SABIC
Innovative
Plastics™

LNP* Specialty Compounds

Long term behavior of reinforced thermoplastics

Sharing our futures

Long term behavior of reinforced thermoplastics

New materials and improved reinforcements have expanded the performance envelope of engineered thermoplastics. Improved properties, such as tensile modulus and strength, make thermoplastics attractive candidates for replacing traditional engineering materials in structural applications. These properties are commonly used in estimating deflections or strengths of components subjected to intermittent or short term static loads. However, when loads are constant over time or cyclic, it is also critical to examine the long term behavior of materials to insure design success.

Creep, stress relaxation and fatigue are examples of long term phenomena which are often neglected in the design process. These issues are typically addressed using estimated properties or are totally ignored. Quite frequently, the reasons for this are a lack of understanding of material response, or a lack of readily available data.

SABIC Innovative Plastics has taken a proactive approach to characterizing long term material performance of its structural materials. In addition, we work continuously towards an understanding of the issues, which affect these phenomena, and provide this information to our customers. The intent of this paper is to provide customers with a range of creep, fatigue and stress relaxation data available at SABIC Innovative Plastics. In addition, a discussion of issues relevant to long term behavior is included to provide insight into these phenomena where data does not exist. Because compounding allows the manufacture of an infinite number of combinations of filler, reinforcement and resins, the generation of data on all products is impossible.

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Creep in thermoplastics

All materials undergo an elongation or deflection when subjected to a load or stress. At moderate stress levels, the percentage change in length or strain that a material experiences is proportional to the applied stress, and inversely proportional to its modulus. This phenomenon is known as hookean or linear stress strain behavior. Further increases in stress result in a departure from this linear behavior. The key characteristic of stress strain behavior is that an increase in strain is coincident with an increase in applied stress.

However, if a material elongates over time without an increase in applied stress, it is exhibiting viscoelasticity. Engineers typically refer to this as elongation over time at a constant stress as creep. Creep behavior is categorized into three distinct stages primary, secondary and tertiary creep.

The primary stage of creep is characterized by a relatively fast onset of strain coincident with the application of a load, as in a tensile test. Secondary creep is the stage marked by a continued elongation while the load is held constant. The third or tertiary stage of creep is recognized by specimen necking and a sharp increase in the rate of creep, followed by creep rupture. Designers and engineers are most concerned with the secondary stage of creep, as it provides important information regarding creep behavior of a material within its effective design envelope (i.e. allowable temperature and stress).

Data taken from the secondary stage of creep yields the most important information creep strain behavior over time, and apparent or creep modulus. Creep data can be displayed in a graph of strain versus time for a given stress and temperature. This type of plot is useful for predicting the strain of a material beyond the duration of the creep test. It is common practice to extrapolate creep data out to ten times the test duration. In this case, one hundred hour tests are extrapolated to describe creep behavior for 1000 hours. An alternate method of presenting creep data is the isochronous stress strain curve (see opposite page for further information on isochronous stress strain curves). These curves display more detailed information on the creep behavior of a material.

The apparent modulus or creep modulus is defined as the ratio of the stress to total strain at any item in this segment of the creep curve. This piece of information is useful when completing hand calculations for creep situations. Apparent modulus can be calculated by dividing the applied load by a total specimen strain measured. Because it varies with time and temperature, it is often presented for several time intervals. Graphs of apparent modulus versus time for a given temperature are useful in designing a component to a specific design life. The shortcoming of apparent modulus is that it does not differentiate between initial strain upon specimen loading, and true creep strain (additional strain occurring after the specimen is fully loaded).

Creep data is typically collected from samples loaded in tension, compression, or flexure. The test apparatus usually consists of a load frame to apply a constant load to the specimen, and a device to accurately measure the resulting deflection over time. The procedure for this testing is quite simple the load is applied, and the specimen deflection or strain is recorded at regular time intervals. It should be noted that data from testing in one of these loading scenarios do not necessarily corroborate with results from another. However, results from one type of testing can generally be used to rank the relative performance of a material under a different type of loading. See tables 1 and 2 for specific flexural and tensile creep data on many SABIC Innovative Plastics.

Creep resistance

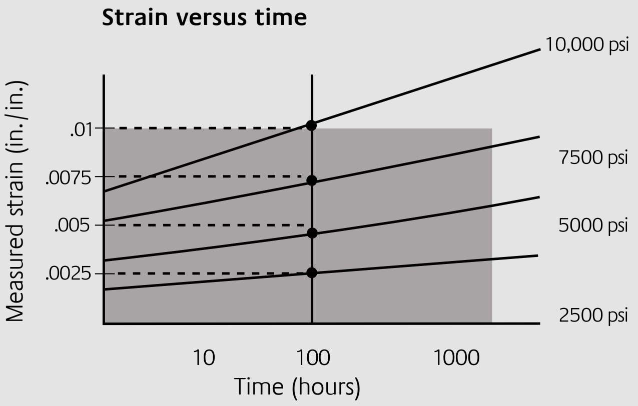
The rate of creep in a material is affected by testing conditions such as applied load, temperature, humidity and time. Often these environmental issues cannot be avoided in a particular application. For this reason, it is very important for designers and engineers to understand the influences of each of these on the creep performance of a reinforced thermoplastic.

Intrinsic material issues which influence creep of thermoplastics include crystallinity, the presence of fillers and/or reinforcements, residual stresses, weld-lines and fiber/matrix bond strength. These issues are governed by the characteristics of the thermoplastic compound itself, component design, tool design and processing. A description of some of these topics is important in understanding the creep behavior of structural thermoplastics.

Isochronous stress strain curves

Isochronous stress strain curves are used as an alternate method to display creep information. Isochronous tensile curves are plotted as a graph of stress versus strain, as in a tensile stress strain curve. However, they represent the strain level of a material after a specified time period at a variety of stress levels. Viewed differently, they are a "slice" through a family of strain versus time curves at one particular point in time. Isochronous stress strain curves are very useful in understanding creep behavior because they clearly differentiate between initial strain and creep strain after a specified period of time. In addition, most components experience a variety of stress levels and creep strains, and that information is readily available on these curves.

The graph shows a typical presentation of a family of creep versus time curves at several stress levels, and the construction of an isochronous tensile stress strain curve.


Strain versus time

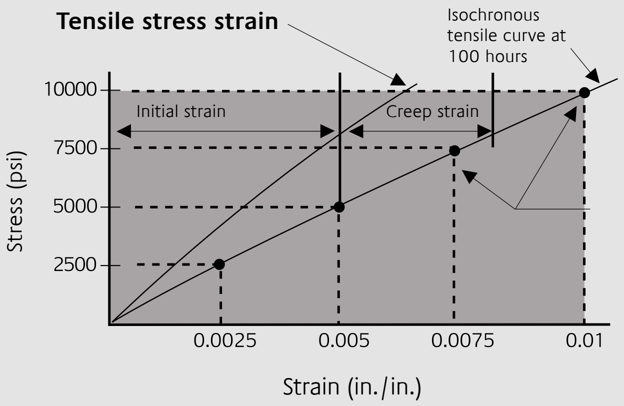

Tensile stress strain

Table 1 flexural creep of fiber reinforced thermoplastics (at 73°F/23°C)

Compound	Stress (psi)	(MPa)	Total strain (%)		
			10 hrs.	100 hrs.	1000 hrs.
Thermocomp* AF-1004	2,500	17.2	0.263	0.288	0.325
	5,000	34.5	0.520	0.607	0.643
Thermocomp AF-1008	5,000	34.5	0.290	0.302	0.332
	10,000	69.0	0.585	0.615	0.660
Thermocomp BF-1004	2,500	17.2	0.277	0.239	0.271
	5,000	34.5	0.455	0.478	0.540
	10,000	69.0	0.910	0.956	1.086
Thermocomp BF-1006	5,000	34.5	0.367	0.389	0.402
Thermocomp BF-1008	10,000	69.0	0.588	0.600	0.642
Thermocomp CF-1004	2,500	17.2	0.273	0.301	0.338
	5,000	34.5	0.519	0.550	0.585
	10,000	69.0	1.090	1.205	1.350
Thermocomp DC-1006	2,500	17.2	0.120	0.128	0.129
	5,000	34.5	0.240	0.251	0.260
Thermocomp DF-1004	5,000	34.5	0.618	0.628	0.654
Thermocomp DF-1006	5,000	34.5	0.451	0.462	0.466
Thermocomp DF-1008	5,000	34.5	0.312	0.319	0.322
Thermocomp EC-1004	10,000	69.0	0.620	0.700	0.710
	5,000	34.5	0.367	0.399	0.420
	10,000	69.0	0.721	0.779	0.820
Thermocomp EF-1004	5,000	34.5	0.512	0.551	0.580
Thermocomp EF-1008	5,000	34.5	0.275	0.299	0.315
	10,000	69.0	0.554	0.599	0.631
Thermocomp FF-1004	5,000	34.5	0.796	0.894	0.936
Thermocomp GC-1006	2,500	17.2	0.098	0.112	0.126
	5,000	34.5	0.224	0.239	0.250
Thermocomp GF-1006	5,000	34.5	0.362	0.439	0.453
Thermocomp GF-1008	5,000	34.5	0.290	0.340	0.340
	10,000	69.0	0.590	0.670	0.680
Thermocomp KF-1006	1,250	8.6	0.159	0.182	0.190
	2,500	17.2	0.278	0.320	0.337
	5,000	34.5	0.546	0.629	0.670
Thermocomp KF-1008	5,000	34.5	0.380	0.480	0.520
	10,000	69.0	0.640	0.800	0.860

Table 1 continued flexural creep of fiber reinforced thermoplastics (at 73°F/23°C)

Compound	Stress (psi)	(MPa)	Total strain (%)		
			10 hrs.	100 hrs.	1000 hrs.
Thermocomp* MF-1006 FR	2,500	17.2	0.368	0.496	0.556
Thermocomp OC-1006	2,500	17.2	0.070	0.078	0.084
	5,000	34.5	0.168	0.170	0.170
Thermocomp OF-1006	2,500	17.2	0.190	0.190	0.190
	5,000	34.5	0.350	0.350	0.350
Thermocomp PC-1006	2,500	17.2	0.221	0.235	0.245
	5,000	34.5	0.443	0.467	0.485
Thermocomp PF-1006 FR	2,500	17.2	0.380	0.448	0.448
	5,000	34.5	0.768	0.896	0.920
Thermocomp QF-1006 FR	2,500	17.2	0.370	0.440	0.440
	5,000	34.5	0.744	0.884	0.891
Thermocomp QF-1008	5,000	34.5	0.550	0.640	0.680
	10,000	69.0	1.320	1.450	1.490
Thermocomp QF-100-12	5,000	34.5	0.280	0.340	0.360
Lubricomp* QFL-4036	2,500	17.2	0.265	0.456	0.480
Thermocomp RC-1006	2,500	17.2	0.140	0.168	0.194
	5,000	34.5	0.334	0.376	0.390
Thermocomp RC-1008	2,500	17.2	0.112	0.133	0.140
	5,000	34.5	0.240	0.254	0.257
Thermocomp RF-1006 FR	2,500	17.2	0.398	0.544	0.548
	5,000	34.5	0.684	0.800	0.824
Thermocomp RF-100-12	5,000	34.5	0.250	0.320	0.350
	10,000	69.0	0.560	0.630	0.640
Stat-Kon* RF15	2,500	17.2	2.160	2.400	2.510
Thermocomp VF-1006	1,250	8.6	0.270	0.290	0.330
	2,500	17.2	0.482	0.534	0.679
	5,000	34.5	1.369	1.719	2.018
Thermocomp WC-1006	2,500	17.2	0.084	0.110	0.112
	5,000	34.5	0.196	0.224	0.243
Thermocomp WF-1006	2,500	17.2	0.210	0.241	0.252
	5,000	34.5	0.416	0.478	0.502
Thermocomp XF-1006	2,500	17.2	0.248	0.275	0.324
	5,000	34.5	0.640	0.678	0.757
Thermocomp ZF-1006	2,500	17.2	0.255	0.277	0.314
	5,000	34.5	0.518	0.548	0.625

Table 2 tensile creep of fiber reinforced thermoplastics (ASTM D2990)

Compound	Temperature		Stress		Total strain (%)				Creep strain (%)
	°F	°C	psi	MPa	0.10 hrs.	1.0 hrs.	10 hrs.	100 hrs.	After 100 hrs.
Verton* MFX-700-10	73	23	3,000	20.7	0.170	0.183	0.203	0.238	0.068
	73	23	5,000	34.5	0.305	0.343	0.450	0.469	0.164
	73	23	7,500	51.7	0.568	0.713	0.840	0.988	0.420
	158	70	2,000	13.8	0.178	0.193	0.225	0.259	0.077
	158	70	4,000	27.6	0.553	0.653	0.835	1.140	0.052
Verton RF-7007	73	23	3,000	20.7	0.260	0.270	0.285	0.305	0.045
	73	23	5,000	34.5	0.388	0.408	0.433	0.458	0.070
	73	23	10,000	69.0	1.055	1.145	1.240	1.343	0.288
	158	70	3,000	20.7	0.295	0.308	0.318	0.320	0.025
	158	70	5,000	34.5	0.500	0.528	0.550	0.568	0.068
	158	70	10,000	69.0	1.198	1.278	1.338	1.375	0.177
	248	120	3,000	20.7	0.325	0.345	0.355	0.368	0.043
	248	120	5,000	34.5	0.653	0.695	0.730	0.758	0.105
	248	120	7,500	51.7	1.070	1.133	1.168	1.190	0.120
	248	120	10,000	69.0	1.548	1.668	1.735	1.778	0.230
Verton RF-700-10	73	23	5,000	34.5	0.280	0.305	0.335	0.350	0.070
	73	23	7,500	51.7	0.420	0.455	0.485	0.523	0.103
	73	23	10,000	69.0	0.553	0.608	0.648	0.698	0.145
	73	23	12,000	82.8	0.770	0.850	0.908	0.973	0.203
	158	70	3,000	20.7	0.193	0.200	0.208	–	–
	158	70	5,000	34.5	0.343	0.368	0.385	0.395	0.052
	158	70	7,500	51.7	0.588	0.628	0.660	0.665	0.077
	158	70	10,000	69.0	0.850	0.923	0.963	0.980	0.130
	248	120	3,000	20.7	0.233	0.243	0.253	0.260	0.027
	248	120	5,000	34.5	0.400	0.415	0.420	0.435	0.035
	248	70	7,500	51.7	0.680	0.728	0.758	0.773	0.093
	248	70	10,000	69.0	1.025	1.118	1.163	1.190	0.165
Verton RF-700-12	73	23	3,000	20.7	0.105	0.115	0.115	0.127	0.022
	73	23	5,000	34.5	0.190	0.200	0.213	0.230	0.040
	73	23	10,000	69.0	0.485	0.513	0.548	0.586	0.101
	158	70	3,000	20.7	0.185	0.195	0.200	0.215	0.030
	158	70	5,000	34.5	0.243	0.263	0.275	0.288	0.045
	158	70	10,000	69.0	0.603	0.650	0.693	0.715	0.112
	248	120	3,000	20.7	0.213	0.233	0.238	0.243	0.030
	248	120	5,000	34.5	0.340	0.363	0.375	0.378	0.038
	248	120	10,000	69.0	0.720	0.780	0.810	0.837	0.117
Verton UF-700-10	73	23	5,000	34.5	0.185	0.190	0.203	0.213	0.028
	73	23	7,500	51.7	0.290	0.290	0.300	0.310	0.020
	73	23	10,000	69.0	0.370	0.370	0.380	0.405	0.035
	158	70	5,000	34.5	–	0.235	0.255	0.270	–
	158	70	7,500	51.7	0.304	0.355	0.400	0.420	0.080
	158	70	10,000	69.0	0.400	0.410	0.455	0.495	0.095
	248	120	3,000	20.7	–	0.240	0.260	0.275	–
	248	120	5,000	34.5	0.318	0.395	0.458	0.500	0.183
	248	120	7,500	51.7	0.675	0.871	1.040	1.156	0.481
Thermocomp* DF-1006	73	23	3,000	20.7	0.250	0.255	0.258	–	–
	73	23	5,000	34.5	0.443	0.450	0.450	0.475	0.033
	73	23	10,000	69.0	0.080	0.083	0.085	–	–
	158	70	2,000	13.8	0.145	0.150	0.158	0.180	0.035
	158	70	3,000	20.7	0.283	0.295	0.308	0.345	0.062
	158	70	5,000	34.5	0.480	0.510	0.553	0.620	0.140
	248	120	1,000	6.9	0.080	0.105	0.130	0.173	0.093
	248	120	2,000	13.8	0.185	0.228	0.295	0.400	0.215
	248	120	3,000	20.7	–	0.378	0.523	0.698	–
	248	120	5,000	34.5	0.565	0.850	1.265	1.748	1.183
Thermocomp JF-1006	356	180	3,000	20.7	0.325	0.395	0.450	0.535	0.210
	356	180	5,000	34.5	0.500	0.675	0.805	0.910	0.410
Thermocomp LC-1008 EM	248	120	3,000	20.7	0.123	0.128	0.133	0.150	0.027
	248	120	5,000	34.5	0.144	0.145	0.158	0.172	0.028
	248	120	10,000	69.0	0.325	0.358	0.393	0.423	0.098
	392	200	3,000	20.7	0.270	0.295	0.320	0.355	0.085
	392	200	5,000	34.5	0.560	0.635	0.695	0.753	0.193
	392	200	7,500	51.7	1.240	1.350	1.448	1.530	0.290

Table 2 continued, tensile creep of fiber reinforced thermoplastics (ASTM D2990)

Compound	Temperature		Stress		Total strain (%)				Creep strain (%)
	°F	°C	psi	MPa	0.10 hrs.	1.0 hrs.	10 hrs.	100 hrs.	after 100 hrs.
Thermocomp* LF-1006	73	23	3,000	20.7	0.220	0.220	0.225	0.230	0.010
	73	23	5,000	34.5	0.328	0.330	0.338	0.348	0.020
	73	23	10,000	69.0	0.730	0.743	0.755	0.775	0.045
	248	120	3,000	20.7	0.208	0.225	0.243	0.265	0.057
	248	120	5,000	34.5	0.358	0.398	0.435	0.475	0.117
	248	120	10,000	69.0	0.968	1.135	1.270	1.381	0.413
	392	200	2,000	13.8	0.575	0.658	0.723	0.772	0.197
	392	200	3,000	20.7	1.150	1.325	1.450	1.535	0.385
	392	200	4,000	27.6	1.825	2.253	2.465	2.615	0.790
	392	200	5,000	34.5	3.568	4.060	4.520	–	–
Thermocomp OF-100-10	72	23	3,000	20.7	0.118	0.120	0.123	0.123	0.005
	73	23	7,500	51.7	0.275	0.280	0.284	0.293	0.018
	73	23	10,000	69.0	0.431	0.440	0.445	0.460	0.029
	248	120	3,000	20.7	0.260	0.316	0.349	0.375	0.115
	248	120	5,000	34.5	0.460	0.528	0.572	0.600	0.140
	248	120	7,500	51.7	1.132	1.373	1.498	1.573	0.441
	356	180	2,000	13.8	0.223	0.255	0.273	0.286	0.063
	356	180	3,000	20.7	0.770	0.863	0.915	0.945	0.175
	356	180	5,000	34.5	1.073	1.203	1.273	1.320	0.247
Thermocomp RF-100-12	73	23	3,000	20.7	0.150	0.158	0.168	0.175	0.025
	73	23	5,000	34.5	0.193	0.203	0.215	0.230	0.037
	73	23	10,000	69.0	0.420	0.448	0.490	0.528	0.108
	158	70	3,000	20.7	0.168	0.188	0.193	0.203	0.035
	158	70	5,000	34.5	0.328	0.353	0.378	0.403	0.075
	158	70	10,000	69.0	0.785	0.860	0.943	1.015	0.230
	248	120	3,000	20.7	.238	0.253	0.260	0.268	0.030
	248	120	5,000	34.5	.430	0.475	0.500	0.520	0.090
	248	120	7,500	51.7	.655	0.725	0.780	0.818	0.163
	248	120	10,000	69.0	1.328	1.480	1.585	1.628	0.300
Lubricomp* DFL-4036	73	23	2,000	13.8	0.158	0.161	0.163	0.170	0.012
	73	23	3,000	20.7	0.248	0.250	0.255	0.264	0.016
	73	23	5,000	34.5	0.400	0.405	0.420	–	–
	158	70	2,000	13.8	0.145	0.148	0.153	0.171	0.026
	158	70	3,000	20.7	0.245	0.264	0.271	0.301	0.056
	158	70	5,000	34.5	0.415	0.445	0.488	0.539	0.124
	248	120	2,000	13.8	0.150	0.175	0.235	0.339	0.189
	248	120	3,000	20.7	0.258	0.318	0.438	0.614	0.356
	248	120	4,000	27.6	.380	.558	0.810	1.159	0.779
	248	120	5,000	34.5	.680	1.078	1.528	2.078	1.398
Lubricomp OFL-4036	73	23	3,000	20.7	.265	.270	0.273	0.275	0.010
	73	23	5,000	34.5	.290	.295	0.300	0.308	0.018
	73	23	7,500	51.7	.483	.488	0.495	0.505	0.022
	73	23	10,000	69.0	.675	.693	0.715	0.738	0.063
	248	120	3,000	20.7	.410	.500	0.560	0.615	0.205
	248	120	4,000	27.6	.608	.815	0.928	1.010	0.402
	248	120	5,000	34.5	1.103	1.363	1.518	1.618	0.515
	248	120	6,000	41.4	1.360	1.905	2.150	–	–
	302	150	1,000	6.9	.370	.438	0.470	0.493	0.123
	302	150	3,000	20.7	.715	.858	0.913	0.965	0.250
	302	150	4,000	27.6	1.048	1.275	1.413	1.518	0.470
	302	150	5,000	34.5	1.615	1.990	2.188	2.323	0.708
Lubricomp RFL-4036	73	23	3,000	20.7	.258	.288	0.310	0.355	0.097
	73	23	5,000	34.5	.310	.352	0.398	0.462	0.152
	73	23	7,500	51.7	.750	.885	1.003	1.173	0.423
	73	23	10,000	69.0	1.260	1.510	1.770	1.965	0.705
	158	70	3,000	20.7	.468	.510	0.545	0.560	0.092
	158	70	5,000	34.5	.935	1.045	1.115	1.140	0.205
	158	70	7,500	51.7	1.710	1.925	2.060	2.115	0.405
	158	70	8,000	55.2	2.045	2.270	2.430	2.495	0.450
	248	120	1,000	6.9	.153	.170	0.178	0.180	0.027
	248	120	3,000	20.7	.703	.813	0.870	0.935	0.232
	248	120	5,000	34.5	1.328	1.445	1.533	1.598	0.270
	248	120	7,500	51.7	2.465	2.803	3.025	3.163	0.698

Application related issues

Loading and creep performance

The rate of creep strain in a steady state situation (as in secondary creep) is proportional to the applied stress. Figure 1 shows a typical graph of creep versus time for Verton* RF-700-10 structural compound tested at four stress levels.

Although the temperature is the same, clearly the slope (i.e. the creep rate) of the specimen tested at 5000 psi is much lower than that of the 12000 psi specimen. Keep in mind that this rate of creep was determined for a material stressed well below its breaking strength, and was, therefore, not subject to creep rupture.

Temperature and creep performance

The relationship between steady-state creep rate, applied stress and temperature is given below.

$$\varepsilon_{ss} = A\sigma e^{-(B/kT)}$$

where A, B are constants
σ = applied stress
T = temperature
k = Boltzman's constant

As indicated in the equation, the most significant factor affecting creep rate is temperature. This is because the phenomenon of creep is based on diffusion, and diffusion is a heat activated process and increases exponentially with temperature. Therefore, steady state creep rate also varies exponentially with temperature.

Figure 2 shows results from tensile creep testing of Thermocomp* DF-1006 compound at several temperatures but at the same stress level. It is clear that the specimens tested at higher temperatures have progressively increased slopes, indicating a higher creep rate. Thermoplastics also suffer from a higher initial strain due to the decreased modulus at elevated temperatures, evident in the total strain after only 1 hour.

Figure 1

Tensile creep behavior of Verton RF-700-10 structural composite creep strain vs time

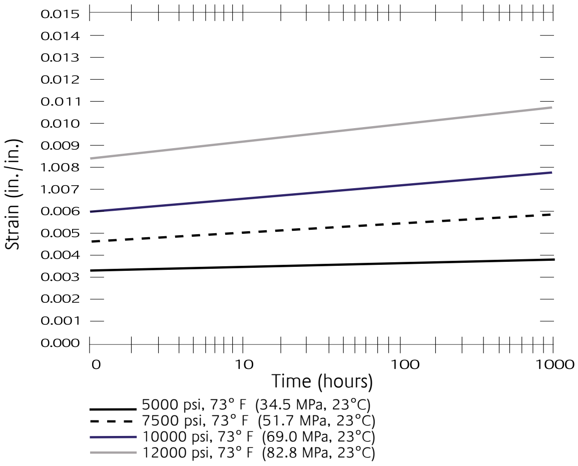
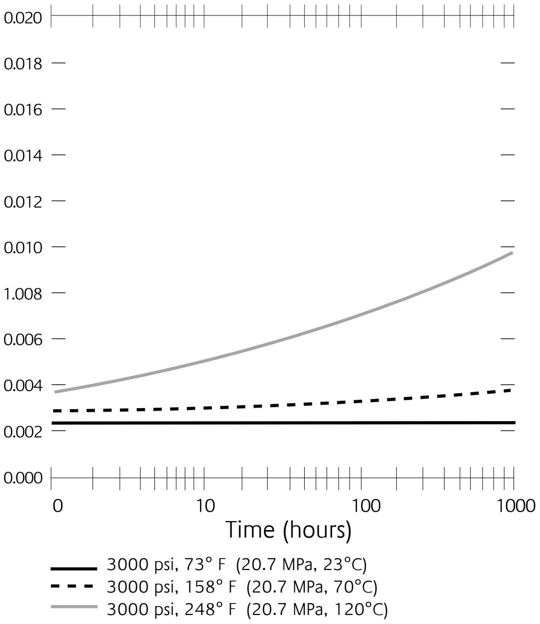


Figure 2

Tensile creep behavior of thermocomp DF-1006 compound creep strain vs time



Humidity and creep performance

Certain materials, particularly those of the nylon family, are classified as hygroscopic. That is, they absorb and retain moisture in proportion to the amount of moisture in their immediate environment. Even at modest humidity levels, such as 50% rh, these materials can absorb as much as 2% moisture by weight. When present in these materials, moisture causes a reduction in the mechanical properties including stiffness and strength. Hygroscopic materials containing moisture have a higher creep rate than the same materials in the “dry-as-molded” state. Therefore, it is very important to test hygroscopic materials which have been moisture conditioned to reflect a realistic application environment. All hygroscopic materials creep tested for this study were conditioned to contain the equilibrium moisture content in a 50% rh, 73°F (23°C) environment.

Intrinsic material characteristics

Fillers and reinforcements

The presence of fiber reinforcement in a thermoplastic material increases its creep resistance significantly, while the effects of different fillers is not as clear. Factors which affect creep resistance of filled/reinforced materials are type of filler/reinforcement and the amount of additive present.

As an example, consider the results from flexural creep testing in nylon 6/6 after 1000 hours. To provide an even basis for comparison of creep rates, it is necessary to subtract the initial (10 hour) strain from the 1000 hour strain. This removes the effect of initial strain, thereby isolating the rate of creep. A neat (unreinforced) nylon 6/6 specimen strains 0.69% at a 1250 psi stress level over a time period of 990 hours. A nylon 6/6 composite containing 30% glass fiber strains only 0.15% (a 78% improvement) under twice the stress. Clearly the presence of glass fiber results in significant improvement in creep performance.

Higher loadings of glass fiber reinforcement provide additional creep performance gains. A 20% glass fiber reinforced polycarbonate strains 0.036% over 990 hours at a stress of 5000 psi. However, a 30% glass fiber reinforced polycarbonate material strains just 0.015% under the same testing conditions. Increasing the glass content to 40% glass fiber shows further improvements, showing a measured strain of 0.01% under identical conditions.

Carbon vs. glass fibers

Although it is clear that carbon fiber increases the tensile strength and stiffness of a material, its effect on creep performance depends on the base resin in which they reside. In all materials tested, the presence of carbon fiber resulted in lower initial strains. A comparison of the change in strain over 990 hours indicates that carbon fiber does not necessarily improve the creep resistance of a material. For example, the difference in measured strain after 990 hours (i.e. creep strain) for 30% glass reinforced polystyrene was 0.026%. The 30% carbon fiber reinforced specimens showed a creep strain of 0.091%, indicating that the composite underwent more creep. In the case of nylon 6/6 and PBT polyester, the carbon fiber versions showed less creep than their glass fiber counterparts. Polycarbonate, however, showed virtually no change. Once again, the effect of glass versus carbon fiber reinforcement on creep is highly dependent on the fiber/base resin compatibility as well as the fiber sizing. It is well documented that sizing of carbon fiber is not as effective as that of glass fiber in providing a strong fiber/resin interface. The result is that the creep performance of a carbon fiber reinforced composite is significantly lower, on a cost basis, than its glass fiber counterpart.

The presence of internal lubricants in reinforced thermoplastics decreases the material‘s creep resistance. For example, adding 15% PTFE to a 30% glass fiber acetal composite increases the creep strain by 10% over a 990-hour period. In the case of nylon 6/6, the addition of 15% PTFE to 30% glass fiber filled composite increases the strain by 40%. The change in a material’s creep performance by the addition of lubricant is highly dependent on the compatibility between the lubricant and base resin and on the mechanical properties of the lubricant itself. In general, the addition of lubricants produces a material with lower properties than the base resin.

Crystallinity and creep resistance

Base on the testing done to date at SABIC Innovative Plastics, there is no evidence that either family of materials provides a clear increase in creep performance over the other. In the specific case of crystalline materials, however, it is generally known that maximizing the crystallinity will improve the creep resistance for that particular material. The decision to employ amorphous or crystalline material should therefore be based on other relevant issues, such as chemical resistance or required tolerances.

Fatigue and thermoplastics

Fatigue is defined as the tendency of a material to fail under repeating stress or deformation. Materials subjected to fatigue stress tend to fail at stresses well below their strength as typically measured in a tensile or flexural strength test. For this reason, it is of great importance that the designers and engineers understand the fatigue behavior of a material prior to using in vibration or repeated stress applications.

Like most metals, thermoplastics can fail in fatigue due to cumulative damage caused by a repeated stress. In this failure mode, cracks grow continuously with each stress cycle until the effective load bearing area is too highly stressed to support the resulting stress. When this occurs, the crack will propagate catastrophically and the component will fail. This type of failure is highly dependent on the stress, material notch sensitivity, material strength, and the number of sites (or defects) from which a crack can initiate.

Unlike metals, thermoplastics have a second failure mode which is due to their viscoelastic nature. A thermoplastic subjected to a loading/unloading cycle at high frequency will generate heat from hysteresis. Because thermoplastics are typically insulative, the heat generated can easily exceed the material's ability to dissipate it. The resulting increase in temperature leads to material softening, diminishing its ability to resist stress. This failure, often referred to as thermal failure, is characterized by excessive deflection resulting in component failure. Thermal failure typically occurs in high loaded, high frequency applications.

Data on fatigue are typically generated by loading and unloading a specimen at a given stress level and measuring the number of cycles which the specimen resists until failure. The mode of stress application can be axial (tensile or compressive) or flexural. In the case of thermoplastics, data are typically generated in flexural fatigue, in accordance with ASTM D671. This test specifies that the specimen is tapered in cross section so that it is subjected to a constant stress along its length. An alternating positive/negative flexural load is then applied at a rate of 1800 cycles per minute (30 Hz). Fatigue data reported in table 3 is tested in compliance with this procedure.

Fatigue data is displayed in graphs of stress versus number of cycles to failure, or “S-n” curves, as in figure 3. These diagrams have a linear scale applied stress as the vertical axis, and a logarithmic scale of number cycles on the horizontal axis. The strength of a material at a given number of cycles is called its fatigue strength. Fatigue strengths are always associated with a number of cycles. For example, the fatigue strength at 1 million cycles for Thermocomp* DC-1006 compound (figure 3) is approximately 10,000 psi. If an “S-n” curve for a material becomes a horizontal line at very high cycles (>10 million), it is said to have an endurance limit. The endurance limit is the stress level below which the material can be subjected to the fatigue load indefinitely. The “S-n” curve shows that Thermocomp LC-1006 compound has an endurance limit of approximately 17,000 psi.

Different test methods, frequencies, and waveforms of loading can significantly affect the results. Some test machines impart a constant stress on the specimen, while others operate under constant deflection (or strain) conditions. It is important to note that data taken from different test methods such as tensile, compressive, or flexural will not necessarily corroborate one another.

Fatigue curves should be used as a relative measure of a material’s resistance to repeated loading. They can also be used to identify if a material has an endurance limit. Because testing conditions are usually much different than end-use conditions, prototype testing is highly recommended for applications involving fatigue loading.

Figure 3

Flexural fatigue behavior of several carbon fiber reinforced thermoplastic compounds

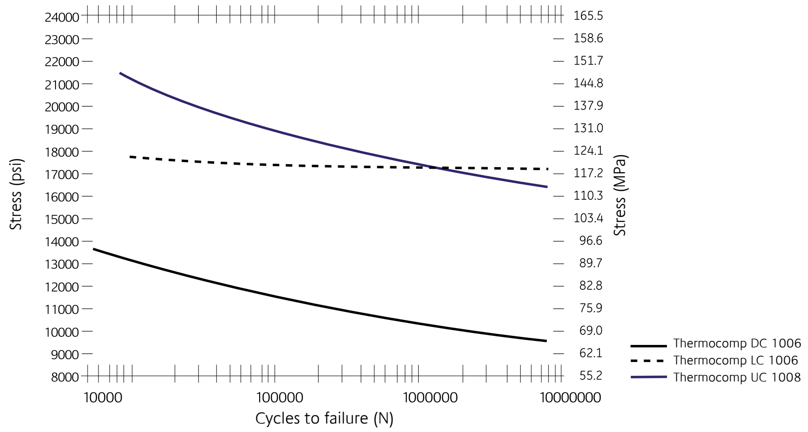


Table 3 fatigue endurance of reinforced thermoplastics (ASTM D671, 1,800 cycles/min)

Compound	Cycles to failure	10^4		10^5		10^6		10^7	
	Stress at failure	psi	MPa	psi	MPa	psi	MPa	psi	MPa
Verton* MFX-700-100		9,700	66.9	8,300	57.2	7,700	53.1	7,500	51.7
Verton RF-7007 HS		–	–	7,810	53.9	6,310	43.5	5.375	37.1
Verton RF-700-10 HS		11,375	78.4	9,875	68.1	8,940	61.7	8,375	57.8
Verton RF-700-12 HS		11,750	81.0	10,250	70.7	9,310	64.2	8,750	60.3
Thermocomp* BF-1006		8,500	58.6	7,500	51.7	6,500	44.8	5,500	37.9
Thermocomp CF-1006		8,000	55.2	7,000	48.3	6,000	41.4	5,000	34.5
Thermocomp CF-1008		9,500	65.5	7,750	53.4	6,500	44.8	5,500	37.9
Thermocomp DC-1003		–	–	7,785	53.7	7,200	49.7	–	–
Thermoomp DC-1006		13,070	90.1	11,390	78.6	10,220	70.5	9,210	63.5
Thermocomp DF-1004		9,000	62.1	6,000	41.4	5,200	35.9	5,000	34.5
Thermocomp DF-1006		12,500	86.2	7,000	48.3	5,500	37.9	5,350	36.9
Thermocomp DF-1008		14,500	100.0	8,750	60.3	6,100	42.1	6,000	41.4
Thermocomp EF-1006		14,070	97.0	11,055	76.2	8,790	60.6	7,030	48.5
Thermocomp GF-1006		14,000	96.5	6,500	44.8	5,000	34.5	4,500	31.0
Thermocomp GF-1008		19,000	131.0	8,500	58.6	7,600	52.4	6,200	42.8
Thermocomp JC-1006		22,000	151.7	10,000	69.0	8,000	55.2	6,700	46.2
Thermocomp JF-1006		16,000	110..3	7,500	51.7	6,000	41.4	5,000	34.5
Thermocomp JF-1008		19,000	131.0	8,500	58.6	7,600	52.4	6,200	42.8
Thermocomp KF-1006		9,000	62.1	7,000	48.3	7,000	48.3	7,000	48.3
Thermocomp LC-1006		18,000	124.1	17,500	120.7	17,500	120.7	17,500	120.7
Thermocomp MF-1006		5,500	37.9	4,500	31.0	4,500	31.0	4,500	31.0
Thermocomp OC-1006		13,000	89.7	9,700	66.9	9,500	65.5	9,500	65.5
Thermocomp PF-1006		7,000	48.3	6,000	41.4	5,750	39.7	5,750	39.7
Thermocomp QF-1006 †		6,800	46.9	5,750	39.7	5,600	38.6	5,500	37.9
Thermocomp QF-1008 †		8,000	55.2	7,000	48.3	7,000	48.3	7,000	48.3
Thermocomp RC-1006 †		13,000	89.7	10.500	72.4	8,000	55.2	8,000	55.2
Thermocomp RC-1008 †		15,000	103.4	10,300	71.0	8,800	60.7	8,500	58.6
Thermocomp RF-1006 †		3,400	23.4	3,200	22.1	3,100	21.4	3,100	21.4
Thermocomp RF-1008 †		8,000	55.2	6,500	44.8	6,000	41.4	5,900	40.7
		9,000	62.1	7,300	50.3	7,000	48.3	7,000	48.3
Thermocomp RF-1008		6,500	44.8	5,900	40.7	5,300	36.6	5,200	35.9
		10,500	72.4	9,300	64.1	9,100	62.8	9,100	62.8
Thermocomp UC-1008		21,280	146.8	18,910	130.4	17,490	120.6	16,545	114.1
Thermocomp WC-1006		13,000	89.7	9,200	63.4	7,400	51.0	6,500	44.8
Thermocomp WF-1006		11,000	75.9	7,200	49.7	5,600	38.6	5,100	35.2
Thermocomp ZF-1006		7,200	49.7	5,800	40.0	4,900	33.8	4,750	32.8
Lubricomp* DAL-4022		–	–	–	–	3,175	21.9	2,250	15.5
Lubricomp DCL-4023		–	–	8,040	55.4	6,525	45.0	5,535	38.2
Lubricomp ECL-4036		–	–	11,390	78.6	8,960	61.8	7,365	50.8
Lubricomp LCL-4033 EM		12,060	83.2	10,300	71.0	9,040	62.3	8,875	61.2
Lubricomp OCL-4036		13,800	95.2	11,575	79.8	10,040	69.2	8,970	61.9
Stat-Kon* DCL-4032 FR		8,025	55.3	6,675	46.0	5,420	37.4	4,475	30.9
Thermocomp RF-10010 HS		10,500	72.4	8,700	60.0	7,800	53.8	7,500	51.7
Verton UF-700-10		17,000	117.2	13,000	89.7	10,300	71.0	9,000	62.1

† Moisture-conditioned to 50% RH.

Loading cycle and fatigue performance

Loading frequently is one variable which has a great effect on results. More heat is generated during high frequency testing because the rate of hysteresis is increased. The result is an increase in thermal failures as described previously. Therefore, data generated at high frequency are a test of the material's heat resistance, as well as its' fatigue resistance.

Some applications have a lower frequency of load cycling with a higher rate of load applications. This type of loading approaches an impact-fatigue situation, and the manner in which the stress is applied greatly affects the material performance. A good example of this situation is the loading present in a nail gun or impact wrench housing. Impact-fatigue loading will generate substantial heat despite relatively low frequencies and static stresses. For this type of application, prototype testing is the best way to insure design success.

Material factors affecting fatigue resistance

Fillers and reinforcements

The use of glass fiber reinforcement for fatigue situations is quite common. Fiber reinforcement adds stiffness and strength to a thermoplastic resin and significantly increases fatigue resistance as well. Reinforced materials perform better in flexural fatigue testing for two reasons. First, stiffer materials generate less heat from hysteresis effects and are therefore not as prone to thermal failure. Secondly, the reinforcement allows higher retention of stiffness and strength at moderately elevated temperatures, preventing excessive deformation and thermal failure. Flexural fatigue strength at 10 million cycles improves 75% for dry-as-molded nylon 6/6 with the addition of 40% short glass fiber. For moisture conditioned nylon 6/6, the addition of 30% short glass fiber improves the flexural fatigue strength by 47% at 10 million cycles.

Carbon fiber, with increased strength and stiffness over glass, is clearly the best reinforcement for fatigue resistance. Typical improvements in 10 million cycles fatigue strengths over glass fiber reinforcement range from 74% improvement for PBT (30% fiber) to a 21% increase for nylon 6/6 (40% fiber). This increased performance may be due to three factors. First, the presence of carbon fiber increases the thermal conductivity of the composite, allowing greater heat dissipation. Secondly, carbon fiber reinforced composites are stiffer and therefore generate less heat due to hysteresis. Finally, carbon fibers have a lower specific gravity than glass fibers. This means that a carbon fiber composite will contain a larger volume percentage of fiber than a glass fiber composite with the same weight percentage of fiber.

In fatigue intensive situations, the materials which perform the best are typically high temperature base resins reinforced with carbon fiber. Materials such as polyetheretherketone, polyethersulfone, polyetherimide and polysulfone offer good fatigue performance, but at a premium price. Polyphthalamide-based materials with long fiber reinforcement approach the performance of these high temperature resins at a significantly lower cost. For applications where fatigue performance is not the most critical issue, several glass fiber reinforced engineering thermoplastics will suffice. The fatigue performance of these can be matched by some highly loaded long glass fiber reinforced commodity resins. For example, Verton* MFX-700-10 HS structural composite, a 50% long glass fiber reinforced polypropylene, matches the fatigue performance of 30% short glass reinforced nylon and polycarbonate at cost and weight savings.

Moisture and fatigue resistance

The presence of moisture in hygroscopic materials has a negative effect on fatigue performance. The stiffness of the material is generally decreased with moisture content, as is the strength. In addition, hysteresis heating is increased due to decreased stiffness, and possibly due to the presence of water within the composite. Due to this decreased performance, it is important to test specimens which have been conditioned to reflect the moisture content of the application environment.

Crystallinity and fatigue resistance

As in creep resistance, it was once believed that crystalline materials performed better in flexural fatigue situations than did most amorphous materials. Data collected to date suggest that no rule of thumb holds true. The differences that exist reflect the different properties of the individual base resins.

Stress relaxation is the gradual decrease in stress in a component subjected to a constant deflection. Stress relaxation occurs in a wide variety of applications, although it is rarely directly addressed in design until problems arise. These problems may appear as a loss in torque, temperature, preload (initial stress) and humidity, which all affect the rate at which a reinforced thermoplastic will stress relax. Reinforcement and base resin are factors which will affect stress relaxation behavior in the same manner as creep behavior, although the magnitude of the effect may be different.

The stress relaxation data presented in this brochure were generated by subjecting tensile bars to a tensile stress of 2500 psi and holding the bars under constant strain while monitoring the decrease in applied load over 15 hours. It is important to note that different materials show different initial strain levels under the same stress levels. This is due to differences in their elastic modulus.

Because stress relaxation is a diffusion-activated process, temperature has a dramatic effect on performance. At elevated temperatures, stresses relaxed more quickly and showed a higher decrease in retained stress at equilibrium. For example, a 30% glass PES reduced its stresses only 7% after 1 hour at 73°F (23°C), and relaxed 9% after 15 hours. At a temperature of 300°F (149°C) the same material relaxed 33% after 1 hour and showed a stress reduction of 39% after 15 hours. Stress relaxation data presented in table 4 indicate similar trends in other materials at elevated temperature.

Table 4 Tensile stress relaxation of thermoplastic composites at elevated temperatures

Decrease in applied stress (%) with time[a] temperature							
Compound	73°F/23°C	200°F/93°C	300°F/149°C	350°F/177°C	400°F/204°C	450°F/232°C	500°F/260°C
Thermocomp* JF-1006	7/8/9	20/21/25	33/35/39	35/40/57	61/74/90	X/X/X	X/X/X
Thermocomp EF-1006	7/9/11	13/16/25	34/39/55	34/39/55	58/69/86	X/X/X	X/X/X
Thermocomp OF-1006	3/5/9	20/21/22	26/28/32	26/28/32	26/33/40	X/X/X	X/X/X
Thermocomp LF-1006	13/14/16	17/21/23	28/32/35	28/32/35	30/33/40	32/38/40	32/38/41

[a] Three values indicate percent stress relaxation for 1h, 5h, and 15h. Example 7/8/9 indicates 7% at 1h, 8% at 5h, and 9% at 15h.
X indicates sample would not sustain the test load. Initial stress for all tests was 2,500 psi.

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