TENSILE STRENGTH ANALYSIS OF HIGH DENSITY POLYETHYLENE FOR INJECTION MOULDED PARTS

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ABSTRACT: This paper investigates the performance of pure high density polyethylene (p-HDPE) and recycled high density polyethylene (r-HDPE) by comparing the tensile strength of both materials. The specimens were injected by injection moulding machine and the parameters investigated were melting temperature (200-240°C), injection pressure (75-95 MPa), and holding time (20-30 s). Response Surface Methodology (RSM) was used to accommodate the experimental run as well as to analyse the experimental results. The result from Analysis of Variance (ANOVA) showed that the melting temperature is the most significant parameters affecting the tensile strength of both materials with the F-value is 307.58, followed by injection pressure (77.32) and holding time (19.67). The result also showed that the tensile strength of both materials increase with increasing of melt temperature, injection pressure and holding time. The optimal tensile strength of p-HDPE (27.04 MPa) was obtained at the melting temperature of 240°C, injection pressure of 95 MPa and holding time of 20 s. On the other hand, the optimal tensile strength of r-HDPE (16.058 MPa) was achieved at the melting temperature of 240°C, injection pressure of 95 MPa, and holding time of 29 s. The reduction percentage of tensile strength for r-HDPE as compared to p-HDPE was in the range of 43.478% - 40.703%. Even though the tensile strength of r-HDPE has been reduced by around 40% as compared to p-HDPE, the r-HDPE can still be utilised for packaging application such as containers, bottles, and jars. Therefore, this will help to significantly reduce waste in order to sustain the environment.

KEYWORDS: *Plastic injection moulding, HDPE, tensile strength; design of experiment; optimization.*

1.0 INTRODUCTION

Plastic injection moulding is a well known process in the high-volume production of plastic parts including medical, electronic, and automotive products to achieve the market demand [1]. The processing parameters, part and mold designs, and material selection

interact to determine the quality of the plastic product in injection moulding process [2]. This lenghty process can contribute to production problems such as high production costs, increase in lead time, defects in products, etc. The complex shape of parts may lead to a problem in sustaining the injection moulding process under control. Injection moulding has many parameters to be controlled where each of them can be divided into four basic groups: temperature, pressure, time and distance [3].

There are three types of experimental strategies that exist: Best Guess, One Factor At a Time (OFAT) and Statistical Designed Experiments (DOE) as proposed by Montgomery [4]. In order to solve the problem with many variables, DOE is the most effective method. Trial-and-error method was labeled as impossible solution in order to achieve the optimal parameter combinations [5]. In OFAT, experiment is conducted by varying a single parameter while holding all other parameters fixed in a given set of combinations [6]. OFAT has been considered a scientific method as presented by Frey et al. [7], but the method is almost unable to determine the optimum results due to it lacking the interaction between the variables.

Nowadays, in order to control the development of industrial alternatives, the research on polymeric substitutes to conventional materials has been studied by some researhers [8,9]. There are still lack of compatible solutions regarding the environmental problem caused by the disposal of plastic. However, recycling the waste of plastic into a useful product would solve both environmental and economic issues [10-12]. For the past ten years, total consumption of plastics and the range of their practical application have shown a significant increase [13]. High Density Polyethylene (HDPE) and PP are nearly not degraded in the natural environment, although they were in a long period left to the environment. [14].

The ASTM and ISO have different procedures in tensile testing which reflect the importance of tensile properties in the product design [15, 16]. Tensile strength value is influenced by the processing parameters in injection molding processes. There are various designs of experiment methods such as RSM, Taguchi, Factorial etc. in controlling the parameters and these methods have been used to

optimize or achieve the best combination for the processing parameters in view of the mechanical strength [17, 18]. This paper presents the study of the tensile strength obtained of pure and recycled HDPE as well as determining the parameters that affect the response of the tensile strength for both materials.

2.0 METHODOLOGY

Pure and recycled HDPE were used as materials for this research. The brand of pure HDPE is Etilinas HD5740UA with a melt flow rate of 3.9 g/10min. While recycled resins came from Wespack Waste Management Sdn Bhd where HDPE natural bottles were crushed and processed with the melt index rate of 0.45 g/10min. Both materials were then injected into Arburg All Rounder 420C 800-250 machine. Table 1 shows the research gap information in order to know the most parameters used starting from 2010 to 2016. The list was also gathered by focusing only on polymer as materials and injection moulding in machining. Three and more marked parameters were chosen as parameters for screening stage. There were six parameters selected in earlier research which are injection pressure, holding pressure, melt temperature, cooling time, injection time and holding time.

Table 1: Research gap of parameters

Authors	Responses	Parameters										
		A	B	C	D	E	F	G	H	I	J	K
Ozcelik et al. [19]	Tensile, impact and flexural strength	/	/		/			/				
Zahid et al. [20]	Tensile, compressive and flexural strength			/	/				/	/		
Fei et al. [21]	Tensile, compressive and flexural strength			/	/				/	/		
Mirvar et al. [22]	Tensile strength			/				/		/		
Rishi and	Tensile strength	/			/			/				
Jaiprakash [23]												
Humbe and Kadam [24]	Tensile strength and cycle time	/		/	/			/				
Chen et al. [25]	Warpage and shrinkage	/	/				/		/			

Kuram et al. [26]	Tensile, flexural and impact strength	/		/	/							
Gu et al. [27]	Tensile, flexural and impact strength	/			/		/	/			/	
Gobinath et al. [28]	Tensile and flexural strength			/	/			/				

Note: (A: Injection pressure; B: Packing pressure; C: Holding pressure; D: Melt temperature; E: Mould temperature; F: Packing time; G: Cooling time; H: Injection time; I: Holding time; J: Injection speed; K: Screw speed)

The parameters were then screened by fractional method and only three parameters had a significant impact on tensile and flexural strength for both materials. These three parameters are melting temperature, injection pressure, and holding time. The parameters and its levels are shown in Table 2. Their ranges were obtained by Moldflow simulation and pilot test based on good shape of specimens for testing procedure. RSM of Box-Behnken was used to accommodate the experimental run for the range of parameters investigated where it was generated by Design Expert 7.0.0 software. The software generated 17 numbers of experiments, including 5 centre points to estimate the error.

Table 2: Parameters and their levels

Parameters	**Level**	
	-1	1
A: Melting Temperature (°C)	200	240
B: Injection Pressure (MPa)	75	95
C: Holding Time (s)	20	30

There were five specimens tested for each experimental run, and the result was then averaged. Experimental tests were carried out according to the method in ASTM D638-10 standard [29] with the speed of testing of 500 mm/min. The dimension of specimens followed Type I in ASTM D638 where the width (W) is 13 mm, the length overall (LO) is 165 mm and thickness (T) is 3 mm as shown in Figure 1.

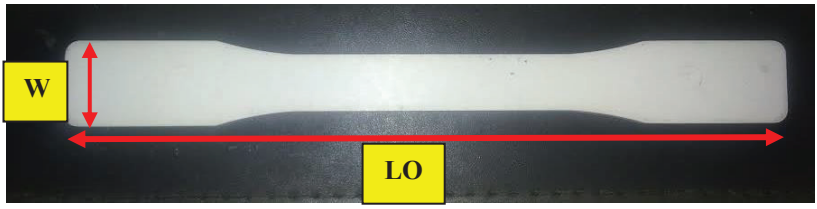

Figure 1: Dimensions of a specimen

The percentage reduction of tensile strength of r-HDPE as compared to the strength of p-HDPE was calculated using equation (1).

$$\text{reduction}\% = \left| \frac{\text{Observed} - \text{Standard}}{\text{Standard}} \right| \times 100 \quad (1)$$

3.0 RESULTS AND DISCUSSION

3.1 Analysis of experimental results

Table 3 shows the result of tensile strength test experiment for both p-HDPE and r-HDPE materials. Reduction of r-HDPE based on tensile strength of p-HDPE was also calculated to show the strength comparison in percentage. Even if there is no standard value for reduction percentage of HDPE, the objective is to get the value of any application strength (eg. If the tensile strength of p-HDPE pipe is 30 MPa, so the r-HDPE pipe should be between 16.957 - 17.789 MPa).

The highest tensile strength of 26.843 MPa and 15.889 MPa were obtained for p-HDPE and r-HDPE respectively. These highest values of tensile strength for both materials were obtained with setting of injection moulding at melting temperature of 240°C, injection pressure of 95 MPa, and holding time of 25 s.

Table 3: Results of tensile strength for both p-HDPE and r-HDPE

Run	Melting Temperature (°C)	Injection Pressure (MPa)	Holding Time (s)	Tensile Strength (p-HDPE) (MPa)	Tensile Strength (r-HDPE) (MPa)	Reduction % of r-HDPE
1	200	75	25	25.305	14.303	43.478
2	240	75	25	26.506	15.521	41.443
3	200	95	25	25.860	14.858	42.544
4	240	95	25	26.843	15.889	40.808
5	200	85	20	25.463	14.467	43.184
6	240	85	20	26.580	15.570	41.422
7	200	85	30	25.630	14.623	42.946
8	240	85	30	26.789	15.885	40.703
9	220	75	20	25.390	14.416	43.222
10	220	95	20	26.418	15.431	41.589
11	220	75	30	26.122	15.187	41.861
12	220	95	30	26.438	15.498	41.380
13	220	85	25	25.910	14.990	42.146
14	220	85	25	25.890	14.850	42.642
15	220	85	25	25.930	14.888	42.584
16	220	85	25	25.850	14.800	42.747
17	220	85	25	25.790	14.830	42.497

Figures 2 and 3 show fractured surfaces of p-HDPE and r-HDPE at injection moulding condition of melting temperature (240 °C), injection pressure (95 MPa) and holding pressure (25 s). It is clearly shown that p-HDPE has a better ductility rather than r-HDPE due to long necking on the fractured surface. It indicates that p-HDPE had a strong bonding which produced a better strength compared to r-HDPE. The better ductility of the p-HDPE is supported by findings from Dasari & Misra [30], that stated the HDPE exhibited a greater susceptibility to plastic deformation and higher resistance to necking i.e. corresponding to higher strain rate sensitivity index. At low displacement rates, the fracture of HDPE was ductile which was characterized by fibrillation while at high strain rates, a mixture of fibrillation and crazing occurred lowering its toughness and ductility. According to Startweather & Brooks [31], the crystallinility could influence the mechanical properties, with the increasing degree of

crystallinity leading to a higher degree of the strength. This indicates that specimens of p-HDPE might have a higher compactness and result in a better crystallinity compared to r-HDPE. The lack of compactness in specimens of r-HDPE can be visualized in Figure 3 where it shows the existence of porosities. This is similarly found by Cruz & Zanin [32] who accounted this could be due to existence of impurities in the r-HDPE during crushing and reheating process to produce the recycled pellets. The reasons why mechanical properties of the r-HDPE are lower than the p-HDPE could also be due to some contaminants, i.e. impurities and air bubbles, that fall into the materials during recycling process.

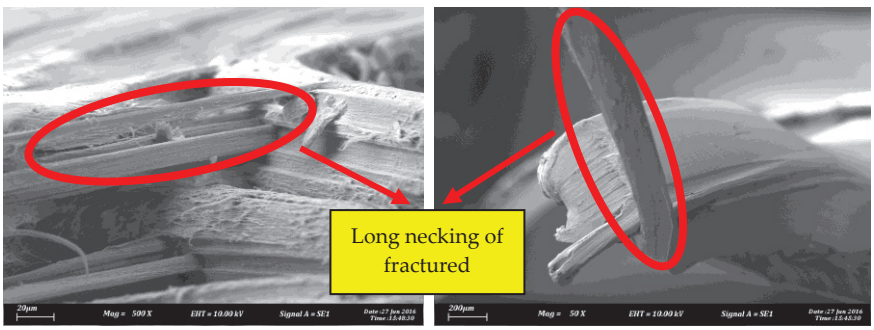

Figure 2: SEM on specimens of p-HDPE at injection moulding condition of melting temperature (240 °C), injection pressure (95 MPa) and holding pressure (25 s)

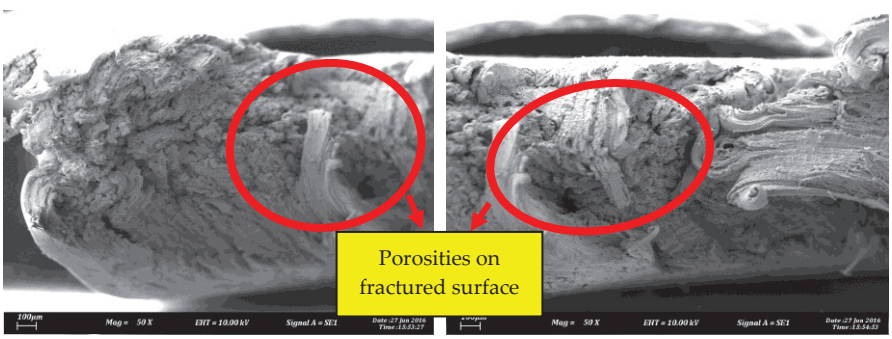

Figure 3: SEM on specimens of r-HDPE at injection moulding condition of melting temperature (240 °C), injection pressure (95 MPa) and holding pressure (25 s)

3.2 Statistical analysis

Table 4 shows the ANOVA results obtained using Design Expert 7.0.0 software. ANOVA was conducted to determine the influence between the parameters and the responses. The melting temperature was found to be the most significant parameter with F value of 307.58, followed by the injection pressure and holding time with F value of 77.31 and 19.67 respectively.

Table 4: ANOVA of tensile strength for p-HDPE

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F (p value)
Model	3.61	9	0.4	49.65	< 0.0001
A-Melting Temperature	2.49	1	2.49	307.58	< 0.0001
B-Injection Pressure	0.62	1	0.62	77.31	< 0.0001
C-Holding Time	0.16	1	0.16	19.67	0.003
AB	0.012	1	0.012	1.47	0.2647
AC	0.0004	1	0.0004	0.055	0.822
BC	0.13	1	0.13	15.68	0.0055
A^2	0.081	1	0.081	10.06	0.0157
B^2	0.056	1	0.056	6.95	0.0336
C^2	0.044	1	0.044	5.47	0.0519
Residual	0.057	7	0.0081		
Lack of Fit	0.044	3	0.015	4.79	0.0821
Pure Error	0.012	4	0.0031		
Cor Total	3.67	16			

Table 5 shows the ANOVA model of tensile strength for r-HDPE. The model is significant as proven by p-value less than 5% (0.05) for parameters A, B, C, A^2, B^2, C^2, and BC while the model terms are significant due to their value of Prob > *F* which is less than 0.05. R-squared also give a good value (0.9847) which is almost equal to 1. Melting temperature gives the highest *F*-value (308.36), followed by injection pressure (73.26) and holding time (24.82).

Table 5: ANOVA of tensile strength for r-HDPE

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F (p value)
Model	3.9	9	0.43	50.16	< 0.0001
A-Melting Temperature	2.66	1	2.66	308.36	< 0.0001
B-Injection Pressure	0.63	1	0.63	73.26	< 0.0001
C-Holding Time	0.21	1	0.21	24.82	0.0016
A^2	0.079	1	0.079	9.19	0.0191
B^2	0.075	1	0.075	8.74	0.0212
C^2	0.069	1	0.069	7.94	0.0259
AB	0.009	1	0.009	1.01	0.3481
AC	0.006	1	0.006	0.73	0.42
BC	0.12	1	0.12	14.35	0.0068
Residual	0.06	7	0.009		
Lack of Fit	0.039	3	0.013	2.39	0.209
Pure Error	0.022	4	0.005		
Cor Total	3.96	16			

The results from Table 4 and 5 show that the most significant factor for both material is the melt temperature. This might have been because during the injection moulding process, the temperature assists in packing of the chains in the flow viscosity. Su et al. [33] found that the tested specimens obtained from low temperature conditions might have a higher degree of orientation. It is also well known that a low temperature in this process would be favourable for fixing the orientation. There was also a finding that showed the results in a low elongation at break caused by orientation [34].

3.3 Optimal parameters for p-HDPE and r-HDPE

Table 6 shows the optimization results that was generated by RSM in Design Expert software where the criterion of higher tensile strength was set as the main objective. These results were performed using melting temperature (240 °C), injection pressure (95 MPa) and holding time (20 s) for p-HDPE while melting temperature (240 °C), injection pressure (95 MPa) and holding time (29 s) for r-HDPE, where the values were rounded due to machine capability. These results show that the best combination result for p-HDPE occur when

melting temperature was set to the highest (240 °C), highest injection pressure (95 MPa), and lowest holding time (20 s). While the best combination for r-HDPE is when melting temperature was set with highest (240 °C), highest injection pressure (95 MPa), and highest holding time (29 s). The same result was also gained by Khan, Kamaruddin, & Siddiquee [20], where they investigated the tensile strength of p-HDPE and r-HDPE. They found that the optimal result of the injection moulding parameters can be achieved with the highest melting temperature and highest holding time. The importance of melt temperature has also been agreed by several researchers who found that melt temperature is the most significant parameter which affects the tensile strength [35-37].

Table 6. Optimization of p-HDPE and r-HDPE

	Melting Temperature (°C)	Injection Pressure (MPa)	Holding Time (s)	Tensile Strength (MPa)
p-HDPE	239.44 ≈ 240	94.96 ≈ 95	20.01 ≈ 20	27.040
r-HDPE	239.60 ≈ 240	94.99 ≈ 95	29.10 ≈ 29	16.058

4.0 CONCLUSION

In this research, the influence of parameters that affect the tensile strength of p-HDPE and r-HDPE were investigated. It was found that melt temperature was the most significant parameters that affect the tensile strength of both materials and this is followed by injection pressure and holding time. The result also shows that the tensile strength of both materials increased with increasing melt temperature, injection pressure and holding time. The optimization of tensile strength (27.04 MPa) for p-HDPE could be obtained by a combination of parameters set at highest melting temperature (240 °C), highest injection pressure (95 MPa), and lowest holding time (20 s). While for r-HDPE, the combination of parameters were set at the highest melting temperature (240 °C), highest injection pressure (95 MPa), and highest holding time (29 s) to get the optimum value of tensile strength (16.058 MPa). The result shows that the reduction in tensile strength of r-HDPE based on the tensile strength of p-HDPE falls within the range of 40.703% to 43.478%. The result was supported by SEM analysis which shows that p-HDPE has a better ductility and strong bonding to produce better strength compared to

r-HDPE. However, the low tensile strength of r-HDPE can still be utilised for packaging application such as containers, bottles, jars, etc. in order to reduce waste and improve sustainability.

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