The strength and ductility of glass fibre reinforced 3D-printed polypropylene

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The possibility of using a mix of recycled polypropylene (PP) with new glass fibre reinforced polypropylene as a materials source for 3D printed engineering components is investigated. The strength and elongation to fracture are determined for various grades of material and in relation to the print direction. The measured values are compared with literature values for these materials in an as new condition. It is shown that the use of recycled PP degrades the material properties. PP recycled from house hold waste has significantly worse properties than PP recycled from industrial waste.

The technical possibilities for 3D printed engineering components based on this reused waste material are discussed.

Key words: Strength, recycling, polypropylene, 3D printing

1 Introduction

The last years, there are attempts to investigate the applicability of large-scale 3D printing components in the construction industry. DUS architects have developed the concept of the canal house with 3D printed components. Van der Veen [7] has looked at the feasibility of using 3D printed components of plastic. Baran [1] has looked at possibility of using 3D printed polymers as a mould for concrete to create unique building components.
As the technology shows promising results and meets the wish of many architect to create unique components or buildings it is expected that there will be a market introduction in the coming years. From an environmental point of view, the problem however is that large scale usage of virgin plastic to create an essentially disposable mould means using a lot of primary material and energy. Utilizing recycled plastics as the raw material for 3D printed

moulds or components is a more practical way to create these moulds while significantly reducing the environmental impact. The use of recycled high density polyethylene has been investigated by [2]. However, there are polymers which are more interesting because they have more suitable properties.

Looking at the common thermoplastic polymers, Polypropylene is the most suitable candidate. According to Plastics Europe 18.9% of the plastic used in Europe is PP, 8.8 MTonne a year. PP is the single most used plastic. It has better mechanical properties than polyethylene and most of the other bulk plastics. It also has the right thermal properties for 3D printing processes.

As recycled polypropylene has a significantly lower strength than virgin polypropylene, as for instance demonstrated by [4] and [5]. In many cases it is mixed with virgin polypropylene and fibres to obtain adequate properties, as demonstrated by [3].

For this research different mixtures of recycled, re-recycled and virgin polypropylene with short glass fibres were tested to look at the various factors influencing the overall properties. This research focussed on the failure strength and strain of the material as these are good indicators for materials performance and are also suitable to compare the different mixtures.

2 Experimental approach

Mixtures of recycled, re-recycled and virgin polypropylene with short glass fibres were blended. These were 3D printed into sheets by inserting the material into a heated extruder. The extruder has four heated chambers (T0 – 50 ºC, T1 - 180 ºC, T2 - 190 ºC, T3 - 200 ºC) and a heated Nozzle (TN - 240 ºC).

The sheet is printed by extruding melted material at 40 mm/s speed onto a flat platform. From the sheets dog bone specimens, as drawn in figure 1, were cut using a laser cutter. These specimens were tested using a Zwick z10 universal testing machine with Test Expert 4.12 software. A constant displacement rate of 10 mm a minute was used. Force and displacement were recorded. The different mixtures used are summarized in Table 1. For mixtures 1 and 2 the properties were determined in the print direction, 0°, at 45° to the print direction and at 90° to the print direction. Mixtures 3, 4 and 5 were only tested in the 0° direction in order to allow comparison between the mixtures. Figure 1 illustrates the specimen and figure 2 the test set-up.

Table 1: Mixtures investigated

mixture	recycled PP (%)	recycled PP source	virgin PP (%)	short glass fibre (%)
1	60	industrial	28	12
2	80	industrial	14	6
3	Rerecyled 3D print material			12
4	Rerecyled 3D print material			6
5	60	domestic	28	12

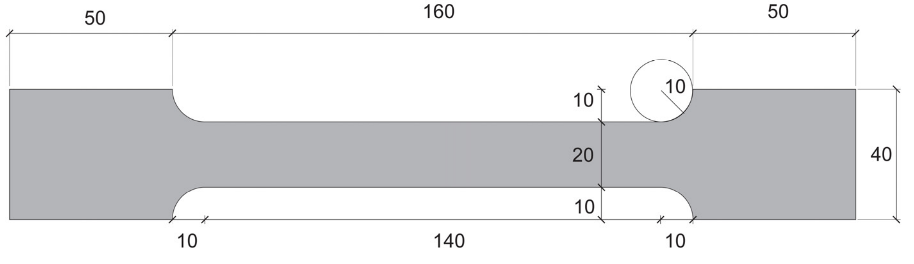
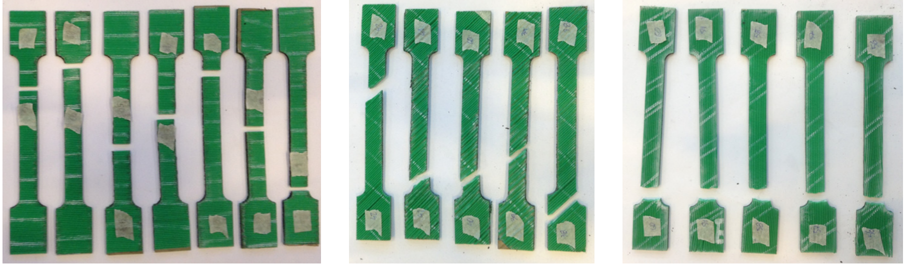


Figure 1: Test specimen (the dimensions are in mm)

Figure 2: Test setup : Zwick z10 universal testing machine with Test Expert 4.12 software

3 Results

The test results are given in appendix A in tables 2 to 10. They are provided so that the reader can further analyse the data if he wants. Table 11 gives a data base data for virgin material. Figure 3 shows specimens after testing to give a better idea of the result.



0° 45° 90°

Figure 3: Tested specimens for the three print directions

4 Discussion

In all cases the scatter in results is quite considerable. In the 0° direction the scatter is less than in the other directions. It is however clear that recycling degrades the predictability of the strength. There is also no clear relationship between tensile strength and fracture strain. Figure 4 shows the failure strength plotted against the fracture strain for mixture 1. The results appear quite random suggesting that the material is not very homogeneous. For the other mixtures the results are essentially the same as can be seen in figures 5, 6 and 7.
The results clearly show that the properties are very anisotropic, as can be seen in figure 4. The mixture 1 0° direction specimens are much stronger than the mixture 1 45° and 90° specimens. For mixture 2 the same can be seen in figure 5. This implies that in any design the print direction has to be taken into account and the structure modelled using direction dependent properties. As the material is a composite, this is not illogical or unreasonable, but does mean that the engineering effort will be much greater than with conventional materials.
The quality of the recycled material is also an important factor. As can be seen in figure 4, the best samples of mixture compare in terms of failure strength and failure strain with database data for virgin material. The average of the strength of mixture 1 is only some 85% of the average strength of the virgin 10% glass fibre filled polypropylene homo

polymer. Recycling the print, however, causes a considerable decrease in properties as is evident from figures 6 and 7 where the original mixture is compared with recycled print material. On average there is a 35% loss of strength , although there is no significant effect on the strain at failure.

Using household waste as a source for the recycled polypropylene is however also a cause for degradation of properties. Comparing mixtures 1 and 5, in figure 6, which use industrial and domestic waste as a source respectively, shows a 45% decrease in failure

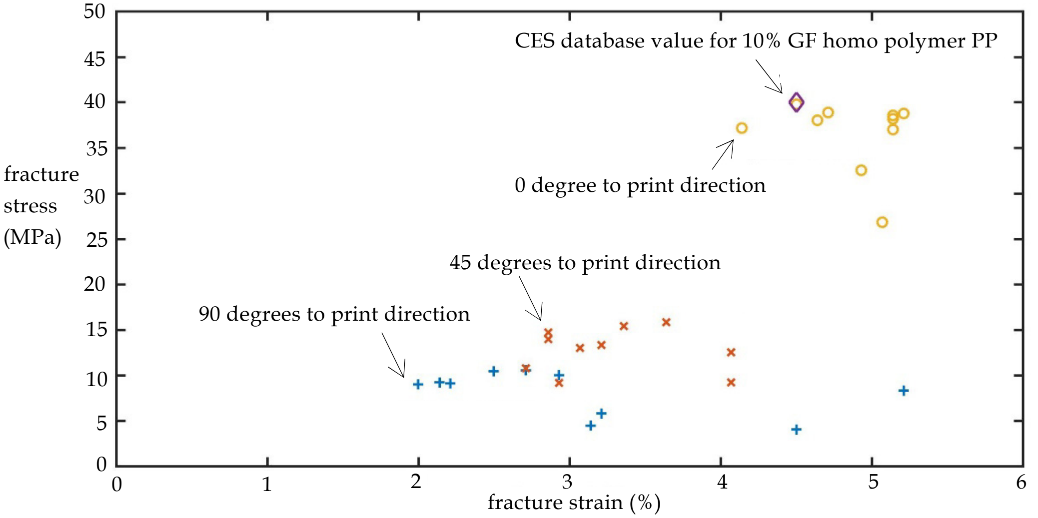


Figure 4: Effect of test orientation relative to print orientation for mixture 1

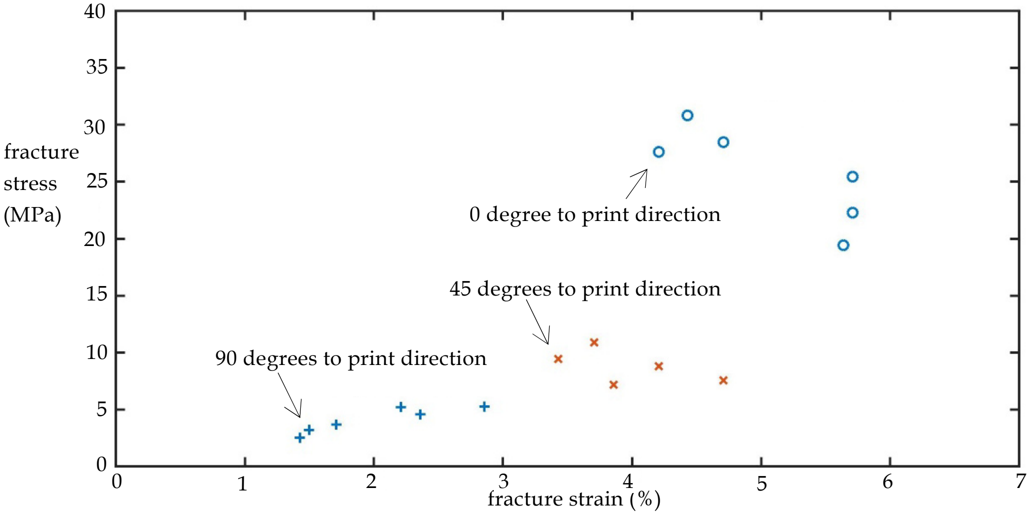


Figure 5: Effect of test orientation relative to print orientation for mixture 2

strength with again no significant effect on the strain at failure.

The quality of the virgin material and mixtures 1 and 2 are compared in figure 8. Adding more glass fibres and using less recycled polypropylene gives a mixture that more clearly approaches that of virgin material. An eco-friendly design using large amounts of recycled material will thus always have significantly decreased properties, leading to the use of more material. In itself this does not have to be a problem, using a larger amount of waste material also means less waste to burn. It is, however, also clear that reusing the material more than once leads to more significant loss of properties as is evident from the loss of

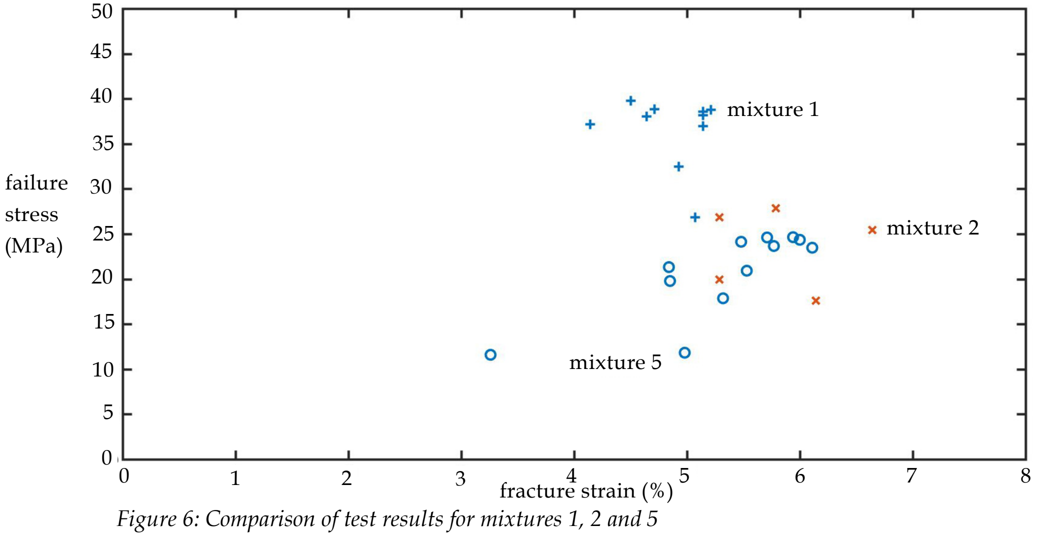


Figure 6: Comparison of test results for mixtures 1, 2 and 5

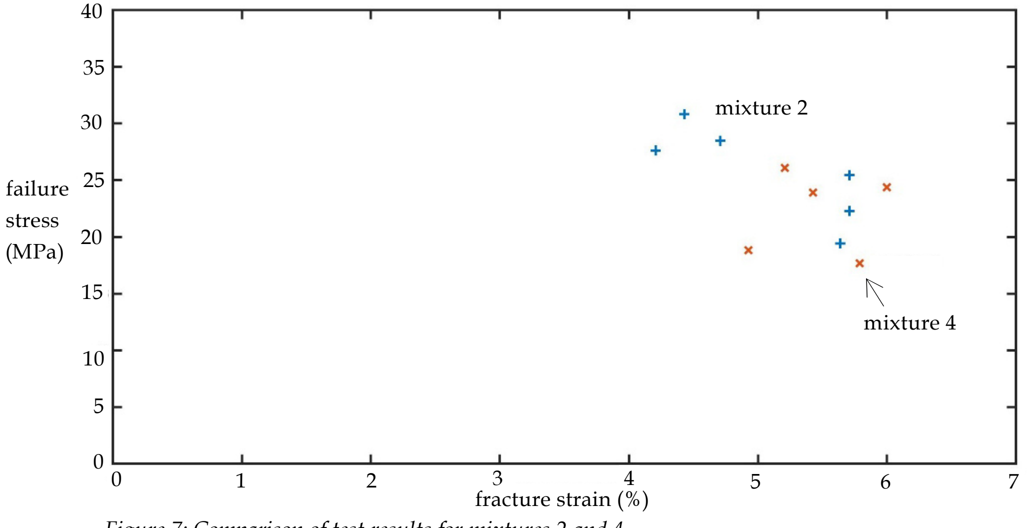


Figure 7: Comparison of test results for mixtures 2 and 4

properties of mixtures 3 and 4 compared with mixtures 1 and 2. Using recycled polypropylene for products with a short service life is thus counterproductive as it produces unusable waste which can only be burned, as it will not biologically degrade in a land fill. It is thus important to use recycled polypropylene in such a way that a sufficiently long life time is achieved with a clear route for final disposal at the end.

5 Conclusions

From the data the authors conclude:

- If recycled PP is used from a good source the properties are significantly better than from recycled PP or PP recovered from household waste.
- The strength of a mixture containing 60 to 80% recycled PP can be as low as 40% or as high as 85%of the strength of virgin PP.
- Properties at 45° or 90° to the print direction are much lower than in the print direction.
- A design using recycled PP thus should allow for the source of the recycled PP as this has a strong effect on the material properties.
- There is no clear relation between failure stress and strain at fracture.
- Failure strain is not significantly affected by the % of recycled material or the quality of the recycled material. Failure stress however is strongly affected by these.

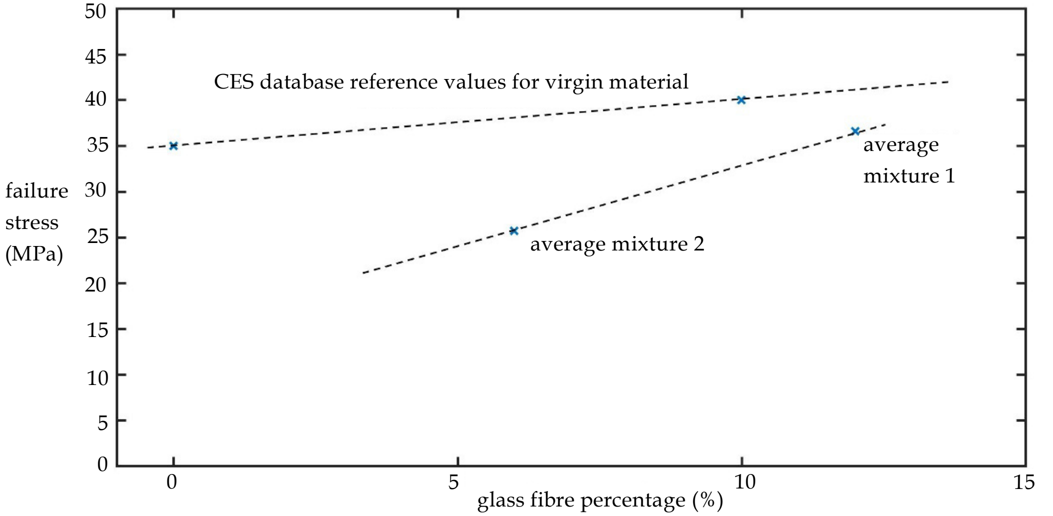


Figure 8: Effect of composition on the mechanical properties of virgin and recycled PP

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Literature

[1] Baran, P. (2016). Methodology and Tools for Testing, Numerical Analysis and Design of the 3D Printed Moulds. MSc thesis Delft University of Technology

[2] Chong, S., Pan, G.T., Khalid, M., Yang, T. C.K., Hung, S.T., Huang C.M. (2016). Physical Characterization and Pre-assessment of Recycled High-Density Polyethylene as 3D Printing Material. Journal of Polymers and the Environment , online on journal web page since 23-07-2016

[3] Giannadakis, K., Szpieg, M., Varna, J. (2011). Mechanical Performance of a Recycled Carbon Fibre/PP Composite. *Experimental Mechanics* 51: 767–777.

[4] La Mantia, F.P. (1999). Recycling of Polypropylene, in *A-Z of Polyproylene*, Editor Karger-Kocsis, J. Springer Verlag: pp. 701-705

[5] Kozderka, M., Rose, B., Bahlouli, N., Koci, V., Caillaud, E. (2016). Recycled high impact polypropylene in the automotive industry - mechanical and environmental properties. International Journal on Interactive Design and Manufacturing (IJIDeM), online on journal web page since 05-12-2016

[6] PlasticsEurope, The association of plastics manufacturers (2016). Plastics the facts 2014/2016. Presentation on the web. Retrieved from http://www.plasticseurope.org/documents/document/20161014113313-plastics_the_facts_2016_final_version.pdf on 19-03-2017

[7] van der Veen, A. (2014). The Structural Feasibility of 3D-printing houses using printable polymers. MSc thesis, Delft University of Technology

Appendix A: test results

Table 2: strength and elongation of mixture 1 at 90°

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
1	4.8	425	4.43	3.14%	Y
2	5.5	1150	10.45	2.50%	Y
3	4.8	865	9.01	2.00%	Y
4	4.8	874	9.10	2.21%	Y
5	4.8	882	9.19	2.14%	Y
6	4.8	385	4.01	4.50%	Y
7	4.8	959	9.99	2.93%	Y
8	4.8	798	8.31	5.21%	Y
9	4.8	1010	10.52	2.71%	Y
10	4.8	558	5.81	3.21%	Y
Average			8.1	2.1%	
Std/average			30.2%	34.3%	

Table 3: strength and elongation to fracture of mixture 1 at 45°

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
13	4.8	879	9.16	2.93%	N
14	4.8	1480	15.42	3.36%	Y
15	4.8	1410	14.69	2.86%	N
16	4.8	1520	15.83	3.64%	N
17	4.8	1200	12.50	4.07%	N
18	4.8	1340	13.96	2.86%	N
19	4.8	1030	10.73	2.71%	N
20	4.8	1250	13.02	3.07%	N
21	4.8	883	9.20	4.07%	N
22	4.8	1280	13.33	3.21%	Y
Average			12.8	3.3%	
Std/average			18.8%	15.2%	

Table 4: strength and elongation to fracture of mixture 1 at 0°

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
23	4.8	3650	38.02	4.64%	Y
24	4.8	3550	36.98	5.14%	Y
25	4.8	3700	38.54	5.14%	Y
26	4.8	3720	38.75	5.21%	Y
27	4.8	3730	38.85	4.71%	Y
28	4.8	3820	39.79	4.50%	Y
29	4.8	3120	32.50	4.93%	Y
30	5.2	2790	26.83	5.07%	Y
31	5	3820	38.20	5.14%	Y
32	4.8	3570	37.19	4.14%	Y
average			36.6	4.9%	
std/average			10.8%	7.3%	

Table 5: strength and elongation to fracture of mixture 2 at 90°

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
33	8	726	4.54	2.36%	N
34	8.2	519	3.16	1.50%	Y
36	8.5	621	3.65	1.71%	Y
37	8.5	426	2.51	1.43%	N
49	9	932	5.18	2.21%	Y
50	9	944	5.24	2.86%	N
average			4.0	2.0%	
std/average			27.6%	27.9%	

Table 6: strength and elongation to fracture of mixture 2 at 45°

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
38	8.5	1600	9.41	3.43%	N
39	9	1580	8.78	4.21%	Y
40	8	1140	7.13	3.86%	Y
41	8.5	1280	7.53	4.71%	Y
42	8	1740	10.88	3.71%	Y
average			8.7	4.0%	
std/average			17.2%	12.4%	

Table 7: strength and elongation to fracture of mixture 2 at 0°

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
43	4.5	2770	30.78	4.43%	Y
44	7	3560	25.43	5.71%	Y
45	8.2	3180	19.39	5.64%	Y
46	9	4010	22.28	5.71%	Y
47	4.8	2730	28.44	4.71%	Y
48	4.2	2320	27.62	4.21%	Y
average			25.7	5.1%	
std/average			16.4%	13.7%	

Table 8: strength and elongation to fracture of mixture 3 at 0°

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
51	7	2460	17.57	6.14%	Y
52	5.5	3060	27.82	5.79%	Y
53	7	3560	25.43	6.64%	Y
54	7	2790	19.93	5.29%	Y
55	6	3220	26.83	5.29%	Y
average			23.5	5.8%	
std/average			19.2%	9.9%	

Table 9: strength and elongation to fracture of mixture 4 at 0°

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
56	6.2	2330	18.79	4.93%	Y
57	6.2	3020	24.35	6.00%	Y
58	6.2	3230	26.05	5.21%	Y
59	6.2	2960	23.87	5.43%	Y
60	6.2	2190	17.66	5.79%	Y
average			22.1	5.5%	
std/average			16.7%	7.9%	

Table 10: strength and elongation to fracture of mixture 5 tested at 0 °

number	thickness	F_{max} (N)	σ_f (MPa)	ε_f (%)	failure between shoulders
61	4.8	2365.035	24.64	5.94%	Y
62	4.8	2253.468	23.47	6.11%	Y
63	4.8	2008.659	20.92	5.53%	Y
64	4.8	2362.853	24.61	5.71%	Y
65	4.8	2271.02	23.66	5.77%	Y
66	4.8	1135.035	11.82	4.98%	N
67	4.8	2046.274	21.32	4.84%	Y
68	4.8	2316.7	24.13	5.48%	Y
69	4.8	2337.421	24.35	6.00%	Y
70	4.8	1714.379	17.86	5.32%	Y
71	4.8	1112.527	11.59	3.26%	N
72	4.8	1899.316	19.78	4.85%	Y
average			20.7	5.3%	
std/average			22.8%	14.7%	

Table 11: reference data for PP according to CES database

Type of PP	σ_f (MPa)	ε_f (%)
Homopolymer low flow	33 – 42.9	168 – 598
Homopolymer high flow	31.9 – 36.4	52.1 – 232
Random copolymer low flow	19.9- 25.9	216 – 662
Random copolymer high flow	16.8 – 21.3	112 – 483
Homo polymer 10% glass fibre	37.7 – 44.1	3.65 – 5.63
Homo polymer 20% glass fibre	54.2 - 67.5	3.23 – 4.48
Homo polymer 30% glass fibre	66.9 – 97.5	2.8 – 4.47
Co polymer 20% glass fibre	39.9 – 50.9	4.17 – 7.39
Co polymer 30% glass fibre	60.4 – 69.2	4.1 – 5.28