

Investigation on Flexural and Compression Strength and Microstructures of Vacuum Assisted 3D Printed Samples

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ABSTRACT

Additive manufacturing (AM) has advanced significantly over the last decade, enabling the creation of complex geometries with functional parts. However, integrating vacuum pressure into open-source Fused Deposition Modeling (FDM) 3D printers remains underexplored, particularly regarding its impact on the flexural and compression strengths of printed samples. This study investigates optimal printing process parameters to enhance these mechanical properties, focusing on infill density (25%, 50%, 75%, and 100%) and vacuum pressure (21 inHg, 24 inHg, 27 inHg, and 30 inHg). Using ABS material, 48 samples were fabricated with an Up Plus 2 FDM printer encapsulated in a vacuum chamber, employing a complete factorial design with three replicates per parameter combination. Samples underwent flexural and compression strength tests, revealing a direct correlation between increased infill density and improved mechanical properties. Vacuum pressure significantly enhanced strengths, achieving up to a 100% increase in flexural strength and a 75% improvement in compression strength. Optimal conditions yielded a flexural stress of 39.76 N/mm² at 30 inHg/100% and a compression stress of 38.69 N/mm² at 27 inHg/100%. Microstructural analysis via optical microscopy confirmed enhanced interlayer bonding in vacuum-assisted samples compared to non-assisted ones. These findings underscore the critical role of vacuum pressure in improving the mechanical properties of 3D-printed components, providing valuable insights for advancing FDM technology.

Keywords: Fused Deposition Modeling; flexural strength; compression strength; ABS; vacuum pressure; microstructure

INTRODUCTION

Additive manufacturing (AM) is a method of joining materials to build parts or products from Computer-Aided Design (CAD) model data, often layer by layer, instead of subtractive manufacturing processes. Other names include 3D printing, additive fabrication, freeform manufacturing, or AM. These innovative approaches are still evolving today, and they are likely to have a significant impact on manufacturing. They may contribute to novel designs, and flexibility, reducing energy consumption, and shortening the time to market in the industry in the future (Gibson et al. 2021). AM, often known as 3D printing, has captured the imagination of many technical experts and manufacturing professionals. This type of technology is viewed as a road that, in the end, allows us to gain digitized production, the demand that will be manufactured, and the type of product

design that will be evaluated and rethought (Maidin et al. 2023).

AM, also known as the developing paradigm in manufacturing technology, acts as the middle of the deposition material concept to obtain the desired shape of goods, in contrast to subtractive manufacturing, a classic technique. The distinction can be recognized since traditional production procedures rely on altering or removing the original material (Sathish et al. 2022). As AM technologies are defined as converting a 3D model into a solid physical part through the controlled combining of materials, which typically occurs layer by layer, there is a distinction between subtractive manufacturing, which requires a huge billet of material to begin the process. Not only that but a process of consecutive material removal is needed to get the correct form by reducing the billet of material (Liu et al. 2021; Salmi 2021). Historically used

for prototyping, AM creates solid objects directly from a device without needing any equipment. Parts are built layer by layer, contrasting with traditional machining methods (Singh et al. 2020).

AM technology was initially created to reduce the time required for prototyping for product development and manufacture. Today's systems are increasingly being used by engineers worldwide to gain a better grasp of and convey their product designs. Furthermore, fast prototyping is one of the most viable manufacturing procedures that can be used for short production runs and complex shapes and designs. Numerous approaches are available for rapid prototyping, but only a few are extensively employed in the market (Chua et al. 2020; Kondaveeti et al. 2021).

One of the approaches is Stereolithography (SLA), also known as photo-solidification or resin printing. It is a type of 3D printing technology commonly employed in AM. SLA uses a liquid-based method and manufactures pieces directly from CAD software. Because the photosensitive resin needs to be hardened, SLA methods employ a low-power laser to achieve polymerization. Recently, it has become the most extensively utilized technology in the 3D printing business. It is an excellent choice for prototypes with complex geometries since it improves precision and can apply a wide range of finishes (Huang et al. 2020).

Fused Deposition Modeling (FDM) is another commonly used AM method that creates things from tiny layers of extruded filament. In FDM processes, warmed thermoplastic fibers are expelled through a tiny nozzle tip to produce pieces layer by layer. Other advantages of adopting FDM technologies include lower costs than other AM methods. Furthermore, the materials in FDM methods are non-hazardous and can be safely handled. It is even one of the AM methods that require more straightforward implementation because support material can be simply removed from the finished parts (Rajan et al. 2022).

Selective Laser Sintering (SLS) is an AM technology that employs a high-power laser to fuse ceramic powders, metal, or plastic to create a desired 3D object. This approach is the most effective in producing a sturdy, solid, and functional prototype for physical testing. One of the primary reasons why SLS is superior to other techniques is that it can create parts from various thermoplastic materials such as polystyrene, polyamide, glass-filled polyamide, and others. Even though SLS prototypes are not as clean or accurate in size as SLA prototypes, they may be made from a wider variety of materials and can be colored (Kruth et al. 2005).

AM can provide flexible production and make complicated parts at almost no additional cost. Because of its design flexibility and ability to build complex and lightweight parts, it has significant potential in the

aerospace industry. The low quantity of units, high-quality requirements, and quick response time are unique issues that must be addressed, particularly in the maintenance, repair, and overhaul industry for aerospace printed parts (Blakey-Milner et al. 2021; Kruth et al. 2005).

Recently, the materials available for 3D printing have allowed the production of large-scale objects (Puzatova et al. 2022). AM also allows the production of buildings using 3D-printed concrete (Xiao et al. 2021). Other than that, AM can aid in manufacturing biomedical implants for joint replacements, which can help reduce cost and time and be resource-saving. Additive fabrication can produce complex shapes resembling a human body form or anatomy, promoting improved mechanical movement for the user (Jang et al. 2020). Likewise, AM is prevalent in the field of dentistry. AM procedures for manufacturing dental polymers (Jockusch & Özcan 2020). Dental polymer production typically involves four additional steps. These polymerization technologies include laser stereolithography (SLA), material jetting (MJ), and digital light processing. In contrast, FDM is commonly used for material extrusion. These methods help produce complex-shaped dentistry implants custom-made for individual users (Demiralp et al. 2021; Revilla-León et al. 2020).

AM provides various advantages to its users. One is that it can implement rapid prototyping technologies that help speed up research and development (Attaran, 2017). Engineers, scientists, and designers can utilize various materials for part design using AM (Maidin, Hayati, et al. 2023). This increased flexibility allows researchers to identify the best materials (through scientific methods) to solve specific design challenges (Maidin, Rajendran, et al. 2023). AM technology can also produce a wide range of products with different characteristics at a reduced cost (Pratheesh Kumar et al. 2021). This helps researchers, designers, and engineers have the freedom to rapidly create multiple prototypes to test design concepts (Cicconi et al. 2021).

AM has drawbacks, such as its limited production volume compared to conventional methods. Producing one complex part takes too long owing to the 3D printing process of building parts layer by layer (Shajahan et al. 2022). Furthermore, 3D printed parts suffer from bad or rough surface finish. This defect requires the part to undergo post-processing, and this results in increased production time, thus contributing to low production volume and increasing cost for finishing processes.

This paper investigates the effect of vacuum pressure on the flexural and compression strength of ABS material printed using an open-source FDM 3D printer. The aim is to identify the optimal printing process parameters for the flexural and compression strength of the printed samples. The parameters considered are the infill density and the

vacuum pressure. Finally, an optical microscope was used to observe the differences in microstructure with and without vacuum pressure.

METHODOLOGY

DESIGN OF TEST SAMPLES

Firstly, two different design samples were made. The samples were designed using SolidWorks CAD software. Figures 1 and 2 show *the CAD designs for both tests*. The samples for flexural and compression designs are based on the American Society for Testing and Materials (ASTM). The sample shapes are consistent with ASTM standards, but custom dimensions determine the size. The flexural test samples have simply a narrow rectangular form. It is fabricated to be 3.2mm x 12.7mm x 125mm and 10mm x 4mm x 80mm sizes for ISO, as per the ASTM D790 and ISO 178 standards, respectively. This is the dimension standard for flexural tests on plastic and the most widely used size for samples. The compression test samples might be blocks or cylinders of various ASTM standard sizes. According to ASTM D695, ISO 604, a typical block's sample size is 12.7mm x 12.7mm x 25.4mm.

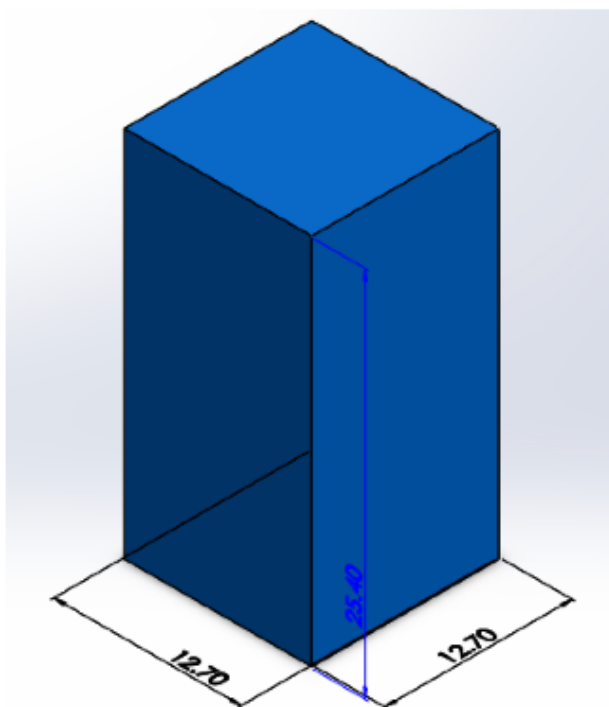


FIGURE 1. Compression test samples

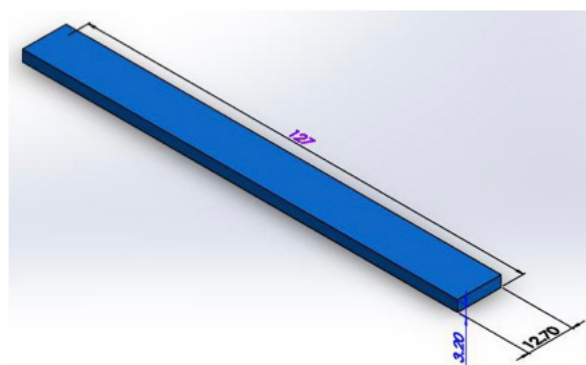


FIGURE 2. Flexural test samples

DESIGN OF EXPERIMENT (DOE)

Full factorial can be studied using all conceivable combinations, and it is the most reliable design technique commonly utilized in every investigation. The factors considered in this study include infill density (25%, 50%, 75%, and 100%) and vacuum pressure (30, 27, 24, and 21 inHg). This design expert software generates a detailed design matrix that displays all conceivable level combinations for each input factor. The data will be inputted using historical data technique for the ANOVA test.

STANDARD OPERATING PROCEDURE (SOP)

A standard operating procedure (SOP) is a series of step-by-step instructions an organization develops to assist employees in carrying out routine tasks. The SOP's objectives are to achieve efficiency, quality output, and uniformity of performance while reducing miscommunication and failure to comply with industry laws. This study uses a Universal Testing Machine (UTM) for flexural and compression tests. Next, an FDM was used because it can easily vary or change the layer thickness of the samples and the type of material used. The FDM printer used is the 'Up Plus 2' 3D printing machine. A sample of the test samples was manufactured using the machine's default parameters of 0.20 mm layer thickness and varying percentages of infill density. This study includes a vacuum pressure parameter since a vacuum chamber will be used with an FDM machine during printing. Likewise, an optical microscope is used during the microstructure inspection process of the samples.

SAMPLES TESTING

ASTM D790 specifies how the flexural characteristics of unreinforced and reinforced polymers should be determined.

It began with the material being placed horizontally over two points of contact. Then, a force is applied to the top of the material via one or two points of contact until the sample fails. In most cases, the samples are placed on a support span before the load is applied to the center of the loading nose. A predetermined rate of three-point bending will be achieved. The specifications in this test are the supported span, the loading speed, and the maximum deflection of the test. These values are based on the thickness of the samples, which is defined differently by ASTM and ISO. ASTM D790 considers the test complete when the samples reach 5% deflection or break before 5%. Meanwhile, ISO 178 requires the test to be terminated when the material begins to shatter.

According to ASTM D695, compression testing investigates the compressive properties of stiff polymers using straining and loading as a single operation. It is done at a modest compression rate. Compression tests assess the overall compressive strength, compressive yield strength, offset yield strength, and modulus of elasticity. Compression strength testing involves placing a small piece of plastic in the middle of two hardened blocks between compressive plates running parallel to the surface and steadily squeezing it constantly until it fractures.

The maximum load is recorded alongside stress-strain data. An extensometer will be fitted to the front of the fixture to determine the modulus. This technology delivers information about the compressive properties of plastic materials under specific conditions. The compressive parameters mentioned above include modulus of elasticity, yield stress, deformation beyond the yield point, and compressive strength (unless the material flattens but does not fracture yet).

ANOVA

Analysis of variance (ANOVA) is a technique used to identify the significant parameters that will influence printed samples' flexural and compression strength. If any included components or combinations of factors utilized in this research have a cumulative P-value of less than 0.05, the factor(s) are statistically significant. The final equation in this research will be constructed in either physical unit or coded form. The model/samples can be validated because the study will conclude with a model diagnostic. Finally, performing an optimization can help determine the optimal parameters to use. The Design-Expert program was used to carry out this ANOVA approach.

VACUUM-ASSISTED OPEN SOURCE FDM SYSTEM

A pilot test for a vacuum-assisted FDM system was completed. It demonstrates that increased vacuum pressure influences the higher/maximum tensile strength achieved. It has been stated that 30 inHg is the pressure at which the typical atmospheric occurs, and this has been used as a benchmark for the experiment. Because all three forms of testing, flexural, tensile, and compression, are all part of mechanical strength, the same benchmark will be used in this research. A vacuum chamber made of PMMA (acrylic) with good optical qualities, abrasion resistance, and rigidity is shown in Figure 3. Bonding adhesives were employed to seal the joints between each wall. Unlike the original design, the chamber will be at the bottom and the lid at the top. The rationale was to cut lead time, and the FDM machine could be positioned inside the chamber rather than constantly being removed.



FIGURE 3. Experimental Set-Up

PREPARATION OF SAMPLES

In this research, the samples are prepared through design testing using CAD model generation, tabulation of FDM parameters, and fabrication of samples. Firstly, the design for both types of samples is created through SolidWorks

software. Then, the designs are converted to STL format and sent to the FDM machine. The FDM machine has varying parameters, as shown in Table 1, while Figure 4 illustrates infill density. Table 2 shows the combination of the parameters for samples whereby 16 sample runs are fabricated.

TABLE 1. Parameters of the 3D printing process.

Level	1	2	3	4
Infill Density (%)	25	50	75	100
Vacuum Pressure (inHg)	21	24	27	30

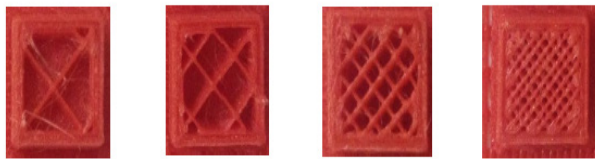


FIGURE 4. Infill density (25%, 50%, 75% and 100%)

TABLE 2. Combination of Parameters

Sample	Infill Density (%)	Vacuum Pressure (inHg)
1	25%	21
2	50%	21
3	75%	21
4	100%	21
5	25%	24
6	50%	24
7	75%	24
8	100%	24
9	25%	27
10	50%	27
11	75%	27
12	100%	27
13	25%	30
14	50%	30
15	75%	30
16	100%	30

RUNNING THE EXPERIMENT

The UTM machine is used for both flexural and compression testing. A three-point bend is conducted in flexural testing, as shown in Figure 5, while compression testing is shown in Figure 6.

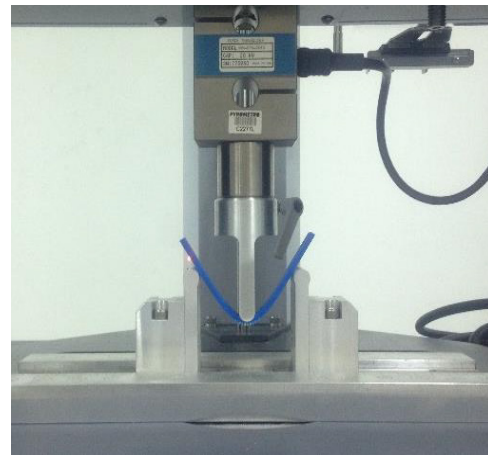


FIGURE 5. Flexural testing

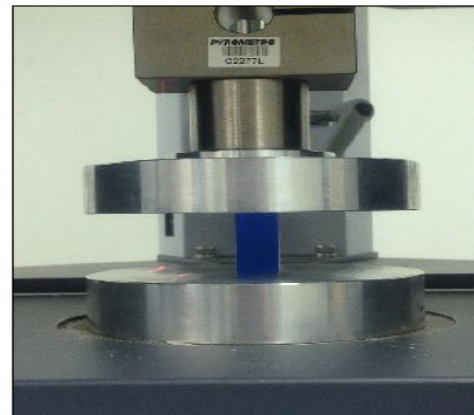


FIGURE 6. Compression testing

RESULTS AND DISCUSSION

RESULT OF FLEXURAL TESTING

STRESS AND STRAIN

Figure 7 depicts the experiment's results, and flexural testing revealed variances depending on several parameters. Most samples had average flexural strength values ranging from 32 to 34 N/mm² and 38 to 40 N/mm², with minor variations and flexural strain ranging from 4.5 to 5.2%. The highest flexural strength was 39.7594 N/mm² at 30 inHg/100%, while the elastic modulus was highest for samples generated at 27 inHg/75%. The 75% (blue) and 100% (black) infill density had the largest set of maximum stress, which could indicate enhanced strength with increased infill density. Values ranging from 25% (red) to 50% (yellow), 75% (blue), and 100% showed greater strength with greater infill density.

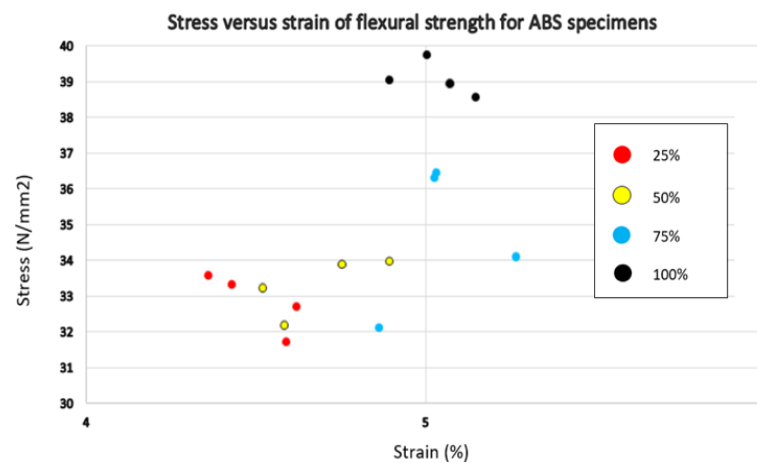


FIGURE 7. Stress versus strain for flexural strength of ABS samples

INFILL DENSITY – LAYER BONDING

At 30 inHg (1 atm), increasing infill density from 25% to 100% increased maximum stress by 21.51%, as illustrated in Figure 8. The bar chart below demonstrates that the greatest stress the samples can withstand is at 100% infill density. Numerous experiments conducted by researchers confirmed that the highest infill density results in maximum

strength since the level of infill influences flexural strength. It was claimed that the infill has a considerable impact on the effect of the deposition angle on the dependent variable (Lužanin et al. 2014). All samples are printed at the same deposition angle (0°) throughout the research. The strength of the samples displayed with 25% to 100% infill density improved dramatically, as did the contact surface area, resulting in superior bonding.

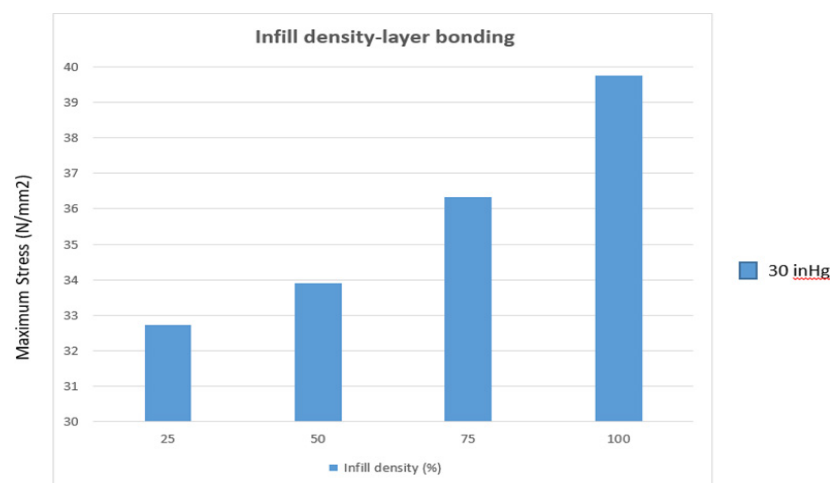


FIGURE 8. Maximum stress of ABS samples produced in different infill density

New samples were reprinted and stopped halfway to analyze further, as shown in Figure 9. The latest samples were in cube shape to ease the observation of the layer bonding. This shows that reduced infill density influences the layer bonding generated between samples. The relationship between deposition angle and infill density is relevant because combining the two can improve flexural strength (Dev & Srivastava, 2021). The experiment confirms prior findings, demonstrating that flexural force greater than 55N may be obtained with both variables at 100% at a deposition angle of 0° .

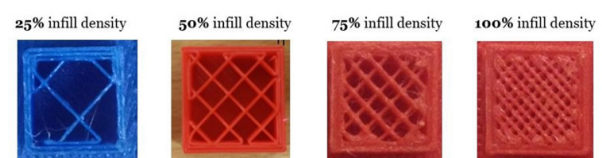


FIGURE 9. Different shapes of layers measured in various infill density

INFILL DENSITY VERSUS VACUUM PRESSURE

As previously stated, increasing infill density resulted in improved flexural strength. However, the question was whether the same trend would be observed when the samples were fabricated under low-pressure (high vacuum) conditions. Figure 10 shows the maximum stress achieved at different vacuum pressures and infill densities for flexural strength analysis.

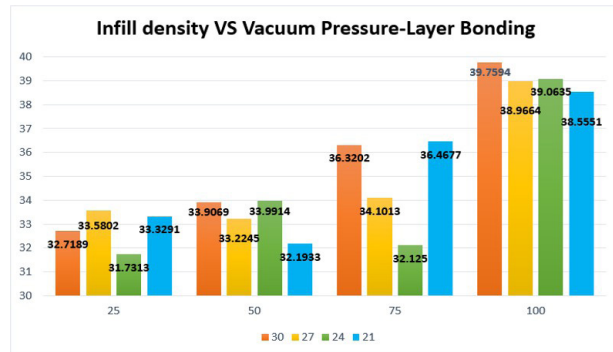


FIGURE 10. Flexural Strength vs Vacuum Pressure

At 100% infill density, the maximum stress increased with vacuum pressure and remained constant after 30 inHg. The highest value was recorded at 30 inHg, with a maximum stress of 39.7594 N/mm², representing a 15.68% improvement. At 75% infill density, a similar trend was observed, with a general decrease in maximum stress and a local peak at 21 inHg. The maximum stress at 21 inHg was 36.4677 N/mm², indicating improvement under this condition. For 50% infill density, the results showed relatively stable behavior with minor variations across vacuum pressure levels. The maximum stress at 21 inHg was 32.1933 N/mm², indicating slight improvement compared to other conditions. Overall, the application of vacuum pressure does not significantly enhance flexural strength across all infill densities. Instead, the results indicate that flexural strength is more strongly governed by infill density rather than vacuum pressure. At 21 inHg, higher infill density consistently results in higher flexural strength.

ANOVA FOR FULL FACTORIAL MODEL

This experiment used ANOVA to assess and validate the model's significance. A full factorial design resulted in 16 trial runs for each type of testing. The experiment data was subsequently entered into the historical data tool in Design-Expert software, as shown in Table 5.

TABLE 5. Full factorial design matrix for flexural

Run	Factor 1	Factor 2	Response 1	Response 2
	A: Infill Density	B: Vacuum Pressure	Stress	Strain
	%	inHg	N/mm ²	%
1	25	30.00	32.7189	4.6181
2	25	27.00	33.5802	4.3592
3	25	24.00	31.7313	4.5893
4	25	21.00	33.3291	4.4287
5	50	30.00	33.9069	4.7523
6	50	27.00	33.2245	4.5206
7	50	24.00	33.9914	4.8941
8	50	21.00	32.1933	4.5835
9	75	30.00	36.3202	5.0255
10	75	27.00	34.1013	5.2678
11	75	24.00	32.125	4.8639
12	75	21.00	36.4677	5.0299
13	100	30.00	39.7594	5.0017
14	100	27.00	38.9664	5.0716
15	100	24.00	39.0635	4.8942
16	100	21.00	38.5551	5.1464

ANALYSIS OF VARIANCE TABLE

The 16 experimental runs were analyzed using Response Surface Methodology with a historical data-based design. The input factors were infill density and vacuum pressure, while the responses were stress and strain. For the stress response, values ranged from 31.7313 to 39.7594 N/mm², giving a maximum-to-minimum ratio of 1.2530; therefore, no transformation was required. Quadratic modelling was identified as the best fit. As shown in Table 6, the model F-value of 11.4 indicates that the model is statistically significant ($p < 0.05$), confirming that the model terms are meaningful.

TABLE 6. ANOVA table for flexural stress model

Source	Sum of Squares	DF	Mean Square	F value	Prob>F	
Model	101.15	6	16.86	11.42	0.0009	Significant
A	96.86	3	32.39	21.87	0.0002	
B	4.29	3	1.43	0.97	0.4487	
Residue	13.29	9	1.48			
Cor Total	6.89	15				

Next, the strain analysis was performed. The response ranged from 4.3592% to 5.2678%, with a maximum-to-minimum ratio of 1.2084; therefore, no data transformation was required. A linear model was suggested by the software. However, as shown in Table 7, the model was

statistically insignificant ($p = 0.0955$). Furthermore, the negative predicted R-squared value (-0.1555) indicated poor predictive capability. Therefore, the strain model was considered unsuitable for optimization purposes, and only the experimental strain observations are discussed.

TABLE 7. ANOVA table for flexural strain model

Source	Sum of Squares	DF	Mean Square	F value	Prob>F	
Model	0.71	6	0.12	2.60	0.0955	Not Significant
A	0.65	3	0.22	4.80	0.0291	
B	0.055	3	0.018	0.41	0.7509	
Residue	0.41	9	0.045			
Cor Total	1.11	15				

As shown in Table 8, the stress model exhibited an adjusted R-squared value of 0.8065 and a predicted R-squared value of 0.6331, indicating acceptable predictive capability. In contrast, the strain model produced a negative predicted R-squared value (-0.1555), suggesting poor predictive performance and limited suitability for

prediction and optimization. Adeq Precision evaluates the signal-to-noise ratio, where a value greater than 4 is desirable. Although both models exhibited Adeq Precision values above the recommended threshold, the strain model was considered statistically unreliable due to its insignificant model p-value and negative predicted R-squared value.

TABLE 8. ANOVA summary statistics for flexural

Stress Analysis	Std. Dev. = 1.22	R-Squared = 0.8839
	Mean = 35	Adj R-Squared = 0.8065
	C.V. = 3.47	Pred R-Squared = 0.6331
	PRESS = 41.99	Adeq Precision = 9.575
Strain Analysis	Std. Dev. = 0.21	R-Squared = 0.6344
	Mean = 4.82	Adj R-Squared = 0.3906
	C.V. = 4.41	Pred R-Squared = -0.1555
	PRESS = 1.28	Adeq Precision = 4.774

The coefficients provided in Table 9 for the factorial post-ANOVA were coded ($-1, +1$). The VIF values for both

analyses were one, indicating that the coefficient was orthogonal to all other coefficients in the model.

TABLE 9. ANOVA for coefficient statistics for flexural

	Factor	Coefficient	DF	Standard	95% CI	95% CI	VIF
		Estimate		Error	Low	High	
Stress Analysis	Intercept	35	1	0.30	34.32	35.69	
	A(1)	-0.216	1	0.53	-3.35	-0.97	1
	A(2)	-1.67	1	0.53	-2.86	-0.48	
	A(3)	-0.25	1	0.53	-1.44	0.94	1
	B(1)	0.13	1	0.53	-1.06	1.32	
	B(2)	-0.77	1	0.53	-1.96	0.42	1
	B(3)	-0.034	1	0.53	-1.22	1.16	1
Strain Analysis	Intercept	4.82	1	0.053	4.70	4.94	
	A(1)	0.063	1	0.092	-0.15	0.27	1
	A(2)	0.11	1	0.092	-0.10	0.31	
	A(3)	0.17	1	0.092	-0.035	0.38	1
	B(1)	0.073	1	0.092	-0.14	0.28	

continue...

...cont.

B(2)	0.034	1	0.092	-0.17	0.24	1
B(3)	-0.083	1	0.092	-0.29	0.13	1

MODEL DIAGNOSTIC REPORT

Design-Expert delivers a diagnostic to help validate the model. The first one on the left was a normal plot of residuals for stress and strain (right) analysis, as shown in

Figure 11 for flexural strength. The optimum normal residual plot is a straight line, as illustrated below. As a rule of thumb, place a pencil over the line to cover up the data points. In this scenario, both plots were fine and acceptable.

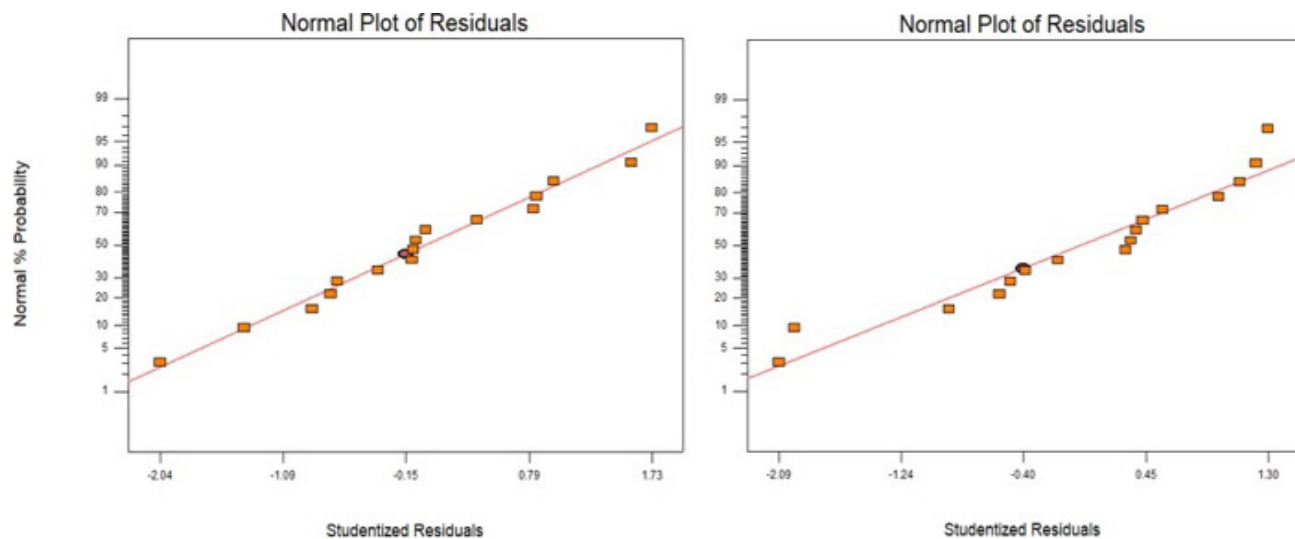


FIGURE 11. Normal plot of residuals for stress (left) and strain (right) analysis

Figure 12 shows a residual vs expected plot, which was used to confirm the constant variable assumption. It demonstrates that all the points fell under the three sigma

limitations for stress and strain assessments. None of the points exceeded the restrictions, which proved that both outcomes were okay and acceptable.

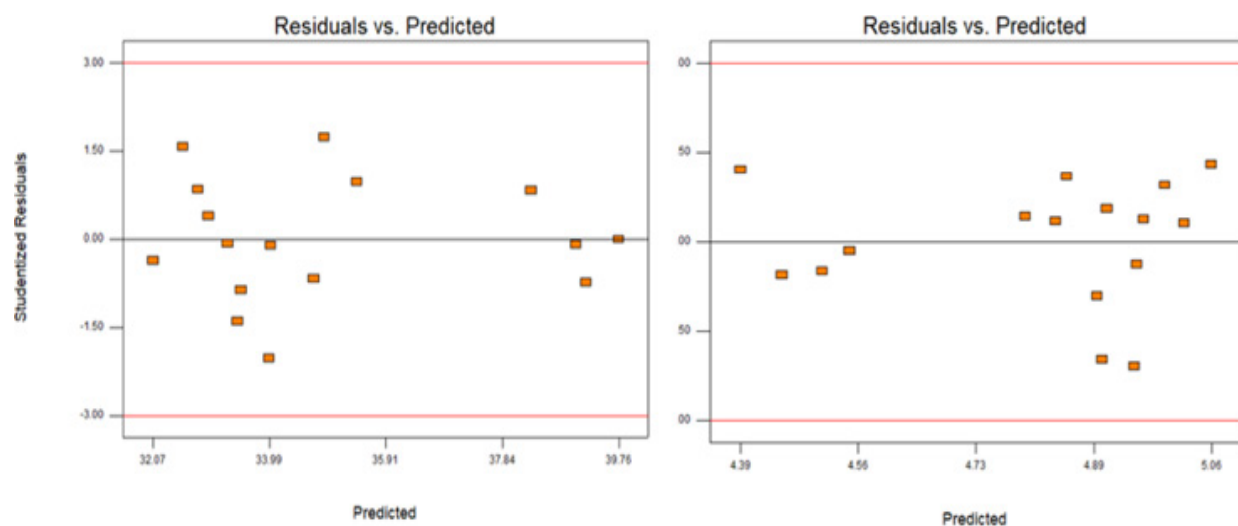


FIGURE 12. Residual versus predicted for stress (left) and strain (right) analysis

Figure 13 shows residual versus run charts. All points must be randomly distributed within three-sigma limits to

confirm the independence assumptions. Both stress and strain analyses were close to meeting the requirements.

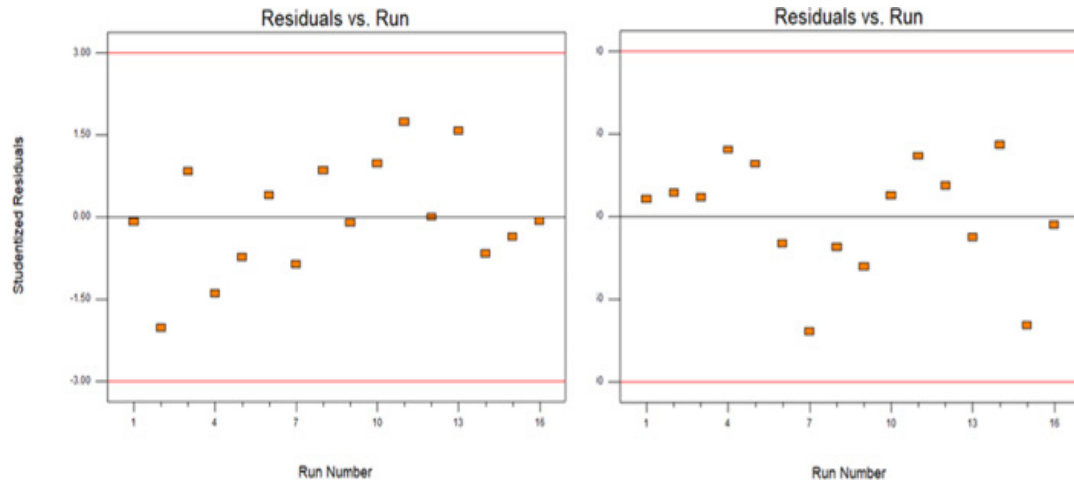


FIGURE 13. Residual versus run-on stress (left) and strain (right) analysis

Predicted versus actual plots, as shown in Figure 14, were to see how the models predict over the range of data.

Both plots exhibited random scatter about the 45-degree line.

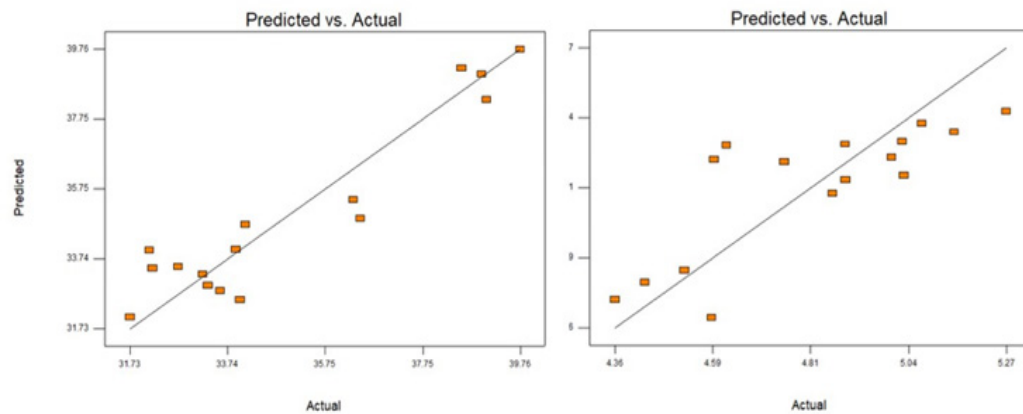


FIGURE 14. Predicted versus actual stress (left) and strain (right) analysis

The box-cox plots were used to determine whether the model required data transformations. In Figure 15, the

design expert claimed neither model was needed for any recommended transformation.

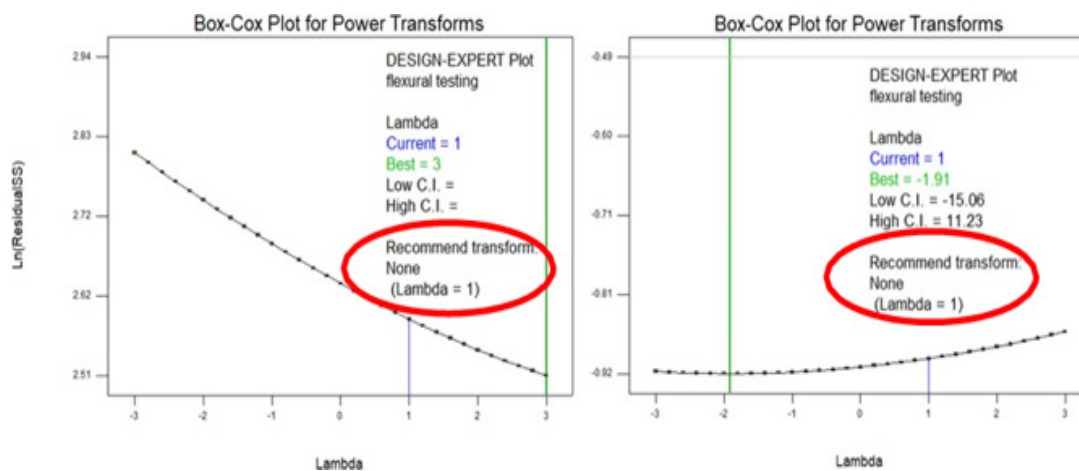


FIGURE 15. Box-cox plot for power transform on stress (left) and strain (right)

OPTIMISATION SET OF PARAMETERS

Design-Expert software is extensively used since it can optimize and identify the best set of parameters. Based on the optimization results, the optimal set of parameters for flexural testing for stress analysis was 100% infill density and 30 inHg vacuum pressure, which produced 39.7594 N/mm². The optimized parameters for strain analysis were 75% infill density and 27 inHg, yielding a result of 5.2678%.

RESULTS OF COMPRESSION TESTING

STRESS AND STRAIN

Tables 10 and 11 show the results of strength samples tested for compression strength.

TABLE 10. Max stress (N/mm²) for each layer thickness at different pressure

Infill				Vacuum Pressure (inHg)				
Density		30			27			
(%)	A	B	C	Mean	A	B	C	Mean
25	14.7160	14.9839	15.5361	15.0787	15.5168	17.1390	14.3982	15.6847
50	17.4956	15.7601	15.5133	16.2563	18.1375	16.9621	17.2117	17.4371
75	17.5114	22.3736	18.7684	19.5511	21.0033	21.6852	20.206	20.9648
100	29.8734	33.3860	38.0667	33.7754	44.6235	33.6541	37.785	38.6875
Infill				Vacuum Pressure (inHg)				
Density		24			21			
(%)	A	B	C	Mean	A	B	C	Mean
25	16.9389	17.6144	16.3051	16.9528	9.87610	11.1088	10.2651	10.4167
50	16.7025	16.8025	18.7749	17.4266	15.1146	18.5549	18.6943	17.4546
75	18.9485	20.3976	22.5858	20.6440	20.4701	23.0534	21.7456	21.7456
100	34.0608	43.0022	25.0460	34.0225	39.2418	33.2327	37.3278	36.6008

TABLE 11. Max strain (%) for each layer thickness at different pressure

Infill		Vacuum Pressure (inHg)						
Density		30			27			
(%)	A	B	C	Mean	A	B	C	Mean
25	4.08779	4.69319	4.72177	4.50090	4.02534	5.94626	3.74168	4.57110
50	8.79118	5.60005	4.28784	6.20969	7.53834	4.82707	4.32810	5.56450
75	6.68529	18.3559	5.25127	10.0975	5.68892	6.47328	4.86441	5.67550
100	26.2447	21.0094	39.7322	32.3288	47.4672	23.3033	31.2369	34.0025
Infill		Vacuum Pressure (inHg)						
Density		24			21			
(%)	A	B	C	Mean	A	B	C	Mean
25	4.23898	4.96481	4.98579	4.72990	2.77440	4.07110	3.19055	3.34530
50	4.22902	8.94529	9.91647	7.69690	5.56902	10.9482	9.22260	8.58000
75	14.2741	21.1268	24.6748	20.0372	23.9781	27.5702	27.1571	26.2351
100	26.9088	47.0249	30.5996	34.8444	36.4407	30.5885	32.7192	33.2495

Figure 16 depicts the results acquired from the experiment, and compression testing revealed variances depending on several parameters. Most samples had compression strength averages of 32 to 34 N/mm² and 38 to 40 N/mm², with minor variations and compression strain ranging from 4% to 10%. The maximum compression strength was 38.6875 N/mm² at 27 inHg/100%, while the

elastic modulus was the highest for samples generated at 24 inHg/100%. The 75% (blue) and 100% (black) infill density had the largest set of maximum stress, which could indicate enhanced strength with increased infill density. 25% (red), 50% (yellow), 75% (blue), and 100% (black) indicated improved strength with increased infill density.

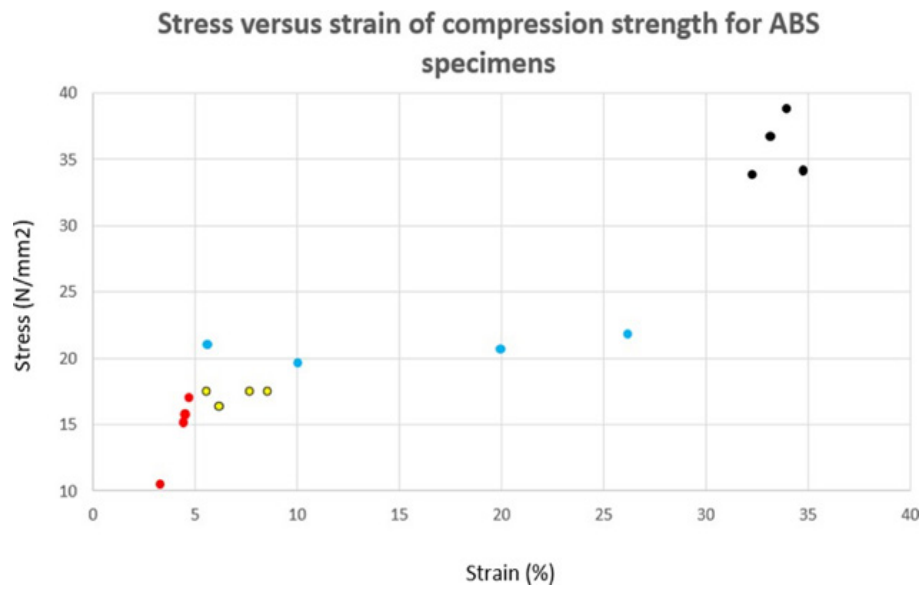


FIGURE 16. Stress versus strain for compression strength of ABS samples

INFILL DENSITY – LAYER BONDING

At 30 inHg (1 atm), increasing infill density from 25% to 100% increased maximum stress by 72.77%, as illustrated in Figure 17. The bar chart below demonstrates that the greatest stress the samples can withstand is at 100% infill density. According to other tests conducted by researchers, the maximum infill density has the advantage of having

the highest strength since compressive strength was the highest for solids, as expected (Pipalla et al. 2021). It was reported that samples with higher infill density had the highest compression strengths. The strength of samples with 25% to 100% infill density rose dramatically, increasing the contact surface area and resulting in superior bonding.

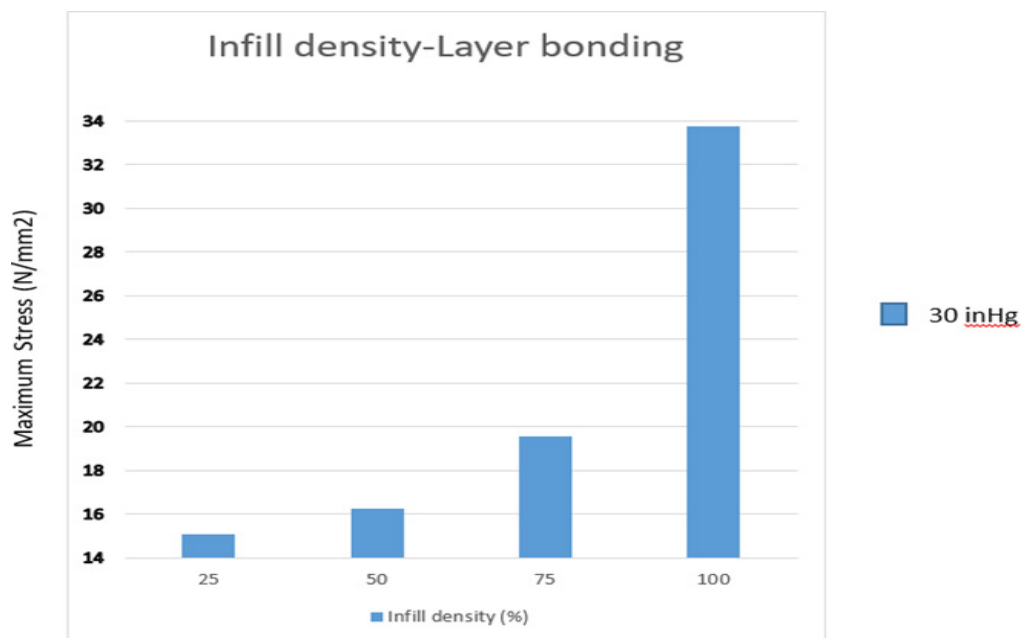


FIGURE 17. Maximum stress of ABS samples produced in different infill density

INFILL DENSITY VERSUS VACUUM PRESSURE

As previously indicated, higher infill density resulted in greater compression strength. As with flexural strength, the question was if it would provide the same findings if

the samples were manufactured in a low-pressure (high vacuum) environment for compression strength. Figure 18 depicts the maximum stress achieved at varied low pressures and infill densities for compression strength.

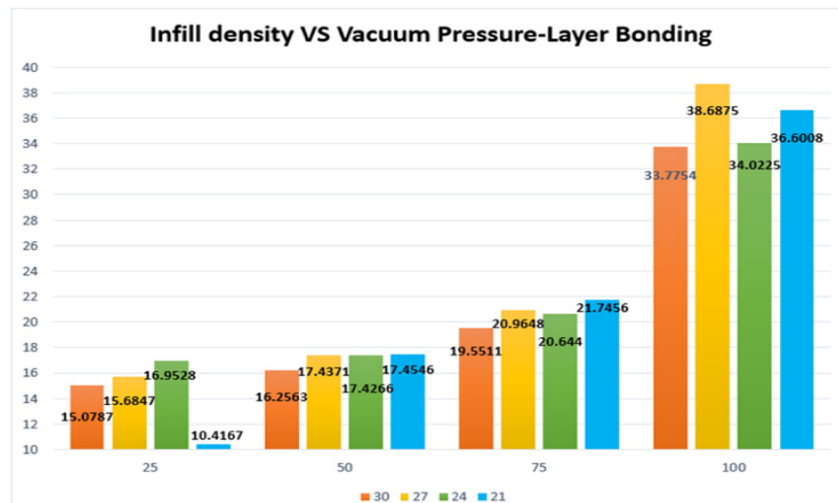


FIGURE 18. Maximum stress at different vacuum pressures with various layer thickness

At 50% infill density, the maximum stress rose with increasing vacuum pressure. The maximum stress was measured at 21 inHg and was 17.4546 N/mm², resulting in a 7.371% improvement. Next, created at 75% infill density, it displayed a similar pattern of increasing maximum stress but with a peak at 21 inHg. The maximum stress was 21 inHg, measuring 21.7456 N/mm², resulting in an 11.22% improvement. The results are constant at 25% infill density, with small improvement at each vacuum pressure increment and a significant reduction at 21 inHg. The maximum stress occurred at 24 inHg, measured at 16.9528 N/mm², representing a 12.43% improvement. At 100% infill density, the maximum stress was highest at 24

inHg, then gradually decreased to 27 inHg before slightly increasing to 21 inHg. The improvement from 24 inHg was 14.54.

ANOVA FOR FULL FACTORIAL MODEL

This experiment employed ANOVA to determine the model's significance and validate it. A full factorial design produced 16 trial runs for compression testing. The experiment data was subsequently entered into the historical data tool in the Design-Expert software, as shown in Table 12.

TABLE 12. ANOVA for coefficient statistics for compression

	Factor 1	Factor 2	Response 1	Response 2
Run	A: Infill Density	B: Vacuum Pressure	Stress	Strain
	%	inHg	N/mm ²	%
1	25	30.00	15.0787	4.50090
2	25	27.00	15.6847	4.57110
3	25	24.00	16.9528	4.72990
4	25	21.00	10.4167	3.34530
5	50	30.00	16.2563	6.20969
6	50	27.00	17.4371	5.56450
7	50	24.00	17.4266	7.69690
8	50	21.00	17.4546	8.58000
9	75	30.00	19.5511	10.0975

continue...

...cont.

10	75	27.00	20.9648	5.67550
11	75	24.00	20.6440	20.0372
12	75	21.00	21.7456	26.2351
13	100	30.00	33.7754	32.3288
14	100	27.00	38.6875	34.0025
15	100	24.00	34.0225	34.8444
16	100	21.00	36.6008	33.2495

ANALYSIS OF VARIANCE TABLE

The 16 tests underwent response surface research with historical data as the starting design. The input factors were infill density and vacuum pressure, while the responses were stress and strain. The first step was to do a stress analysis. The reaction spans between 10.4167 N/mm² and

38.6875 N/mm². The maximum-to-minimum ratio is merely 3.7140; thus, no alteration is required. The Design Expert then analyzed each degree of the model, finding that quadratic was the best fit. As seen in Table 13, the model F-value of 47.2 indicated that the model was significant. The P value given is less than 0.05, indicating that the model terms are important.

TABLE 13. ANOVA table for compression stress model

Source	Sum of Squares	DF	Mean Square	F value	Prob>F	
Model	1091.91	6	181.99	47.20	< 0.0001	Significant
A	1082.40	3	360.80	93.57	< 0.0001	
B	9.51	3	3.17	0.82	0.5138	
Residue	34.70	9	3.86			
Cor Total	1126.61	15				

Next, the strain analysis was performed. The response ranges from 3.34530% and 34.8444%. The maximum-to-minimum ratio is 10.4160, which requires no transformation.

The suggested model is linear. As seen in Table 14, the model F-value of 0.8 indicated that the model was not significant.

TABLE 14. ANOVA table for compression strain model

Source	Sum of Squares	DF	Mean Square	F value	Prob>F	
Model	12.99	6	2.17	0.80	0.5955	Not Significant
A	10.64	3	3.55	1.31	0.3314	
B	2.35	3	0.78	0.29	0.8332	
Residue	24.46	9	2.72			
Cor Total	37.45	15				

In Table 15, for stress analysis, the pred R-squared of 0.9026 was not close to the adj R-squared of 0.9487; however, for strain analysis, the pred R-squared of -1.0614 is rather close to the adj R-squared of -0.0885. Adeq

accuracy evaluates the signal-to-noise ratio; a value greater than four is preferred. Both the stress and strain ratios provided an acceptable signal in this scenario.

TABLE 15. ANOVA summary statistics for compression

Stress Analysis	Std. Dev. = 1.96	R-Squared = 0.9692
	Mean = 22.04	Adj R-Squared = 0.9487
	C.V. = 8.91	Pred R-Squared = 0.9026
	PRESS = 109.68	Adeq Precision = 17.913
Strain Analysis	Std. Dev. = 1.65	R-Squared = 0.3469
	Mean = 3.57	Adj R-Squared = -0.0885
	C.V. = 46.14	Pred R-Squared = -1.0641
	PRESS = 77.30	Adeq Precision = 2.669

The coefficients indicated in Table 16 for the factorial post-ANOVA were coded (-1, +1). The VIF values for both

analyses were one, indicating that the coefficient was orthogonal to all other coefficients in the model.

TABLE 16. ANOVA summary statistics for compression

	Factor	Coefficient Estimate	DF	Standard Error	95% CI Low	95% CI High	VIF
Stress	Intercept	22.04	1	0.49	20.93	23.15	
Analysis	A(1)	-7.51	1	0.85	-9.43	-5.59	1
	A(2)	-4.90	1	0.85	-6.82	-2.98	
	A(3)	-1.32	1	0.85	-3.24	0.61	1
	B(1)	-0.49	1	0.85	-2.41	1.44	
	B(2)	0.22	1	0.85	-1.71	2.14	1
	B(3)	1.15	1	0.85	-0.77	3.07	1
Strain	Intercept	3.57	1	0.41	2.64	4.50	
Analysis	A(1)	0.78	1	0.71	-0.84	2.39	1
	A(2)	0.66	1	0.85	-0.95	2.28	
	A(3)	-0.18	1	0.85	-1.80	1.43	1
	B(1)	-0.42	1	0.85	-2.03	1.20	
	B(2)	0.46	1	0.85	-1.16	2.07	1
	B(3)	0.30	1	0.85	-1.32	1.91	1

MODEL DIAGNOSTIC REPORT

Design-Expert delivers a diagnostic to help validate the model. Figure 19 depicts the normal plot of residuals for stress and strain (right) analysis. The optimum normal residual plot is a straight line, as illustrated below. As a rule of thumb, place a pencil over the line to cover up the data points. In this scenario, both plots were fine and acceptable.

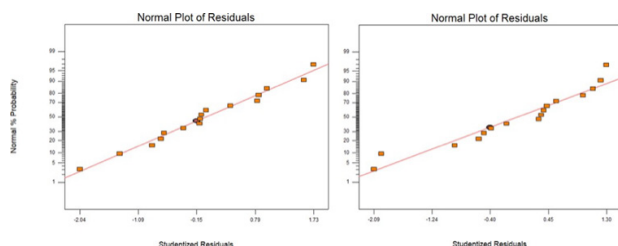


FIGURE 19. Normal plot of residuals for stress (left) and strain (right) analysis

Figure 20 shows a residual vs predicted plot used to confirm the constant variable assumption. It demonstrates that all points fell under the three sigma limitations for stress and strain assessments. None of the points exceeded the restrictions, which proved that both outcomes were okay and acceptable.

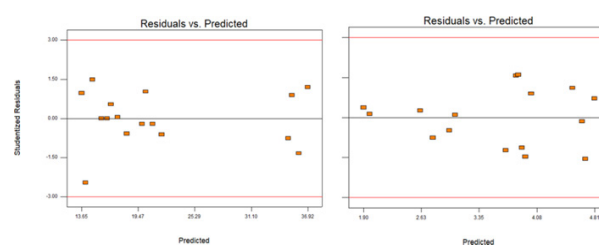


FIGURE 20. Residual versus predicted for stress (left) and strain (right) analysis

Figure 21 shows residual versus run charts. All points must be randomly distributed within three-sigma limits to confirm the independence assumptions. Both stress and strain analyses were close to meeting the requirements.

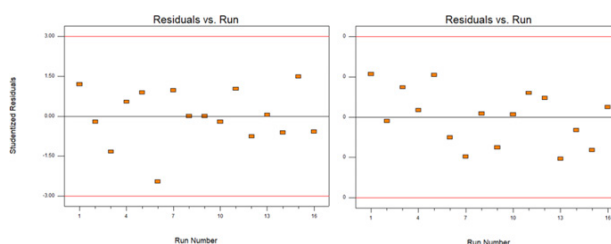


FIGURE 21. Residual versus run-on stress (left) and strain (right) analysis

Figure 22 shows predicted versus real charts to demonstrate how the models predict across various data points. Both plots showed random distribution about the 45-degree line, which is acceptable as the 45-degree line was reached.

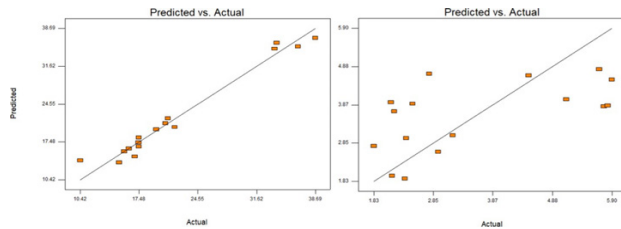


FIGURE 22. Predicted versus actual stress (left) and strain (right) analysis

The box-cox plots were used to determine whether the model required data transformations. In Figure 23, the design expert claimed neither model was needed for any recommended transformation.

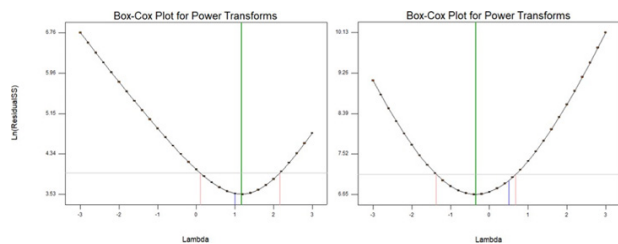


FIGURE 23. Box-cox plot for power transform on stress (left) and strain (right)

MICROSTRUCTURE OBSERVATION

FLEXURAL TESTING

One of ABS's material properties is that it is unsuitable for low-temperature environments. The samples were printed at low temperatures using varying levels of infill density. Thus, infill density significantly impacts the mechanical characteristics of the samples. As demonstrated in the images above, bubbles may form in the samples due to an abrupt temperature drop that occurs while the samples are being printed. Figures 24 (a) and (b) show samples for flexural testing at 30 inHg with varying levels of infill density, from the lowest (25% to the maximum (100%). Figure 24 (a) demonstrates increased porosity with 25% infill density compared to 24 (b) with 100% infill density.

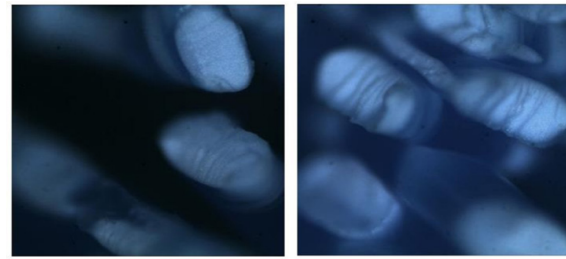


FIGURE 24. (a) bubble in the sample, infill density 25% (left) (b) Bubble in the sample, infill density 100% (right)

COMPRESSION TESTING

The images shown in Figures 25 and 26 detail how infill density affects the mechanical properties of printed items utilizing FDM across compression test samples. The figures detail the difference in the microstructure of selected samples obtained from compression testing. Figures 25 and 26 show samples for compression testing at 30 inHg with varying levels of infill density, from the lowest (25% to the greatest (100%). Figure 25 indicates that the layer-to-layer contact area of the sample structure is larger than in Figure 26. Figure 25 shows a bigger crack between two layers compared to Figure 26.

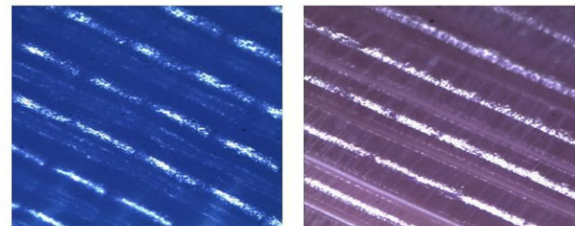


FIGURE 25. Cracks between layers, infill density 25%

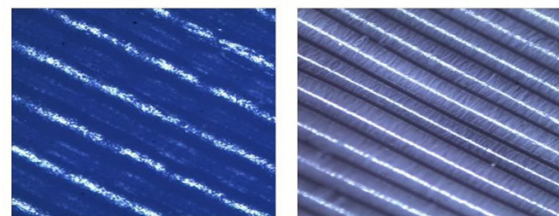


FIGURE 26. Crack between layers, infill density 100%

CONCLUSION

All the objectives of this research were effectively met. The sample was designed using the ASTM standard. The ASTM standards utilized for flexural and compression testing were ASTM D790 and D695. The model was

translated to STL format and submitted to the Up Plus 2 machine, which fabricated all the samples. Then, the printer was configured for various sample characteristics, including layer thickness, infill density, and material types. It printed 96 samples in total for flexural and compression testing. The flexural and compression test was done with various infill densities (25%, 50%, 75%, and 100%) and vacuum pressures (21, 24, 27, and 30 inHg), utilizing ABS as the input material to determine the best results. The flexural samples were tested using a three-point bending test with a UTM. The protocol was followed to ensure the data was collected accurately and consistently. The flexural test graph's results were examined. Similarly, compression testing is carried out utilizing a UTM.

The procedures are virtually identical to flexural testing. A total of 16 runs with three times repeatability resulted in 48 total samples for each flexural and compression test utilizing complete factorial. Finally, all the samples were examined for their strengths, and the findings were evaluated. It was discovered that as infill density increased, so did flexural and compression strength. When exposed to vacuum pressure, flexural and compression strength improve by 100% and 75%, respectively, whereas 50% and 25% do not due to different infill patterns. The maximum flexural stress was 39.76 N/mm², produced by 30 inHg/100%, while the highest flexural strain was 5.27%, made by 27 inHg/75%. When compared to non-assisted Hoover, 100% infill density resulted in the largest proportion of improvements (21.51%). Next, in compression testing, the greatest compression stress was 38.69 N/mm², produced by 27 inHg/100%, and the highest compression strain was 34.84%, made by 24 inHg/100%. The maximum percentage of improvement as compared to non-assisted Hoover was 72.77%, which was also achieved with 100% infill density.

An optical microscope was used to observe the differences in microstructure with and without vacuum pressure. The results indicate that the vacuum-assisted printed samples bind the layers of the printed samples better than non-assisted ones, showing the usefulness of the vacuum system in improving flexural and compression strengths. Finally, the microstructure was examined, and the effect was shown due to the varying infill density levels applied, producing excellent results.

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DECLARATION OF COMPETING INTEREST

None.

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