

Recycled Composite Cast Glass Panels made of C&D Waste

Assessing the structural performance

MSc Architecture, Urbanism and Building Sciences
Technical University of Delft (TU Delft)

Building Technology Graduation Project

P5 Presentation

Student:

Véronique van Minkelen
4552156

Supervisors:

First mentor: Dr. Ir. Faidra Oikonomopoulou
Second mentor: Dr. Ing. Marcel Billow







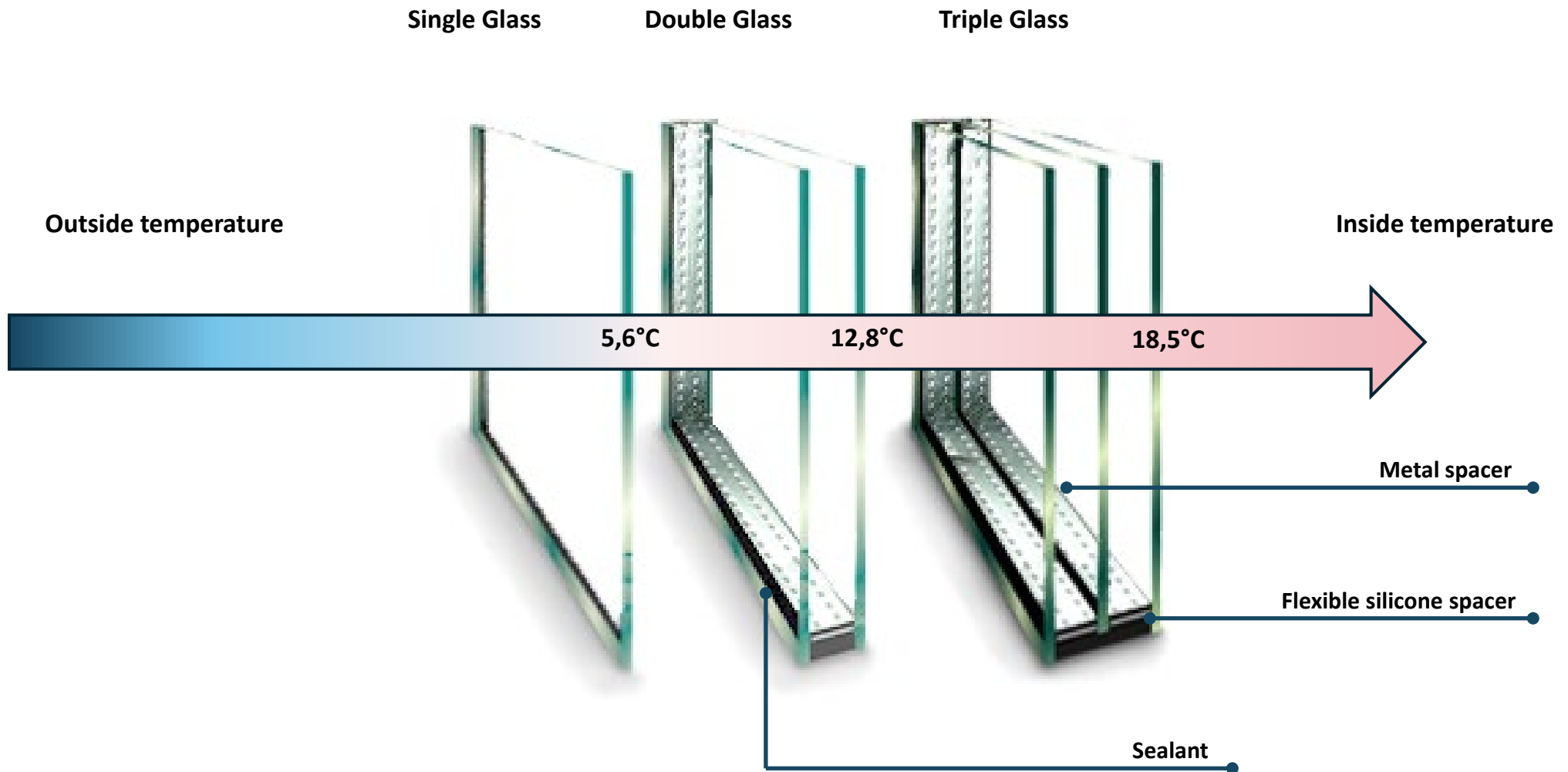
0 | START

0 | START



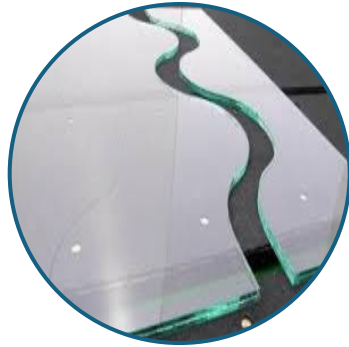
0 | START

CONTAMINATIONS



CONTAMINATIONS

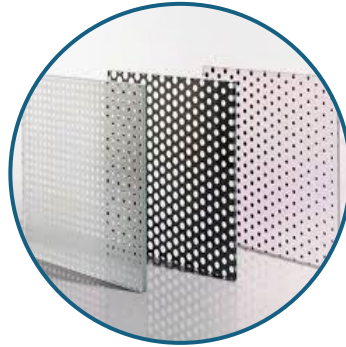
Cutting



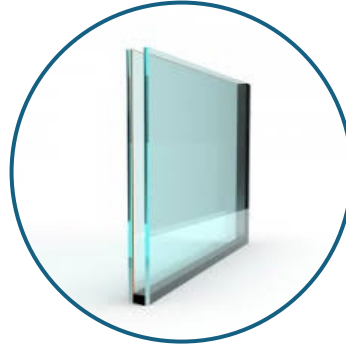
Drilling



Printed Glass



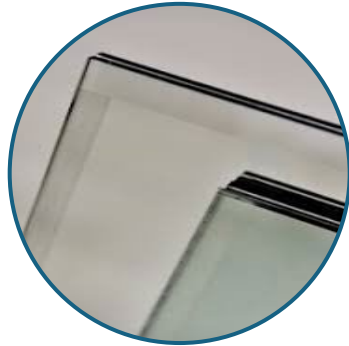
HR Glass



Chemical treating



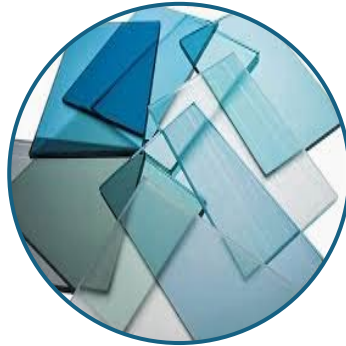
Coating



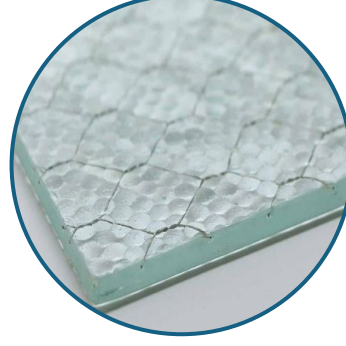
Laminated Glass



Tinted Glass



Metallic Pollutants



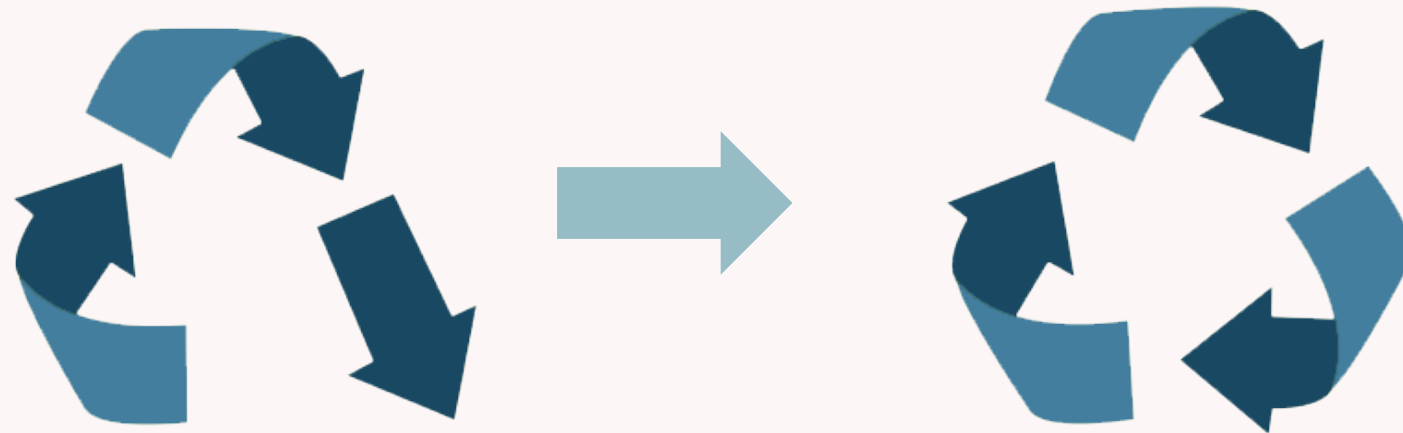
CSP Pollutants



“Glass is **100% recyclable**. Despite its recyclability, end-of-life building glass is rarely recycled into new flat glass products ” (Oikonomopoulou et al., 2023)

“End-of-life insulating glass units (IGUs) continue to follow a linear, **wasteful path** from renovation and demolition sites into landfills or **low-value recycling**” (Geboes et al., 2022)

“How to transition from an open-loop to a closed-loop recycling process despite the contaminations?”



1 | INTRODUCTION TO THE RESEARCH

2 | EXPERIMENTAL METHODOLOGY

3 | DESIGN APPLICATION

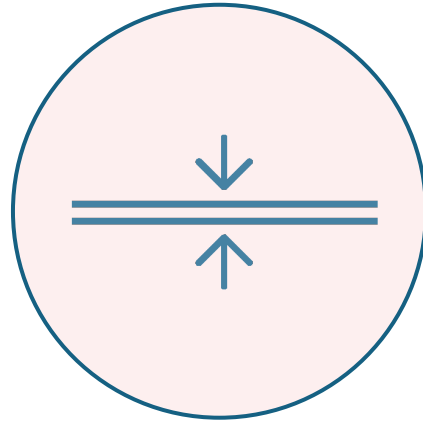
4 | CONCLUSION

5 | RECOMMENDATION

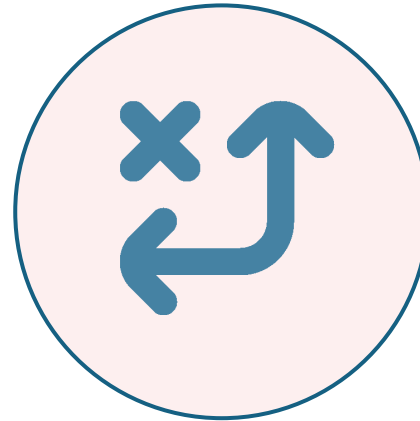
6 | REFLECTION

1 | INTRODUCTION TO THE RESEARCH

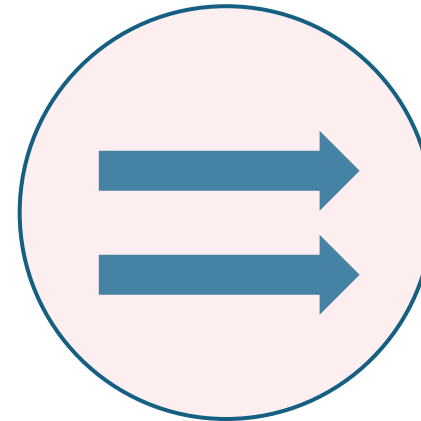
WHY DO WE NEED TO CHANGE THE WAY WE PRODUCE GLASS?



Thin walled



Changing recipes not easy



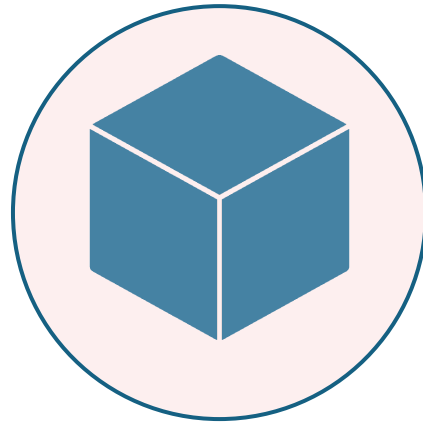
Can't have impurities



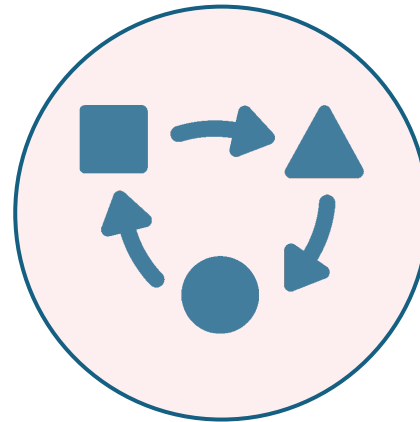
Ends into landfill

FLAT GLASS FLOAT GLASS

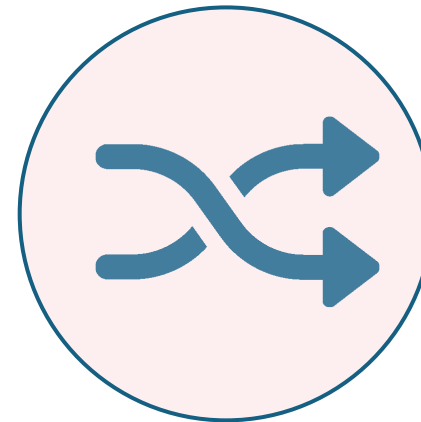
CAST GLASS VOLUMETRIC GLASS



Volumetric



Flexible design, create all sorts of shapes and design



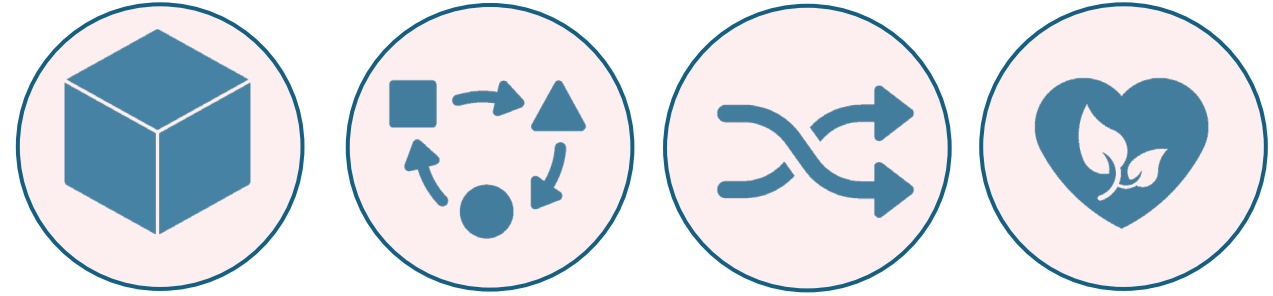
Works well with **mixed** or imperfect glass



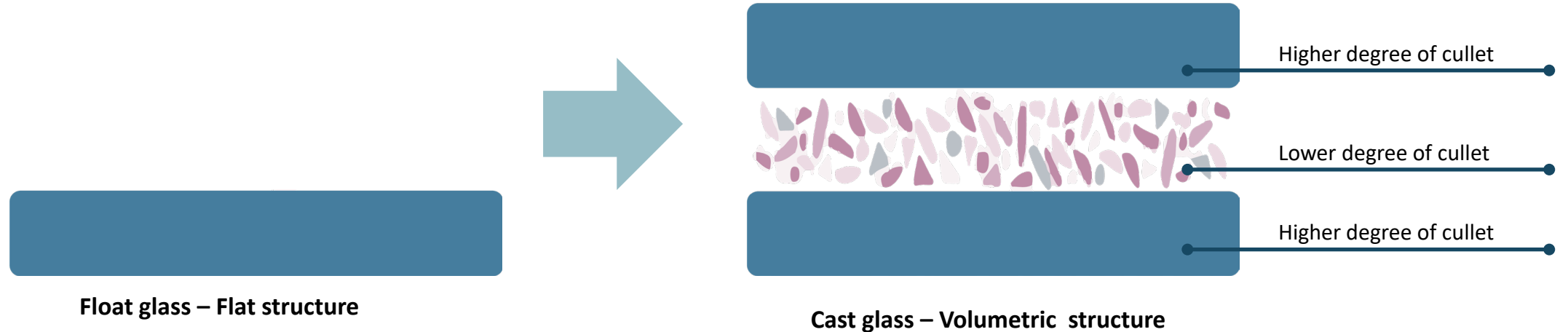
Better for the environment, glass casting reuses cullet, cutting down waste

1 | INTRODUCTION TO THE RESEARCH

WHY CAST GLASS



*Littleton (1942) observed that: “We never test the strength of glass: all we test is the **weakness of its surface**”*

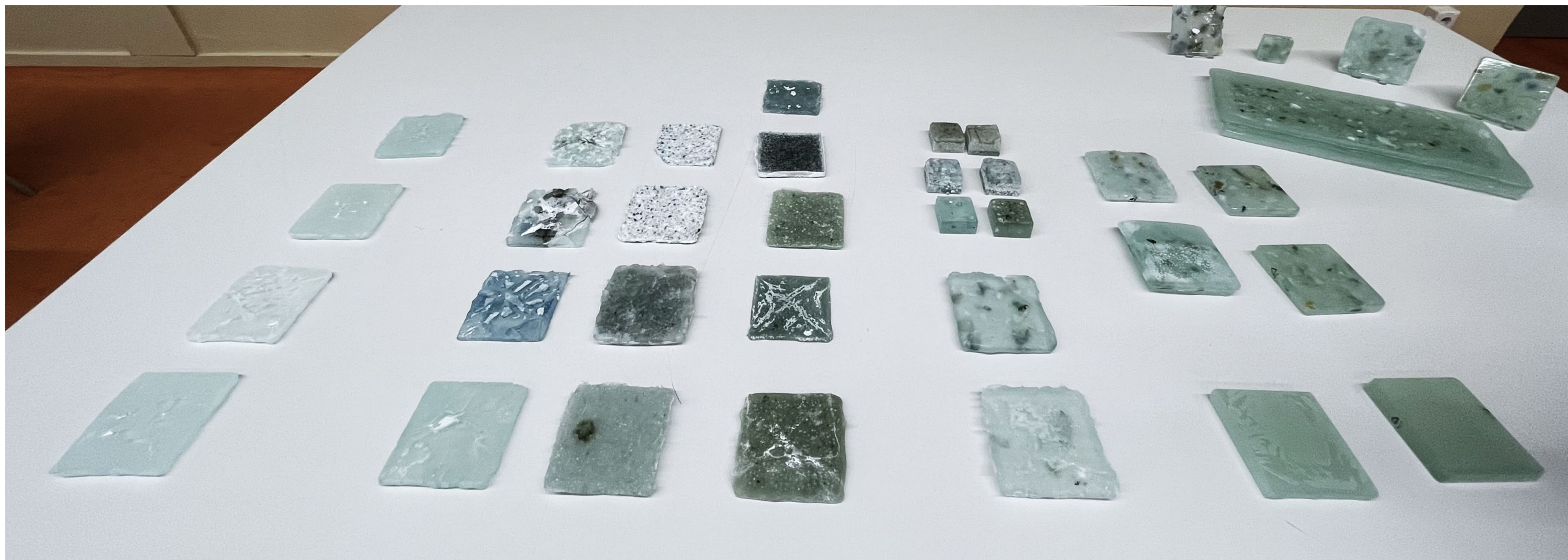




**Composite cast
glass C&D waste
panels?**

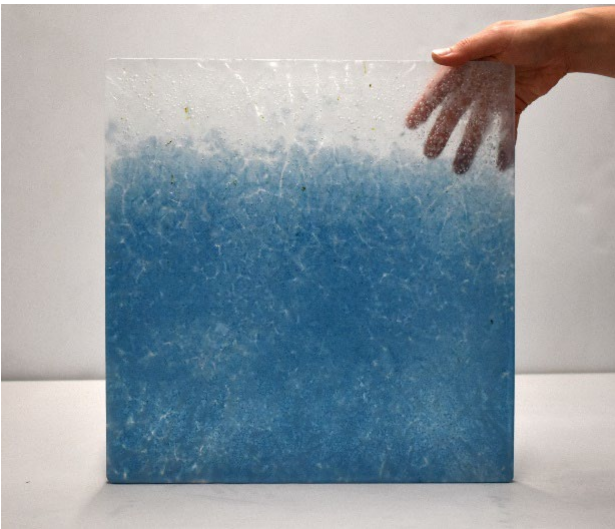
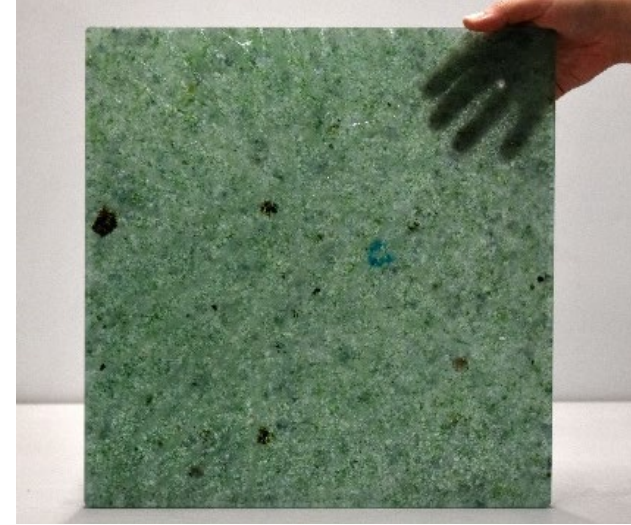
1 | INTRODUCTION TO THE RESEARCH

PREVIOUS WORK FROM TU DELFT



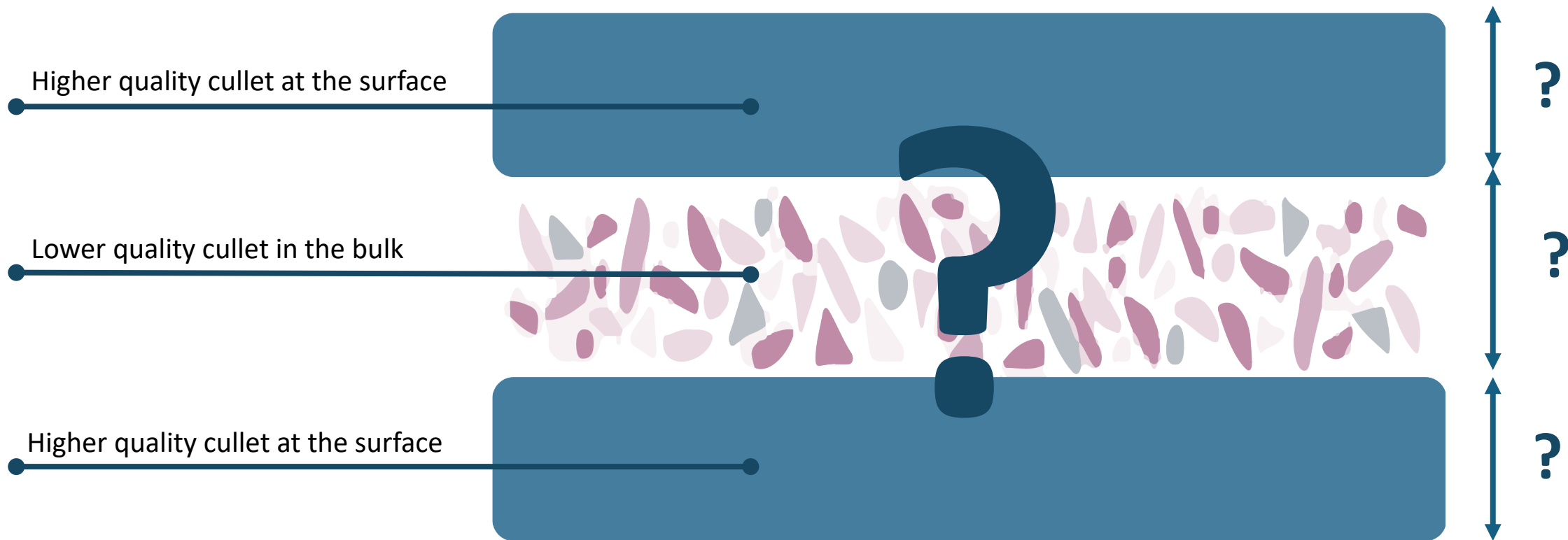
1 | INTRODUCTION TO THE RESEARCH

PREVIOUS WORK FROM TU DELFT



1 | INTRODUCTION TO THE RESEARCH

COMPOSITE CAST GLASS WASTE PANELS



RESEARCH GAP

MAIN RESEARCH QUESTION

*“What is the effect of the different parameters in respect to the geometry and glass composition of **composite cast glass beams** to their overall structural performance made out of Construction and Demolition (**C&D**) (float) glass waste?”*



1 | INTRODUCTION TO THE RESEARCH

2 | EXPERIMENTAL METHODOLOGY

3 | DESIGN APPLICATION

4 | CONCLUSION

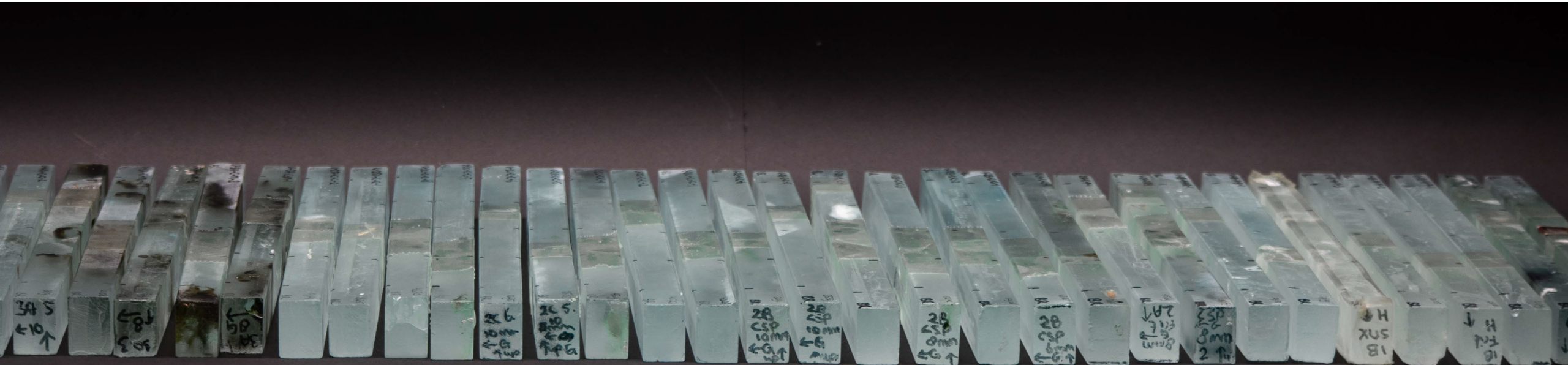
5 | RECOMMENDATION

6 | REFLECTION

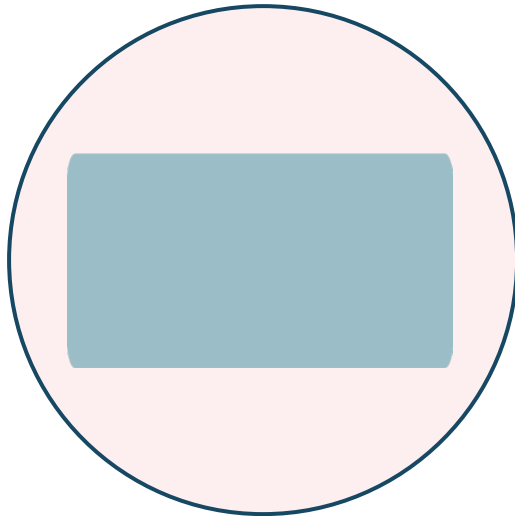
2 | EXPERIMENTAL METHODOLOGY

EXPERIMENTAL OVERVIEW

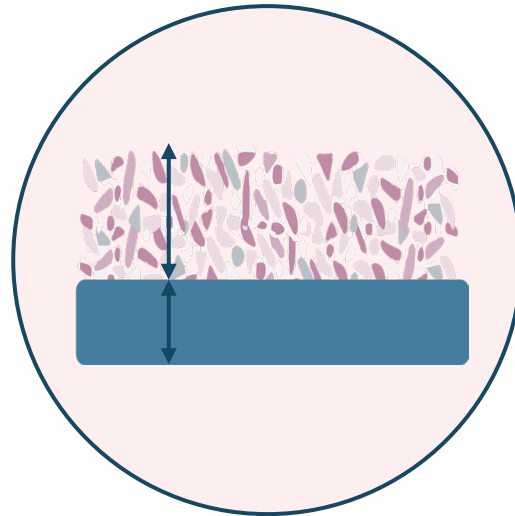
- 250 kg of Silica Crystal Moulds produced
- 3 Tiles with pure contaminants
- 1 Prototype
- 8 Fire Rounds
- 58 Beams produced, tested and evaluated
- 4 Four-point bending tests
- + 250 hours of Lab work at Civil Engineering
- Microscopic research



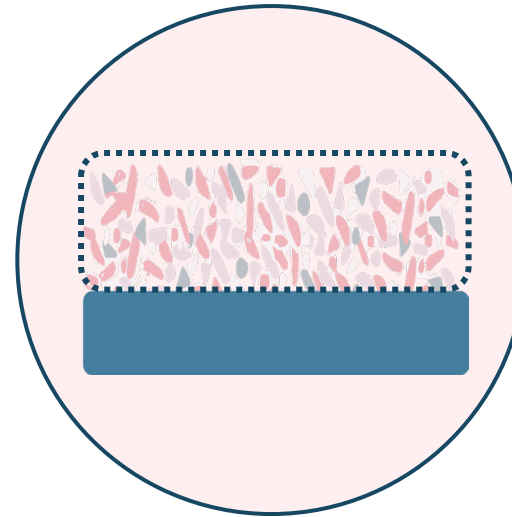
EXPERIMENTAL OVERVIEW



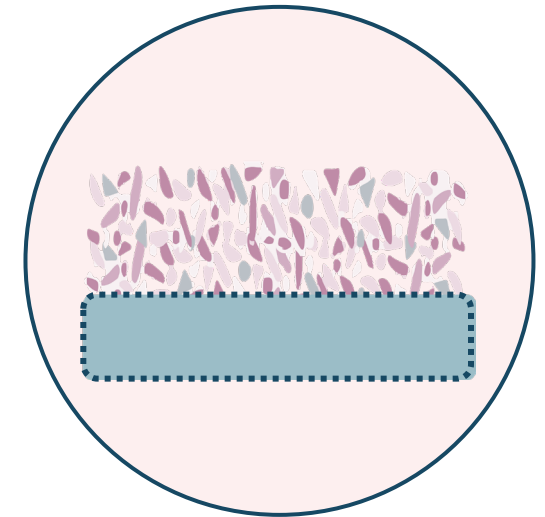
Experiment Type 1:
Homogeneous beams



Experiment Type 2:
Composite beams:
What is the influence of the **ratio**
between surface and bulk



Experiment Type 3:
Composite beams
What is the influence of the
bulk material



Experiment Type 4:
Composite beams
What is the influence of the
surface material

1



Theoretical framework

2



Design concept

3



Mechanical tests

4



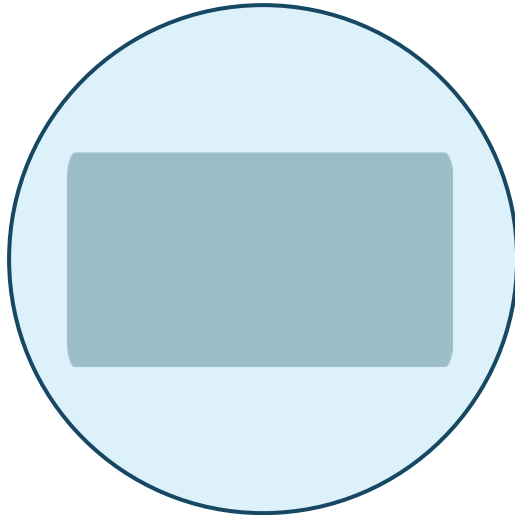
Microscopic validation

5

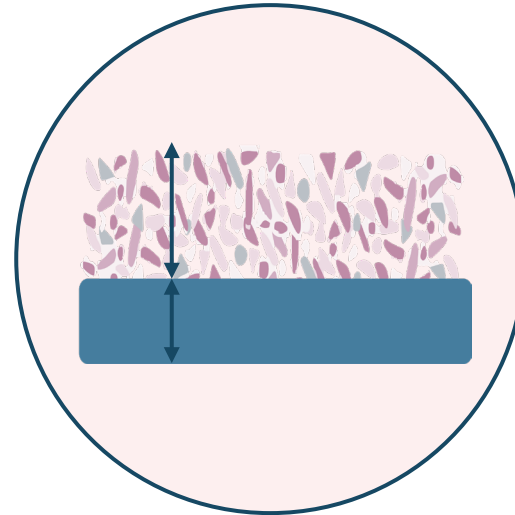


Design optimisation

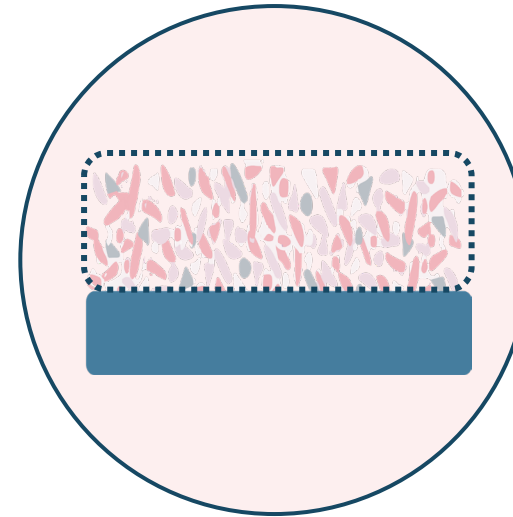
EXPERIMENTAL OVERVIEW



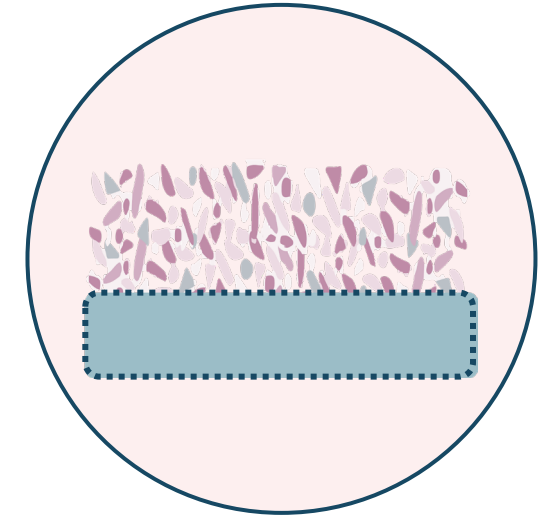
Experiment Type 1:
Homogeneous beams



Experiment Type 2:
Composite beams:
What is the influence of the **ratio**
between surface and bulk



Experiment Type 3:
Composite beams
What is the influence of the **bulk material**

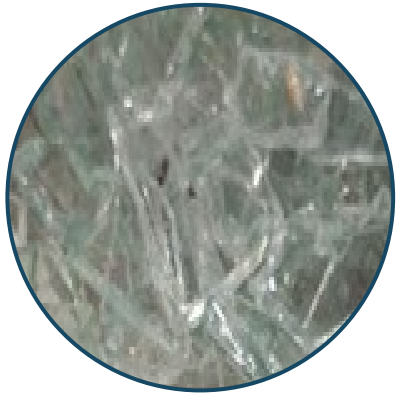


Experiment Type 4:
Composite beams
What is the influence of the **surface material**

CULLET CLASSIFICATION

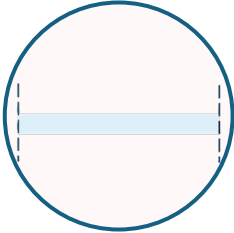


(Source: (20) DeBrincat & Babic, 2023)

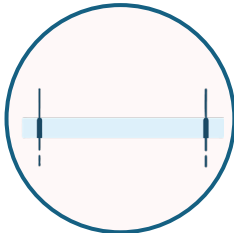


Class A Cullet: High-quality, contaminant-free, ideal for new glass production

Cutting

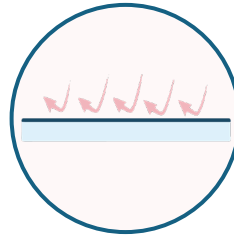


Drilling

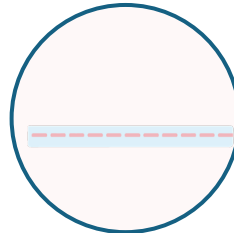


Class B Cullet: Mixed quality, may have contaminants

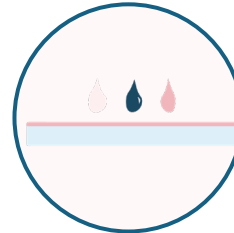
Coated Glass



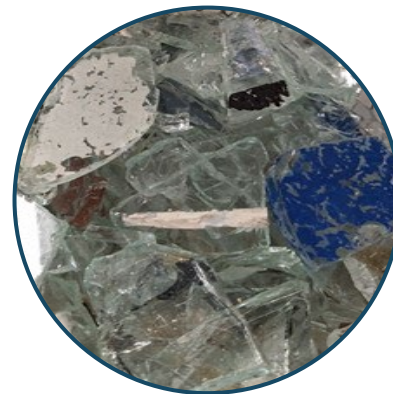
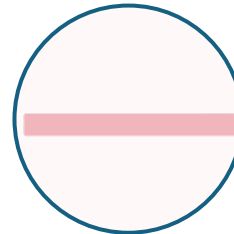
Laminated Glass



Printed Glass

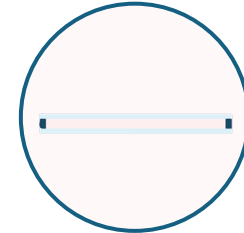


Tinted Glass

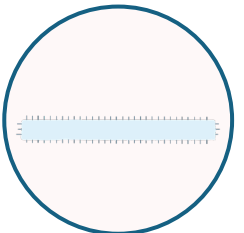


Class C Cullet: Contaminated, unsuitable for remelting

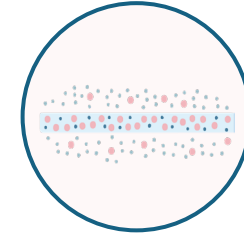
IGU



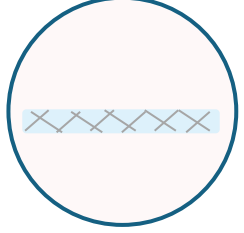
HR Glass



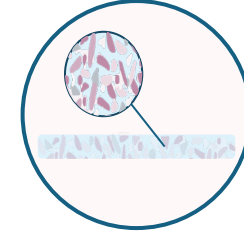
Chemical treating



Metallic Pollutants



CSP Pollutants

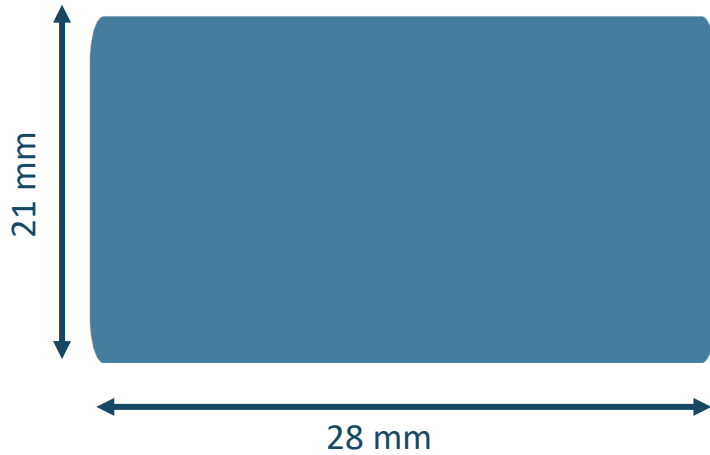




DESIGN CONCEPT

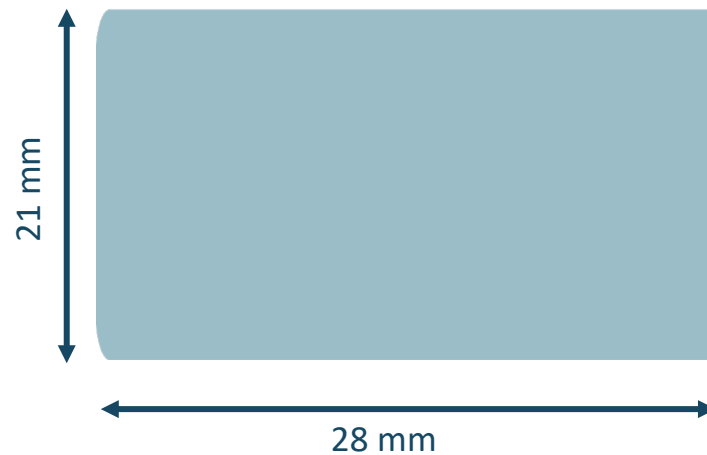
Experimental set-up for homogeneous beam

TYPE A CULLET



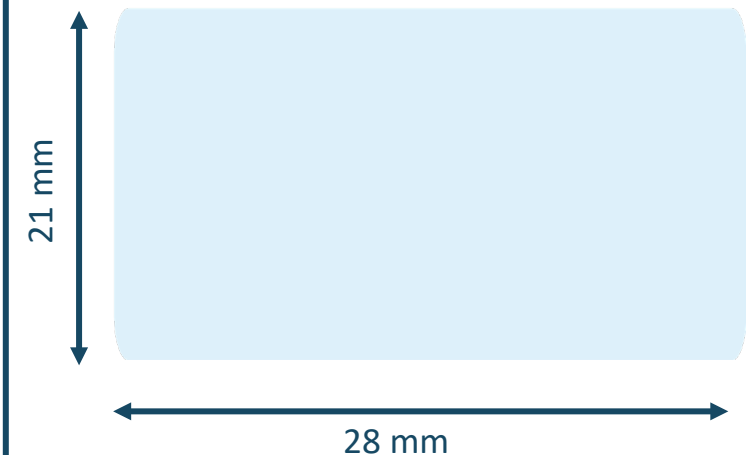
- Float glass

TYPE B CULLET



- Soft coated glass
- Fritted glass

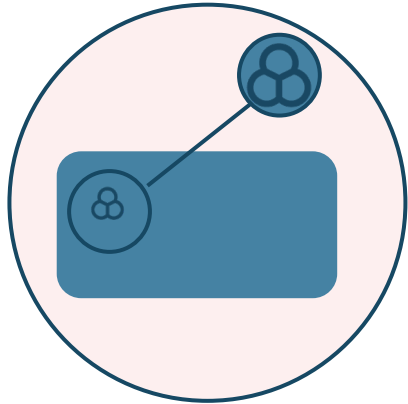
TYPE C CULLET



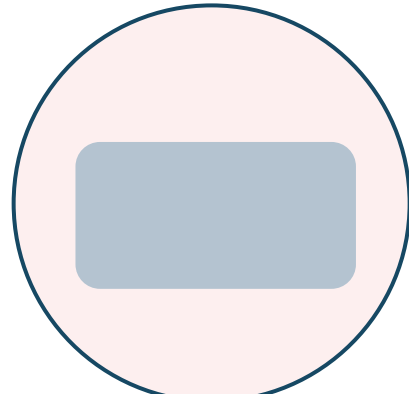
- CSP Pollutants
- Heat Resistant glass
- Metallic Pollutants



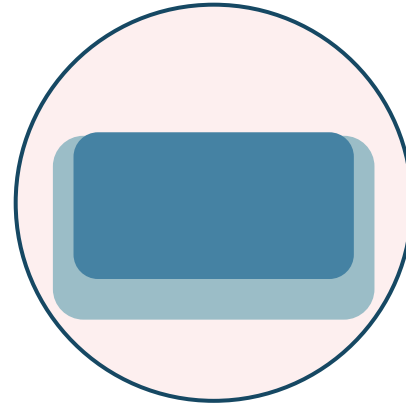
STRUCTURAL FEASIBILITY VALIDATION



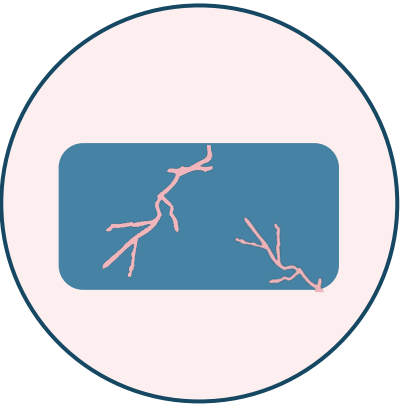
Compatibility



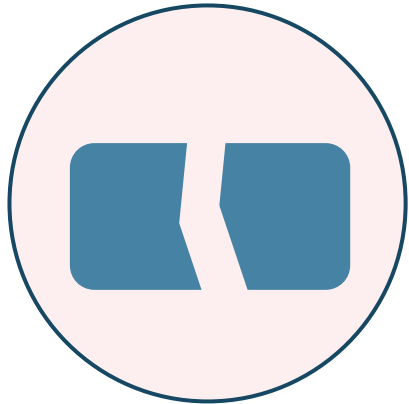
Transparency



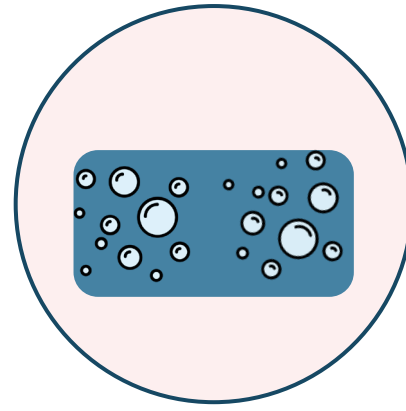
Mould reaction



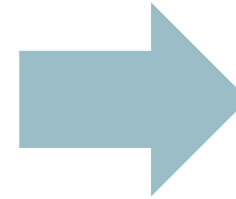
Cracks presence



Breakage



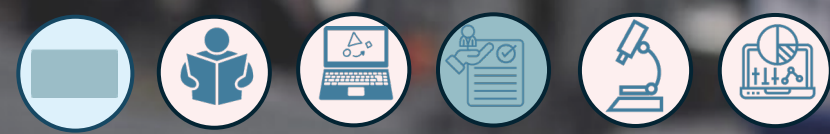
Bubbles level



Structural performance



FOUR-POINT BENDING MACHINE

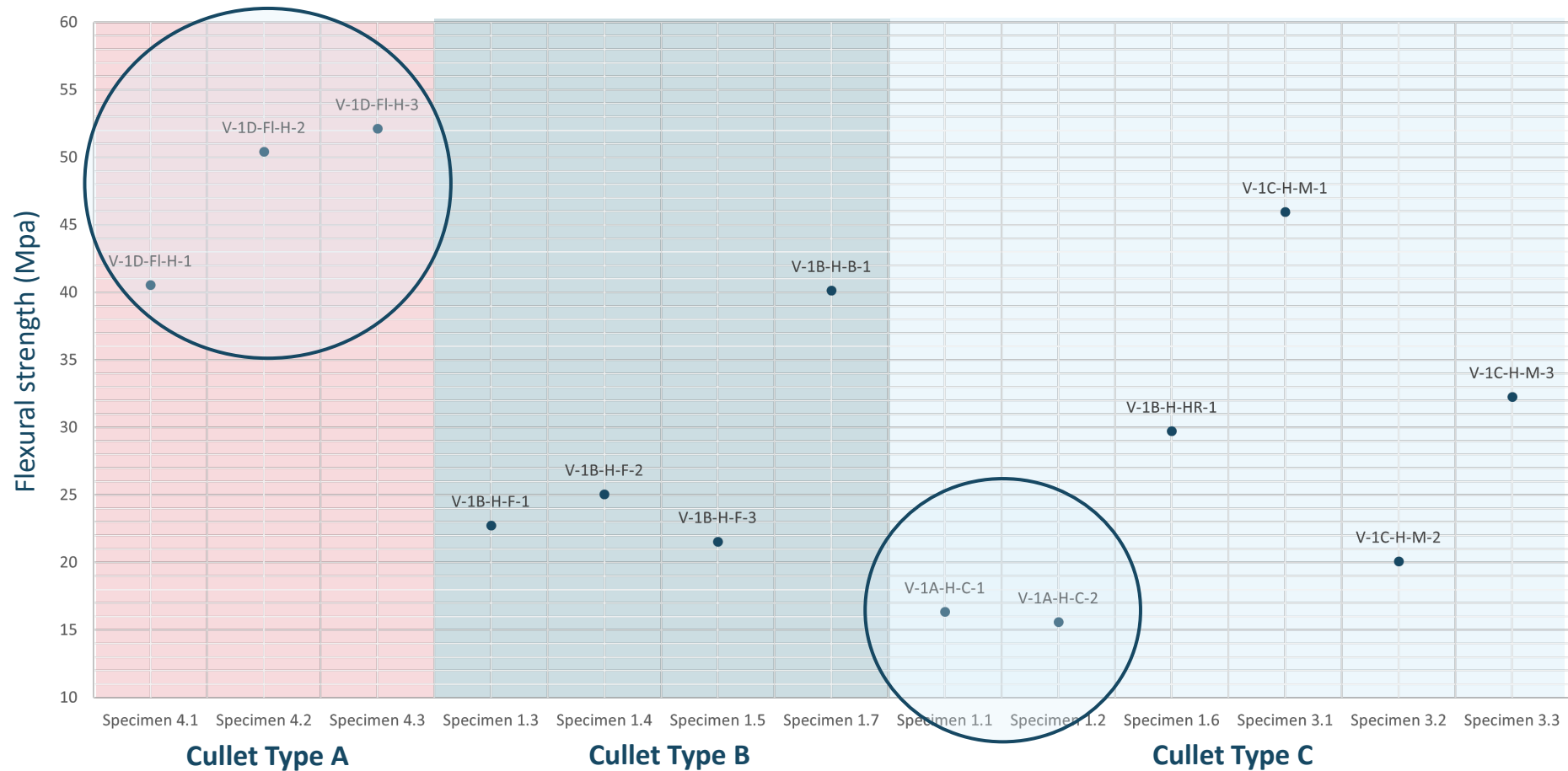




FOUR POINT BENDING TESTS

Homogeneous beams: A cullet vs B cullet vs C cullet

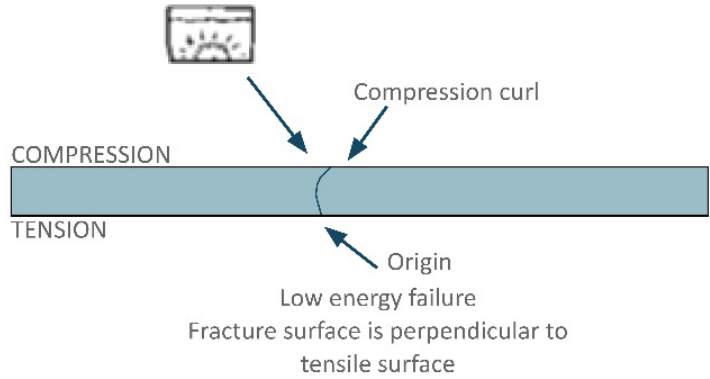
Flexural strength of homogeneous beams of Cullet Type A, Cullet Type B and Cullet Type C





CRACK PATTERNS

Low energy vs High energy



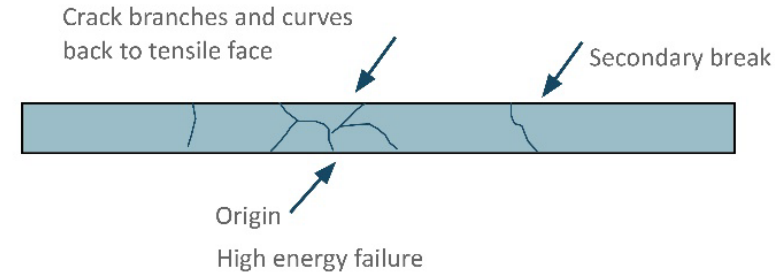
Beam: V-1A-H-C-2

Homogeneous beam with CSP Pollutants

Cullet Type C

LOW ENERGY FAILURE

HIGH ENERGY FAILURE



Beam: V-1D-H-FI-3

Homogeneous beam with Float glass

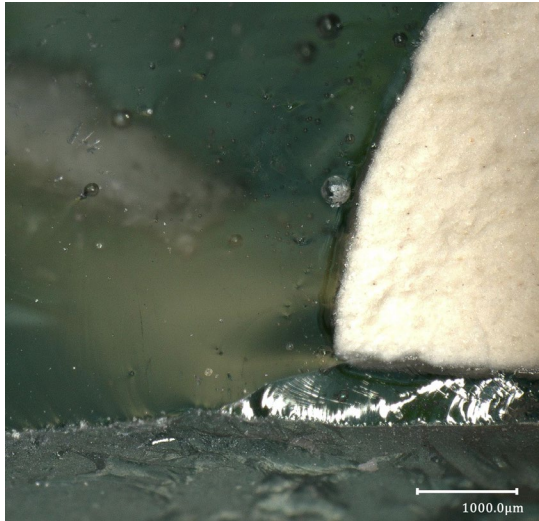
Cullet Type A



FLAW CATEGORIES

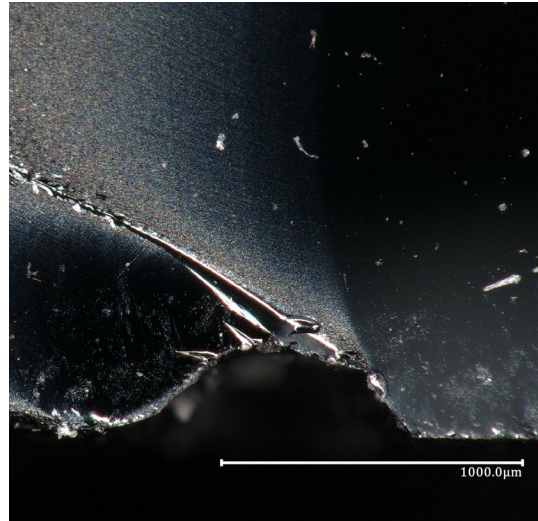
Theory

INCLUSIONS



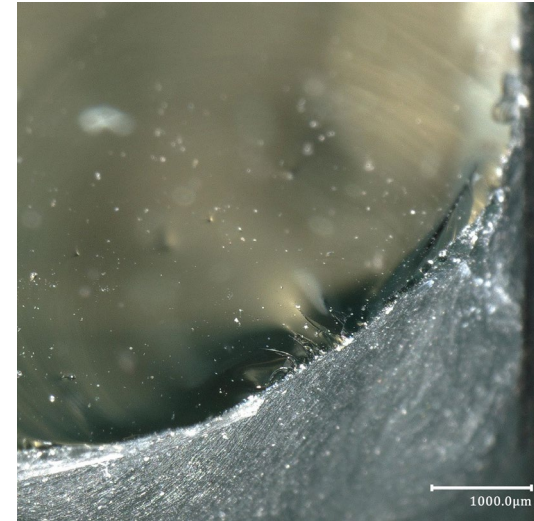
- **Bulk flaw**
- Ceramic inclusion
- Silica inclusion

INFOLDS



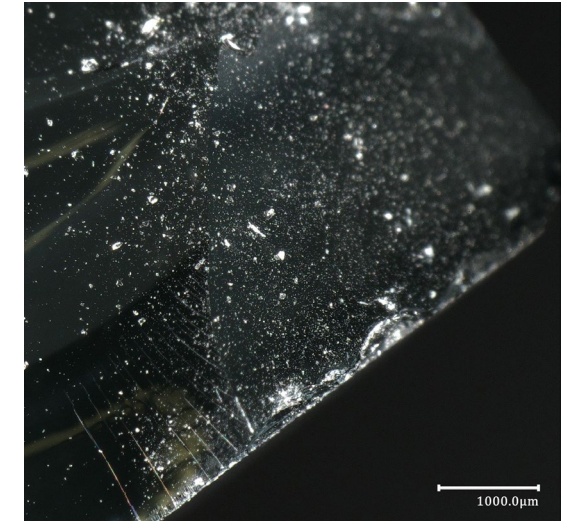
- **Surface flaw**
- Culletts did not fully interfere
- Small gaps in the glass

CRYSTALLIZATION



- **Surface flaw**
- High temperature reaction
- Affected by the heating and cooling ramp at various speeds

MACHINING



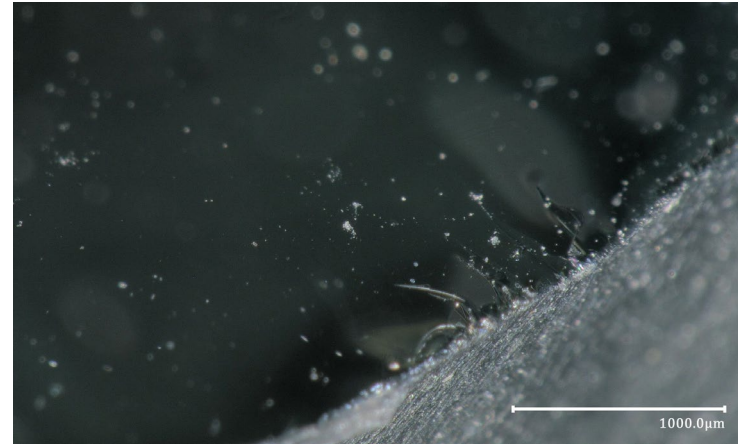
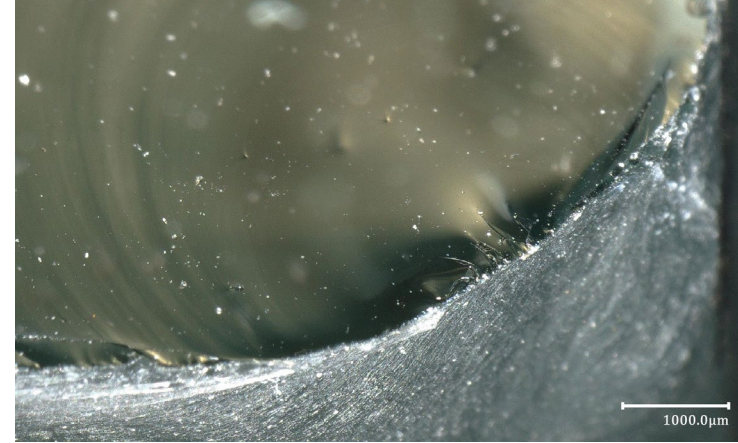
- **Surface flaw**
- Surface and edge treatment by grinding and cutting



FLAW CATEGORIES

Crystallization

CRYSTALLIZATION



Beam V-1B-H-HR-1



FLAW CATEGORIES

Inclusions

INCLUSIONS AT THE SURFACE



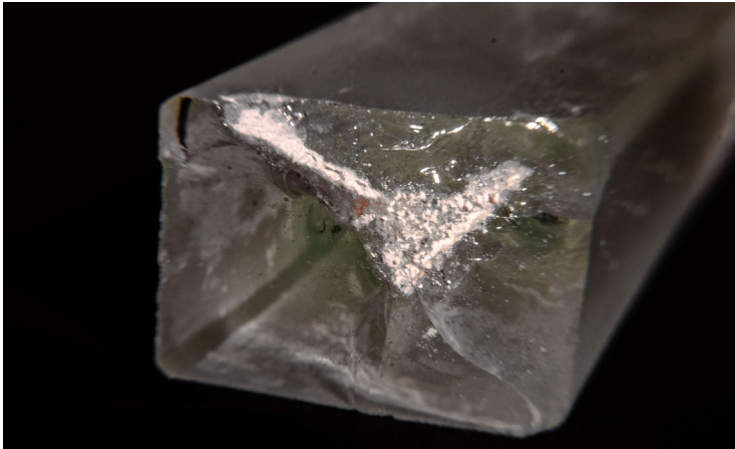
Beam V-1A-H-C-2



FLAW CATEGORIES

Inclusions

SILICONE INCLUSIONS



Beam V-1B-H-S-1



Beam V-1A-H-HR-2

CERAMIC INCLUSIONS

2 | EXPERIMENTAL METHODOLOGY

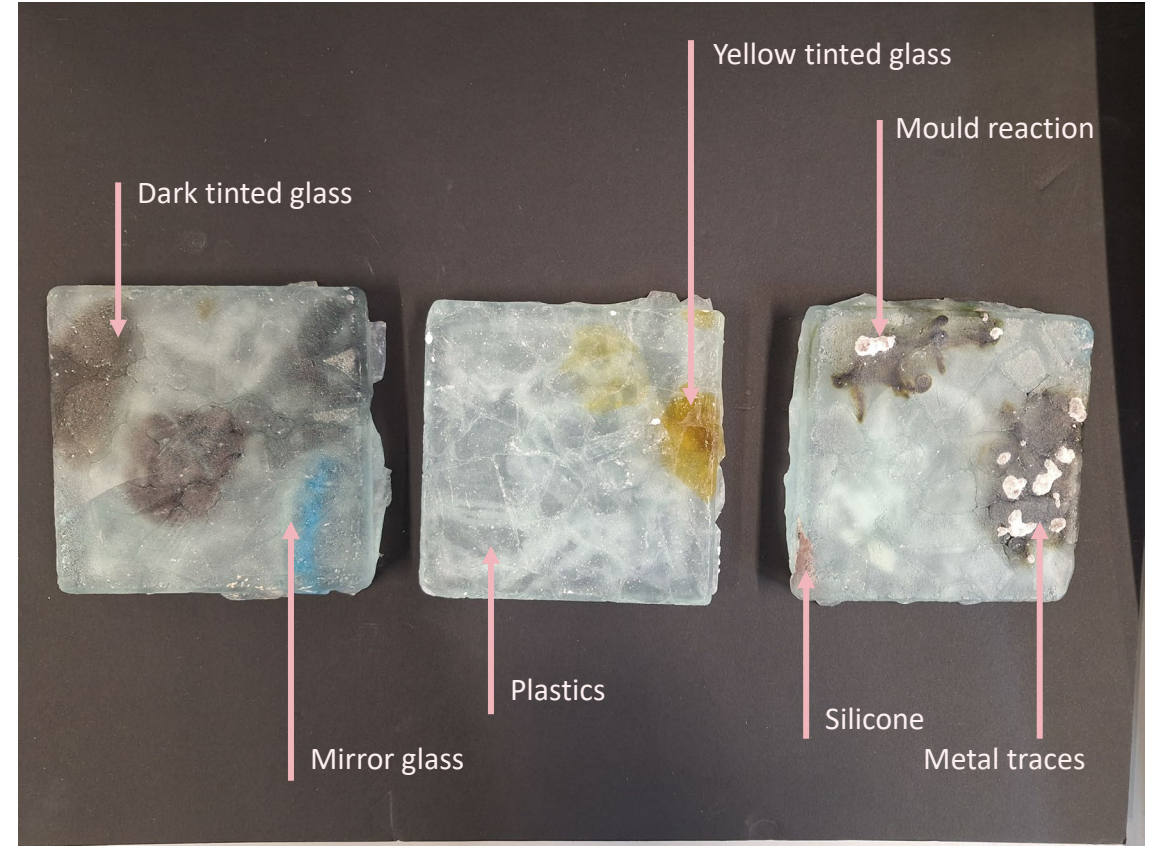
CULLET SELECTION





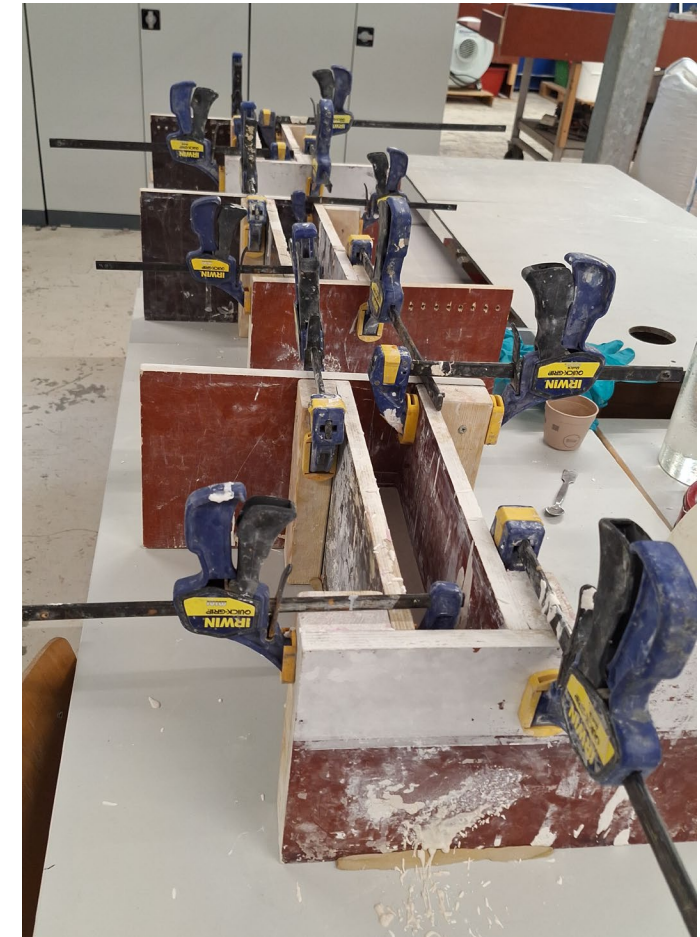
CULLET SELECTION

Tiles arrangement



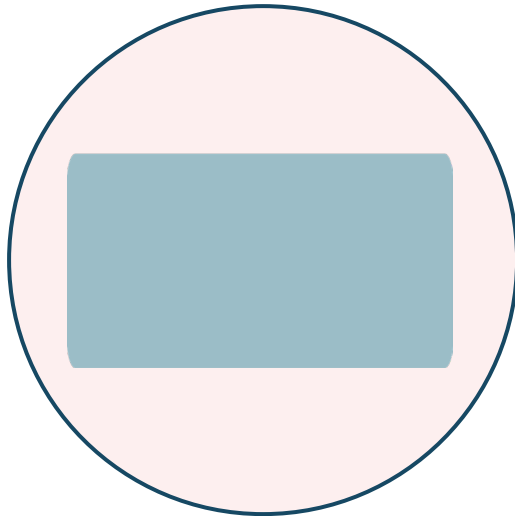
- Silicone inclusions
- Ceramic inclusions
- Metal traces
- CSP Pollutants
- Mirror
- Tinted glass
- Plastics
- Papers
- Wood

MAKING MOULDS

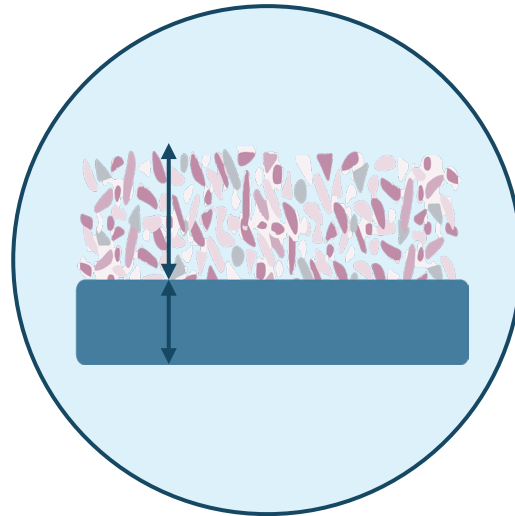




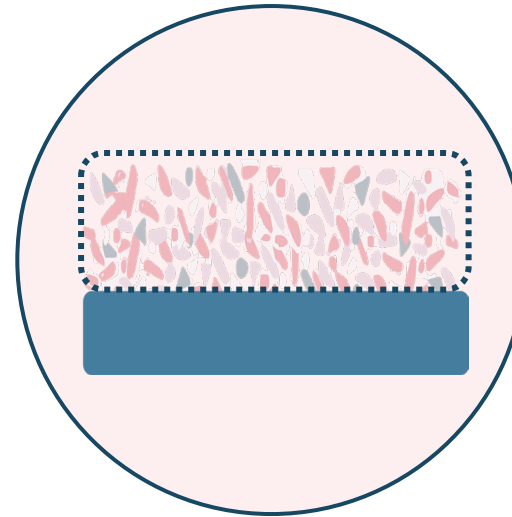
EXPERIMENTAL OVERVIEW



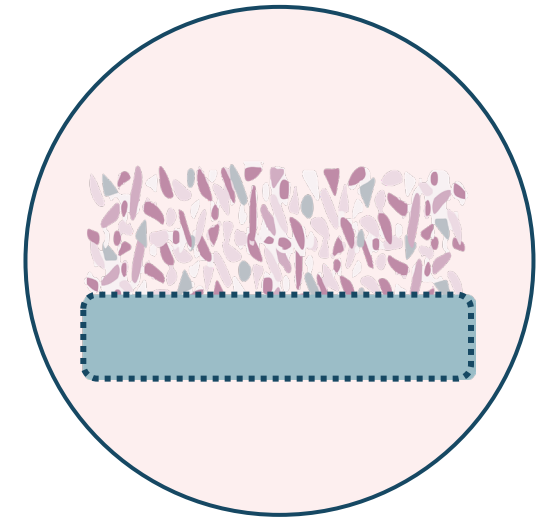
Experiment Type 1:
Homogeneous beams



Experiment Type 2:
Composite beams:
What is the influence of the **ratio**
between surface and bulk

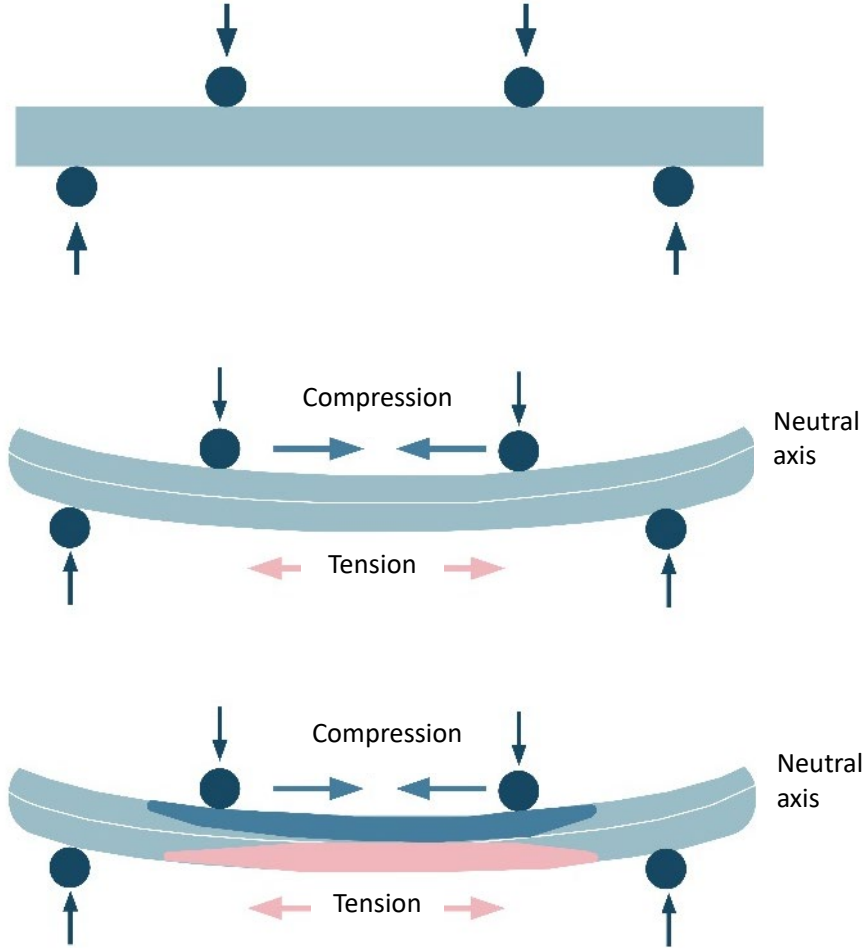


Experiment Type 3:
Composite beams
What is the influence of the
bulk material

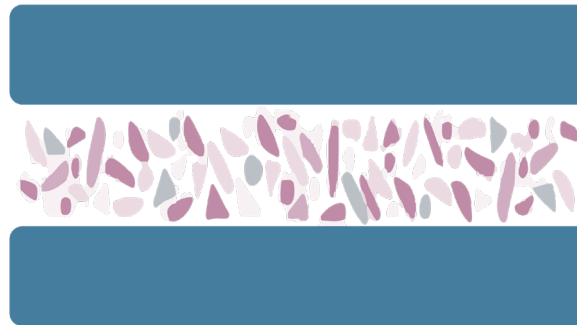


Experiment Type 4:
Composite beams
What is the influence of the
surface material

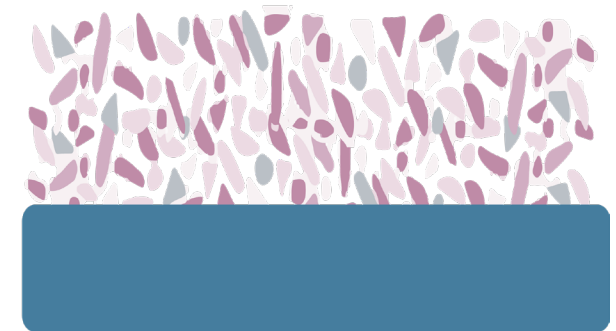
MECHANICAL BEHAVIOUR



3 layered structure for composite beam



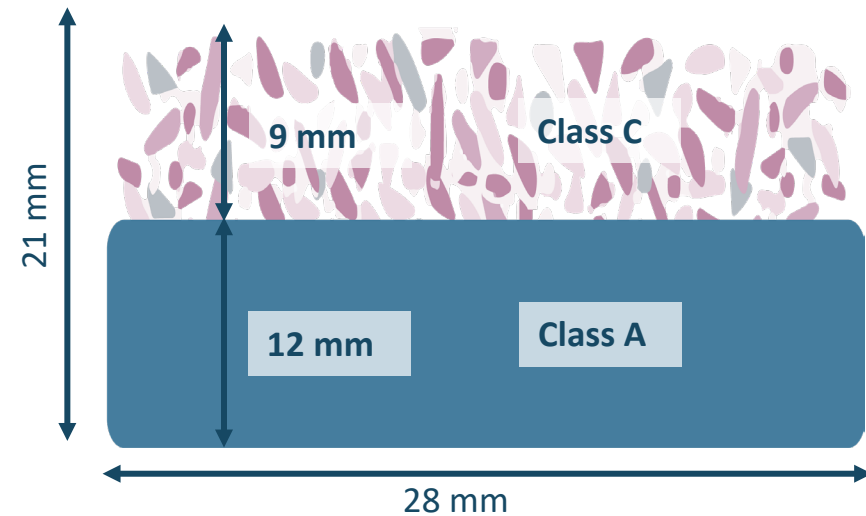
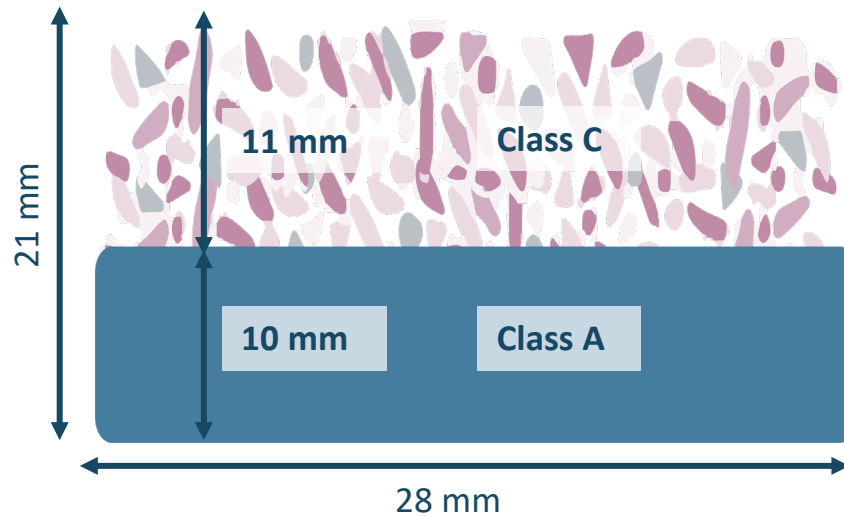
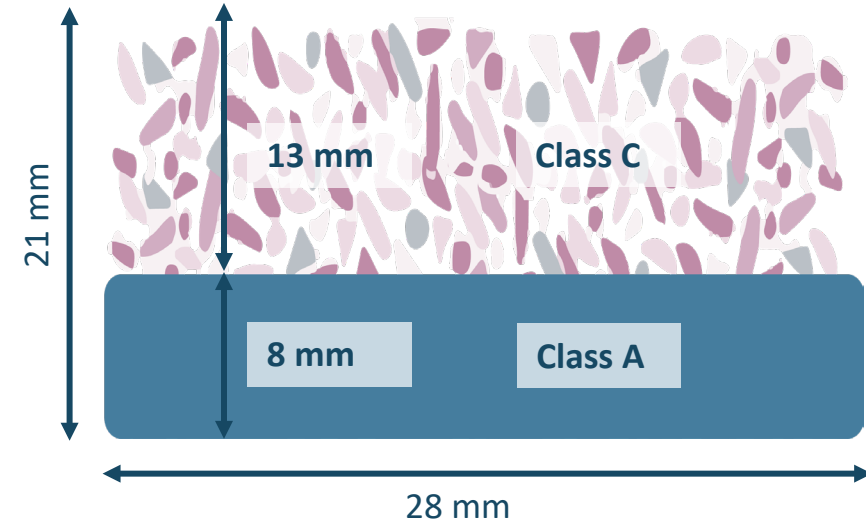
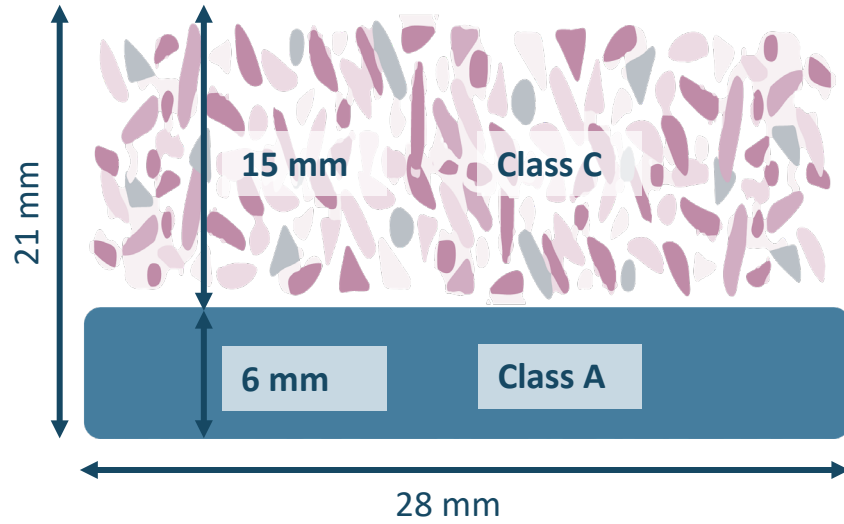
2 layered structure for composite beam

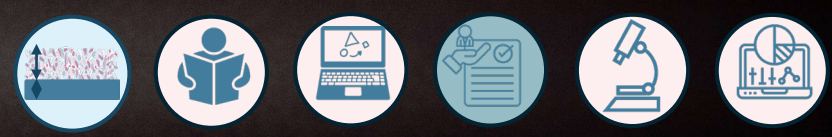




DESIGN CONCEPT

Experimental set-up for composite beams – What is the influence of the ratio between surface and bulk?



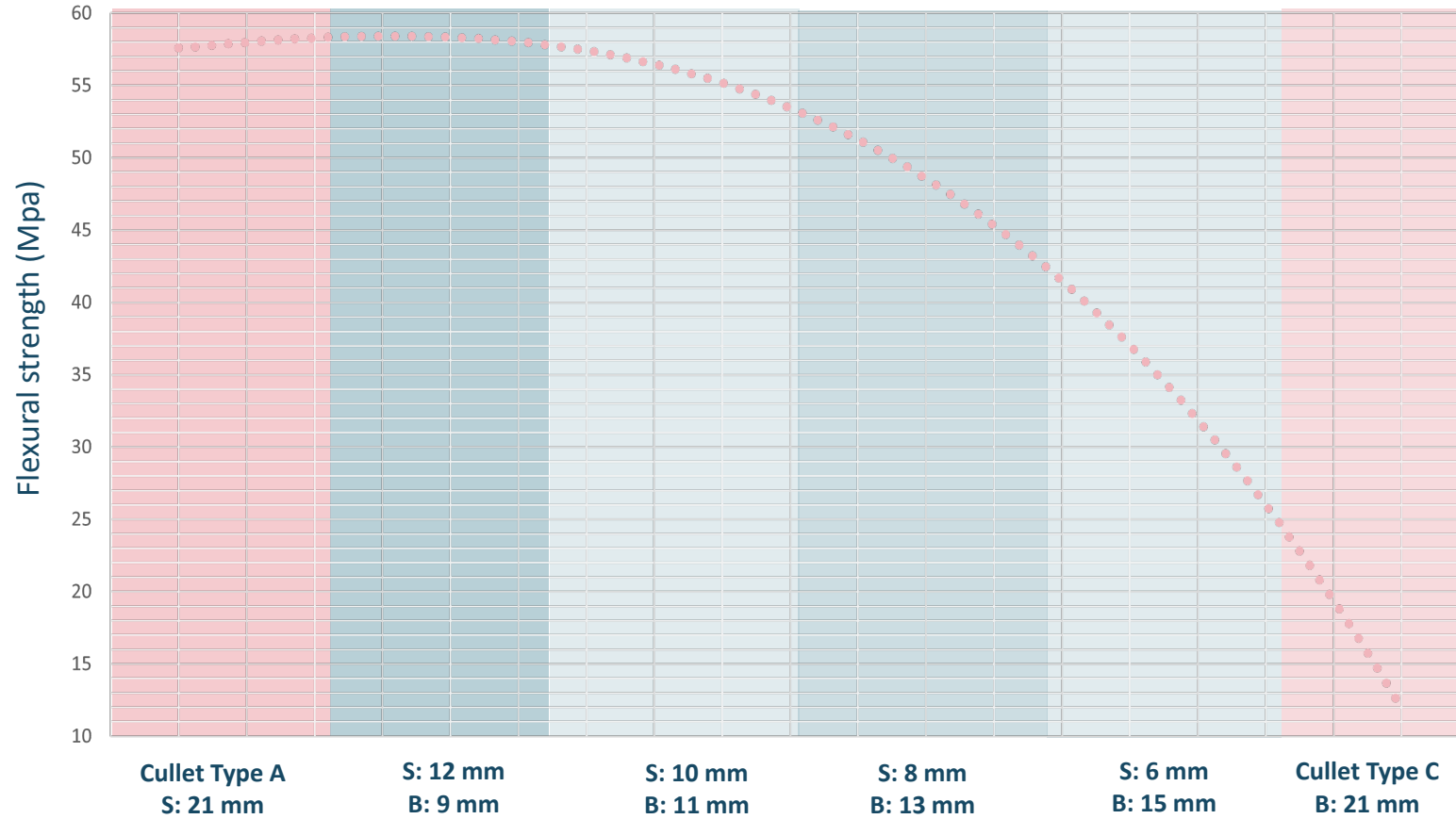




FOUR POINT BENDING TESTS

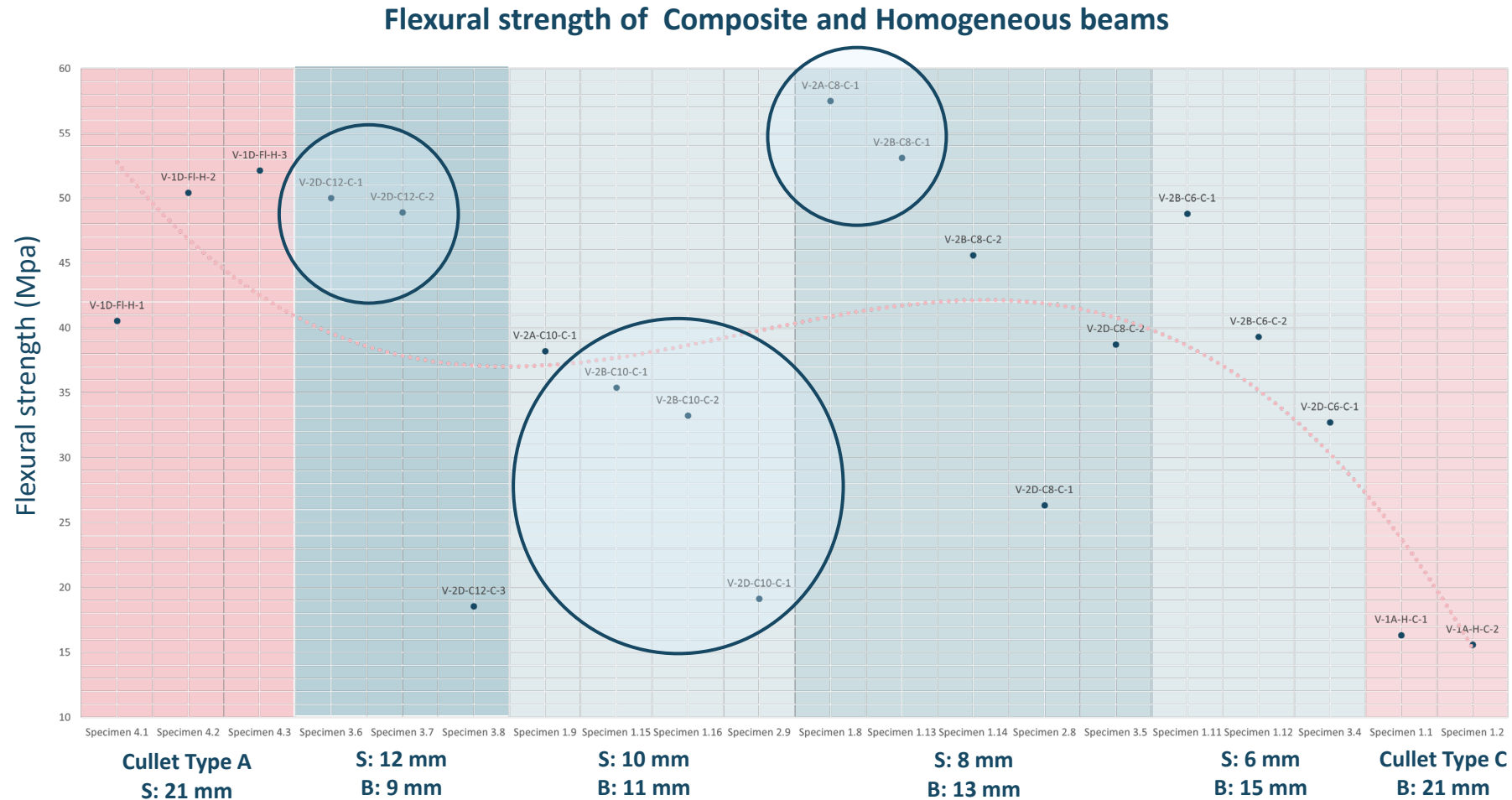
Composite vs Homogeneous beams

Expected curve for the flexural strength of Composite and Homogeneous beams





FOUR POINT BENDING TESTS Composite vs Homogeneous beams

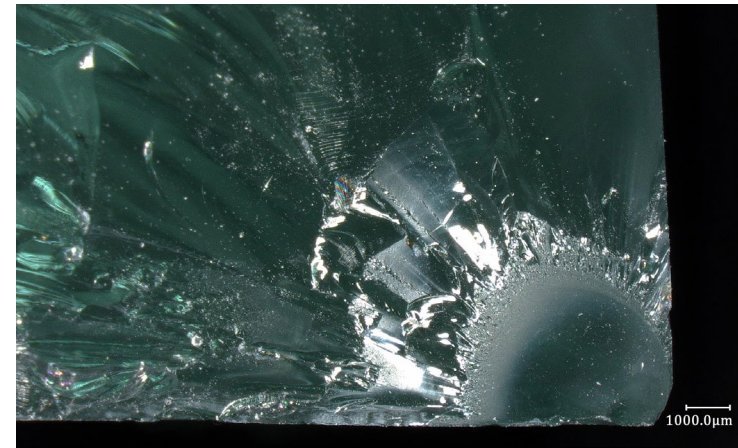
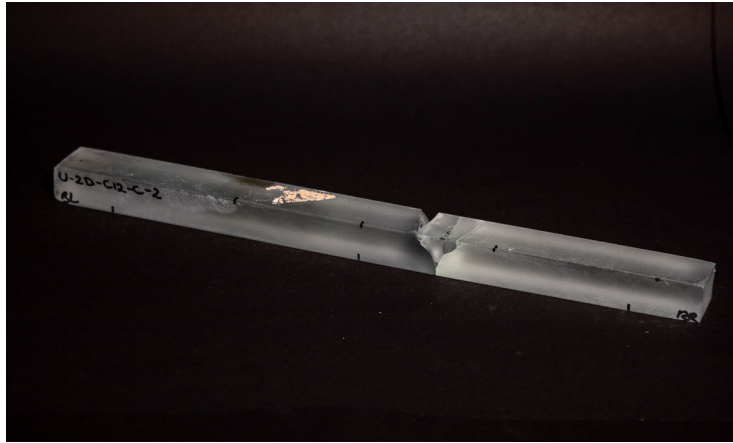




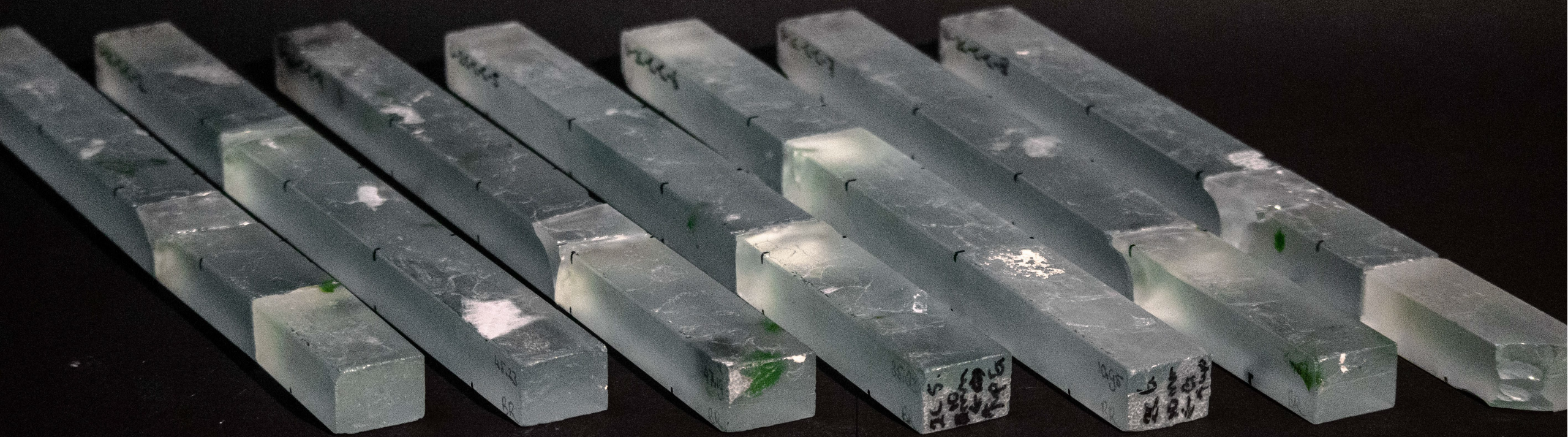
FLAW CATEGORIES

Infolds

INFOLDS



Beam V-2D-C12-C-2

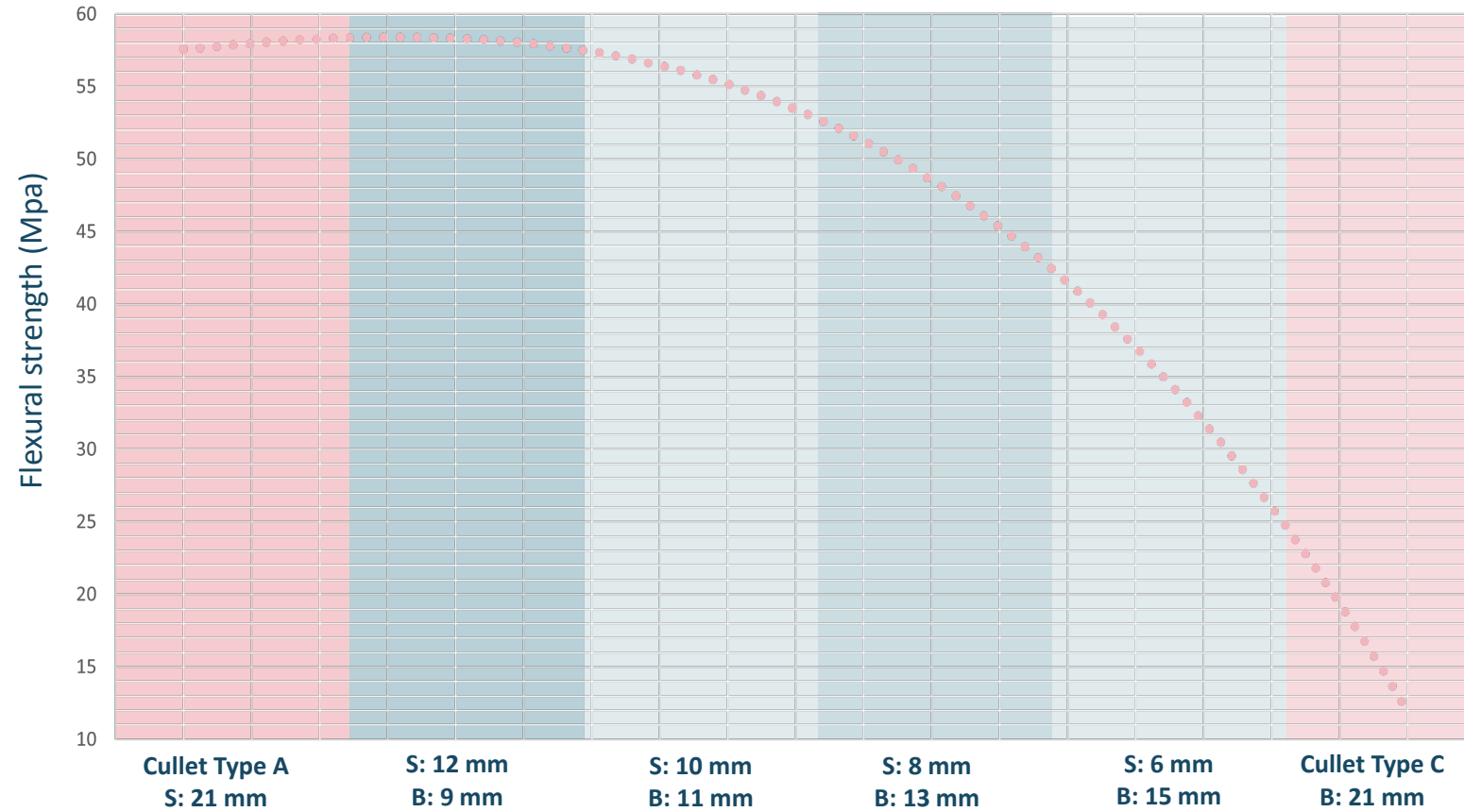




FOUR POINT BENDING TESTS

Composite vs Homogeneous beams

Expected curve for the flexural strength of Composite and Homogeneous beams

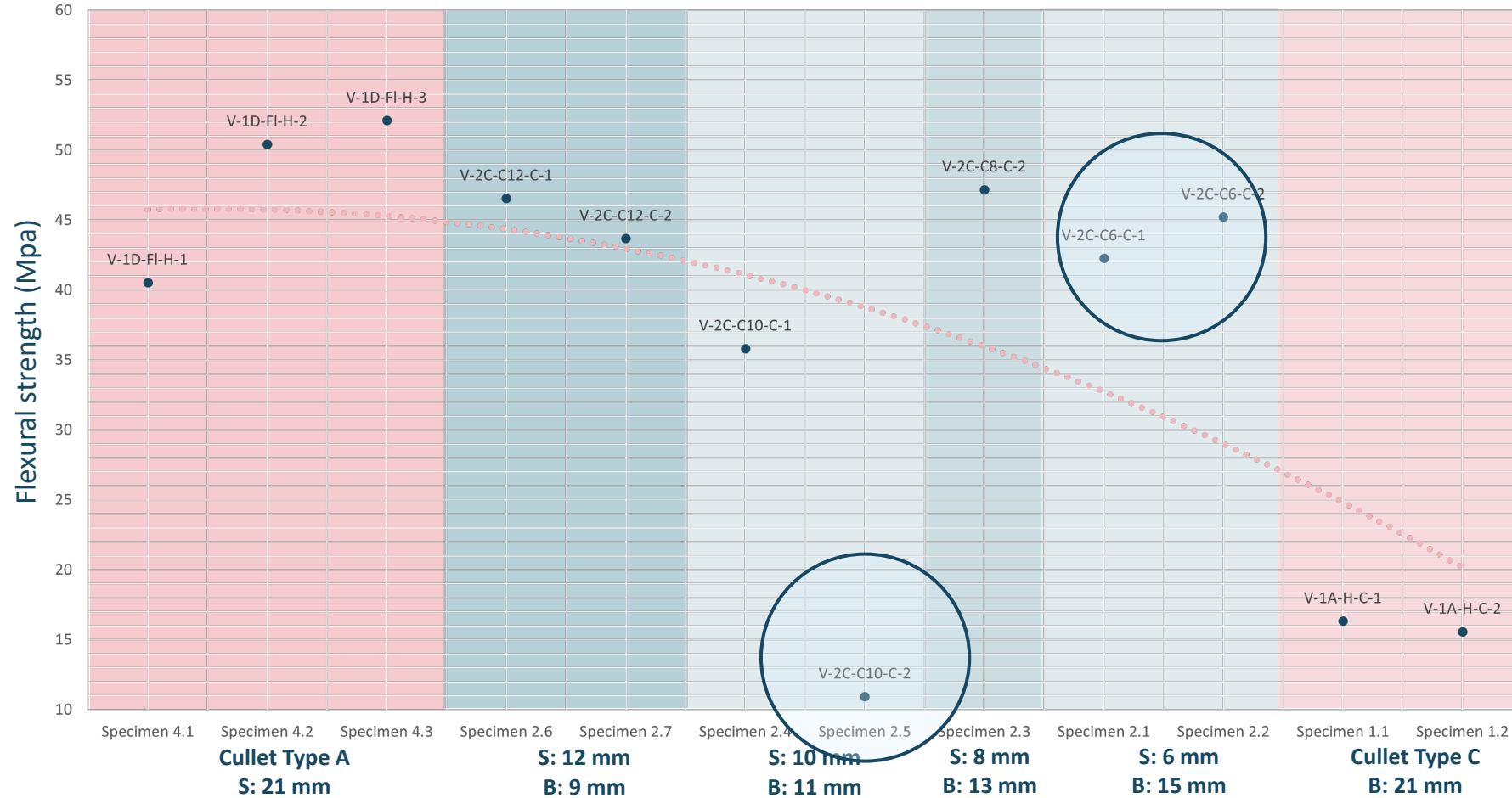




FOUR POINT BENDING TESTS

Composite vs Homogeneous beams

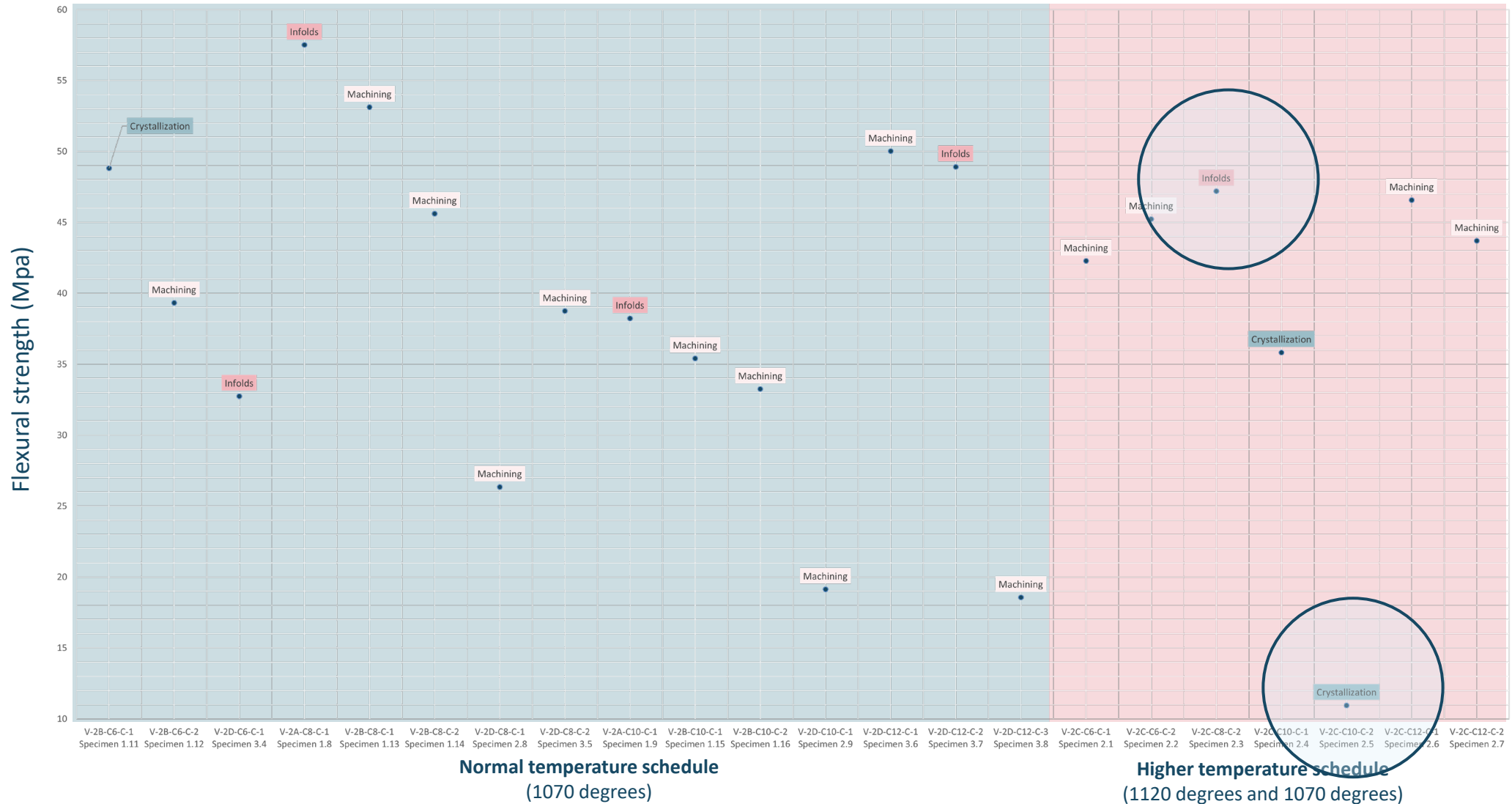
Flexural strength of Composite and Homogeneous beams
Influence of a higher temperature schedule





FLAW CATEGORIES

Relation between flaw types and the flexural strength of composite beams

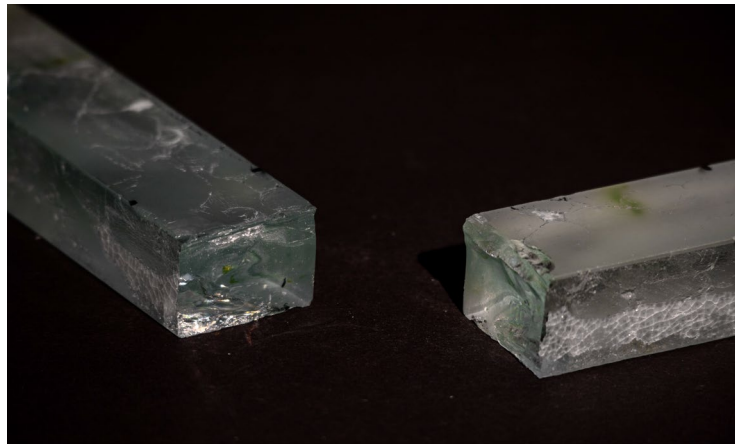
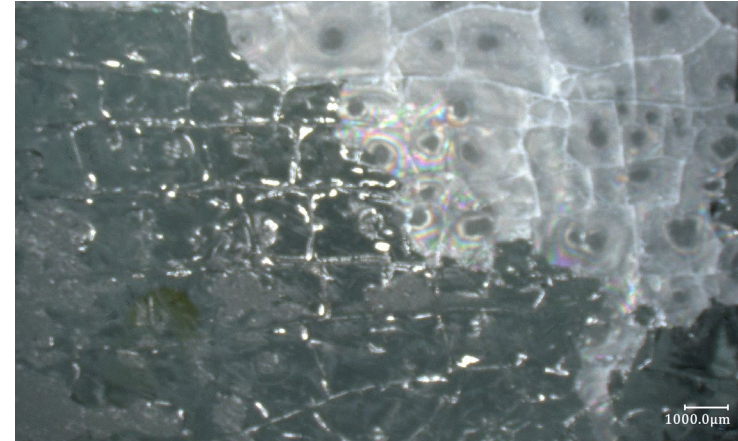
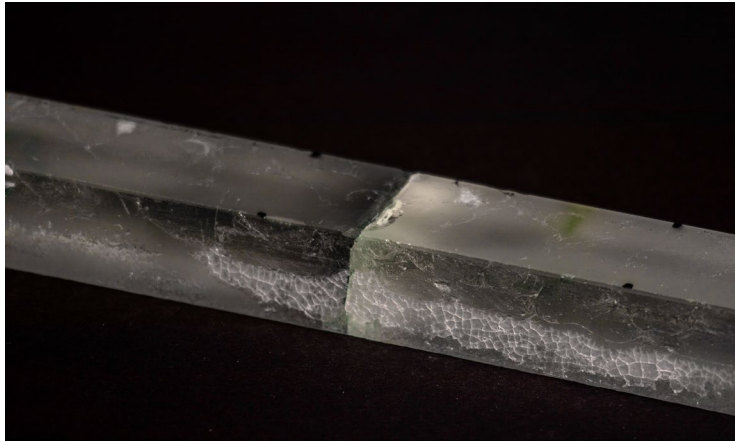




FLAW CATEGORIES

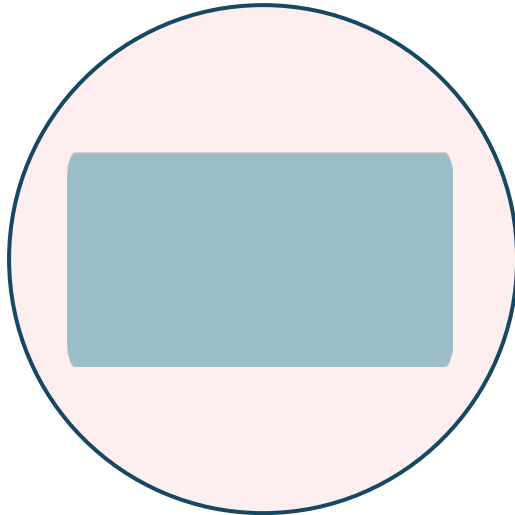
Crystallization

CRYSTALLIZATION

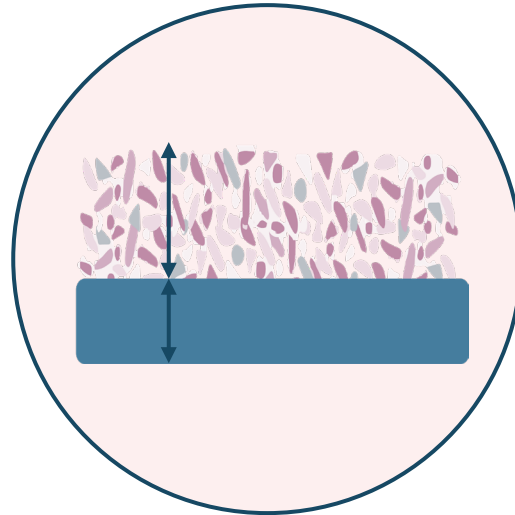


Beam V-2C-C10-C-1

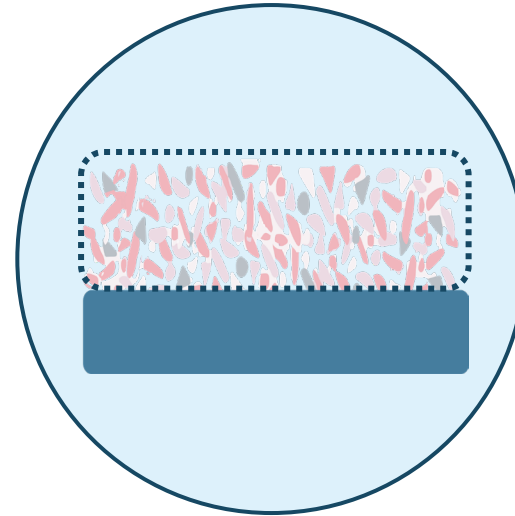
EXPERIMENTAL OVERVIEW



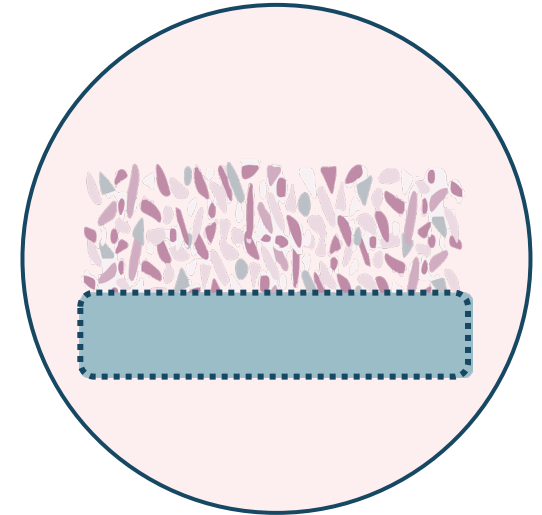
Experiment Type 1:
Homogeneous beams



Experiment Type 2:
Composite beams:
What is the influence of the **ratio**
between surface and bulk



Experiment Type 3:
Composite beams
What is the influence of the
bulk material

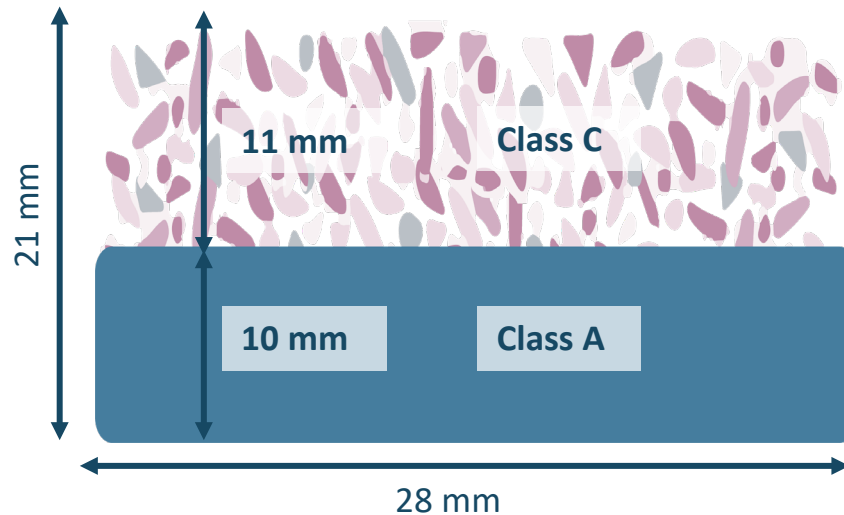
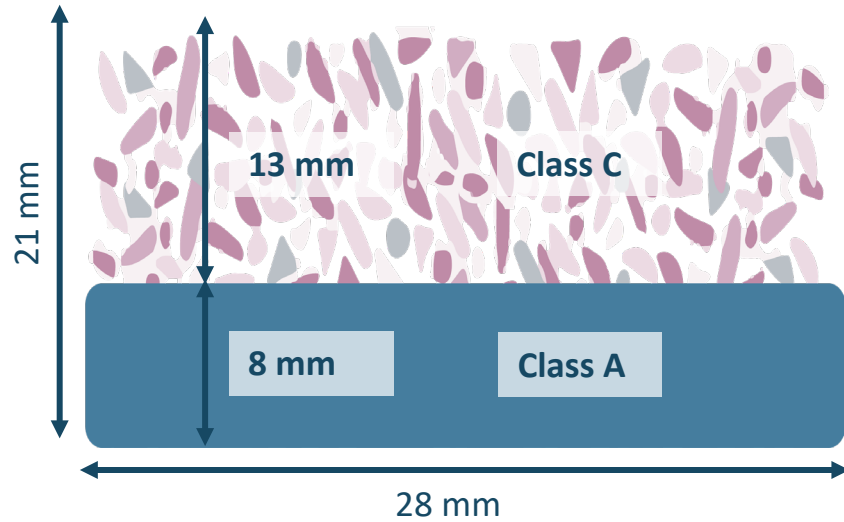


Experiment Type 4:
Composite beams
What is the influence of the
surface material



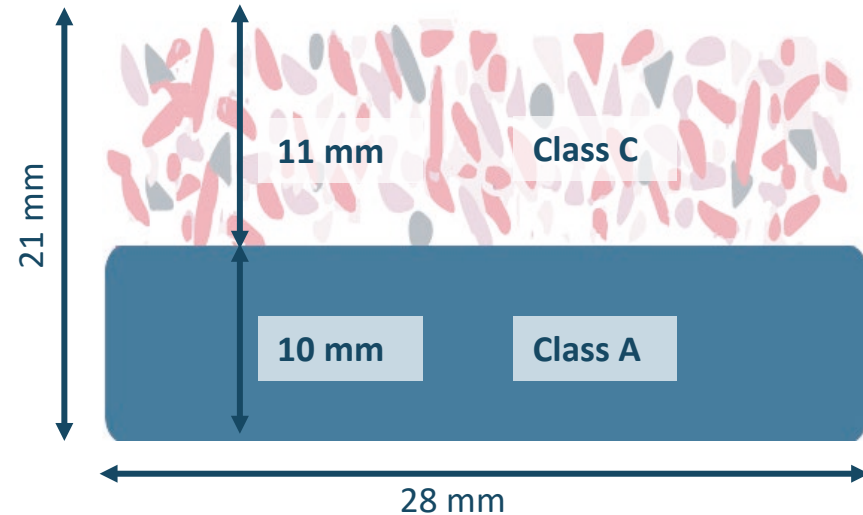
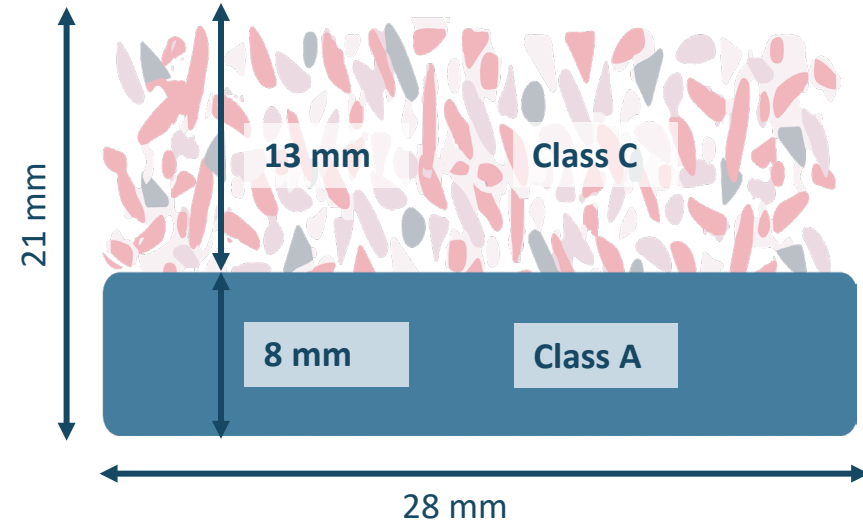
DESIGN CONCEPT

Fire Round 3: Experimental set-up for composite beams – What is the influence of the bulk material ?

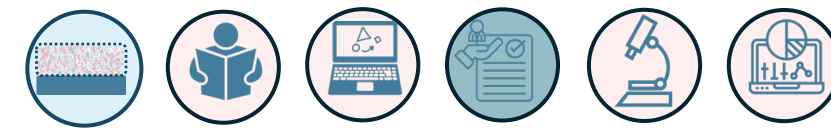


CSP POLLUTANTS

METALLIC POLLUTANTS



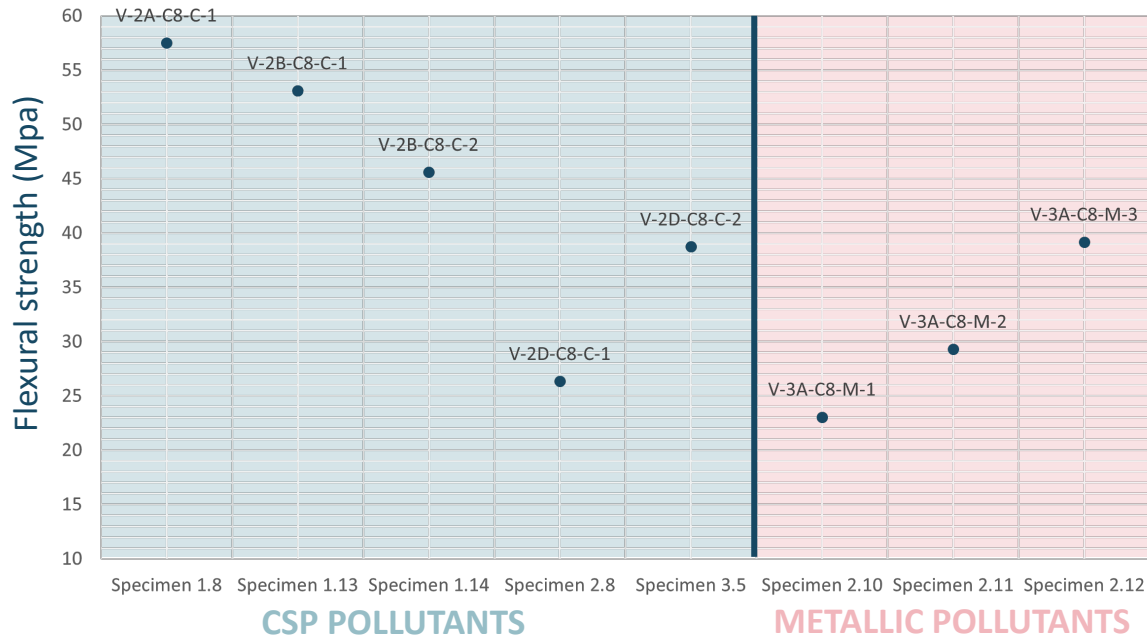




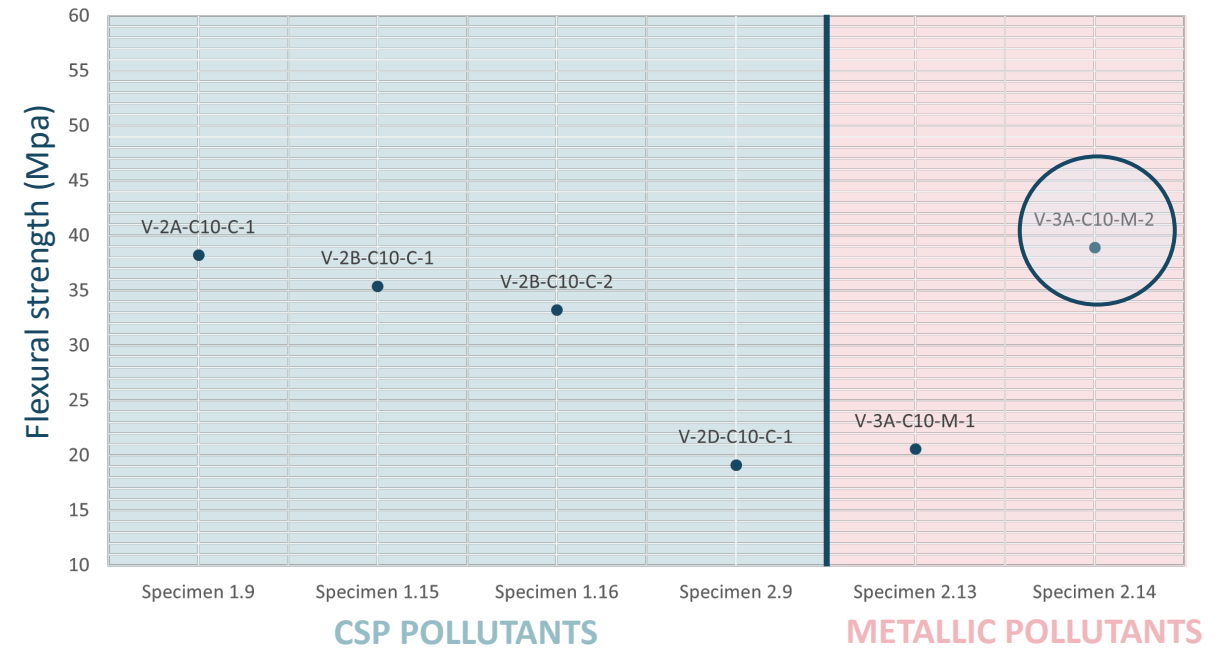
FOUR POINT BENDING TESTS

Composite beams – What is the influence of the bulk material?

**Flexural strength of Composite beams with 8 mm Float glass
Influence of bulk material**



**Flexural strength of Composite beams with 10 mm Float glass
Influence of bulk material**





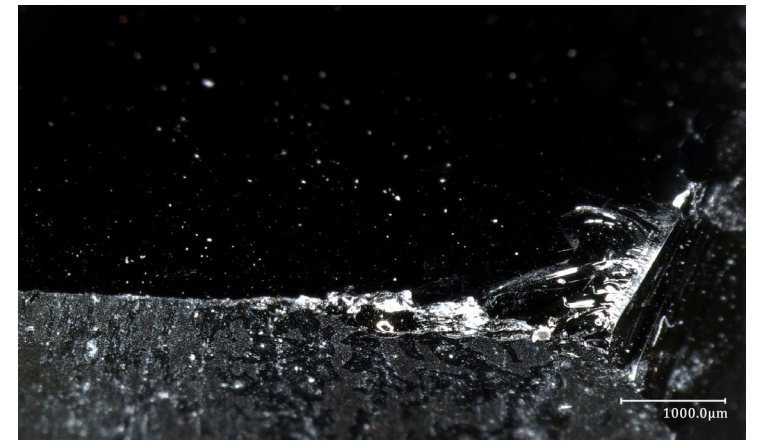
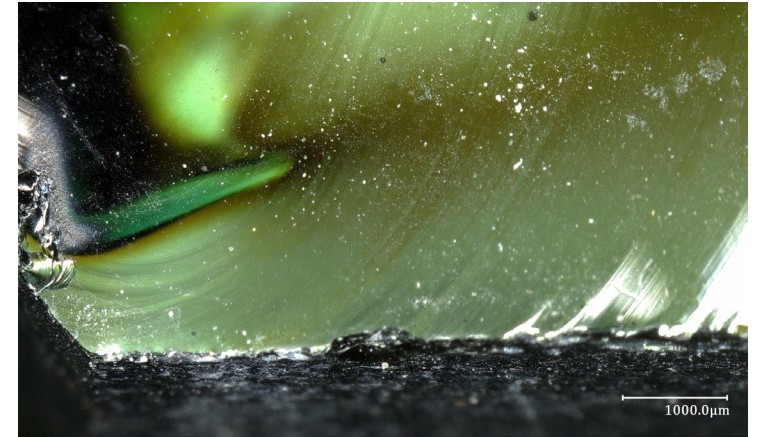
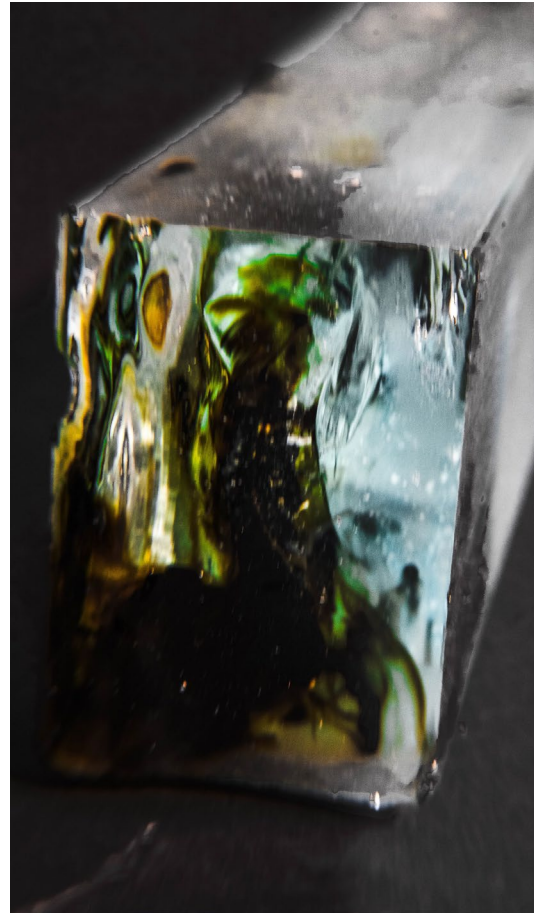
FLAW CATEGORIES

Machining

MACHINING



Beam V-3A-C8-M-1

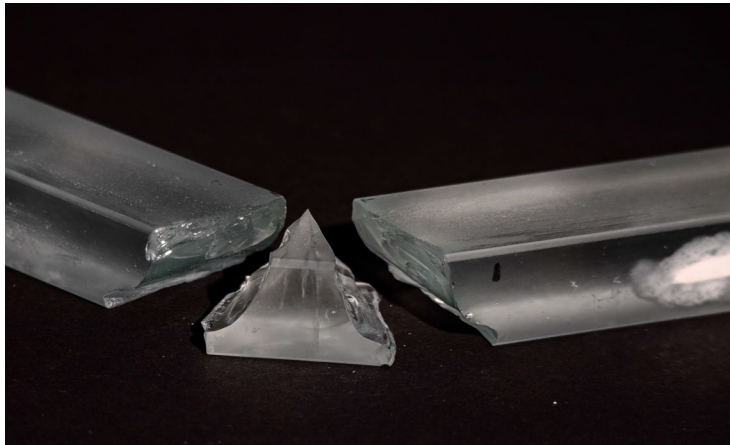




FLAW CATEGORIES

Machining

INCLUSIONS IN THE BULK

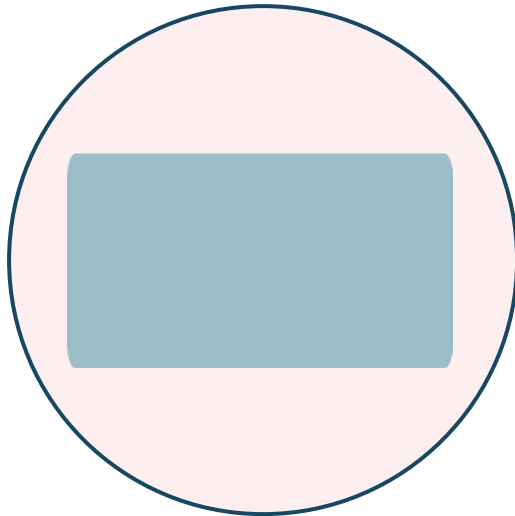


Beam V-2A-C8-F-1

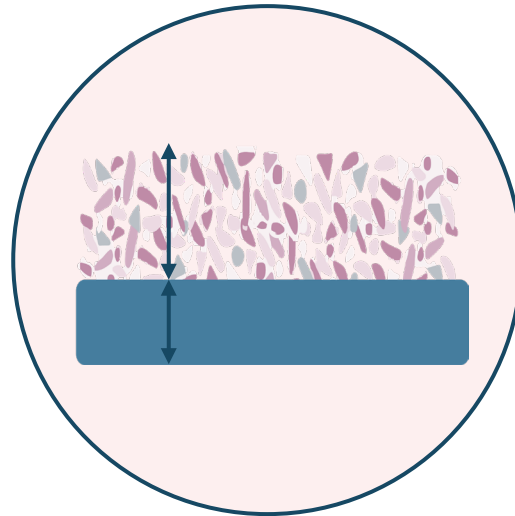


MACHINING

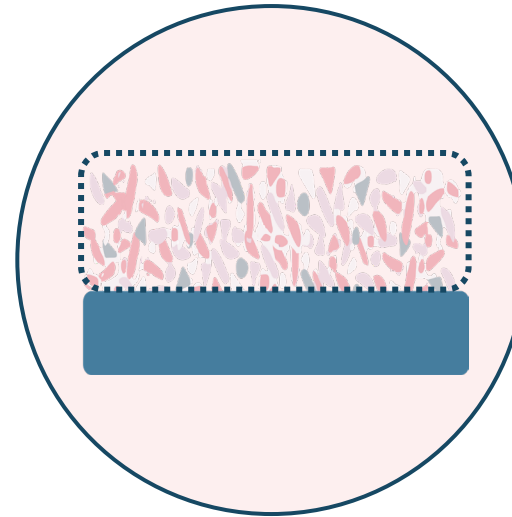
EXPERIMENTAL OVERVIEW



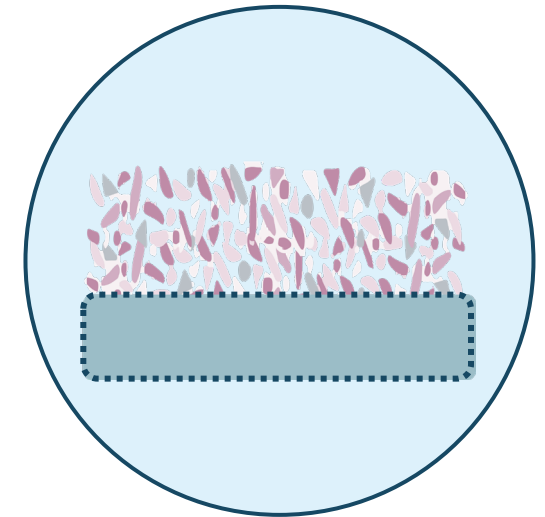
Experiment Type 1:
Homogeneous beams



Experiment Type 2:
Composite beams:
What is the influence of the **ratio**
between surface and bulk



Experiment Type 3:
Composite beams
What is the influence of the **bulk material**

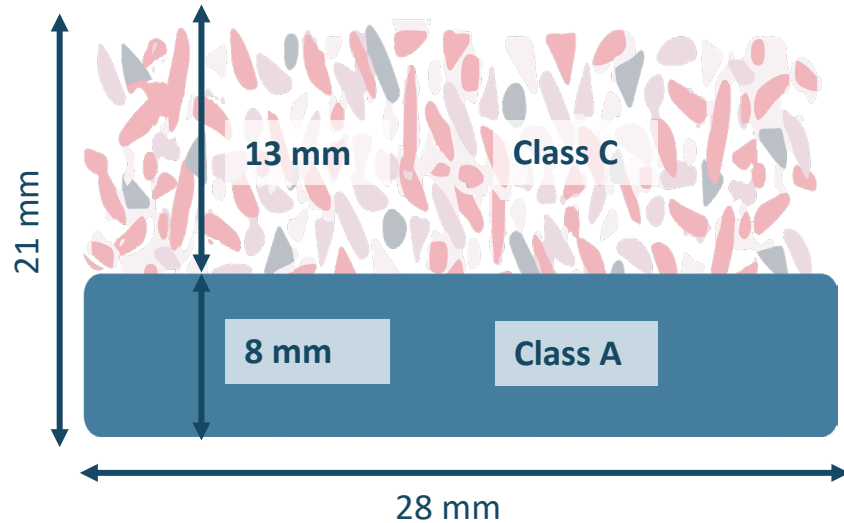
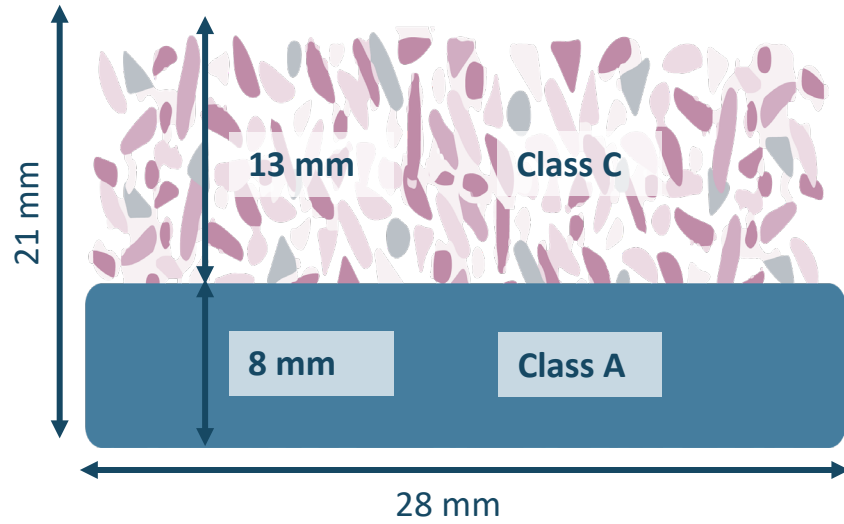


Experiment Type 4:
Composite beams
What is the influence of the **surface material**



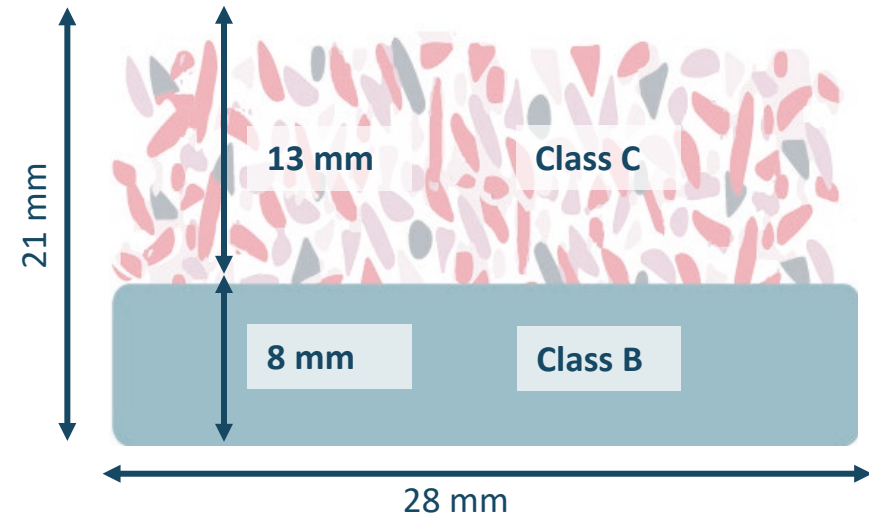
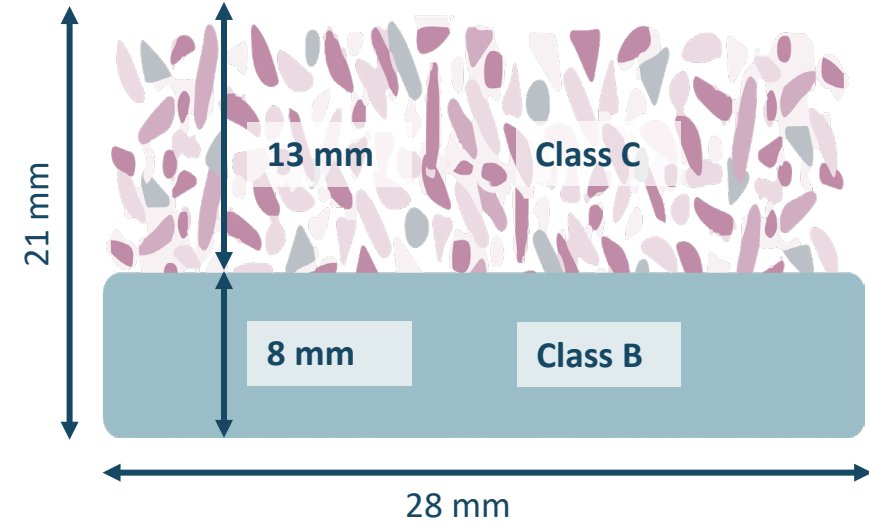
DESIGN CONCEPT

Fire Round 4: Experimental set-up for composite beams – What is the influence of the surface material ?



FLOAT GLASS

FRITTED GLASS





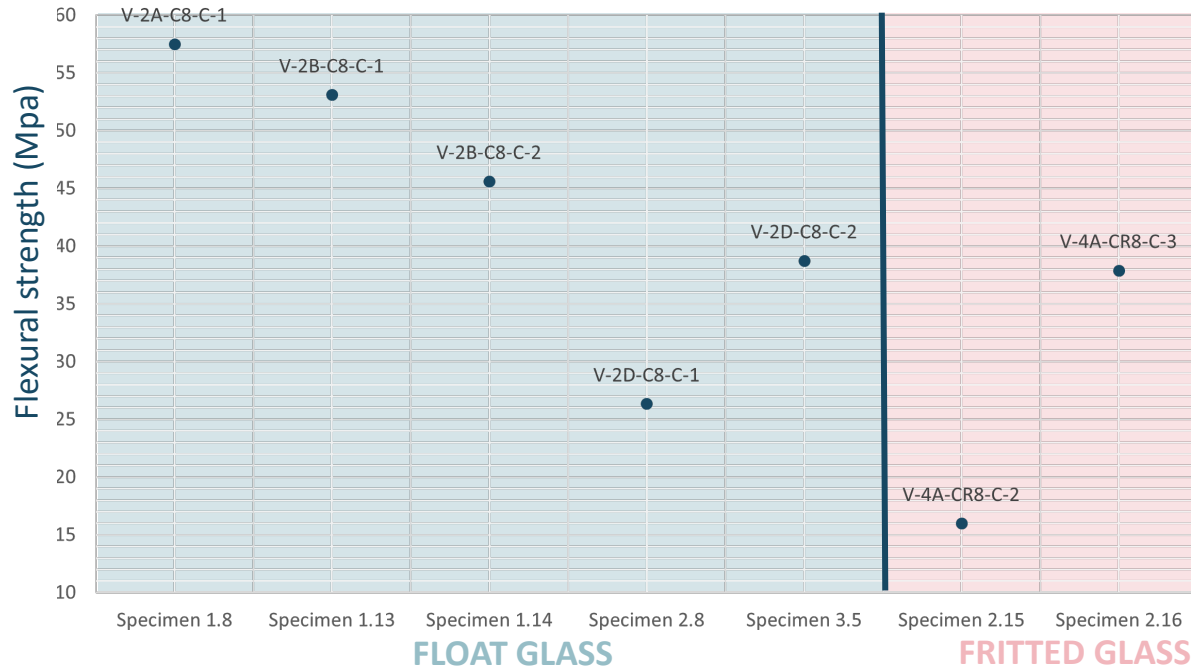
3 | MECHANICAL TESTS



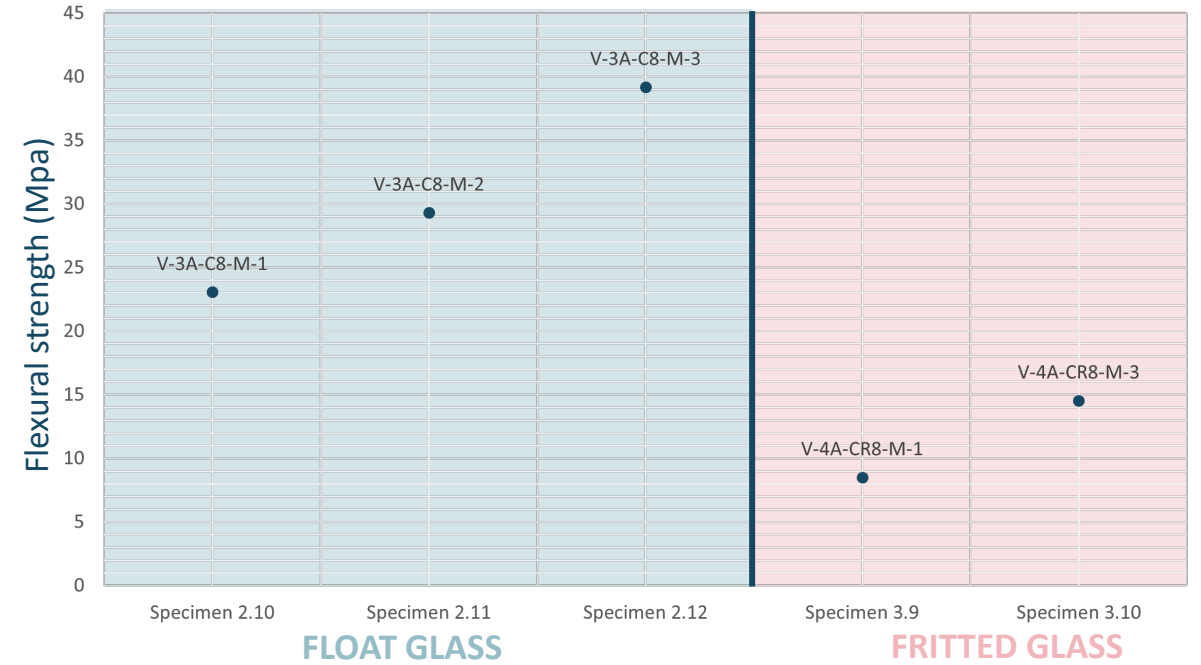
FOUR POINT BENDING TESTS

Composite beams – What is the influence of the surface material?

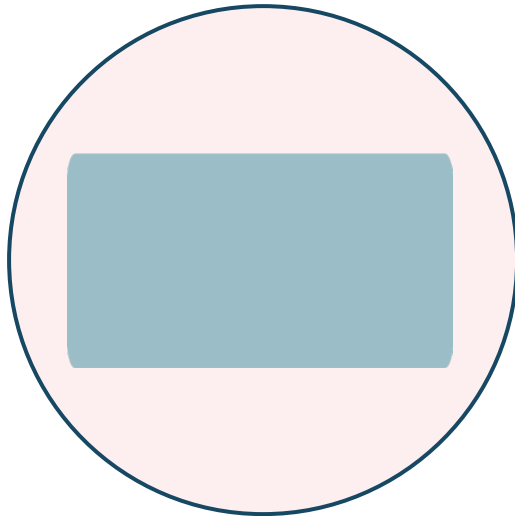
Flexural strength of Composite beams with CSP Pollutants in the bulk
Influence of surface material – Fritted Glass



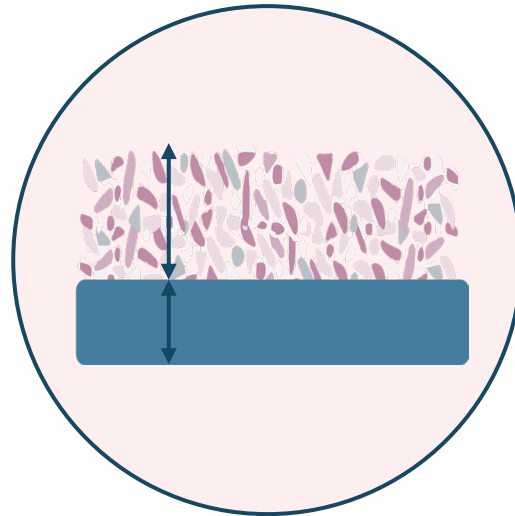
Flexural strength of Composite beams with Metallic Pollutants in the bulk
Influence of surface material – Fritted Glass



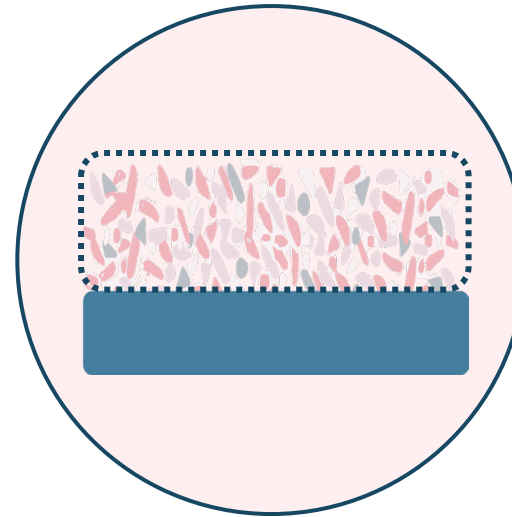
CONCLUSIONS



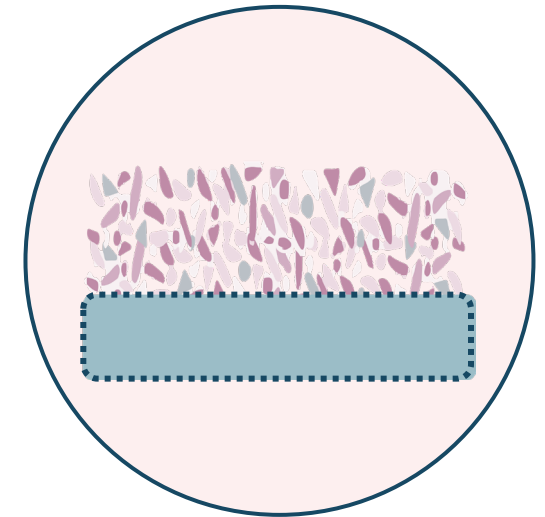
Experiment Type 1:
Homogeneous beams



Experiment Type 2:
Composite beams:
What is the influence of the **ratio**
between surface and bulk



Experiment Type 3:
Composite beams
What is the influence of the
bulk material

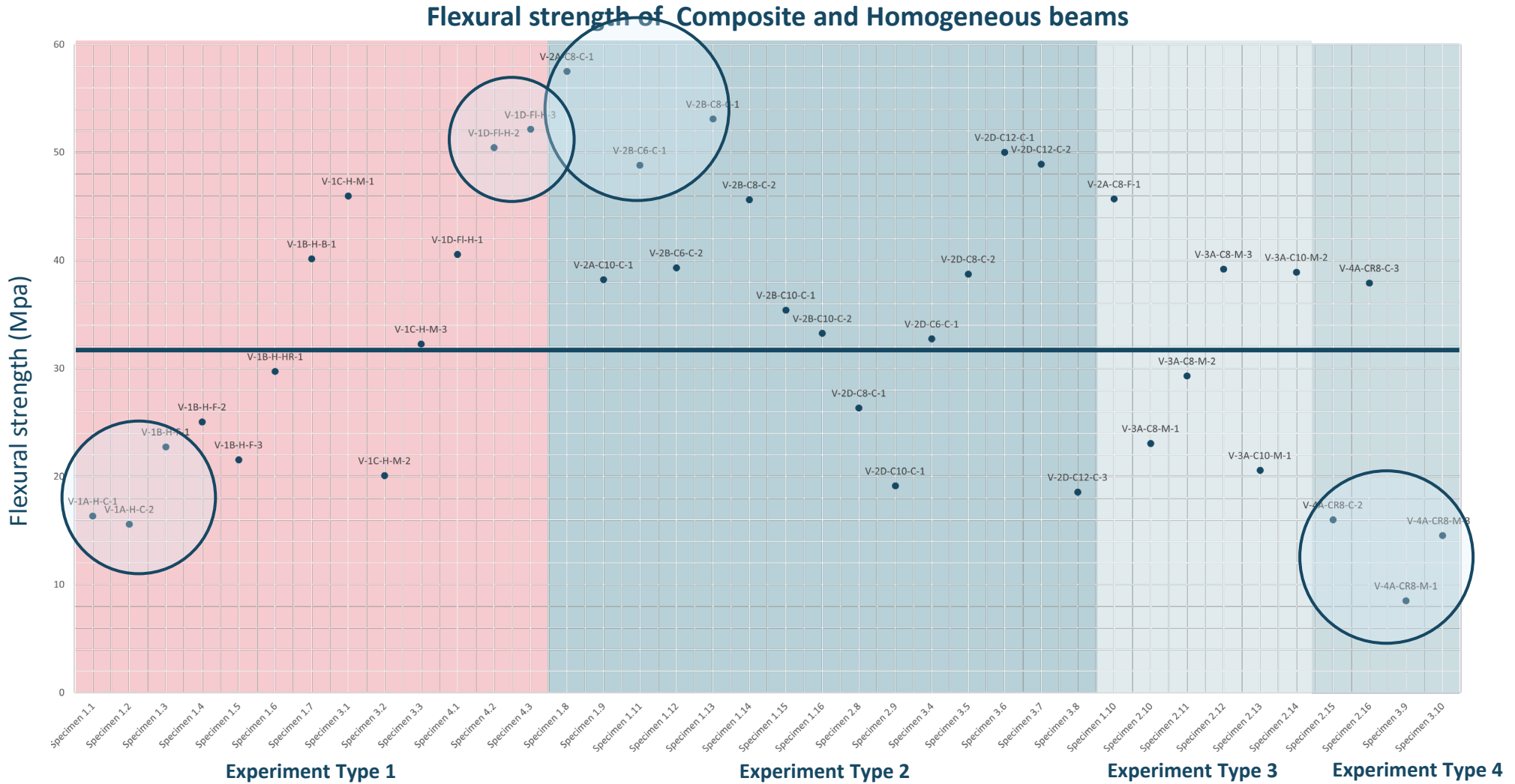


Experiment Type 4:
Composite beams
What is the influence of the
surface material



FOUR POINT BENDING TESTS

Conclusion

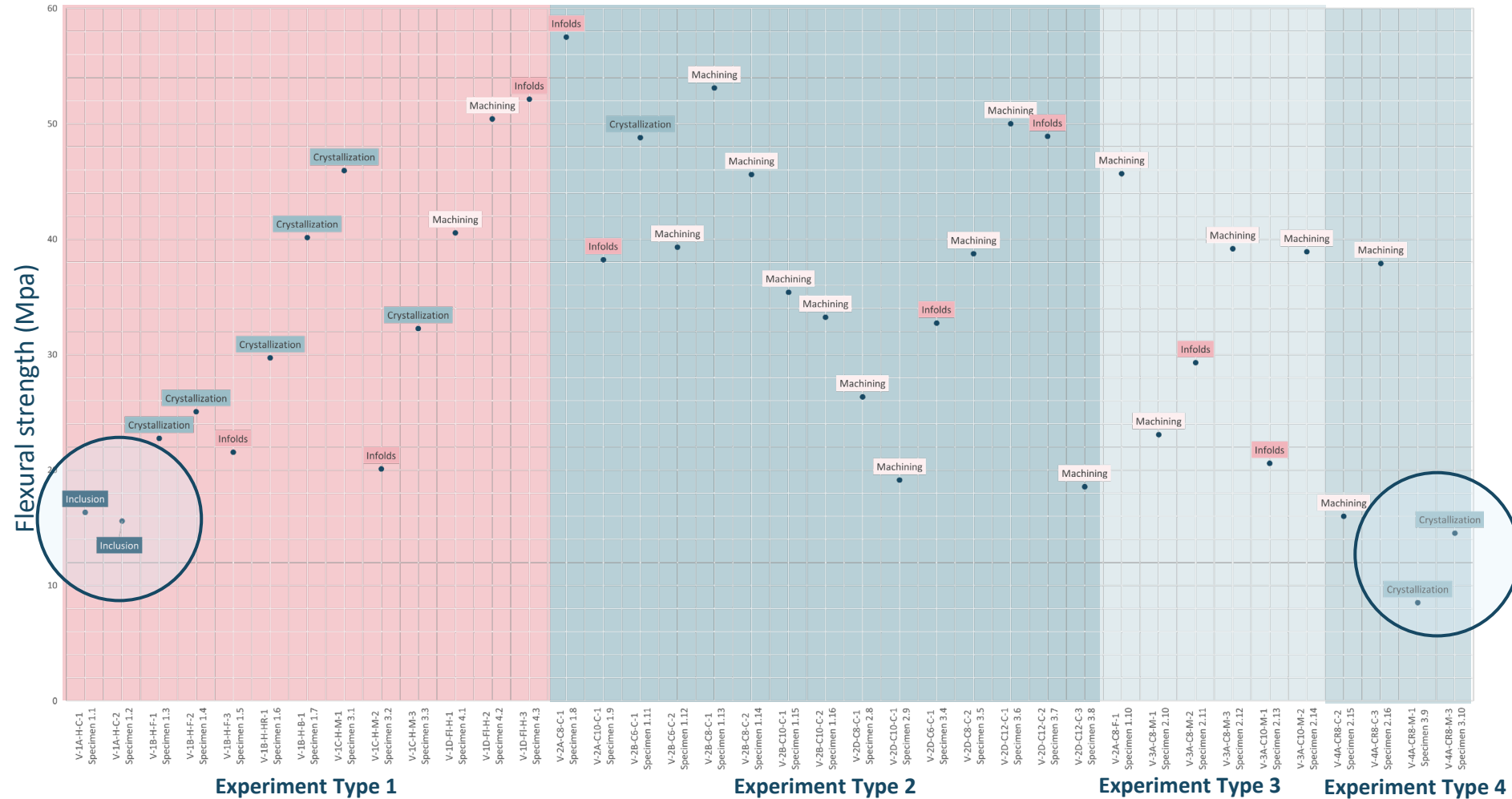




FLAW CATEGORIES

Conclusion

Flaws in Composite and Homogeneous beams



2 | EXPERIMENTAL METHODOLOGY

FOUR POINT BENDING TEST

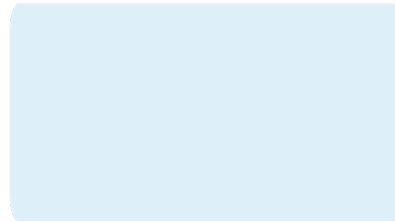
Conclusions

HOMOGENEOUS BEAMS



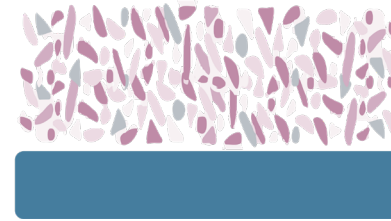
TYPE B CULLET

TYPE C CULLET

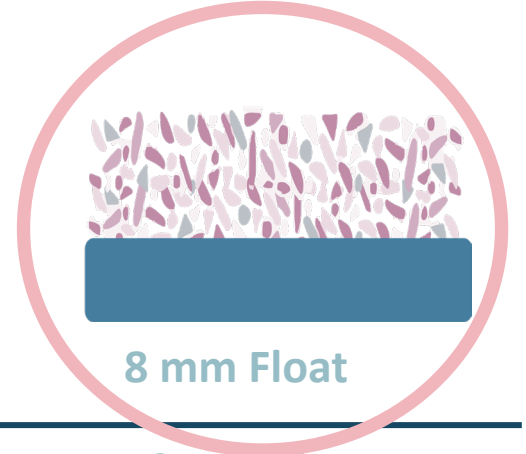


HOMOGENEOUS BEAMS

COMPOSITE BEAMS – RATIO SURFACE VS BULK



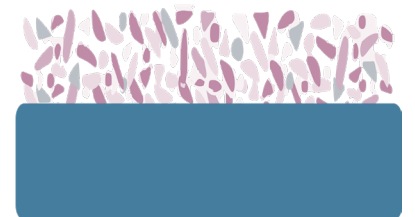
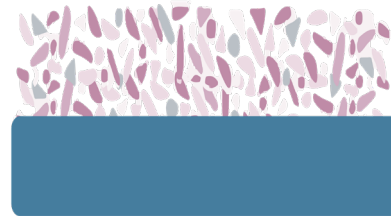
6 mm Float



8 mm Float

10 mm Float

12 mm Float

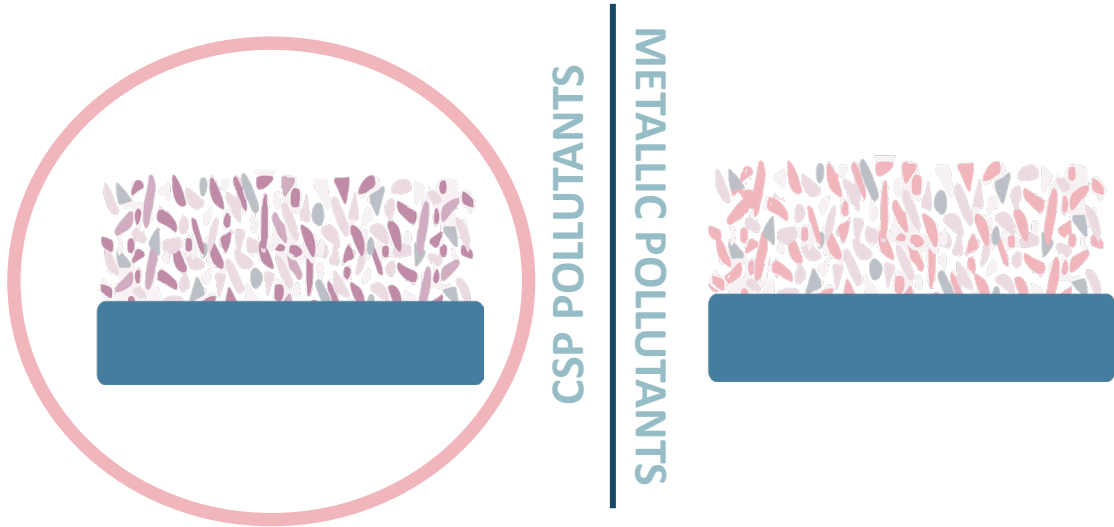


COMPOSITE BEAMS

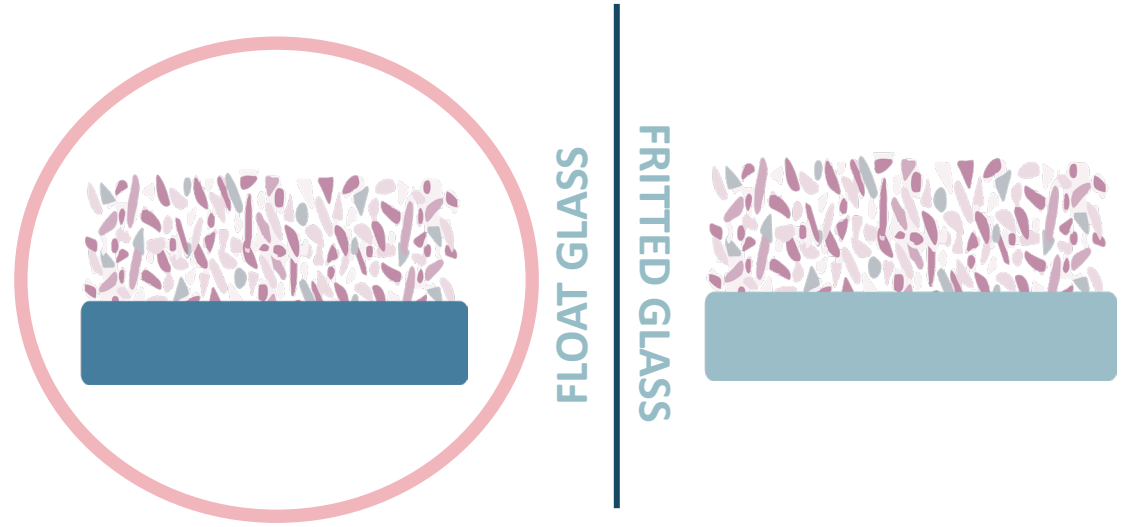
FOUR POINT BENDING TEST

Conclusions

COMPOSITE BEAMS – INFLUENCE BULK MATERIAL



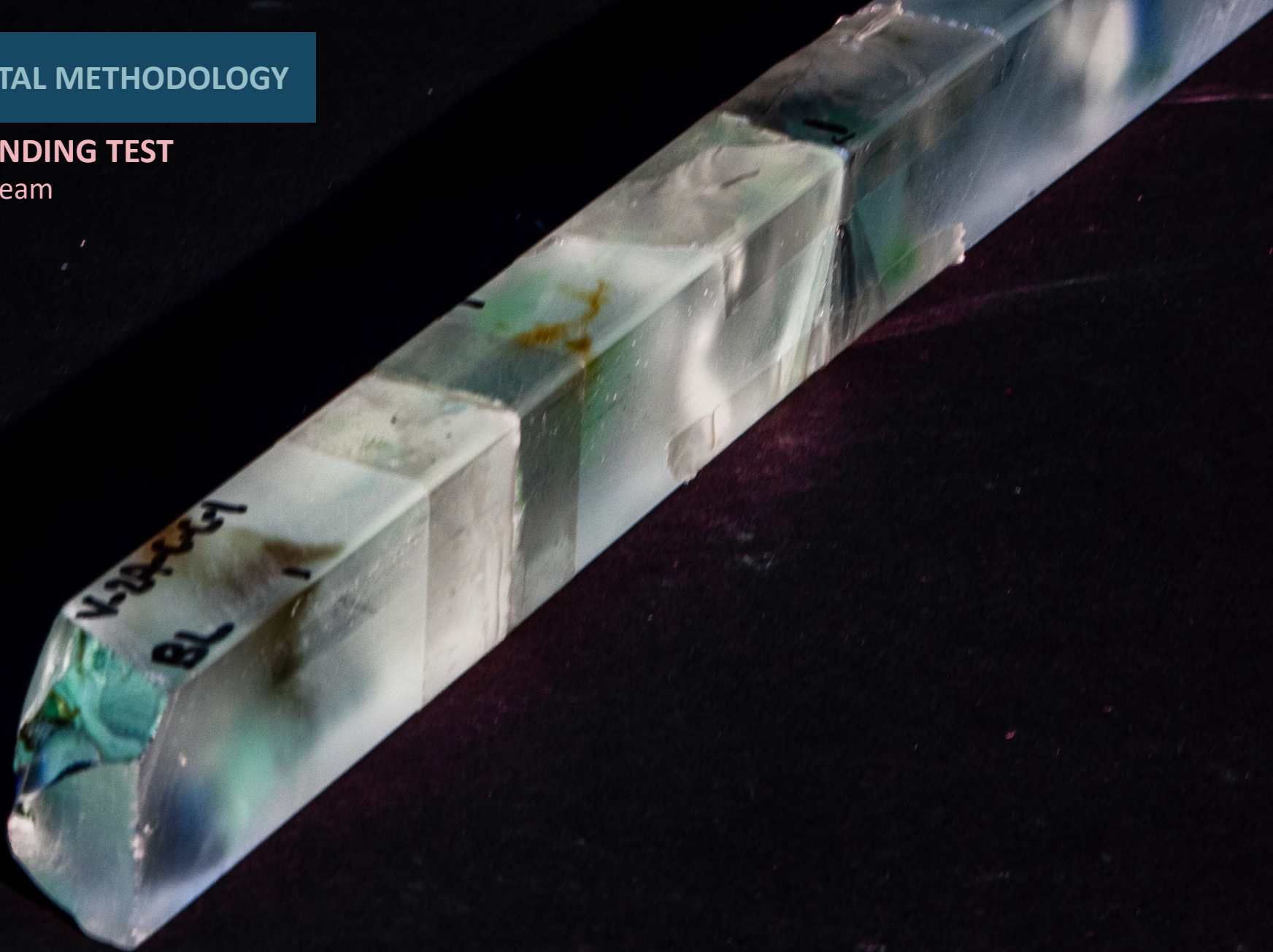
COMPOSITE BEAMS – INFLUENCE SURFACE MATERIAL



2 | EXPERIMENTAL METHODOLOGY

FOUR POINT BENDING TEST

Best performing beam





1 | INTRODUCTION TO THE RESEARCH

2 | EXPERIMENTAL METHODOLOGY

3 | DESIGN APPLICATION

4 | CONCLUSION

5 | RECOMMENDATION

6 | REFLECTION

A FACADE CLADDING APPLICATION

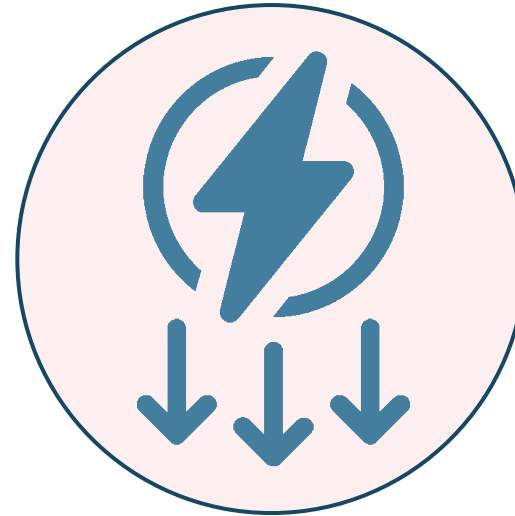
WHY



The current facade panels end up in the **landfill**



Reduction of the use of **raw materials**



Reduction of **energy consumption**



Turns **cullet** into new, useful building materials

3 | DESIGN APPLICATION

RECYCLED COMPOSITE CAST GLASS PANELS

How to integrate in buildings



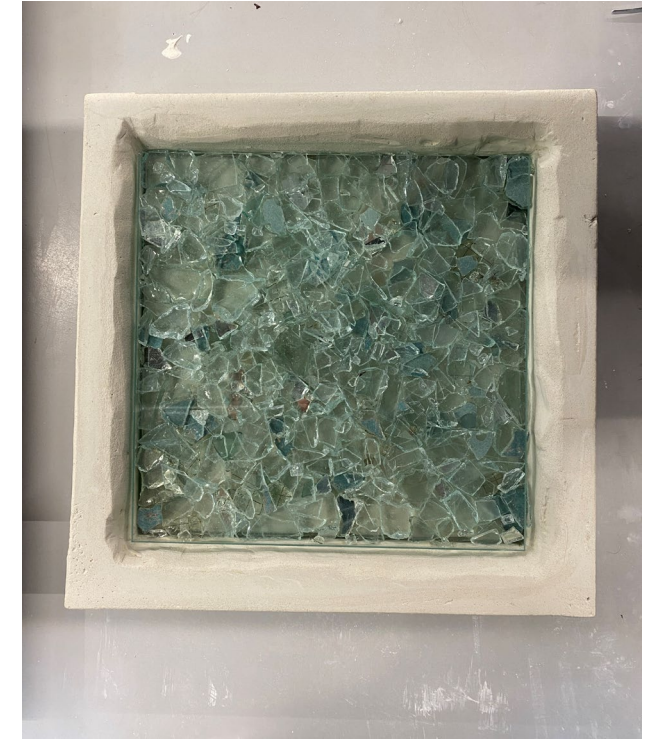
Step 1: Create a mould



Step 2: Place the surface



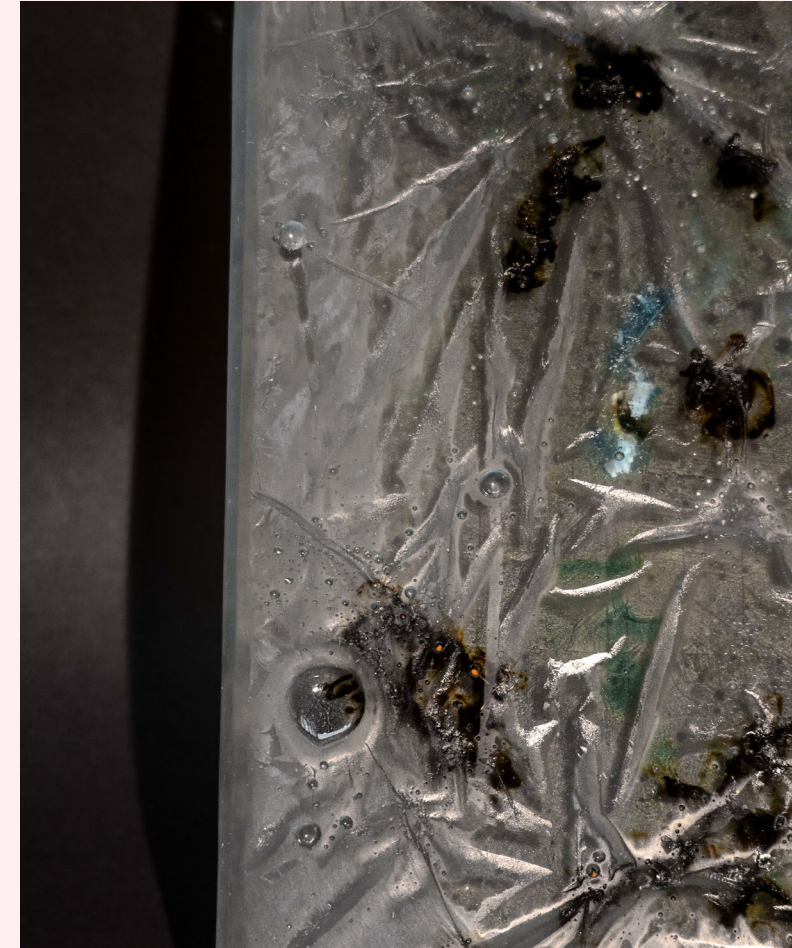
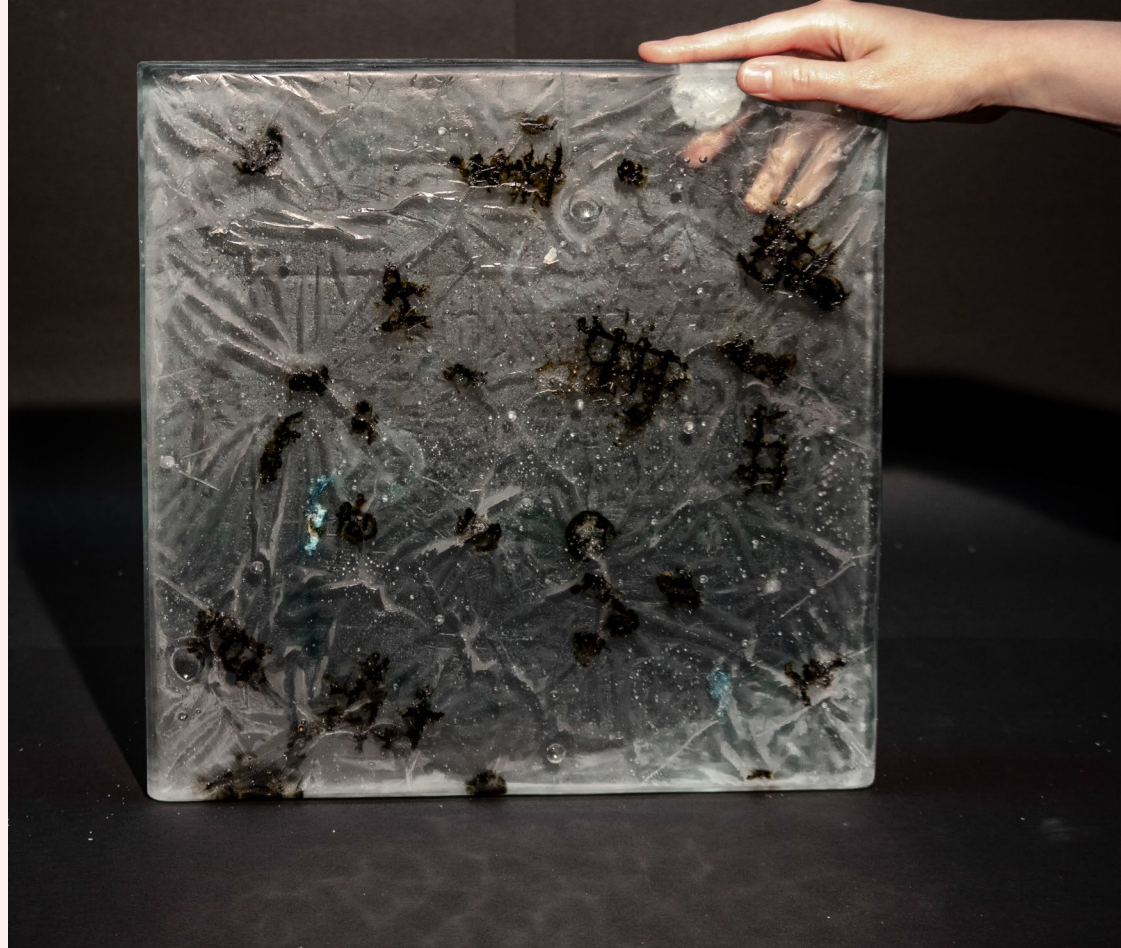
Step 3: Place the bulk



Step 4: Place the surface

3 | DESIGN APPLICATION

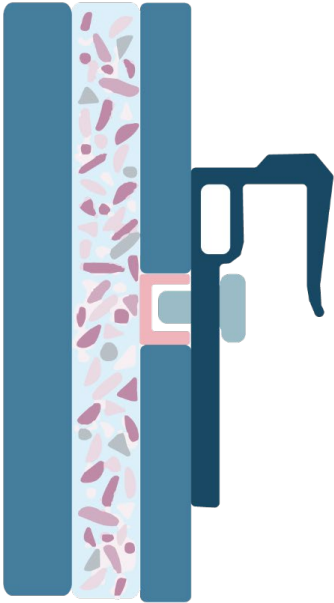
RECYCLED COMPOSITE CAST GLASS PANELS



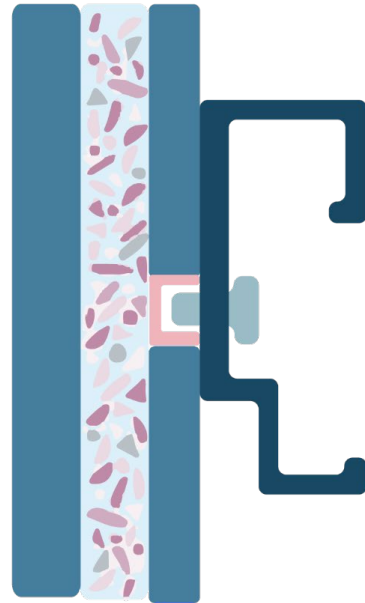
RECYCLED COMPOSITE CAST GLASS PANELS

Connections

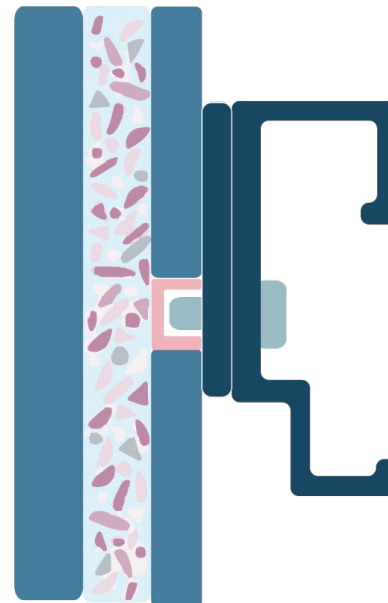
Straight insert



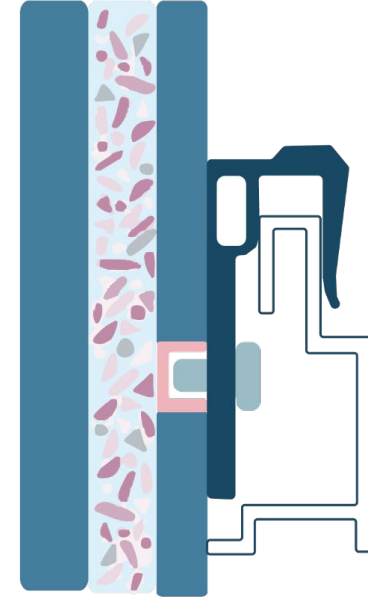
Thread cutting screw



Conical insert



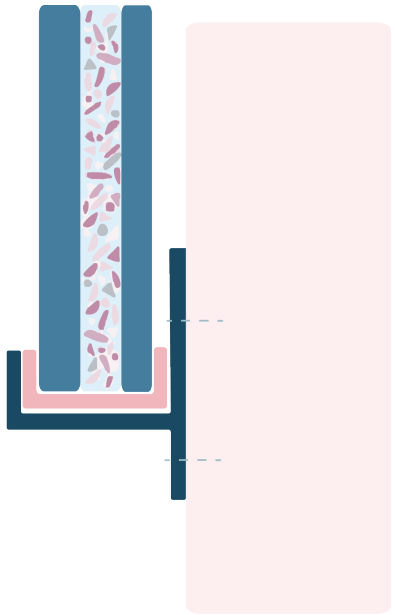
Rivet screw



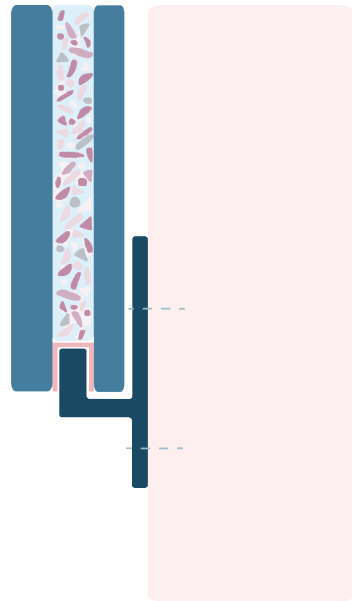
3 | DESIGN APPLICATION

RECYCLED COMPOSITE CAST GLASS PANELS

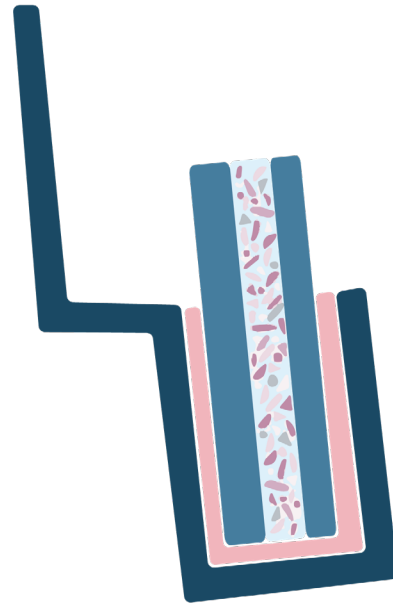
Connections



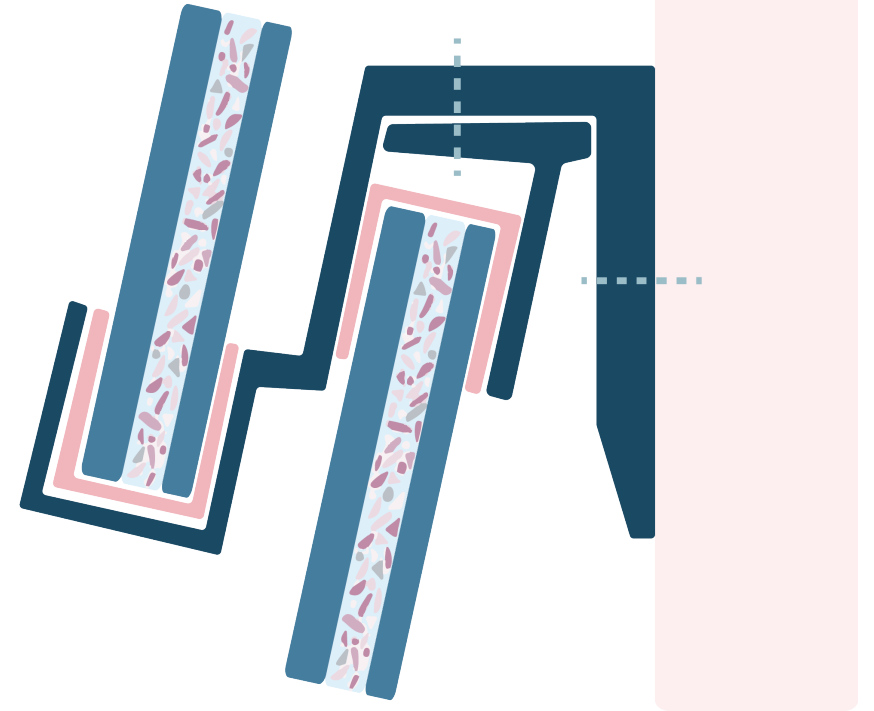
Clamp on the outer edge



Clamp in the bulk



Clamp on the outer edge



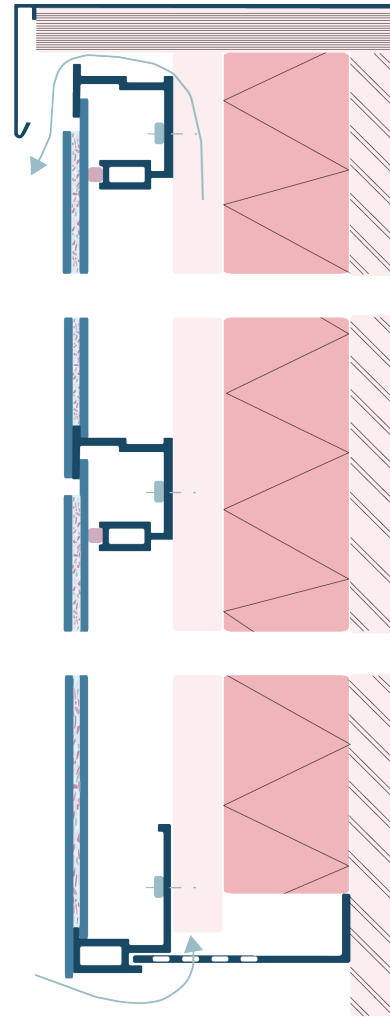
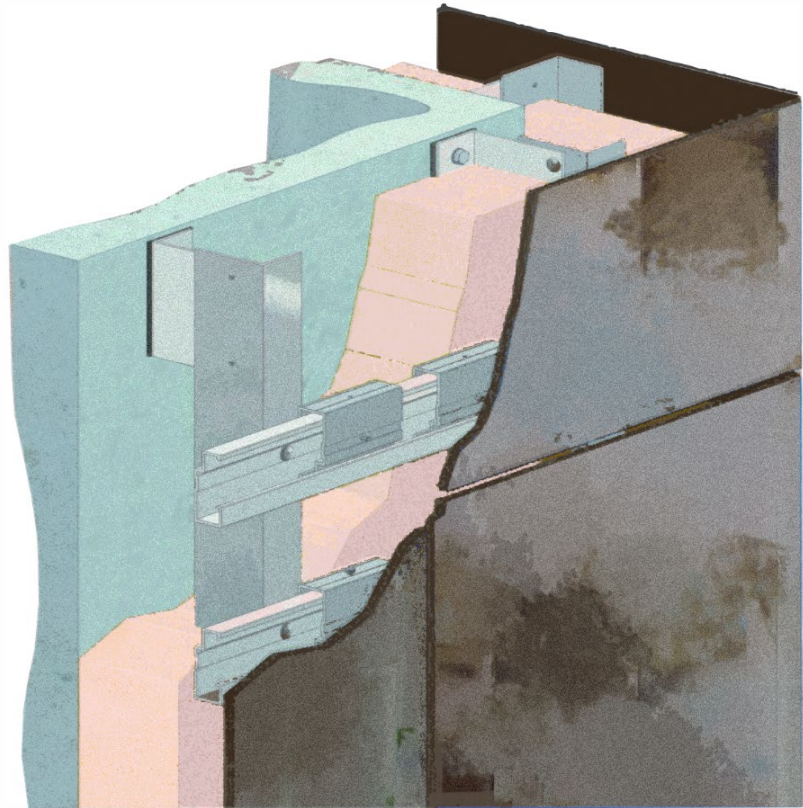
Clamp on the outer edge on an angle

3 | DESIGN APPLICATION

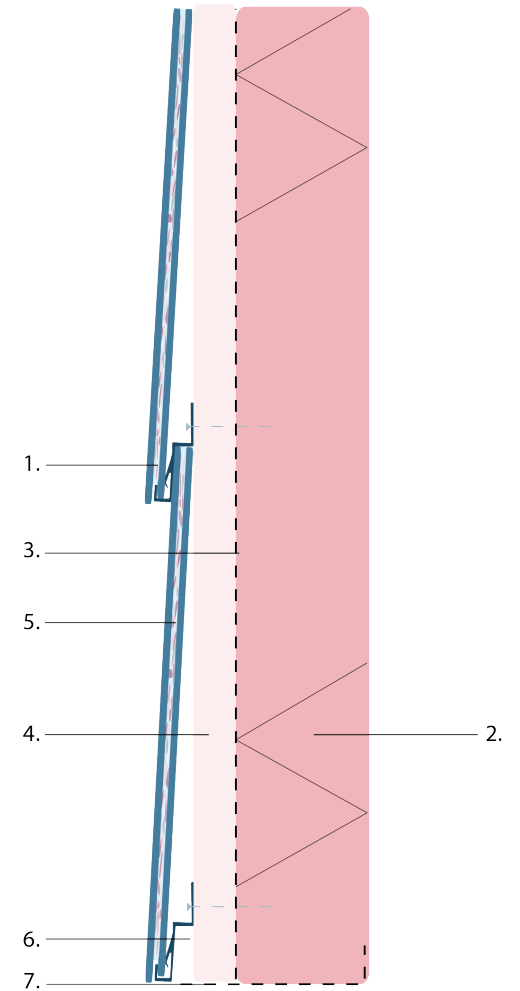
RE3 COMPOSITE CAST GLASS PANELS

Connections

3D Blind Connection



1. Stainless steel clamp screwed onto timber
2. Thermal insulation
3. Weather barrier (vapour permeable)
4. Ventilated cavity



5. Recycled Composite Cast Glass Panels
6. Adjustment block thickness 8 mm
7. Ventilation profile



1 | INTRODUCTION TO THE RESEARCH

2 | EXPERIMENTAL METHODOLOGY

3 | DESIGN APPLICATION

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5 | RECOMMENDATION

6 | REFLECTION

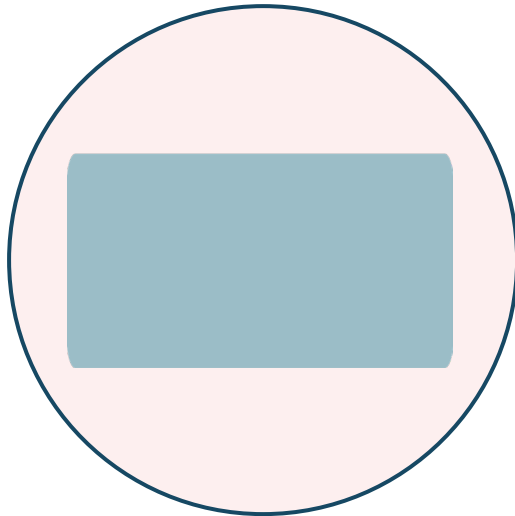
RECYCLED COMPOSITE CAST GLASS PANELS

Recap

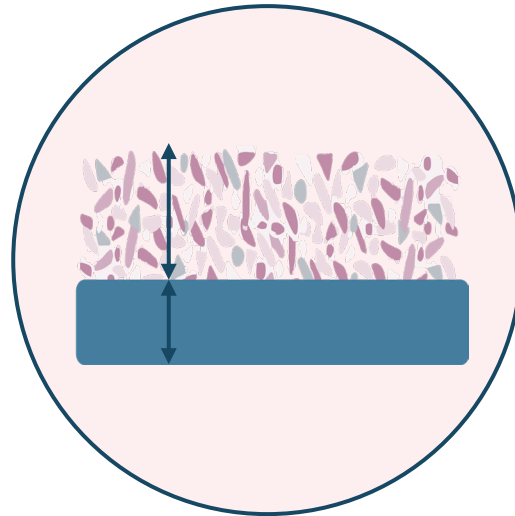
*“What is the effect of the different parameters in respect to the geometry and glass composition of **composite cast glass beams** to their overall structural performance made out of Construction and Demolition (**C&D**) (float) glass waste?”*

RECYCLED COMPOSITE CAST GLASS PANELS

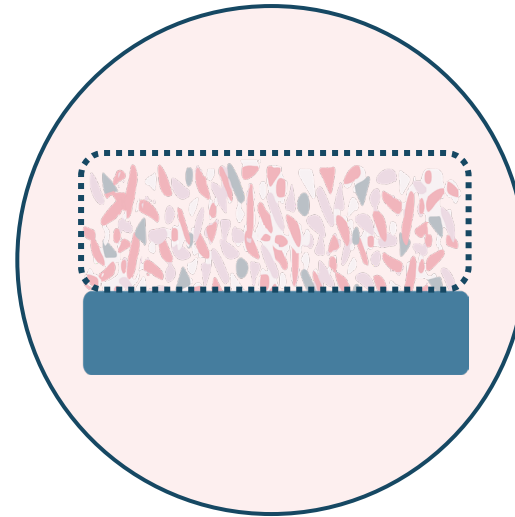
Recap



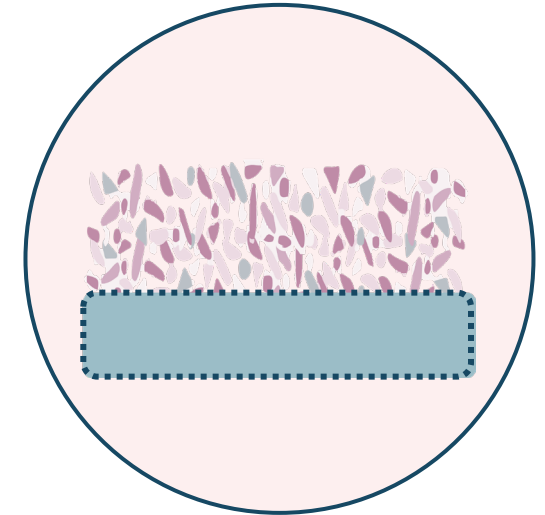
**Experiment Type 1:
Homogeneous beams**



**Experiment Type 2:
Composite beams:**
What is the influence of the **ratio**
between surface and bulk

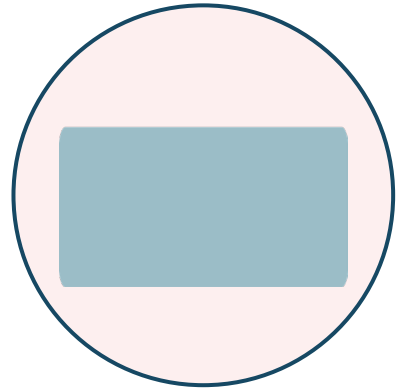


**Experiment Type 3:
Composite beams**
What is the influence of the
bulk material

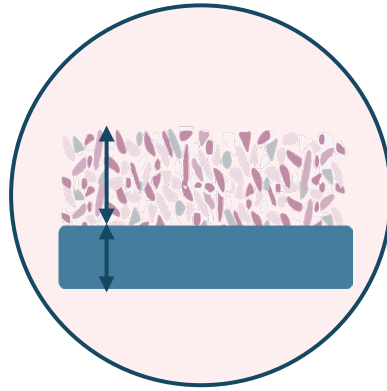


**Experiment Type 4:
Composite beams**
What is the influence of the
surface material

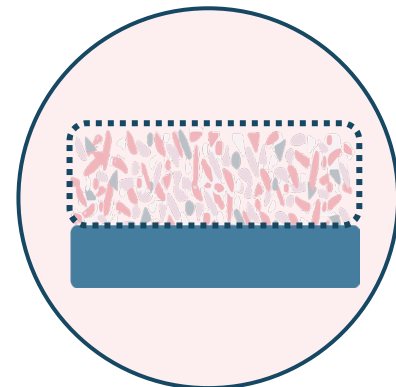
RECYCLED COMPOSITE CAST GLASS PANELS



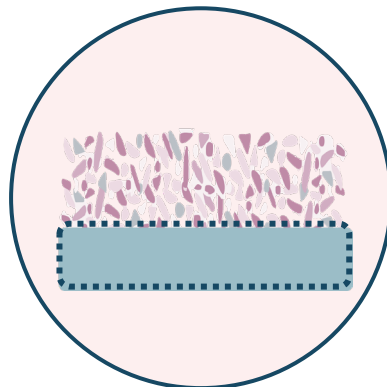
Fire Round 1:
Homogeneous beams



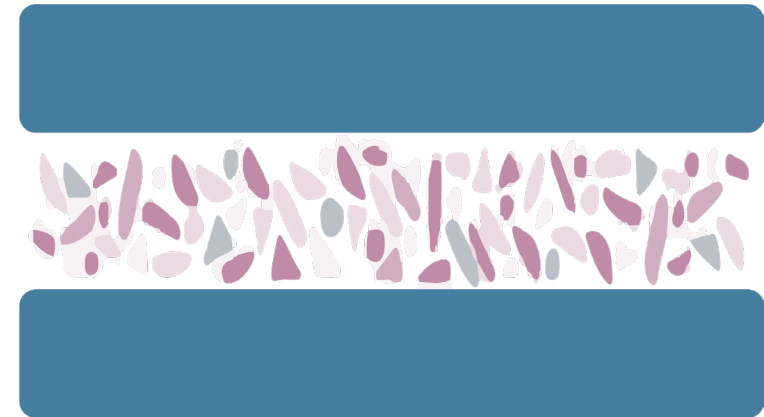
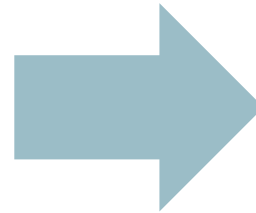
Fire Round 2:
Composite beams
Ratio 8 mm surface and 13 mm bulk



Fire Round 3:
Composite beams
CSP Pollutants in the bulk



Fire Round 4:
Composite beams
Float glass





1 | INTRODUCTION TO THE RESEARCH

2 | EXPERIMENTAL METHODOLOGY

3 | DESIGN APPLICATION

4 | CONCLUSION

5 | RECOMMENDATION

6 | REFLECTION

RECYCLED COMPOSITE CAST GLASS PANELS

How to continue



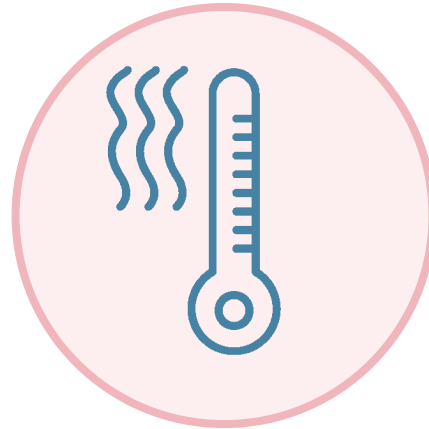
Literature review

- Optimise the recycling process



Shape

- Other beam lengths
- Tiles



Thermal shock

- Behaviour of cast glass
- Stress



Safety requirements

- Experimental tests



Design optimisation

- FEM Model
- Structural behaviour



1 | INTRODUCTION TO THE RESEARCH

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RECYCLED COMPOSITE CAST GLASS PANELS

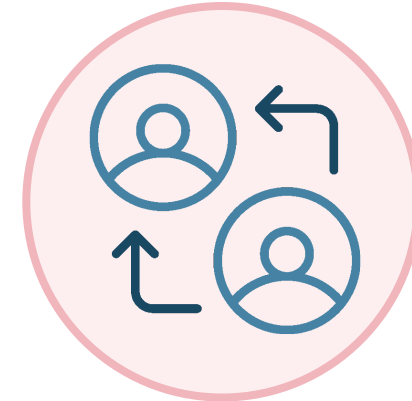
Thesis trajet



Academic value



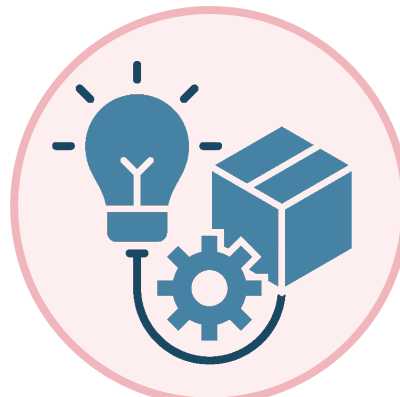
Societal value



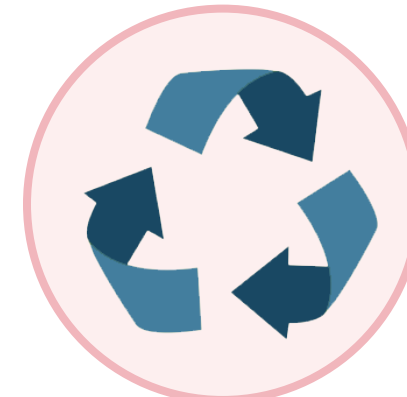
Value of transferability



Applicable in the built environment



Innovative research

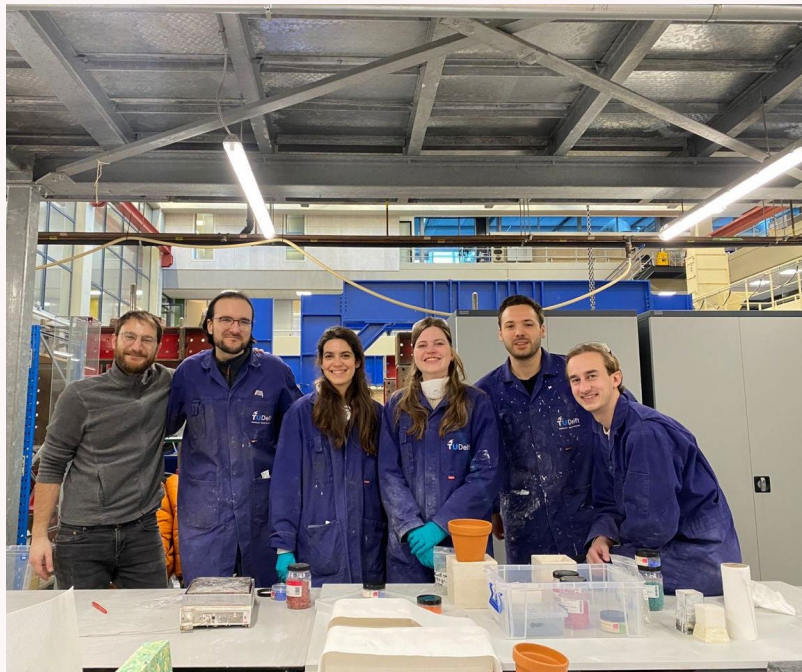


Circular economy



RECYCLED COMPOSITE CAST GLASS PANELS







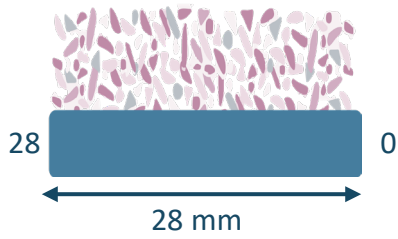
Thank You!

Are there any questions?

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FRACTURE ORIGINS
Results



Fracture origin location compared with flaw types

