PET foams – Characteristics and properties

MILAN, 15/05/2024

AGENDA

- *PET in techical detail*
- *PET in composite, design and use*
- *PET in production*

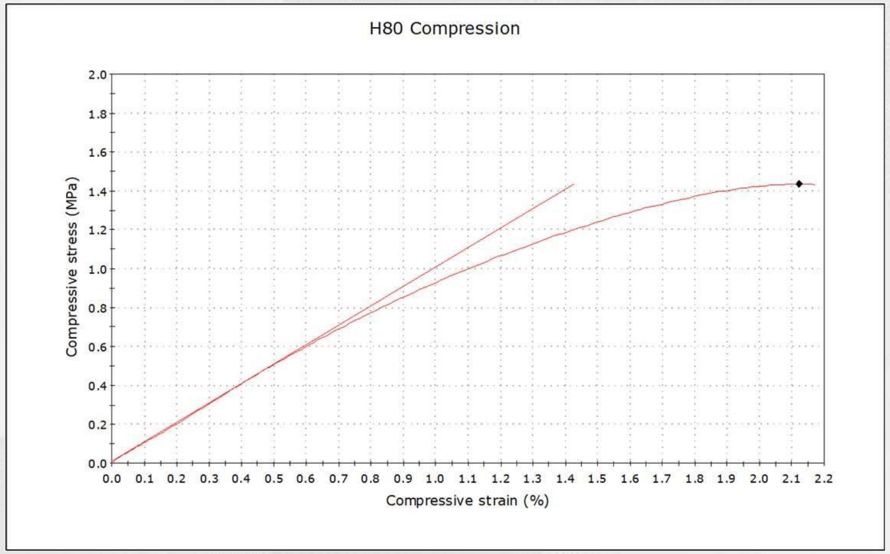
- *PET and PVC: basic differences*
- *PET foaming process*
- *PET recycling*
- *Development history of the PET product family and technical specifications*

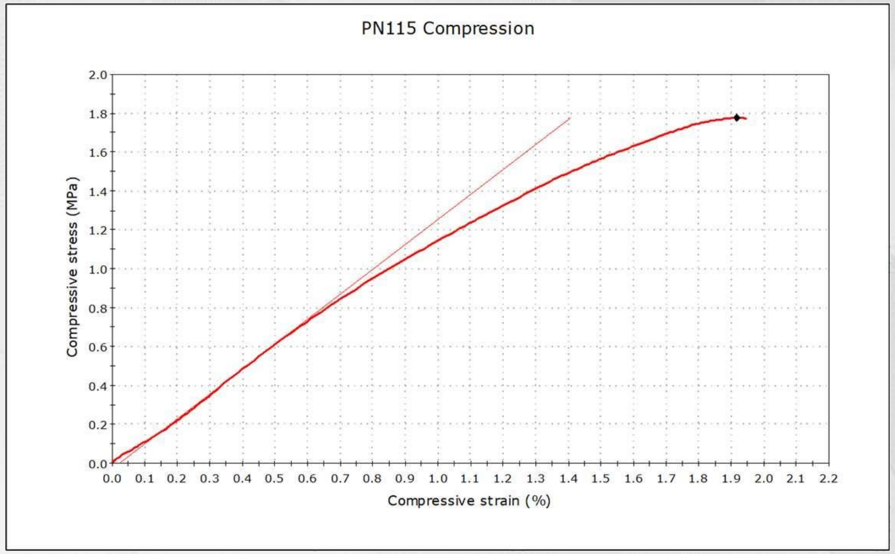
PET AND PVC: BASIC DIFFERENCES

- ***Expanded PVC*** *is a cross-linked polymer (IPN: Interpenetrated Polymer Network) with excellent mechanical performance compared to its density*
- *The production process of PVC foams is discontinuous,*
- *The raw materials and manufacturing process of PVC foams are expensive*
- *PET is a thermoplastic polymer that has found its main application in the plastic bottle market.*
- *PVC cannot be reworked*
- *PET can be reworked/thermoformed*
- *PET is heat sealable, PVC is not*

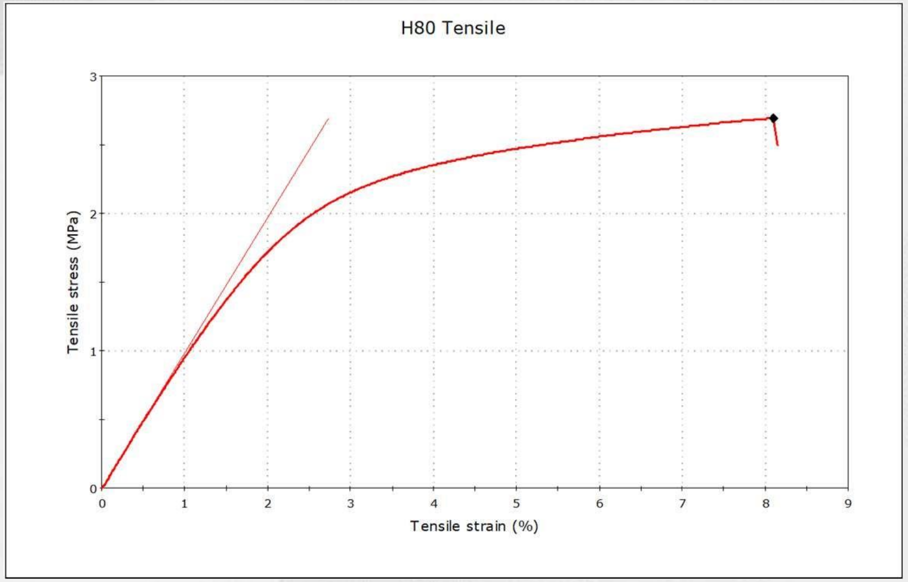
PET AND PVC: MECHANICAL COMPARISON

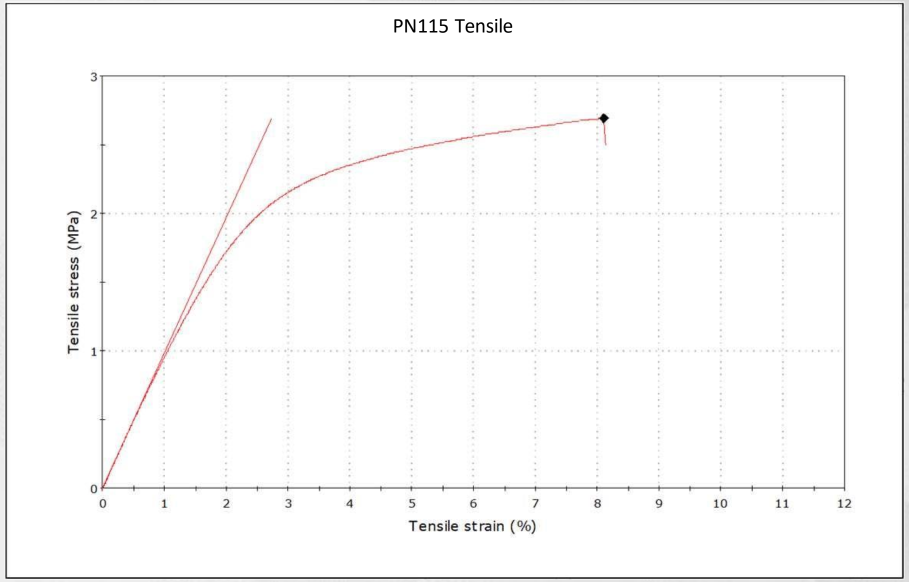
- *When tested at room temperature, PET exhibits inferior mechanical properties to PVC*
- *PET can achieve the mechanical properties of PVC with 15-20% higher density*



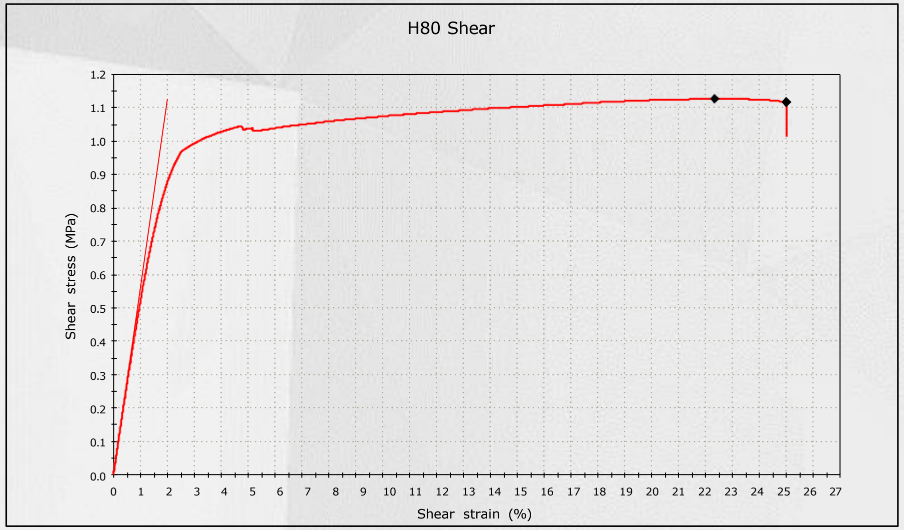


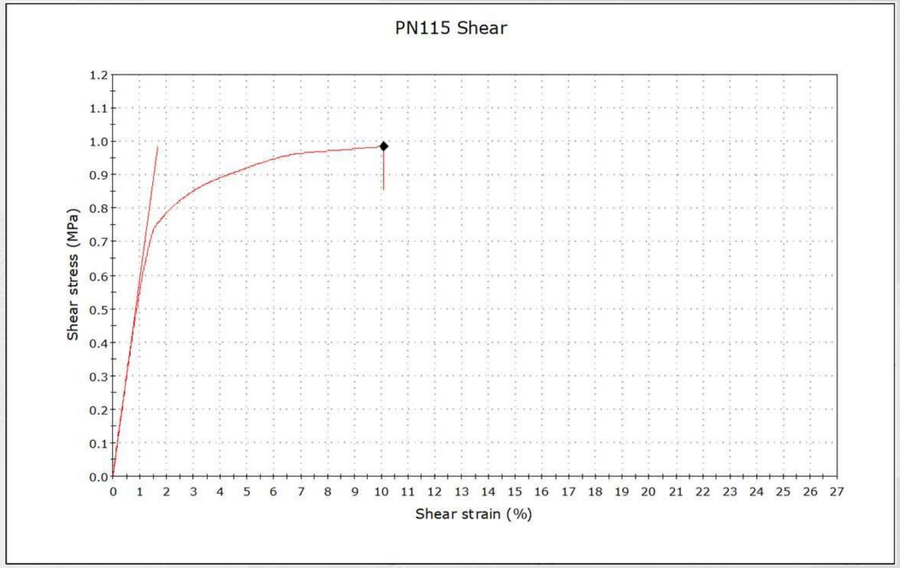
PET AND PVC: MECHANICAL COMPARISON





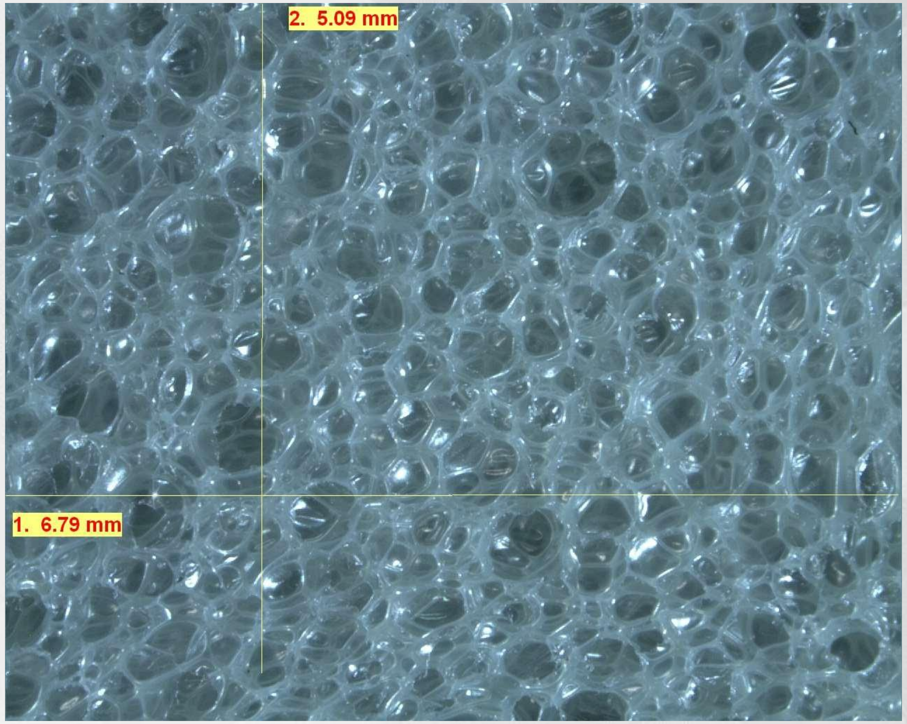
PET AND PVC: MECHANICAL COMPARISON





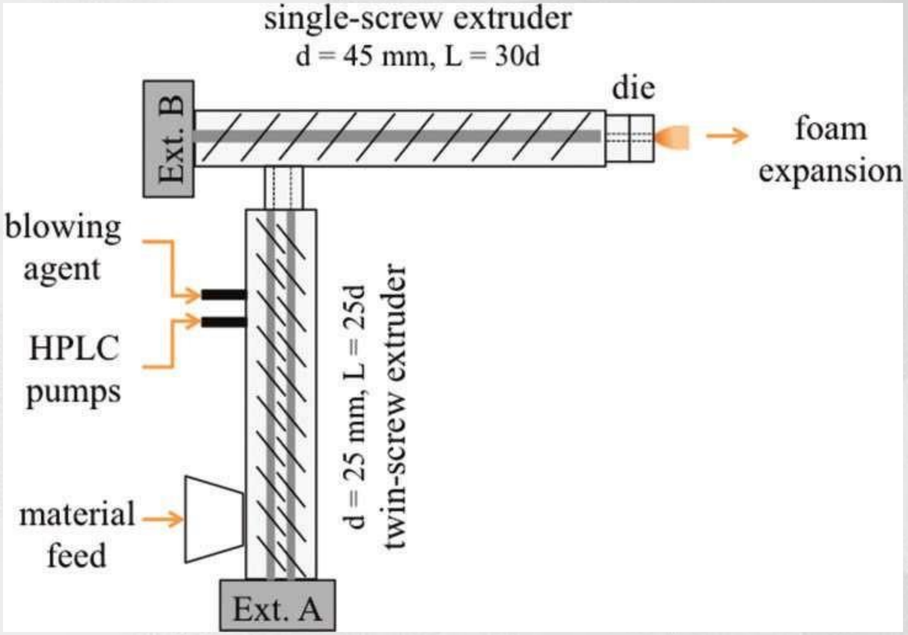
PET FOAMING

- *What does it take to produce PET?*
- *PET is a semi-crystalline material (approximately 30% crystalline – 70% amorphous)*
- *<u>The blowing of the bottles</u> is carried out at 110° between the glass transition temperatures (≈ 80°C) and melting (≈ 260°C). Under these conditions, PET softens enough to stretch but not break.*



PET FOAMING

- *Foaming can be more economical if extrusion, a continuous process, is used.*
- *Foaming is achieved by adding a physical expanding agent to PET, which expands when the melt comes out of the mold.*
- *If the molten, unmodified PET comes out of the extruder, its viscosity is too low: it softens too much and the cell walls give way under the pressure of the blowing agent, forming large holes (coalescence)*
- *A good dispersion of the liquid blowing agent together with some nucleating agents guarantee an adequate and uniform cell size*



PET RECYCLING

- *Thermoplastic polymers can be reprocessed*
- *Thermosetting Polymers cannot be reprocessed. When brought to high temperatures they degrade.*
- *The attention towards PET, rather than a discussion towards the mechanical properties (which are starting to be significant and comparable with old generation foams) is essentially due to the <<green brand>> of thermoplastic polymers*

PET RECYCLING

- *Two types of recycled PET are currently used in DIAB:*

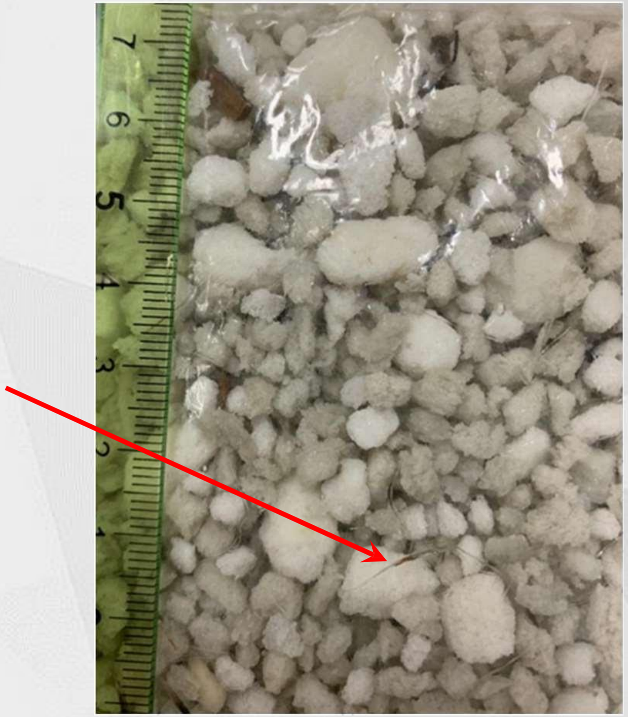
- The dust and waste produced during planing and cutting operations are reused as raw material. This is a high quality material for foaming as it is PET with very high molecular weight.

- The bottles collected by the consortia are ground and reduced into flakes (chips)

- *Recycled PET in DIAB PR products can make up more than 50% of the formulation*

PET RECYCLING

- *Wind blade manufacturers are showing increasing interest in recycling materials to further increase the sustainability of their products and processes. In collaboration with a wind blade manufacturer, a new type of recycled PET is being tested, obtained by shredding their post-industrial waste*
- *Due to contaminants, material obtained through a simple shredding process requires investment in extrusion melt filtration*
- *Innovative solutions for blade recycling are in development phase, like selective solvolysis od shredded wind blades or replacement of standard resins with thermoplastic or reversible ones*



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PET PRODUCT FAMILIES - DEVELOPMENT HISTORY

- *History of Diab PET foams product families*

P
1st generation of PET
- Train applications
- Focus: FST properties

PN
2nd generation of PET
- Wind and industry
- Focus: Costs

PY
3rd generation PET
- Wind Vestas
- Focus: - Peel requirements
  - SS requirements
  - RU requirements

PL
4th generation PET
- Wind All
- Focus: - Improved RU (-200g vs PY)
  - Costs

PR
4bth generation PET
- Post consumers (R-PET)
- Focus MIA: RU (-100g vs PN); cost
  Wind: RU, mechanical properties

P?
5th generation PET
- SM, cells size uniformity
- Improved machinability
- Surface

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TECHNICAL SPECIFICATIONS - 1

Property	Test Method	Unit	Value	P100	P150	PY105	[1]PY115	PY200	PY250	PL105	PN65	PN80	PN115	PN200	PN250
Compressive Strength (33 direction)	ASTM D 1621 ISO 844:2014	MPa	Nominal	1.5	2.3	1.5	TBD	3.4	4.4	1.5	0.7	1	1.7	3.8	4.8
			Minimum	1.1	2.0	1.4	1.65	3.2	4	1.4	0.55	0.8	1.35	3.2	4.3
Compressive Modulus (33 direction)	ASTM D 1621: 1973 B ISO 844:2014 -proc. B	MPa	Nominal	100	152	112	TBD	185	210	112	65	80	115	205	237
			Minimum	60	115	85	115	150	200	85	42	65	85	175	200
Tensile Strength (33 direction)	ASTM D 1623	MPa	Nominal	1.8	2.45	2.4	TBD	TBD	5.0	2.4	TBD	1.5	2.4	TBD	TBD
			Minimum	1.35	1.85	1.9	TBD	TBD	3.0	1.9	TBD	TBD	1.5	TBD	TBD
Tensile Modulus (33 direction)	ASTM D 1623	MPa	Nominal			110	TBD	TBD	230	110	TBD	95	130	TBD	TBD
			Minimum	65	110	90	TBD	TBD	200	90	TBD	TBD	100	TBD	TBD
Shear Strength ((13 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	0.85	1.25	0.95	TBD	1.95	2.5	0.95	0.45	0.6	0.95	1.7	2.3
			Minimum	0.69	0.95	0.8	TBD	1.65	2.0	0.8	0.35	0.5	0.8	1.4	1.7
Shear Modulus (Parallel to weld lines(13))	ISO 1922 or ASTM C 273	MPa	Nominal	28	40	25	TBD	57	70	25	12	20	31	60	78
			Minimum	22	36	23	28	50	68	23	10	15	23	53	68
Shear Strength (23 direction)	ISO 1922 or ASTM C 273	MPa	Nominal			0.85	TBD	1.75	2.2	0.85	TBD	TBD	TBD	1.7	2.3
			Minimum			0.75	TBD	1.50	1.8	0.8	TBD	TBD	TBD	1.4	1.7
Shear Modulus (Transverse to weld lines (23))	ISO 1922 or ASTM C 273	MPa	Nominal	28	40	23	TBD	50	60	23	TBD	TBD	TBD	55	68
			Minimum	22	36	19	25	45	56	19	TBD	TBD	TBD	49	65
Shear Strain (13 and 23 direction)	ISO 1922 or ASTM C 273	%	Nominal	12	7.5	30	TBD	15	15	30	20	15	12	6	5.3
			Minimum	3	3	15	10	5	5	15					
Open cell	ASTM D 1626	%	Maximum average			7	TBD	TBD	TBD						
			Maximum individual			10	TBD	TBD	TBD						
Density	ISO 845 ASTM D 1622	kg/m³	Nominal	110	150	105	TBD	200	250	105	65	80	115	205	250
			Maximum	117	158	115	120	210	255	115	75	85	120	215	265
			Minimum	103	142	100	115	190	240	100	60	75	110	195	235

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TECHNICAL SPECIFICATIONS - 2

- *New PR80 and PR100 preliminary* technical data*

Property	Test Method	Unit	Value	P100	PY105	[1]PY115	PL105	PN80	PN115	PR80	PR100	H80	HP80
Compressive Strength (33 direction)	ASTM D 1621 ISO 844:2014	MPa	Nominal	1.5	1.5	TBD	1.5	1	1.7	1	1,45	1,4	1,5
			Minimum	1.1	1.4	1.65	1.4	0.8	1.35	0,8	1,25	1,15	1,2
Compressive Modulus (33 direction)	ASTM D 1621: 1973 B ISO 844:2014 -proc. B	MPa	Nominal	100	112	TBD	112	80	115	100	140	90	105
			Minimum	60	85	115	85	65	85	80	115	80	90
Tensile Strength (33 direction)	ASTM D 1623	MPa	Nominal	1.8	2.4	TBD	2.4	1.5	2.4	2,3	2,8	2,5	2,8
			Minimum	1.35	1.9	TBD	1.9	TBD	1.5	1,6	2,1	2,2	2,2
Tensile Modulus (33 direction)	ASTM D 1623	MPa	Nominal		110	TBD	110	95	130	95	125	95	100
			Minimum	65	90	TBD	90	TBD	100	60	95	85	80
Shear Strength ((13 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	0.85	0.95	TBD	0.95	0.6	0.95	0,6	0,9	1,15	1,25
			Minimum	0.69	0.8	TBD	0.8	0.5	0.8	0,5	0,75	0,95	1,0
Shear Modulus (Parallel to weld lines(13))	ISO 1922 or ASTM C 273	MPa	Nominal	28	25	TBD	25	20	31	20	26	27	28
			Minimum	22	23	28	23	15	23	15	22	23	22
Shear Strength (23 direction)	ISO 1922 or ASTM C 273	MPa	Nominal		0.85	TBD	0.85	TBD	TBD	-	-	-	-
			Minimum		0.75	TBD	0.8	TBD	TBD	-	-	-	-
Shear Modulus (Transverse to weld lines (23))	ISO 1922 or ASTM C 273	MPa	Nominal	28	23	TBD	23	TBD	TBD	-	-	-	-
			Minimum	22	19	25	19	TBD	TBD	-	-	-	-
Shear Strain (13 and 23 direction)	ISO 1922 or ASTM C 273	%	Nominal	12	30	TBD	30	15	12	15	30	30	38
			Minimum	3	15	10	15			-	-	15	25
Open cell	ASTM D 1626	%	Maximum average		7	TBD				-	-	-	-
			Maximum individual		10	TBD				-	-	-	-
Density	ISO 845 ASTM D 1622	kg/m³	Nominal	110	105	TBD	105	80	115	80	100	80	80
			Maximum	117	115	120	115	85	120	85	105	87	92
			Minimum	103	100	115	100	75	110	75	95	67	72
			RU (g/m2)=					700-750		600-650	500-550		

* DNV approval pending

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TECHNICAL SPECIFICATIONS - 3

- *Preliminary technical sheet of the new PR150, PR210*

Property	Test Method	Unit	Value	PY200	PY250	PN200	PN250	PR150[1]	PR200[1]	PL230[1]	H130	H200
Compressive Strength (33 direction)	ASTM D 1621 ISO 844:2014	MPa	Nominal	3.4	4.4	3.8	4.8	2,5	3,8	4,5	3,0	5,4
			Minimum	3.2	4	3.2	4.3	2,2	3,2	4,1	2,4	4,5
Compressive Modulus (33 direction)	ASTM D 1621: 1973 B ISO 844:2014 -proc. B	MPa	Nominal	185	210	205	237	165	230	246	170	310
			Minimum	150	200	175	200	130	190	214	145	265
Tensile Strength (33 direction)	ASTM D 1623	MPa	Nominal	TBD	5.0	TBD	TBD				4,8	7,1
			Minimum	TBD	3.0	TBD	TBD				3,5	6,3
Tensile Modulus (33 direction)	ASTM D 1623	MPa	Nominal	TBD	230	TBD	TBD				175	250
			Minimum	TBD	200	TBD	TBD				135	210
Shear Strength ((13 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	1.95	2.5	1.7	2.3	1,45	2,3	2,6	2,2	3,5
			Minimum	1.65	2.0	1.4	1.7	1,25	2,0	2,3	1,9	3,2
Shear Modulus (Parallel to weld lines(13))	ISO 1922 or ASTM C 273	MPa	Nominal	57	70	60	78	42	65	76	50	73
			Minimum	50	68	53	68	37	50	69	40	65
Shear Strength (23 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	1.75	2.2	1.7	2.3	1,35	2,15	2,5	-	-
			Minimum	1.50	1.8	1.4	1.7	1,25	1,8	2,2	-	-
Shear Modulus (Transverse to weld lines (23))	ISO 1922 or ASTM C 273	MPa	Nominal	50	60	55	68	36	55	66	-	-
			Minimum	45	56	49	65	32	47	58	-	-
Shear Strain (13 and 23 direction)	ISO 1922 or ASTM C 273	%	Nominal	15	15	6	5.3	15	15	15	40	45
			Minimum	5	5						30	35
Open cell	ASTM D 1626	%	Maximum average	TBD	TBD						-	-
			Maximum individual	TBD	TBD						-	-
Density	ISO 845 ASTM D 1622	kg/m³	Nominal	200	250	205	250	150	210	230	130	200
			Maximum	210	255	215	265	155	220	240	149	230
			Minimum	190	240	195	235	145	195	220	117	180

** DNV approval pending for PR150 and PR210*

CONCLUSIONS FIRST PART

- *PET is sustainable as it is a thermoplastic polymer that can be recycled*
- *Its use combined with thermoplastic resins can make the product completely recyclable*
- *The mechanical properties of PET require a greater density or thickness to match the properties of PVC. However, its anisotropy imparts higher mechanical properties in the preferred direction*
- *PET is easily weldable, it can be thermoformed unlike other foams*

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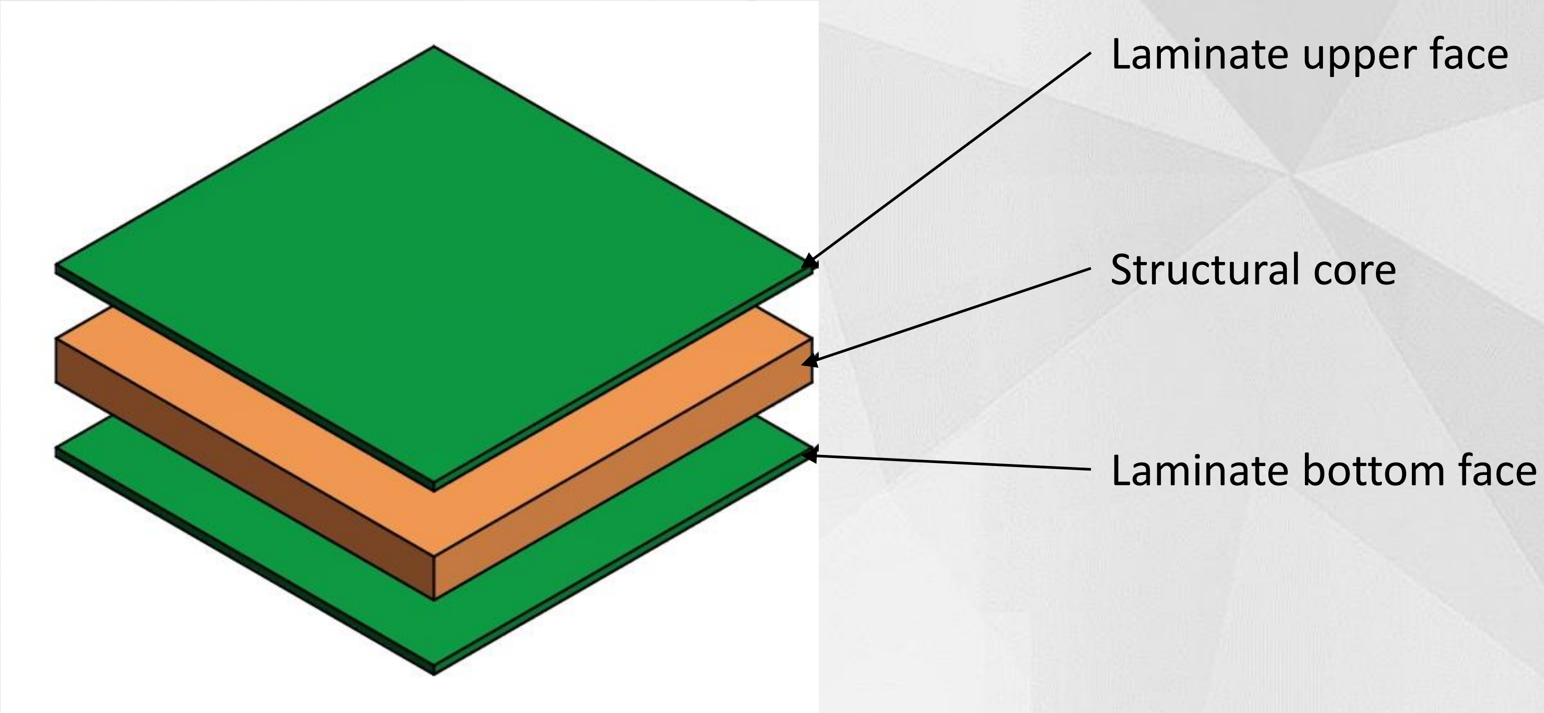
PET in Sandwich Design



REAL CASES OF PROJECTS MADE WITH COMPOSITE SANDWICHES

Aeronautical

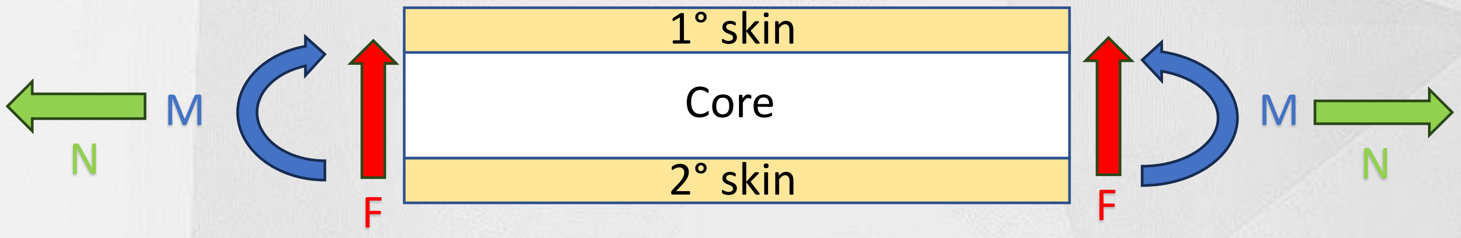
Naval

Automotive

Project Hypothesis

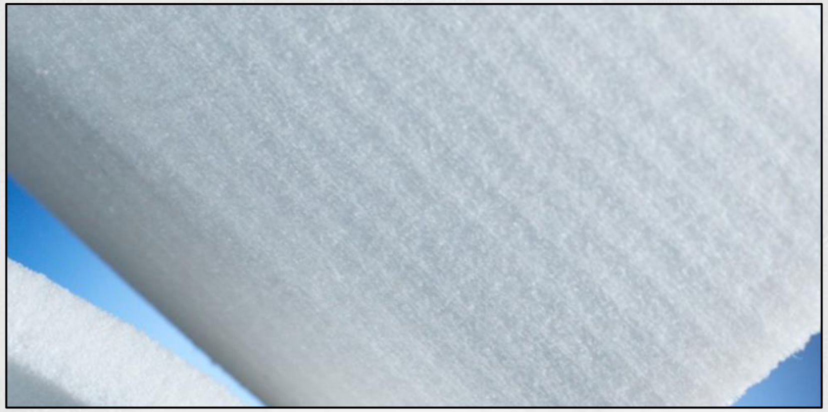
In a sandwich panel loaded as in the figure below:

- *The bending moment M and the normal force N do not produce stresses in the web*
- *The cutting force T is discharged on the core, giving rise to uniformly distributed shear stresses*



PET

Divinycell PET can be processed by most common manufacturing methods, including closed molding such as RTM and infusion, and high-temperature processing with prepregs.



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Comparison PVC H80-PET PR80

MECHANICAL PROPERTIES DIVINYCELL® H

Property	Test Procedure	Unit		H45	H60	H80	H100	H130	H160	H200	H250
Compressive Strength[1]	ASTM D 1621	MPa	Nominal	0.6	0.9	1.4	2.0	3.0	3.4	5.4	7.2
			Minimum	0.5	0.7	1.15	1.65	2.4	2.8	4.5	6.1
Compressive Modulus[1]	ASTM D1621-B-73	MPa	Nominal	50	70	90	135	170	200	310	400
			Minimum	45	60	80	115	145	175	265	350
Tensile Strength[1]	ASTM D 1623	MPa	Nominal	1.4	1.8	2.5	3.5	4.8	5.4	7.1	9.2
			Minimum	1.1	1.5	2.2	2.5	3.5	4.0	6.3	8.0
Tensile Modulus[1]	ASTM D 1623	MPa	Nominal	55	75	95	130	175	205	250	320
			Minimum	45	57	85	105	135	160	210	260
Shear Strength	ASTM C 273	MPa	Nominal	0.56	0.76	1.15	1.6	2.2	2.6	3.5	4.5
			Minimum	0.46	0.63	0.95	1.4	1.9	2.2	3.2	3.9
Shear Modulus	ASTM C 273	MPa	Nominal	15	20	27	35	50	60	73	97
			Minimum	12	16	23	28	40	50	65	81
Shear Strain	ASTM C 273	%	Nominal	12	20	30	40	40	40	45	45
Density	ISO 845	kg/m³	Nominal	48	60	80	100	130	160	200	250

MECHANICAL PROPERTIES DIVINYCELL® PR

Property	Test Procedure[1]	Unit		PR80	PR100
Compressive Strength[2]	ASTM D 1621	MPa	Nominal	1	1.45
			Minimum	0.8	1.25
Compressive Modulus[2]	ASTM D1621	MPa	Nominal	100	112
			Minimum	80	85
Shear Strength[3]	ISO 1922	MPa	Nominal	0.6	0.8
			Minimum	0.5	0.7
Shear Modulus[3]	ISO 1922	MPa	Nominal	20	25
			Minimum	15	22
Shear Strain[2]	ISO 1922	%	Nominal	15	15
Density	ISO 845	kg/m³	Nominal	80	100
			Maximum	85	105
			Minimum	75	95

Cutting characteristics comparison (nominal values)
PVC H80 vs PET PR80

Shear modulus PVC H80 = 1.35x*Shear modulus PR80*

Comparison PVC H80-PET PR80

Change in CORE thickness with the same Shear Stiffness

Let's consider equalizing the shear stiffness (GA) of two sandwiches, one with PVC H80 and the other with PET PR80 with the same length of the sandwich and thickness of the skins, in this way we evaluate the increase in thickness of the PET core for have the same rigidity:

$$GA = L * Gc * tc$$

L=sandwich length [mm]

Gc= core shear modulus[N/mm2]

tc= core thickness(ta) + half sum of skins thickness(t) [mm]

$$L * Gc1 * (ta1 + t) = L * Gc2 * (ta2 + t)$$

Simplifying the terms and solving in ta2

$$ta2 = \left(\frac{Gc1}{Gc2} - 1\right) * t + \frac{Gc1}{Gc2} * ta1$$

With a thickness of 5mm of skins and 20mm of core respectively, using the modules of PVC H80 and PET PR 80, we obtain:

ta2=28.75 mm (to obtain equivalence in terms of shear stiffness)

THE PET SANDWICH, DENSITY 80, REQUIRES A DELTA THICKNESS OF 9 MM (OVER 20 MM) COMPARED TO A SIMILAR PVC SANDWICH THIS DELTA THICKNESS TRANSLATES INTO A DELTA WEIGHT OF 720 GRAMS/SQM UNFAVORABLE OF PET FOAM

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Comparison PVC H130-PET PR150

MECHANICAL PROPERTIES DIVINYCELL® H

Property	Test Procedure	Unit		H45	H60	H80	H100	H130	H160	H200	H250
Compressive Strength[1]	ASTM D 1621	MPa	Nominal	0.6	0.9	1.4	2.0	3.0	3.4	5.4	7.2
			Minimum	0.5	0.7	1.15	1.65	2.4	2.8	4.5	6.1
Compressive Modulus[1]	ASTM D1621-B-73	MPa	Nominal	50	70	90	135	170	200	310	400
			Minimum	45	60	80	115	145	175	265	350
Tensile Strength[1]	ASTM D 1623	MPa	Nominal	1.4	1.8	2.5	3.5	4.8	5.4	7.1	9.2
			Minimum	1.1	1.5	2.2	2.5	3.5	4.0	6.3	8.0
Tensile Modulus[1]	ASTM D 1623	MPa	Nominal	55	75	95	130	175	205	250	320
			Minimum	45	57	85	105	135	160	210	260
Shear Strength	ASTM C 273	MPa	Nominal	0.56	0.76	1.15	1.6	2.2	2.6	3.5	4.5
			Minimum	0.46	0.63	0.95	1.4	1.9	2.2	3.2	3.9
Shear Modulus	ASTM C 273	MPa	Nominal	15	20	27	35	50	60	73	97
			Minimum	12	16	23	28	40	50	65	81
Shear Strain	ASTM C 273	%	Nominal	12	20	30	40	40	40	45	45
Density	ISO 845	kg/m³	Nominal	48	60	80	100	130	160	200	250

Property	Test Method	Unit	Value	PR150	PR200	PR250
Compressive Strength (33 direction)	ASTM D 1621 ISO 844:2014	MPa	Nominal	2.5	3.8	5.0
			Minimum	2.2	3.2	4.3
Compressive Modulus (33 direction)	ASTM D 1621: 1973 B ISO 844:2014 -proc. B	MPa	Nominal	165	230	280
			Minimum	130	190	220
Shear Strength (13 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	1.45	2.3	2.85
			Minimum	1.25	2.0	2.25
Shear Modulus (13 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	42	65	87
			Minimum	37	50	65
Shear Strength (23 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	1.35	2.15	2.6
			Minimum	1.25	1.8	2.2
Shear Modulus (23 direction))	ISO 1922 or ASTM C 273	MPa	Nominal	36	55	75
			Minimum	32	47	60
Shear Strain (13 and 23 direction)	ISO 1922 or ASTM C 273	%	Nominal	15	15	15

Cutting characteristics comparison (nominal values)
PVC H130 vs PET PR150
Shear modulus PVC H130 = 1.19xShear modulus PR150

Comparison PVC H130-PET PR150

Change in CORE thickness with the same Shear Stiffness

Let's consider equalizing the shear stiffness (GA) of two sandwiches, one with PVC H130 and the other with PET PR150 with the same length of the sandwich and thickness of the skins, in this way we evaluate the increase in thickness of the PET core for have the same rigidity:

$$GA = L * Gc * tc$$

L=sandwich length [mm]

Gc= core shear modulus[N/mm2]

tc= core thickness(ta) + half sum of skins thickness(t) [mm]

$$L * Gc1 * (ta1 + t) = L * Gc2 * (ta2 + t)$$

Simplifying the terms and solving in ta2

$$ta2 = \left(\frac{Gc1}{Gc2} - 1\right) * t + \frac{Gc1}{Gc2} * ta1$$

With a thickness of 5mm of skins and 20mm of core respectively, using the modules of PVC H130 and PET PR 150, we obtain:

ta2=24.75 mm (to obtain equivalence in terms of shear stiffness)

THE SANDWICH WITH PET DENSITY 150, COMPARED TO A PVC SANDWICH DENSITY 130 REQUIRES A DELTA THICKNESS OF 5 MM (OVER 20 MM) THIS DELTA THICKNESS TRANSLATES INTO A DELTA WEIGHT OF 1100 GRAMS/SQM UNFAVORABLE OF PET FOAM

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Comparison PVC H200-PET PR200

MECHANICAL PROPERTIES DIVINYCELL® H

Property	Test Procedure	Unit		H45	H60	H80	H100	H130	H160	H200	H250
Compressive Strength[1]	ASTM D 1621	MPa	Nominal	0.6	0.9	1.4	2.0	3.0	3.4	5.4	7.2
			Minimum	0.5	0.7	1.15	1.65	2.4	2.8	4.5	6.1
Compressive Modulus[1]	ASTM D1621-B-73	MPa	Nominal	50	70	90	135	170	200	310	400
			Minimum	45	60	80	115	145	175	265	350
Tensile Strength[1]	ASTM D 1623	MPa	Nominal	1.4	1.8	2.5	3.5	4.8	5.4	7.1	9.2
			Minimum	1.1	1.5	2.2	2.5	3.5	4.0	6.3	8.0
Tensile Modulus[1]	ASTM D 1623	MPa	Nominal	55	75	95	130	175	205	250	320
			Minimum	45	57	85	105	135	160	210	260
Shear Strength	ASTM C 273	MPa	Nominal	0.56	0.76	1.15	1.6	2.2	2.6	3.5	4.5
			Minimum	0.46	0.63	0.95	1.4	1.9	2.2	3.2	3.9
Shear Modulus	ASTM C 273	MPa	Nominal	15	20	27	35	50	60	73	97
			Minimum	12	16	23	28	40	50	65	81
Shear Strain	ASTM C 273	%	Nominal	12	20	30	40	40	40	45	45
Density	ISO 845	kg/m³	Nominal	48	60	80	100	130	160	200	250

Property	Test Method	Unit	Value	PR150	PR200	PR250
Compressive Strength (33 direction)	ASTM D 1621 ISO 844:2014	MPa	Nominal	2.5	3.8	5.0
			Minimum	2.2	3.2	4.3
Compressive Modulus (33 direction)	ASTM D 1621: 1973 B ISO 844:2014 -proc. B	MPa	Nominal	165	230	280
			Minimum	130	190	220
Shear Strength (13 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	1.45	2.3	2.85
			Minimum	1.25	2.0	2.25
Shear Modulus (13 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	42	65	87
			Minimum	37	50	65
Shear Strength (23 direction)	ISO 1922 or ASTM C 273	MPa	Nominal	1.35	2.15	2.6
			Minimum	1.25	1.8	2.2
Shear Modulus (23 direction))	ISO 1922 or ASTM C 273	MPa	Nominal	36	55	75
			Minimum	32	47	60
Shear Strain (13 and 23 direction)	ISO 1922 or ASTM C 273	%	Nominal	15	15	15

Cutting characteristics comparison (nominal values)
PVC H200 vs PET PR200
Shear modulus PVC H200 = 1.12xShear modulus PR200

Comparison PVC H200-PET PR200

Change in CORE thickness with the same Shear Stiffness

Let's consider equalizing the shear stiffness (GA) of two sandwiches, one with PVC H200 and the other with PET PR200 with the same length of the sandwich and thickness of the skins, in this way we evaluate the increase in thickness of the PET core for have the same rigidity:

$$GA = L * Gc * tc$$

L=sandwich length [mm]

Gc= core shear modulus[N/mm2]

tc= core thickness(ta) + half sum of skins thickness(t) [mm]

$$L * Gc1 * (ta1 + t) = L * Gc2 * (ta2 + t)$$

Simplifying the terms and solving in ta2

$$ta2 = \left(\frac{Gc1}{Gc2} - 1\right) * t + \frac{Gc1}{Gc2} * ta1$$

With a thickness of 5mm of skins and 20mm of core respectively, using the modules of PVC H200 and PET PR 200, we obtain:

ta2=23 mm (to obtain equivalence in terms of shear stiffness)

THE SANDWICH WITH PET DENSITY 200, COMPARED TO A SIMILAR PVC SANDWICH REQUIRES A DELTA THICKNESS OF 3 MM (OVER 20 MM)
THIS DELTA THICKNESS TRANSLATES INTO A DELTA WEIGHT OF 600 GRAMS/SQM UNFAVORABLE OF PET FOAM

Calculation of shear stiffness (GA) of Sandwich panels 1000 (mm) x 1000 (mm) xh (mm)

Below we compare the cutting characteristics for the different cores with the same panel geometry and the same thickness of the skins

Rigidità a taglio pannello sandwich								
Core	*Core Thickness [mm]*	*Density [kg/mc]*	*Shear Modulus [Mpa]*	*Skins Thickness[mm]*	*Shear Stiffness of the sandwich[N]*	*Shear Stiffness of the sandwich/Shear Stiffness of the sandwich PUR 35*	*Core weight panel[Kg]*	*Shear Stiffness of the sandwich/Panel weight[N/Kg]*
H80	*20.00*	*80.00*	*27.00*	*2.31*	*571185*	*6.74*	*1.6*	*356,990.63*
H80	*30.00*	*80.00*	*27.00*	*2.31*	*841185*	*9.93*	*2.4*	*350,493.75*
H130	*50.00*	*130.00*	*50.00*	*2.31*	*2557750*	*30.19*	*6.5*	*393,500.00*
H200	*50.00*	*200.00*	*73.00*	*2.31*	*3734315*	*44.08*	*10*	*373,431.50*
PR80	*20.00*	*80.00*	*20.00*	*2.31*	*423100*	*4.99*	*1.6*	*264,437.50*
PR80	*30.00*	*80.00*	*20.00*	*2.31*	*623100*	*7.36*	*2.4*	*259,625.00*
PR100	*20.00*	*100.00*	*25.00*	*2.31*	*528875*	*6.24*	*2*	*264,437.50*
PR100	*30.00*	*100.00*	*25.00*	*2.31*	*778875*	*9.19*	*3*	*259,625.00*
PR150	*50.00*	*150.00*	*42.00*	*2.31*	*2148510*	*25.36*	*7.5*	*286,468.00*
PR200	*50.00*	*200.00*	*65.00*	*2.31*	*3325075*	*39.25*	*10*	*332,507.50*
PUR 35	*50.00*	*35.00*	*1.66*	*2.31*	*84712.68*	*1.00*	*1.65*	*51,341.02*

Comparison PUR 35 Kg/mc -PET PR 80

Change in CORE thickness with the same Shear Stiffness

Let's consider equalizing the shear stiffness (GA) of two sandwiches, one with PER PR 80 and the other with PUR 35 kg/mc with the same length of the sandwich and thickness of the skins, in this way we evaluate the increase in thickness of the PET core to have the same rigidity:

$$GA = L * Gc * tc$$

L=sandwich length [mm]

Gc= core shear modulus[N/mm2]

tc= core thickness(ta) + half sum of skins thickness(t) [mm]

$$L * Gc1 * (ta1 + t) = L * Gc2 * (ta2 + t)$$

Simplifying the terms and solving in ta2

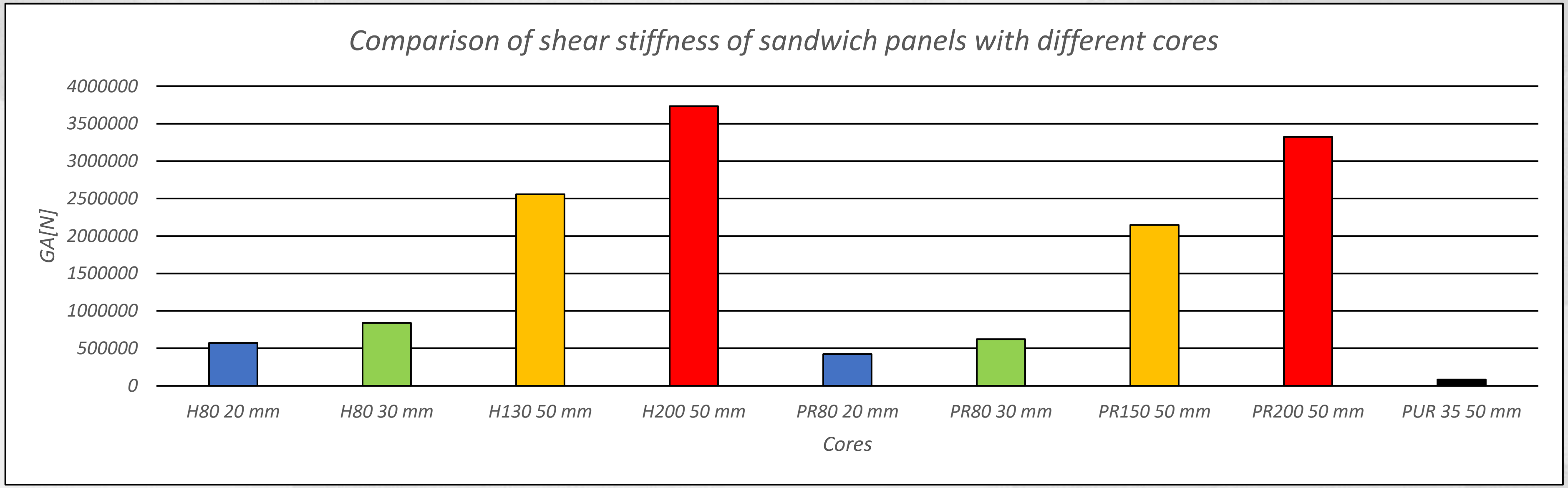
$$ta2 = \left(\frac{Gc1}{Gc2} - 1\right) * t + \frac{Gc1}{Gc2} * ta1$$

With a thickness of 5mm of skins and 20mm of core respectively, using the modules of PET PR 80 and PUR 35 kg/mc , we obtain:

ta2=296 mm (to obtain equivalence in terms of shear stiffness)

THE SANDWICH WITH PUR DENSITY 35 KG/Mc, COMPARED TO A SANDWICH WITH PET PR 80 REQUIRES A DELTA THICKNESS OF 276 MM (OVER 20 MM), THIS DELTA THICKNESS TRANSLATES INTO A DELTA WEIGHT OF 8700 GRAMS/SQM UNFAVORABLE OF PUR FOAM

Shear Stiffness (GA)



H80 20 mm	PR80 20 mm	DELTA [%]
571,185.00 [N]	423,100.00 [N]	35
H80 30 mm	PR80 30 mm	DELTA [%]
841,185.00 [N]	623,100.00 [N]	35
H130 50 mm	PR150 50 mm	DELTA [%]
2,557,750.00 [N]	2,148,510.00 [N]	19
H200 50 mm	PR200 50 mm	DELTA [%]
3,734,315.00 [N]	3,325,075.00 [N]	12

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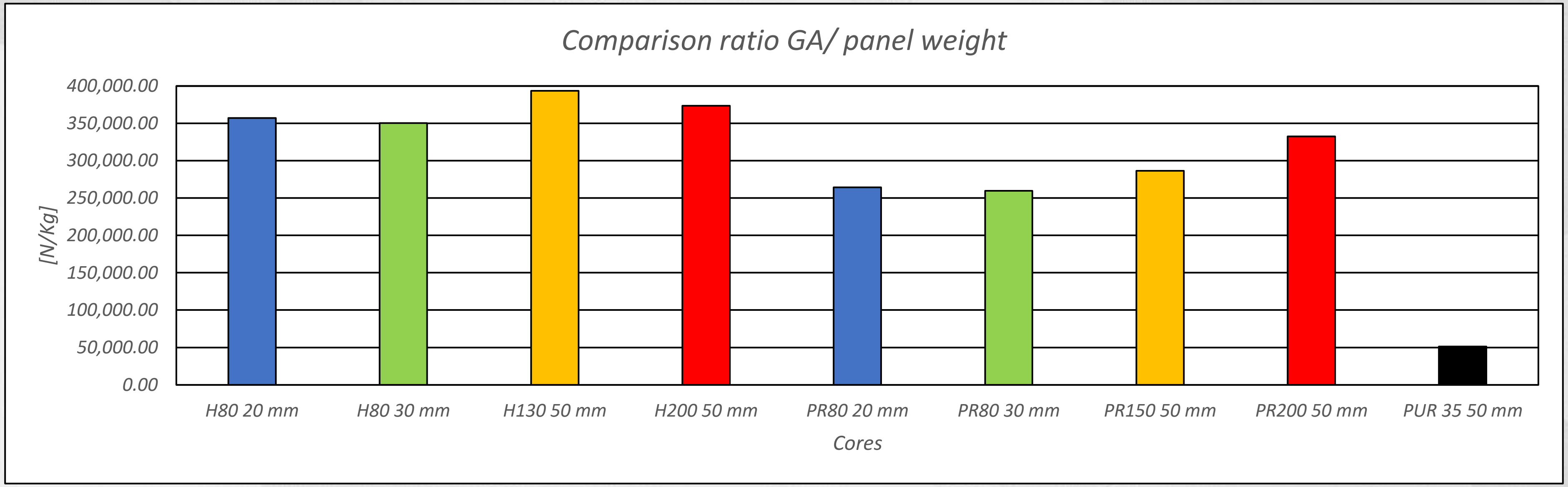
Shear stiffness(GA) and panel weight

The results obtained for the GA of the various panels can be displayed compared to the weight of the panel itself.



H80 20 mm	PR80 20 mm	DELTA [%]
356,990.63 [N/Kg]	264,437.50 [N/Kg]	35
H80 30 mm	PR80 30 mm	DELTA [%]
350,493.75 [N/Kg]	259,625.00 [N/Kg]	35
H130 50 mm	PR150 50 mm	DELTA [%]
393,500.00 [N/Kg]	286,468.00 [N/Kg]	37
H200 50 mm	PR200 50 mm	DELTA [%]
373,431.50 [N/Kg]	332,507.50 [N/Kg]	12

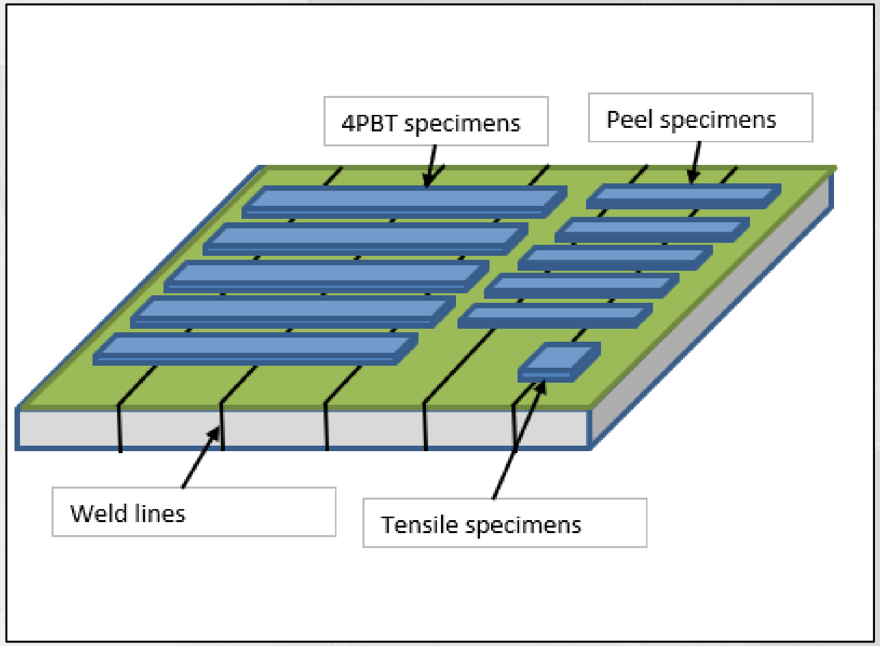
Test Campain

MATERIALS USED TO MAKE SANDWICHES

1. *LINEN FIBER, BASALT FIBERS, GLASS FIBERS*
2. *PET FOAM*
3. *ELIUM 151 INFUSION RESIN*

MECHANICAL TEST

1. *PEEL TEST – INTERNAL METHOD*
2. *SANDWICH TENSILE TEST – ASTM C297*
3. *FLEXURAL TEST – ASTM C393*
4. *SKIN TENSILE TEST – INTERNAL METHOD*



Peel test of a Sandwich with PET core and LINEN skins

Spec. N°	Peel Load (N/25mm)	Peel Energy (J/m^2)	Peeled Length (mm)	Failure mode
1	130,6	934	23,8	Core failure
2	125,2	849	23,8	Core failure
3	130,0	927	23,7	Core failure
4	89,3	957	22,3	Core failure
5	100,3	781	25,0	Core failure
6	78,3	971	24,7	Core failure
7	83,7	939	22,3	Core failure
8	87,7	1.003	24,3	Core failure
Media	103,1	920,1	23,7	
Dev.st	22,02	71,54	1,00	

Comments on the first Peel Test (PET/LINEN Sandwich)

- *Comments:*
- *The samples present two families of data: VALUES BETWEEN 90 N AND 130 N*
- *The energy has good and repeatable values.*
- *The samples present a homogeneous layer of core, indicating good fibre/foam compatibility*
- *THE PEEL TEST OF THE SANDWICH WITH PET CORE AND LINEN FIBERS HIGHLIGHTS THAT THE CELLULARITY OF THE MATERIAL GUARANTEES A GOOD BONDING BETWEEN THE FOAM AND LINEN SKINS.*

Peel test of a Sandwich with PET core and Basalt skins

	Sample ID	Peel Load (N/25mm)	Peel Energy (J/m^2)	Peeled Length (mm)	Failure mode	Spessore (mm)	Fibra
1	80	114,6	4.018	10,0	Interface failure	21,7	Basalto
2	80	86,5	2.136	14,0	Interface failure	21,7	Basalto
3	80	149,2	2.651	15,0	Interface failure	21,7	Basalto
4	80	94,1	3.093	10,0	Interface failure	21,7	Basalto
5	80	98,6	2.884	12,0	Interface failure	21,7	Basalto
6	80	99,3	2.327	14,0	Interface failure	21,7	Basalto
1	80	112,1	1.411	18,0	Core failure	41,4	Basalto
2	80	65,1	864	15,0	Core failure	41,4	Basalto
3	80	98,8	2382	12,0	Interface failure	41,4	Basalto
4	80	99,1	2981	11,0	Core failure	41,4	Basalto
5	80	93,8	2408	12,0	Core failure	41,4	Basalto
1	100	107,4	3.587	10,0	Interface failure	21,7	Basalto
2	100	105,3	2.467	14,0	Interface failure	21,7	Basalto
3	100	144,4	1.619	19,0	Core failure	21,7	Basalto
4	100	99,9	4.092	9,0	Interface failure	21,7	Basalto
5	100	116,3	3.264	11,0	Interface failure	21,7	Basalto
6	100	122,6	2.392	13,0	Core failure	21,7	Basalto
Media	P80 (21.7)	107,1	2851,5	12,5		21,7	
Media	P80 (41.4)	93,8	2009,2	13,6		41,4	
Media	P100 (21.7)	116,0	2903,5	12,7		21,7	
Media solo core	P80 (41.4)	92,5	1916,0				
Media solo core	P100 (21.7)	133,5	2005,5				

Peel test of a Sandwich with PET core and glass skins

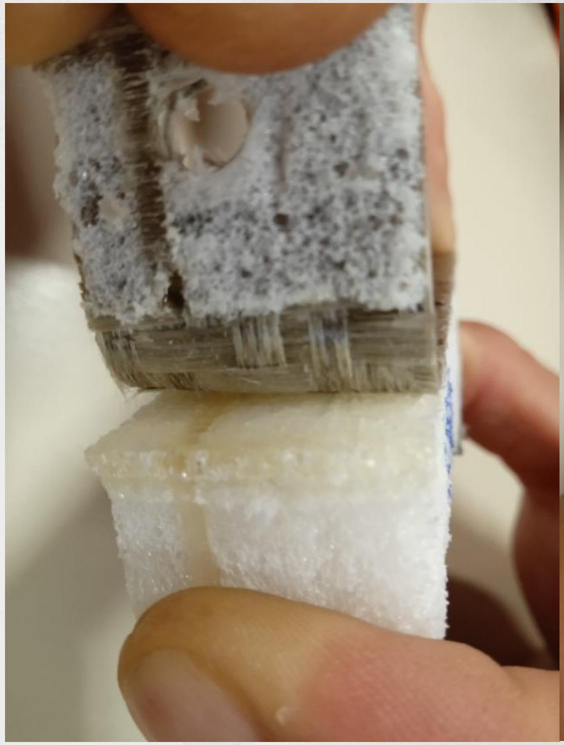
	Sample ID	Peel Load (N/25mm)	Peel Energy (J/m^2)	Peeled Length (mm)	Failure mode	Spessore (mm)	Fibra
1	80	111,5	1.594	14,0	Core failure	21,7	Vetro
2	80	108,5	1.635	13,5	Core failure	21,7	Vetro
3	80	186,0	1.710	21,8	Core failure	21,7	Vetro
4	80	139,7	1.830	17,0	Core failure	21,7	Vetro
1	80	101,7	1.171	17,0	Core failure	41,4	Vetro
2	80	119,0	2.234	20,0	Core failure	41,4	Vetro
3	80	244,5	3.379	15,0	Core failure	41,4	Vetro
4	80	161,2	1.472	23,0	Core failure	41,4	Vetro
1	100	114,8	1.947	19,0	Core failure	21,7	Vetro
2	100	77,1	1.499	14,0	Core failure	21,7	Vetro
3	100	130,0	2.162	20,0	Core failure	21,7	Vetro
4	100	64,6	2.674	8,0	Core failure	21,7	Vetro
5	100	83,3	2.686	10,0	Core failure	21,7	Vetro
6	100	82,7	2.100	11,0	Core failure	21,7	Vetro
Media	P80 (21.7)	136,4	1692,3	16,6		21,7	
Media	P80 (41.4)	156,6	2064,0	18,8		41,4	
Media	P100 (21.7)	92,1	2178,0	13,7		21,7	

Peel test comments

- *Comments:*
- *The statistical results appear conflicting:*

  Density 80 Glass peel load > Peel load Basalt,

  Density 100 Glass peel load < Peel load Basalt
- *causes of variability found are:*
- *The positioning of the resin groove and the through holes with respect to the fracture trigger point.*
- *Basalt has cracks in the interface. The presence of resin on the foam in delaminated samples, however, indicates good fibre/resin/core compatibility.*



Basalt = fiber/resin delamination, which remains on core.

Glass = core fracture

Tensile sandwich test: Basalt/PET & Glass/PET comparison

Tensile sandwich test
evaluation of differences with glass and basalt sandwiches

	Sample ID	Spessore (mm)	Strength (MPa)	Modulus (MPa)	Failure mode	Fibra
1	80	21,7	1,31	129,6	Core failure	Vetro - 6 pins
2	80	21,7	0,88	66,4	Core failure	Vetro - 4 pins
3	80	21,7	1,37	65,5	Core failure	Vetro - 4 pins
4	80	21,7	1,23	89,1	Core failure	Vetro - 6 pins
5	80	21,7	1,10	65,5	Core failure	Vetro - 4 pins
1	80	41,4	0,90	76,4	Core failure	Vetro - 6 pins
2	80	41,4	0,93	116,4	Core failure	Vetro - 9 pins
3	80	41,4	1,08	89,3	Core failure	Vetro - 6 pins
4	80	41,4	1,24	102,1	Core failure	Vetro - 6 pins
5	80	41,4	0,87	138,2	Core failure	Vetro - 9 pins
1	100	21,7	1,00	111,7	Core failure	Vetro - 9 pins
2	100	21,7	1,35	193,3	Core failure	Vetro - 9 pins
3	100	21,7	1,59	142,9	Core failure	Vetro - 9 pins
4	100	21,7	1,59	122,1	Core failure	Vetro - 9 pins
5	100	21,7	1,61	132,6	Core failure	Vetro - 9 pins
Media	P80 (21.7)	21,7	1,18	83,2		
Media	P80 (41.4)	41,4	1,00	104,5		
Media	P100 (21.7)	25,0	1,43	140,5		

	Sample ID	Spessore (mm)	Strength (MPa)	Modulus (MPa)	Failure mode	Fibra	
1	80	21,7	1,23	126,6	Core failure	Basalto	
2	80	21,7	1,04	95,7	Core failure	Basalto	
3	80	21,7	1,17	108,9	Core failure	Basalto	
4	80	21,7	0,90	129,7	Core failure	Basalto	
5	80						
1	80	41,4	1,00	92,1	Core Failure	Basalto - 6 pin	WL
2	80	41,4	1,11	90,2	Core Failure	Basalto - 6 pin	WL
3	80	41,4	0,92	114,2	Core Failure	Basalto - 6 pin	2WL fatte a
4	80	41,4	0,97	122,7	Core Failure	Basalto - 6 pin	WL
5	80	41,4	1,00	88,8	Core Failure	Basalto - 4 pin	WL
1	100	21,7	1,35	202,9	Core failure	Basalto - 6 pin	
2	100	21,7	1,40	163,2	Core failure	Basalto - 4 pin	
3	100	21,7	1,21	120,3	Core failure	Basalto - 4 pin	
4	100	21,7	1,40	112,4	Core failure	Basalto - 4 pin	
5	100	21,7	1,45	167,3	Core failure	Basalto - 4 pin	
Media	P80 (21.7)	21,7	1,09	115,2			
Media	P80 (41.4)	41,4	1,00	101,6			
Media	P100 (21.7)	25,0	1,36	153,2			

SW tensile test - samples

Sandwich tensile test comments

- *Comments:*
- *There are no differences between the two types of sandwich (Glass/PET – Basalt/PET) with regards to tensile strength.*
- *The variability present in the modules can be traced back to the number of holes filled.*
- *All samples exhibit foam breakage, no delamination.*
- *Net of the variability on the modules, the two types have no differences.*

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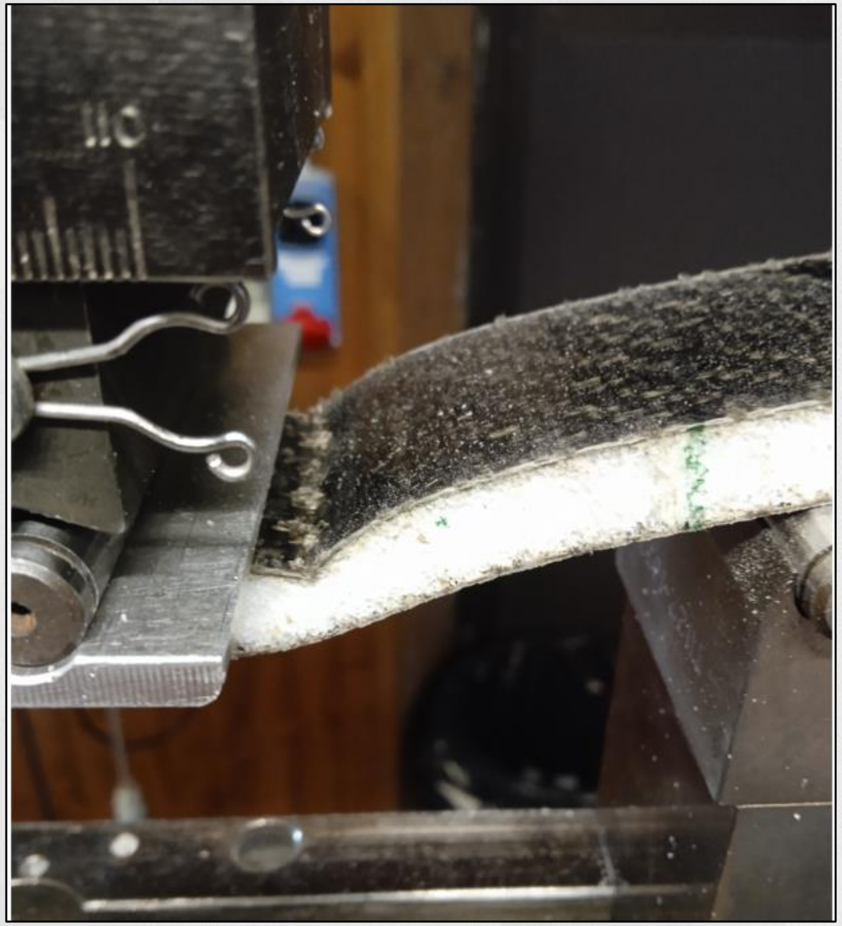
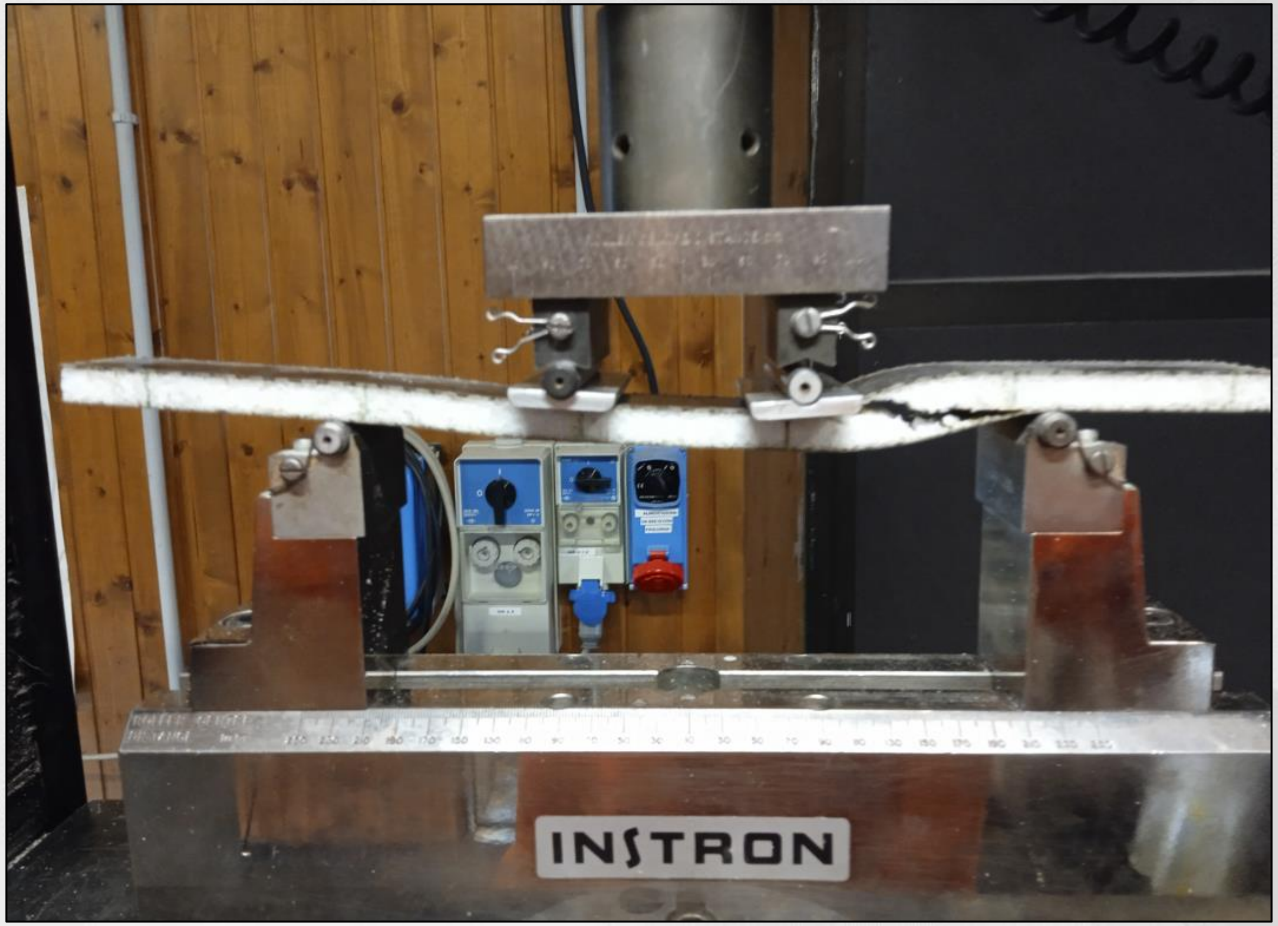
Flexural test (4pbt)



Compression failure under the load point (Skin failure) Sample n°2



Correct core failure (Foam failure), Samples 1-3-4

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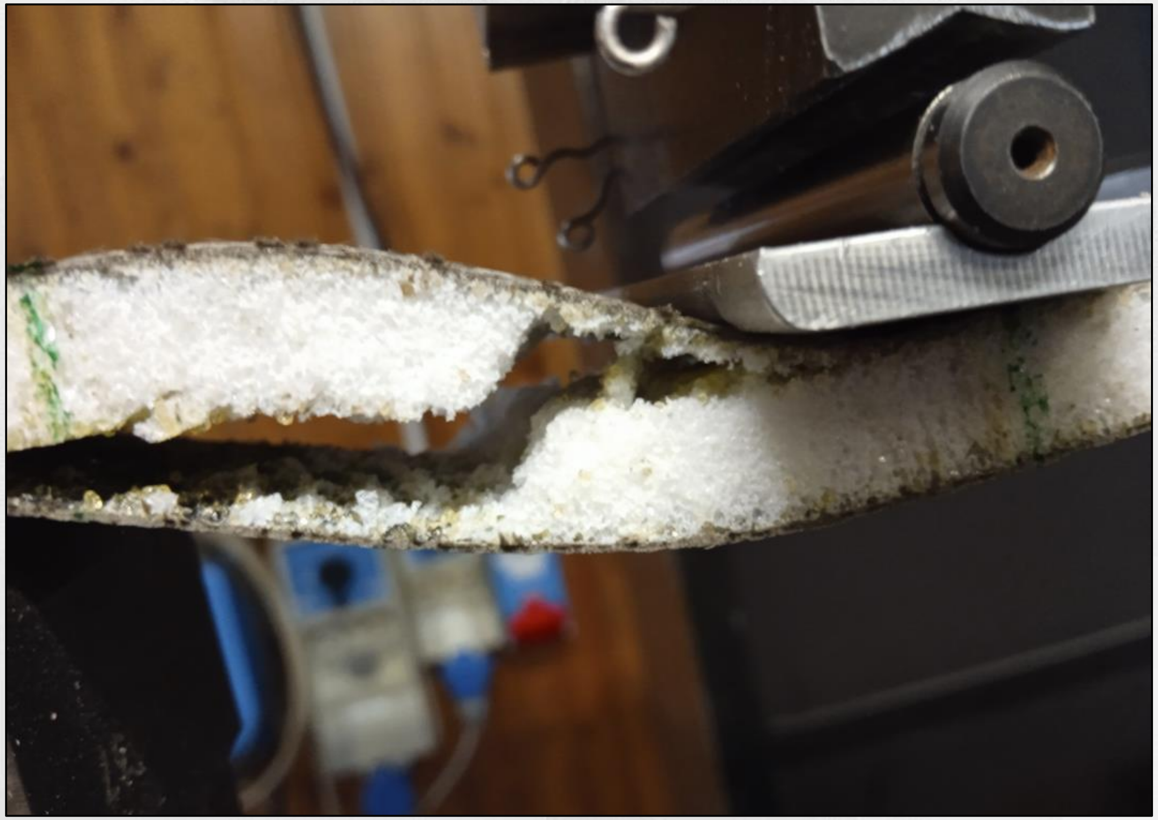
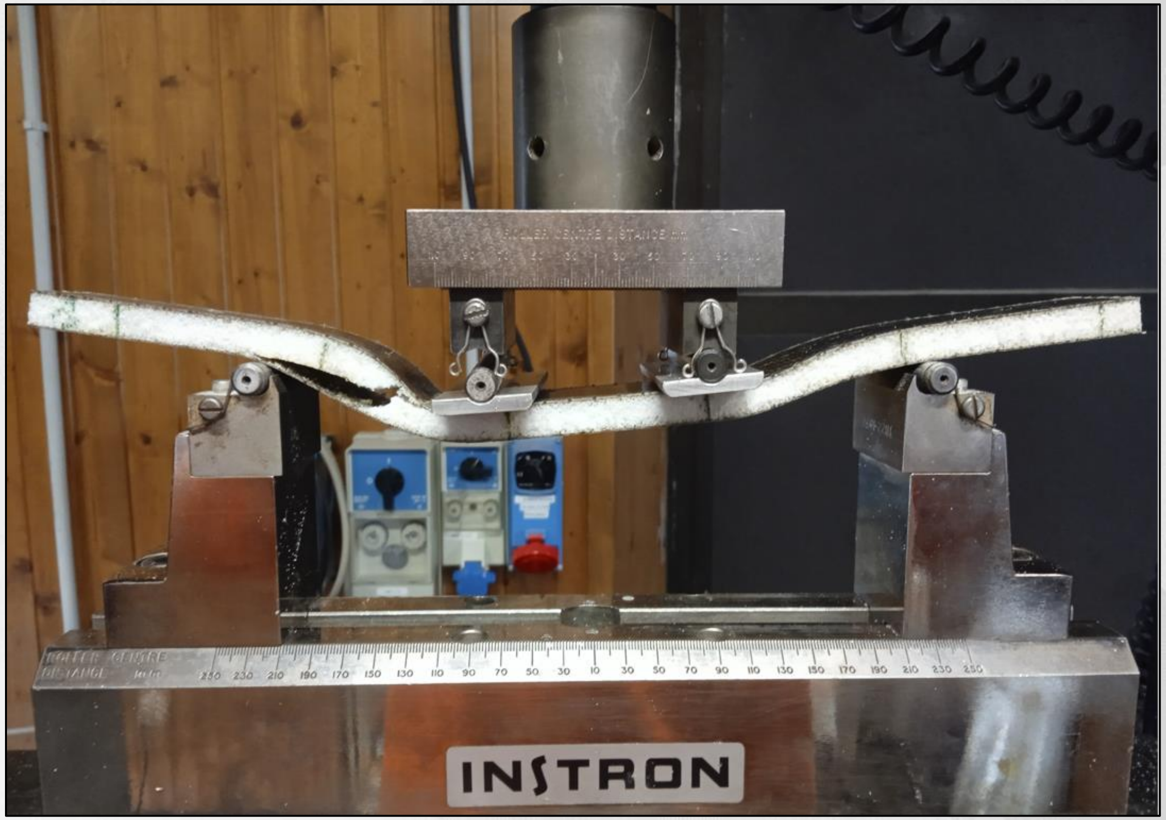
Flexural test (3pbt)



Foam Failure



Foam Failure

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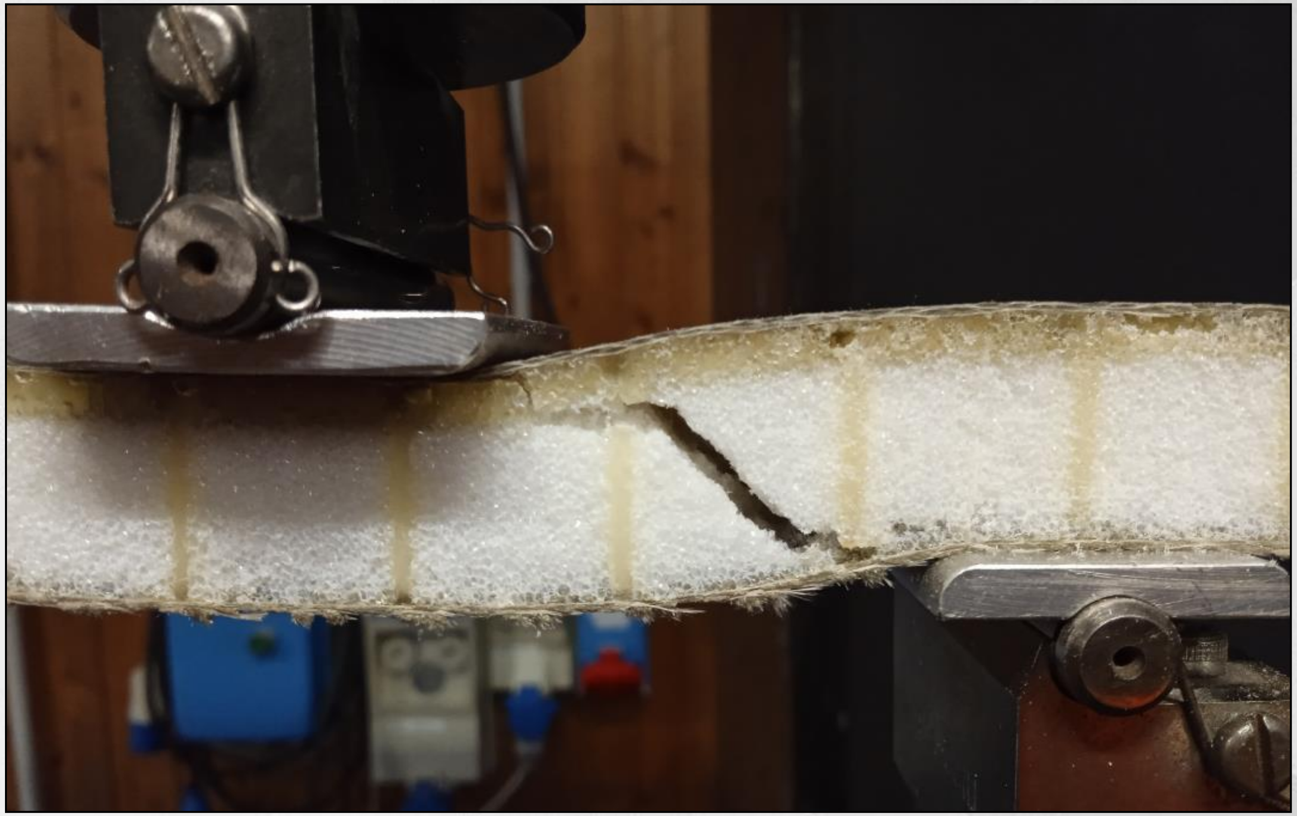
Flexural test (3pbt)

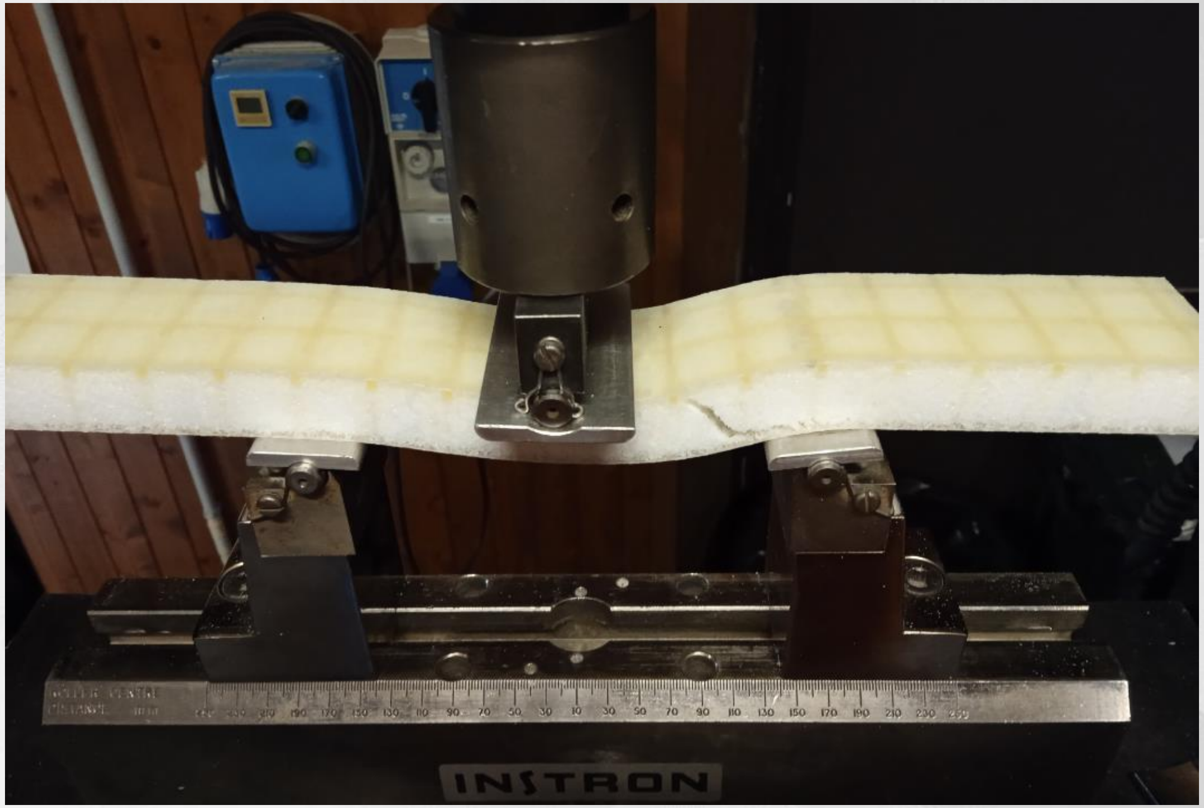
Compression failure under the load point (Skin failure)



Basalt = correct core failure (foam failure)

Flexural test (3pbt)

Glass = correct core breakage



Test set-up

Flexural test

- *The purpose of the test is to induce, through bending, shear failure of the core material,*
- *The samples have good flexural shear strength*
- *The shear strength values found are in line with the core property.*

PET IN PRODUCTION

PET is currently used in various sectors, but the main sector that uses it is WIND

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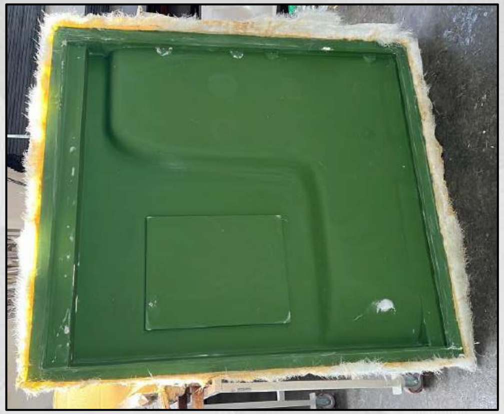
PET IN PRODUCTION

DIAB is carrying out experiments with the ISOTHERMAL Vans Sector

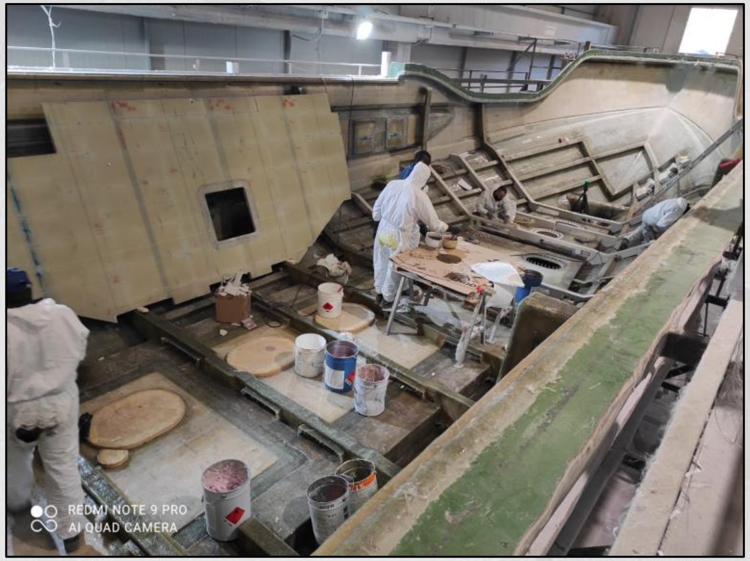
PET IN PRODUCTION

DIAB has developed with ANSALDO TRASPORTI a series of MOLDS for the creation of an ELECTRIC BUS as well as an aluminium-PET sandwich platform



PET IN PRODUCTION

Developments in NAUTICS
- BULKHEADS
- COUNTER-PRINTED
- SPARS AND FRAMES FLOOR (REPLACEMENT OF PUR)
- HULLS AND DECKS



Final conclusions

- *PET is a polymer foam with good mechanical characteristics*
- *If compared to PVC it is inferior in terms of mechanical characteristics by an average of 30% on medium-low density*
- *This difference decreases as the density of the foams increases (for density masses greater than or equal to 200Kg/m3 substantial equivalence is achieved)*
- *The ideal use of PET is in totally recyclable sandwich composites and therefore the design of the near future will increasingly consider the use of Flax, Basalt and BIO Resins*
- *The mechanical characterization of these sandwiches is at the beginning of a journey which, however, it promises the achievement of satisfactory results in the medium term.*