Method Article

Calculation of Measurement Uncertainty for Tensile Strength and Flexural Strength of Thermoplastic

Abstract: In this study, a thermoplastic such as polycarbonate (PC) has been characterized to determine its tensile strength and flexural strength properties. The width and thickness of the PC samples have been measured, and then their average dimensions and standard deviation values were calculated. The samples have been characterized by using a universal testing machine. The tensile strength values of the dumbbell-shaped PC samples were determined according to ASTM D638-10, whereas ASTM D790-10 was applied to ascertain the flexural strength values of the rectangular-shaped PC samples. Based on the obtained results, the average tensile strength value is 58.978 ± 0.258 MPa, whilst the average flexural strength value is 97.437 ± 0.240 MPa. From the measurement uncertainty, the calculated expanded uncertainty for the tensile strength is 0.467 MPa at a confidence level of 95%. On the other hand, the calculated expanded uncertainty for the flexural strength is 0.806 MPa at a confidence level of 95% as well. In summary, the values of expanded uncertainty for the PC samples were particularly influenced by the standard uncertainty values of the tested samples and the expanded uncertainty values of the equipment used.

Keywords: measurement uncertainty; tensile strength; flexural strength; ASTM D638; ASTM D790

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1. Introduction

Measurement uncertainty is an array of feasible results in which the possibilities are designated to each result. All measurements are only finalised if they are followed by a statement of the accompanied uncertainty, which are dependent on measured values and their uncertainties. On the other hand, the performance of measurement affects the distribution of the measured values. The estimated true value obtained from their average value is highly trustworthy compared to a sole measured value. The calibration and measurement works have given the vital effects on the measurement uncertainty that are also influencing the consistency of the attained results. The quality of the laboratory usually indicated by the range of the expanded uncertainty from produced calibration reports, smaller the uncertainty values frequently resulted in greater the testing charges.

Tensile strength is the maximum tensile stress which a material can tolerate while being extended before fracturing. In other words, it is the limit of the material to withstand exerted force without causing faulty. Furthermore, the tensile strength can be calculated as force per unit area. On the other hand, flexural strength is the maximum flexure stress that a material can resist before failure. The material typically subjected to bending state, therefore it possesses stress and compressive properties. The three-point bending technique is the most commonly used in determination of the flexural strength. Moreover, the flexural strength can be computed as the coefficient of three over two times with the product of the load at the fracture point and the length of support span divide by the product of the width and the square of thickness.

Hitherto, the study regarding the calculation of measurement uncertainty for the tensile strength and flexural strength of thermoplastic specifically polycarbonate (PC) has not been reported yet. Hence, the aim of this study is to demonstrate on how to calculate the expanded uncertainty for the results of tensile strength and flexural strength for the PC samples. On the other hand, the sources of uncertainty for both strengths have also been thoroughly identified, computed and separately tabulated based on their test methods. Additionally, the factors that are influenced the values of calculated expanded uncertainty were extensively described as well.

2. Materials and Methods

The thermoplastic samples used are polycarbonate (PC) that has been procured from GT Instruments Sdn. Bhd., Malaysia. For tensile test, the samples were dumbbell-shaped (Type I), whereas for flexural test, the samples were rectangular-shaped with nominal size of 126 × 12 × 3 mm^3. All samples were characterized as purchased without any alterations.

The width and thickness of the dumbbell-shaped PC samples were measured by using a calibrated Mitutoyo digimatic micrometer, and at least three different places within the gauge length (grip separation) area were recorded. The samples were conditioned according to the ASTM D618-13 [1] at temperature of 23 ± 2°C and relative humidity of 50 ± 10% for not less than 40 hours prior to testing. The ASTM D638-10 [2] was applied to determine tensile strength at the same temperature and relative humidity as sample conditioning procedure. The test was conducted by using an Instron universal testing machine (model 5567) equipped with a 30 kN load cell. The crosshead speed was 5 mm min^{-1} [3-5] with a 125 mm gauge length. The average data value and the standard deviation value from five samples were calculated and recorded.

The rectangular-shaped PC samples were also measured for their width and thickness with the same micrometer for at least three different places within the support span area, and then the values were recorded and averaged. The similar conditioning procedure as mentioned earlier was carried out to condition the samples before testing as well. The flexural strength of the samples was measured according to the ASTM D790-10 [6] by using the same universal testing machine equipped with the unchanged load cell. The lengths of support span were obtained by multiplying the thickness of the samples with 16 [6]. The length of support span was then fixed by using a calibrated Mitutoyo digimatic caliper. The crosshead speed was calculated according to the equation which consisted of their length of support span and thickness of the samples. The average crosshead speed was used for flexural testing. Five samples were tested to obtain the average value and the standard deviation value.

3. Results

3.1. Tensile strength

Throughout the tensile test was conducted, there are some sources of uncertainty that can be detected which are from the tested PC samples and the measuring equipment used. For the PC samples, the sources of uncertainty are the measured width and thickness of the samples themselves. Meanwhile, the sources of uncertainty for the measuring equipment are measured force, calibrated micrometer and universal testing machine. The values of measured width and thickness for the dumbbell-shaped PC samples with their calculated averages are shown in Table 1. In addition, the values of obtained force and tensile strength for the PC samples with their computed averages are also presented in Table 1.

Table 1. Width, thickness, force, tensile strength and their averages for the PC samples.

No. of sample	Width (mm)	Thickness (mm)	Force (N)	Tensile strength (MPa)
1	13.173	3.026	2349.215	58.934
2	13.238	3.005	2329.533	58.560
3	13.232	3.006	2349.223	59.062
4	13.262	3.009	2364.229	59.246
5	13.303	3.009	2365.122	59.086
Average	13.242	3.011	2351.464	58.978

The standard deviations were also calculated to determine the standard uncertainties aside from been used to show the error range [7]. The standard deviations of width, thickness, force and tensile strength of the samples have been computed according to Equation 1. The standard deviation values for the width, thickness, force and tensile strength of five PC samples measured are displayed in Table 2. On the other hand, the standard uncertainties of width, thickness, force and tensile strength of the samples have been calculated based on Equation 2. The standard uncertainty values of width, thickness, force and tensile strength for the five PC samples measured are also displayed in Table 2. From the obtained results, it can be observed that the smaller standard deviation values resulted in lower standard uncertainty values. This is due to the fact that the standard uncertainty values are directly proportional to the standard deviation values.

$$s = \sqrt{\frac{\sum_{n-1}^{n} (p - \bar{p})^2}{n-1}}, \tag{1}$$

$$u(p) = \frac{s}{\sqrt{n}}, \tag{2}$$

Where,

s = Standard deviation of sample

p = Parameter (width, thickness, force, or tensile strength) of sample

$\bar{p}$ = Average parameter

n = Number of sample

$u(p)$ = Standard uncertainty of parameter

Table 2. Standard deviation and standard uncertainty values of width, thickness, force and tensile strength for the PC samples.

Parameter	Standard deviation	Standard uncertainty
Width (mm)	0.047	0.021

Thickness (mm)	0.009	0.004
Force (N)	14.496	6.483
Tensile strength (MPa)	0.258	0.116

The expanded uncertainty of calibrated micrometer has been obtained from accredited laboratory namely Calibration and Measurement Centre, Vitar-Segatec Sdn. Bhd., whereas the expanded uncertainty for the universal testing machine has been procured from Instron Calibration Laboratory, National Voluntary Laboratory Accreditation Program. The expanded uncertainty values of calibrated micrometer and universal testing machine (tension value) are indicated in Table 3. The standard uncertainties of equipment specifically micrometer and universal testing machine have been calculated according to Equation 3. The divisor values for each parameter are equal to 2 because of their confidence level is 95% and their distribution type is normal [8] as shown in calibration certificate of equipment. The standard uncertainty values of micrometer and universal testing machine are also demonstrated in Table 3. From the acquired results, it is indicated that the standard uncertainty values of equipment are thoroughly dependent on the expanded uncertainty values of calibrated equipment.

$$u(e)=\frac{U(e)}{K}, \tag{3}$$

Where,

$u(e)$ = Standard uncertainty of calibrated equipment (micrometer or universal testing machine)

$U(e)$ = Expanded uncertainty of calibrated equipment

K = Divisor of parameter

Table 3. Expanded uncertainty and standard uncertainty values of micrometer and universal testing machine for the tensile test results.

Equipment	Expanded uncertainty	Standard uncertainty
Micrometer (mm)	0.002	0.001
Universal testing machine, tension (N)	1.1 x 10^{-3}	5.5 x 10^{-4}

The average tensile strength of tested samples is actually calculated by using Equation 4. On the other hand, the partial derivative of the average tensile strength with respect to the average parameter (width, thickness or force) yields the sensitivity coefficient [9] as showed in Equation 5. The sensitivity coefficients of width, thickness and force can be directly computed according to Equation 6, 7 and 8, respectively. The calculated sensitivity coefficient values of width, thickness and force for the PC samples are demonstrated in Table 4. Besides that, the sensitivity coefficients of calibrated micrometer and universal testing machine are calculated based on Equation 9. The computed sensitivity coefficient values of calibrated micrometer and universal testing machine are also indicated in Table 4. The degrees of freedom for the width, thickness and force are computed according to Equation 10, while the degree of freedom values of calibrated micrometer and universal testing machine are commonly regarded as much as 10^{13}. The calculated degree of freedom values for the width, thickness and force are demonstrated in Table 4 as well.

$$\overline{\sigma}_{TS} = \frac{\overline{F}}{\overline{A}} = \frac{\overline{F}}{\overline{w}\overline{t}}, \tag{4}$$

Where,

$\overline{\sigma}_{TS}$ = Average tensile strength

$\overline{F}$ = Average force

$\overline{A}$ = Average area

$\overline{w}$ = Average width

$\overline{t}$ = Average thickness

$$c_p = \frac{\partial \overline{\sigma}_{TS}}{\partial \overline{p}}, \tag{5}$$

Where,

c_p = Sensitivity coefficient of parameter (width, thickness or force)

$\partial \overline{\sigma}_{TS}$ = Differentiation of average tensile strength

$\partial \overline{p}$ = Differentiation of average parameter

$$c_w = \frac{\partial \overline{\sigma}_{TS}}{\partial \overline{w}} = -\frac{\overline{F}}{\overline{w}^2 \overline{t}} = -\frac{\overline{\sigma}_{TS}}{\overline{w}}, \tag{6}$$

$$c_t = \frac{\partial \overline{\sigma}_{TS}}{\partial \overline{t}} = -\frac{\overline{F}}{\overline{w}\overline{t}^2} = -\frac{\overline{\sigma}_{TS}}{\overline{t}}, \tag{7}$$

$$c_F = \frac{\partial \overline{\sigma}_{TS}}{\partial \overline{F}} = \frac{1}{\overline{w}\overline{t}} = \frac{\overline{\sigma}_{TS}}{\overline{F}}, \tag{8}$$

Where,

c_w = Sensitivity coefficient of sample width

c_t = Sensitivity coefficient of sample thickness

c_F = Sensitivity coefficient of sample force

$\partial \overline{w}$ = Differentiation of average width

$\partial \overline{t}$ = Differentiation of average thickness

$\partial \overline{F}$ = Differentiation of average force

$$c_e = \frac{\partial y}{\partial x}, \tag{9}$$

Where,

c_e = Sensitivity coefficient of calibrated equipment (micrometer or universal testing machine)

∂y = Change in output of equipment

∂x = Change in input of standard

$$v_p = n - 1 , \tag{10}$$

Where,

v_p = Degree of freedom for parameter (width, thickness or force)

n = Number of sample

Table 4. Sensitivity coefficient and degree of freedom values for width, thickness, force, micrometer and universal testing machine of the tensile test results.

Sources of uncertainty	Sensitivity coefficient	Degree of freedom
Width	-4.454 (N mm^{-3})	4
Thickness	-19.587 (N mm^{-3})	4
Force	0.025 (mm^{-2})	4
Micrometer	1 (N mm^{-3})	10^{13}
Universal testing machine	1 (mm^{-2})	10^{13}

The uncertainty contributions of parameter and calibrated equipment have been calculated using standard uncertainty and sensitivity coefficient in accordance with Equation 11, and the values of uncertainty contribution for the width, thickness, force, micrometer and universal testing machine are tabulated in Table 5. On the other hand, the combined uncertainties for parameter and equipment can be computed by squaring the uncertainty contribution of width, thickness, force, micrometer and universal testing machine (Equation 12), and the values of calculated combined uncertainty for each parameter and equipment are also indicated in Table 5. On top of that, the combined standard uncertainty and effective degree of freedom for the tensile strength can be computed based on Equation 13 and 14, respectively. Aside from that, the coverage factor for effective degree of freedom has been determined through Student's T-distribution table at 95% confidence level. The values of combined standard uncertainty, effective degree of freedom and coverage factor are displayed in Table 6. From the computation, it can be seen that the values of combined standard uncertainty and effective degree of freedom are certainly dependent on uncertainty contribution of parameter or equipment. Finally, the expanded uncertainty of the tensile strength can be calculated by multiplying the combined standard uncertainty with the coverage factor (Equation 15). The value of calculated expanded uncertainty is also demonstrated in Table 6. From the obtained value, the standard uncertainty values of the tested PC samples and the expanded uncertainty values of the equipment used have clearly influenced the expanded uncertainty value of the tensile strength.

$$u_{con} = uc , \tag{11}$$

$$u_{com} = u_{con}{}^{2} , \tag{12}$$

$$u_c = \sqrt{\sum u_{com}}, \tag{13}$$

$$v_{eff} = \frac{u_{con}^{4}}{\sum u_{com}^{4} / v}, \tag{14}$$

$$U(TS) = u_c k, \tag{15}$$

Where,

u_{con} = Uncertainty contribution of parameter or equipment

u = Standard uncertainty of parameter or equipment

c = Sensitivity coefficient of parameter or equipment

u_{com} = Combined uncertainty of parameter or equipment

u_c = Combined standard uncertainty of tensile strength

v_{eff} = Effective degree of freedom for tensile strength

v = Degree of freedom for parameter or equipment

$U(TS)$ = Expanded uncertainty of tensile strength

k = Coverage factor for effective degree of freedom

Table 5. Uncertainty contribution and combined uncertainty values of width, thickness, force, micrometer and universal testing machine for the tensile test results.

Sources of uncertainty	Uncertainty contribution (N mm^{-2})	Combined uncertainty (N^2 mm^{-4})
Width	-0.094	0.009
Thickness	-0.075	0.006
Force	0.163	0.026
Micrometer	0.001	10^{-6}
Universal testing machine	5.5×10^{-4}	3.0×10^{-7}

Table 6. Combined standard uncertainty, effective degree of freedom, coverage factor and expanded uncertainty of the tensile strength.

Combined standard uncertainty (N mm^{-2})	Effective degree of freedom	Coverage factor	Expanded uncertainty (MPa)*
0.202	8.298	2.306	0.467

*MPa = N mm^{-2}

3.2. Flexural strength

For the flexural test, there are some additional sources of uncertainty that can be identified which are also from the tested PC samples and the measuring equipment used. For the PC samples, the additional source of uncertainty is the length of support span, whilst the additional source of uncertainty for the measuring equipment is calibrated caliper. On the other hand, the length of support span was obtained by multiplying the thickness of each sample with 16 (Equation 16). Besides that, the crosshead speed was calculated according to Equation 17. The measured width and thickness of the rectangular-shaped PC samples values and the length of support span values with their calculated averages are displayed in Table 7. In addition, the values of acquired force and flexural strength for the PC samples with their computed averages are also exhibited in Table 7.

$$l = 16t \,, \tag{16}$$

$$s = \frac{0.01l^2}{6t} \,, \tag{17}$$

Where,

l = Length of support span

t = Thickness of sample

s = Crosshead speed

Table 7. Width, thickness, length of support span, force, flexural strength and their averages for the PC samples.

No. of sample	Width (mm)	Thickness (mm)	Length (mm)	Force (N)	Flexural strength (MPa)
1	12.469	3.162	50.600	160.008	97.415
2	12.476	3.160	50.560	160.487	97.699
3	12.472	3.184	50.940	161.364	97.515
4	12.463	3.158	50.530	159.899	97.508
5	12.463	3.171	50.740	159.796	97.050
Average	12.469	3.167	50.674	160.311	97.437

The standard deviations were calculated to determine the standard uncertainties as mentioned earlier. The standard deviations and standard uncertainties of width, thickness, length of support span, force and flexural strength of the PC samples have also been computed based on Equation 1 and 2, respectively. The standard deviation and standard uncertainty values for the width, thickness, length of support span, force and flexural strength of five PC samples measured are presented in Table 8. From the attained results, it is obviously implied that the standard uncertainty values are also directly proportional to the standard deviation values, which is the same trend with the tensile strength results.

Table 8. Standard deviation and standard uncertainty values of width, thickness, length of support span, force and flexural strength for the PC samples.

Parameter	Standard deviation	Standard uncertainty

Width (mm)	0.006	0.003
Thickness (mm)	0.011	0.005
Length (mm)	0.169	0.076
Force (N)	0.645	0.289
Flexural strength (MPa)	0.240	0.107

The expanded uncertainties of calibrated micrometer, caliper and universal testing machine have been procured from the same accredited laboratories that are mentioned above. The expanded uncertainty values of calibrated micrometer, caliper and universal testing machine (compression value) are demonstrated in Table 9. The standard uncertainties of calibrated equipment specifically micrometer, caliper and universal testing machine have also been calculated according to Equation 3. Moreover, the divisor values for each parameter are equal to 2 due to their confidence level is 95% and their distribution type is normal as well. The standard uncertainty values of micrometer, caliper and universal testing machine are also displayed in Table 9. From the results, it is clearly showed that the standard uncertainties of calibrated equipment are dependent on their expanded uncertainties as well.

Table 9. Expanded uncertainty and standard uncertainty values of micrometer, caliper and universal testing machine for the flexural test results.

Equipment	Expanded uncertainty	Standard uncertainty
Micrometer (mm)	0.002	0.001
Caliper (mm)	0.010	0.005
Universal testing machine, compression (N)	1.7×10^{-3}	8.5×10^{-4}

The average flexural strength of tested PC samples is frequently computed according to Equation 18. The sensitivity coefficients of width, thickness, length of support span and force can be straightly calculated by using Equation 19, 20, 21 and 22, respectively. The computed sensitivity coefficient values for the width, thickness, length of support span and force of the PC samples are demonstrated in Table 10. The sensitivity coefficients of calibrated micrometer, caliper and universal testing machine are also calculated based on Equation 9. The computed sensitivity coefficient values of the calibrated equipment are indicated in Table 10 as well. The degrees of freedom for the width, thickness, length of support span and force are also calculated according to Equation 10, whereas the degree of freedom values for the calibrated micrometer, caliper and universal testing machine are regarded as much as 10^{13} as well. The computed degree of freedom values for the width, thickness, length of support span and force are also demonstrated in Table 10.

$$\bar{\sigma}_{FS} = \frac{3\overline{F}\bar{l}}{2\bar{w}\bar{t}^{2}}, \tag{18}$$

Where,

$\bar{\sigma}_{FS}$ = Average flexural strength

$\overline{F}$ = Average force

$\bar{l}$ = Average length of support span

$\overline{w}$ = Average width

$\bar{t}$ = Average thickness

$$c_w = \frac{\partial \overline{\sigma}_{FS}}{\partial \overline{w}} = -\frac{3\overline{F}\,\overline{l}}{2\overline{w}^2\,\overline{t}^2} = -\frac{\overline{\sigma}_{FS}}{\overline{w}}\,, \tag{19}$$

$$c_t = \frac{\partial \overline{\sigma}_{FS}}{\partial \bar{t}} = -\frac{3\overline{F}\,\overline{l}}{\overline{w}\,\bar{t}^3} = -\frac{2\overline{\sigma}_{FS}}{\bar{t}}\,, \tag{20}$$

$$c_l = \frac{\partial \overline{\sigma}_{FS}}{\partial \bar{l}} = \frac{3\overline{F}}{2\overline{w}\,\bar{t}^2} = \frac{\overline{\sigma}_{FS}}{\bar{l}}\,, \tag{21}$$

$$c_F = \frac{\partial \overline{\sigma}_{FS}}{\partial \overline{F}} = \frac{3\bar{l}}{2\overline{w}\,\bar{t}^2} = \frac{\overline{\sigma}_{FS}}{\overline{F}}\,, \tag{22}$$

Where,

c_w = Sensitivity coefficient of sample width

c_t = Sensitivity coefficient of sample thickness

c_l = Sensitivity coefficient of length of support span

c_F = Sensitivity coefficient of sample force

$\partial \overline{w}$ = Differentiation of average width

$\partial \bar{t}$ = Differentiation of average thickness

$\partial \bar{l}$ = Differentiation of average length of support span

$\partial \overline{F}$ = Differentiation of average force

Table 10. Sensitivity coefficient and degree of freedom values for width, thickness, length of support span, force, micrometer, caliper and universal testing machine of the flexural test results.

Sources of uncertainty	Sensitivity coefficient	Degree of freedom
Width	-7.815 (N mm^{-3})	4
Thickness	-61.533 (N mm^{-3})	4
Length	1.923 (N mm^{-3})	4
Force	0.608 (mm^{-2})	4
Micrometer	1 (N mm^{-3})	10^{13}
Caliper	1 (N mm^{-3})	10^{13}
Universal testing machine	1 (mm^{-2})	10^{13}

The uncertainty contributions of parameter and calibrated equipment have also been calculated by means of standard uncertainty and sensitivity coefficient in accordance with Equation 11. The values of uncertainty contribution for the width, thickness, length of support span, force, micrometer, caliper and universal testing machine are presented in Table 11. Besides that, the combined uncertainties of parameter and equipment can be computed by squaring the uncertainty contribution of width, thickness, length of support span, force, micrometer, caliper and universal testing machine (Equation 12). The values of calculated combined uncertainty for each parameter and equipment are indicated in Table 11 as well. The combined standard uncertainty and effective degree of freedom for the width, thickness, length of support span, force, micrometer, caliper and universal testing machine can also be computed based on Equation 13 and 14, respectively. The coverage factor for effective degree of freedom has been determined through Student's T-distribution table at 95% confidence level. The values of combined standard uncertainty, effective degree of freedom and coverage factor were displayed in Table 12. From the computation, it can be seen that the values are also dependent on combined uncertainty of parameter or equipment. On the other hand, the expanded uncertainty of the flexural strength can be computed by using Equation 15. The value of calculated expanded uncertainty is indicated in Table 12 as well. From the attained value, it is clearly implied that the value of expanded uncertainty of the flexural strength was also influenced by the standard uncertainty values of the tested PC samples and the expanded uncertainty values of the equipment used.

Table 11. Uncertainty contribution and combined uncertainty values of width, thickness, length of support span, force, micrometer, caliper and universal testing machine for the flexural test results.

Sources of uncertainty	**Uncertainty contribution (N mm^{-2})**	**Combined uncertainty (N^2 mm^{-4})**
Width	-0.020	3.9×10^{-4}
Thickness	-0.295	0.087
Length	0.145	0.021
Force	0.175	0.031
Micrometer	0.001	10^{6}
Caliper	0.005	2.5×10^{-5}
Universal testing machine	8.5×10^{-4}	7.2×10^{-7}

Table 12. Combined standard uncertainty, effective degree of freedom, coverage factor and expanded uncertainty of the flexural strength.

Combined standard uncertainty (N mm^{-2})	**Effective degree of freedom**	**Coverage factor**	**Expanded uncertainty (MPa)***
0.330	5.876	2.447	0.806

*MPa = N mm^{-2}

4. Conclusions

From this study, it can be perceived that the dumbbell-shaped PC samples have the average tensile strength value of 58.978 ± 0.258 MPa, whereas the average flexural strength value for the rectangular-shaped PC samples is 97.437 ± 0.240 MPa. Based on the obtained values, at a confidence level of 95%, the calculated expanded uncertainty of tensile strength is 0.467 MPa. On top of that, at the same confidence level (95%), the calculated expanded uncertainty of flexural strength is 0.806 MPa. In conclusion, the standard uncertainty values of the tested samples and the expanded uncertainty values of the equipment used have obviously influenced the expanded uncertainty values of the measured tensile strength and flexural strength of the PC samples.

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