Nigerian Research Journal of Engineering and Environmental Sciences 4(2) 2019 pp. 874-883

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Modelling and Optimisation of the Mechanical Properties of Injection Moulded High Density Polyethylene-Sawdust Composite

***Aliyegbenoma, C.O. and Akpobi, J.A.**
Department of Production Engineering, University of Benin, Benin City, Edo State, Nigeria
*cyril.aliyegbenoma@eng.uniben.edu

ARTICLE INFORMATION

Article history:
Received 12 Nov, 2019
Revised 12 Dec, 2019
Accepted 13 Dec, 2019
Available online 30 Dec, 2019

Keywords:
Central composite design
Composite
Modeling
High density polyethylene
Sawdust
Tensile strength

ABSTRACT

The focus of this study is on the modeling and optimisation of an injection moulded high density polyethylene-Sawdust (HDPE-sawdust) composite. The HDPE material and sawdust were mixed together to form a homogenous mixture with various percentage composition by volume as obtained by the central composite design (CCD). A two-screw plunger injection moulding machine with maximum clamping force of 120 tons and shot capacity of 3.0 oz was used to produce the HDPE-sawdust composite at various temperatures. The produced composites were evaluated for their mechanical properties such as tensile strength, proof stress, flexural modulus and flexural strength. The response surface methodology (RSM) was used to determine the effect of the interaction of temperature and percentage by volume of material on the mechanical properties of the produced HDPE-sawdust composite. Models were developed for predicting the mechanical properties (tensile strength, proof stress, flexural strength and flexural modulus) for the produced composites. The models were validated using coefficient of determination (R^2). The coefficient of determination (R^2) obtained ranged from 0.9213 (92.13%) to 0.981 (98.10%) which indicates a good fit was achieved between the model and experimental results. The optimization results for HDPE-Sawdust composites shows that the tensile strength, proof stress, flexural strength and flexural modulus were maximized with values of 25.80 MPa, 28.17 MPa, 43.77 MPa and 0.83 GPa obtained at barrel temperature of 164.64 ^oC and polymer level of 68.54%.

1. INTRODUCTION

The research and development of new materials together with its design is the engine that drives economic progress (Andrew, 2014). Composite are man-made materials which are currently being used in wide application in the manufacture of industrial as well as consumer products. The deformable state achieved by plastic-sawdust composites at elevated temperature before chemically setting, allow them to be shaped to any intricate form (Martins et al., 2017). Composites are a combination of two materials in which one of the materials, called the reinforcing phase, is in the form of fibers, sheets, or particles, and is embedded in the other materials called the matrix phase. Typically, reinforcing materials are strong with low densities, while the matrix is usually a ductile or tough material. If the composite is designed and fabricated correctly, it combines the strength of the reinforcement with the toughness of the matrix to achieve a combination of desirable properties not available in any single conventional material (Adeyemi and Adeyemi 2002). Injection moulding is a cost-effective way to produce complex, three shapes at high volumes. In the plastic industry, injection moulding makes up approximately 32% weight of all plastic processing methods, second only to extrusion which is 36% weight (Jozsef and Tibor 2005).

Injection moulding is a very complex process and its process variable like barrel temperature, injection pressure, the material flow rate, mould temperature and flow pattern usually influence the properties of polymeric materials. A qualitative analysis of the influence of these factors in this case barrel temperature on the mechanical properties of a moulded part will be helpful in gaining better insight into the presently used processing methods (Ahmad et al., 2015).

In the work of Mosle et al. (2009) on composite using the hot press compression moulding, the tensile strength, proof stress and percentage elongation were 38.32 N/mm^2, 34.22 N/mm^2 and 182% at a melt temperature of 210 ^{o}C while the flexural strength was 40.22×10^2 N/mm^2 at a melt temperature of 170 ^{o}C. Osarenmwinda and Nwachukwu, (2010) developed a composite from agro-waste consisting of sawdust and palm kernel shell and determined its physical and mechanical properties. The results obtained for yield strength (4.47 N/mm^2), ultimate tensile strength (7.75 N/mm^2), modulus of elasticity (2603 N/mm^2,) modulus of rupture (16.67 N/mm^2), internal bond strength (0.54 N/mm^2), density (996.18 kg/m^3), thickness of swelling (10.30%) and water absorption (18.90%) were found to be satisfactory.

The effect of reinforcement combination on the mechanical strength of glass reinforced plastic using compression mouldingwas examined by Zhou and Mallick, (2005) as well as Njoku and Obikwelu, (2008). A proof stress of 29.52 N/mm^2 at a barrel temperature of 232 ^{o}C was obtained. The effects of temperature relative humidity and feedstock temperature on injection moulded part dimension and short term mechanical properties observed from tensile testing was investigated by Westerdale et al. (2008). The results indicated that environmental conditions influenced the moulded part quality to varying degrees and that the environmental conditions should be controlled for applications with tight tolerances.

Among other raw materials used by past researchers for composite production are tea leaves waste (Yalinkilic et al., 1998), almond shells (Guru et al., 2006), wheat traw and corn pith (Wang and Sun, 2002), durian peel and coconut coir (Khedari et al., 2004), cob and maize husk (Sampathrajan et al., 1992), groundnut husk (Osaremwinda, 2006) and rice husk (Osaremwinda and Nwachukwu, 2007). In this work, the focus is on using sawdust (from mahogany) and HDPE and optimizing the responses using response surface methodology (RSM).

2. MATERIALS AND METHODS

2.1. Materials

The materials used for this work include high density polyethylene (HDPE), in powder form obtained from Adig plastic limited Lagos, sawdust obtained from Mahogany tree procured from a saw mill in Benin City, Edo State, two stage-screw plunger Injection machine, 120 tons two stage-screw plunger, toggle clamp attached to the injection end of injection moulding, Monsanto tensometer, Type ‘W’ Serial No. 8991 and a mould made of silicon- killed forging quality steel AISI type HI40 treated to 252-302 brine 11.

2.2. Methods

2.2.1. Design of experiment

For this study, a two-variable central composite design (CCD) was used to plan the experiments, develop statistical models for predicting the chosen responses and to optimise the responses and factors. The CCD is a very versatile experimental design method. The design points are made up of 2n factorial points as well as star points. The star points are particularly necessary for estimating the curvature of the response surface especially for nonlinear models. The CCD is the only response surface design that can be used for planning experiments with two factors as shown in Table 1 (Amenaghawon et al., 2014). Design Expert® software version 7.0.0, (Stat-ease, Inc. Minneapolis, USA) was used to design the experiment and to analyze the experimental data obtained. The factors considered were temperature and the level of polymer (HDPE) in the matrix. In generating the experimental design matrix, the Design Expert® software utilizes the concept of randomisation and the essence of this is to minimise the effect of unexplained variability in the chosen responses (Montgomery, 2005). In this case, the responses chosen for consideration were tensile strength, proof stress, flexural strength, and flexural modulus.

The statistical analysis of the results was carried out using the Design Expert software. The fit of the models representing the responses (tensile strength, proof stress, flexural strength, and flexural modulus) was determined using analysis of variance (ANOVA). The ANOVA results helped to also assess the statistical significance of the models representing the responses and this was done using parameters line p value, F value, sum of squares, mean square, lack of fit, standard deviation, coefficient of variation, coefficient of determination (R^2), adjusted R^2, adequate precision, predicted residual sum of squares (PRESS).

Table 1: Coded and actual levels of the factors for HDPE polymer composite

Factors	Unit	Symbols	Coded and Actual Levels				
			-1.414	-1	0	1	1.414
Temperature	^oC	X_1	150.00	164.64	200.00	235.36	250.00
HDPE level	%	X_2	60.00	61.46	65.00	68.54	70.00

2.2.2. Composite production process

The hydraulic and mechanical functions of the moulding machine were checked and ascertained to be in order. Also, the mould and barrel heating functions, including the associated temperature sensors were checked. The mould was then clamped on the platen and the heaters for the mould and barrel were switched on. The temperature control for the mould was set at 60 ^oC and that of the barrel at 150 ^oC. To encourage rapid heating, the mould was closed and the nozzle was allowed to rest slightly on the mould sprue opening in order to pick up some heat. The machine was left undisturbed for 30 minutes for the temperature to stabilize. The moulding process for HDPE-Sawdust composites was between temperatures of 150 ^oC and 250 ^oC as suggested by the CCD which was for 13 runs with various compositions of the polymer and sawdust. HDPE was mixed with sawdust in the proportion obtained by the CCD. The prepared HDPE sawdust composite was blended in a cylindrical container until a homogenous mixture was obtained in the composite. The homogenous mixture of the composite was feed into the hopper of injection moulding machine and was produced at barrel temperature ranging from 150 ^oC to 250 ^oC respectively.

3. RESULTS AND DISCUSSION

3.1. Determination of Appropriate Model

Different statistical models were examined with the intention of selecting the one most appropriate to represent the process under consideration. The quadratic model was chosen and this decision was reached based on the statistical parameters backing up the quadratic model. Among a number of alternatives, the model chosen was the one with the desirable statistical parameters such as high R^2 value, low standard deviation, and low PRESS. The quadratic model was found to have the highest R^2 values for all the responses for the HPPE-Sawdust composite. The quadratic model was also found to have the lowest standard deviation and PRESS.

3.2. Statistical Analysis of Models

Statistical analysis of the quadratic model was carried out. This was done by fitting the quadratic model to the experimental data obtained for all the responses. There was a total of 13 experimental runs as shown in Tables 2a and 2b. After fitting the quadratic model to the experimental data, the model parameters were estimated to obtain the final model equations in terms of actual experimental factors.

$$\text{Tensile strength} = 421.77 - 0{,}20X1 - 11.84X2 + 0.00051X_1^2 + 0.090X_2^2 \quad (1)$$

$$\text{Proof stress} = 510.46 - 0.11X_1 - 14.28X_2 + 0.00028X_1^2 + 0.11X_2^2 \quad (2)$$

$$\text{Flexural strength} = -68.48 - 0.030X_1 + 2.65X_2 - 0.00010X_1X_2 + 0.000085X_1^2 - 0.014X_2^2 \quad (3)$$

$$\text{Flexural modulus} = 1.06 + 0.00070X_1 + 0.041X_2 - 0.000020X_1X_2 + 0.0000017X_1^2 + 0.00057X_2^2 \quad (4)$$

Table 2a: Experimental and RSM predicted results for tensile strength and proof stress

Run	Factors				Response			
	Coded values		Actual values		Tensile strength		Proof stress	
	X_1	X_2	X_1	X_2	Experiment	Predicted	Experiment	Predicted
1	1	1	235.36	68.54	25.90	25.93	28.30	28.14
2	-1	1	164.64	68.54	26.00	25.77	28.50	28.17
3	0	0	200.00	65.00	23.60	23.40	27.20	27.30
4	-1	-1	164.64	61.46	25.40	24.44	30.90	29.86
5	1	-1	235.36	61.46	25.30	24.61	30.70	29.83
6	0	0	200.00	65.00	23.10	23.40	27.10	27.30
7	0	0	200.00	65.00	23.30	23.40	27.90	27.30
8	-1.414	0	150.00	65.00	23.90	24.55	27.30	28.02
9	1.414	0	250.00	65.00	24.50	24.78	27.50	27.98
10	0	-1.414	200.00	60.00	23.80	24.78	30.10	31.20
11	0	0	200.00	65.00	23.70	23.40	27.40	27.30
12	0	0	200.00	65.00	23.30	23.40	26.90	27.30
13	0	1.414	200.00	70.00	26.70	26.65	28.70	28.80

Table 2b: Experimental and RSM predicted results for flexural strength and flexural modulus

Run	Factors				Response			
	Coded values		Actual values		Flexural strength		Flexural modulus	
	X_1	X_2	X_1	X_2	Experiment	Predicted	Experiment	Predicted
1	1	1	235.3	68.54	43.60	43.52	0.81	0.83
2	-1	1	164.6	68.54	43.80	43.77	0.79	0.83
3	0	0	200.0	65.00	40.55	40.83	0.69	0.72
4	-1	-1	164.6	61.46	38.95	37.97	0.62	0.62
5	1	-1	235.3	61.46	38.80	37.77	0.65	0.64
6	0	0	200.0	65.00	40.50	40.83	0.70	0.72
7	0	0	200.0	65.00	40.80	40.83	0.72	0.72
8	-1.414	0	150.0	65.00	40.71	41.20	0.75	0.72
9	1.414	0	250.0	65.00	40.32	40.88	0.73	0.73
10	0	-1.414	200.0	60.00	35.20	36.40	0.58	0.59
11	0	0	200.0	65.00	41.00	40.83	0.74	0.72
12	0	0	200.0	65.00	41.30	40.83	0.76	0.72
13	0	1.414	200.0	70.00	44.71	44.56	0.92	0.88

The model equations for the respective responses and the composite materials are summarised as follows. The equations represent tensile strength, proof stress, flexural strength, and flexural modulus as a function of temperature (X_1) and level of polymer (X_2). Equations 1 to 4 were used to predict the tensile strength, proof stress, flexural strength, and flexural modulus for the HDPE composite and the results are shown in Tables 2a and 2b respectively.

3.3. Analysis of Variance of Models

The other statistical parameters that were used to assess the significance and fit of the response models are presented in Table 3. All the models were characterised by high R^2 value and adjusted R^2 value. The R^2 value is used as an indication of model fit. The ideal R^2 value is unity in which case there is perfect fit between the experimental data and the model prediction. For the results reported in Table 3, the closeness of the R^2 value to unity indicates that the models were able to adequately represent the actual relationship between the variables considered in this study. Furthermore, the adjusted R^2 values obtained were within reasonable agreement with the corresponding R^2 values further confirming the fit of the models. The models displayed very minimal standard deviation compared to the mean. This means that there was very little dispersion about the mean for the data predicted by the (Khuri and Mukhopadhyay, 2010). This further corroborates the significant fit of the models. The coefficient of variation (C.V) obtained for the models were relatively small in magnitude. The coefficient of variation indicates the degree of precision with which the runs were carried out. A low value of C.V suggests a high reliability and reproducibility of the results (Montgomery, 2005). The adequate precision values obtained were all greater than the recommended minimum value of 4 (Myers and Montgomery, 1995). They presented report that the adequate precision measures the signal to noise ratio and a value greater than 4 is generally desirable and this means that the models can be used to navigate the design space (Cao et al., 2009).

Table 3: Statistical information for ANOVA for quadratic models

Parameter	HDPE composite			
	Tensile	Proof stress	Flexural	Flexural
R^2	0.8219	0.8051	0.9377	0.9077
Adjusted R^2	0.6948	0.6659	0.8931	0.8418
Mean	24.50	28.35	40.79	0.73
Standard deviation	0.67	0.80	0.80	0.035
C.V %	2.73	2.83	1.96	4.76
Adeq. Precision	7.141	7.147	15.055	12.180

3.4. Model Diagnostics

Model diagnostics was carried out to further assess the adequacy of the quadratic models developed to represent the responses and the results are presented in Figure 1. Figures 1 show the normal probability plots representing all the responses for the HDPE-Sawdust composite. This is an important plot which is used to determine whether the residuals follow a normal distribution. A desirable situation is when a normal distribution of the residuals is obtained and this is usually when all the points cluster around the straight line. Indeed, this was the case for the results presented in Figure 1 thus showing that the residuals followed a normal distribution.

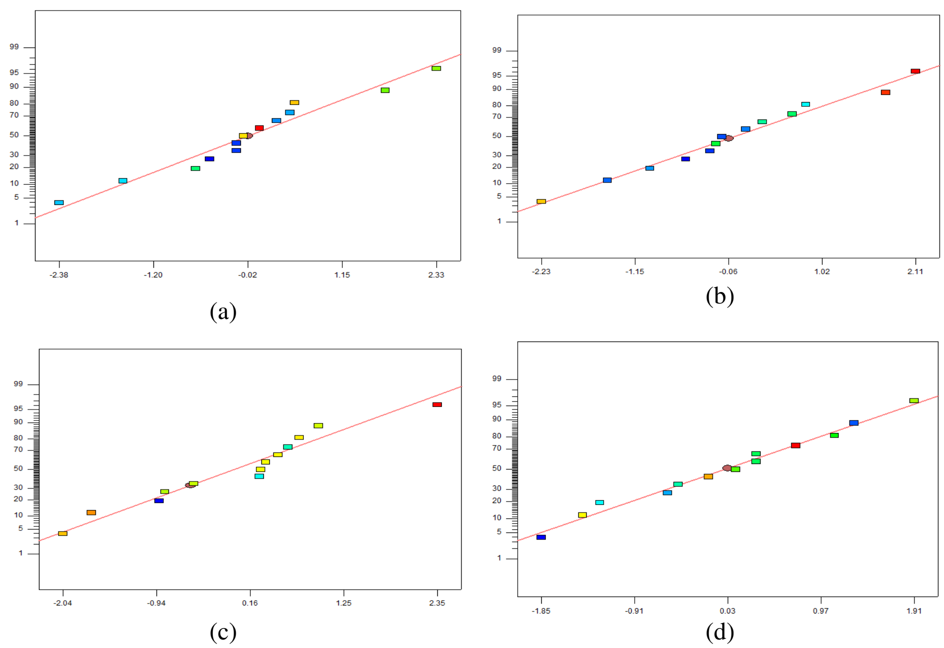


Figure 1: Normal probability plot for (a) tensile strength (b) proof stress (e) flexural strength (f) flexural modulus for HDPE composite

3.5. Validation of RSM Model Results

Figure 2 shows the parity plot for the HDPE-Sawdust composite. This is a plot of the predicted response values versus the experimental response values. The purpose of this plot is to determine the predictive capacity of the models. The purpose is also to detect a value, or group of values, that are not easily predicted by the model. Comparison of the experimental values of the response and those predicted by the statistical models as shown in Figure 2 shows that there was an acceptable level of fit between the experimental and model predicted results. This is evident from the fact that the data points all clustered around the 45^{o} diagonal line showing that there was minimal deviation between experimental and predicted values thus indicating optimal fit of the model.

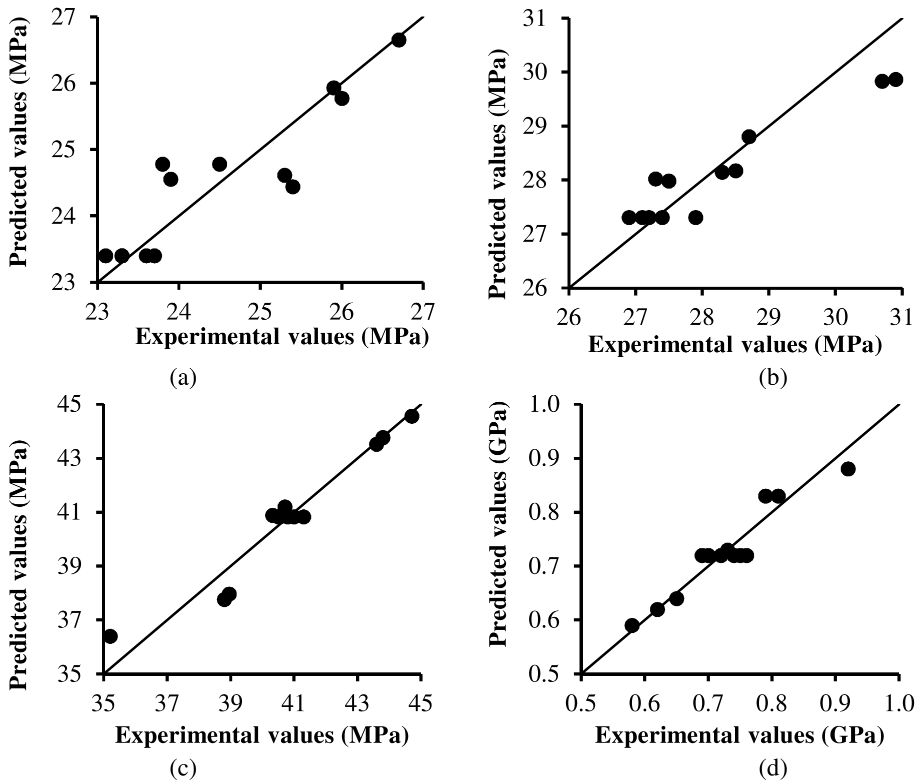
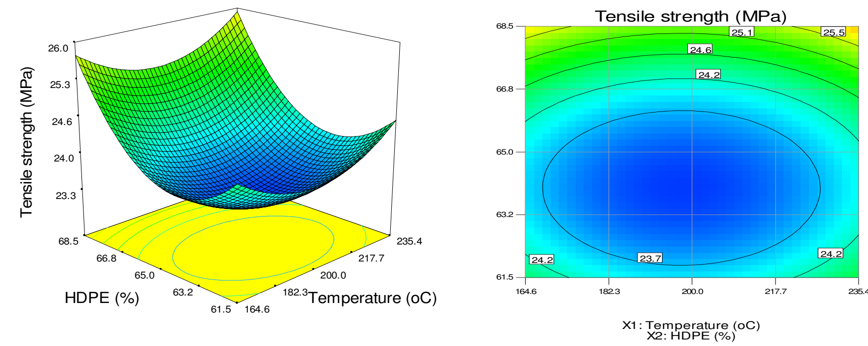


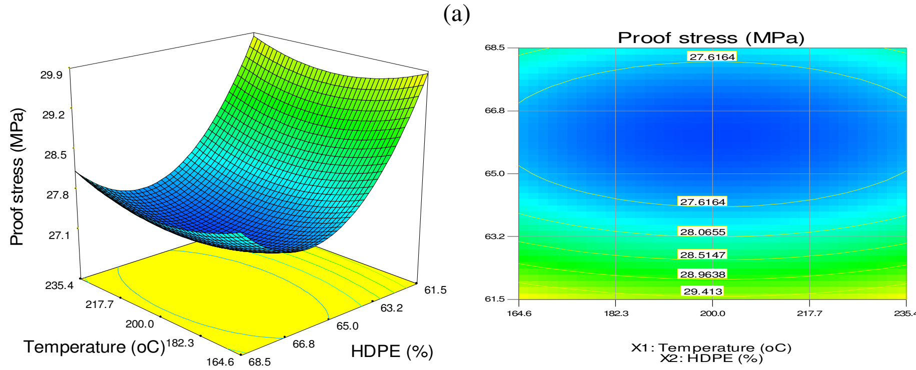
Figure 2: RSM parity plot for (a) tensile strength (b) proof stress (c) flexural strength (d) flexural modulus for HDPE composite

3.6. Response Surface Plots

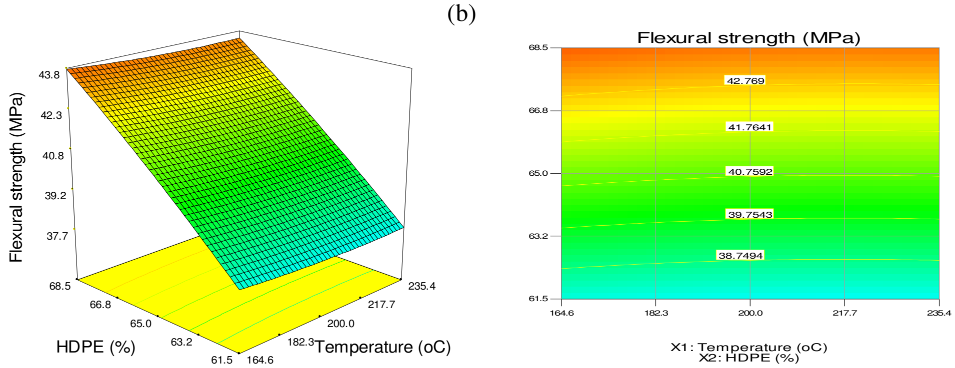
The three-dimensional (3D) plots were generated by varying two variables within the experimental range. Figure 3 shows the response surface and contour plot showing the effect of temperature and polymer level on (a) tensile strength (b) proof stress (c) flexural strength (d) flexural modulus for the HDPE composite. Increasing the polymer level (HDPE) increased the tensile strength of the composite material. Thus, high levels of polymer were beneficial to tensile strength. On the other hand, the effect of temperature on tensile strength was not very significant. Nevertheless, high levels of temperature were favourable to tensile strength as shown in Figure 3(a). Increasing the level of HDPE in the composite resulted in a decrease in the proof stress of the HDPE composite material as shown in Figure 3(b). Temperature did not have any significant influence on the proof stress as seen from the fact that increasing the temperature did not result in any appreciable change in the proof stress.



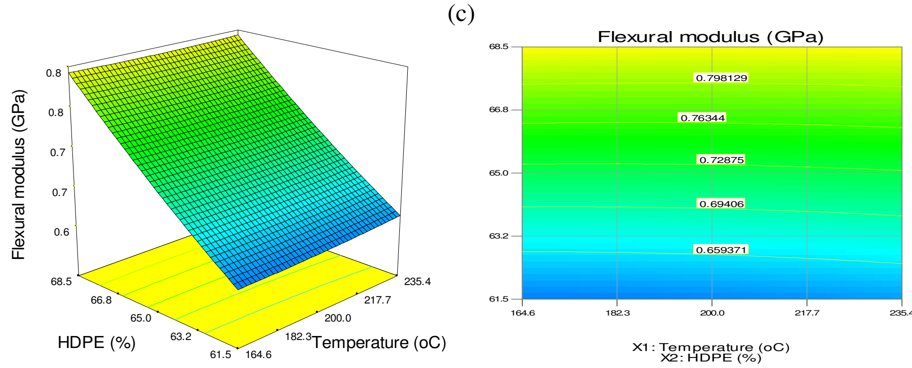
(a)



(b)



(c)



(d)

Figure 3: Response surface and contour plot showing effect of temperature and polymer level on (a) tensile strength (b) proof stress (c) flexural strength (d) flexural modulus for HDPE composite

Increasing the level of HDPE in the composite material positively influenced the flexural strength of the material as shown in Figure 3(c). Temperature only had a minor effect on the flexural strength of the material. The trend observed for flexural modulus with respect to HDPE level and temperature is similar to that observed for flexural strength. HDPE positively affected the flexural modulus while temperature did not have any significant influence as shown in Figure 3(d).

4. CONCLUSION

In this study central composite design was used to determine the various compositions (percentage volume) of the HDPE-sawdust composite at given temperatures. The composite was produced using the injection moulding process. Models were developed for predicting the mechanical properties (tensile strength, proof stress, percentage elongation and flexural strength) for the produced composites. The models were validated using coefficient of determination (R^2). The coefficient of determination (R^2) obtained ranged from 0.9213 (92.13%) to 0.981 (98.10%) which indicates that a substantial good fit was achieved by the model developed. The optimization results showed that the tensile strength, proof stress, flexural strength and flexural modulus were maximized with values of 25.80 MPa, 28.17 MPa, 43.77 MPa and 0.83 GPa obtained at barrel temperature of 164.64 ^{o}C and polymer level of 68.54% respectively.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Adeyemi, S.O. and Adeyemi, M.B. (2002) Curing temperature and hardener resin addition Affecting drying and properties of particleboards. *International Journal of Materials and Product Technology*, 17 (7), pp. 590-599.

Ahmad, A.A.A., Shamsuddin, S., Aung, L.M., Aminudin, B.A. (2015), investigation of plasticinjection moulding process optimization in complex shape product. *Applied mechanics and materials*, 695(2015), pp. 260-264

Amenaghawon, N.A., Ogbeide, S.E. and Okieimen, C.O. (2014). Application of Statistical Experimental Design for the Optimisation of Dilute Sulphuric Acid Hydrolysis of Cassava Bagasse. *Acta Polytechnica Hungarica*, 11(9), pp. 1-12.

Andrew, R. (2014). The impacts of technological invention on economic growth – a review of the literature, the second machine age: work, progress, and prosperity in a time of brilliant technologies, *New York: W.W. Norton & Co*. (2014), pp. 72-73

Cao, G., Ren, N., Wang, A., Lee, D.J., Guo, W., Liu, B., Feng, Y. and Zhao, Q. (2009). Acid hydrolysis of corn stover for biohydrogen production using *Thermoanaerobacterium thermosaccharolyticum* W16. *International Journal of Hydrogen Energy*, 34, pp. 7182–7188.

Guru, M., Tekeli, S. and Bilici, I. (2006). Manufacturing of Urea Formadelhyde based composite particle board from Almond Shell. *Material and design*, 27, pp. 1148-1151.

József, G.K. and Tibor, B. (2005). Influence of mold properties on the quality of injection molded parts. *Periodica Polytechnica Ser. Mechanical Engineering,* 49(2), pp. 115–122.

Khedari, J., Nankongnab, J. and Hirunlabh, T. (2004). New low cost insulation particleboards from mixture of peel and coconut coir. *Building and Environment Journal*, 39, pp. 59-65.

Khuri, A.I. and Mukhopadhyay, S. (2010). Response surface methodology: Advanced Review. *WIREs Computational Statistics*, 2, pp. 128-149.

Martins, G., Antunes, F., Mateus, A. and Malca, C. (2017). Optimization of wood plastic composite for architectural application. *Procedia manufacturing* 12(2017) 203-220

Montgomery, D.C. (2005). *Design and Analysis of experiments, 6th ed.,* New York: John Wiley & Sons, Inc.

Mosle, H. G., Bruller, O. S. and Dick, H. (2009). On the influence of the geometry and processing parameters on the mechanical properties of injection moulded plastic. 38th SPE Annual Technical Conference, New York Hilton

Myers, R.H. and Montgomery, D.C. (1995). *Response Surface Methodology*. New York: John Wiley & Sons.

Njoku, R.E. and Obikwelu, D.O.N. (2008). Swelling characteristics and tensile properties of natural fiber reinforced plastic in selected solvents, *Nigerian journal of Technology*, 27, (2), pp. 58-63

Osaremwinda, J.O. (2006). Effect of resin concentration on the properties of groundnut husk Particleboard. *Global Journal of Mechanical Engineeing*, 7(1), pp. 60-64.

Osaremwinda, J. O. and Nwachukwu, J.C, (2007). Effect of particles size on some properties of Rick husk particle board. *Advanced Materials Research,* p. 18

Osarenmwinda, J.O, and Nwachukwu J.C. (2010). Development of Composite Material from Agricultural Waste. *International Journal of Engineering Research in Africa*. 3, pp. 42-48.

Sampathrajan, A., Vijayaaghavan, N.C, and Swaminathan K.R, (1992). Mechanical and thermal properties of particleboards made from farm residues. *Bioresource Technology*, 40, pp. 249-251.

Wang, D. and Sun, X.S. (2002). Low density particleboard from wheat straw and corn pith. *Industrial crops and products*, 15, pp. 43-50.

Westerdale, S., kazmer, D. O. and Hazen, D. (2008). A comparison of statistical process control (SPC) and on-line multivariate analyses (MVA) for injection molding. *International polymer processing*, 23(5), pp. 447-458.

Yalinkilic, M.K., Imamura, Y., Tahashi, M., Kalaycioglu, H., Nemli, G., Demirci, Z. and Ozdemir, T. (1998). Biological, Physical and Mechanical Properties of Particleboard manufactured from waste tea leave. *International Biodeterioration and Biodegradation*, 41, pp. 75-84.

Zhou, Y. and Mallick, P. K. (2005). Fatigue performance of an injection molded talc-filled polypropylene. *Polymer engineering and science,* 45(4), pp. 510-516.