A valuable application for shredded composite material from wind turbine blades

Tjits Tuinhof

APPENDICES MASTER THESIS
Delft, June 2018

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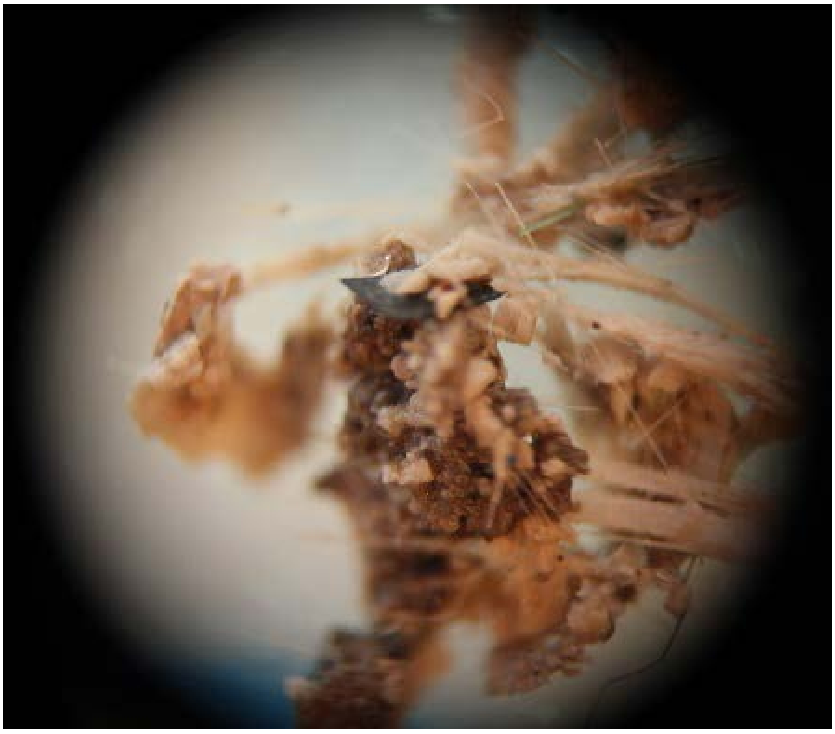
Appendix 1

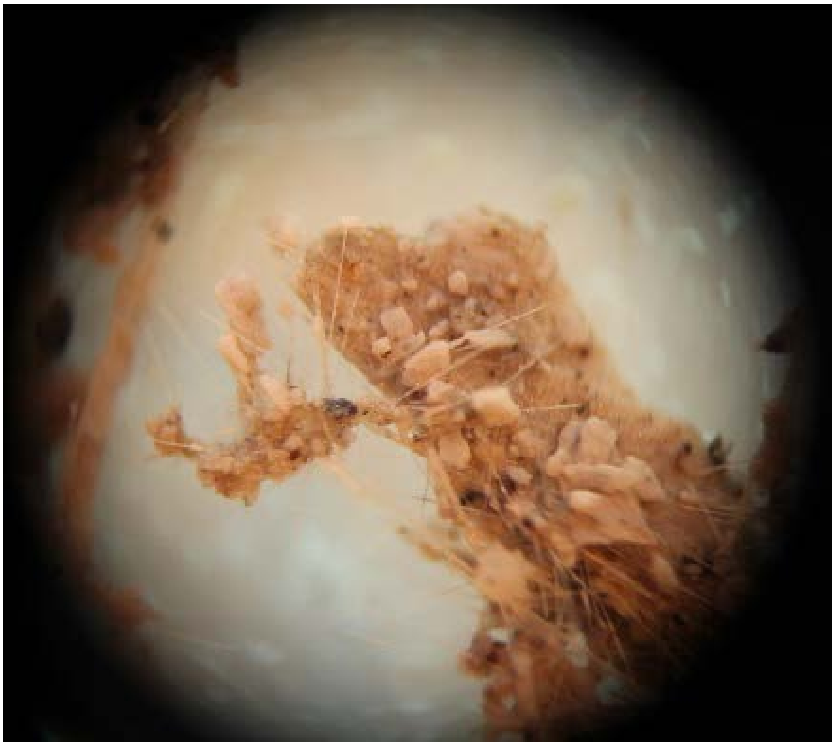
Microscope images SC1 and SC2

SC1 – A few fibers stuck together

SC1 – A piece of foam



SC2 – Different materials



SC2 - Different materials

Appendix 2

Drying test SC2

The drying test is done to calculate the amount of moisture present in the batch of SC2. The test is done in two steps: first one sample was dried in the oven while being weight every hour until the weight was stable, secondly two other samples where dried in the oven for an appropriate time determined in the first test. The procedure and results are explained below.

FIRST TEST

For the first drying test, the oven was heated to 105 °C. A sample of the shreds was placed in a glass cup of which the weight was measured beforehand. The weight of the sample with cup was measured before going into the oven. When the sample was placed in the oven, it was taken out every hour to check its weight. When the weight is stable for multiple measurements, it can be assumed that all moisture is evaporated. Below in table 2.1, the results from the test can be found.

Time (h)	**Weight (gram)**
0	111,3
1	108,1
2	108,1
3	108,2

Table 2.1 – Results from the first test

The weight of the cup was 99,0 gram. This means that the weight of the sample was 111,3-99 = 12,3 gram before drying and 108,1 – 99 gram = 9,1 gram after drying. The amount of moisture that was in the shreds had a weight of 12,3 – 9,1 = 3,2 gram. This means that a percentage of 26 wt% of moisture is present in this batch of shreds. As visible in results from this first test, all moisture is already evaporated after the first hour that the sample is in the oven. Therefore, the next samples will be placed in the oven for only one hour.

SECOND TEST

In the second test, two samples are placed in separate cups inside an oven of 105 °C for one hour. Similar to the first test, the cups with and without samples are weight before going into the oven. After one hour drying in the oven, the samples were taken out and the weight was measured again. The results from these two samples (sample 2 and 3) together with the results from the first test (sample 1) are visible in table 2.2. It can be seen that the average amount of moisture within SC2 is 22.6 wt%.

Sample	**Weight cup**	**Weight before**	**Weight after**	**Weight sample before**	**Weight sample after**	**Weight moisture**	**wt% moisture**
1	99,065	111,3	108,1	12,235	9,035	3,200	26,2
2	12,516	15,056	14,541	2,540	2,025	0,515	20,3
3	12,49	15,236	14,651	2,746	2,161	0,585	21,3
Average							**22,6**

Table 2.2 – Results from both oven tests

Appendix 3

Burn off test of shreds

Multiple burn-off test are done with the batches of shredded composites SC1 and SC2. Before the burn-off test, the porcelain cups used for the test were weighted without and with the sample. After the test, the same measurements were performed. With these results, the weight percentage of the residue can be calculated. In the first test, the samples were heated in the oven to 600 °C at which the temperature was kept stable for 1 hour. After this hour, the oven would stop heating and cool down in a few hours. When the temperature was dropped to around 250°C, the samples were removed from the oven. The results are visible in table 3.1.

sample #	*1*	*2*	*3*	*4*	*5*
content	dried SC2	wet SC2	wet SC2	SC1	SC1
empty cup before *[gram]*	17,483	17,325	17,072	14,975	15,444
cup with sample before *[gram]*	18,318	18,739	18,355	15,552	16,099
cup with sample after *[gram]*	17,952	17,752	17,571	15,316	15,829
empty cup after *[gram]*	17,48	17,325	17,072	14,974	15,444
weight sample before [gram]	0,835	1,414	1,283	0,577	0,655
weight sample after [gram]	0,472	0,427	0,499	0,342	0,385
wt% glass fiber	**56,5**	**30,2**	**38,9**	**59,3**	**58,8**
without 22,6 wt% water		1,094	0,993		
wt% glass fiber		39,0	50,2		

Table 3.1 – First burn-off test

In the second and third burn-off test, two samples of the first test were again placed in the oven. This was done to see if the weight of the residue would further drop or stay stable to conclude if all the matrix material was burned-off in the first test. The second test was done at a temperature of 570°C which was kept stable for one hour. The third test was also done with an oven of 570°C but then for a time period of two hours. The results from the second and third test can be found in table 3.2.

sample #	*10**	*15***
content	Sample 4 - SC 1	Sample 3 - wet SC2
empty cup before *[gram]*	15,444	15,444
cup with sample before *[gram]*	15,651	15,699
cup with sample after *[gram]*	15,649	15,692
empty cup after *[gram]*	15,444	15,444
weight sample before [gram]	0,207	0,255
weight sample after [gram]	0,205	0,248
wt% residue	**99,0**	**97,3**

Table 3.2 – Second burn-off test

*Oven 570 °C for 1 hour **Oven 570 °C for 2 hours

The percentages that the residue dropped in weight during the second and third test is not large, which means that most material was burned off during the first test. However, to be able to compare the results correctly, the measured percentages are also processed in the samples that had a shorter heating time. The final results can be found in table 3.3.

	sample	second sample (if applicable)	weight before [gram]	weight after [gram]	wt% weight left after second burn	wt% glass fiber after first burn	**wt% gf would be after second burn**
dried SC2	*1*		0,835	0,472		56,5	**55,0**
wet SC2	*2*		1,094*	0,427		39,0	37,9
	3	*15*	0,993*	0,499	97,3	48,9	**48,9**
SC1	*4*	*10*	0,577	0,342	99,0	58,7	**58,7**
	5		0,655	0,385		58,8	**58,2**
					average	55,7	**55,2**
					% variation	12,3	**11,4**

Table 3.3 – Results from the burn-off tests

*The 22.6 wt% moisture is eliminated from the measured weight.

Appendix 4

Burn-off test of profiles

Multiple samples of the PE and PP profiles are used in the burn-off test. Before the burn-off test, the porcelain cups used for the test were weighted without and with the sample. After the test, the same measurements were performed. With these results, the weight percentage of the residue can be calculated.

In the first test, the samples were heated in the oven to 570 °C at which the temperature was kept stable for 1 hour. After this hour, the oven would stop heating and cool down in a few hours. When the temperature was dropped to around 250°C, the samples were removed from the oven. The results are visible in table 4.1.

sample #	*6*	*7*	*8*	*9*
content	PP	PP	PE	PE
Empty cup before *[gram]*	17,325	17,48	17,072	14,975
Cup with sample before *[gram]*	19,569	19,006	19,686	17,189
Cup with sample after *[gram]*	17,553	17,633	17,366	15,217
Empty cup after *[gram]*	17,325	17,48	17,072	14,976
weight sample before [gram]	2,244	1,526	2,614	2,214
weight sample after [gram]	0,228	0,153	0,294	0,241
wt% glass fiber	**10,2**	**10,0**	**11,2**	**10,9**

Table 4.1 – First burn-off test

In the second burn-off test, another sample of the PE and PP profile were placed in the oven together with sample 6 and 8 from the first burn-off test. This was done to see if the weight of the residue would further drop or stay stable to conclude if all the matrix material was burned-off in the first test. The second test was done at a temperature of 570°C which was kept stable for two hours. The results are visible in table 4.2.

sample #	*11*	*12*	*13*	*14*
content	PP	PE	8. PE	6. PP
Empty cup before *[gram]*	17,072	17,48	17,325	14,974
Cup with sample before *[gram]*	18,495	19,631	17,428	15,099
Cup with sample after *[gram]*	17,211	17,715	17,425	15,097
Empty cup after *[gram]*	17,072	17,48	17,325	14,974
weight sample before [gram]	1,423	2,151	0,103	0,125
weight sample after [gram]	0,139	0,235	0,1	0,123
wt% residue	**9,8**	**10,9**	**97,1**	**98,4**

Table 4.2 – Second burn-off test

The percentages that the residue from sample 8/13 and 6/14 dropped in weight during their second burn is not large, which means that most material was burned off during the first test. However, to be able to compare the results correctly, the measured percentages are also processed in the samples that had a shorter heating time. The final results can be found in table 4.3.

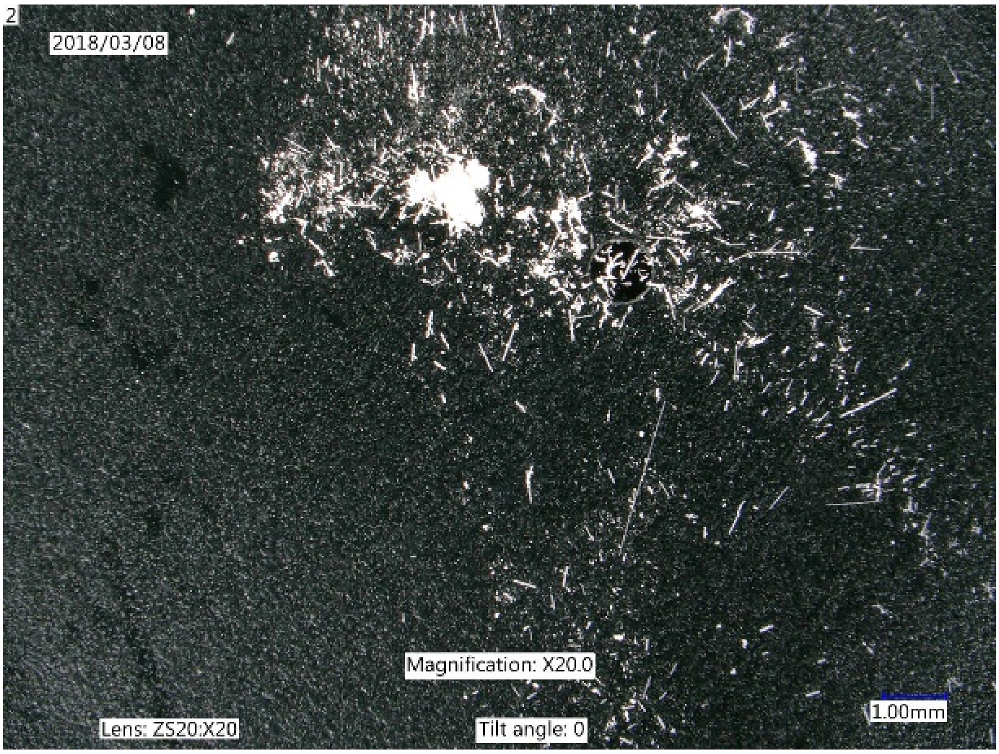
	sample #	second sample # (if applicable)	weight before [gram]	weight after [gram]	wt% weight left after second burn	total wt% glass fiber	**wt% gf would be after second burn**
PE	*6*	*14*	2,244	0,228	98,4	10,0	**10,0**
	7		1,526	0,153		10,0	**9,9**
	12		2,151	0,235		10,9	**10,8**
PP	*8*	*13*	2,614	0,294	97,1	10,9	**10,9**
	9		2,214	0,241		10,9	**10,6**
	11		1,423	0,139		9,8	**9,5**
		average	2,029	0,215		10,42	10,26
		% variation				6,26	7,61

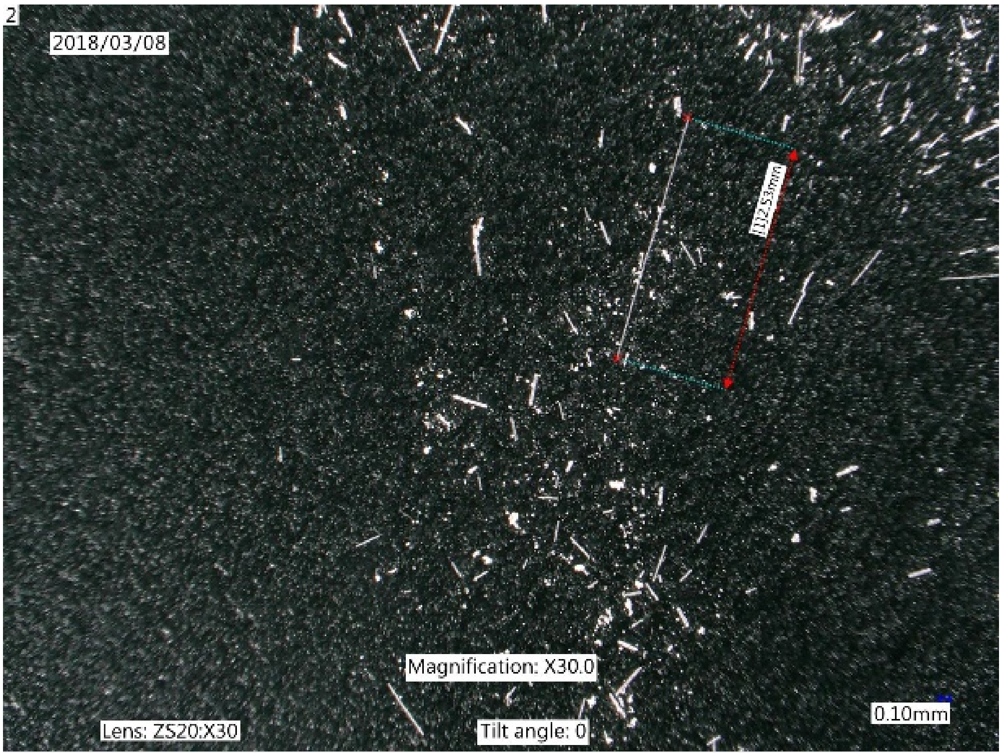
Table 4.3 – Results from the burn-off tests

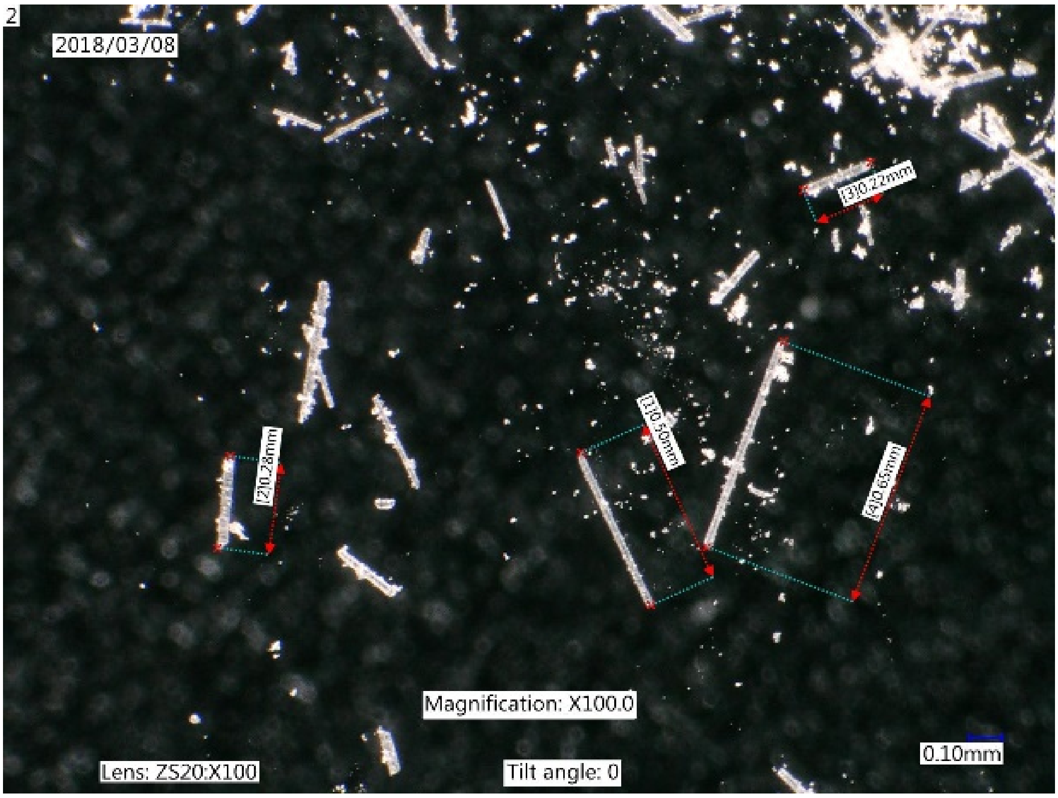
Appendix 5

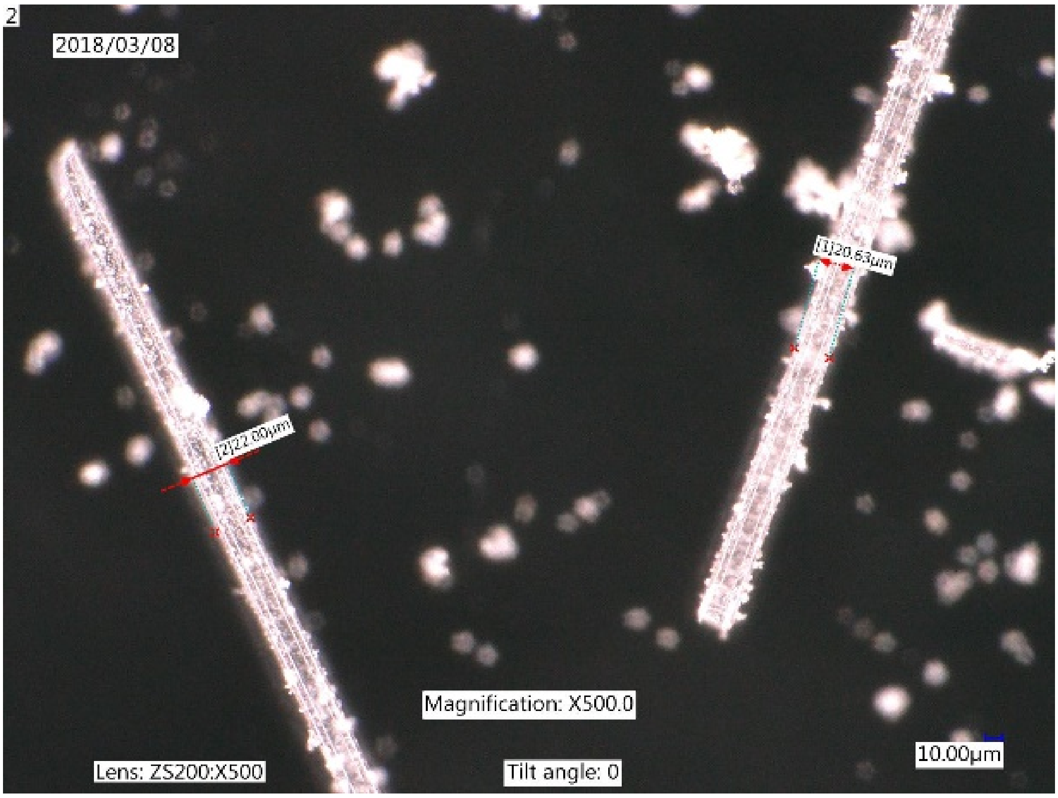
Microscopic images of burn-off test residue

SAMPLE 8 – PE PROFILE RESIDUE



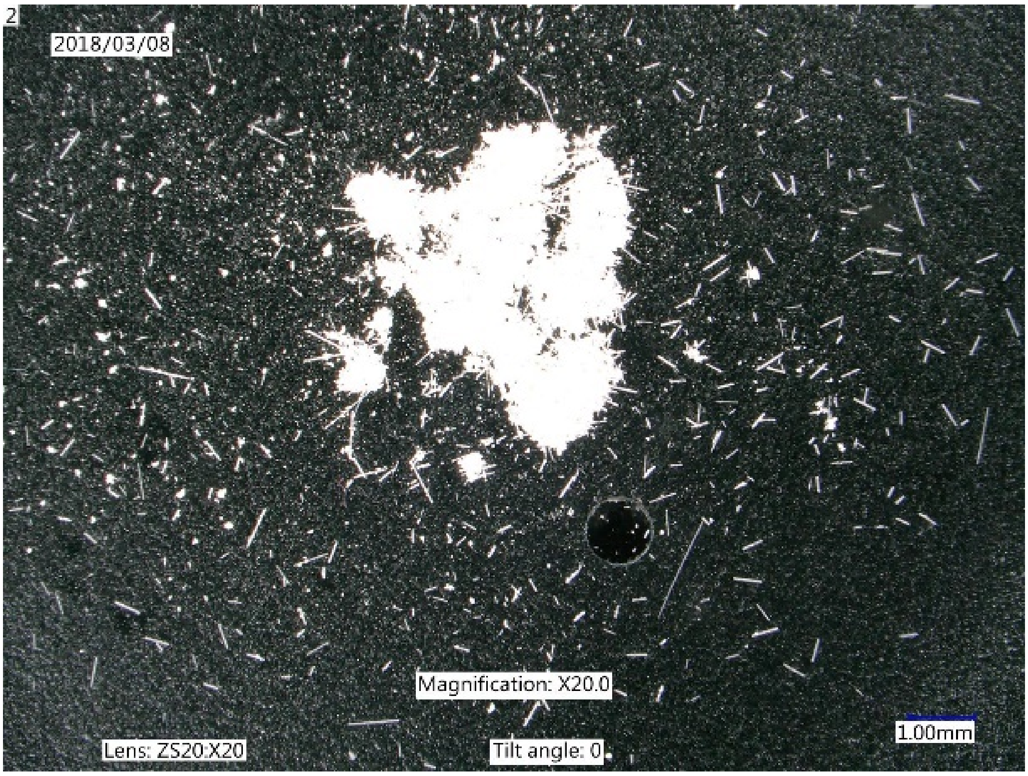


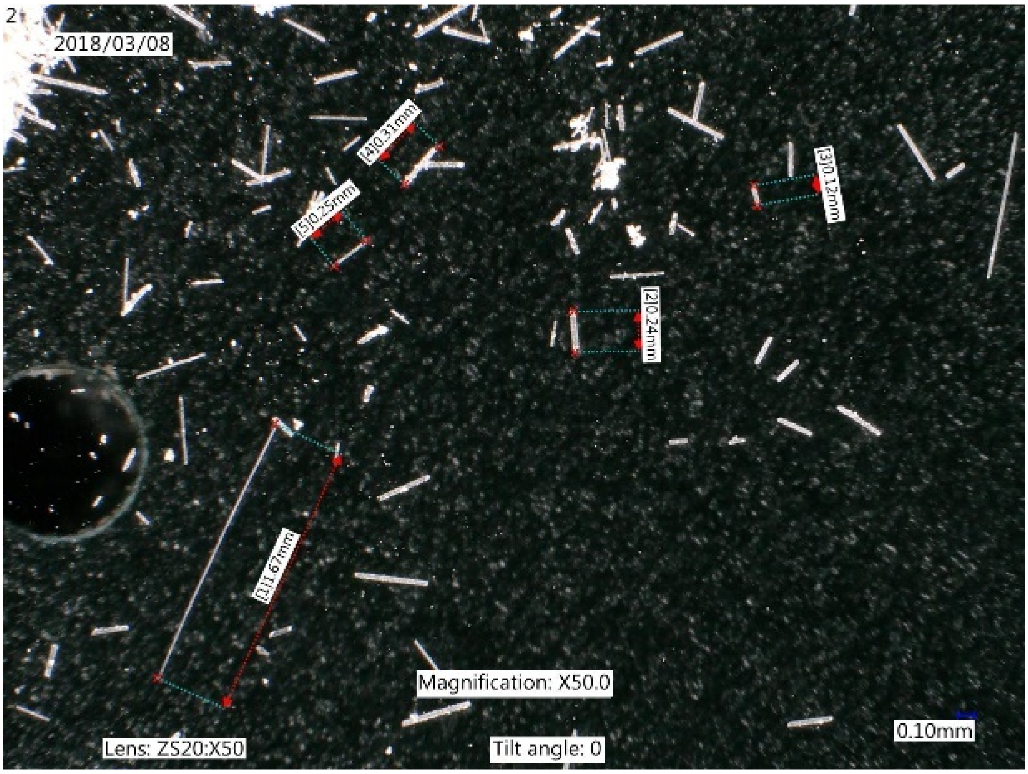

2
2018/03/08
[3]0.22mm
[1]0.50mm
[2]0.28mm
[4]0.65mm
Magnification: X100.0
0.10mm
Lens: ZS20:X100
Tilt angle: 0


2
2018/03/08
[1]20.63µm
[2]22.00µm
Magnification: X500.0
10.00µm
Lens: ZS200:X500
Tilt angle: 0

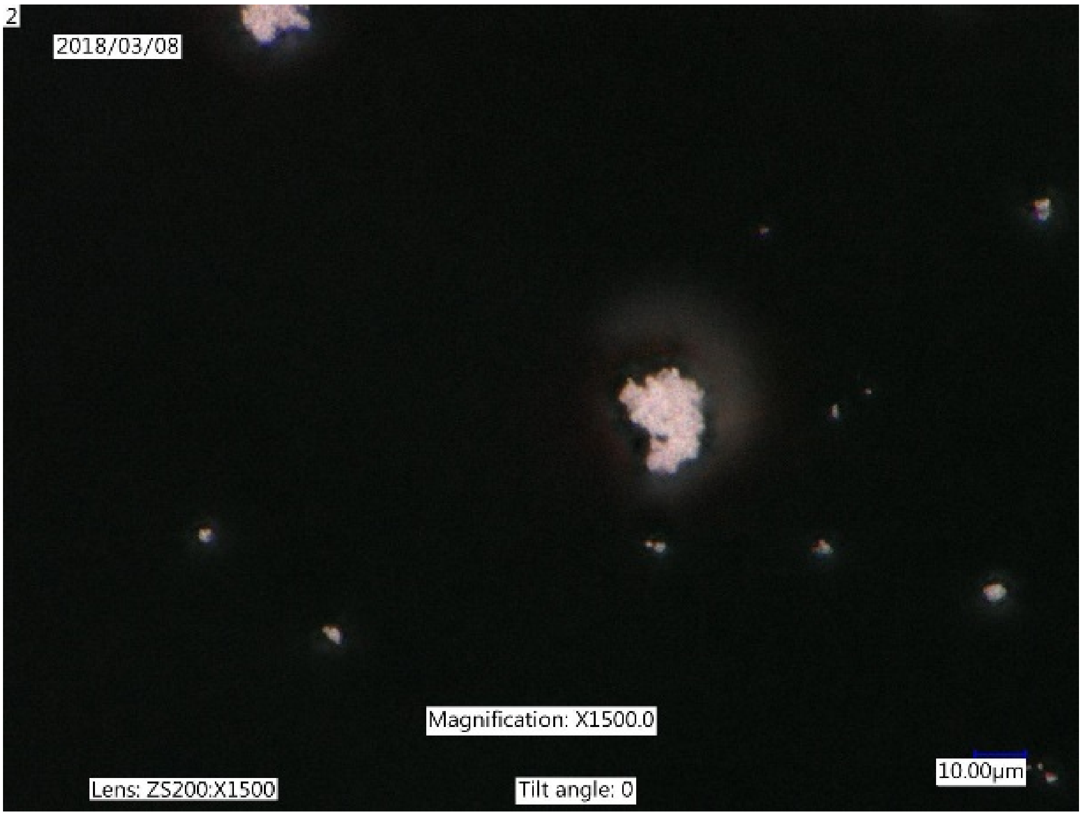
SAMPLE 9 – PE PROFILE RESIDUE

A second sample of PE profile residue was analyzed to be able to see if difference is occuring between the samples of the different profiles.

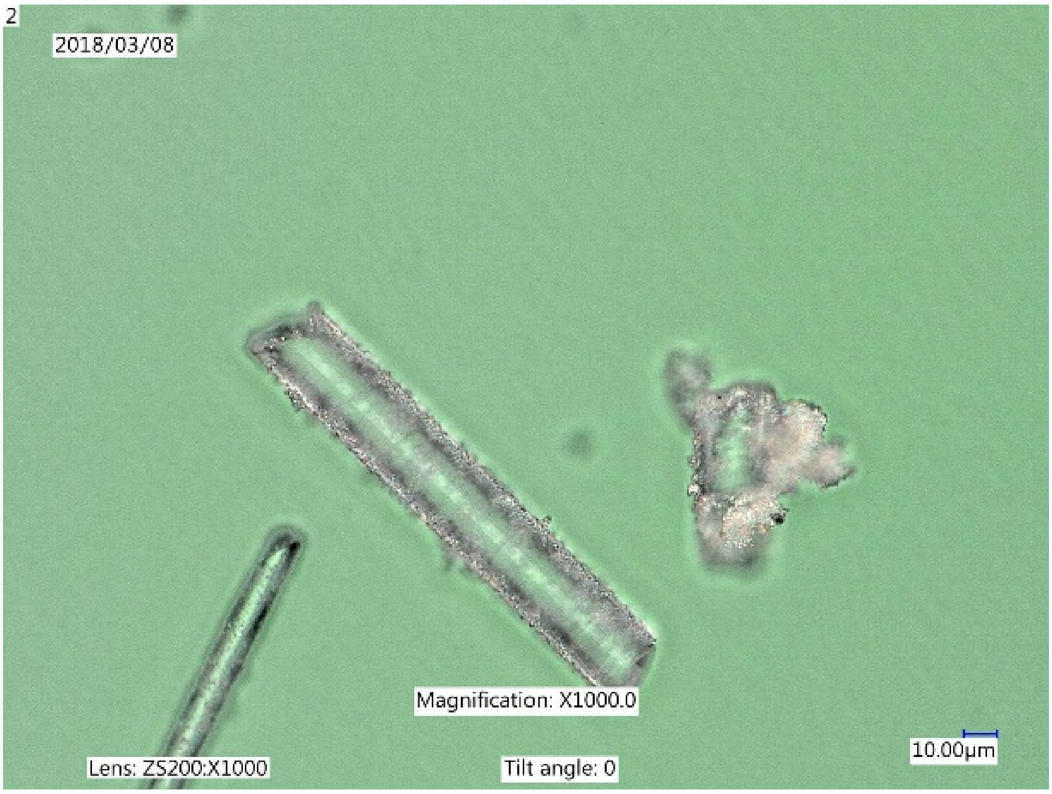




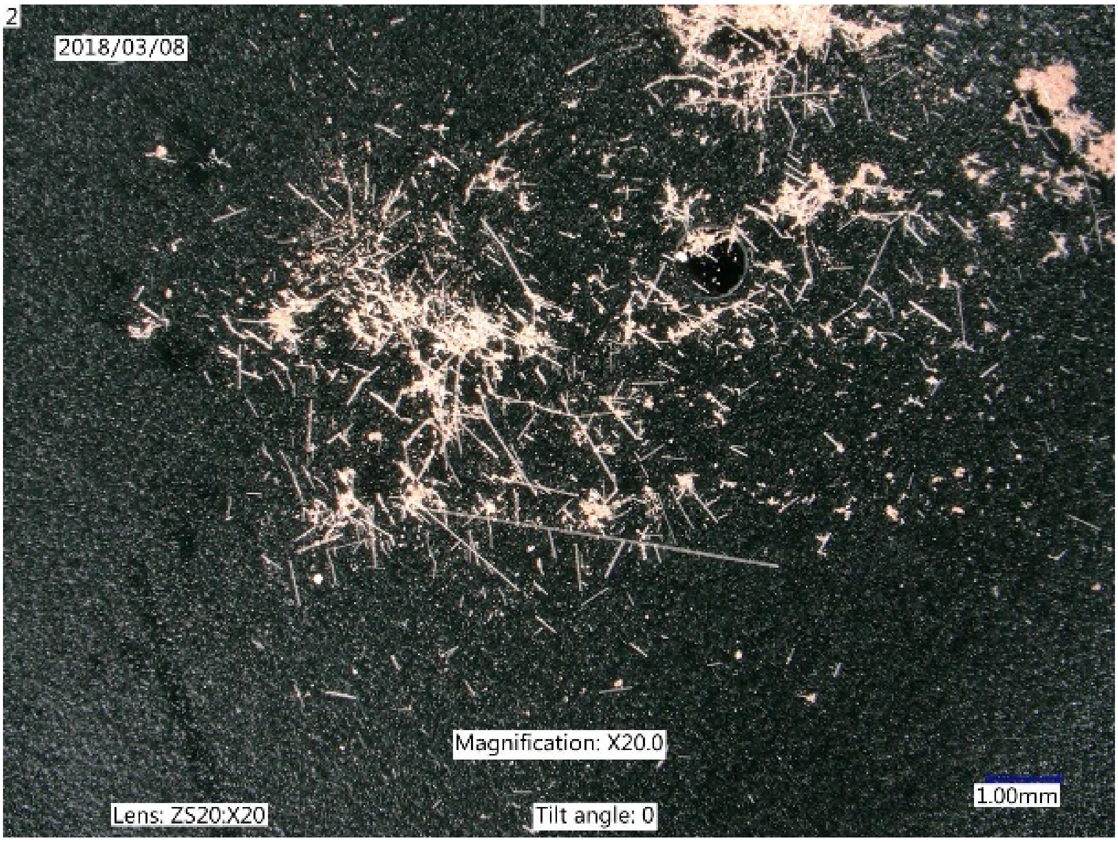

2
2018/03/08
[3]17.53µm
[4]30.62µm
[2]30.79µm
[5]19.84µm
[1]11.76µm
Magnification: X200.0
Lens: ZS200:X200
Tilt angle: 0
100.00µm

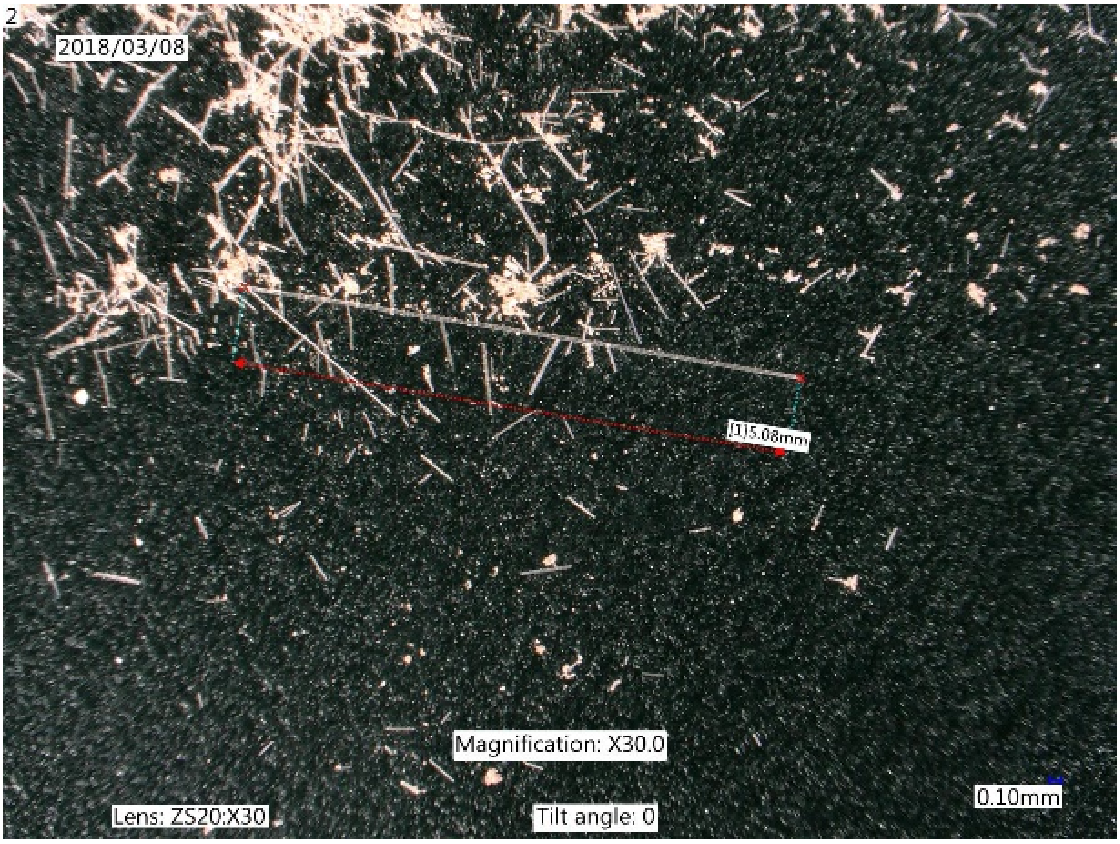

2
2018/03/08
Magnification: X1500.0
Lens: ZS200:X1500
Tilt angle: 0
10.00µm

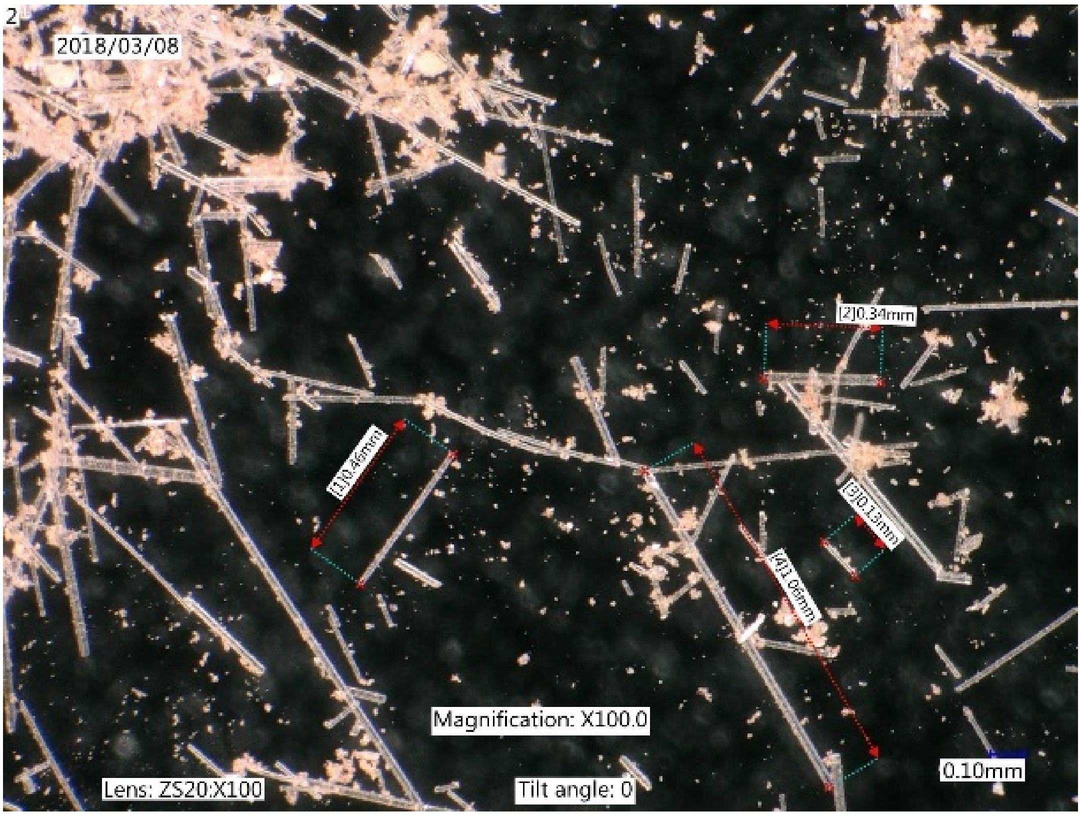

2
2018/03/08
Magnification: X1500.0
Lens: ZS200:X1500
Tilt angle: 0
10.00µm


2
2018/03/08
Magnification: X1000.0
Lens: ZS200:X1000
Tilt angle: 0
10.00µm

SAMPLE 14 – PP PROFILE RESIDUE






2
2018/03/08
[2]0.34mm
[1]0.46mm
[3]0.13mm
[4]1.06mm
Magnification: X100.0
0.10mm
Lens: ZS20:X100
Tilt angle: 0


2
2018/03/08
[1]24.66μm
Magnification: X500.0
10.00μm
Lens: ZS200:X500
Tilt angle: 0

FIBER DIMENSIONS

In the images of the different samples, several dimensions are identified. In the table below, these results are listed. From visual analysis it becomes clear that differences are existing in the length and thickness of the fibers in all samples. No real difference is seen between the fibers dimensions in the PE and PP profiles.

Sample	**Length [mm]**	**Thickness [µm]**
8 – PE	0.22	22.00
	0.28	20.63
	0.50	
	0.65	
	2.53	
9 - PE	0.12	11.76
	0.24	17.53
	0.25	19.84
	0.31	30.62
	1.67	30.79
14 - PP	0.13	24.66
	0.34	
	0.46	
	1.06	
	5.08	

Appendix 6

Density measurement of the profiles

Sample		**Width**	**Length**	**Thickness**	**Volume**	**Weight**	**Density**	
		mm	*mm*	*mm*	*cm^3*	*gr*	*gr/cm^3*	
PE2	B3	14,9	7,7	160,4	18,40	22,4	1,22	
PE3	B1	14,9	7,7	160	18,36	22,1	1,20	
PE1	B2	15,1	7,7	160	18,60	22,4	1,20	
PE1	B1	15,2	7,7	159,2	18,63	22,2	1,19	
PE2	B1	15,1	7,7	160,5	18,66	22,2	1,19	
PE3	B3	14,9	7,8	160	18,60	22,3	1,20	*Variation %*
Average PE							**1,20**	1,4
PP2	B1	15	8	160,4	19,25	22	1,14	
PP2	B2	15,2	8	160,7	19,54	22,1	1,13	
PP1	B1	15,1	8	159,1	19,22	21,9	1,14	
PP1	B2	15	8	160	19,20	22	1,15	
PP3	B2	15	8	160	19,20	21,9	1,14	
PP3	B3	15	8	160	19,20	21,7	1,13	*Variation %*
Average PP							**1,14**	0,7

Appendix 7

Mechanical properties of content materials profiles

The content information of the PP and PE profiles received from the production company is visible in table 6.1.

PP PROFILES		**PE PROFILES**	
Material	*Weight fraction [%]*	*Material*	*Weight fraction [%]*
Shredded WTB of which:	20	Shredded WTB of which:	20
- Fibers	12	- Fibers	12
- Matrix	8	- Matrix	8
Wood pellet	40	Wood pellet	40
PP	30	HDPE	30
Additives	10	Additives	10

Table 6.1 – Profiles content

Additional information that was given on the materials:

- PP: recycled PP in mixed colors from bottles in flake form from the company Swerec.
- Wood pellets: pellets from the company Versowood aimed for energy purposes, typically made of Nordic pine and spruce species.
- HDPE: virgin powder.
- Additives include lube (stearine), coupling (PPMA), color (FeO) and compatibilizer.

With this information, the mechanical properties of the materials are determined. For this, different sources are used estimate the correct values for the properties. CES EduPack from Granta is a good source for material properties, however the full range of possibilities are included in this database. This means that the values given have a wide range that is not fully corresponding with the reality. Therefore, these values are also compared with other courses.

For the PP and HDPE, data sheets were delivered by the production company (Borealis, 2008; Prospector, 2018). The missing characteristics were estimated from values delivered by other companies. To complement the values of PP, the lowest value of the PP homopolymer (MakeItFrom.com, 2018a) and copolymers (MakeItFrom.com, 2018b) were used to not overestimate the properties. The resulting properties are found in table 6.2. For HDPE, the additional values are determined by comparing values from CES EduPack (2017) and other sources (MakeItFrom.com, 2018c; MatWeb, 2018). HDPE is already a more specific type of polyethylene plastics and therefore the values given by CES were on a smaller range. The values were comparable with other courses. Therefore, the average values available on CES are used for the properties of HDPE.

	Density [g/cm^3]	**E-modulus [MPa]**	**Tensile strength [MPa]**	**Flexural modulus [MPa]**	**Flexural strength [MPa]**
PP	0.906	1300	33	1300	31
HDPE	0.954	1200	26	1274	37
Norway spruce	0.44	9700	95	12500	77
Scots pine	0.55	10080	104	11100	90
E-glass fiber	2.58	78500	2000	-	-
Polyester matrix	1.38	2500	63	-	-
Epoxy matrix	1.54	3500	60	-	-

Table 6.2 - Mechanical properties of the materials

For the wood pellets that are used, the production company specified that typically Nordic pine and spruce is used. It was found that in Europe, Scots pine and Norway spruce are the most common species. The properties of these species (European Wood 2018a; European Wood 2018b; The Wood Database, 2018a; The Wood Database, 2018b) are compared which shows that Norway spruce has the lowest properties. These will initially be used to not overestimate the properties. The values of both species can be found in table 6.2.

According to Mishnaevsky et al. (2017), E-glass is typically used as reinforcement in wind turbine blades. Therefore, the properties of this material will be used of which the results can be found in table 6.2 (AZO Materials, 2018). The flexural modulus and strength were not included because no estimation could be found of these properties. The fibers are also used in a situation in which they are covered with matrix material. If necessary, these properties can be determined for the matrix material that encloses the fibers.

The matrix material of the shredded composite is partly stuck on the glass fibers. However, initially the matrix material will be included separately within the material table of 6.2. As Mishnaevsky et al. (2017) explains, polyester was the most common-used matrix material when the first fiber-reinforced composites were used for wind turbine blades. Later, epoxy matrices became more interesting when the wind turbine blades were growing in size. It is not sure which matrix material is used in the profiles, but if the blade is recently shredded after a 30 years lifetime the matrix material is probably polyester. The properties of both matrix materials can be found in table 6.2. For the polyester properties the values from CES Edupack (2017) are compared with other sources to come to the most common values (Davallo, Pasdar and Mohseni, 2010; Pilling, n.d.). An identical approach was used to determine the values for epoxy resin (Pilling, n.d.; CES EduPack, 2017).

Appendix 8

Results three-point bending test

MEASURED RESULTS

Specimen	a_0 (thickness) [mm]	b_0 (width) [mm]	s_0 [mm^2]	F_{max} [N]	dL at F_{max} [mm]	Slope (F/d) [N/mm]
PE1 B1	7,72	15,22	117,5	117,7	9,3	39,90
PE1 B2	7,73	15,13	117,0	113,4	10,2	34,73
PE1 B3	7,74	15,36	118,9	138,0	10,4	42,00
PE2 B1	7,72	15,06	116,3	121,0	11,1	36,60
PE2 B2	7,69	14,92	114,7	138,1	8,3	45,43
PE2 B3	7,76	14,95	116,0	122,0	7,9	42,93
PE3 B1	7,69	14,94	114,9	140,0	10,2	46,80
PE3 B2	7,77	14,97	116,3	120,9	10,3	40,20
PE3 B3	7,77	14,93	116,0	116,7	9,8	41,16
PP1 B1	8,02	15,17	121,7	85,2	3,5	41,44
PP1 B2	8,00	15,05	120,4	91,8	3,3	46,33
PP1 B3	7,98	15,13	120,7	82,7	3,8	40,18
PP2 B1	7,96	15,00	119,4	95,0	3,9	46,86
PP2 B2	8,02	15,18	121,7	95,0	3,8	44,31
PP2 B3	7,95	15,05	119,6	100,4	3,5	46,74
PP3 B1	8,11	15,27	123,8	82,4	4,1	35,32
PP3 B2	8,01	15,07	120,7	89,7	3,3	43,73
PP3 B3	7,97	14,97	119,3	78,5	3,7	36,48

The slope is determined by finding the direction of the linear elastic curve of the force – travel graph of each specimen.

CALCULATED RESULTS

With the results above and the following formulas, the properties from the table below could be calculated:

$$\sigma_f = \frac{3 \cdot F \cdot L}{2 \cdot b0 \cdot a0^2}$$

$$\varepsilon_f = \frac{6 \cdot dL \cdot a0}{L^2}$$

$$E_f = \frac{L^3 \cdot m}{4 \cdot b0 \cdot a0^3}$$

with L being the support span and m being the slope.

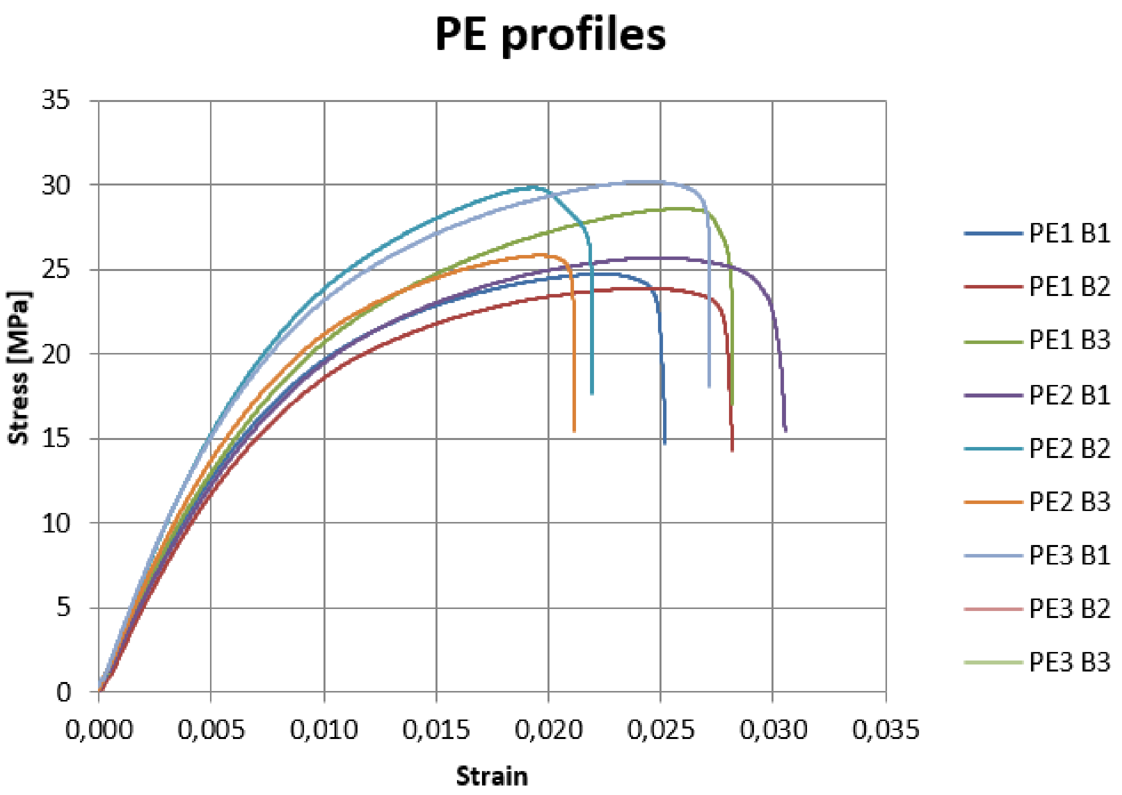
Specimen	**Flexural Strength σ_{max} [MPa]**	**Strain at flexural strength ε_{max}**	**Stress at break σ_b [MPa]**	**Strain at break ε_b**	**Flexural Modulus E_f [MPa]**
PE1 B1	24,7	0,024	14,8	0,027	2917,6
PE1 B2	23,9	0,025	14,3	0,029	2545,3
PE1 B3	28,6	0,028	17,1	0,030	3020,1
PE2 B1	25,7	0,026	15,4	0,032	2705,0
PE2 B2	29,8	0,021	17,7	0,024	3429,2
PE2 B3	25,8	0,021	15,5	0,023	3147,2
PE3 B1	30,2	0,026	18,1	0,029	3527,4
PE3 B2	25,5	0,026	15,2	0,030	2931,4
PE3 B3	24,7	0,025	14,7	0,028	3009,7
PP1 B1	16,6	0,010	10,0	0,011	2712,0
PP1 B2	18,2	0,009	10,9	0,010	3079,0
PP1 B3	16,3	0,011	9,8	0,011	2676,2
PP2 B1	19,0	0,011	11,4	0,011	3172,3
PP2 B2	18,5	0,011	11,1	0,011	2898,0
PP2 B3	20,1	0,010	12,0	0,010	3165,2
PP3 B1	15,6	0,012	9,3	0,012	2220,3
PP3 B2	17,7	0,009	10,6	0,010	2891,7
PP3 B3	15,7	0,010	9,4	0,011	2465,3
Average PE	26,5	0,025	15,8	0,028	3025,9
Average PP	17,5	0,010	10,5	0,011	2808,9

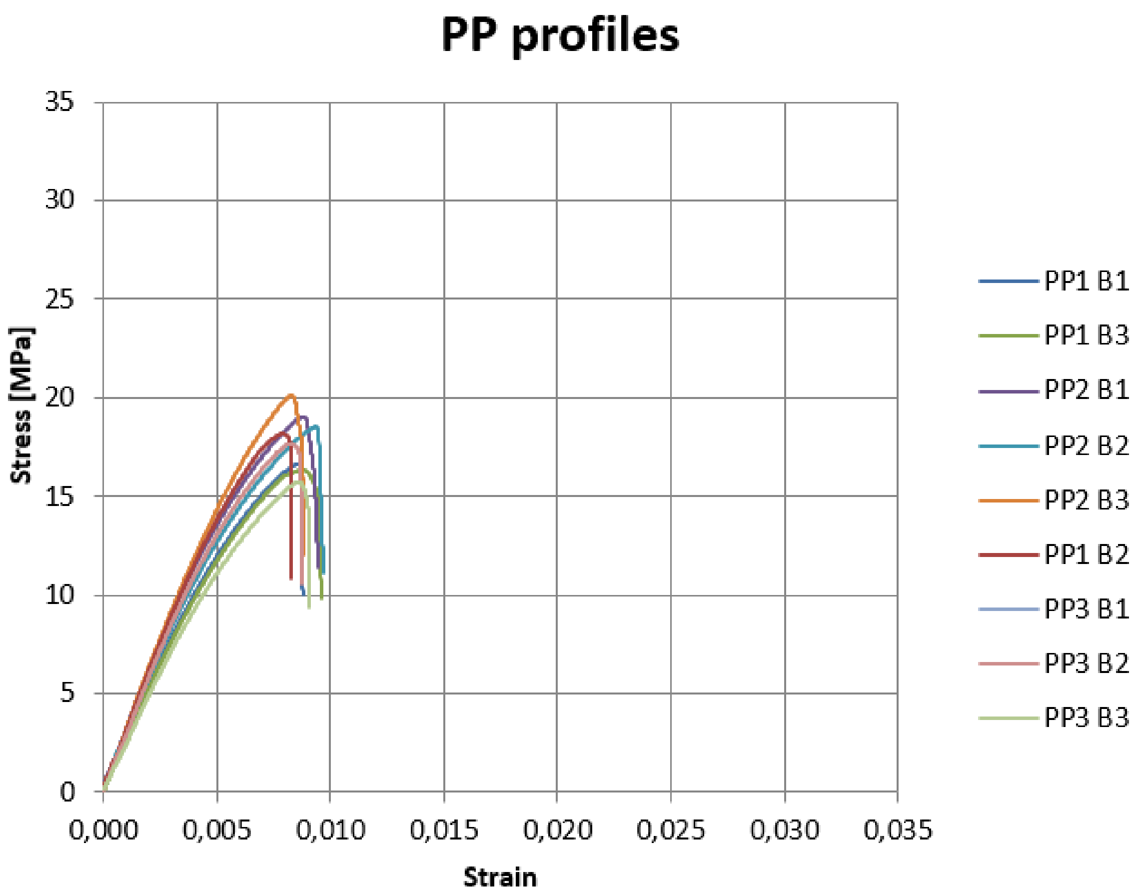
The variation of the flexural strength and modulus within each profile is visible in the table below:

	Flexural Strength σmax		**Flexural Modulus Ef**	
	average; MPa	Variation; MPa	average; MPa	Variation; MPa
PE1	25,7	1,8	2827,7	282,4
PE2	27,1	2,7	3093,8	388,8
PE3	26,8	3,4	3156,2	371,3
PP1	17,0	1,1	2822,4	256,6
PP2	19,2	0,9	3078,5	180,5
PP3	16,3	0,7	2525,8	365,9

The variation of these properties between the different profiles of one material is visible in the table below:

	Flexural Strength σmax		**Flexural Modulus Ef**	
	average; MPa	Variation; MPa	average; MPa	Variation; MPa
PE	26,5	3,6	3025,9	501,5
PP	17,5	2,6	2808,9	588,6


PE profiles
Stress [MPa]
35
30
25
20
15
10
5
0
0,000
0,005
0,010
0,015
0,020
0,025
0,030
0,035
Strain
PE1 B1
PE1 B2
PE1 B3
PE2 B1
PE2 B2
PE2 B3
PE3 B1
PE3 B2
PE3 B3


PP profiles
Stress [MPa]
35
30
25
20
15
10
5
0
0,000
0,005
0,010
0,015
0,020
0,025
0,030
0,035
Strain
PP1 B1
PP1 B3
PP2 B1
PP2 B2
PP2 B3
PP1 B2
PP3 B1
PP3 B2
PP3 B3

Appendix 9

Results tensile test

MEASURED RESULTS

Specimen	a_0 (thickness) [mm]	b_0 (width) [mm]	A_0 [mm^2]	F_{max} [N]
PE1 T1	6,23	9,97	62,11	956,0
PE1 T2	6,26	9,99	62,54	962,0
PE1 T3	6,35	10,23	64,96	982,9
PE2 T1	6,13	10,46	64,12	934,0
PE2 T2	6,13	10,23	62,71	871,8
PE2 T3	6,16	10,23	63,02	950,1
PP1 T1	6,61	9,91	65,51	730,3
PP1 T2	6,64	9,92	65,87	660,0
PP1 T3	6,62	9,96	65,94	716,2
PP2 T1	6,68	10,25	68,47	701,4
PP2 T2	6,65	10,21	67,90	760,4
PP2 T3	6,68	10,1	67,47	639,1

CALCULATED RESULTS

With the results above and the following formulas, the properties from the table below could be calculated:

$$\sigma max = \frac{Fmax}{A}$$

$$\varepsilon = \frac{\Delta L}{L0}$$

with L_0 being the support span and ΔL being the travel at a given moment. The E-modulus is obtained by calculating the direction on the linear elastic curve of the graph of each specimen.

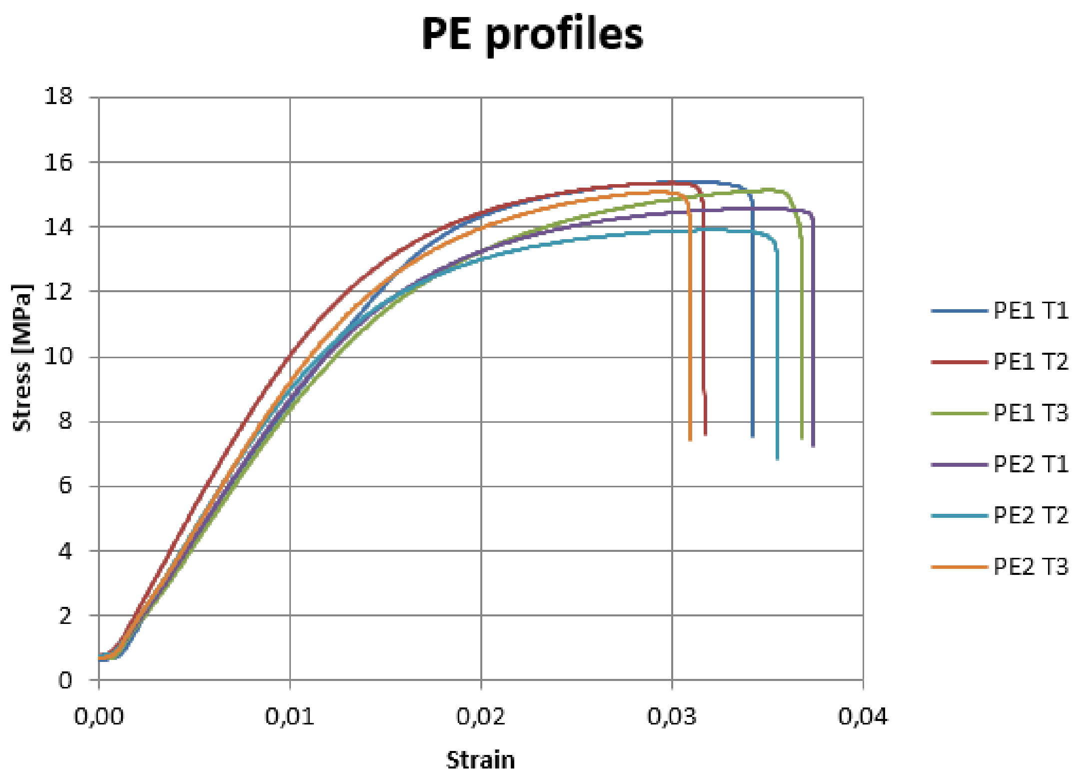
Specimen	**Tensile strength σ_{max} [MPa]**	**E-modulus [MPa]**
PE1 B1	15,4	866,44
PE1 B2	15,4	1054,38
PE1 B3	15,1	856,44
PE2 B1	14,6	889,53
PE2 B2	13,9	937,38
PE2 B3	15,1	943,48
PE3 B1	11,1	821,34
PE3 B2	10,0	878,79
PE3 B3	10,9	715,91
PP1 B1	10,2	957,21
PP1 B2	11,2	899,92
PP1 B3	9,5	849,86
PP2 B1	15,4	866,44
PP2 B2	15,4	1054,38
PP2 B3	15,1	856,44
PP3 B1	14,6	889,53
PP3 B2	13,9	937,38
PP3 B3	15,1	943,48
Average PE	14,9	924,6
Average PP	10,5	853,8

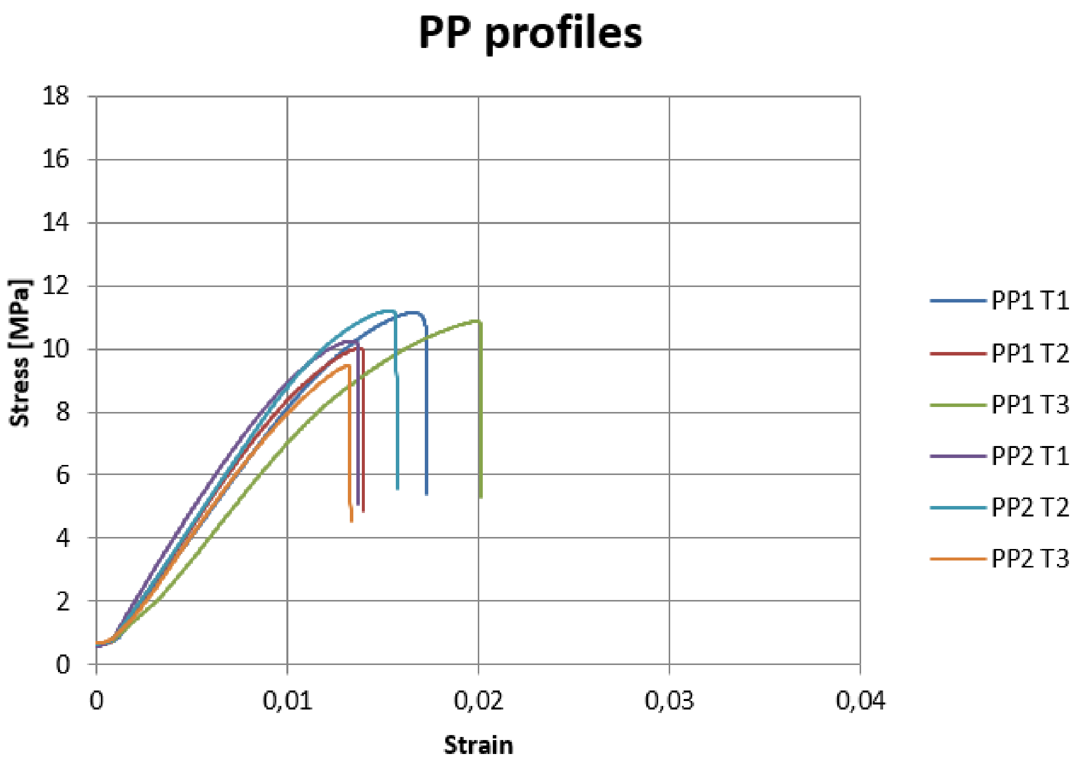
The variation of the flexural strength and modulus within each profile is visible in the table below:

	Tensile strength σ_{max}		**E-modulus**	
	average; MPa	Variation; MPa	average; MPa	Variation; MPa
PE1	15,3	0,2	925,8	128,6
PE2	14,5	0,6	923,5	33,9
PP1	10,7	0,7	805,3	89,4
PP2	10,3	0,9	902,3	54,9

The variation of these properties between the different profiles of one material is visible in the table below:

	Tensile strength σ_{max}		**E-modulus**	
	average; MPa	Variation; MPa	average; MPa	Variation; MPa
PE	14,9	1,0	924,6	129,8
PP	10,5	1,0	853,8	137,9


PE profiles
Stress [MPa]
18
16
14
12
10
8
6
4
2
0
0,00
0,01
0,02
0,03
0,04
Strain
PE1 T1
PE1 T2
PE1 T3
PE2 T1
PE2 T2
PE2 T3


PP profiles
Stress [MPa]
18
16
14
12
10
8
6
4
2
0
0
0,01
0,02
0,03
0,04
Strain
PP1 T1
PP1 T2
PP1 T3
PP2 T1
PP2 T2
PP2 T3

Appendix 10

Calculations density

VOLUME FRACTION

As visible in appendix 7, the weight fractions are now available of the different materials in the profiles. However for many calculations on composite materials, the volume fractions are necessary. The formula to calculate the volume fraction of for example glass fiber in the PP and PE profile is (derived from Nijhof, 2004):

$$Vgf(pp) = \frac{Mgf}{Mgf + \rho gf \cdot (\frac{Mm}{\rho m} + \frac{Mw}{\rho w} + \frac{Mpp}{\rho pp})}$$

$$Vgf(pe) = \frac{Mgf}{Mgf + \rho gf \cdot (\frac{Mm}{\rho m} + \frac{Mw}{\rho w} + \frac{Mpe}{\rho pe})}$$

of which:
V = volume fraction
M = weight fraction
ρ = density
gf = glass fiber
m = matrix (epoxy/polyester)
w = wood
pp = polypropylene
pe = polyethylene

To simplify this calculation, the additive materials are considered as being PP or PE material. A similar formula can be used for calculating the other volume fractions. The resulting fractions are:

$V_{gf,pp} = 0.036$
$V_{m,pp} = 0.046$
$V_{w,pp} = 0.571$
$V_{pp} = 0.347$

$V_{gf,pe} = 0.037$
$V_{m,pe} = 0.046$
$V_{w,pe} = 0.581$
$V_{pe} = 0.335$

DENSITY

The density of the composite can be calculated based on the content information of the profiles with the use of the rule of mixtures (Nijhof, 2006):

$\rho c,pp = \rho gf \cdot Vgf,pp + \rho m \cdot Vm,pp + \rho w \cdot Vw,pp + \rho pp \cdot Vpp$

$\rho c,pe = \rho gf \cdot Vgf,pe + \rho m \cdot Vm,pe + \rho w \cdot Vw,pe + \rho pe \cdot Vpe$

in which ρgf, ρm, ρw, ρpp and ρpe are the densities of the glass fibers, epoxy/polyester matrix, wood, polypropylene and polyethylene respectively and V is the volume fraction the material within the composite.

To simplify the calculation, the additives are not specified separately but will be included in PP and PE. This means that the volume fraction of these materials will be slightly higher. Together with the material properties of E-glass, PE, HDPE, Scots pine and polyester specified in appendix 7 and calculations of the volume fractions, the calculated densities are:

$\rho c,pp = 0.785$ gram/cm3 $\rho c,pe = 0.799$ gram/cm3

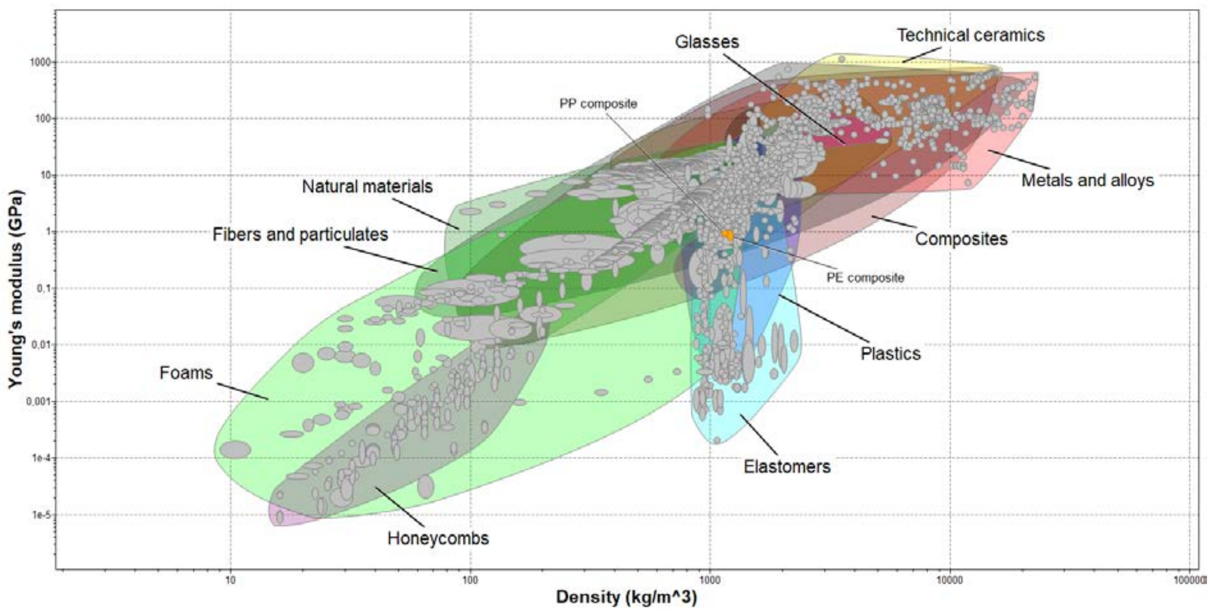
When this calculation is compared with the measured density, it becomes clear that the calculated values are significantly lower than the measured ones. This can mean that the used properties of the material are not corresponding with the reality. This can be caused by multiple aspects:

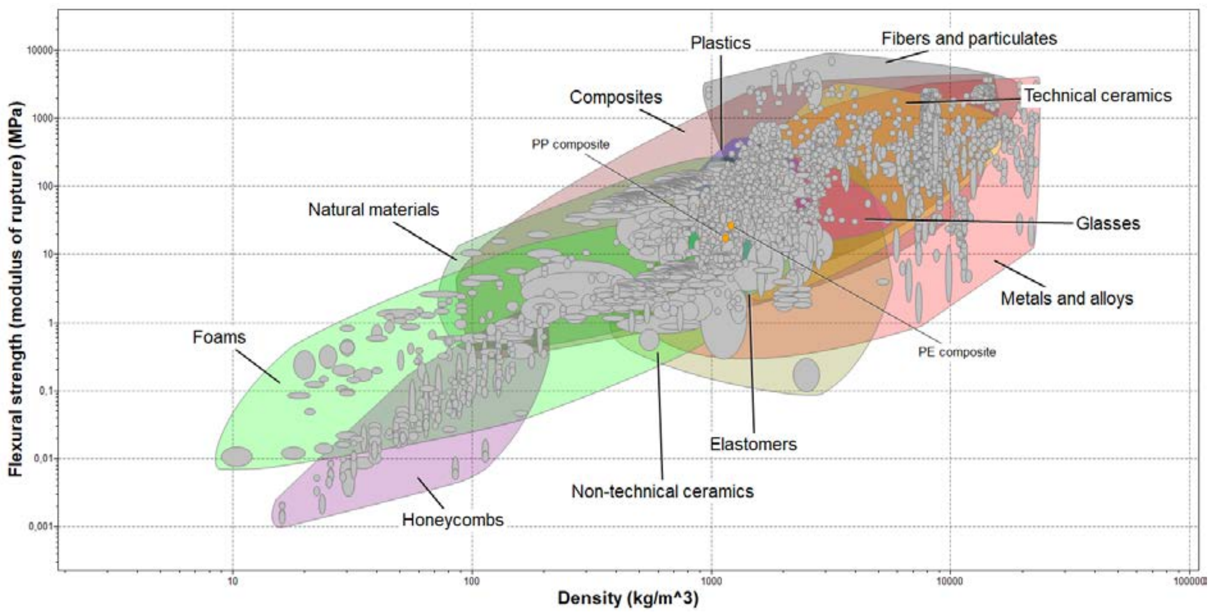
- The 12% weight fraction of glass fiber specified by the production company is not corresponding with the reality. As shown in the burn-off test, the residue was 10% of the original weight. This means that less glass fiber was present in the sample. However lowering the weight fraction of the fibers and rising that of the matrix material has almost no effect on the calculation of the density.
- The density values used in the calculation are not corresponding well to the reality (the values used can be found in appendix 7). Using the properties of the Scots pine instead of the Norway spruce causes a rise in the density. According to CES EduPack 2017 the upper bound of the densities of epoxy and polyester are both similar to the used value so this value should not be causing the fault. The same is true for PP and PE. Also the glass fiber density seems to correspond well with available sources.
- The additive materials have a density that is strongly differentiating from PP or PE which makes the simplification an incorrect representation of the reality. However, the additives are only corresponding to 10 wt%, so this influence should be limited.

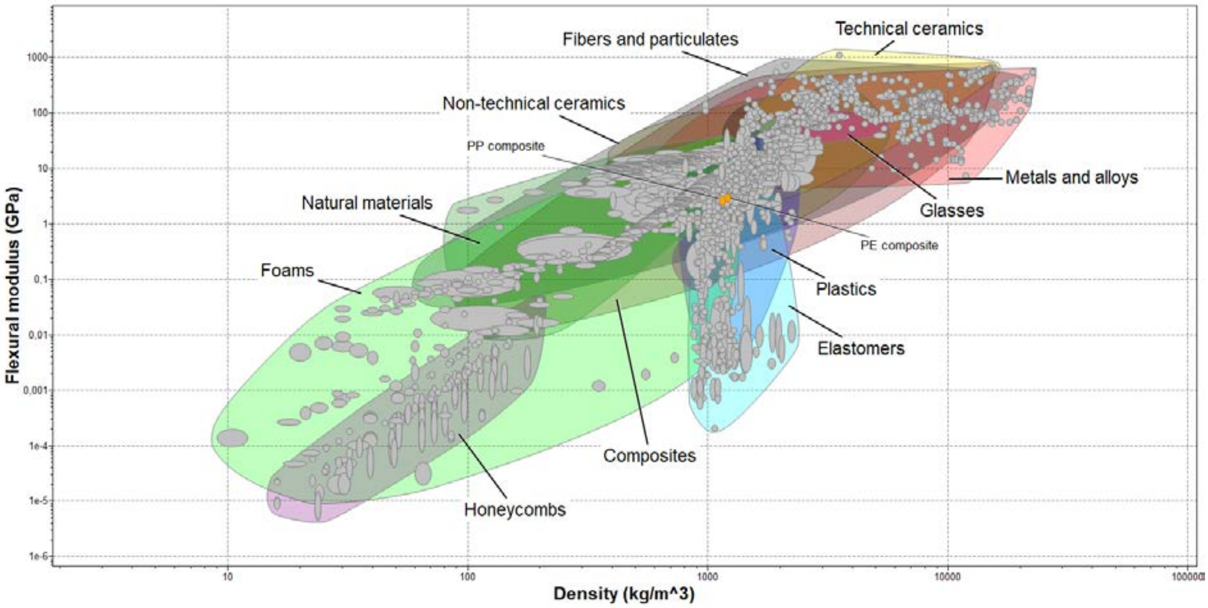
Appendix 11

CES charts

COMPARISON TO ALL MATERIALS

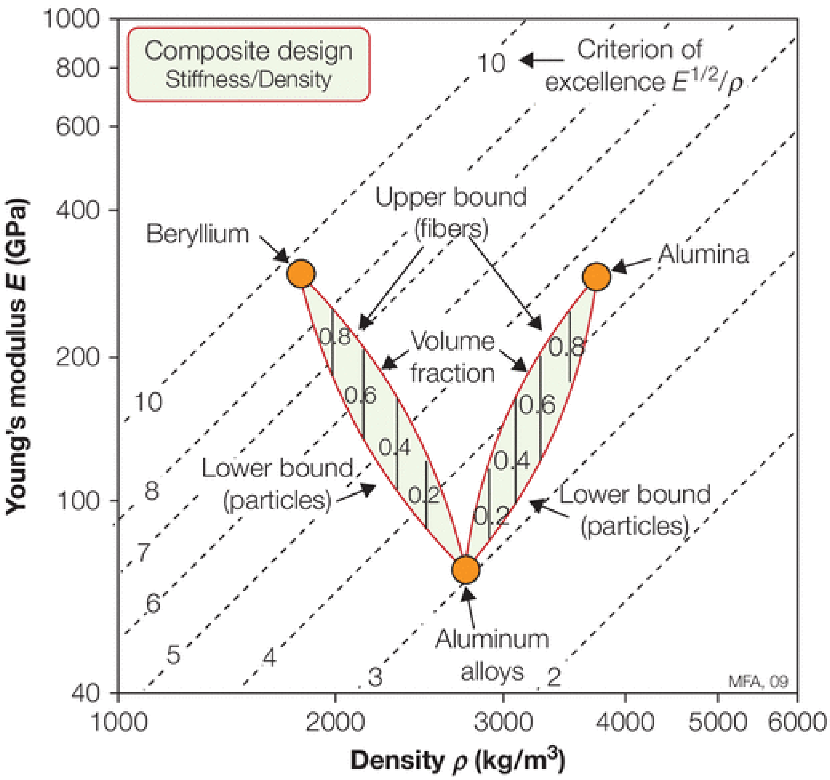




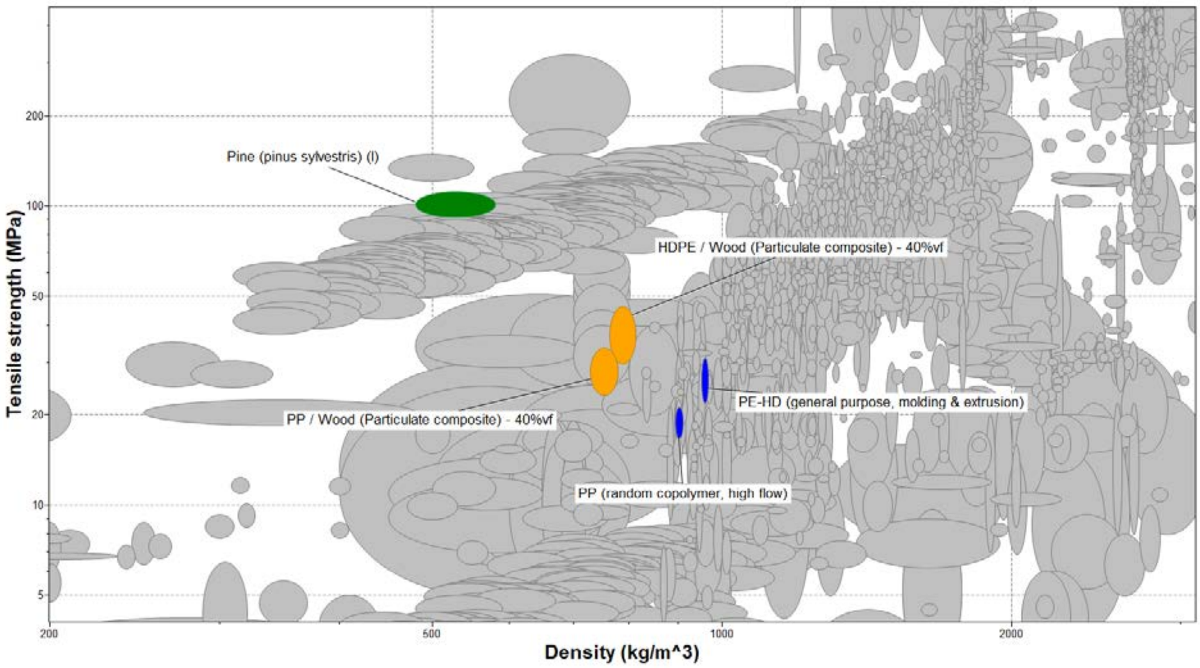


PLACEMENT WITHIN SEPARATE MATERIALS OF COMPOSITE

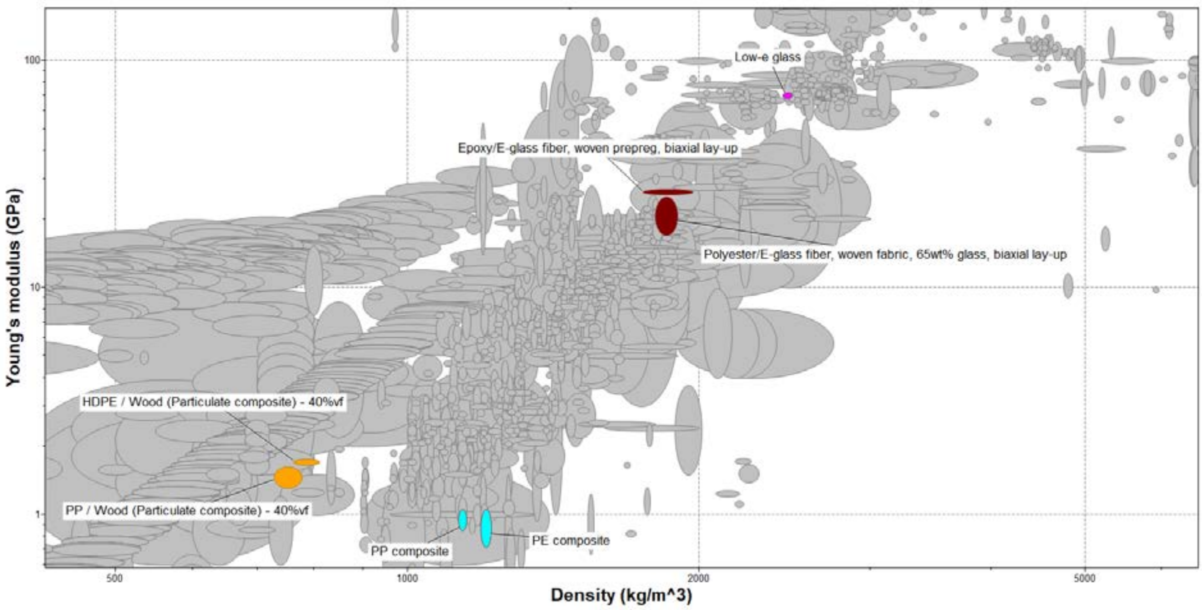
All content materials of the profiles can be plotted to locate where the composite is located relative to these materials. As visible in the figure below, Ashby (2011) shows how you can do this using the the properties of the two composition materials.

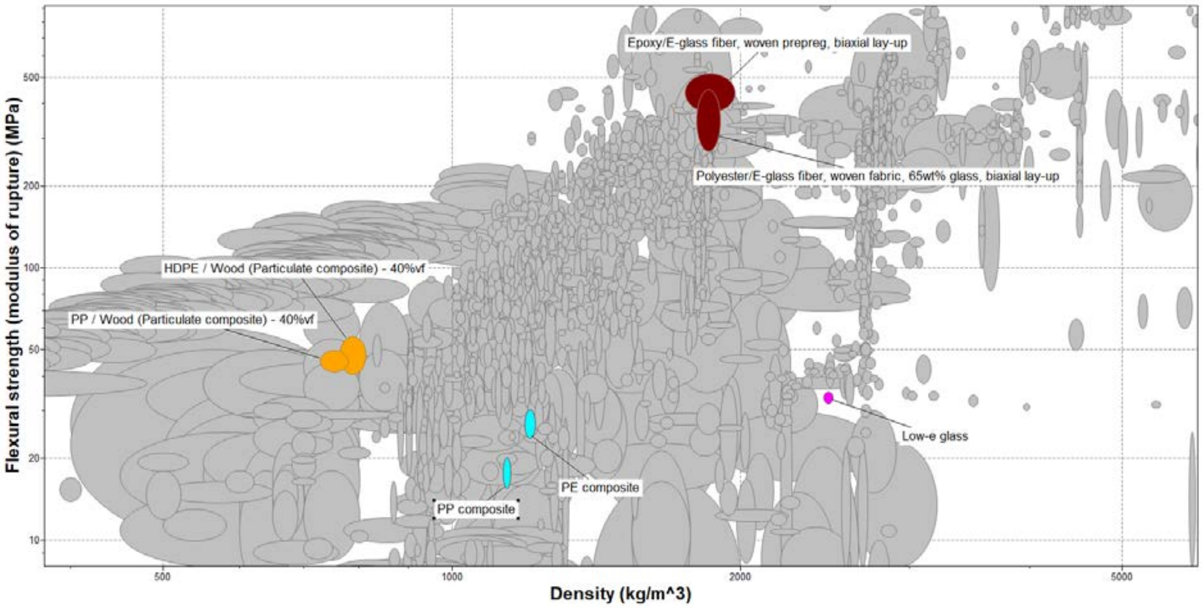


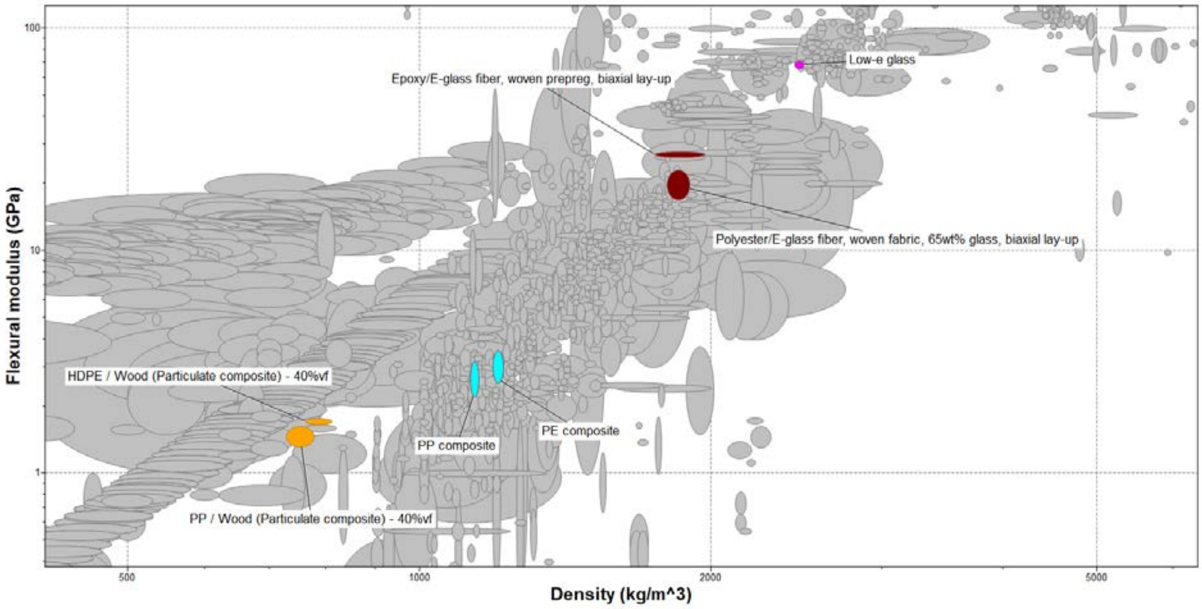
However, the profiles consist of more than two materials. Therefore, first a wood and PP/PE composite (WPC) is created with the synthesizer tool in CES Edupack 2017. In the figure below, the location on this WPC can be seen. If the arches from the example of Ashby are imagined, the location of this composite seems to be correct.



Now this WPC can be used to be plotted together with the shredded composite. For the shredded composite, it is unclear if the properties of E-glass should be taken or those of glass-fiber epoxy. Therefore, both are plotted in the graphs. In the figure below, the results are visible for the different properties.







It can be seen that for the Flexural modulus, the profiles seem to be laying on the arches as it is supposed to. However for the other properties, the profiles seem to be scoring lower than expected.

Appendix 12

Material properties shredded composite

	Characteristic	**Glass fiber 55 wt-%**	**Polyester 45 wt-%**	**Epoxy 45 wt-%**	**Shredded composite**
GENERAL	*Price*	1.7 EUR/kg	2.75 EUR/kg	2.32 EUR/kg	0.1 EUR/kg*
	Aesthetics	Glistering, optical transparent	Transparent	Transparent	Translucent, anisotropic, glistering, rough surface
MECHANICAL	*Abrasive resistance*	Good	Good	Good	Good
THERMAL	*Maximum service temperature*	897 °C	130 °C	140 °C	130 °C
	Minimum service temperature	-273 °C	-73 °C	-73 °C	-73 °C
	Thermal conductivity	Fair; 0.8 W/m·°C	Poor; 0.293 W/m·°C	Poor; 0.34 W/m·°C	Fair
	Flammability	Non-flammable	Highly flammable	Slow-burning	Highly flammable
ELECTRICAL	*Electrical conductivity*	Poor	Poor	Poor	Poor
CHEMICAL	*Chemical resistance*	Excellent	Good	Excellent	Good
	UV resistance	Excellent	Good	Fair	Fair
	Water resistance	Excellent	Excellent	Excellent	Excellent

***Price of shredded composite**

The price of the shredded composite is especially determined by the costs of the mechanical recycling process. Currently, the supply of the material does not provide any costs, because the recycling company even receives a fee to handle the blades. However, it is difficult to predict the exact price of the shredded composite. Therefore the Professor of Circular Product Design at the TU Delft, Ruud Balkenende, is consulted who made the estimation that the shredded composite will cost 50 – 100 Euros per tonne.

Appendix 13

Markets and functions

With a brainstorm, potential markets for applications are determined. To get an idea of which characteristics of the shredded composite are most favorable for the different markets, a matrix is made which is visible below.

Characteristics ↓ / Markets →	Clothing	Consumer products	Data centra	Furniture public spaces	Boats	Sanitary	Home furniture	Lights	Building material	Paint/coating	Infrastructure	Glass	Automotive	Gravestones	Office/shope funriture	Boards	Isolation	Train/metro/bus
Appearance	○	○		○	○	○	○	○	○	○		○	○	○		○		○
Eletrical isolator		○	○						○								○	
Resistant to chemicals																		
Resistant to water	○	○		○	○	○	○	○	○	○	○		○	○		○	○	○
Abrasive resistant		○		○	○	○	○		○	○	○		○	○	○	○		○
Thermal isolator	○	○	○						○								○	
Sound isolator			○						○								○	
Light-weight	○	○		○	○		○	○	○		○	○	○	○		○		○

It is visible that the characteristics appearance, resistant to water, abrasive resistance and light-weight are most often useful in the selected markets. This means that probably the most possibilities are present in these characteristics of the material. Therefore, these will be focused on in the continuation of the project.

Appendix 14

Program of Requirements and Wishes

GENERAL		
	Requirements	***Wishes***
Vision	The product benefits from the specific characteristics, namely water and abrasive resistant, light-weight and appearance, of the shredded composite.	
	The shredded composite is visible in the product.	
Function	The product is visible when in use.	
	The product has functional because of the use of the shredded composite, which means that the product is better, more extensive, lighter (et cetera) due to the water resistant, abrasive resistant, light weight, structure and appearance characteristics of the shredded composite.	
	The product has sustainable value because of the use of the shredded composite, which means that the product is made of a sustainable material and can be recycled after its use.	
	The product is not carrying a significant load.	
		The product has functional, sustainable, economic, symbolic and emotional value because of the use of the shredded composite.
Shredded composite	The shredded composite is not only used as filler or reinforcement.	
		The shredded composite is substituting for an endangered, expensive, less good or unsustainable material resource.
		The shredded composite is used as large as possible.
Matrix material	The material does not disintegrate undesirably in the following use conditions: - Contact with water - Under forces occurring with normal use	
	The material is recyclable without the need of additional material.	

	The material is producible including the shredded composite.	
Market		The buyer of the product has a strong link with the origin of the material, for example because it is the supplier of the material.
		The market in which the product is functioning attaches value to sustainable alternatives.
		The product gets a higher value because of the link that it has with the origin of the composite material.
Quantity		The market has a size that fits the size of and variation in the supply of composite material.
Production	Medium to high production volume is possible with the production method.	
Safety	The product should not cause environmental, health or safety problems, by e.g. abrasion and loss of glass fibers.	
End of life	The end of life of the product is controllable and the product will be brought back for recycling.	
	FINAL DESIGN	
Function	The charger for electrical cars is meant for home or work use.	
	The product contains a fixed output cable.	
Shredded composite	The shredded composite should have a length of approximately 3 to 5 cm.	
	The shredded composite should have a thickness of maximum 1 mm.	
Matrix material	The material is recyclable.	
	The material is recycled or bio-based.	
	The service temperature of the material is between -50 and 50 ˚C.	
	The material has at least a fair resistance to UV radiation.*	The material has a good UV radiation resistance.*
	The material is transparent, translucent or has optical quality.*	
	The moldability of the material is scored with at least a 4.*	
	The material is at least acceptable resistant to fresh water.*	
	The material is polar, which means it has a carbonyl or hydroxyl group in its structure.	
		The price of the material should be as low as possible.

		The mechanical properties (yield, compression and tensile strength and E-modulus) should be as high as possible.
		The fracture toughness should be at least 2 MPa.m^0.5.
		The material is not highly flammable.*
		The material can at least endure limited use of gasoline.*
		The material can at least endure limited use of lubricating oil.*
		The material can at least endure limited use of diesel oil.*
		The recycle fraction in the current supply is as high as possible.*
		The machinability of the material is scored with at least a 3.*
Size	The size of the housing should have a minimum of length, width, thickness and volume of 160, 150, 52 mm and 2,2 dm^3.	
Safety	The shredded composite should not stick out from the surface.	
Shape	Minimum radii of 0.8 mm are used when produced with a male mold and of 0.4 mm for female molds.	
	The walls of the shape are slightly tapered to facilitate demolding.	
		Sharp corners should be avoided as much as possible due to the shape restrictions of the shredded composite.
End of Life	The components of the product can be disassembled.	

*This requirements are based on the classification used in CES EduPack 2017.

Appendix 15

Creative session

The steps taken in the creative session are explained in this appendix.

First, divergent topics were used to associate on to get familiar with the assignment. These topics were:

- Wind turbine
- Electricity
- Value
- Mass production
- Water resistance

Some topic seems to be distant from the assignment, however those were used to open up the mind and generate out-of-the-box ideas. The results can be seen on the sheets in the picture below (the creative session was in Dutch as well as the presented results in the pictures).

Secondly, brainwriting was done on several How Tos, namely:

- How to use a chemical resistant material?
- How to use snippets?
- How to use composite shreds as filler material?
- How to give value to cables?
- How to express appreciation?
- How to use light-weight material?
- How to demolish a wind turbine?

With this method, everybody is offered a How To question on which they can generate as much ideas as possible for several minutes. After this time, the questions will be rotated and the procedure will start again. This will be done until everybody has generated ideas on all topics. A pictures of the process can be found below.

Thirdly, the generated ideas were categorized with the C-box method in which they are located on an axial system based on their feasibility and innovativeness. The resulted classification can be found on the next page.

Fourthly, the participants could select the most valuable ideas from this classification by assigning them with a dot. Lastly, the participants formed groups of two and create a concept based on three ideas that they picked from the classification. These concepts were presented to each other, which was the conclusion of the creative session.

Classification of the ideas on innovativeness and feasibility

Appendix 16

Generated ideas

In this chapter, the relevant ideas that were generated can be found:

- Pallet
- Boiler housing
- Visible product to function as conversation starter
- Furniture
- Side table
- Skateboard
- Plant pots
- Replacement of tropical wood (railway sleepers, fender)
- Garbage cans
- In between foil
- Wind cheater
- OSB
- Tiles
- Housing of headlights of cars
- Hectometer poles
- Slats
- Rain barrel
- Surf board
- Toilet seat
- Corrugated sheets
- Emergency barrier
- Modular building blocks
- Raft
- Refugee boat
- Interior cars
- Mail box
- Electricity box
- Floor in truck
- Roof
- Moving boxes
- Groceries crate
- Outside furniture
- Kitchen counter
- Sink
- Replacement of wood chips
- Kitchen cabinets
- Filler in a heavy material
- Between two plates
- Container
- 3D printing with fibers
- Dampening floor
- Podium floor
- Paint bucket
- Gasoline tank
- Storage chemical waste
- Outlet
- Jerry can
- PCBs
- Snow globe
- Design lamp
- Key chain
- Cutting board
- Pavilion at the coast close to wind turbine park
- Filler material of beanbag, soccer ball et cetera
- Filler of buffer block
- Doormat
- In public space to counteract vandalism
- Binding of windows
- Reinforced glass
- Precast concrete products
- Isolator in high voltage mast
- Sound wall
- Protection against water erosion (at the coast)
- Sport equipment
- For transport of vulnerable materials
- Protection
- For on festivals
- Isolation
- Between walls
- Façade cladding
- Glass fiber wallpaper
- Paint with structure
- Bumper cuffs
- Imitation of (natural) stone
- Sidewalk tile
- Nose of protection shoes
- Products for the army
- Between glass
- Spraying on inside of tunnels
- Sanding paper
- Hiking gear
- Wrecking ball
- Filler of life vest
- In a bag or block
- For in a sandbox
- Mattress filler
- Office building of energy supply companies
- Bottom material of a suitcase
- Ikea furniture
- Terrazzo
- Smoke detector
- To give structure to material
- Small wind mills
- Grip on boat decks
- Floor of playground
- Anti-slip
- Beach houses
- Smart thermostat
- Train interior
- Park bench
- Charger for electrical cars
- Market stall

Appendix 17

Matrix material selection

Criteria

- The material does not disintegrate undesirably, for example when it comes in contact with water or a small force.
  - ✗ – The material does easily disintegrate.
  - ✓– The material does not easily disintegrate.
- The material is recyclable.
  - ✗ – The material is only recyclable with the addition of new matrix material.
  - ✓ – The material is fully recyclable without the need of additional material.
- The material is producible with shredded composite on a large scale.
  - ✗ – The material is not easily producible with shredded composite on a large scale.
  - ✓ – The material is producible with shredded composite on a large scale.

	Thermoset	Clay	Concrete	Rubber	Chalk	Alginate	Thermoplastic	Cover
Material does not disintegrate undesirable	✓	✗	✓	✓	✗	✗	✓	✗
Recyclability	✗	✗	✗	✗	✗	✗	✓	✓
Producibility with fibers on large scale	✓	✗	✓	✓	✓	✓	✓	✓

Appendix 18

Scoring on wishes

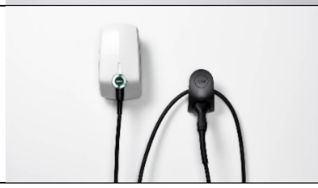
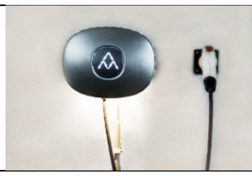
- Functional value

  The product is better, more extensive, lighter (et cetera) due to the water resistant, abrasive resistant, light weight, structure and appearance characteristics of the shredded composite.
  - 1 – The product is not better, more extensive, lighter (et cetera) due to one of the above mentioned characteristics of the shredded composite.
  - 5 – The product is better, more extensive, lighter (et cetera) due to all of the above mentioned characteristics of the shredded composite.
- Economic value
  - 1 – The costs of the product are not lower than with the currently most used material.
  - 5 – The costs of the product are lower than with the currently most used material.
- Sustainable value
  - 1 – The product is not made of a sustainable material and is not recycled after its use.
  - 5 – The product is made of a sustainable material and is recycled after its use.
- Symbolic value

  The product gives you a certain status (for example environmentally oriented) or represents something.
  - 1 – The product does not provide a certain status or represent something.
  - 5 – The product provides a certain status or represents something.
- Emotional value
  - 1 – The product is not attractive or enjoyable or evokes an emotional link.
  - 5 – The product is attractive or enjoyable or evokes an emotional link.
- Substituting material
  - 1 – The shredded composite is not substituting an endangered, expensive, less good or unsustainable material resource.
  - 5 – The shredded composite is substituting an endangered, expensive, less good or unsustainable material resource.
- Quantity
  - 1 – The quantity and size of the product doesn't fit the size of and the variation in the supply of composite material.
  - 5 – The quantity and size of the product fits the size of and the variation in the supply of composite material.
- Size shredded composite
  - 1 – The size of the shredded composite is particle size.
  - 5 – The size of the shredded composite is around 10 cm.
- Market
  - 1 – The buyer of the product has no link with the origin of the material.
  - 5 – The buyer of the product has a strong link with the origin of the material, for example because it is the supplier of the material.
- Sustainable market
  - 1 – The market in which the product is functioning attaches no value to sustainable alternatives.
  - 5 – The market in which the product is functioning attaches value to sustainable alternatives.
- Link with origin
  - 1 – The product does not get a higher value because of the link that it has with the origin of the composite material.
  - 5 – The product gets a higher value because of the link that it has with the origin of the composite material.

Appendix 19

Market research chargers

Brand	Home/work/public	Material	Lowest price	Dimensions	Picture
EV-Box Business-line	Work	Plastic (Bay-Blend) [1, 2], Polycarbonate [4]	€1082,95 [3]	600x250x200mm [30]	
EV-Box Elvi	Home	Polycarbonate	Not yet released		
EV-Box HomeLine	Home	Polycarbonate	€780,45 [6]	490 x 310 x 170 mm [29]	
EV-Box publicLine	Public	Stainless steel	€3495,- ex. Btw [5]		
Halo Charge Amps	Home/work/public	Aluminum [8]	€785,29 [7]	262.4 x 230.3 x 159.4 mm [31]	
ICU EVe	Work/public	Glass fiber polyester [12]	€2249,- [10]	590x338x230 mm [28]	
ICU Eve mini	Home/work	Polycarbonate [14]	€825,- [9]	370 x 240 x 130 mm [32]	

ICU Twin	Work/public	Stainless steel [13]	€3999,- [15]		
ICU Compact Mini	Home/work	Aluminum [11]	€459,- [11]	179 x 190 x 91mm [33]	
New Motion Lolo	Home/work/public	Plastic [17]	€849,- [16]	503,5 x 200 x 137 mm [34]	
LS24 Single [19]	Home	Polycarbonate	€569,50	200x200x120mm [35]	
LS24 Double [19]	Work/public	Polycarbonate [18]	€1165,-		
LS24 Column [19]	Work/public	Stainless steel	€883.29		
Ratio EV	Home/work	PC/ABS [21]	€485,- [20]	250x400x100 mm [36]	

Ratio Evita	Home/work	Polyurethane [22]	€2294,95 [23]		
KEBA KeContact	Home/work	Plastic [24]	€980,- [24]	440 x 200 x 140mm [37]	
Wallbox Copper	Home/work	Unknown	€1090,- [25]	254x163x52 mm [38]	
Wallbox Pulsar	Home/work	Unknown	€660,- [27]	160x160x90mm [39]	
Wallbox Commander	Home/work	Unknown	€990,- [26]	220x150x135mm [40]	

1. https://www.elektrobode.nl/products/ev-box-cover-business-line-ral5017-blauw-705017
2. https://www.plastics.covestro.com/en/Products/Bayblend
3. https://www.laadpaal24.nl/ev-box-businessline-laadpaal-type1-met-spiraal-kabel-1-fase-16a-37-kw
4. https://www.evbox.com/about
5. https://www.laadpunt.nl/laadpaal/ev-box-publicline/
6. https://www.laadpaal24.nl/ev-box-homeline-laadpaal-met-6-meter-kabel-1-fase-16a-3-7kw-incl-abonnement
7. https://www.laadpaal24.nl/halo-charge-amp-3-7-kw-16-a-type-1-met-5-meter-kabel
8. https://evcompany.eu/laadpalen/laadpalen/halo-laadpaal-elektrische-auto/
9. https://evcompany.eu/laadpalen/laadpalen/icu-eve-mini-laadpaal-elektrische-auto/
10. https://evcompany.eu/laadpalen/laadpalen/icu-eve-laadpaal-elektrische-auto/
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13. https://alfen.com/nl/icu-twin
14. https://alfen.com/sites/alfen.com/files/downloads/Handboek-EveMini.pdf
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16. https://evcompany.eu/laadpalen/uncategorized/new-motion-lolo-oplaadpunt/
17. https://designspuiterij.nl/the-new-motion-lolo-laadpaal-zink-uitgevoerd/
18. https://www.laadpaal24.nl/Files/2/50000/50461/Attachments/Product/99o13Jw11n5i50e756e07Mw9Z51ss467.pdf
19. https://www.laadpaal24.nl/ls24
20. https://www.laadkabelwinkel.nl/ratio-ev-charging-station-type-2-socket-1f16a
21. https://www.laadkabelwinkel.nl/ratio-ev-charging-station-type-2-socket-1f16a
22. https://www.ratio.nl/media/files/Tech.%20Information%20cable%2007BQ-F%203G2,50+1x0,75.pdf

23. https://www.4ev.nl/evita-laadpalen
24. https://www.laadkabelwinkel.nl/keba-kecontact-p30b-wallbox-type2-socket-22kw
25. https://www.wallbox.com/nl/producten/copper-cable/
26. https://www.wallbox.com/nl/producten/commander/
27. https://www.wallbox.com/nl/producten/pulsar/
28. https://www.flowcharging.com/nl_be/product/laadpaal-icu-eve-11-kw-duo/
29. https://www.flowcharging.com/nl_be/product/laadpaal-thuis-smart-11-kw/
30. https://www.samangroep.nl/wp-content/uploads/2015/12/BusinessLine-Datasheet.pdf
31. http://charge-amps.com/wp-content/uploads/2018/02/Product-sheet-HALO-Wallbox-11kW.pdf
32. https://www.flowcharging.com/product/laadpaal-icu-eve-mini-37-kw/
33. https://laadpalenexpert.nl/icu-compact-mini-laadpaal-kopen/icu-auto-oplader
34. http://www.vanleeuwenoplaad.nl/producten/lolo-3-7kw
35. https://www.elektramat.nl/thuislader-mode-3-1-fase-16a-vaste-kabel-type-2/
36. https://evcompany.eu/en/laadpalen/laadpalen/tesla-oplaadpunt/
37. https://www.keba.com/web/downloads/e-mobility/KeContact_KCP20_30_ih_en.pdf
38. https://www.wallbox.com/content/productos/wallbox-copper-type-1_en.pdf
39. https://www.wallbox.com/content/productos/wbplsr01-pulsar-tipo-1_en.pdf
40. https://www.wallbox.com/content/productos/wbcomm01-commander-tipo-1_en.pdf

Appendix 20

Production tests

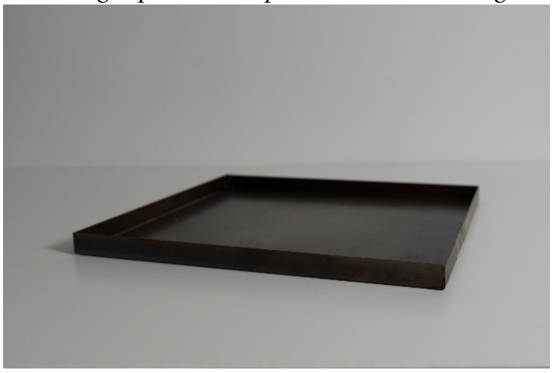
The production method is tested to experience the challenges that occur during these processes. First, a sheet should be produced included the shredded composite. After this, the sheet should be thermoformed in the desired shape. These two processes are tested of which the results are described below.

PRODUCING THE SHEET

Sheets are produced with various equipment, namely an oven, a t-shirt press and a heated press. Below, the results for each test will be explained.

Oven test

With the oven, several tests were executed with PETG sheets of 1 mm thickness (unless indicated otherwise):

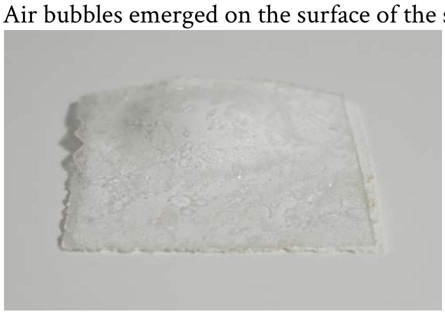
1. Two sheets in oven heated to 100 ˚C for 5 minutes. After this, the material has been taken from the oven and 8.4 kg is placed on top of the mold (see image below). Result: the two sheets were not melted together.

2. The two sheets from test 1 are heated to 200 ˚C for 5 minutes. After this, the material has been taken from the oven and 8.4 kg is placed on top of the mold. Result: the two sheets were fully melted together. The mold and the plastic have a brownish color, which could mean that the temperature was higher than necessary. Air bubbles were also visible inside the material.

3. Two sheets with shredded composite in between were heated to 145 ˚C for 5 minutes. After this, the material has been taken from the oven and 8.4 kg is placed on top of the mold. Result: the sheets were not fully melted together.
4. The two sheets with shredded composite in between from test 3 were heated to 160 ˚C for 10 minutes. The weight of 8.4 kg is placed on top of the mold while the sheets are heated. Result: the two sheets are melted together with the shredded composite between them. Many impurities are visible on the surface of the material and air bubbles are present within the material.

5. Two sheets with shredded composite are heated to 200 ˚C for 5 minutes. The weight of 8.4 kg is placed on top of the mold while the sheets are heated. Result: the two sheets are melted together with the shredded composite between them. Many impurities are visible on the surface of the material and air bubbles are present within the material.

6. The procedure of sample 5 was again followed to produce a larger sample. Result: the two sheets are melted together with the shredded composite between them. Many impurities are visible on the surface of the material and air bubbles are present within the material.

7. Two PMMA sheets of 1 mm thickness were heated: one colored white and the other transparent. They are heated to 200 ˚C for 10 minutes with 8.4 kg weight placed on top of the mold. Result: the two sheets did not sufficiently melt together. Air bubbles emerged on the surface of the sheets.



T-shirt press test

A t-shirt press is used for the second test to create sheets. The press was heated to 160 ˚C for all samples. When this temperature was reached, the sheets were placed between the press and heated for a certain time, without closing the press. After this heating time, pressure was applied for a certain amount of time. While this pressure was applied, the press was still heating the material. The thermoplastic sheets were placed on metal plates or baking paper before going into the press to prevent the material from sticking to the press.

The information on the different samples can be found in table 18.1. Pictures of the resulting sheets can be found afterwards. The numbers correspond with the information in the table.

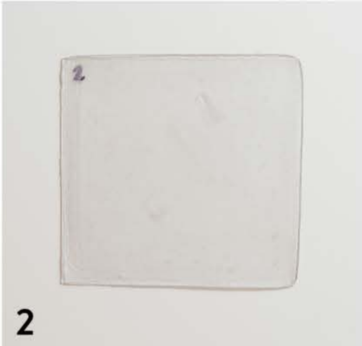
#	Thermoplastic	Shreds	Surface	Heating time	Pressure time	Other comments	Result
1	PETG* 2 sheets 1 mm	-	Baking paper both sides	-	2 min	Turned it around after 1 min	Translucent, little bit milky color, few air bubbles but less visible
2	PETG 2 sheets 1 mm	-	Baking paper both sides	-	2 min	Cooled with air pump	Translucent, less milky, some air bubbles that stick out on one side (side of flexible mat)
3	PETG 2 sheets 1 mm	-	One side metal (bottom), one side baking paper	-	2 min		Smooth on the metal side, larger air bubbles
4	PETG 2 sheets 1 mm	-	Metal both sides	-	2 min		Transparent, smooth on both sides, small air bubbles that create small dimples
5	PETG 2 sheets 1 mm	-	Metal both sides	1 min	2 min	Heating up next to each other and afterwards placed on top of each other	Transparent and smooth, only a few air bubbles
6	PETG 2 sheets 1 mm	Small fibers	Metal both sides	1 min	2 min	Heating up next to each other and afterwards placed on top of each other	Transparent, smooth, some air bubbles around fibers, only few between the sheets
7	PETG 2 sheets 1 mm	Small fibers	Baking paper both sides	-	2 min		Translucent, some air bubbles around the fibers and between the sheets
8	PETG 2 sheets 1 mm	Small fibers	Metal both sides	-	2 min		Transparent, smooth, some air bubbles around fibers, only few between the sheets
9	PETG 1 sheet 3 mm	Small fibers	Metal both sides	4 min	4 min		Transparent, smooth, fibers sticking out on bottom part, on top the fibers are really pushed into the surface, no air bubbles
10	PETG + PS** 1 mm	Small fibers	One side metal (bottom), one side baking paper	4 min	4 min	Only PET heating up, metal on PET side, baking paper on PS side	Did not melt together well, fibers went through the white
11	PETG 2 sheets 1 mm	Powder	One side metal (bottom), one side baking paper	2 min	4 min	Only bottom sheet heating up	Many small air bubbles, no air bubbles around the fibers

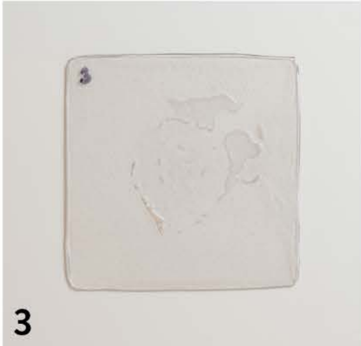
12	PETG 1 sheet 1 mm	Vertical fibers	One side metal (bottom), one side baking paper	6 min	2 min	In the same press as 11 and 13, so it was not fully pressed at first. 2 min extra to press it better	Smooth, no air bubbles, small relief due to the fibers
13	PETG 2 sheets 1 mm	Grid fibers	One side metal (bottom), one side baking paper	2 min	4 min	Only bottom sheet heating up	Small relief on baking paper side, few air bubbles, not around the fibers, lot of small air bubbles
14	PETG 2 sheets 1 mm	Large fibers	One side metal (top), one side baking paper	2 min	4 min	Only bottom sheet heating up	Many small air bubbles, air bubbles around the fibers that caused dimples, relief on the backing paper side
15	PETG 2 sheets 1 mm	Powder	One side metal (bottom), one side baking paper	2 min	2 min	Only bottom sheet heating up	Some steam seemed to appear between the layers, not many air bubbles
16	PETG 2 sheets 1 mm	Small fibers	One side metal (bottom), one side baking paper	2 min	4 min	Only bottom sheet heating up	many small air bubbles, and some air bubbles around the fibers
17	PETG 2 sheets 1 mm	Small fibers	Baking paper both sides	2 min	4 min	Only bottom sheet heating up	small air bubbles, some air bubbles around the fibers

Table 18.1 – Information on material samples

*Polyethylene terephthalate glycol-modified
** Polystyrene


1


2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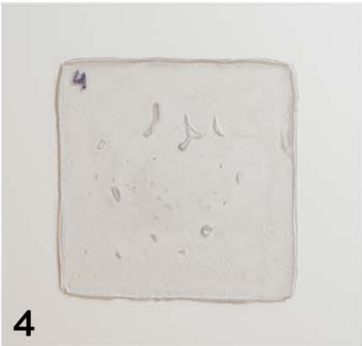
4


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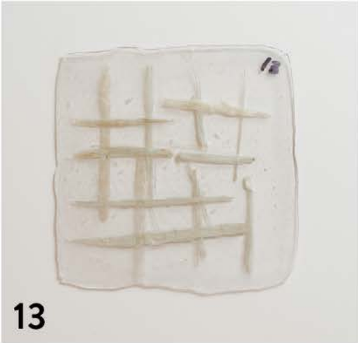
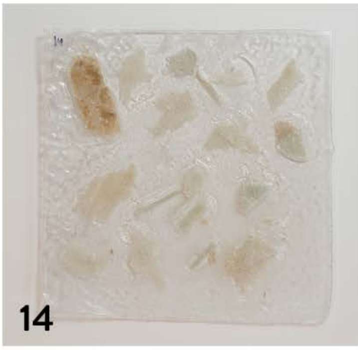
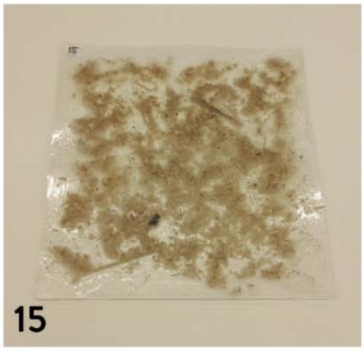
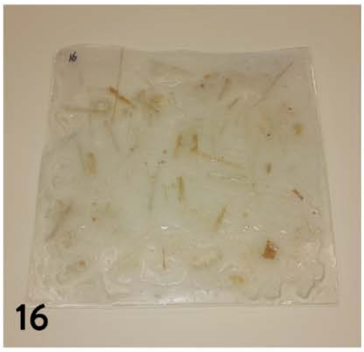


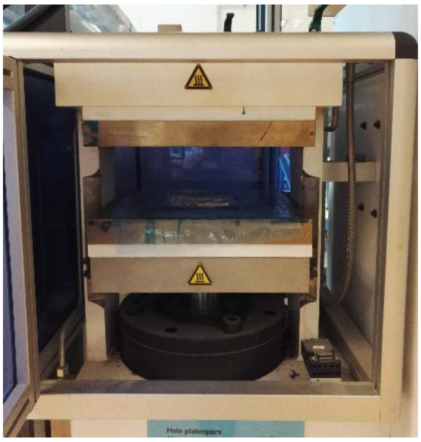






Heated press test

Eventually, a heated press from Fontijne Presses was used to execute a third test. With this press, the sheets were placed on the bottom sheet after which the press was first heated to 160 ˚C. After this, the press would start applying a pressure of 30 kN for 2 minutes. After this, the press would cool down to 60 ˚C while still applying pressure. Once this temperature was reached, the pressure was released and the sheets could be removed from the press.



The following samples were created of PETG sheets with 1 mm thickness (unless indicated otherwise):

1. Two sheets without shredded composite. Result: a smooth sheet with little air bubbles.

2. Sheet #8 from the t-shirt press test. Result: a smooth sheet with shredded composite with little air bubbles.

3. Two sheets with dried shredded composite in between. Result: a smooth sheet with shredded composite with little air bubbles.

4. Two sheets with undried shredded composite in between. Result: a smooth sheet with shredded composite with little air bubbles.

5. One sheet of 2 mm thickness with shredded composite on one side. Result: a smooth sheet with shredded composite with little air bubbles.

THERMOFORMING THE SHEET

Two tests have been done on vacuum forming a sheet with shredded composite. In the first test, two separate sheets with shredded composite between the layers are taped together. These loose sheets are directly thermoformed to see if the sheet would melt together. It turned out that the heating temperature was not high enough to really melt the sheets together. Because of this, the shredded composite was still loose between the layers.

The second test was done with a sheet produced with the oven test. The result showed that vacuum forming is definitely possible with the material. However, some shreds were not flexible enough to bend according to the molds. This caused impurities in the final part.

Appendix 21

Thermoplastic selection

The values below are originally from CES EduPack (2017) Level 2. The red values indicate which values are significantly lower and are not or less sufficient for the application.

	PA	*PC*	*PET*	*PHA*	*PMMA*
Price	2.31-2.51 EUR/kg	3.04-3.26 EUR/kg	1.64-1.67 EUR/kg	5.37-6.27 EUR/kg	2.47-2.57 EUR/kg
E-modulus	2.62-3.2 GPa	2-2.44 GPa	2.76-4.14 GPa	0.8-4 GPa	2.24-3.8 GPa
Yield strength	50-94.8 MPa	59-70 MPa	56.5-62.3 MPa	35-40 MPa	53.8-72.4 MPa
Tensile strength	90-165 MPa	60-72.4 MPa	48.3-72.4 MPa	35-40 MPa	48.3-79.6 MPa
Compressive strength	55-104 MPa	69-86.9 MPa	62.2-68.5 MPa	40-45 MPa	72.4-131 MPa
Fracture toughness	2.22-5.62 MPa.m^0.5	2.1-4.6 MPa.m^0.5	4.5-5.5 MPa.m^0.5	0.7-1.2 MPa.m^0.5	0.7-1.6 MPa.m^0.5
Maximum service temperature	110-140 ℃	101-144 ℃	66.9-86.9 ℃	60-80 ℃	41.9-56.9 ℃
Minimum service temperature	-123- - 73.2 ℃	-123- - 73.2 ℃	-123- - 73.2 ℃	-70- -60 ℃	-123 - -73.2 ℃
Transparency	Translucent	Optical quality	Transparent	Transparent	Optical quality
UV radiation (sunlight)	Fair	Fair	Good	Good	Good
Flammability	Slow-burning	Slow-burning	Highly flammable	Highly flammable	Highly flammable
Gasoline resistant	Excellent	Excellent	Excellent	Acceptable	Excellent
Diesel oil resistant	Excellent	Acceptable	Excellent	Limited use	Excellent
Lubricating oil	Acceptable	Excellent	Excellent	Limited use	Excellent
Recycle fraction	0.5 - 1 %	0.5 - 1 %	20 - 22 %	0.5 - 1 %	0.5 - 1 %
Machinability	3 - 4	3 - 4	3 - 4	4 - 5	3 - 4

Appendix 22

Dimensions chargers

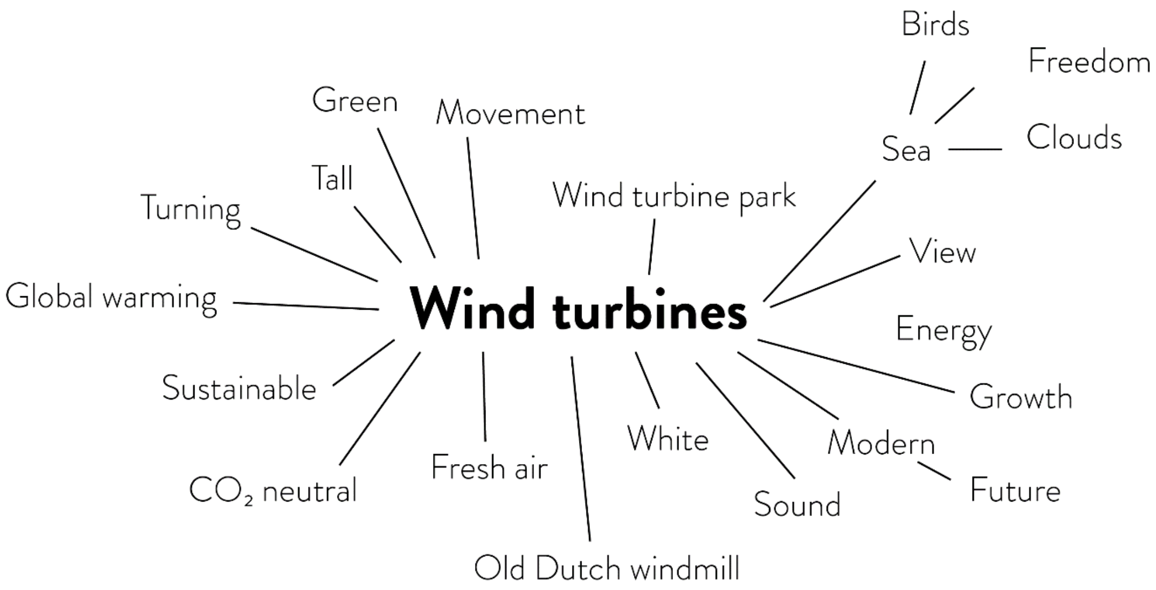
The dimensions listed in appendix 19 are also visible in the table below. For the length, width and thickness the average, highest and lowest values are determined. Also the volumes of the chargers are determined. The highest values are assigned with a red color and the lowest with a green color.

	Length (mm)	**Width (mm)**	**Thickness (mm)**	**Volume (dm^3)**
	190	179	91	3,1
	600	250	200	30,0
	490	310	170	25,8
	262,4	230,3	159,4	9,6
	590	338	230	45,9
	370	240	130	11,5
	503,5	200	137	13,8
	200	200	120	4,8
	400	250	100	10,0
	440	200	140	12,3
	254	163	52	2,2
	160	160	90	2,3
	220	150	135	4,5
Average	**360**	**221**	**135**	**14**

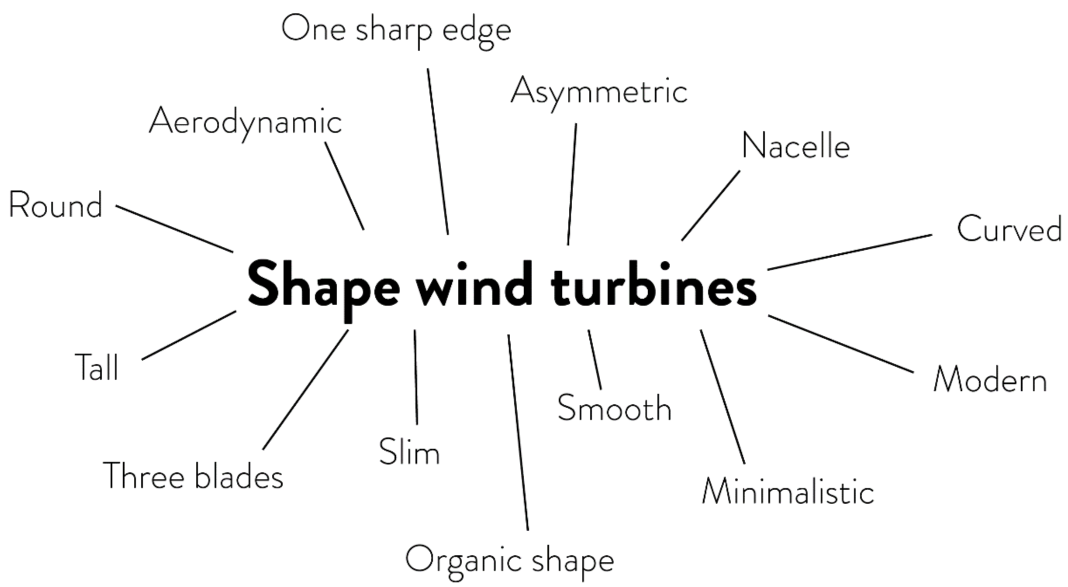
Appendix 23

Designing the shape

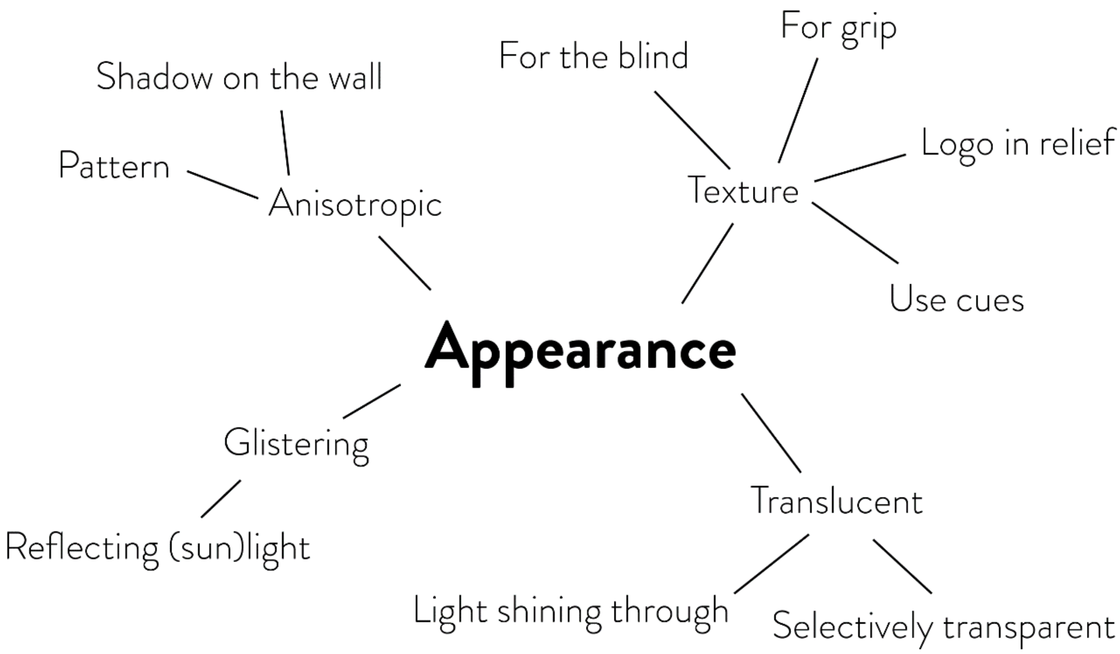
In the creative session held during the ideation phase, associations were made on wind turbine. The results are visible in the figure below.



Next to this, the shape of the wind turbines were evaluated. The results from this evaluation are visible below.



Eventually, possibilities to use the appearance of the shredded composite inside the product are generated:



Appendix 24

Clay models of shapes

Different clay models have been created to evaluate shapes for the design of the charger. Pictures of the clay model can be found below.

TU Delft