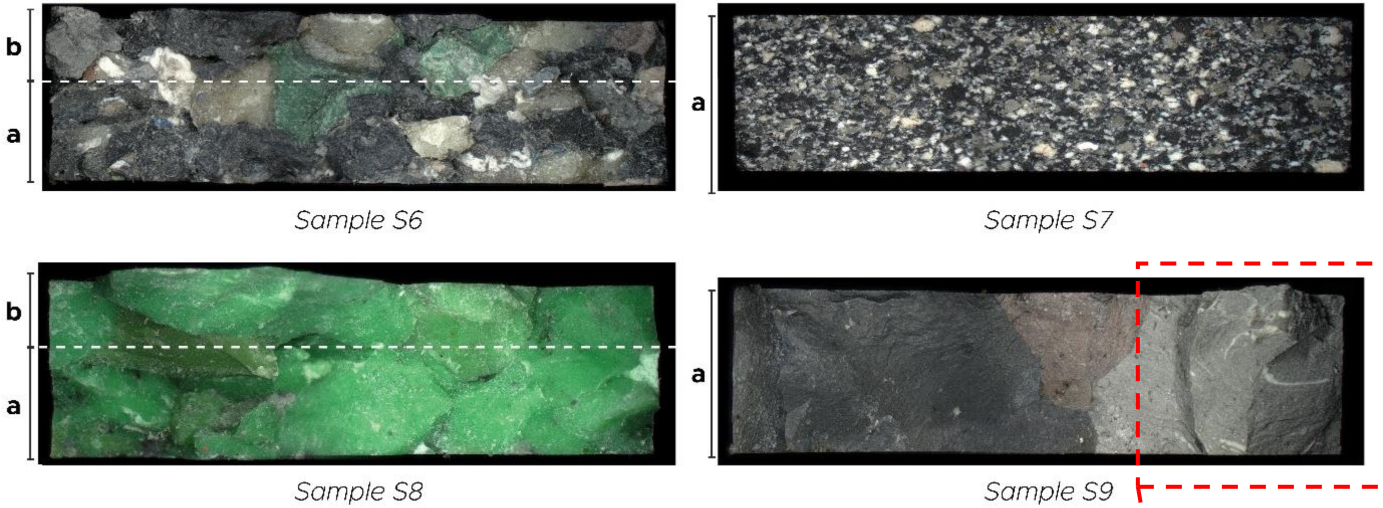
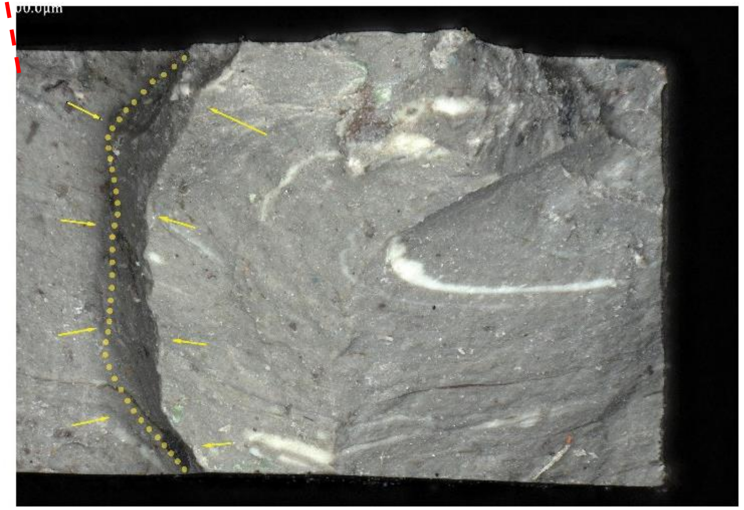


Figure 67: Microscopic view of the fractured surface showing the two zones (Source : Author)
*Legend : **a** - Zone of compaction ; **b** - Zone of shreds with interfacial connections*



Parameter optimisation and quality control

- Shred Characterisation
- Production tests
- **Parameter Optimisation**
- Application

Pressure, temperature and dwell time → Shred Size → Compositional variation

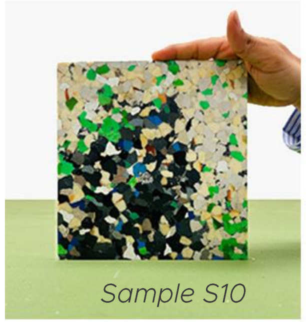
100% powder	70% powder+ 30% shred	50% powder+ 50% shred	50% powder+ 50% shred of window sample	70% shred+ 30% powder	100% shred


Sample S7


Sample S12


Sample S11


Sample S13


Sample S10


Sample 9

Production plan

Composition	S7	100% PVC_p 3mm shred	3	5	130	100	60	Sample C_f
	S9	100% PVC_p 10 mm powder	3	5	130	100	60	
	S10	30% PVC_p 0.2mm powder + 70% PVC_p 10mm shred	3	5	130	100	60	
	S11	50% PVC_w 0.2mm powder + 50% PVC_p 10mm shred	3	5	130	100	60	
	S12	70% PVC_w 0.2mm powder + 30% PVC_p 10mm shred	3	5	130	100	60	
	S13	50% PVC_w 0.2mm powder + 50% PVC_w 10mm shred	3	5	130	100	60	

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Parameter optimisation and quality control

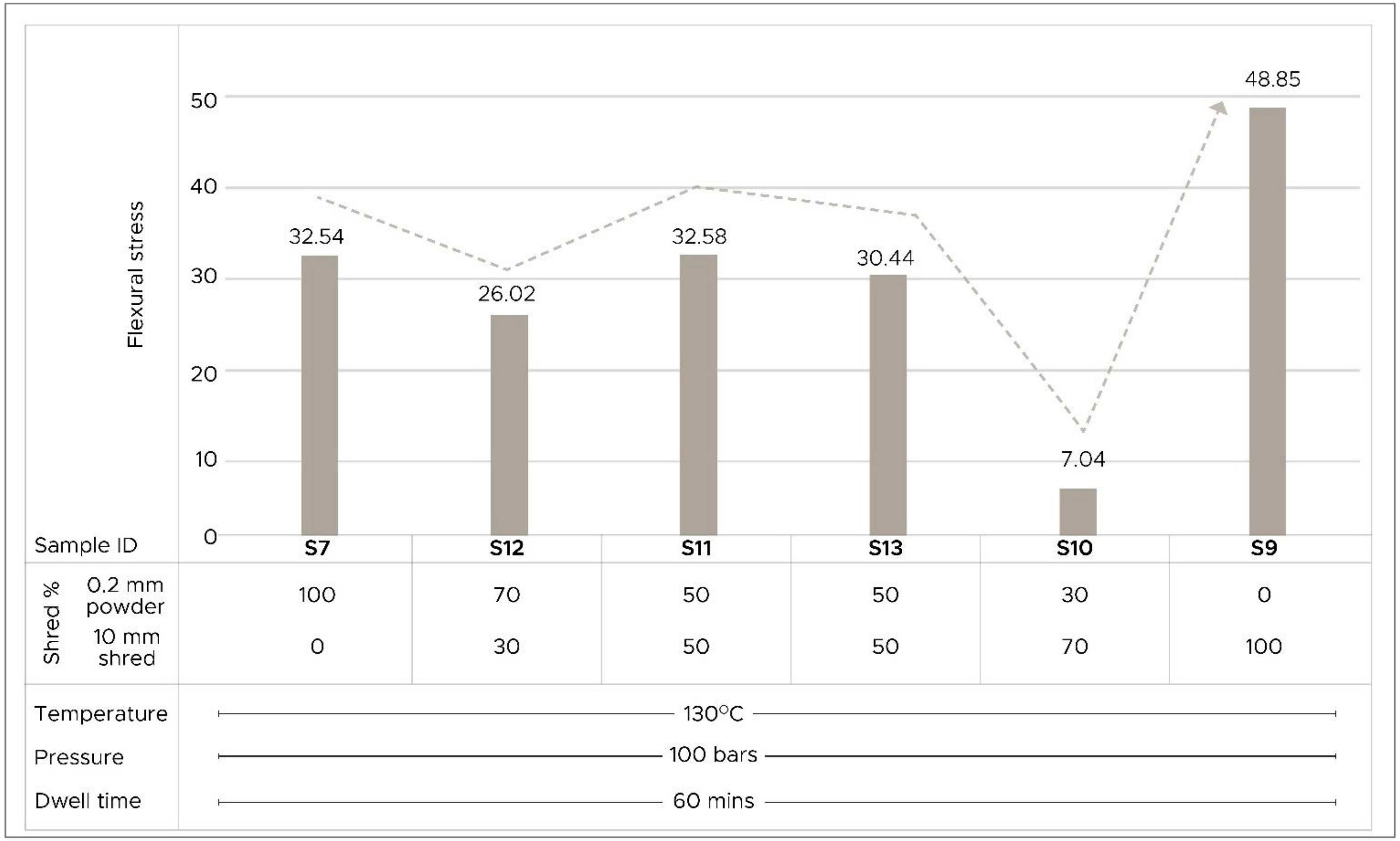
Shred Characterisation

Production tests

Parameter Optimisation

Application

Pressure, temperature and dwell time → Shred Size → Compositional variation



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Parameter optimisation and quality control

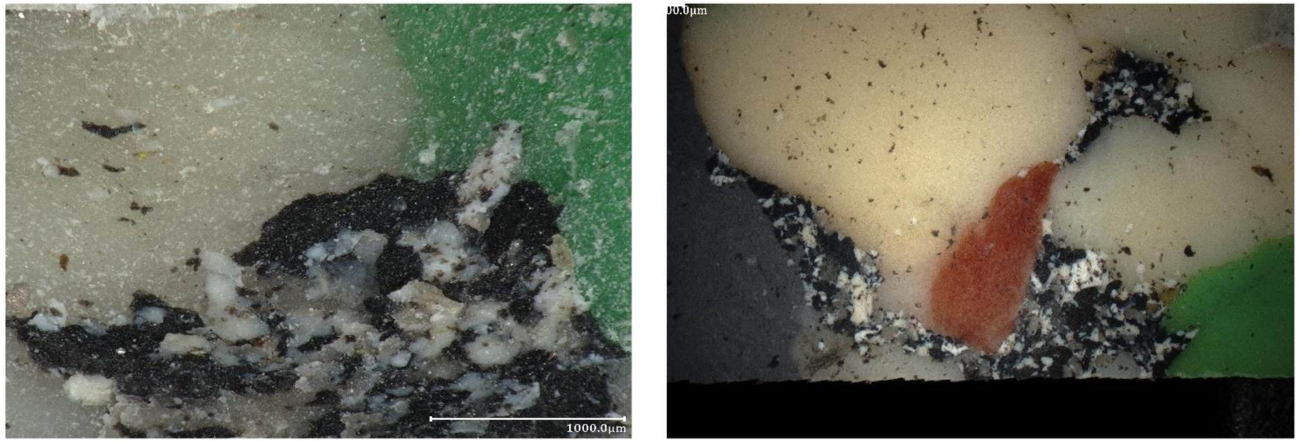
Shred Characterisation

Production tests

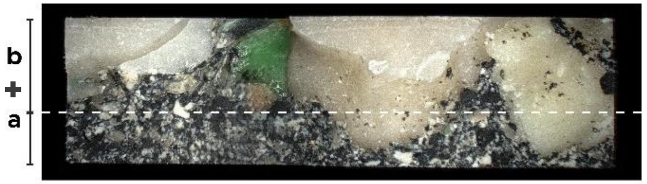
Parameter Optimisation

Application

Pressure, temperature and dwell time → Shred Size → Compositional variation

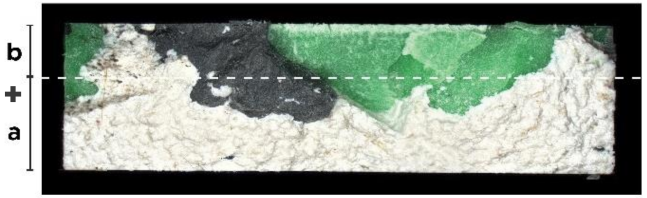


Left- Sample S6 shows powder compacting the gaps between shreds
(Source : Author)



Sample S10

Sample S12



Sample S11

Sample S13

Microscopic view of the fractured surface showing the two zones (Source : Author)
*Legend : **a** - Zone of compaction ; **b** - Zone of shreds with interfacial connections*

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Parameter optimisation and quality control

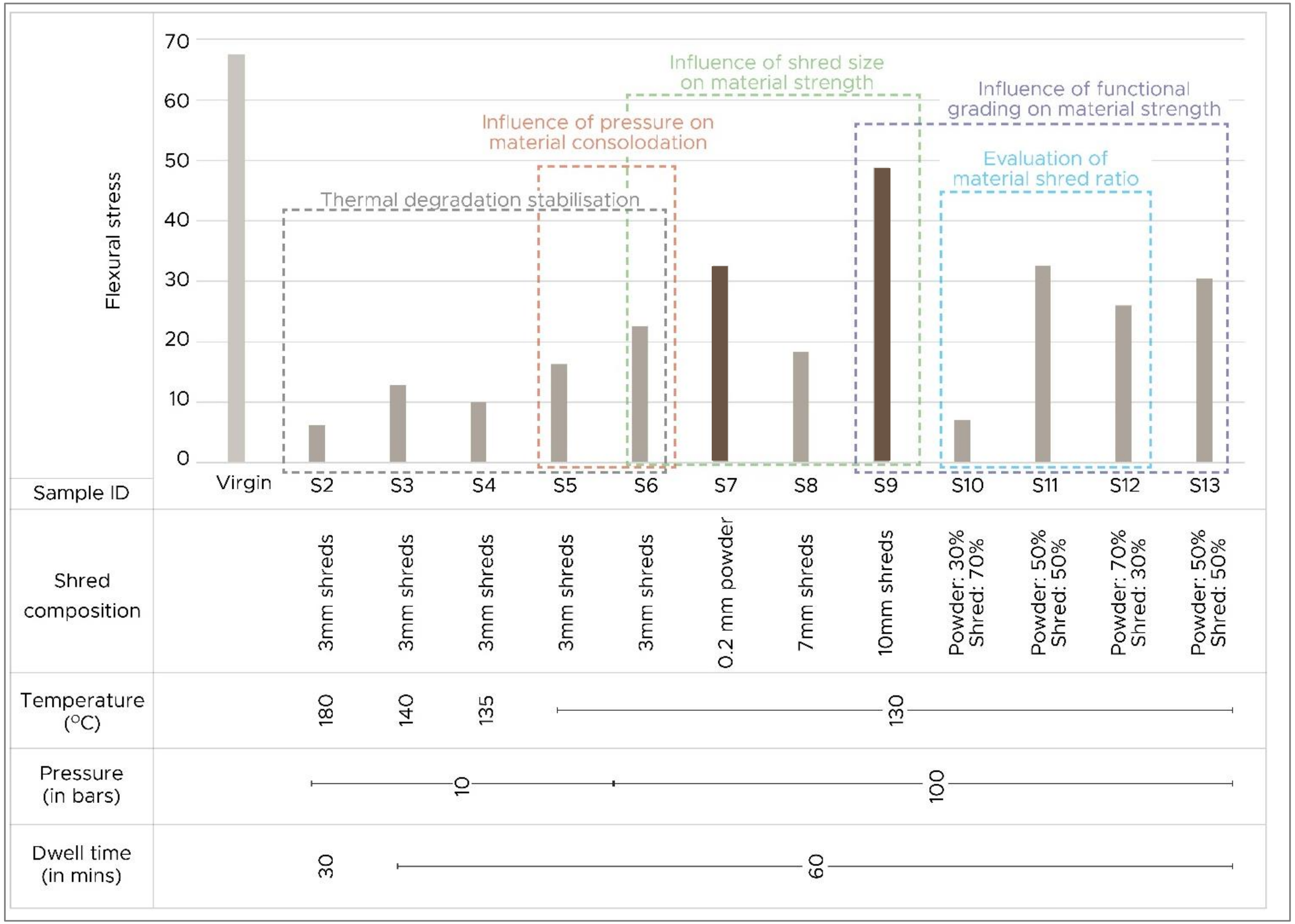
Shred Characterisation

Production tests

Parameter Optimisation

Application

Pressure, temperature and dwell time → Shred Size → Compositional variation



Parameter optimisation and quality control

Shred Characterisation

Production tests

Parameter Optimisation

Application

Pressure, temperature and dwell time → Shred Size → Compositional variation

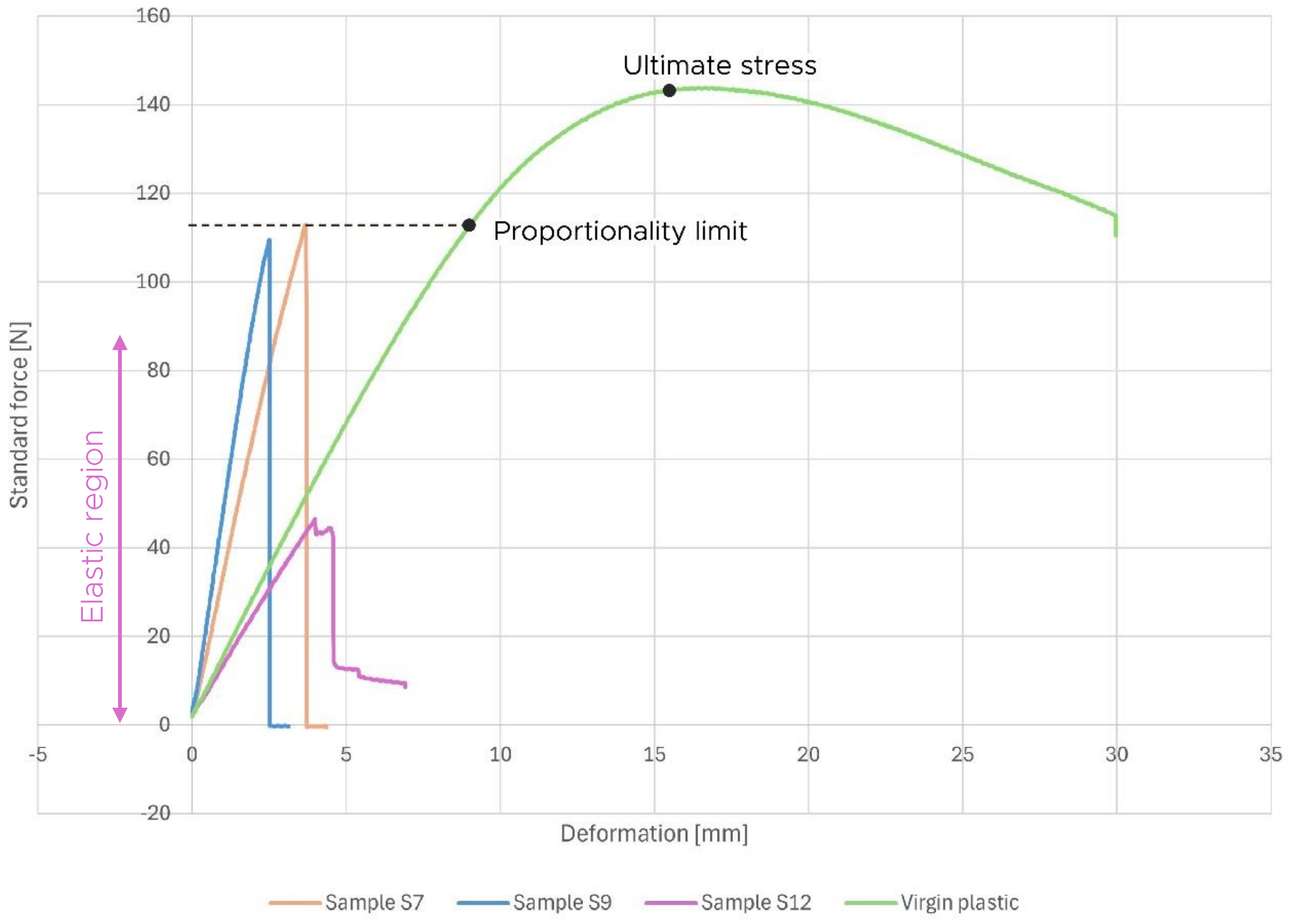


Figure 73: Comparision of material fracture pattern with virgin PVC solid plate (Source: Author)

Application

Shred Characterisation

Production tests

Parameter Optimisation

Application

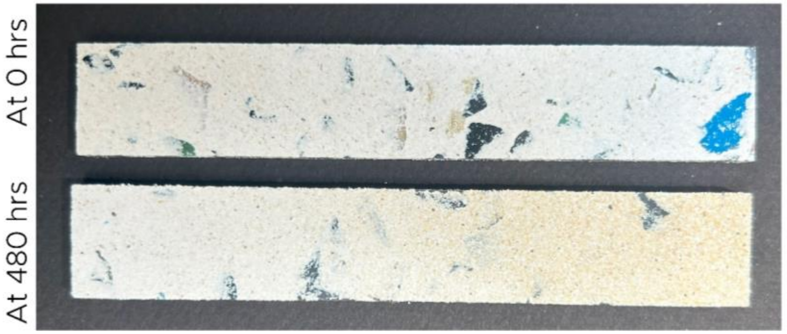
- **Façade tile/cladding tile** → Go-no Go factors would be UV vs Flammability
- Floor tile
- Roofing tile
- Interior partition wall
- Insulation
- Skylights
- Structural element
- Interior furniture
- Products

Flammability \ UV radiation (sunlight)	Poor	Fair	Good	Excellent
Non-flammable	0	0	1 PTFE	0
Self-extinguishing	0	1	1 PVC	1 PEEK
Slow-burning	0	3	0	0
Highly flammable	2	3	1	0

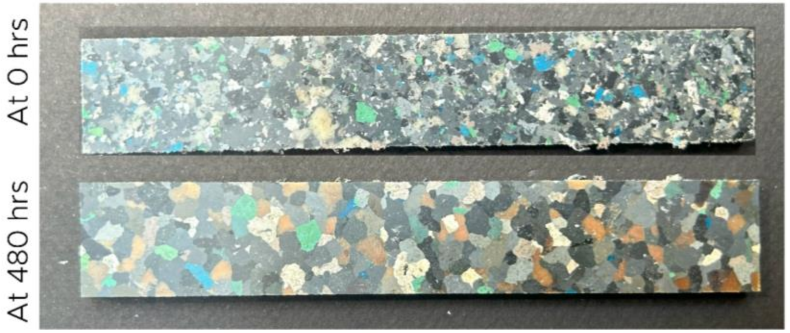
Durability test for UV

Sample 13

Sample 8



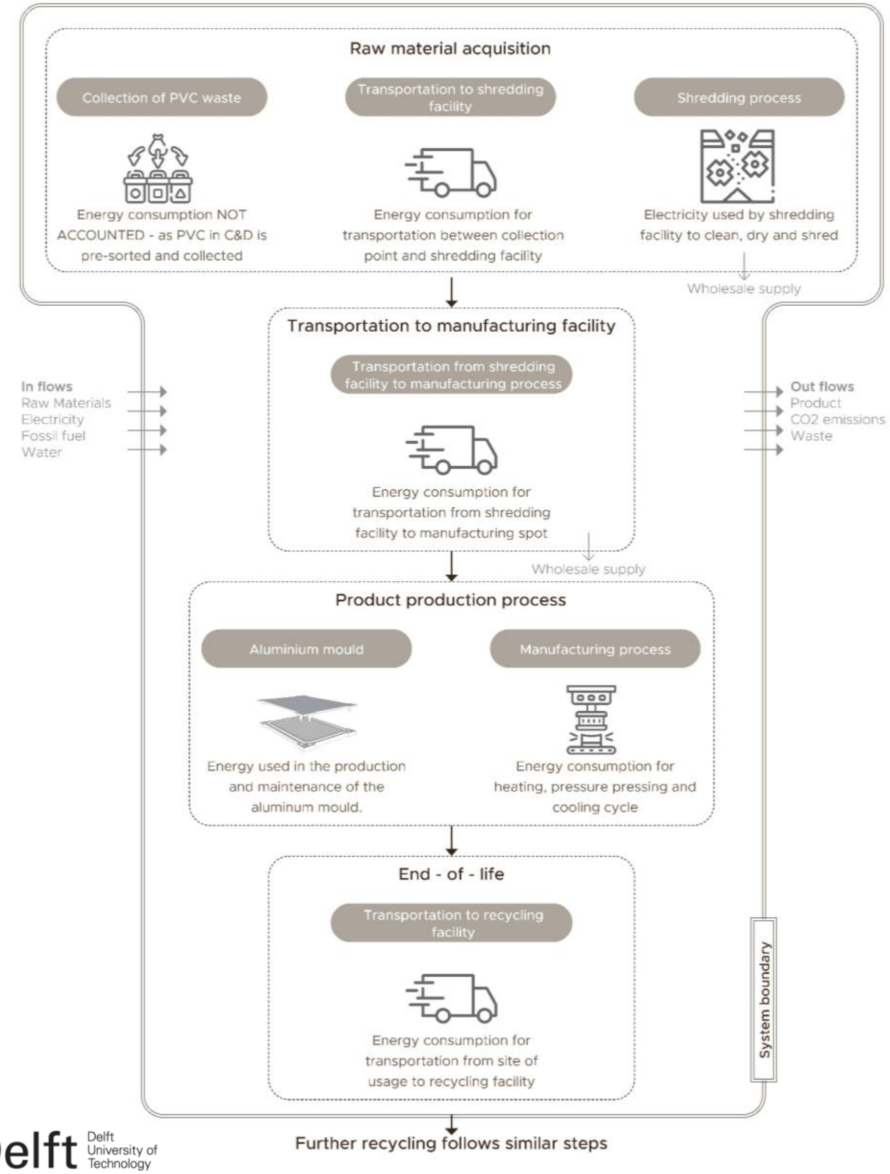
Sample 12



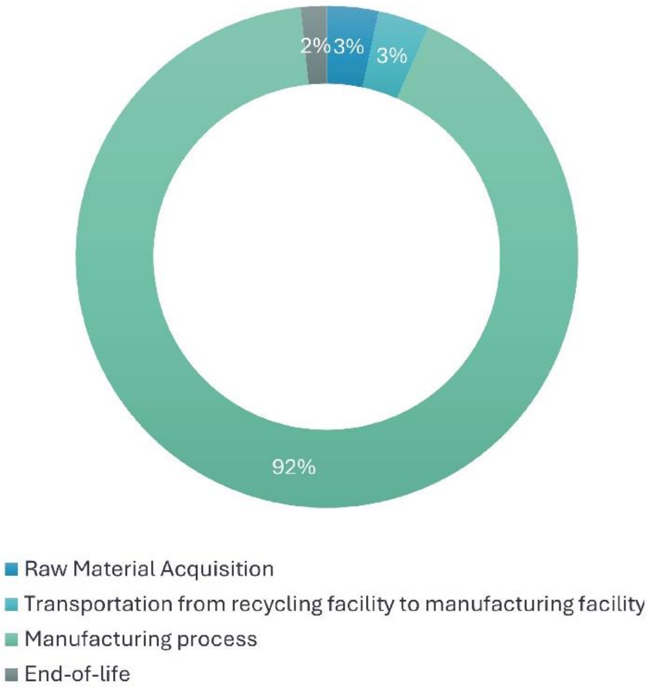
Sample 6

Sustainability evaluation

Life cycle inventory



Data analysis



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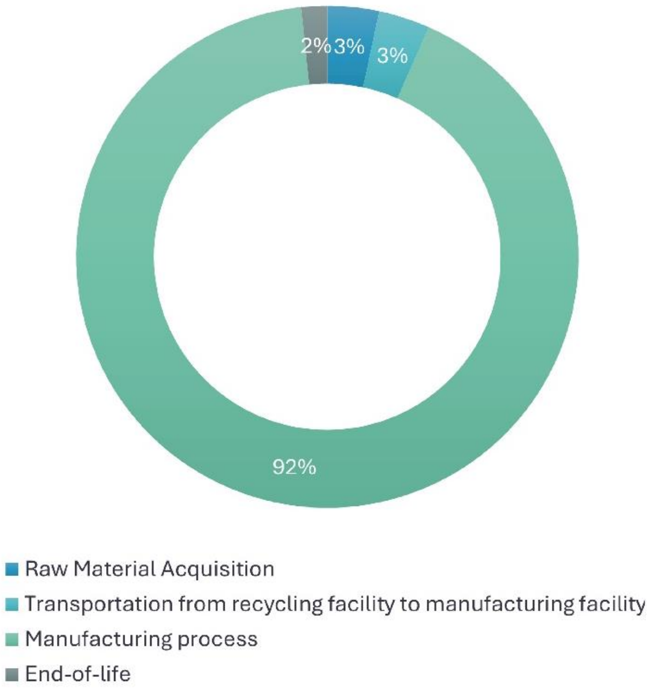
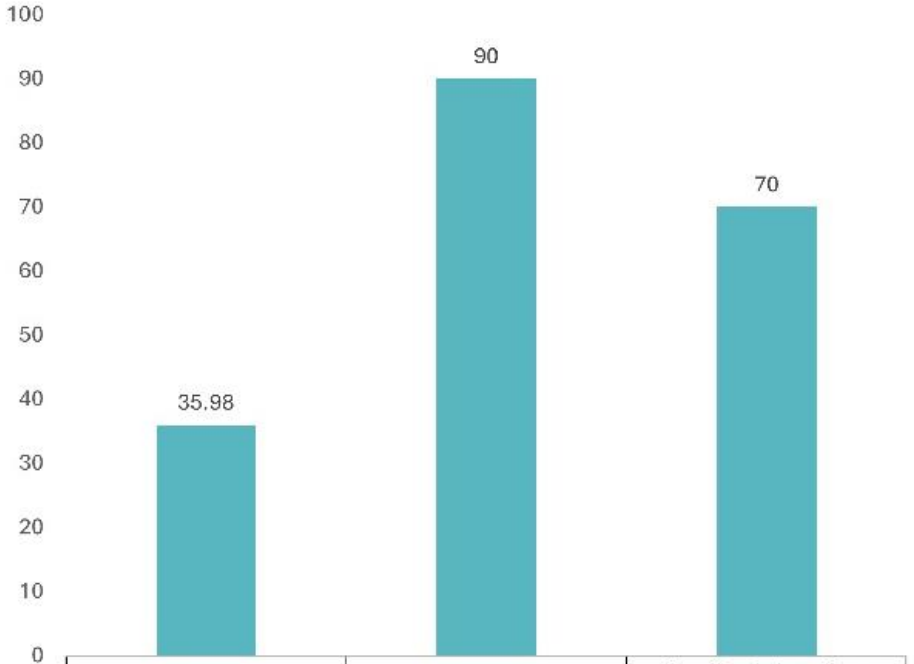
Sustainability evaluation

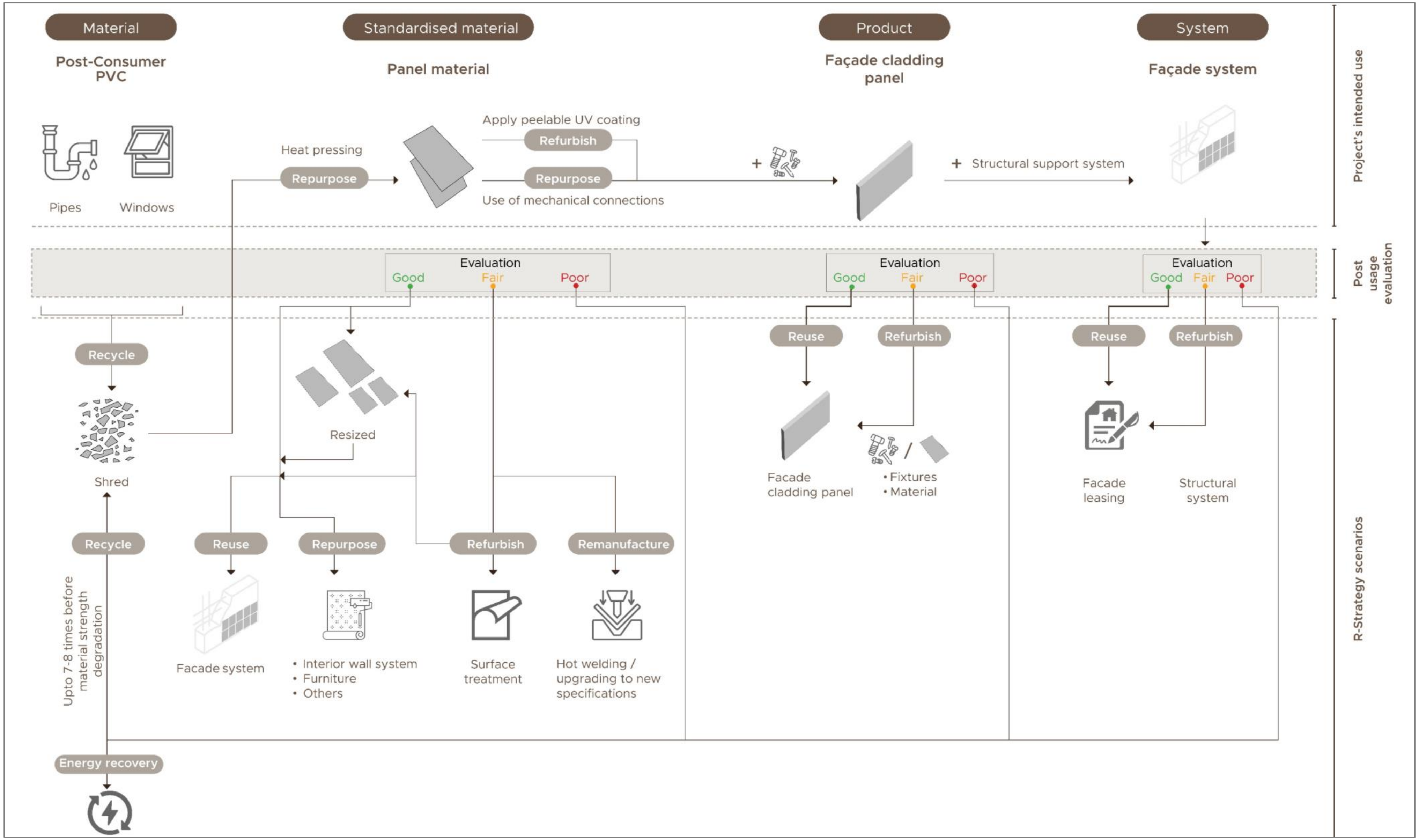
Data analysis





	rPVC panel	Ceramic tile	Anodized alumnium (3mm)
Embodied carbon per sqm	35.98	90	70
Life cycle	Shorter	Longer comparitively	

Sustainability evaluation



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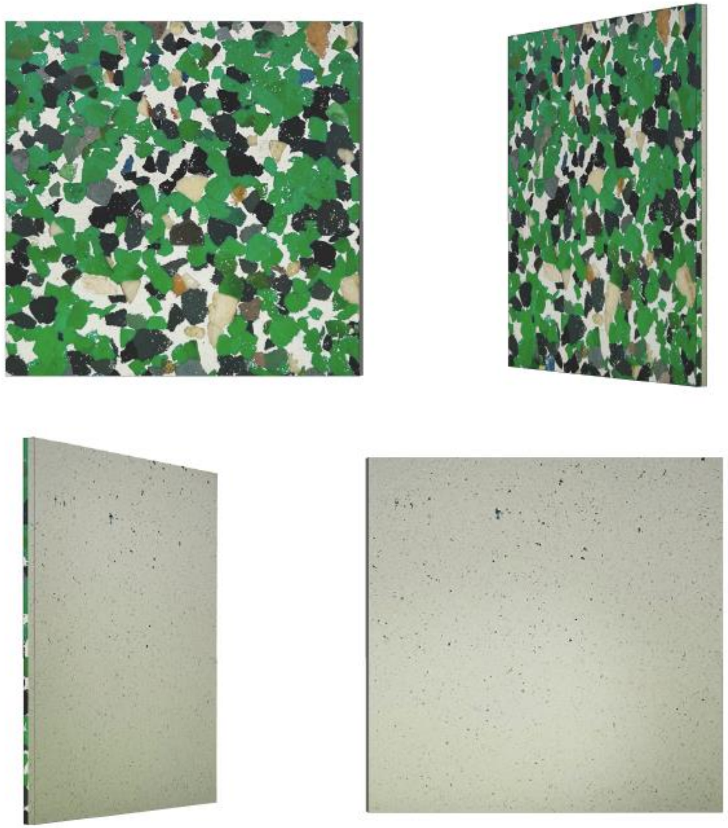
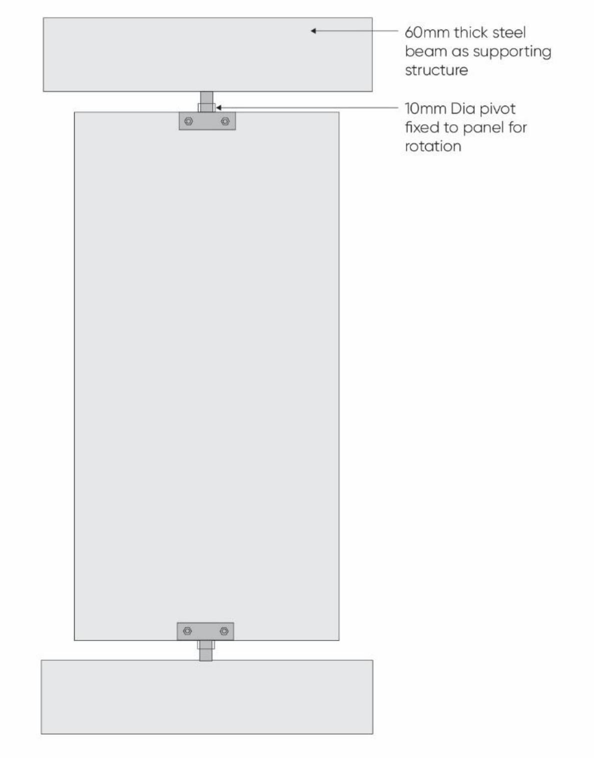
Product – Façade tile

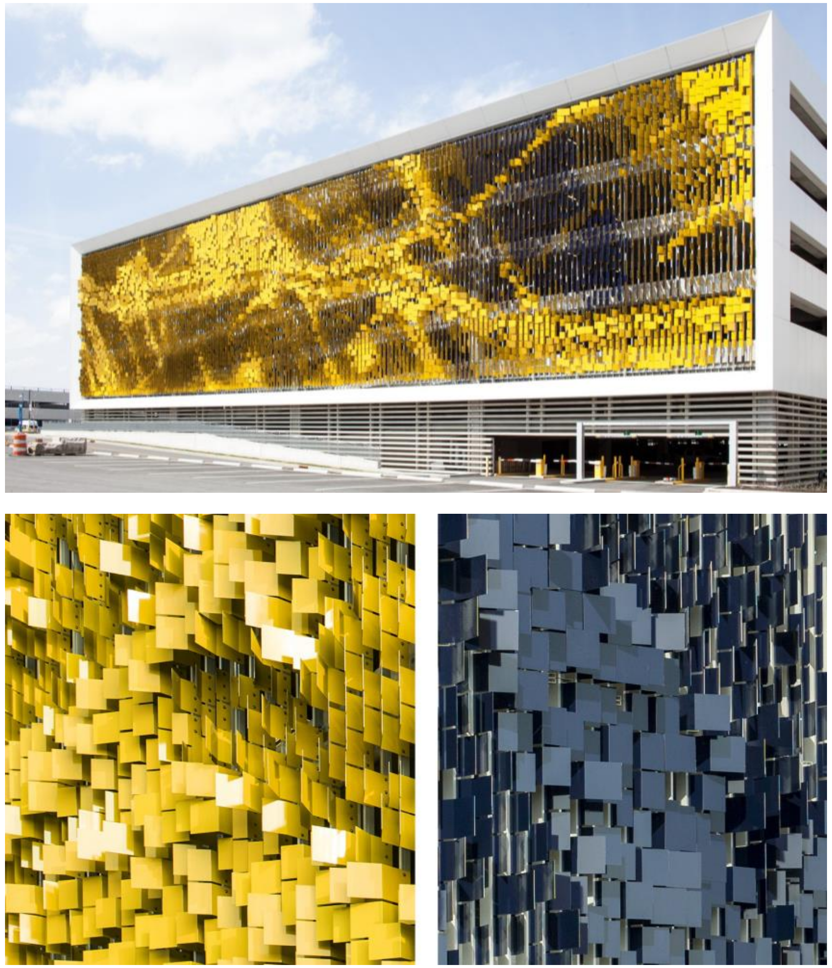
Functional grading as a design technique



Detail

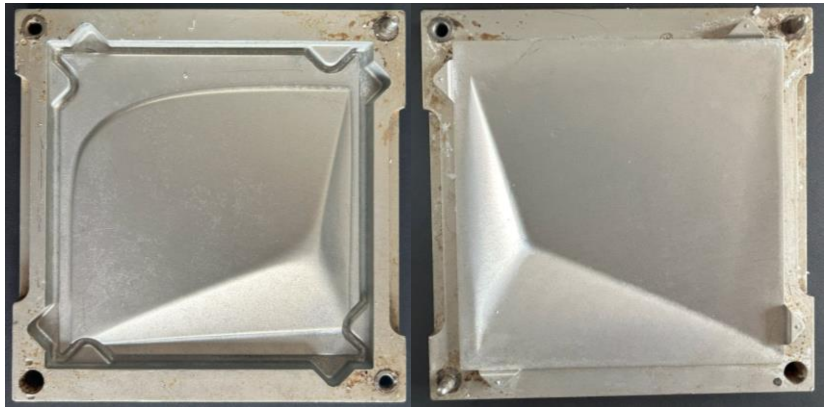


Façade example



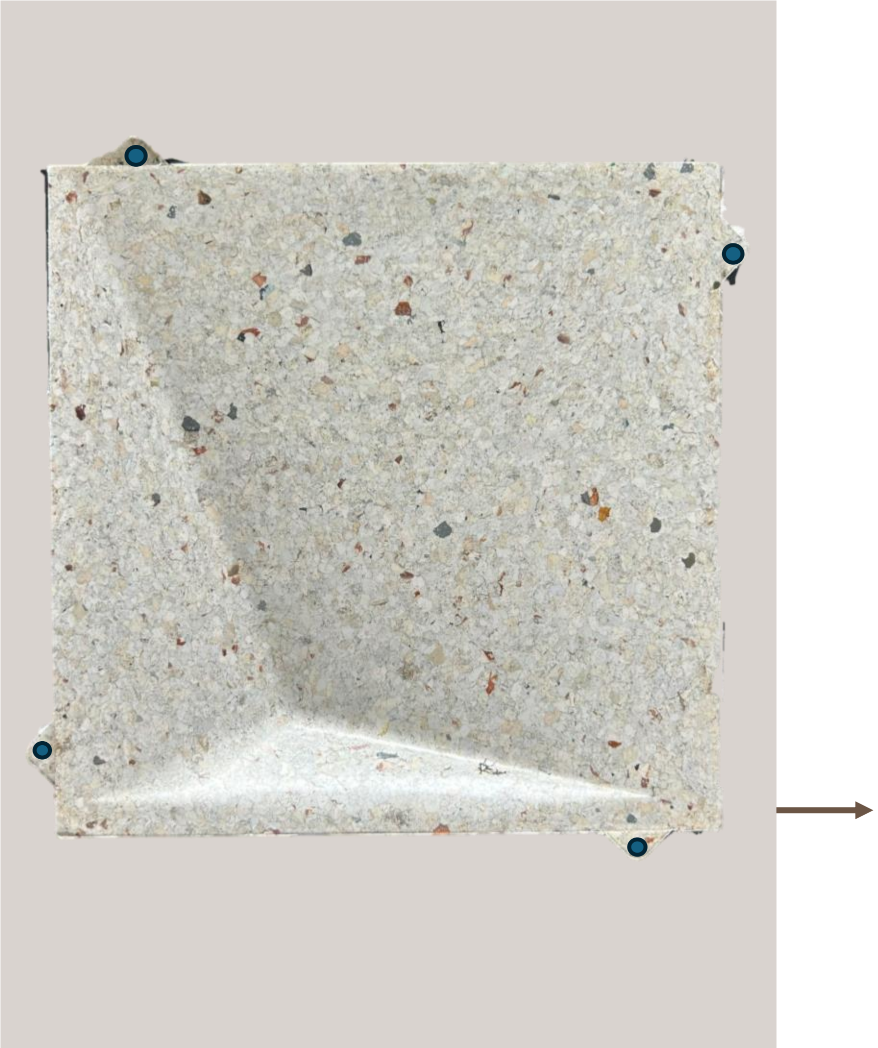
Project : Parking, Indianapolis, US
Architects: Rob Ley Studio

Product – Façade tile prototype



Mould

Façade tile



Panel designed by NPSP.B.V

“ waste is a design flaw ”

- Kate Kreba

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Mr. Willem Bottger
NPSP B.V. , The Netherlands

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Research Director of the Recycling Laboratory at Delft University of Technology

Dr. Maarten Bakker
Resources & Recycling, CiTG, TU Delft

Mr. Hajo Reinders
Pretty plastic , Amsterdam

Mr. Casper van der Meer
Better Future Factory, Rotterdam

Coolrec Netherlands B.V

Van Waren B.V, The Netherlands

Re-P-Tile

Master thesis presentation by
Ramya Kumaraswamy

First Mentor
Dr. Telesilla Bristogianni
Chair of Structural design and mechanics

Second Mentor
Dr. Olga Ioannou
Chair of Build product innovation

External Examiner
Ir.Robert.J.Nottrot

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