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Statistical Analysis of Tensile Strength and Flexural Strength Data from Universal Testing Machine

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Authors' contributions

This study was conducted in collaboration between both authors. Author SAAZMD managed the literature searches, designed the study, managed the analyses of the study and wrote the protocol. Author AAS wrote the first draft of the manuscript. Both authors read and approved the final manuscript.

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Abstract

The tensile strength and flexural strength are the most important mechanical properties as they provide the value of maximum tensile stress and flexural stress. The objective of this study is to analyze statistically the tensile strength and flexural strength data obtained from a universal testing machine. The tests were conducted upon a thermoplastic, specifically high-density polyethylene (HDPE), which was in-house molded by using an injection-molding machine. Three different persons have performed the tensile and flexural tests. Three other laboratories have also been involved in these tests. The relative standard deviation (RSD) values were calculated to express the precision and repeatability of the tests. Later, the standard score (z-score) values were also calculated to aid the comparison of the data. Finally, the single-factor analysis of variance (ANOVA) was employed to investigate statistically significant differences between the means of the tensile strength and flexural strength data of each person and laboratory. From the calculation, the RSD values of all three persons and laboratories were lower than 5%, indicating that the data were consistent. The z-score values of all three persons were within the range from -2 to 2,

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suggesting that the data were close to average. However, the z-score value for one of three laboratories was not within the range, demonstrating that the data was unusual. The P-values of all three persons were higher than 0.05 (except for flexural strength), implying that the difference between the means of the data was not statistically significant. Nevertheless, the P-values of all three laboratories were lower than 0.05, indicating that the difference between the means of the data was statistically significant.

Keywords: Tensile strength; flexural strength; RSD; z-score; ANOVA.

1 Introduction

Tensile strength can be calculated as force per unit area applied to the material. It is maximum tensile stress, which is the limit of the material to withstand exerted tension force without causing faulty. Generally, it is the ability of the material to tolerate the force while being extended before fracturing [1-3]. On the other hand, the flexural strength can be calculated by multiplying the force by the length of the material, and then multiply this by three. Then multiply the thickness of the material by itself, multiply the result by the width of the material and then multiply this by two. Finally, divide the first result by the second. It is maximum flexural stress, which is the maximum of the material to withstand exerted bending force without causing faulty. In general, the material can resist the force while being bent before failure. The three-point bending technique is frequently applied for determining the flexural strength [4,5]. Commonly, a universal testing machine is used to determine the tensile and flexural strengths of materials. The machine is equipped with a load cell, and the speed of test can be varied according to the standard test methods.

High-density polyethylene (HDPE) is a thermoplastic made from the monomer ethylene. HDPE is resistant to numerous organic solvents. It has a high strength-to-density ratio, and it possesses a density range from 0.93 to 0.97 g/cm^3. The tensile strength of HDPE is higher than low-density polyethylene (LDPE). This is due to HDPE having little branching that provides strong intermolecular forces. Besides, HDPE has a slightly higher density compared to LDPE. Moreover, HDPE is opaquer and more rigid than LDPE [6], it has a high specific strength, and it can also endure high temperatures up to 120°C for short times [7]. On the other hand, an injection-molding machine is a machine for producing plastic products via the injection molding process. It has two main parts, namely an injection unit and a clamping unit. The injection unit consists of three main components: 1) screw motor drive, 2) reciprocating screw and barrel, 3) heaters, thermocouple, and ring plungers. The clamping unit also consists of three main components: 1) mold, 2) clamping motor drive, 3) tie bars. In this study, an injection-molding machine was used to mold HDPE into dumbbell and rectangular shapes. The samples with these shapes were mechanically tested to determine tensile strength and flexural strength data.

The relative standard deviation (RSD) is sometimes known as the coefficient of variation; it is a calculation of precision and repeatability of a test. The RSD can be calculated by multiplying the standard deviation by 100 and dividing the result by the average. It is regularly expressed as a percentage. On top of that, the standard score (more commonly referred to as a z-score) is a way to compare results with the average distribution. Z-score can be calculated by subtracting the average from an individual raw score and then dividing the result by the standard deviation. A positive z-score implies that the value is above the average, whereas a negative z-score implies that the value is below the average. On the other hand, single-factor analysis of variance (ANOVA) is a hypothesis test that can be used to determine whether there are any statistically significant differences between the means of three or more independent groups. Single-factor ANOVA can automatically be calculated by using Microsoft® Excel® software or IBM® SPSS® Statistics software to obtain the P-value. If the P-value is less than the significance level (usually 0.05), the zero hypothesis will be rejected, and vice versa. In this study, three different persons from the same laboratory have performed the tensile and flexural tests. Three other laboratories have also been involved in these tests. The main objective is to analyze statistically the tensile strength and flexural strength data of the HDPE samples obtained from a universal testing machine for determining the significant differences between the means of the samples.

2 Materials and Methods

2.1 Materials

The thermoplastic used is high-density polyethylene (HDPE), purchased from Polyethylene (M) Sdn. Bhd., Malaysia. The HDPE pellet was used as received without further modification [8].

2.2 Preparation of molded HDPE

The HDPE pellet was molded into dumbbell (ASTM D638, type I) and rectangular (3.4 × 12.5 × 125 mm) shapes through the injection molding process by using an injection-molding machine [9]. The molding process was carried out at a temperature of 150°C. The molded HDPE samples were conditioned at a temperature range of 21–25°C and relative humidity from 40 to 60% for at least 24 hours prior to tensile and flexural tests [10].

2.3 Tensile and flexural tests of HDPE samples

The tensile strength of the HDPE samples was determined by using a universal testing machine (Instron, model 5567) equipped with a 30 kN load cell. The crosshead speed was 5 mm/min with a 10 cm gauge length. The test was conducted according to the ASTM D638-10 at a temperature range of 21–25°C and relative humidity from 40 to 60%. Five samples were tested to obtain the mean values. The flexural strength of the HDPE samples was also determined by using the same universal testing machine. The test was conducted according to the ASTM D790-10 (procedure B) at a temperature range of 21–25°C and relative humidity from 40% to 60% [9]. The test rate was 13 mm/min with a 50 mm support span length. Five samples were also tested to attain the mean values.

2.4 Statistical analysis of tensile and flexural strengths data

The tensile strength and flexural strength data were analyzed by using a statistical software (Microsoft® Excel® of Microsoft 365). The single-factor analysis of variance (ANOVA) was employed to discover statistically significant differences between the mean values of the tensile strength and flexural strength data of each person and laboratory at a 95% confidence level.

3 Results and Discussion

Table 1 indicates the tensile strength, average and standard deviation values of HDPE samples measured by different persons. The standard deviation of tensile strength and flexural strength of HDPE samples was calculated according to Equation 1. It can be seen that the average values of tensile strength were almost the same, and low standard deviation values were obtained. These results showed that the data were more reliable because they clustered closely around the average. Table 2 shows the flexural strength, average and standard deviation values of HDPE samples measured by different persons. The average values of flexural strength were also almost the same, with low standard deviation values. These results showed that the data were more reliable because they clustered closely around the average as well.

$$S = \sqrt{\frac{\sum_{n-1}^{n}(x-\bar{x})^2}{n-1}} \tag{1}$$

Where,

$S =$ Standard deviation of tensile or flexural strength
$x =$ Tensile or flexural strength value

$\bar{x}$ = Average value of tensile or flexural strength
n = Number of sample

Table 1. Tensile strength, average and standard deviation values of HDPE samples measured by different persons

Sample	Tensile strength (MPa)		
	A	B	C
1	21.04	20.87	20.78
2	20.96	21.28	21.30
3	21.25	21.52	21.14
4	21.09	21.45	21.33
5	21.12	21.30	21.27
Average	21.09	21.28	21.16
Standard deviation	0.11	0.25	0.23

Table 2. Flexural strength, average and standard deviation values of HDPE samples measured by different persons

Sample	Flexural strength (MPa)		
	A	B	C
1	33.22	33.72	32.86
2	33.41	32.44	32.62
3	33.32	33.24	32.99
4	33.80	32.85	31.73
5	33.31	32.94	31.46
Average	33.41	33.04	32.33
Standard deviation	0.23	0.48	0.69

Table 3 indicates the relative standard deviation (RSD) values of tensile strength and flexural strength obtained from different persons. The RSD values of tensile strength and flexural strength of HDPE samples were calculated according to Equation 2. The higher the RSD values (>5%), the more spread out the results are from the mean of the data. However, in this study, lower RSD values (<5%) had been obtained for tensile strength and flexural strength. These results demonstrated that the measurement of data was more precise. Therefore, all three persons had precisely measured the tensile strength and flexural strength data since the results were consistent.

$$RSD = \frac{S}{\bar{x}} \times 100 \qquad (2)$$

Where,

RSD = Relative standard deviation of tensile or flexural strength
S = Standard deviation of tensile or flexural strength
$\bar{x}$ = Average value of tensile or flexural strength

Table 3. Relative standard deviation (RSD) values of tensile strength and flexural strength obtained from different persons

Test	RSD (%)		
	A	B	C
Tensile	0.51	1.19	1.07
Flexural	0.68	1.44	2.14

Table 4 shows the z-score values of tensile strength and flexural strength obtained from different persons. The z-score of tensile strength and flexural strength of HDPE samples was calculated according to Equation 3. It can be seen that there were positive and negative values of z-score obtained. The positive z-score value means higher or bigger than the average, whereas the negative z-score value means lower or smaller than the average. In addition, z-score within the range from -2 to 2 is considered significant since its confidence level is 95% and close to average. In this study, the z-score values of all three persons for tensile strength and flexural strength were within the range, suggesting that the data were close to average.

$$Z = \frac{x - \bar{x}}{S} \tag{3}$$

Where,

$Z =$ Z-score
$x =$ Tensile or flexural strength value
$\bar{x} =$ Average value of tensile or flexural strength
$S =$ Standard deviation of tensile or flexural strength

Table 4. Z-score values of tensile strength and flexural strength obtained from different persons

Test	Z-score		
	A	B	C
Tensile	-0.28	0.33	-0.05
Flexural	0.65	0.15	-0.80

Statistical analysis was conducted by employing a single-factor analysis of variance (ANOVA) to discover statistically significant differences in the tensile strength and flexural strength between the different persons. Table 5 shows the single-factor ANOVA result of the tensile strength of HDPE samples obtained from different persons. The total numbers of the persons were three, and five replicates were tested by each person. The source of variation of the tensile strength had been divided into two categories, namely, between groups (BG) and within groups (WG). F-value is the ratio of the mean square of BG to the mean square of WG. The P-value was more than 0.05 in Table 5, which accepted the zero hypothesis. Therefore, it can be concluded that there is no statistically significant difference in the tensile strength among the different persons at a 95% confidence level.

Table 5. Single-factor ANOVA result of the tensile strength of HDPE samples obtained from different persons

Source of Variation	SS	df	MS	F	P-Value
BG	0.09408	2	0.04704	1.115308622	0.359538208
WG	0.50612	12	0.042176667	-	-

SS = sum of square, df = degree of freedom, MS = mean square, F = F-value, Number of samples = 3, Number of observations = 15

Table 6 shows the single-factor ANOVA result of the flexural strength of HDPE samples obtained from different persons. The total numbers of the persons were three, and five replicates were tested by each person. The source of variation of the flexural strength had been divided into two categories, namely, between groups (BG) and within groups (WG). F-value is the ratio of the mean square of BG to the mean square of WG. The P-value was less than 0.05 in Table 6, which rejected the zero hypothesis [9]. Therefore, it can be concluded that there is a statistically significant difference in the flexural strength among the different persons at a 95% confidence level.

Table 6. Single-factor ANOVA result of the flexural strength of HDPE samples obtained from different persons

Source of Variation	SS	df	MS	F	P-Value
BG	3.007853333	2	1.503926667	5.951745244	0.016007354
WG	3.03224	12	0.252686667	-	-

SS = sum of square, df = degree of freedom, MS = mean square, F = F-value, Number of samples = 3, Number of observations = 15

Table 7 indicates the tensile strength, average and standard deviation values of HDPE samples measured by different laboratories. It can also be seen that the average values of tensile strength were almost the same, and low standard deviation values were obtained. These results showed that the data were more reliable because they clustered closely around the average. Table 8 shows the flexural strength, average and standard deviation values of HDPE samples measured by different laboratories. The average values of flexural strength were also almost the same, with low standard deviation values. These results showed that the data were more reliable because they clustered closely around the average as well.

Table 7. Tensile strength, average and standard deviation values of HDPE samples measured by different laboratories

Sample	Tensile strength (MPa)		
	X	Y	Z
1	21.04	21.27	20.20
2	20.96	21.44	20.50
3	21.25	21.16	20.20
4	21.09	20.98	20.20
5	21.12	21.10	20.40
Average	21.09	21.19	20.30
Standard deviation	0.11	0.17	0.14

Table 8. Flexural strength, average and standard deviation values of HDPE samples measured by different laboratories

Sample	Flexural strength (MPa)		
	X	Y	Z
1	33.72	20.41	30.90
2	32.44	20.61	31.00
3	33.24	20.48	31.90
4	32.85	20.85	30.60
5	32.94	20.71	30.80
Average	33.04	20.61	31.04
Standard deviation	0.48	0.18	0.50

Table 9 indicates the RSD values of tensile strength and flexural strength obtained from different laboratories. The higher the RSD values (>5%), the more spread out the results are from the mean of the data. However, in this study, lower RSD values (<5%) had been obtained for tensile strength and flexural strength. These results demonstrated that the measurement of data was more precise. Therefore, all three laboratories had precisely measured the tensile strength and flexural strength data since the results were consistent.

Table 9. RSD of tensile strength and flexural strength obtained from different laboratories

Test	RSD (%)		
	X	Y	Z
Tensile	0.51	0.82	0.70
Flexural	1.44	0.86	1.62

Table 10 shows the z-score values of tensile strength and flexural strength obtained from different laboratories. It can be seen that there were positive and negative values of z-score obtained. The positive z-score value means higher or bigger than the average, and vice versa. In addition, z-score within the range from -2 to 2 is considered significant since its confidence level is 95% and close to average. In this study, the z-score values of all three laboratories for tensile strength were within the range, suggesting that the data were close to average. However, the z-score value of the Y laboratory for flexural strength was not within the range, indicating that the data was unusual.

Table 10. Z-score of tensile strength and flexural strength obtained from different laboratories

Test	Z-score		
	X	Y	Z
Tensile	0.33	0.47	-0.80
Flexural	1.86	-2.95	1.09

Tables 11 and 12 show the single-factor ANOVA results of the tensile strength and flexural strength of HDPE samples obtained from different laboratories. The total numbers of the laboratories were three, and five replicates were tested by each laboratory. The source of variation of the tensile strength and flexural strength had been divided into two categories, namely, between groups (BG) and within groups (WG). F-value is the ratio of the mean square of BG to the mean square of WG. The P-values were less than 0.05 in Tables 11 and 12, which rejected the zero hypothesis [9]. Therefore, it can be concluded that there are statistically significant differences in the tensile strength and flexural strength among the different laboratories at a 95% confidence level.

Table 11. Single-factor ANOVA result of the tensile strength of HDPE samples obtained from different laboratories

Source of Variation	SS	df	MS	F	P-Value
BG	2.381613333	2	1.190806667	57.64757141	7.01805×10^{-7}
WG	0.24788	12	0.020656667	-	-

SS = sum of square, df = degree of freedom, MS = mean square, F = F-value, Number of samples = 3, Number of observations = 15

Table 12. Single-factor ANOVA result of the flexural strength of HDPE samples obtained from different laboratories

Source of Variation	SS	df	MS	F	P-Value
BG	445.23444	2	222.61722	1306.336867	9.13346×10^{-15}
WG	2.04496	12	0.170413333	-	-

SS = sum of square, df = degree of freedom, MS = mean square, F = F-value, Number of samples = 3, Number of observations = 15

4 Conclusions

In this study, all three persons and laboratories had the RSD values lower than 5%, based on the calculation. These results indicated that the obtained data from the tensile and flexural tests were consistent. Moreover, all three persons had the z-score values within the range from -2 to 2. These results suggested that the obtained data from the tests were close to average. Nevertheless, one of three laboratories did not possess the z-score value within the range; the result demonstrated that the data was unusual. From the statistical analysis, all three persons had the P-values higher than 0.05; the results implied that the means of the data were not significantly different (except for flexural strength). Nonetheless, all three laboratories had the P-values lower than 0.05; the results implied that the means of the data were significantly different. It can be inferred that the tensile strength and flexural strength data obtained from a universal testing machine for all three persons from the same laboratory are almost the same. However, the tensile strength and flexural strength data of all three laboratories are slightly different from one another.

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Competing Interests

Authors have declared that no competing interests exist.

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