CHARACTERIZATION OF MATERIAL PROPERTIES

Fortus® Polycarbonate (PC)

STRATASYS
3D Printers and Production Systems

OVERVIEW

Material properties are an important consideration when evaluating additive manufacturing for advanced applications such as production runs of end-use parts. Since these products will be in service for extended periods and in varying conditions, it is imperative to qualify the properties beyond published specifications.

To characterize the effects of time, temperature and environment, Loughborough University (Loughborough, UK) performed extensive testing on Fortus® polycarbonate (PC) thermoplastic. Conducted over a 52-week period, the evaluation measured five properties at temperatures ranging from -40 °C to 140 °C. Additionally, testing evaluated the samples in three environmental conditions: wet (immersed in water), dry (15% relative humidity) and controlled (50% relative humidity). The mechanical properties included:

- Tensile strength
- Young's modulus
- Flexural strength
- Flexural modulus
- Elongation at break

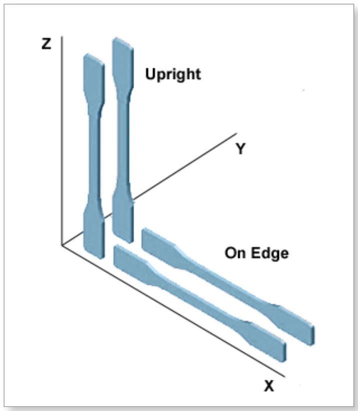

Figure 1: Test sample orientations

**To optimize mechanical properties, Fortus offers user-controls that will alter construction parameters.*

In accordance with ISO 527 and ISO 178 standards, the evaluation tested 10 samples for each condition. Each sample was produced on a Fortus 400mc 3D Production System using default build parameters* and a T12 tip, which produces a 0.18 mm slice height. To quantify the effects of orientation, test samples used both an upright and on-edge alignment (Figure 1).

The university's comprehensive report, which is available upon request, documents 1500 combinations of mechanical properties and test conditions. To summarize these findings, the following graphs present PC's performance as time, temperature and environment change while all other factors remain constant. For each condition, graphical illustrations depict the change in tensile strength, flexural modulus and elongation at break for samples built in the on-edge orientation[1]. Also included is a comparison of test values to published properties.

Tested vs. Published

To substantiate previously published material properties, Table 1 presents the differences in values of the test data and published specifications. With variances of ± 16%, the university's testing validates four of the five properties.

Elongation at break is the exception. Test samples have an average of 8.3%, which is 73% higher than the published value. In general, elongation at break is higher than the published value for all test conditions, with the exception of temperatures above 80 °C. Although there is no definitive explanation for the variance, one possibility is that small changes between the two test methods yielded a large difference. Loughborough found that elongation at break is more sensitive to changes in build characteristics than all other properties.

Testing standards were similar for both cases. Loughborough followed ISO 527 and ISO 178, which are technically equivalent to the ASTM standards (D838 and D790) that the published data used. Both used samples at approximately 20 °C, controlled condition and on-edge orientation. However, slice heights differed. Loughborough used 0.18 mm slices; the published data used 0.25 mm.

Property	Published		Test Result		% Difference
Tensile Strength	ASTM D638	68 MPa	ISO 527	57 MPa	-16%
Young's Modulus	ASTM D638	2280 MPa	ISO 527	2475 MPa	9%
Flexural Strength	ASTM D790	104 MPa	ISO 178	92 MPa	-12%
Flexural Modulus	ASTM D790	2234 MPa	ISO 178	1870 MPa	-16%
Elongation at Break	ASTM D638	4.8%	ISO 527	8.3%	73%

Table 1: Test results compared to published material properties. Testing standards are technically equivalent, so results are directly comparable.

[1]*Part orientation, as well as build parameters, will alter mechanical properties. Please consider the report data accordingly.*

INTRODUCTION

To show the effects of age on PC, mechanical properties were measured at 1, 4, 13, 26 and 52 weeks. The bar graphs for each mechanical property show the value at 20 °C for samples built on edge and stored in a controlled environment. Each graph also shows reference markers for wet and dry samples as well as line graphs for temperatures of -40, 0, 40, 80, 120 and 140 °C.

The test results show that all mechanical properties are stable over a 52-week period. Comparing 1-week and 52-week samples, there is only a 3.5% and 0.2% change for tensile strength and flexural modulus (respectively). While elongation at break declined at the half-year mark, the total variance over 52 weeks was small (12.0%). Likewise, the variances between wet, dry and controlled environmental conditions are also small at nearly all combinations of temperature and age.

TENSILE STRENGTH

Over 52 weeks, tensile strength varies by 2.1 MPa (3.5%), which shows that it is unaffected by age (Figures 2a and 2b). But this stability seems to be reached over time. For all temperatures below 140 °C, there is a spike at week 26, ranging from 3.0 MPa to 6.2 MPa. These spikes are preceded by a dip at either week 4 or 13 and followed by a dip at week 52. The latter brings tensile strength within -3.4 MPa to +0.8 MPa of the 1-week sample value.

Week 26 also yields a deviation from other periods for wet and dry samples. For all other ages, both wet and dry samples have similar tensile strengths as those stored in a controlled environment. At week 26, the wet sample has similar values to those in weeks 13 and 52 but a sharply lower value (-5.9 MPa) than the controlled sample. The dry sample follows the control, increasing by 2.3 MPa in week 26.

Figure 2 also shows a significant decrease in tensile strength between 80 °C and 140 °C. This is expected because the higher temperature is near to PC's glass transition temperature (Tg) of 161 °C. A similar, sharp decline at 140 °C is seen for all mechanical properties in all graphs throughout the report.

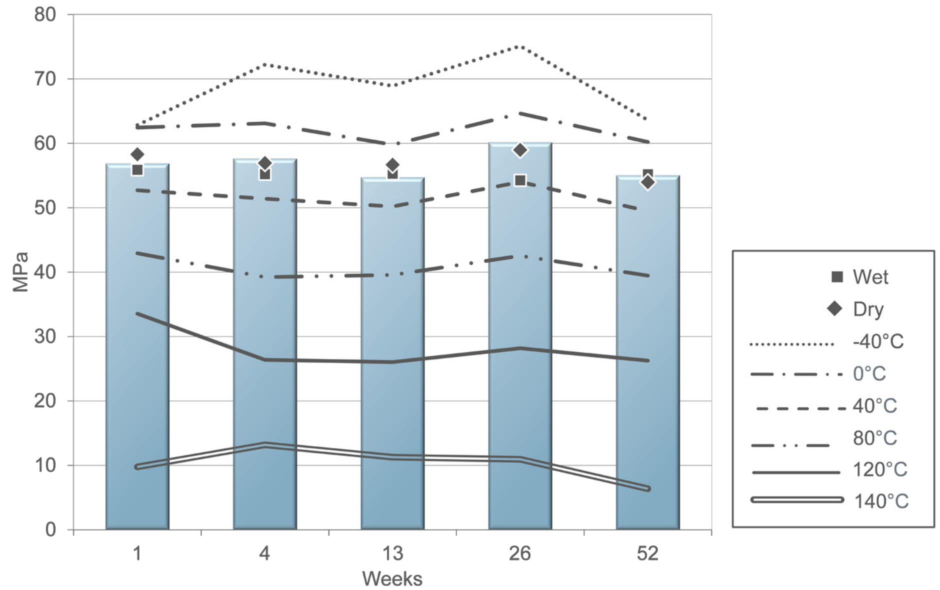

Figure 2a: Tensile strength - 20 °C, controlled environment, on edge.

	Tensile Strength (MPa)		
Week	Chart Data	Min	Max
1	56.9	56.6	57.3
4	57.7	57.5	57.8
13	54.8	54.6	54.9
26	60.2	59.6	61.1
52	55.1	54.7	55.5

Figure 2b: Tensile strength - 20 °C, controlled environment, on edge.

	Tensile Strength (MPa)							
Week	Wet	Dry	-40 °C	0 °C	40 °C	80 °C	120 °C	140 °C
1	55.9	58.3	62.8	62.5	52.7	42.9	33.6	9.8
4	55.2	56.9	72.2	63.1	51.4	39.2	26.4	13.2
13	55.3	56.7	68.9	59.8	50.2	39.6	26.0	11.3
26	54.3	59.0	75.1	64.7	54.0	42.6	28.2	11.0
52	55.2	54.0	63.6	60.2	49.5	39.5	26.3	6.4

Figure 2c: Secondary data, tested in various conditions.

FLEXURAL MODULUS

As with tensile strength, aging has little effect on flexural modulus. Compared to week 1, there is only 4.0 MPa (0.2%) difference for the 52-week sample. For all periods, the maximum variance is only 106 MPa (5.6%), which is the result of a small decline at weeks 4 and 13.

In general, flexural modulus is relatively stable for all temperatures and environmental conditions. Wet conditions follow the trend of controlled parts and are within 3.2%. Dry conditions, on the other hand, rise through week 26 and then return to the 1-week value at the end of the testing period.

Temperature has varying effects on flexural modulus over time. But in general, the values for this property are similar to those for the controlled conditions, differing by a maximum of 207 MPa. The exception is at 140 °C, which has a sharp 962 MPa (62.6%) drop over time.

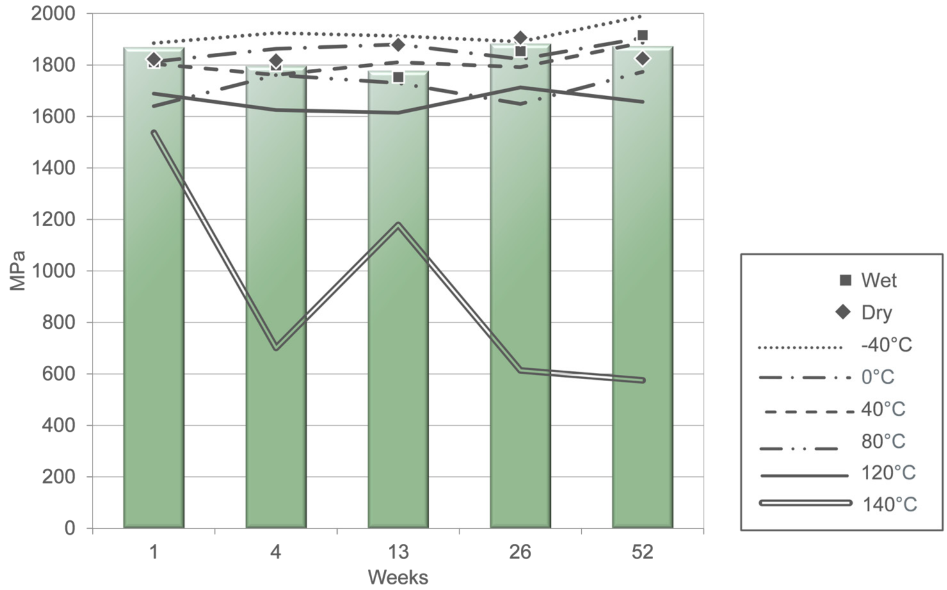

Figure 3a: Tensile strength - 20 °C, controlled environment, on edge.

	Flexural Modulus (MPa)		
Week	**Chart Data**	**Min**	**Max**
1	1870	1668	1947
4	1797	1712	1913
13	1778	1651	1912
26	1884	1689	1976
52	1874	1795	1954

Figure 3b: Tensile strength - 20 °C, controlled environment, on edge.

	Flexural Modulus (MPa)							
Week	**Wet**	**Dry**	**-40 °C**	**0 °C**	**40 °C**	**80 °C**	**120 °C**	**140 °C**
1	1811	1823	1885	1813	1805	1640	1689	1537
4	1799	1818	1924	1863	1762	1761	1625	701
13	1754	1879	1913	1880	1811	1730	1615	1179
26	1854	1907	1891	1823	1792	1649	1713	613
52	1917	1826	1990	1905	1887	1774	1657	575

Figure 3c: Secondary data, tested in various conditions.

ELONGATION AT BREAK

Elongation at break shows a small, downward trend over time (Figure 4a and 4b). Its range is 1.0 point (12.0%) over the 52-week testing period. As parts age, environmental conditions have negligible impact. At 52 weeks, there is only a 0.1 point difference across the three part storage conditions. For each period, wet and controlled samples have similar elongation at break. Although dry conditions yield higher values at weeks 13 and 26, the difference from controlled samples is small (0.3 and 0.5 points).

The combination of age and temperature shows no obvious trends. Over the 52-week test period, each temperature yields different patterns of change, and none have either a consistent upward or downward trend. At 52 weeks, however, elongation at break for all temperatures is equal to or below the starting values. These differences range from + 0.1 point to -3.0 points.

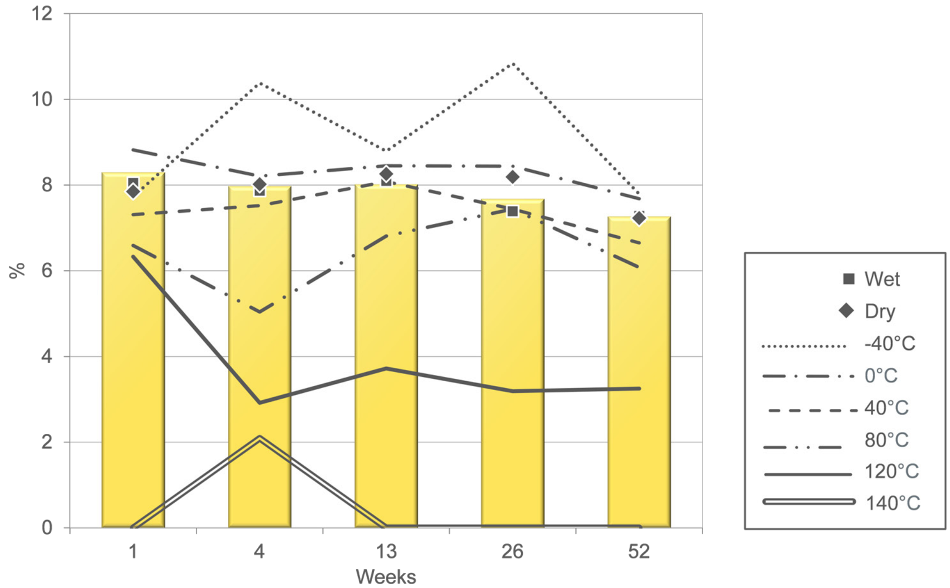

Figure 4a: Elongation at break - 20 °C, controlled environment, on edge.

	Elongation at Break (%)		
Week	**Chart Data**	**Min**	**Max**
1	8.3	7.9	9.0
4	8.0	7.6	8.3
13	8.0	7.7	8.6
26	7.7	7.2	8.4
52	7.3	7.0	7.5

Figure 4b: Elongation at break - 20 °C, controlled environment, on edge.

	Elongation at Break (%)							
Week	**Wet**	**Dry**	**-40 °C**	**0 °C**	**40 °C**	**80 °C**	**120 °**	**140 °C**
1	8.1	7.9	7.7	8.8	7.3	6.6	6.3	0.0
4	7.9	8.0	10.4	8.2	7.5	5.0	2.9	2.1
13	8.1	8.3	8.8	8.5	8.1	6.8	3.7	0.0
26	7.4	8.2	10.8	8.4	7.4	7.4	3.2	0.0
52	7.3	7.2	7.8	7.7	6.7	6.1	3.3	0.0

Figure 4c: Secondary data, tested in various conditions.

INTRODUCTION

To show the effects of temperature on PC, mechanical properties were measured at -40, -20, 0, 20, 40, 60, 80, 100, 120 and 140 °C. The bar graphs for each mechanical property show the value for 4-week-old samples built on edge and stored in a controlled environment. Each graph also includes markers for the values of wet and dry samples and line graphs for samples at ages of 1, 13, 26 and 52 weeks.

The results of the material testing show that temperature, as would be expected, has a significant impact on the mechanical properties of PC. At 120 °C and below, all properties have a somewhat linear, downward trend as temperatures rise. Above 120 °C, there is a sharp decline for tensile strength and flexural modulus.

TENSILE STRENGTH

At 120 °C and below, falling temperatures produce higher tensile strengths. The 45.8 MPa change over the 160 °C range is roughly linear. Above 120 °C, there is a sharp 13.2 MPa (49.2%) drop, which is expected since the samples are approaching PC's Tg.

Excluding the values at 60 °C and 140 °C, environmental conditions prove to have negligible effect on tensile strength. All part storage conditions demonstrated the same linear, downward trend. For each temperature, the difference across wet, dry and controlled conditions fell between -2.8 MPa and +0.9 MPa. For unknown reasons, at 60 °C and 140 °C, wet conditions decreased the value by 4.8 MPa and 8.1 MPa, respectively. For temperature between -20 ° and 120 °C, the age of the sample had negligible effect on tensile strength. However, at the temperature extremes, age had noticeable but varied effects.

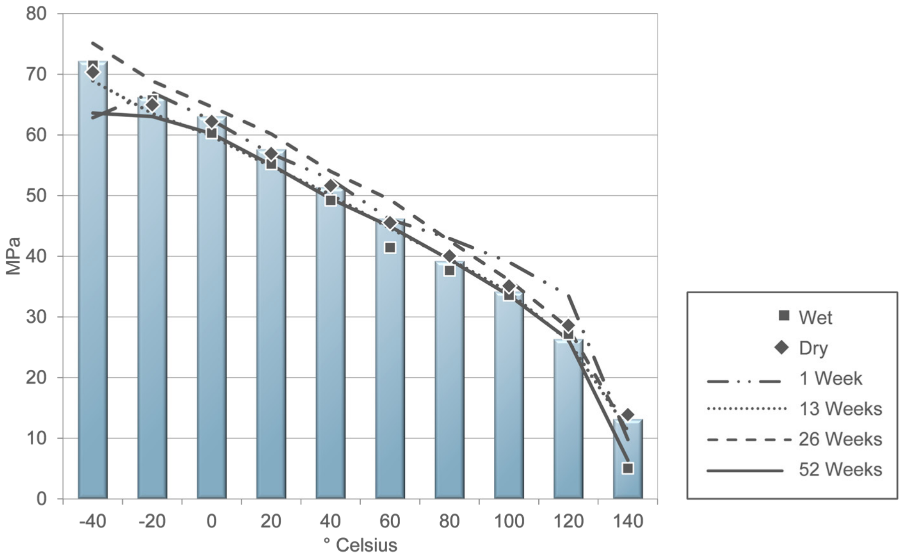

Figure 5a: Tensile strength - 4 weeks, controlled environment, on edge.

	Tensile Strength (MPa)		
°C	Chart Data	Min	Max
-40	72.2	70.1	72.6
-20	66.3	63.5	67.8
0	63.1	62.2	63.8
20	57.7	57.5	57.8
40	51.4	51.0	51.9
60	46.2	45.9	46.7
80	39.2	31.3	41.7
100	34.2	33.5	35.0
120	26.4	24.9	27.0
140	13.2	10.8	16.3

Figure 5b: Tensile strength - 4 weeks, controlled environment, on edge.

	Tensile Strength (MPa)					
°C	Wet	Dry	1 Week	13 Weeks	26 Weeks	52 Weeks
-40	71.5	70.4	62.8	68.9	75.1	63.6
-20	65.8	65.0	67.0	63.6	68.9	63.1
0	60.3	62.2	62.5	59.8	64.7	60.2
20	55.2	56.9	56.9	54.8	60.2	55.1
40	49.2	51.7	52.7	50.2	54.0	49.5
60	41.4	45.6	46.1	44.6	49.3	44.9
80	37.7	40.1	42.9	39.6	42.6	39.5
100	33.6	35.1	39.1	34.1	36.1	33.5
120	27.2	28.6	33.6	26.0	28.2	26.3
140	5.1	13.9	9.8	11.3	10.9	6.4

Figure 5c: Secondary data, tested in various conditions.

FLEXURAL MODULUS

While not as linear as tensile strength, flexural modulus also demonstrates a downward trend as temperature increases. From -40 °C to 120 °C, flexural modulus decreases by 299 MPa (15.5%). As with tensile strength, there is also a sharp drop for the 140 °C sample (924 MPa).

At or below 120 °C, the impact of sample age is reasonably small with maximum variances of -121 MPa (6.9%) to 142 MPa (7.6%) when compared to the 4-week sample. At 140 °C, however, there is a 962 MPa (62.6 %) variance between samples that is inconsistent with other data. The 4-week-old sample (701 MPa) is similar to the values for the 26- and 52-week samples, but it is significantly less (478 MPa and 836 MPa) than that for the 1-week and 13-week samples.

Between 0 °C and 120 °C, the environmental conditions have minimal effect on flexural modulus. Dry storage tends to yield slightly higher values with the largest difference from the control being 67 MPa (3.8%). Wet samples have equal or slightly lower values with the greatest variance being 43 MPa (2.4%). Below freezing, the wet condition increases flexural modulus significantly (14.5% to 18.2%) while dry decreased the value by 4.3% to 5.5%. At 140 °C, both conditions resulted in lower flexural moduli.

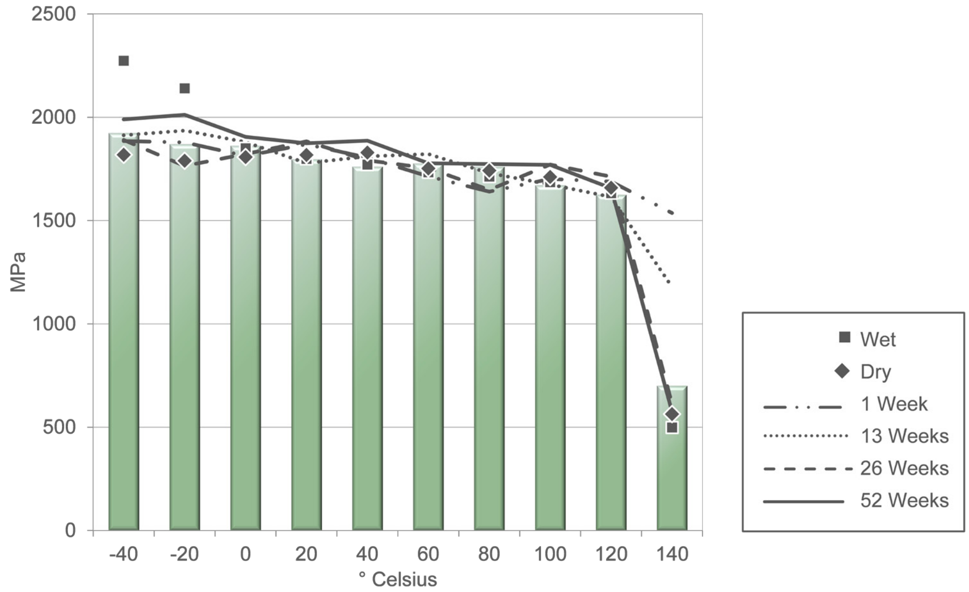

Figure 6a: Flexural modulus - 4 weeks, controlled environment, on edge.

°C	Flexural Modulus (MPa) Chart Data	Min	Max
-40	1924	1842	1966
-20	1870	1784	1951
0	1863	1824	1951
20	1797	1712	1913
40	1762	1672	1827
60	1777	1600	1877
80	1761	1666	1827
100	1671	1598	1723
120	1625	1525	1697
140	701	599	767

Figure 6b: Flexural modulus - 4 weeks, controlled environment, on edge.

°C	Flexural Modulus (MPa) Wet	Dry	1 Week	13 Weeks	26 Weeks	52 Weeks
-40	2274	1819	1885	1913	1891	1990
-20	2140	1790	1879	1936	1765	2012
0	1850	1808	1813	1880	1823	1905
20	1799	1818	1870	1778	1884	1874
40	1771	1829	1805	1811	1792	1887
60	1734	1752	1714	1822	1754	1778
80	1714	1742	1640	1730	1649	1774
100	1686	1711	1702	1675	1772	1770
120	1633	1659	1689	1615	1713	1657
140	499	563	1537	1179	613	575

Figure 6c: Secondary data, tested in various conditions.

ELONGATION AT BREAK

Elongation at break declined 8.2 points (78.9%) over the tested temperature range. This decrease is fairly consistent, and somewhat linear, with the exception of a 1.9-point decline between 60 °C and 80 °C. This temperature band also presents a distinct change in the effects of environmental conditions and age.

Below 80 °C, wet storage conditions yield a linear decline with a steeper slope than that for the controlled condition. This results in higher elongation at break for temperatures below freezing and lower values for temperatures between 20 °C and 60 °C. A similar trend occurs between 80 °C and 140 °C where temperatures below 140 °C have higher elongation at break.

Below 80 °C, dry storage conditions produce elongation at break values below or roughly equal to those for controlled conditions. Above 80 °C, this condition produces sharply higher values, with the exception of the 140 °C condition.

Although age has a noticeable effect on elongation at break, the values loosely followed the trends seen in the 4-week, controlled test condition for all temperatures.

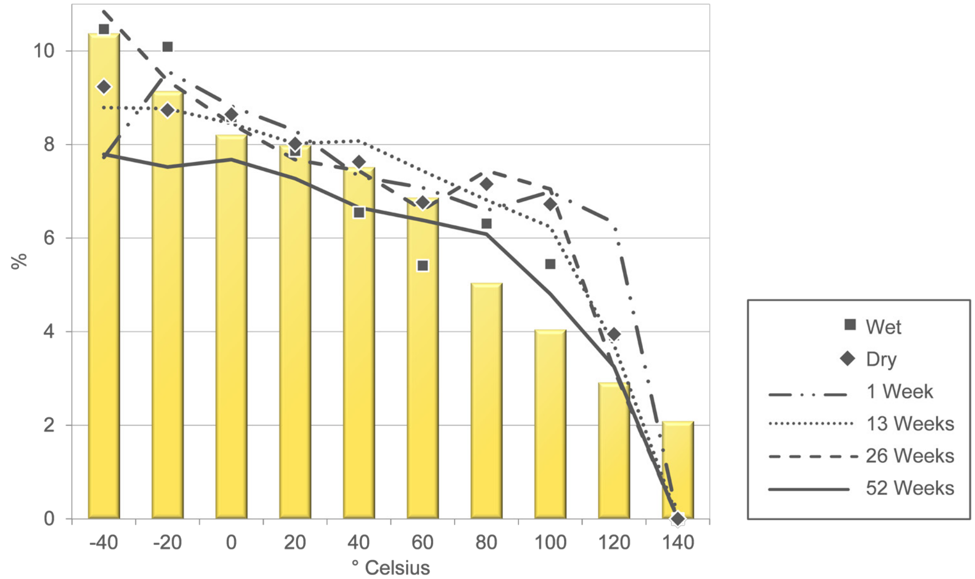

Figure 7a: Elongation at Break - 4 weeks, controlled environment, on edge.

	Elongation at Break (%)		
°C	Chart Data	Min	Max
-40	10.4	9.4	11.0
-20	9.1	8.7	9.5
0	8.2	7.9	8.6
20	8.0	7.6	8.3
40	7.5	6.9	8.4
60	6.9	6.3	7.4
80	5.0	2.9	6.6
100	4.0	3.6	4.6
120	2.9	2.6	3.1
140	2.1	2.1	2.1

Figure 7b: Elongation at Break - 4 weeks, controlled environment, on edge.

	Elongation at Break (%)					
°C	Wet	Dry	1 Week	13 Weeks	26 Weeks	52 Weeks
-40	10.5	9.2	7.7	8.8	10.8	7.8
-20	10.1	8.7	9.6	8.8	9.4	7.5
0	8.6	8.6	8.8	8.4	8.4	7.7
20	7.9	8.0	8.3	8.0	7.7	7.3
40	6.6	7.6	7.3	8.1	7.4	6.7
60	5.4	6.8	7.1	7.4	6.6	6.4
80	6.3	7.2	6.6	6.8	7.4	6.1
100	5.4	6.7	7.0	6.2	7.0	4.8
120	3.9	3.9	6.3	3.7	3.2	3.3
140	0.0	0.0	0.0	0.0	0.0	0.0

Figure 7c: Secondary data, tested in various conditions.

INTRODUCTION

Test samples were stored in three conditions— wet, dry and controlled— to show the influence of moisture on PC's mechanical properties. Wet samples were immersed in water; dry samples were exposed to 15% relative humidly; and controlled samples were maintained at 50% relative humidity. The bar graphs for each mechanical property show the value for 20 °C, 4-week-old samples built on edge. Each graph also includes a marker for the 52-week-old samples and line graphs for samples at -40, 0, 40, 80, 120 and 140 °C.

The testing data shows that part storage conditions have minimal effect on tensile strength and flexural modulus for samples between -20 °C and 120 °C. While elongation at break was steady at room temperature, the combination of environment and temperature has differing effects at lower and higher temperatures.

TENSILE STRENGTH

Tensile strength is stable across the three environmental conditions, varying by only 2.5 MPA (4.3%). Samples at 52 weeks are also stable, showing a 2.2% variance.

With the exception of the 140 °C samples, tensile strength is also fairly consistent for all temperatures across the three environmental conditions. At 140 °C, the wet storage condition produces much lower tensile strength (8.2 MPa and 8.9 MPa) than that for dry and controlled.

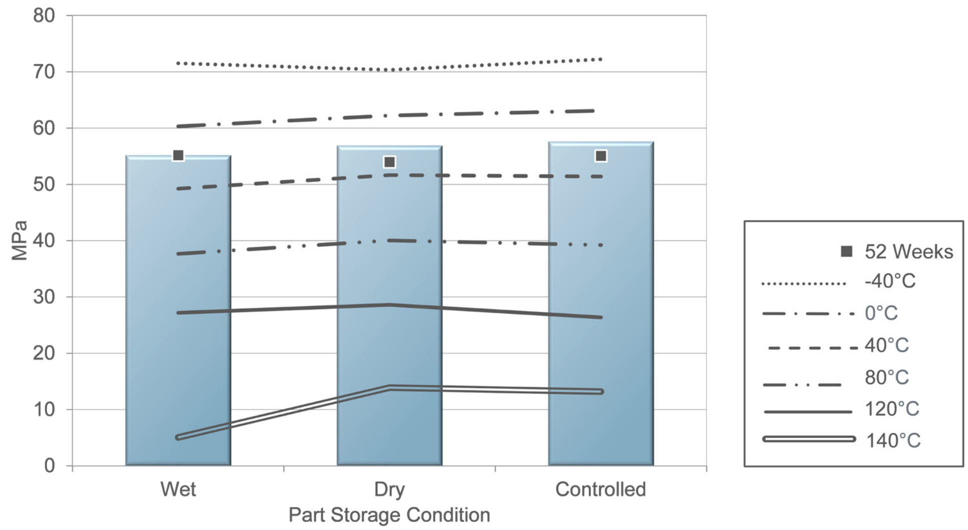

Figure 8a: Tensile strength - 4 weeks, controlled environment, on edge.

	Tensile Strength (MPa)		
Condition	**Chart Data**	**Min**	**Max**
Wet	55.2	54.7	55.5
Dry	56.9	56.2	57.7
Controlled	57.7	57.5	57.8

Figure 8b: Tensile strength - 4 weeks, controlled environment, on edge.

	Tensile Strength (MPa)						
Condition	**52 Weeks**	**-40 °C**	**0 °C**	**40 °C**	**80 °C**	**120 °C**	**140 °C**
Wet	55.2	71.5	60.3	49.2	37.7	27.2	5.0
Dry	54.0	70.3	62.2	51.7	40.0	28.6	13.9
Controlled	55.1	72.2	63.1	51.4	39.2	26.4	13.2

Figure 8c: Secondary data, tested in various conditions.

FLEXURAL MODULUS

Figures 9a and 9b show that environmental conditions have no effect on flexural modulus. For the three conditions, there is only a 21 MPa (1.2%) variance. At 52-weeks, the controlled condition has a 90 MPa (5.0%) increase, but there is no change in either the wet or dry test conditions.

In the temperature range of 0 °C to 120 °C, flexural modulus remains relatively consistent over wet, dry and controlled conditions. For each temperature, the largest variance is only 67 MPa (3.8%). At the extremes, however, the combination of temperature and environment has significant influence on flexural modulus. At -40 °C, the range is 455 MPa (25.3%), which is due to a sharp increase for the wet condition. At 140 °C, the range is 202 MPa (28.8%) with the lowest value being for the wet part storage condition.

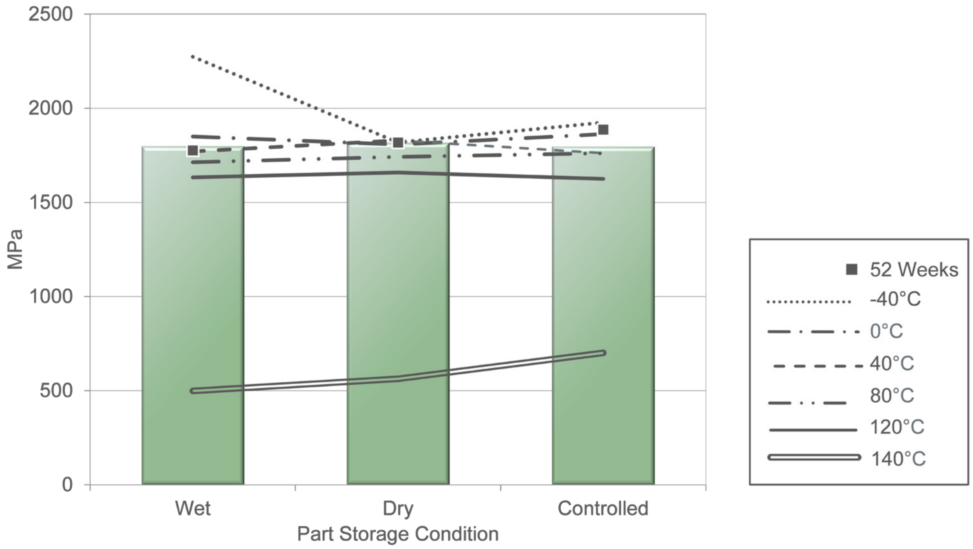

Figure 9a: Flexural modulus - 4 weeks, controlled environment, on edge.

	Flexural Modulus (MPa)		
Condition	**Chart Data**	**Min**	**Max**
Wet	1799	1736	1865
Dry	1818	1751	1862
Controlled	1797	1732	1887

Figure 9b: Flexural modulus - 4 weeks, controlled environment, on edge.

	Flexural Modulus (MPa)						
Condition	**52 Weeks**	**-40 °C**	**0 °C**	**40 °C**	**80 °C**	**120 °C**	**140 °C**
Wet	1776	2274	1850	1771	1714	1633	499
Dry	1819	1819	1808	1829	1742	1659	563
Controlled	1887	1924	1863	1762	1761	1625	701

Figure 9c: Secondary data, tested in various conditions.

ELONGATION AT BREAK

The effects of part storage conditions on elongation at break are insignificant for the 20 °C test condition. The aged, 52-week-old samples are consistent, but slightly lower, for wet, dry and controlled samples.

At all other temperatures, part storage conditions had moderate to significant influence on elongation at break. However, the presence of moisture in the samples had inconsistent effects. In some cases, wet conditions decrease elongation at break by up to 2.2 points. In others, it increases it by 1.3 points.

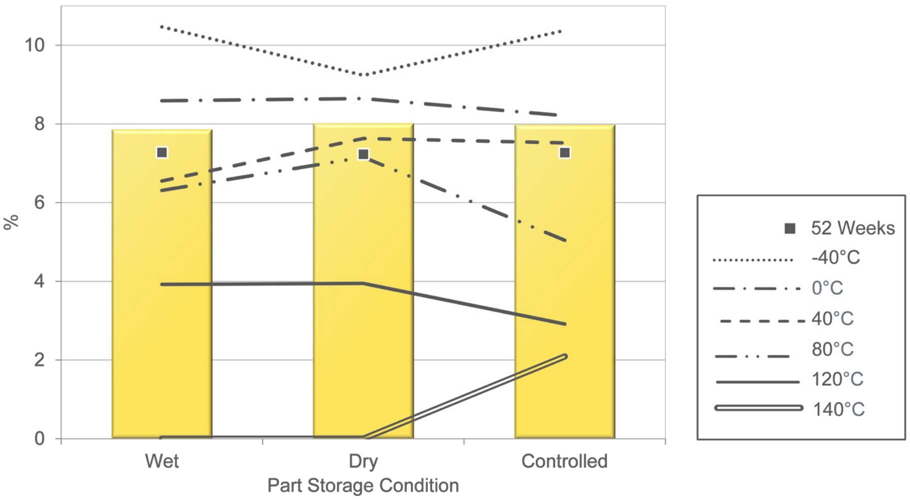

Figure 10a: Elongation at break - 4 weeks, controlled environment, on edge.

	Elongation at Break (%)		
Condition	**Chart Data**	**Min**	**Max**
Wet	7.9	7.5	8.2
Dry	8.0	7.6	8.6
Controlled	8.0	7.6	8.3

Figures 10b: Elongation at break - 4 weeks, controlled environment, on edge

	Elongation at Break (%)						
Condition	**52 Weeks**	**-40 °C**	**0 °C**	**40 °C**	**80 °C**	**120 °C**	**140 °C**
Wet	7.3	10.5	8.6	6.6	6.3	3.9	0.0
Dry	7.2	9.2	8.6	7.6	7.2	3.9	0.0
Controlled	7.3	10.4	8.2	7.5	5.0	2.9	2.1

Figure 10c: Secondary data, tested in various conditions.

REPORT CONCLUSION:

Characterization of Material Properties for Fortus Polycarbonate (PC)

As expected of a thermoplastic, temperature had the greatest effect on the mechanical properties of Fortus polycarbonate. In the temperature range of -40 °C to 120 °C, the values are consistent and predictable. At the uppermost temperature, 140 °C, properties tend to change significantly or break from the trend in the moderate range. Age, on the other hand has little influence on these properties. They prove to be consistent across all samples used in the 52-week testing period. The second most influential factor is environmental conditions. Yet, the influence of wet or dry storage is relatively small for moderate temperatures at or above 0 °C.

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