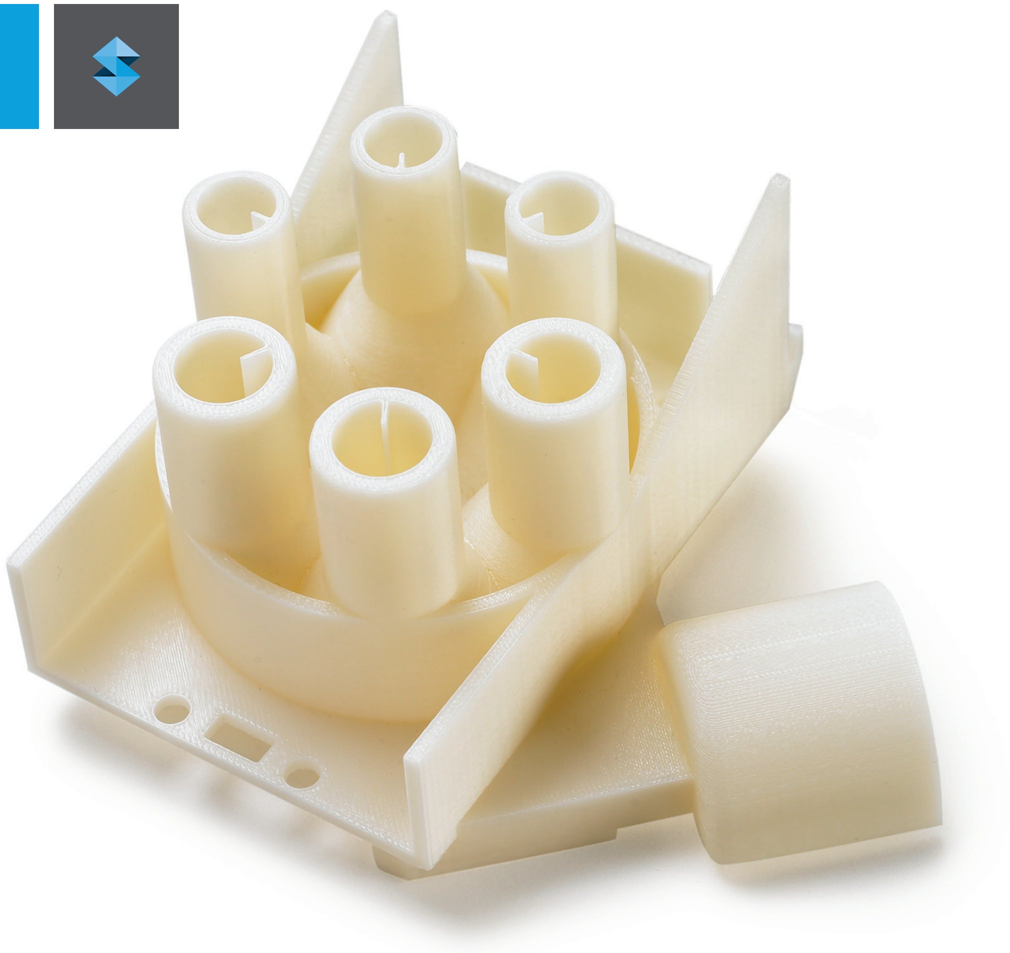

Characterization Of Material Properties

FORTUS ABS-M30

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.

Characterization Of Material Properties

FORTUS ABS-M30

To characterize the effects of time, temperature and environment, Loughborough University (Loughborough, UK) performed extensive testing on Fortus® ABS-M30 thermoplastic. Conducted over a 52-week period, the evaluation measured five properties at temperatures ranging from -40° C to 100°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

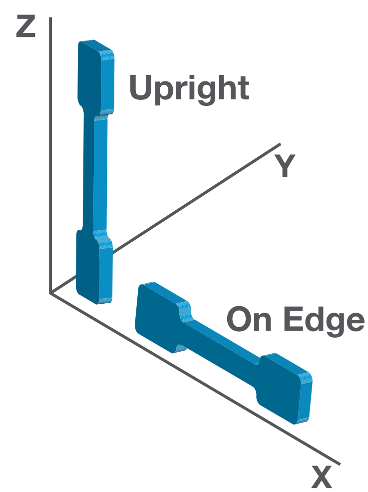

Figure 1: Test sample orientations

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).

PROPERTY	PUBLISHED		TEST RESULT		% DIFFERENCE
Tensile Strength	ASTM D638	36 MPa	ISO 527	33 MPa	-10%
Young's Modulus	ASTM D638	2413 MPa	ISO 527	2771 MPa	15%
Flexural Strength	ASTM D790	61 MPa	ISO 178	64 MPa	5%
Flexural Modulus	ASTM D790	2317 MPa	ISO 178	2028 MPa	-12%
Elongation at Break	ASTM D638	4%	ISO 527	7%	78%

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

Characterization Of Material Properties

FORTUS ABS-M30

The university's comprehensive report, which is available upon request, documents 1200 combinations of mechanical properties and test conditions. To summarize these findings, the following graphs present ABS-M30's performance as time, temperature and environment change while all other factors remain constant.

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

TESTED VS. PUBLISHED

To substantiate previously published material properties, Table 1 presents the differences in values for test data and published specifications. 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. With variances of ± 15%, the university's testing validates four of the five properties.

Elongation at break is the exception. Test samples have an average of 7%, which is 78% higher than the published value. Although there is no definitive explanation for the variance, one possibility is that the published data's samples were exposed to elevated humidity levels. As shown in later graphs, moisture tends to decrease elongation at break. Another 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.

[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 ABS-M30, 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 and 100°C.

The test results show that all properties are stable over a 52-week period. There is little variance as the samples age. Changes in part storage conditions and temperatures do not affect stability

Characterization Of Material Properties

FORTUS ABS-M30

over time, with the exception of elongation at break. Exposed to moisture, elongation at break decreases with age.

TENSILE STRENGTH

Over 52 weeks, tensile strength varies by just 0.73 MPa (2.3%), which shows that it is unaffected by age (Figure 2a, b, c). This is also true for wet and dry samples. Although wet conditions tend to increase tensile strength, the change is small (<2.8 MPa) and fairly stable over time.

At temperatures ≥0 °C, tensile strength is stable over the 52-week period. For the -40°C sample, there is a decline of 6.9°C (13.5%). Figure 2 also shows a significant decrease in tensile strength between 80°C and 100°C for all time periods. This is expected because the higher temperature is near to ABS-M30's glass transition temperature (Tg) of 108°C. The following graphs show a similar drop at 100°C for all mechanical properties.

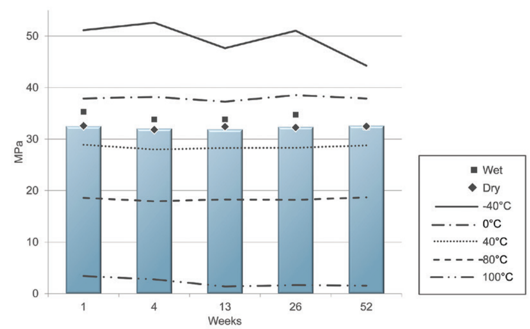

Figure 2a: Tensile strength - 20 °C, controlled environment, on edge.

Tensile Strength (MPa)

WEEK	CHART DATA	MIN	MAX
1	32.5	32.3	33.0
4	32.1	32.0	32.2
13	31.9	31.6	32.3
26	32.4	32.3	32.6
52	32.6	32.5	33.1

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

Tensile Strength (MPa)

WEEK	WET	DRY	-40 °C	0 °C	40 °C	80 °C	100 °C
1	35.3	32.6	51.2	37.9	28.9	18.6	3.4
4	33.8	31.8	52.6	38.2	28.0	17.9	2.8
13	33.8	32.4	47.7	37.3	28.3	18.3	1.4
26	34.7	32.3	51.0	38.6	28.3	18.2	1.7
52	32.5	32.5	44.3	37.9	28.8	18.7	1.6

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

Characterization Of Material Properties

FORTUS ABS-M30

FLEXURAL MODULUS

As with tensile strength, aging has little effect on flexural modulus. The maximum variance is only 162 MPa (7.8%), and the difference between weeks 1 and 52 is just 36 MPa (1.8 %). The sharp decline at week 13 and subsequent rise at week 26 are inconsistent with the values for the wet and dry samples, which have slight increases for these periods. Weeks 13 and 26 results are also inconsistent with those at other temperatures.

In general, flexural modulus is relatively stable for all temperatures and environmental conditions. While each has a tendency to increase through week 13, the values stabilize afterwards. The exception is at 100 °C, which has a sharp 954 MPa drop over time.

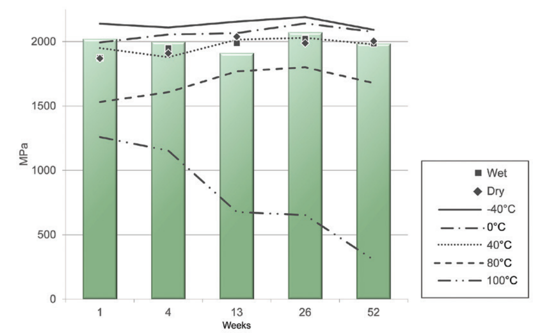

Figure 3a: Tensile strength - 20 °C, controlled environment, on edge.

Tensile Strength (MPa)			
WEEK	CHART DATA	MIN	MAX
1	2022	1896	2134
4	1999	1750	2167
13	1911	1828	1987
26	2073	1893	2223
52	1986	1911	2018

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

Tensile Strength (MPa)							
WEEK	WET	DRY	-40 °C	0 °C	40 °C	80 °C	100 °C
1	1874	1869	2139	1993	1950	1531	1259
4	1949	1909	2109	2055	1879	1607	1154
13	1988	2039	2155	2066	2015	1768	677
26	2023	1988	2191	2141	2029	1801	653
52	1986	2004	2092	2075	1978	1678	305

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

Characterization Of Material Properties

FORTUS ABS-M30

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ELONGATION AT BREAK

Elongation at break proves to be somewhat erratic with a range of 1.2 points (16.5%) over the 52-week testing period. However, the variance decreases to 0.7 points (9.8%) if week 13, which is inconsistent with the values for other conditions, is excluded. Also, elongation at break stabilizes after the first week, having only a 0.24-point variance between weeks 4, 26 and 52.

The combination of age and temperature has no trend; results vary widely. Environmental conditions are more consistent. Part storage has considerable impact on elongation at break as the material ages. Wet storage conditions produce a sharp drop between weeks 1 and 13 (3.1 points) that places elongation at break well below that for the controlled condition. On average, wet samples are 2.0 points below the controlled condition for weeks 4 through 52. Dry conditions, on the other hand, have a large increase over the controlled conditions after week 4.

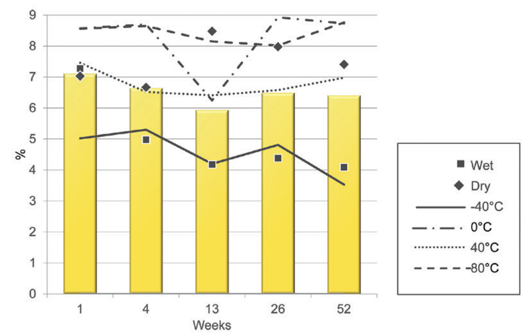

Figure 4b: Elongation at break - 20 °C, controlled environment, on edge.

Tensile Strength (MPa)			
WEEK	CHART DATA	MIN	MAX
1	7.1	6.2	9.3
4	6.7	6.0	7.4
13	5.9	5.3	7.1
26	6.5	3.5	8.8
52	6.4	3.2	8.0

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

Tensile Strength (MPa)							
WEEK	WET	DRY	-40 °C	0 °C	40 °C	80 °C	100 °C
1	7.3	7.0	5.0	8.6	7.5	8.6	N/A
4	5.0	6.7	5.3	8.7	6.5	8.7	N/A
13	4.2	8.5	4.2	8.2	6.4	6.3	N/A
26	4.4	8.0	4.8	8.0	6.6	8.9	N/A
52	4.1	7.4	3.5	8.8	7.0	8.7	N/A

Figure 4c: Secondary data, tested in various conditions. Note: Values for 100° C were not reported. The tests were ended prior to sample breakage due to severe deformation.

Characterization Of Material Properties

FORTUS ABS-M30

INTRODUCTION

To show the effects of temperature on ABS-M30, mechanical properties were measured at -40, -20, 0, 20, 40, 60, 80 and 100° 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 representing the values for wet and dry part storage conditions and line graphs for samples at 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 ABS-M30. While temperature's effect on elongation at break is irregular, both tensile strength and flexural modulus demonstrate a somewhat linear, downward trend as temperatures rise. For both properties, there is also a sharp decline above 80° C. Elongation at break is not only erratic; it is also heavily influenced by the combination of environmental conditions and temperature

TENSILE STRENGTH

At 80°C and below, a temperature drop increases tensile strength (Figures 5a, b, c). The 34.7 MPa change over a 120° C range is nearly linear. Above 80° C, there is a sharp, 15.2 MPa drop, which is expected since the temperature is approaching ABS-M30's Tg. For temperatures at or above freezing, the age of the sample has negligible effect on tensile strength. Below freezing, younger samples have higher values. For example, at -40° C the 1-week sample's value is 6.9 MPa (15.6%) higher than that for the 52-week sample. At or above 20° C, dry samples have roughly the

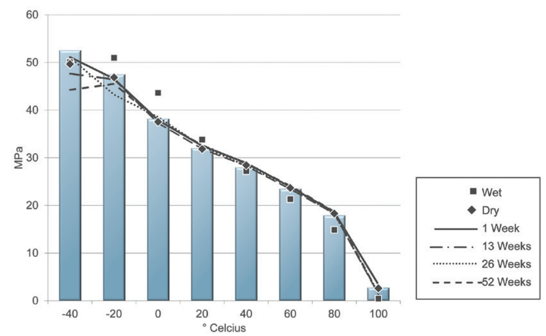

Figure 5a: Tensile strength - 4 weeks, controlled environment, on edge.

Tensile Strength (MPa)			
°C	CHART DATA	MIN	MAX
-40	52.6	50.4	53.8
-20	47.3	47.0	48.0
0	38.2	37.5	39.8
20	32.1	32.0	32.2
40	28.0	27.2	28.4
60	23.5	23.4	23.6
80	17.9	17.7	18.3
100	2.8	1.9	4.2

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

Characterization Of Material Properties

FORTUS ABS-M30

Tensile Strength (MPa)						
°C	WET	DRY	1 WEEK	13 WEEKS	26 WEEKS	52 WEEKS
-40	50.1	49.7	51.2	47.7	51.0	44.3
-20	51.0	46.9	46.6	46.4	43.3	45.5
0	43.6	37.5	37.9	37.3	38.6	37.9
20	33.8	31.8	32.5	31.9	32.4	32.6
40	27.2	28.5	28.9	28.3	28.3	28.8
60	21.3	23.7	23.9	23.4	23.9	24.1
80	14.9	18.3	18.6	18.3	18.2	18.7
100	0.4	2.6	3.4	1.4	1.7	1.6

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

same tensile strength as the controlled samples. Moisture, on the other hand, has a noticeable effect. Between -20° C and 20° C, the wet samples have higher tensile strengths (1.8 MPa to 5.4 MPa greater than the controlled samples). Above 20° C, the wet samples have lower tensile strengths than both the dry and controlled samples.

Characterization Of Material Properties

FORTUS ABS-M30

ELONGATION AT BREAK

The erratic, seemingly random values of elongation at break are evident in Figures 7a, b, c. The spike at 0 °C for all but the wet test condition underscores this observation. At 0 °C, there is a 2.1 to 3.5 point increase in elongation at break followed by a sharp drop of 1.5 to 2.4 points.

However, if this spike is disregarded, there is an upward trend as temperatures rise for controlled and dry samples of all ages. For 4-weekold, controlled samples, elongation at break increases 3.4 points (39%). For dry, the increase is 2.6 points (55.3%). Moisture does the opposite; decreasing values by as much as 64.6%.

Note: Values for 100 °C were not reported. The tests were ended prior to sample breakage due to severe deformation.

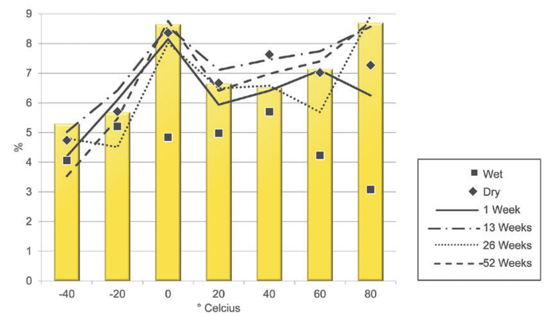

Figure 7a: Elongation at Break - 4 weeks, controlled environment, on edge.

Elongation at Break (%)

°C	CHART DATA	MIN	MAX
-40	5.3	4.7	5.6
-20	5.7	5.2	6.3
0	8.7	7.1	10.1
20	6.7	6.0	7.4
40	6.5	4.5	8.0
60	7.1	6.5	8.0
80	8.7	6.0	11.2
100	NA	NA	NA

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

Tensile Strength (MPa)

°C	WET	DRY	1 WEEK	13 WEEKS	26 WEEKS	52 WEEKS
-40	4.1	4.7	5.0	4.2	4.8	3.5
-20	5.2	5.7	6.4	6.1	4.8	5.5
0	4.8	8.4	8.7	8.2	8.0	8.8
20	5.0	6.7	7.1	5.9	6.5	6.4
40	5.7	7.6	7.5	6.4	6.6	7.0
60	4.2	7.0	7.7	7.1	5.7	7.4
80	3.1	7.3	8.6	6.3	8.9	8.7
100	NA	NA	NA	NA	NA	NA

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

Characterization Of Material Properties

FORTUS ABS-M30

INTRODUCTION

Test samples were stored in three conditions—wet, dry and controlled—to show the influence of moisture on 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 and 100 °C.

The testing data shows that, in general, part storage conditions have only modest effect on the mechanical properties for samples between 0 °C and 60 °C. At temperature extremes, moisture levels have greater effect on the properties. Also, wet conditions, at any temperature, significantly decrease elongation at break.

TENSILE STRENGTH

Figures 8a and 8b show that samples at 20 °C, both at 4 weeks and 52 weeks, have stable tensile strengths across the three environmental conditions. The range is only 2.0 MPa (5.9%). With the exception of the 0 °C sample, tensile strength is also fairly consistent for all temperatures in wet, dry and controlled conditions. For each temperature, the variances range from 1.3 MPa to 3.4 MPa for the wettest to driest

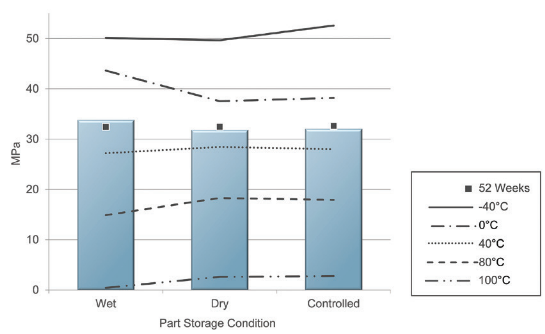

Figure 8a: Tensile strength - 4 weeks, controlled environment, on edge.

Tensile Strength (MPa)			
CONDITION	CHART DATA	MIN	MAX
Wet	33.8	33.6	33.9
Dry	31.8	31.7	32.0
Controlled	32.1	32.0	32.2

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

Tensile Strength (MPa)						
CONDITION	52 WEEKS	-40 °C	0 °C	40 °C	80 °C	100 °C
Wet	32.5	50.1	43.6	27.2	14.9	0.4
Dry	32.5	49.7	37.5	28.5	18.3	2.6
Controlled	32.6	52.6	38.2	28.0	17.9	2.8

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

Characterization Of Material Properties

FORTUS ABS-M30

FLEXURAL MODULUS

Part storage conditions have little influence on flexural modulus (Figures 9a, b, c). At 4 weeks, there is only a 50 MPa (2.5%) difference for the wet, dry and controlled samples. At 52 weeks, the difference is even smaller, just 18 MPa (0.9%). In the moderate temperature range (0 °C to 60 °C), flexural modulus remained relatively independent of wet, dry and controlled conditions. For each temperature, the largest variance is only 91 MPa. At the extremes, however, the combination of temperature and environment has significant effect on flexural modulus. At -40 °C, the range is 294 MPa (12.2%). At 100 °C, the range is 993 MPa (86.0%).

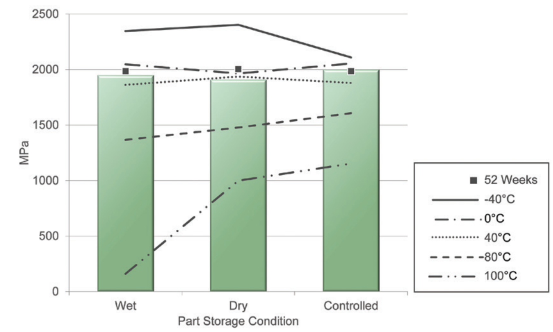

Figure 9a: Flexural modulus - 4 weeks, controlled environment, on edge.

Flexural Modulus (MPa)

CONDITION	CHART DATA	MIN	MAX
Wet	1949	1768	2061
Dry	1909	1708	2184
Controlled	1999	1750	2167

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

Flexural Modulus (MPa)

CONDITION	52 WEEKS	-40 °C	0 °C	40 °C	80 °C	100 °C
Wet	1986	2347	2047	1862	1367	161
Dry	2004	2403	1964	1937	1477	999
Controlled	1986	2109	2055	1879	1607	1154

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

Characterization Of Material Properties

FORTUS ABS-M30

ELONGATION AT BREAK

The effects of moist storage conditions on elongation at break are significant for all temperature ranges. Wet samples decrease elongation at break by 1.7 to 3.8 points (25.0% to 44.0%) when compared to the dry and controlled conditions. For all but 40 °C and 52-week samples, elongation at break is relatively stable for dry and controlled conditions. These two exceptions show increases of 0.7 MPa and 1.1 MPa over the value for the controlled sample.

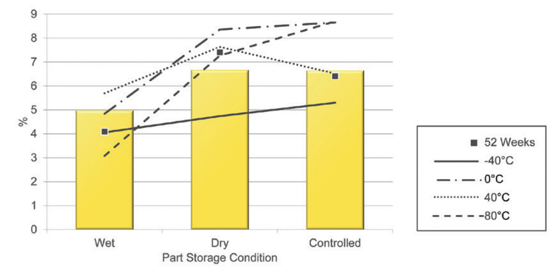

Figure 10a: Elongation at break - 4 weeks, controlled environment, on edge.

Elongation at Break (%)

CONDITION	CHART DATA	MIN	MAX
Wet	5.0	4.6	5.5
Dry	6.7	5.9	8.0
Controlled	6.7	6.0	7.4

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	100 °C
Wet	4.1	4.1	4.8	5.7	3.1	0.0
Dry	7.4	4.7	8.7	7.6	7.3	0.0
Controlled	6.4	5.3	8.7	6.5	8.7	0.0

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

REPORT CONCLUSION: Characterization of Material Properties for Fortus ABS-M30

As expected of a thermoplastic, temperature has the greatest effect on the mechanical properties of Fortus ABS-M30. In the moderate temperature range (0 °C to 60 °C), the values are consistent and predictable. At the extremes (below 0 °C and above 60 °C), mechanical properties tend to change significantly or break from the trends seen in the moderate range. Age, on the other hand, has little influence on these properties. Each proves to be consistent across the 52-week testing period.

The second most influential factor is exposure to moist conditions. While dry and controlled environments produce similar results for most test conditions, continuous exposure to a wet environment often alters the mechanical properties significantly. This is especially true when measuring mechanical properties at the temperature extremes.

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