10 High Temperature Polymers

This chapter contains information and multipoint properties for several high temperature, high-performance plastics. They might be classified or been appropriate to include in another chapter, but they are grouped in this chapter because of their performance levels.

10.1 Polyketones (PAEK)

Polyketones (or chemically accurate polyaryletherketones (PAEK)) are a family of semicrystalline thermoplastics with high temperature stability and high mechanical strength. Some of the commercial plastics that fall within this family include those listed with their structures in Table 10.1.

The good strength of the semicrystalline aromatic polymers is maintained even at high temperatures. In addition, PAEK materials show very good impact strength at low temperatures, high mechanical fatigue strength, a very low tendency to creep as well as good sliding and wear properties. The chemical resistance is also very good. Due to their unusual characteristics, PAEK are used for particularly demanding applications:

- High mechanical strength, even at high temperatures
- Very good impact strength
- Low tendency to creep
- Good chemical resistance
- Good sliding and wear properties
- Low moisture absorption
- Very good dielectric strength, volume resistivity, tracking resistance
- Good radiation resistance
- Poor resistance to weathering

Manufacturers and trade names: *PEEK*: Victrex Victrex® and APTIV®, Greene, Tweed & Co. Arlon®, Solvay Advanced Polymers GATONE™ and KetaSpire®; *PEKK*: Polymics Arylmax® K, Arkema Kepstan®; *PEKEEK*: Victrex Victrex® ST; *PEK*: Victrex Victrex® HT; *PAEK* (unspecified): Solvay Advanced Polymers Avaspire®, Polymics Arylmax® P.

Applications and uses: medical implants, sealing rings, bearings, piston parts, pumps, high pressure liquid chromatography (HPLC) columns, compressor plate valves, and cable insulation.

The various PAEK types are discussed in separate sections.

10.1.1 Polyether Ether Ketones (PEEK)

The data for PEEK-based plastics are given in Tables 10.2–10.5 and shown in Figures 10.1–10.31.

The following Solvay Advanced Polymers products are referred to in this section's figures and tables:

- KetaSpire® KT-820 NT—Low melt flow for extrusion and injection molding
- KetaSpire® KT-880 NT—High melt flow for injection molding
- KetaSpire® KT-820 GF30—Low melt flow, 30% glass fiber
- KetaSpire® KT-880 GF30—High melt flow, 30% glass fiber
- KetaSpire® KT-820 CF30—Low melt flow, 30% carbon fiber
- KetaSpire® KT-880 CF30—High melt flow, 30% carbon fiber
- KetaSpire® KT-820 SL10—Reduced friction coefficient grade
- KetaSpire® KT-820 SL30—Very good wear resistance, dry and lubricated
- KetaSpire® KT-880 FW30—High melt flow, very good wear resistance, dry and lubricated

McKeen: The Effect of Temperature and other Factors on Plastics and Elastomers.
DOI: http://dx.doi.org/10.1016/B978-0-323-31016-1.00010-6

Table 10.1 The Structures of Several Commercial Polyketone Polymers

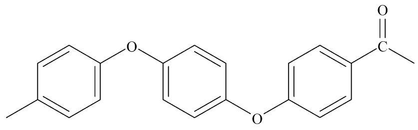
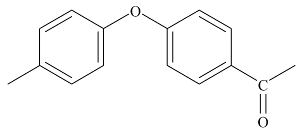
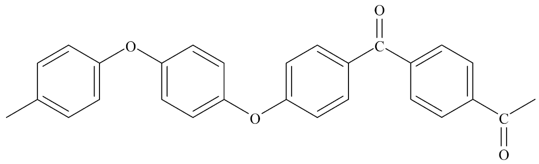
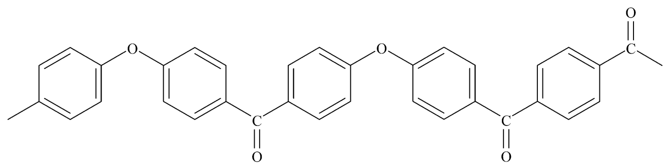
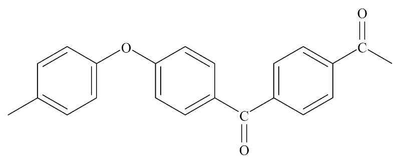
Polymer (Abbreviation)	Approximate T_g/T_m (°C)	Structure
Polyether ether ketone (PEEK)	151/338	
Polyether ketone (PEK)	160/372	
Polyether ether ketone ketone (PEEKK)	160/360	
Polyether ketone ether ketone ketone (PEKEKK)	165/384	
Polyether ketone ketone (PEKK)	156/338	

Table 10.2 Compressive Yield Strength of Solvay KetaSpire® PEEK at Several Temperatures [1]

Grade	23°C	100°C	150°C	200°C
KT-820 NT 123	83.5	63.5	23.8	
KT-820 GF30 BG20	168	120	80.2	36.6
KT-820 CF30	170	124	83.9	44.4
KT-820 SL10	114	76.1	55.0	22.3
KT-820 SL30	112	85.0	61.3	32.0
KT-820 SL45	128	100	71.0	39.1

The following Victrex products are referred to in this section's figures and tables:

- Victrex® 150G—Easy flow grade for injection molding of thin sections and complex parts
- Victrex® 450G—General-purpose grade for injection molding and extrusion
- Victrex® 150GL30—Easy flow, 30% glass fiber reinforced for injection molding
- Victrex® 450GL30—General-purpose, 30% glass fiber-reinforced grade for injection molding and extrusion
- Victrex® 150CA30—Easy flow, 30% carbon fiber reinforced for injection molding
- Victrex® 450CA30—Standard viscosity, 30% carbon fiber-reinforced grade for injection molding

Table 10.3 Tensile Properties at Elevated Temperatures of Select Solvay KetaSpire® PEEK Grades [1]

Temperature (°C)	KetaSpire® KT-820 NT	KetaSpire® KT-880 NT	KetaSpire® KT-820 GF30	KetaSpire® KT-880 GF30	KetaSpire® KT-820 CF30	KetaSpire® KT-880 CF30
Tensile strength at yield (MPa)						
23	103	105				
100	69	70				
150	34	39				
200		20				
Tensile strength at break (MPa)						
23	76	69	175	197	209	234
100	48	46	126	147	152	179
150	43	44	77	95	91	112
200	(26	28	44	58	57	68
Tensile modulus (GPa)						
23	3.8	4.0	10.6	11.4	19.0	24.0
100	3.4	2.5	10.1	10.9	18.1	23.4
150	2.5	1.7	8.1	8.6	13.1	16.4
200		0.4				5.4
Tensile elongation at yield (%)						
23	5.0	5.9				
100	3.0	6.7				
150	12.0	14.0				
200		19.0				
Tensile elongation at break (%)						
23	17.0	19.0	3.2	2.8	2.2	1.6
100	52.0	45.0	3.0	2.7	2.6	1.7
150	120.0[a]	120.0[a]	4.4	3.6	4.2	2.5
200	120.0[a]	120.0[a]	8.6	6.0	9.4	4.4

[a] 120.0 = limit of testing machine.

- Victrex® 150FC30—Easy flow, 30% carbon/PTFE grade for injection molding
- Victrex® 450FC30—Standard viscosity, 30% carbon/PTFE grade for injection molding and extrusion
- Victrex® 90HMF40—High-performance thermoplastic material, 40% carbon fiber for injection molding, easy flow, color black

10.1.2 Polyether Ketones (PEK)

The data for PEK-based plastics are shown in Figures 10.32–10.34.

10.1.3 Polyether Ketone Ether Ketone Ketones (PEKEKK)

The data for PEKEKK-based plastics are shown in Figures 10.35 and 10.36.

Table 10.4 Tensile Properties at Elevated Temperatures of Wear-Resistant Solvay KetaSpire® PEEK Grades [1]

Temperature (°C)	KetaSpire® KT-820 SL10	KetaSpire® KT-820 SL30	KetaSpire® KT-820 SL45
Tensile strength at yield (MPa)			
23	91		
100	60		
150	33		
200			
Tensile strength at break (MPa)			
23	77	139	173
100	51	104	130
150	43	66	81
200	25	40	47
Tensile modulus (GPa)			
23	2.7	13.4	22.5
100	2.7	12.5	21.4
150	1.9	9.7	15.7
200	0.3		
Tensile elongation at yield (%)			
23	6.4		
100	4.0		
150	18.0		
200			
Tensile elongation at break (%)			
23	27.0	2.0	1.2
100	52.0	2.2	1.2
150	120.0[a]	4.8	2.1
200	120.0[a]	9.0	4.6

[a] *120.0 = limit of testing machine.*

Table 10.5 Flexural Properties vs. Temperature of Select Solvay KetaSpire® PEEK Grades [1]

Temperature (°C)	Flexural Strength (MPa)		Flexural Modulus (GPa)	
	KT-820 NT	KT-820 GF30 BG20	KT-820 NT	KT-820 GF30 BG20
23	156	268	3.77	10.0
100	112	210	3.44	9.34
150	56	136	2.35	6.60
200	13	61	0.32	2.26

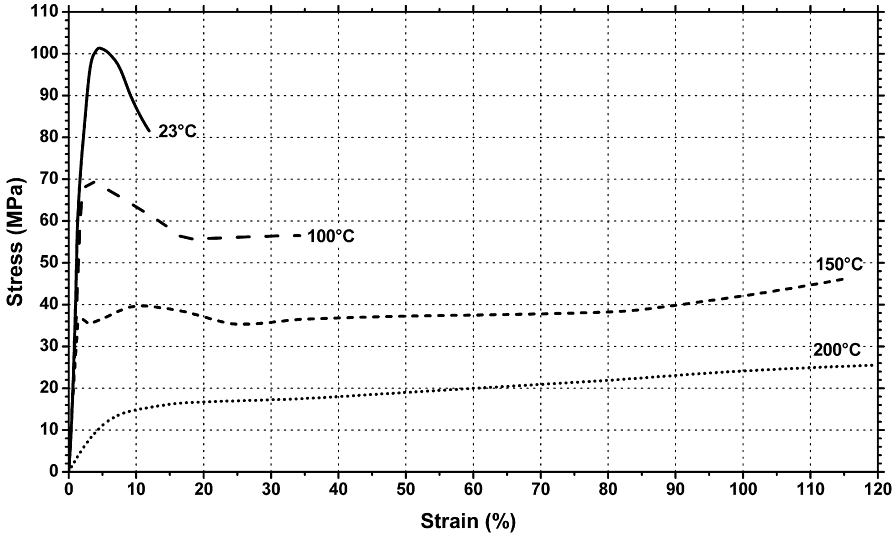


Figure 10.1 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-820 NT—low melt flow for extrusion and injection molding PEEK resin [1].

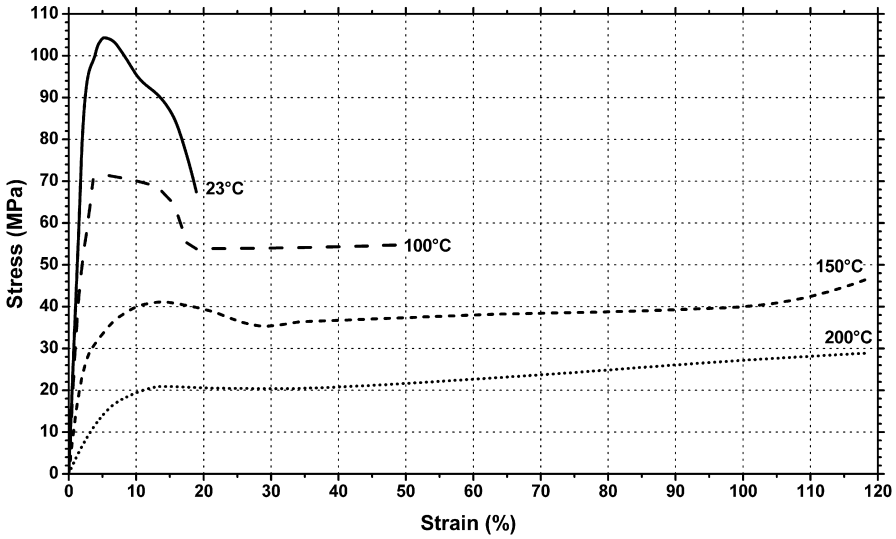


Figure 10.2 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-880 NT—high melt flow for injection molding PEEK resin [1].

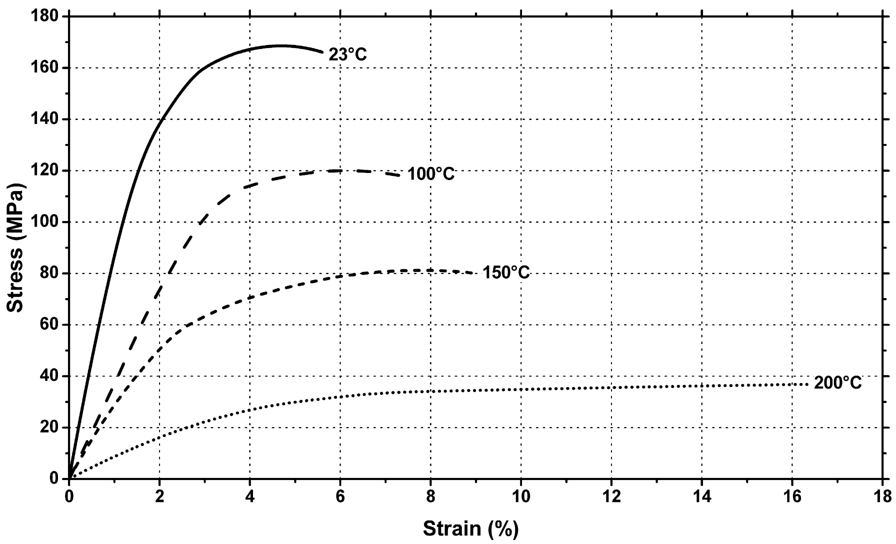


Figure 10.3 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-820 GF30—low melt flow, 30% glass fiber PEEK resin [1].

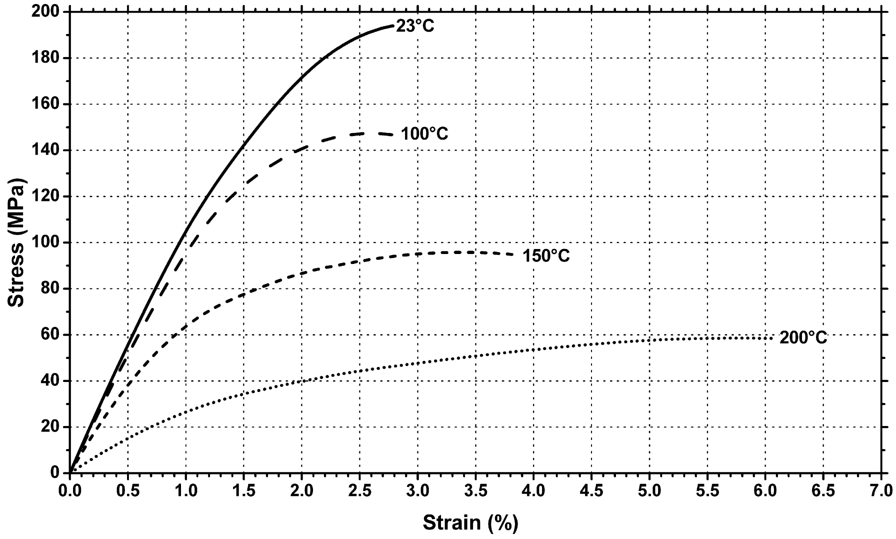


Figure 10.4 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-880 GF30—high melt flow, 30% glass fiber PEEK resin [1].

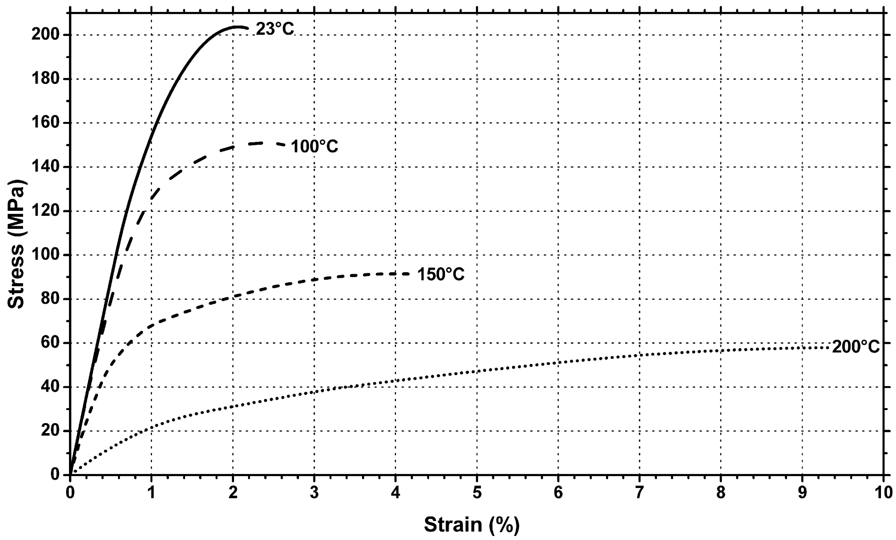


Figure 10.5 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-820 CF30—low melt flow, 30% carbon fiber PEEK resin [1].

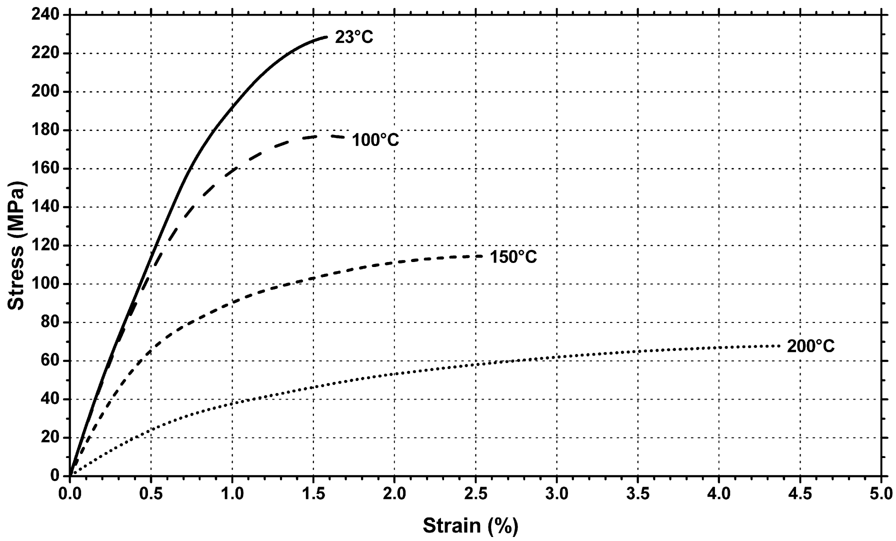


Figure 10.6 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-880 CF30—high melt flow, 30% carbon fiber PEEK resin [1].

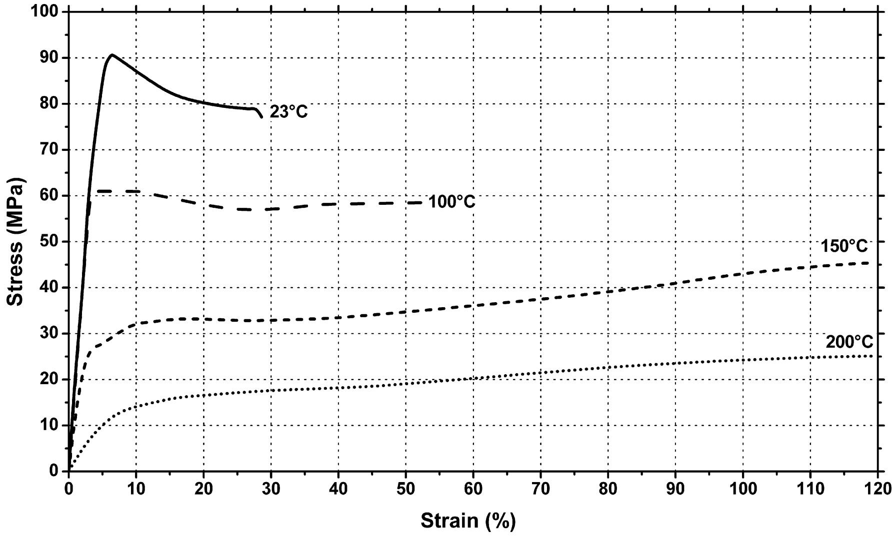


Figure 10.7 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-820 SL10—reduced friction coefficient grade PEEK resin [1].

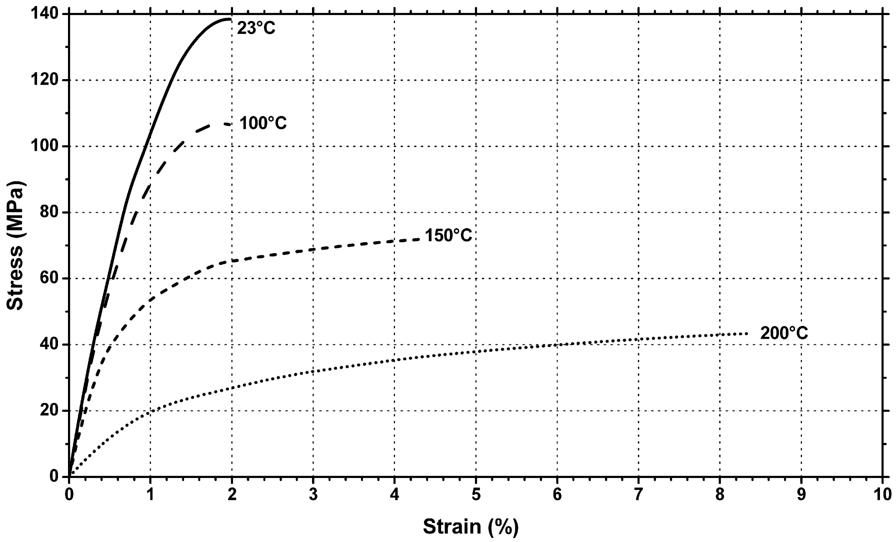


Figure 10.8 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-820 SL30—very good wear resistance, dry and lubricated PEEK resin [1].

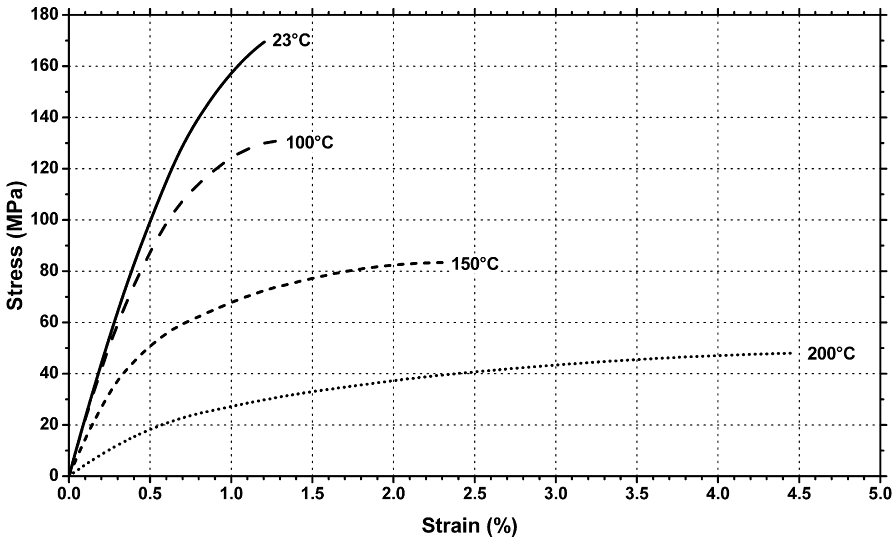


Figure 10.9 Stress vs. strain at various temperatures for Solvay KetaSpire® KT-880 FW30—high melt flow, very good wear resistance, dry and lubricated PEEK resin [1].

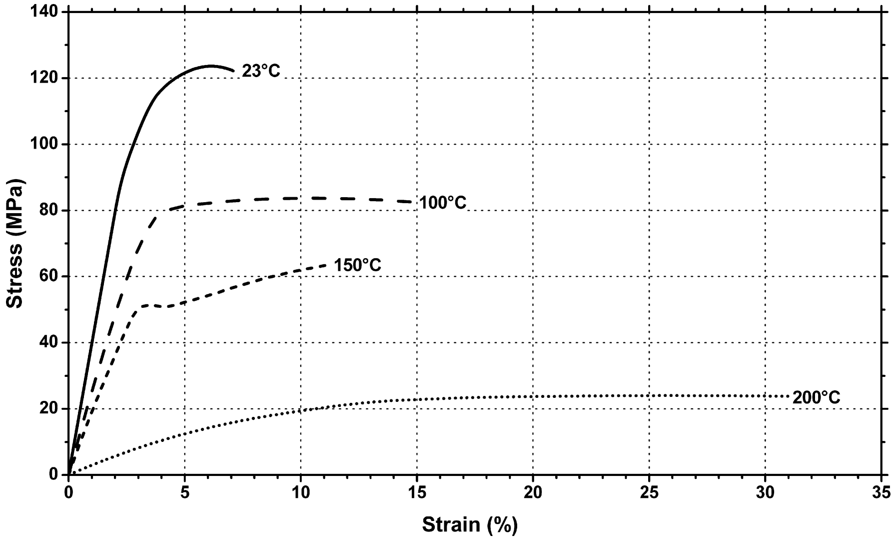


Figure 10.10 Compressive stress vs. strain at various temperatures for Solvay KetaSpire® KT-820 NT [1].

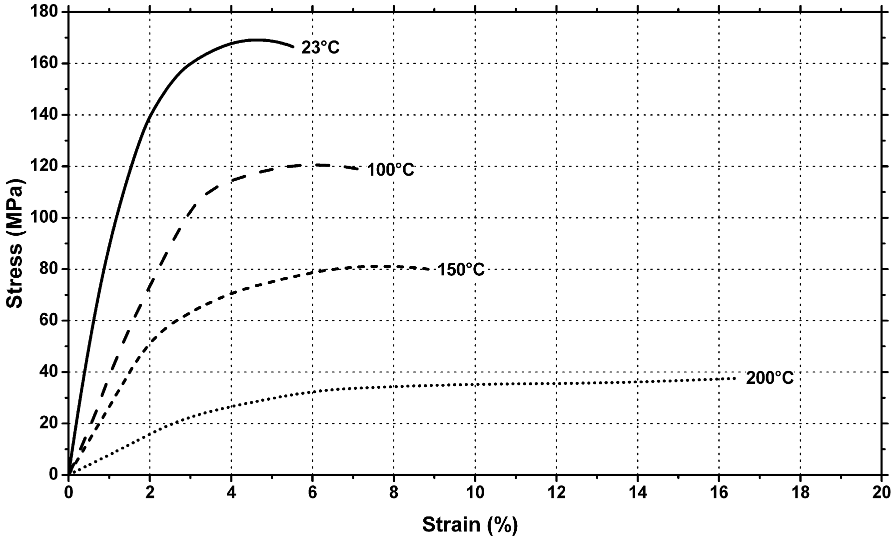


Figure 10.11 Compressive stress vs. strain at various temperatures for Solvay KetaSpire® KT-820 GF30 [1].

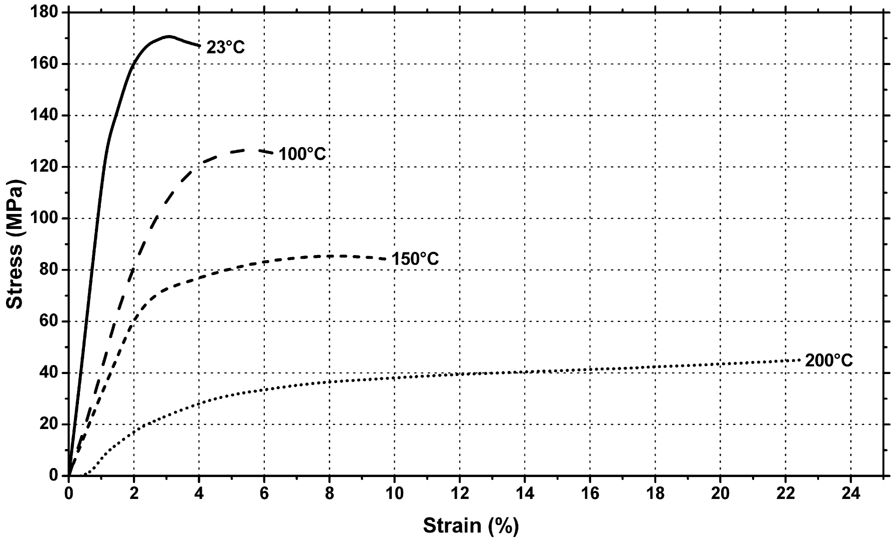


Figure 10.12 Compressive stress vs. strain at various temperatures for Solvay KetaSpire® KT-820 CF30 [1].

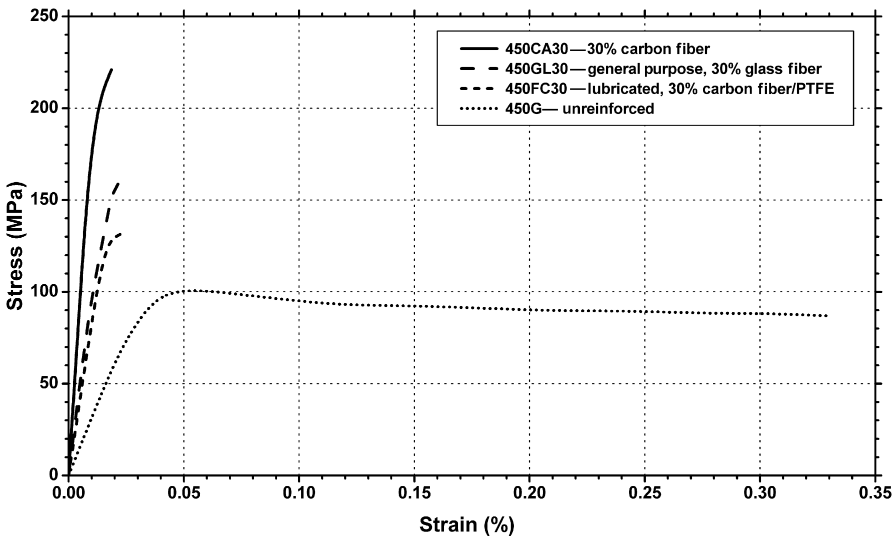


Figure 10.13 Stress vs. strain at 23°C for various Victrex® PEEK resins.

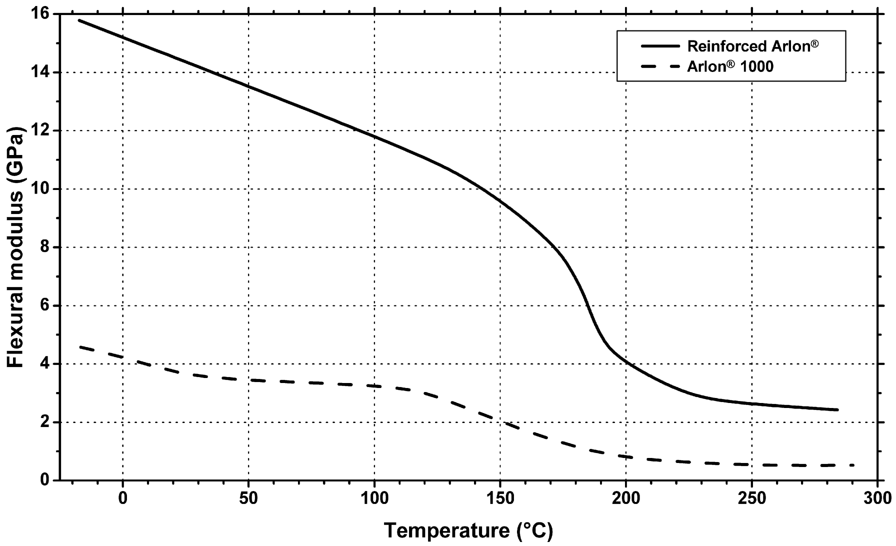


Figure 10.14 Flexural modulus vs. temperature for Greene, Tweed Arlon® PEEK resins.

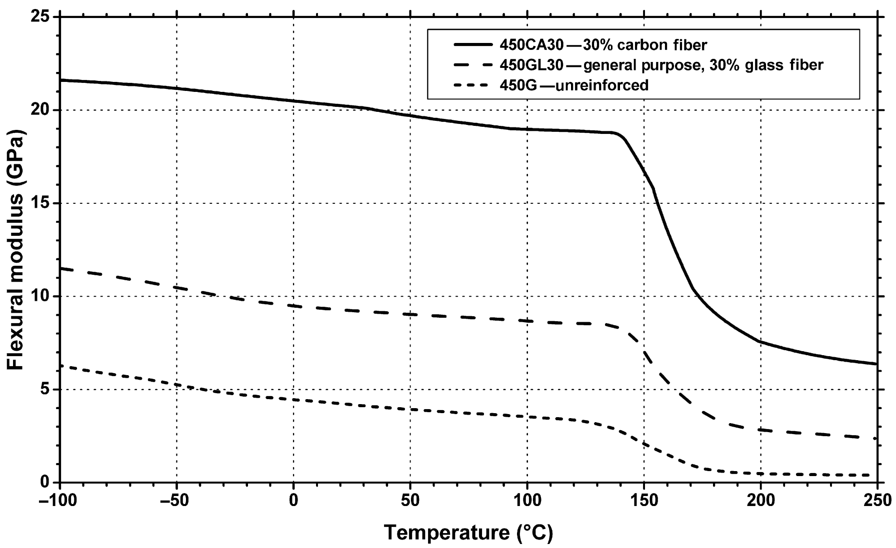


Figure 10.15 Flexural modulus vs. temperature for different fiber-filled Victrex® PEEK resins.

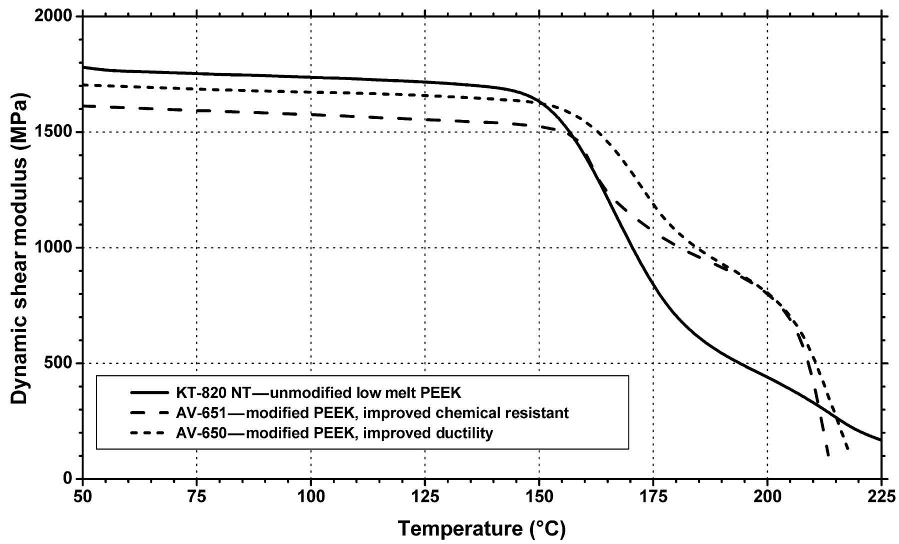


Figure 10.16 Dynamic shear modulus vs. temperature for Solvay KetaSpire® and AviSpire® PEEK resins.

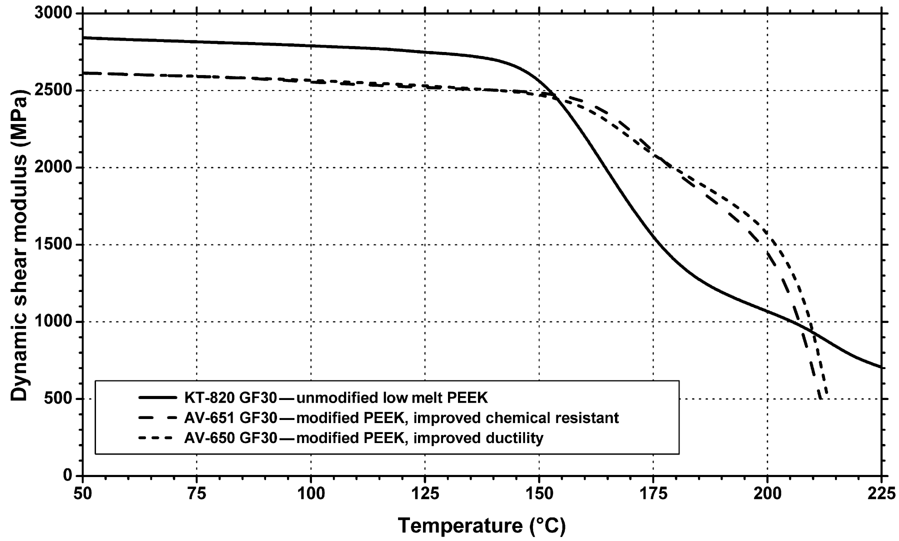


Figure 10.17 Dynamic shear modulus vs. temperature for Solvay KetaSpire® and AviSpire® 30% glass fiber-reinforced PEEK resins.

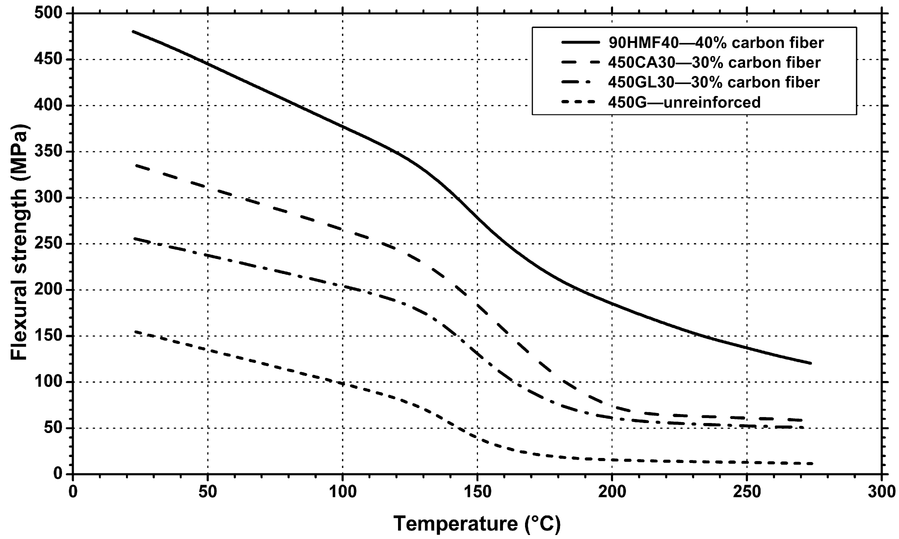


Figure 10.18 Flexural strength vs. temperature for different fiber-filled Victrex® PEEK resins [2].

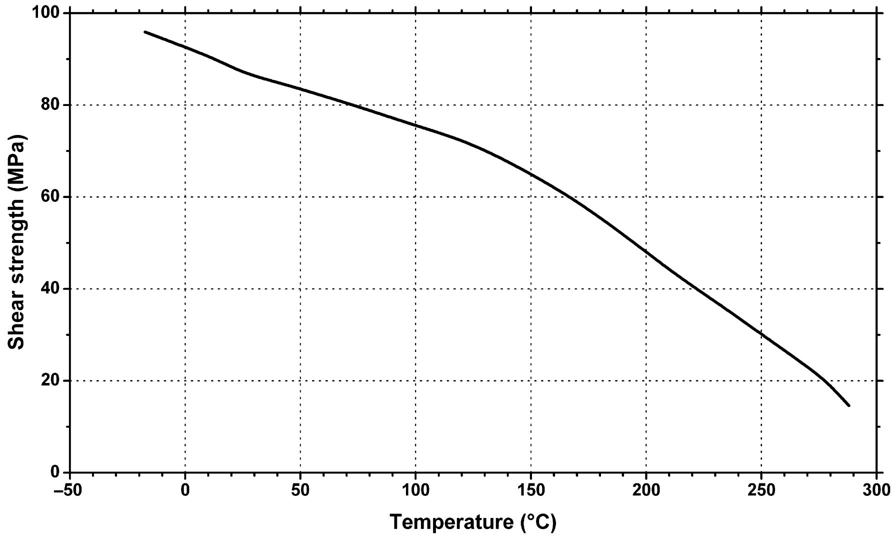


Figure 10.19 Shear strength vs. temperature for Greene, Tweed Arlon® 1000—unreinforced, general-purpose PEEK resin.

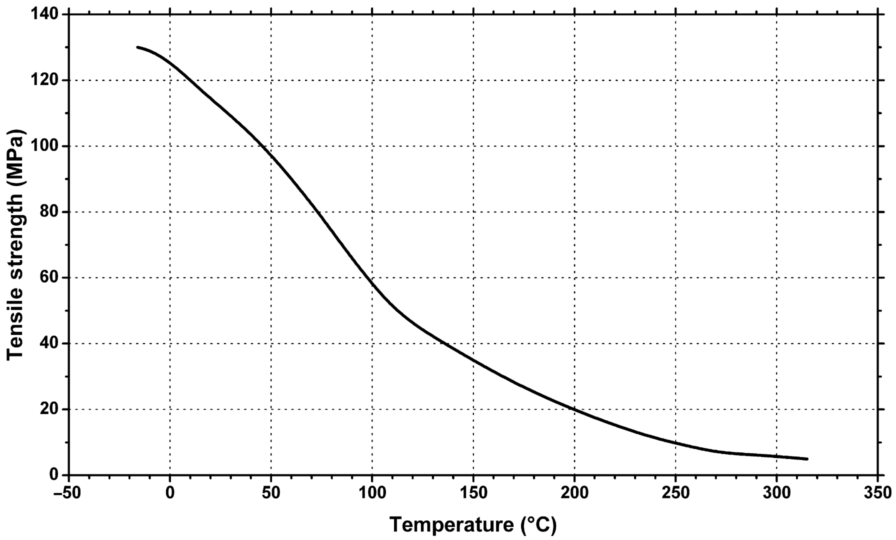


Figure 10.20 Tensile strength vs. temperature for Greene, Tweed Arlon® 1000—unreinforced, general-purpose PEEK resin.

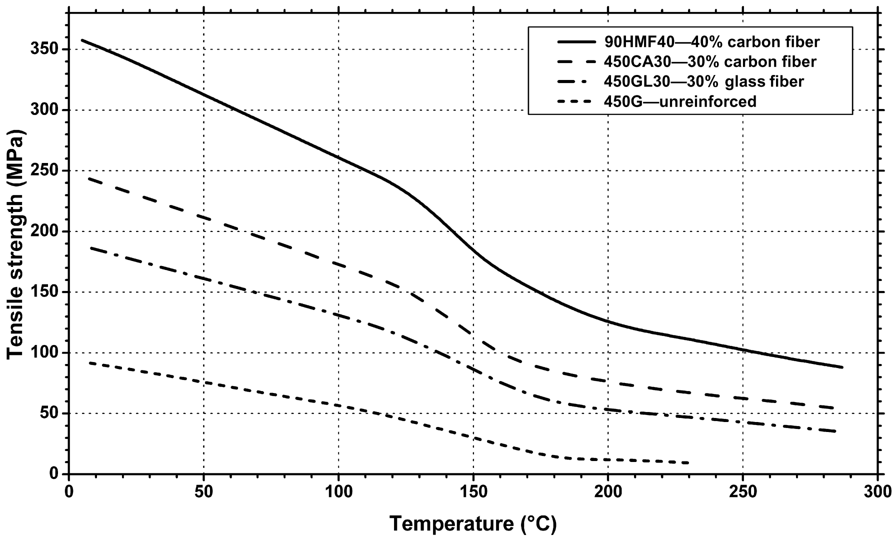


Figure 10.21 Tensile strength vs. temperature for Victrex® PEEK resins [2].

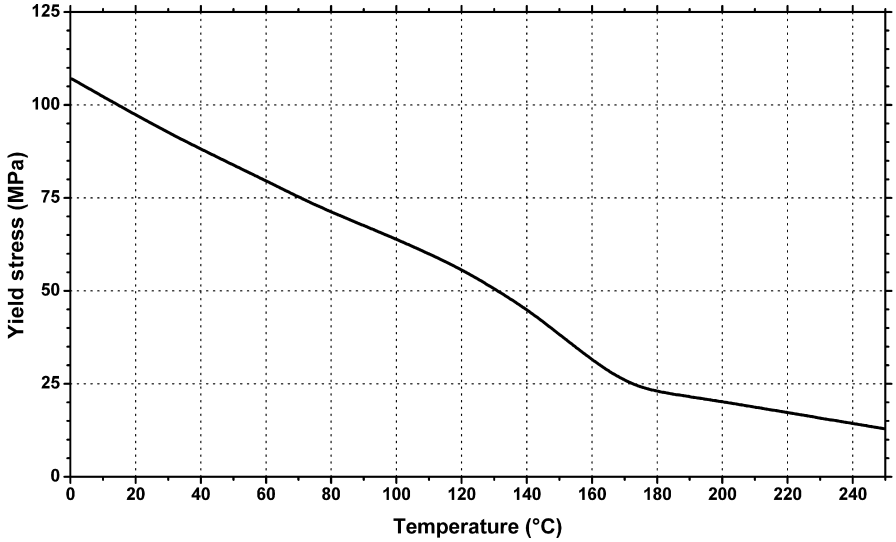


Figure 10.22 Yield stress vs. temperature for Victrex® 450G PEEK resin.

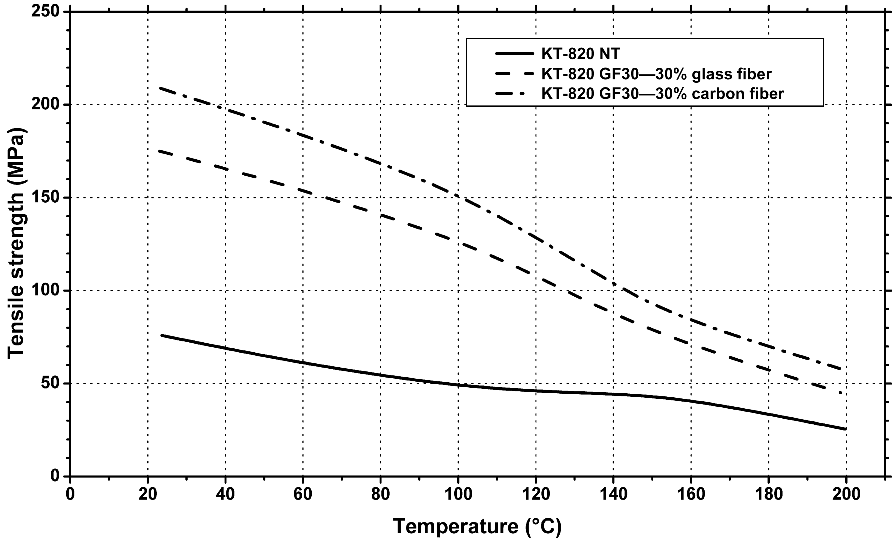


Figure 10.23 Tensile strength vs. temperature for Solvay KetaSpire® KT-820 Series PEEK resins [1].

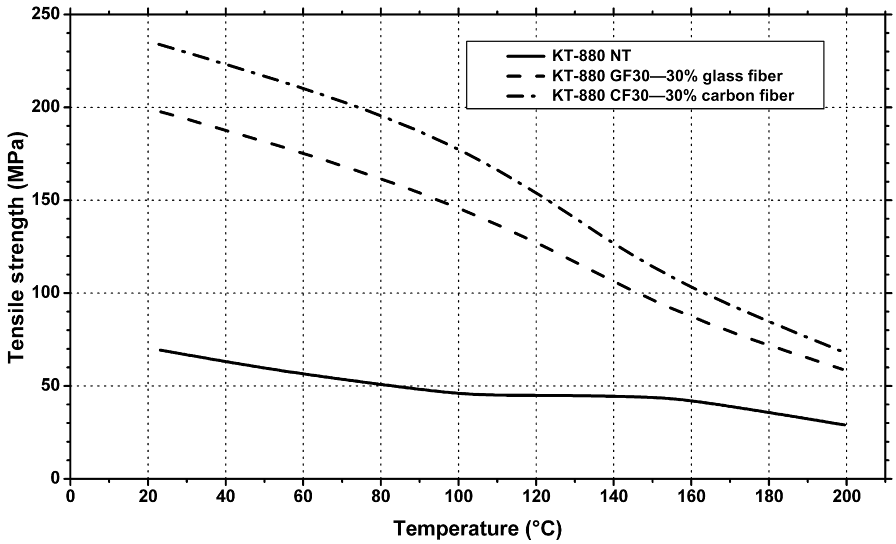


Figure 10.24 Tensile strength vs. temperature for Solvay KetaSpire® KT-880 Series PEEK resins [1].

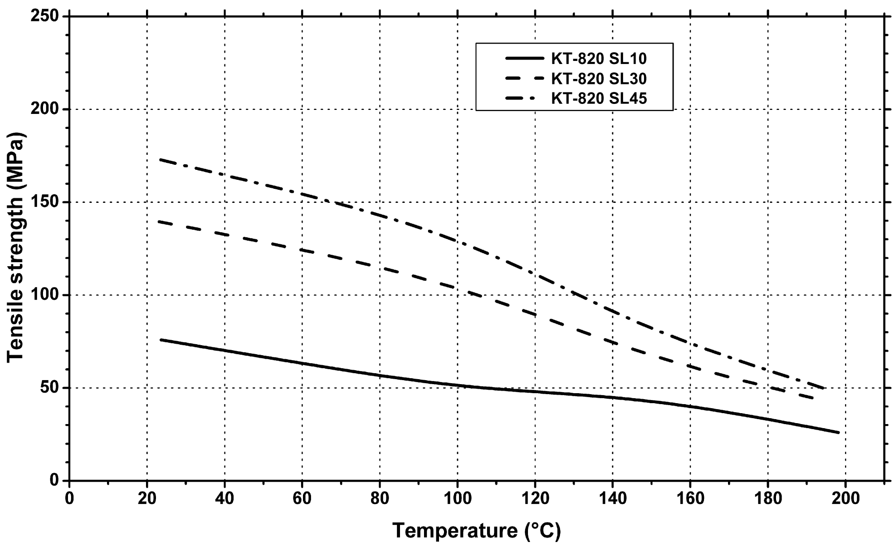


Figure 10.25 Tensile strength vs. temperature for Solvay KetaSpire® KT-820 wear-resistant series PEEK resins [1].

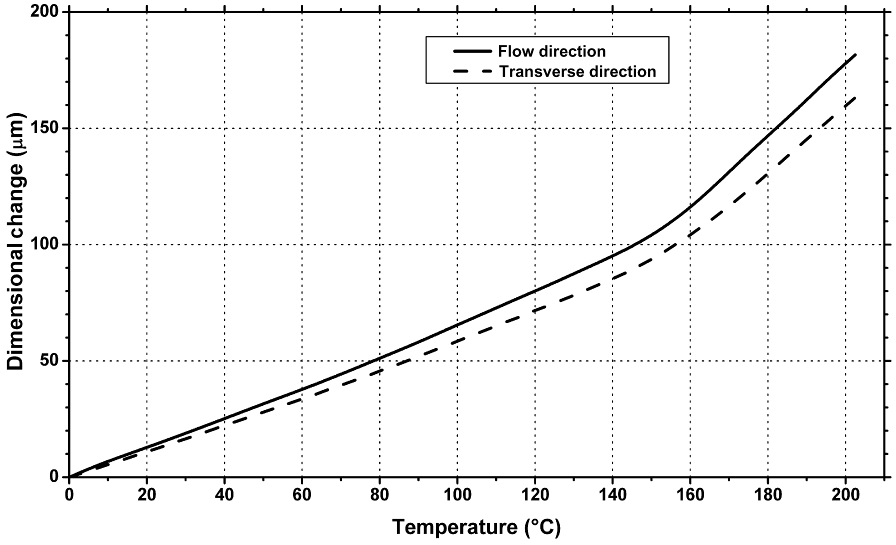


Figure 10.26 Coefficient of linear thermal expansion vs. temperature for Solvay KetaSpire® KT-880 NT PEEK resin [1].

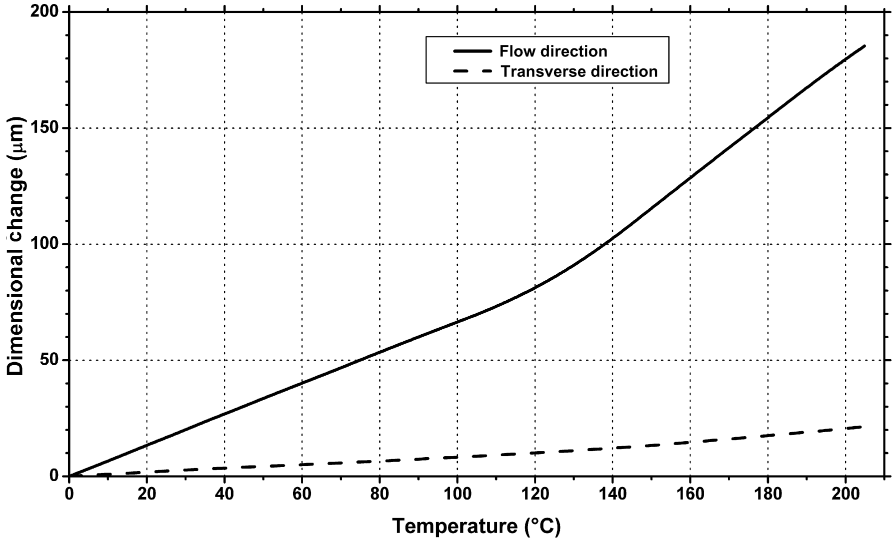


Figure 10.27 Coefficient of linear thermal expansion vs. temperature for Solvay KetaSpire® KT-880 CF30—30% carbon fiber-reinforced PEEK resin [1].

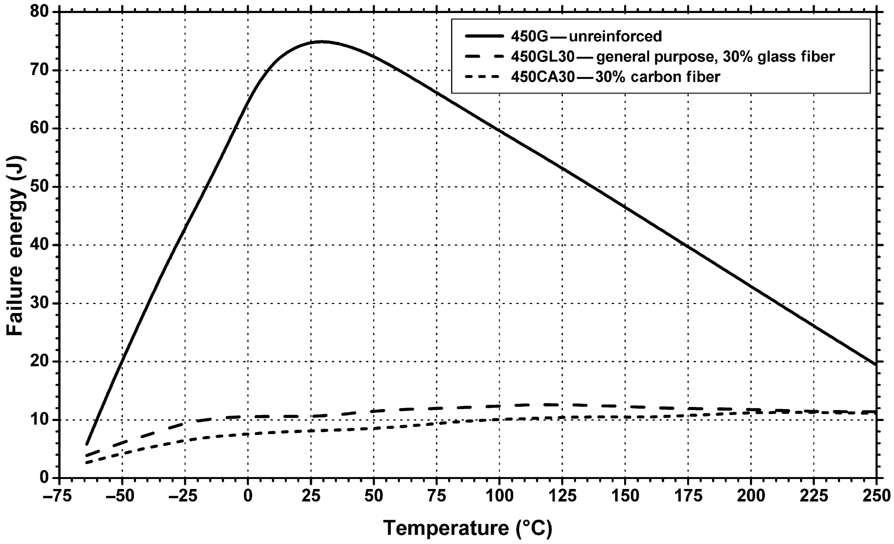


Figure 10.28 Falling weight impact failure energy vs. temperature for Victrex® PEEK resins.

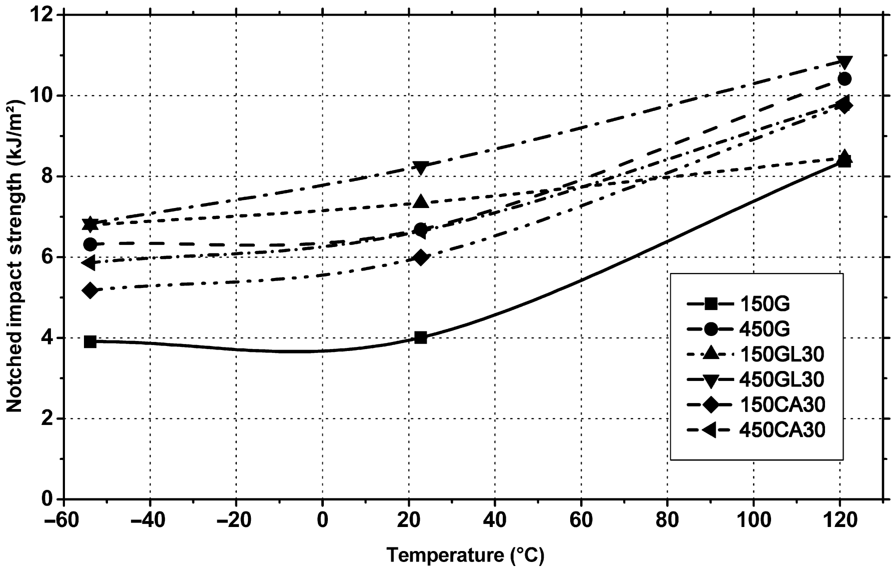


Figure 10.29 Notched Charpy impact strength vs. temperature for Victrex® PEEK resins [2].

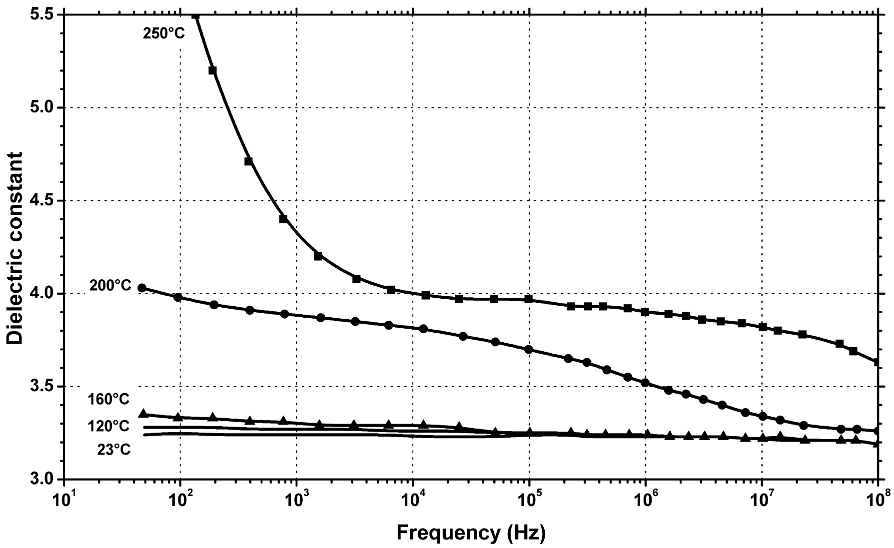


Figure 10.30 Dielectric constant vs. frequency and temperature for Victrex® 450G unreinforced PEEK resin.

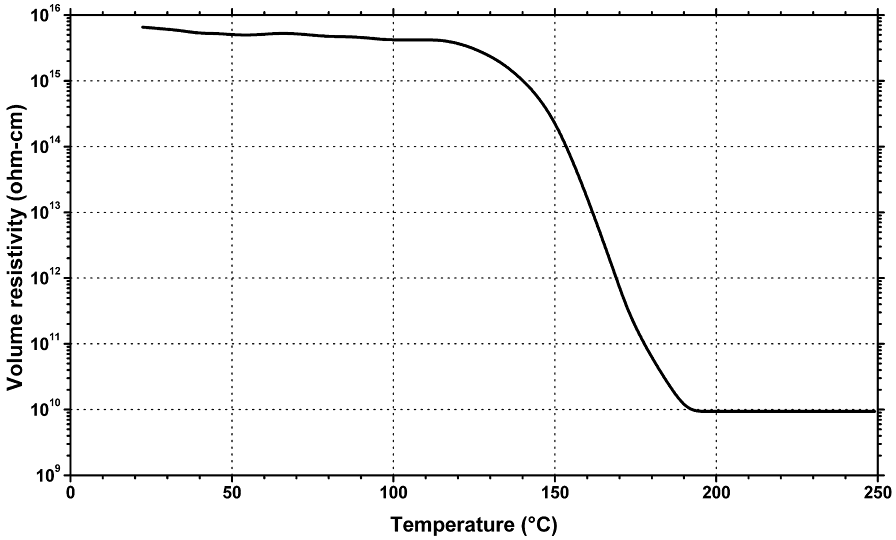


Figure 10.31 Volume resistivity vs. temperature for Victrex® 450G unreinforced PEEK resin.

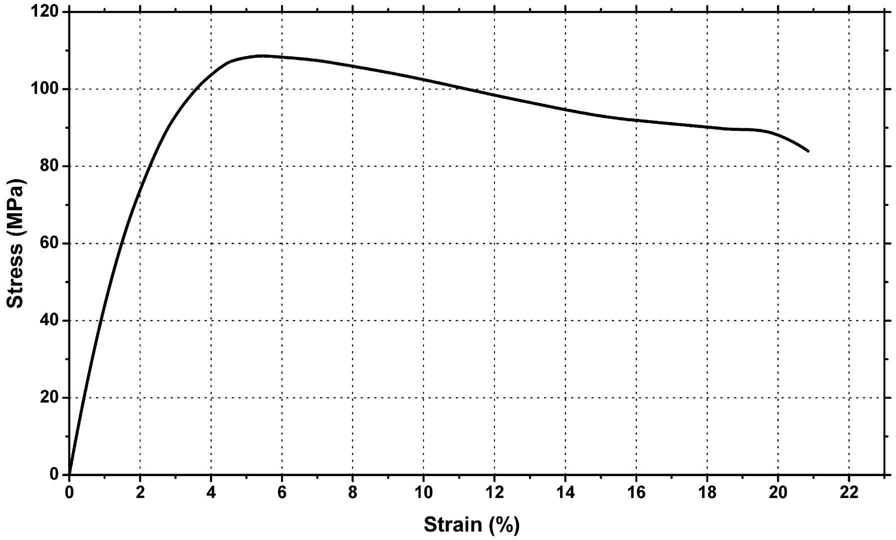


Figure 10.32 Stress vs. strain at room temperature for Victrex® HT G22 PEK resin [2].

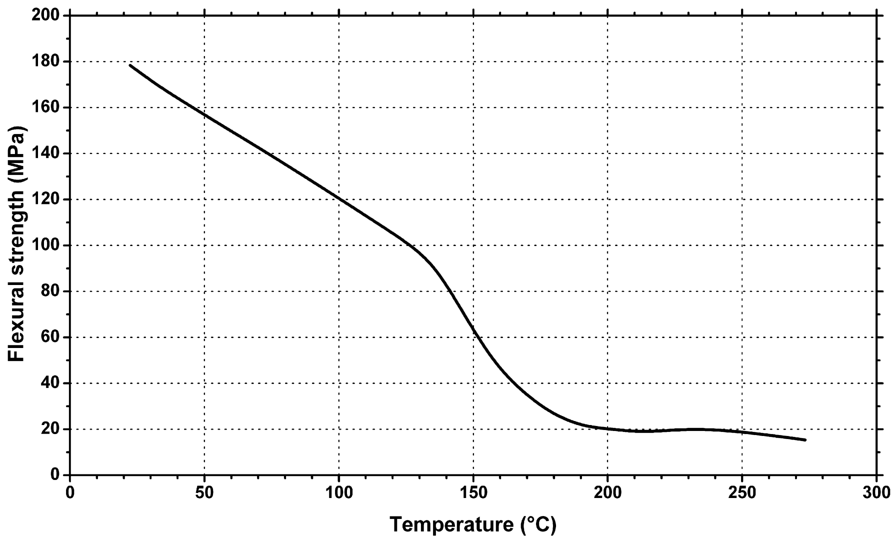


Figure 10.33 Flexural strength vs. temperature for Victrex® HT G22 PEK resin [2].

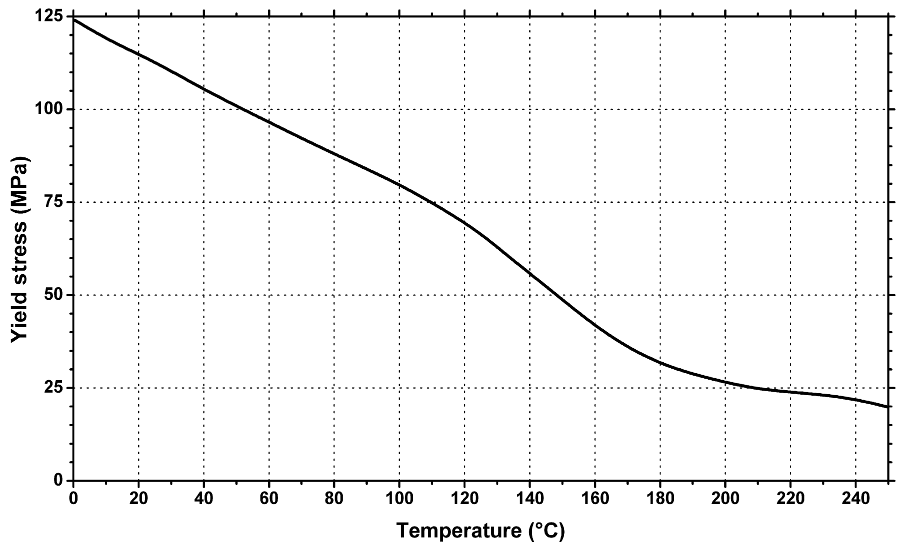


Figure 10.34 Yield stress vs. temperature for Victrex® HT G22 PEK resin [2].

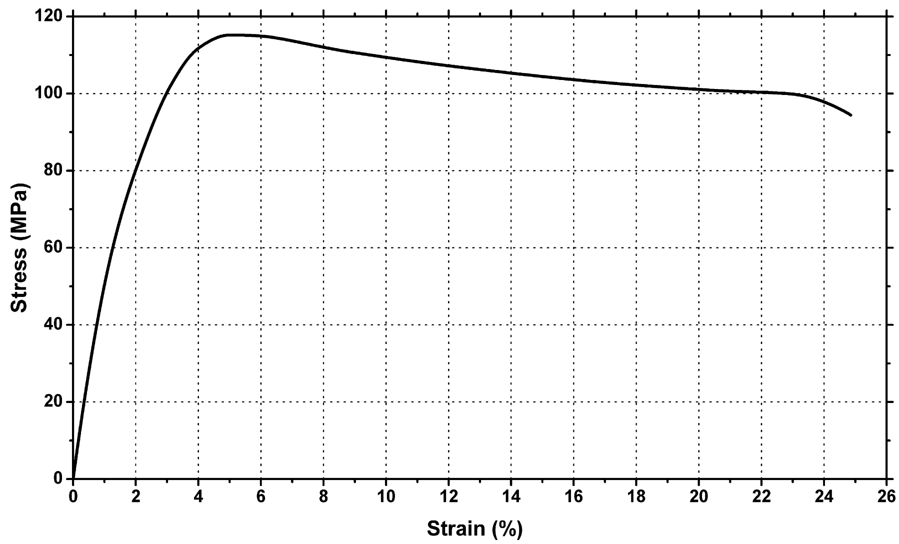


Figure 10.35 Stress vs. strain at room temperature for Victrex® ST G45 PEKEEK resin [2].

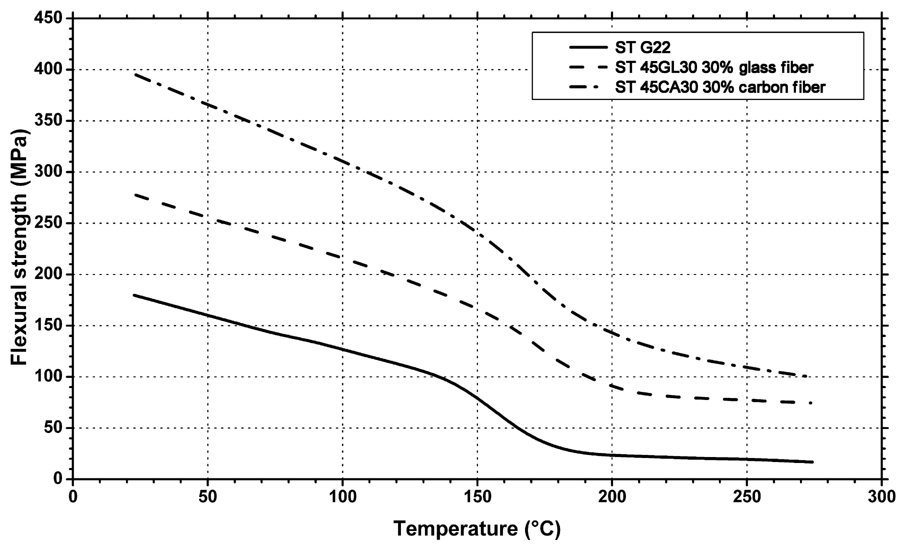


Figure 10.36 Flexural strength vs. temperature for Victrex® ST PEKEEK resin [2].

10.1.4 Polyaryletherketones (PAEK)

The industry classifies some of their products as polyaryletherketones (PAEK) even though PAEK also describes the other polyketone resins. These chemical structures of these resins differ slightly from the other polyketone resins described in this chapter; those structures are generally not disclosed.

The data for PAEK-based plastics are given in Tables 10.6–10.11 and shown in Figures 10.37–10.57.

Solvay Advanced Polymers AvaSpire® products in the following graphs and tables are summarized as follows:

AV-600 Series: Distinctive Performance

Key features:

- Higher stiffness than PEEK from 150°C to 190°C
- Improved ductility and toughness
- Excellent chemical resistance
- UL 94 V0 rating at 0.8 mm
- Excellent esthetics and colorability
- AvaSpire® AV-651—Better ductility and higher heat deflection temperature (HDT) than comparable PEEK, high melt flow for injection molding
- AvaSpire® AV-630—Optimized for ultra-thin film thicknesses down to 5 microns, low melt flow

Table 10.6 Tensile Properties at Elevated Temperature for Unreinforced AvaSpire® PAEK Grades [3]

Temperature (°C)	AvaSpire® AV-621 NT	AvaSpire® AV-651 BG20	AvaSpire® AV-722 BG20	AvaSpire® AV-848 NT
Tensile strength at yield (MPa)				
23	77	88	95	94
100	55	61	58	62
150	25	33	33	
200		14		
Tensile strength at break (MPa)				
23	68	73	85	73
100	59	59	67	49
150	37	40	50	48
200	23	19	26	
Tensile modulus (GPa)				
23	3.0	3.1	4.0	3.1
100	2.6	2.2	2.5	2.9
150	1.6	1.8	1.4	1.4
200	0.6	0.6		1.4
Tensile elongation at yield (%)				
23	6.2	6.4	5.4	7.0
100	4.0	5.0	13	5.8
150	4.0	4.5		5.4
200		14		
Tensile elongation at break (%)				
23	64	93	35	35
100	120[a]	120[a]	91	53
150	120[a]	120[a]	120[a]	70
200	120[a]	120[a]		92

[a] 120 = limit of testing machine

Table 10.7 Tensile Properties at Elevated Temperature for Glass Fiber-Reinforced AvaSpire® PAEK Grades [3]

Temperature (°C)	AvaSpire® AV-621 GF30	AvaSpire® AV-651 GF30 BG20	AvaSpire® AV-750 GF40	AvaSpire® AV-848 GF30
Tensile strength at break (MPa)				
23	160	148	185	171
100	120	111	132	136
150	82	74	74	101
200	41	35	50	67
Tensile modulus (GPa)				
23	10.4	9.9	15.7	11.3
100	9.9	9.1	13.8	10.7
150	9.1	7.7	7.8	9.3
200	3.1	3.6	5.2	4.4
Tensile elongation at break (%)				
23	2.8	2.7	1.7	2.1
100	2.7	2.4	1.8	1.9
150	3.5	3.1	2.9	2.5
200	9.3	6.7	2.8	5.1

Table 10.8 Tensile Properties at Elevated Temperature for Carbon Fiber-Reinforced AvaSpire® PAEK Grades [3]

Temperature (°C)	AvaSpire® AV-621 CF30	AvaSpire® AV-651 CF30	AvaSpire® AV-722 CF30	AvaSpire® AV-848 CF30
Tensile strength at break (MPa)				
23	194	207	201	204
100	146	155	119	152
150	103	105	76	106
200	45	48	54	63
Tensile modulus (GPa)				
23	21.2	21.9	21.6	22.8
100	20.3	21.4	23.5	21.5
150	19.1	18.7	6.7	17.8
200	6.7	6.7	3.2	7.9
Tensile elongation at break (%)				
23	1.6	1.6	1.7	1.4
100	1.6	1.6	1.8	1.2
150	1.6	1.7	2.9	1.4
200	4.1	3.7	2.8	2.8

Table 10.9 Tensile Properties at Elevated Temperature for Wear-Resistant Solvay Advanced Polymers AvaSpire® PAEK Grades [3]

Temperature (°C)	AvaSpire® AV-722 SL30	AvaSpire® AV-742 SL30	AvaSpire® AV-755 SL45
Tensile strength at break (MPa)			
23	152	149	174
100	105	106	137
150	68	69	79
200	40	46	60
Tensile modulus (GPa)			
23	14.7	13.9	34.5
100	12.7	11.7	18.3
150	7.9	6.9	12.8
200	2.4	2.7	6.5
Tensile elongation at break (%)			
23	2.0	1.8	0.9
100	2.7	2.3	2.5
150	5.2	4.5	3.4
200	7.7	6.4	4.6

Table 10.10 Compressive Yield Strength of AvaSpire® PAEK at Various Temperatures [4]

AvaSpire® Grade	Compressive Yield Strength (MPa)			
	23°C	100°C	150°C	200°C
AV-621 NT	102	77.7	55.7	23.9
AV-621 CF30	150	109	79.7	37.8
AV-722 BG20	114	76.6	48.3	18.7
AV-722 CF30	169	124	73.0	42.5
AV-722 SL30	106	75.8	47.9	26.8
AV-742 SL30	121	91.7	59.0	32.8

- AvaSpire® AV-621—Highest performing unreinforced AvaSpire grade, tough, better ductility, and higher HDT than comparable PEEK, low melt flow for extrusion and injection molding
- AvaSpire® AV-650 GF30—30% Glass fiber, better dimensional stability than AV-621, high melt flow for injection molding
- AvaSpire® AV-651 GF30—30% Glass fiber, better chemical resistance than AV-621, high melt flow for injection molding
- AvaSpire® AV-651 CF30—30% Carbon fiber, high melt flow for injection molding
- AvaSpire® AV-621 GF30—30% Glass fiber, low melt flow for extrusion and injection molding
- AvaSpire® AV-621 CF30—30% Carbon fiber, low melt flow for extrusion and injection molding

AV-700 Series: Lower Cost Alternative
Key features:

- Comparable strength and stiffness to PEEK
- Equal or better chemical resistance than PEEK
- Very good friction and wear properties
- Up to 30% lower cost
- AvaSpire® AV-722—Low melt flow for extrusion and injection molding reinforced grades
- AvaSpire® AV-722 CF30—30% Carbon fiber, low melt flow for extrusion and injection molding
- AvaSpire® AV-750 GF40—40% Glass fiber, high melt flow for injection molding wear-resistant grades

Table 10.11 Elevated Temperature Flexural Properties of AvaSpire® PAEK [5]

Grade	Temperature (°C)			
	23	**100**	**150**	**200**
Flexural strength (MPa)				
AV-621 NT	137	110	72	18
AV-621 GF30 BG20	256	205	150	56
Flexural modulus (GPa)				
AV-621 NT	3.28	2.98	2.63	0.58
AV-621 GF30 BG20	8.96	8.40	7.90	2.44

- AvaSpire® AV-722 SL30—Very good wear resistance, dry and lubricated, low melt flow for extrusion and injection molding
- AvaSpire® AV-742 SL30—Very good wear resistance, dry and lubricated, high melt flow for injection molding
- AvaSpire® AV-755 SL45—Very good wear resistance, lubricated, high load bearing, high melt flow for injection molding

10.1.5 Blends

Polybenzimidazole (PBI) is a unique and highly stable linear heterocyclic polymer that is often

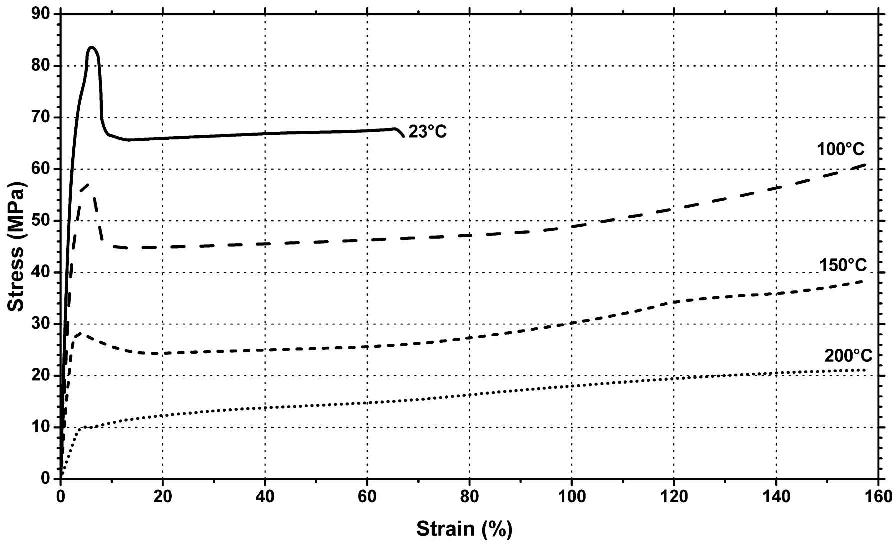


Figure 10.37 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-621 NT unreinforced PAEK [3].

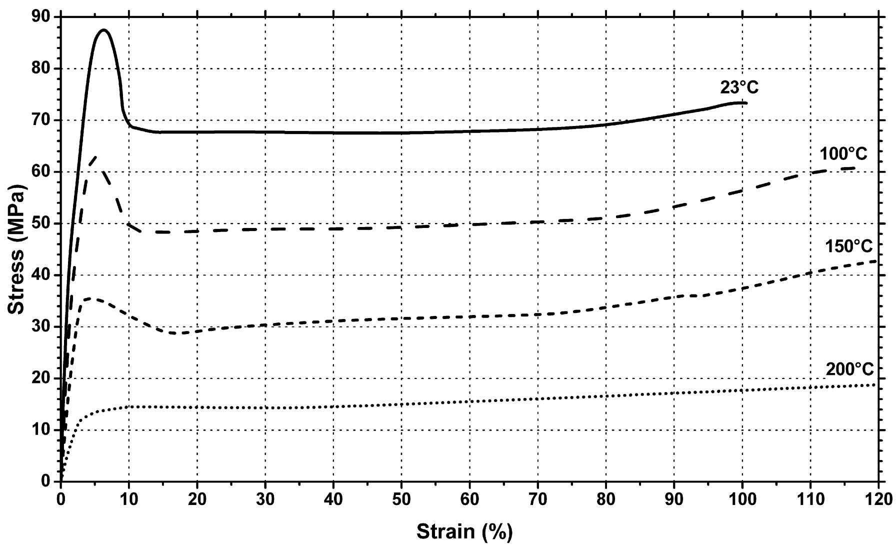


Figure 10.38 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-651 BG15 PAEK [3].

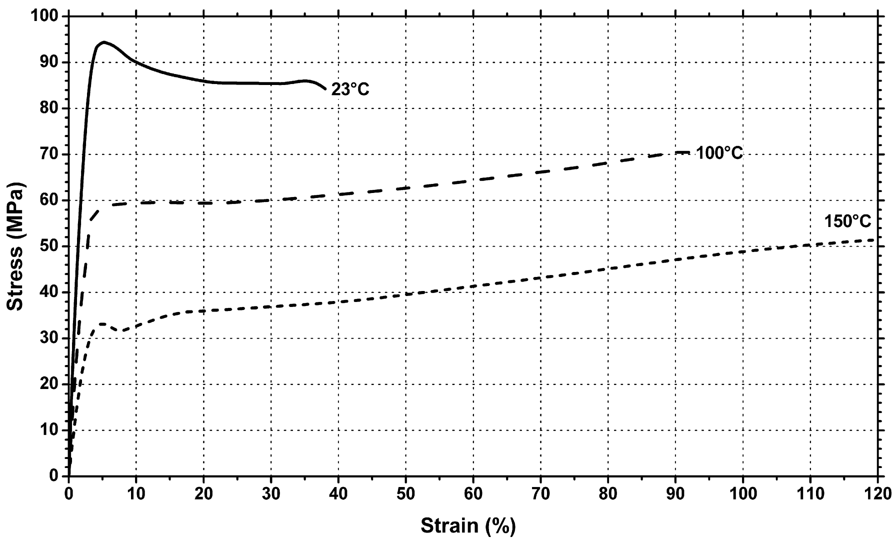


Figure 10.39 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-722 BG20 PAEK [3].

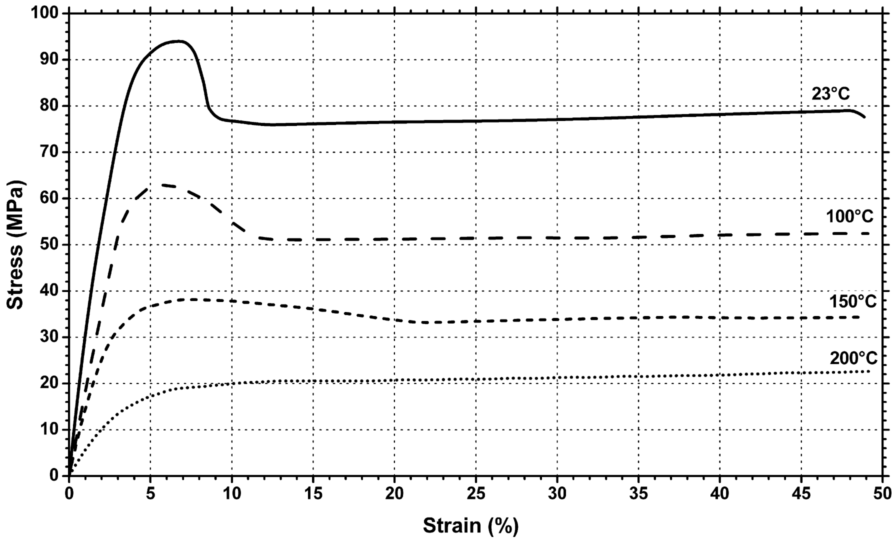


Figure 10.40 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-848 NT PAEK [3].

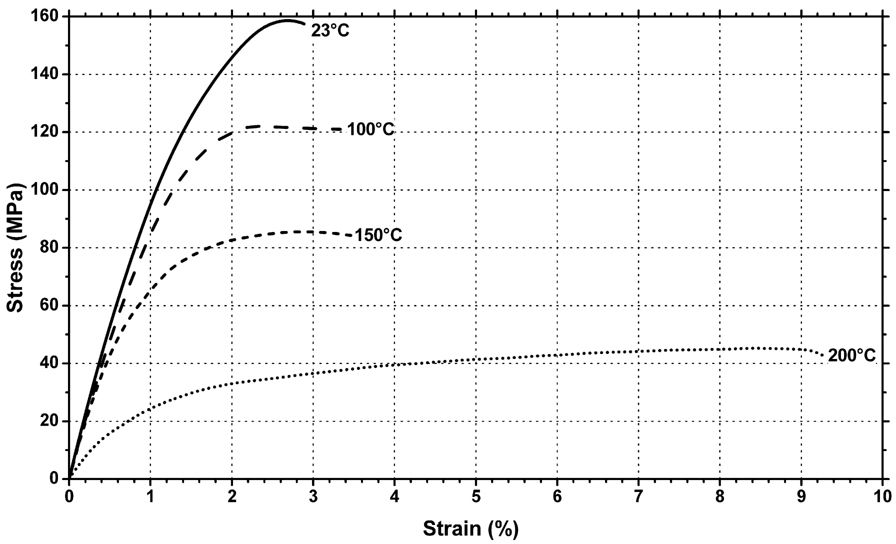


Figure 10.41 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-621 GF30—30% glass fiber PAEK [3].

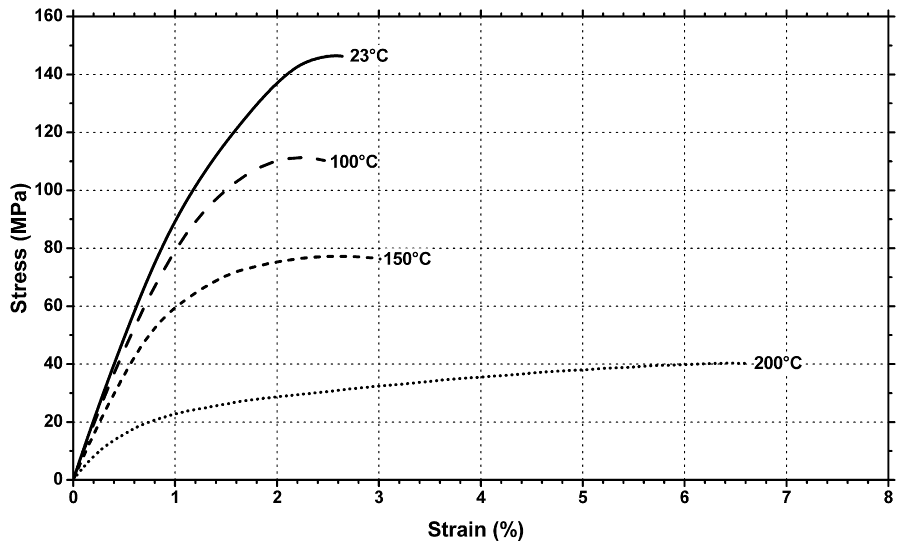


Figure 10.42 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-G51 GF30—30% glass fiber PAEK [3].

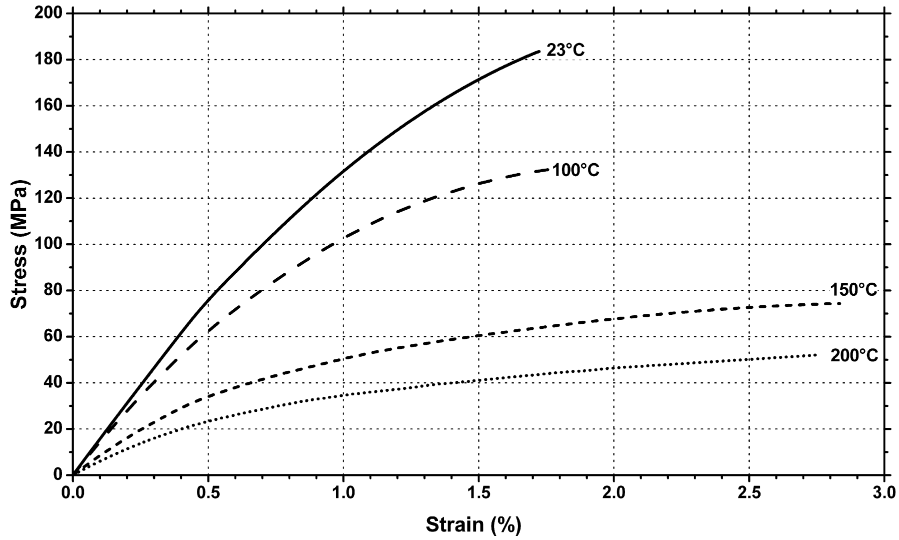


Figure 10.43 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-750 GF40—40% glass fiber PAEK [3].

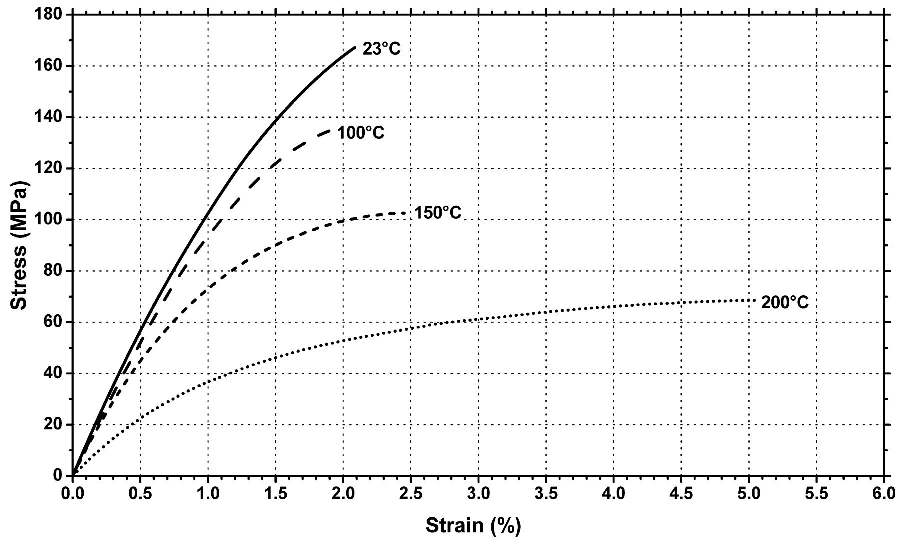


Figure 10.44 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-848 GF30—30% glass fiber PAEK [3].

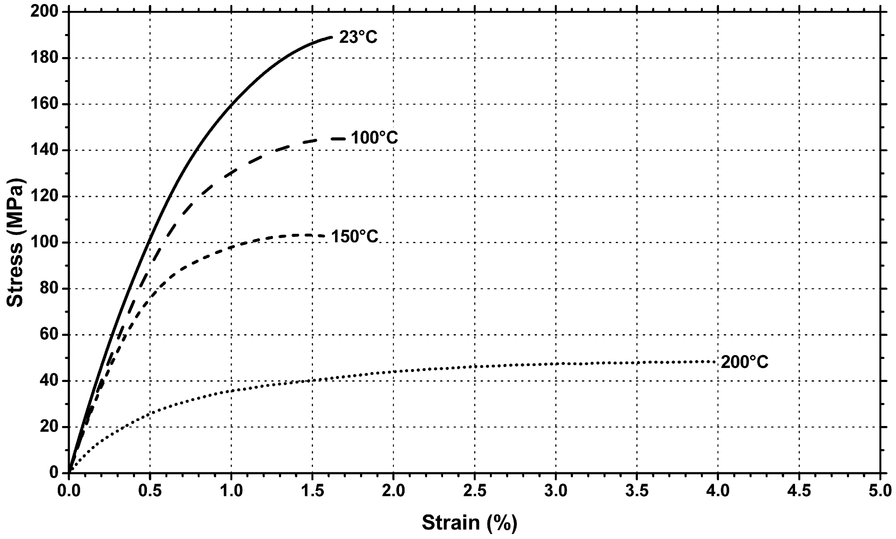


Figure 10.45 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-621 CF30—30% carbon fiber-reinforced PAEK [3].

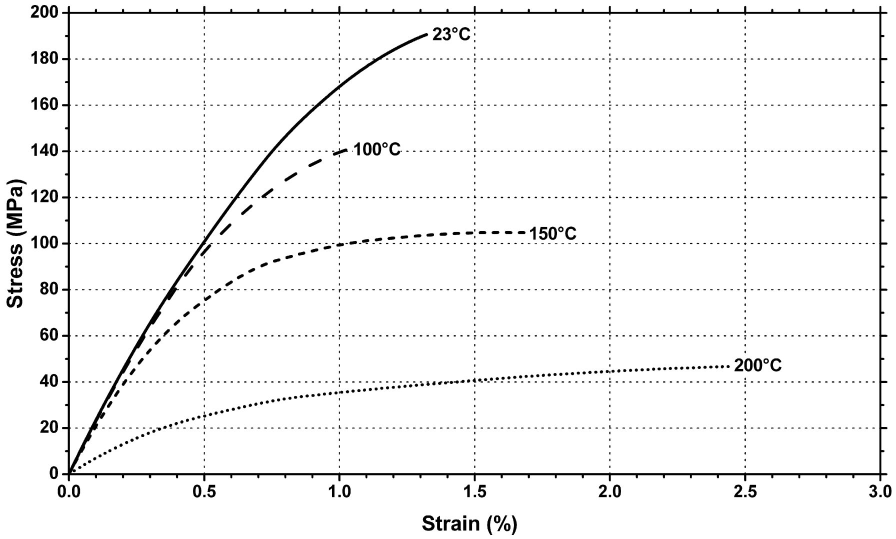


Figure 10.46 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-651 CF30—30% carbon fiber-reinforced PAEK [3].

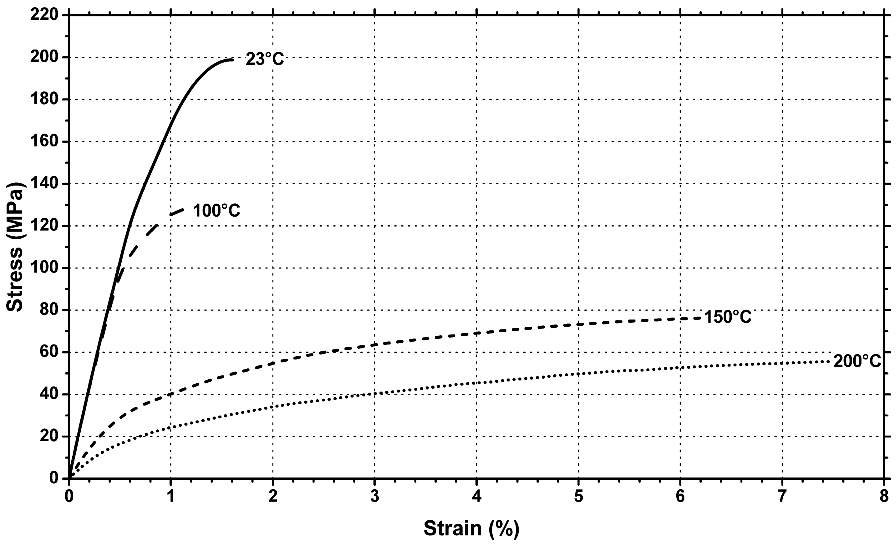


Figure 10.47 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-722 CF30—30% carbon fiber-reinforced PAEK [3].

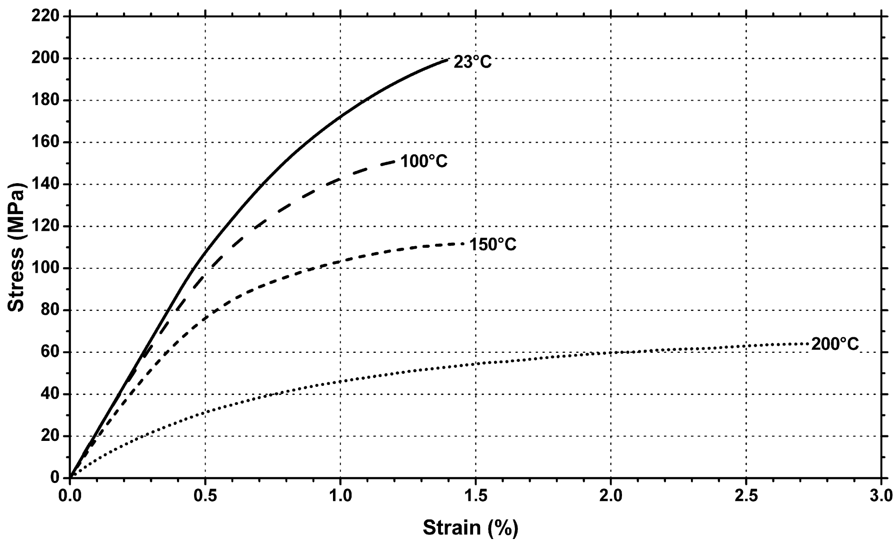


Figure 10.48 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-848 CF30—30% carbon fiber-reinforced PAEK [3].

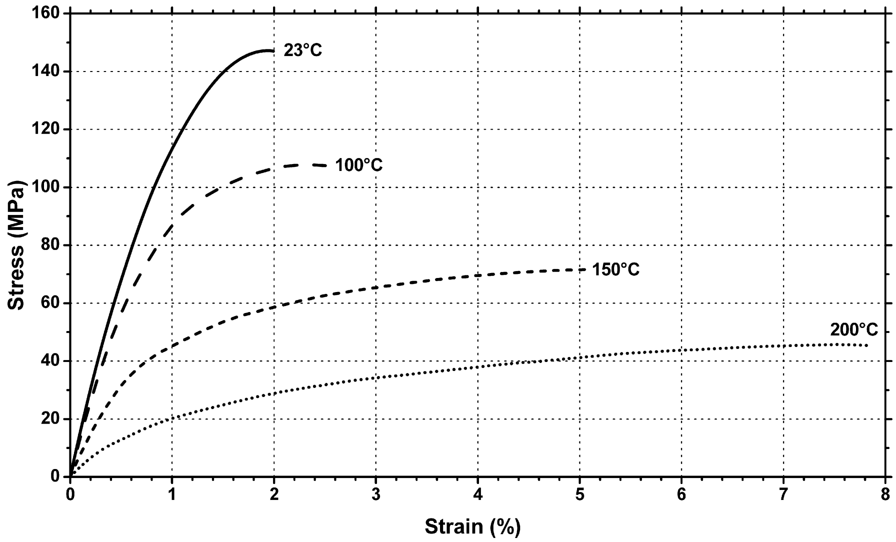


Figure 10.49 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-722 SL30 wear-resistant PAEK with carbon fiber, graphite, and PTFE [3].

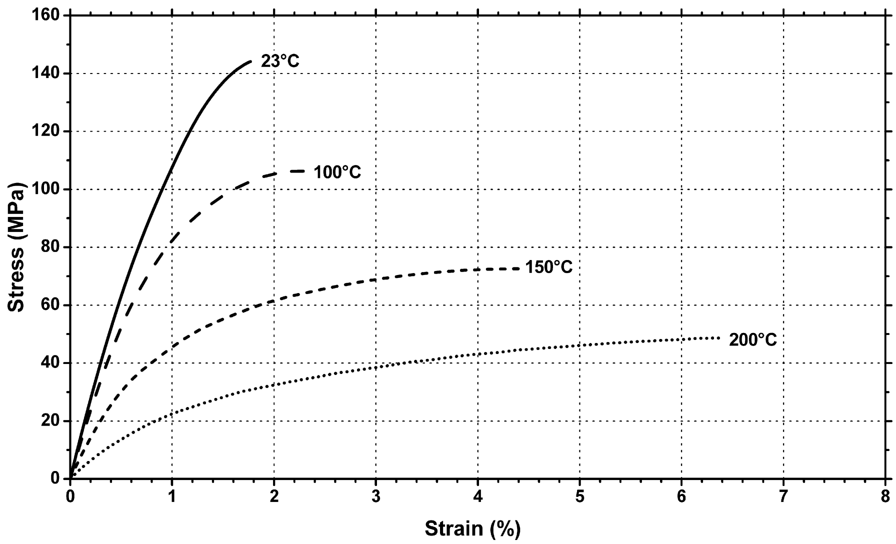


Figure 10.50 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-742 SL30 wear-resistant PAEK with carbon fiber, graphite, and PTFE [3].

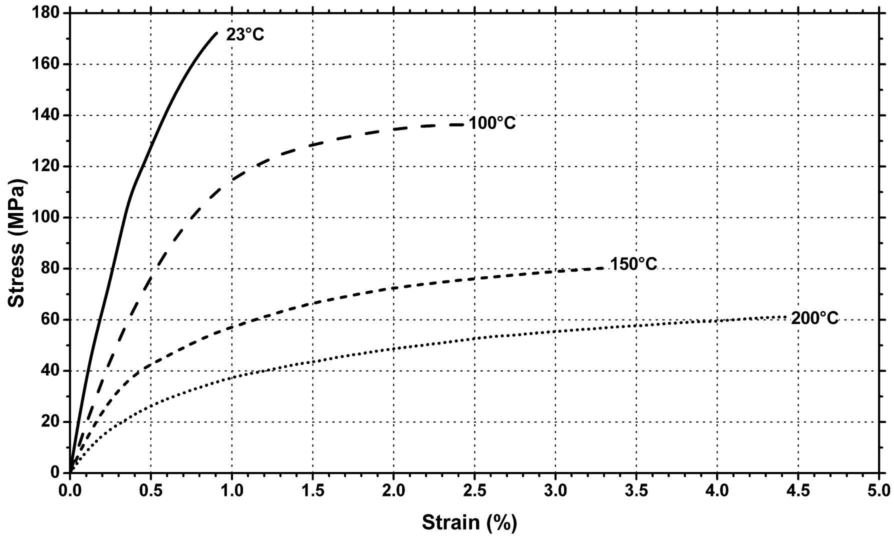


Figure 10.51 Stress vs. strain curves at various temperatures for Solvay Advanced Polymers AvaSpire® AV-755 SL45 wear-resistant PAEK with carbon fiber, graphite, and PTFE [3].

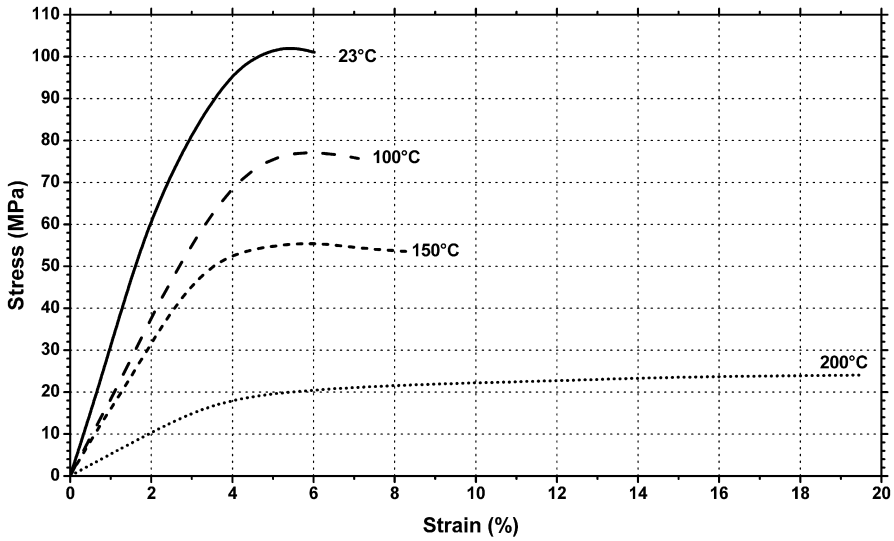


Figure 10.52 Compressive stress vs. strain curves for Solvay Advanced Polymers AvaSpire® AV-621 NT unreinforced PAEK [4].

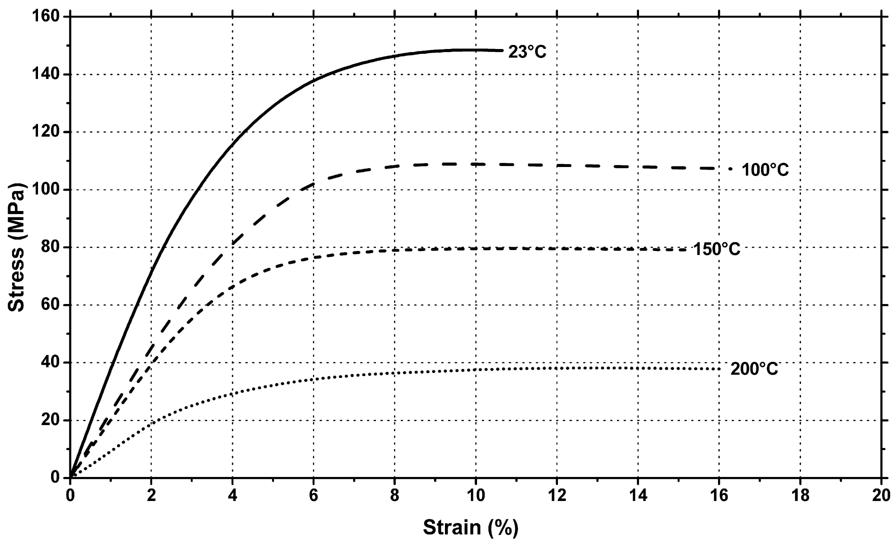


Figure 10.53 Compressive stress vs. strain curves for Solvay Advanced Polymers AvaSpire® AV-621 CF30—30% carbon fiber-reinforced PAEK [4].

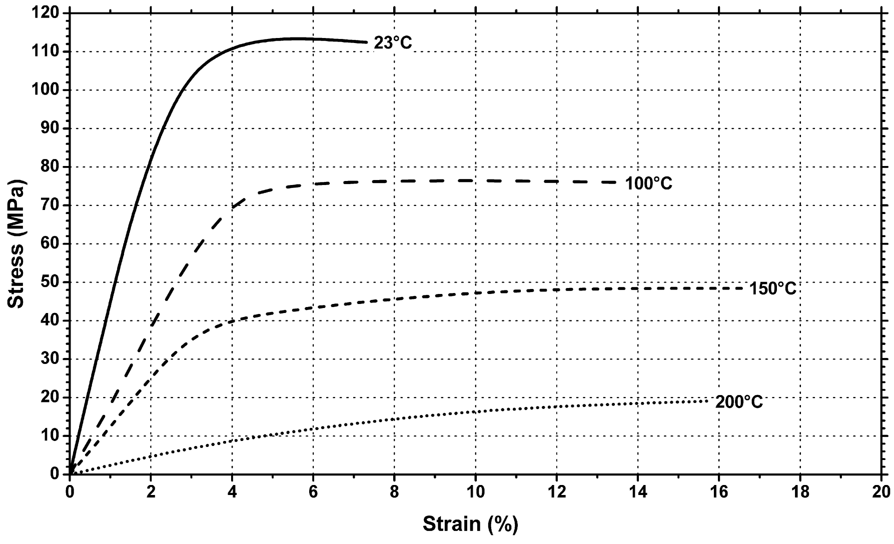


Figure 10.54 Compressive stress vs. strain curves for Solvay Advanced Polymers AvaSpire® AV-722 BG20 low melt unreinforced PAEK [4].

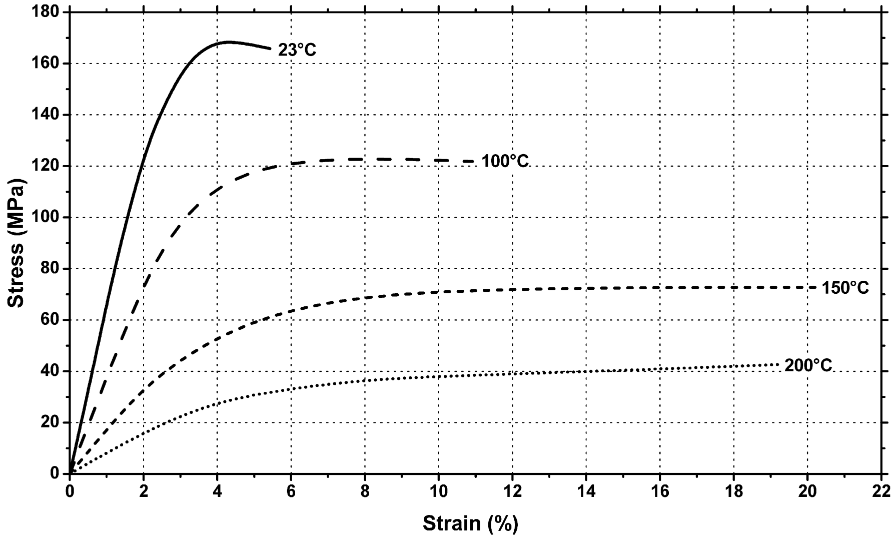


Figure 10.55 Compressive stress vs. strain curves for Solvay Advanced Polymers AvaSpire® AV-722 CF30—30% carbon fiber-reinforced PAEK [4].

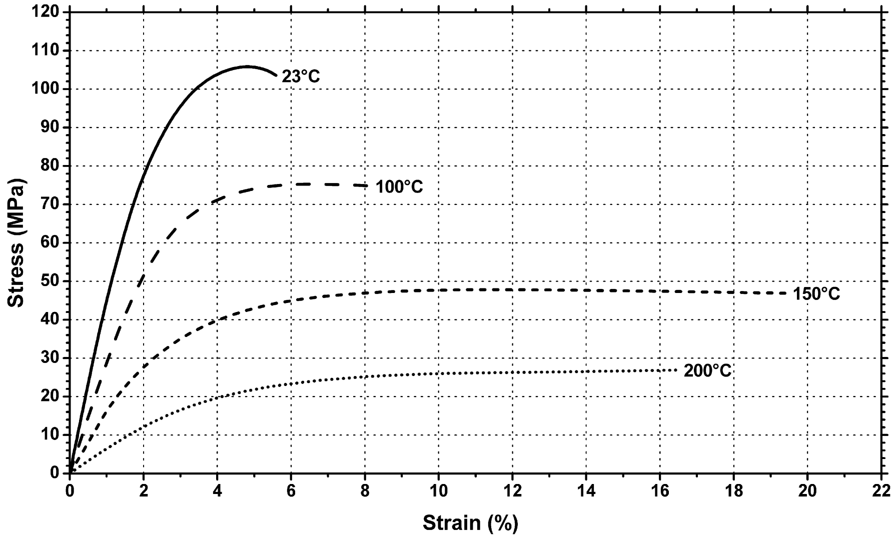


Figure 10.56 Compressive stress vs. strain curves for Solvay Advanced Polymers AvaSpire® AV-722 SL30 wear-resistant PAEK with carbon fiber, graphite, and PTFE [4].

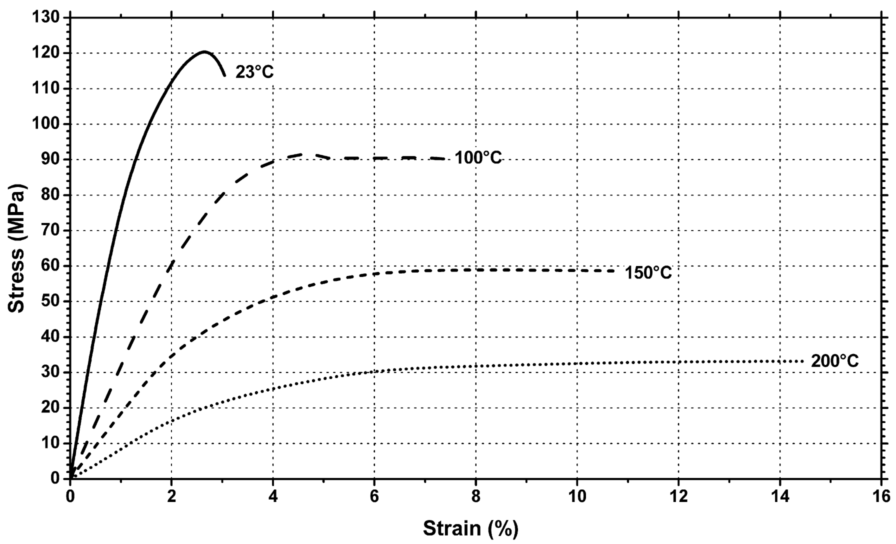


Figure 10.57 Compressive stress vs. strain curves for Solvay Advanced Polymers AvaSpire® AV-742 SL30 wear-resistant PAEK with carbon fiber, graphite, and PTFE [4].

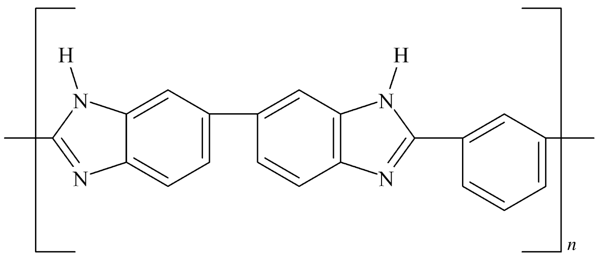


Figure 10.58 Structure of PBI.

blended with other polymers, particularly PEEK. The chemical structure is shown in Figure 10.58. PBI exhibits excellent thermal stability, resistance to chemicals, acid and base hydrolysis, and temperature resistance. PBI can withstand temperatures as high as 430°C, and in short bursts, to 760°C. PBI does not burn and maintains its properties as low as −196°C.

The data for PEEK-based blends are shown in Figures 10.59 and 10.60.

10.2 Polyethersulfone (PES)

PES is an amorphous high temperature engineering thermoplastic. Even though PES has high temperature performance, it can be processed on conventional plastics processing equipment. Its chemical structure is shown in Figure 10.61. PES has an outstanding ability to withstand exposure to elevated temperatures in air and water for prolonged periods.

Because PES is amorphous, mold shrinkage is low and it is suitable for applications requiring close tolerances and little dimensional change over a wide temperature range. Its properties include:

- Excellent thermal resistance—T_g 224°C
- Outstanding mechanical, electrical, flame, and chemical resistance
- Very good hydrolytic and sterilization resistance
- Good optical clarity
- Processed by all conventional techniques

Manufacturers and trade names: BASF Ultrason® E, Sumitomo Chemical Co., Ltd. Sumika Excel® PES, Solvay Advanced Polymers Veradel®, Radel® A.

The data for PES plastics are shown in Figures 10.62−10.87.

10.3 Polyphenylene Sulfide (PPS)

PPS is a semicrystalline material. It offers an excellent balance of properties, including high temperature resistance, chemical resistance, flowability, dimensional stability, and electrical characteristics. PPS must be filled with fibers and fillers to overcome its inherent brittleness. Because of its low viscosity, PPS can be molded with high loadings of fillers and reinforcements. Because of its outstanding flame

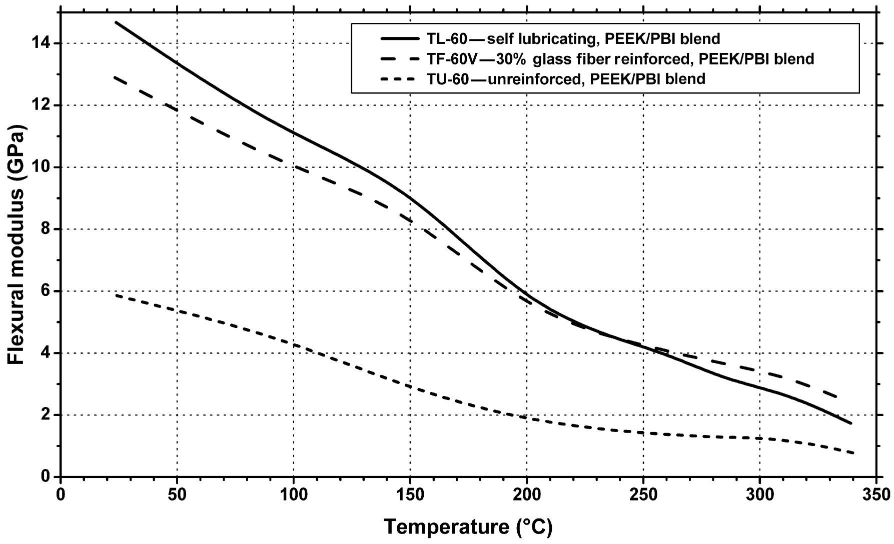


Figure 10.59 Flexural modulus vs. temperature for various Victrex® PEEK resins.

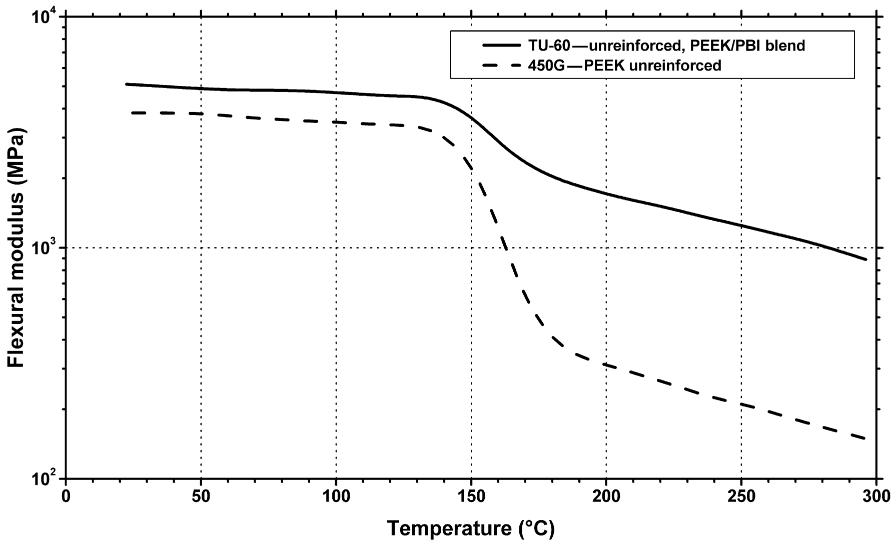


Figure 10.60 Flexural modulus vs. temperature for Victrex® PEEK resins, comparing a PBI/PEEK blend to PEEK resin.

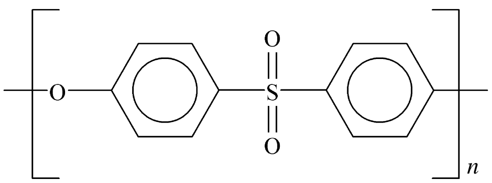


Figure 10.61 The structure of PES.

resistance, PPS is ideal for high temperature electrical applications. It is unaffected by all industrial solvents. The structure of PPS is shown in Figure 10.88. The CAS number is 26125-40-6.

There are several variants to regular PPS that may be talked about by suppliers or may be seen in the literature. They are:

- Regular PPS is of "modest" molecular weight. Materials of this type are often used in coating products.
- Cured PPS is PPS that has been heated to high temperature, above 300°C, in the presence of air or oxygen. The oxygen causes some cross-linking and chain extension called oxidative cross-linking. This results in some thermoset-like properties such as improved thermal stability, dimensional stability, and improved chemical resistance.

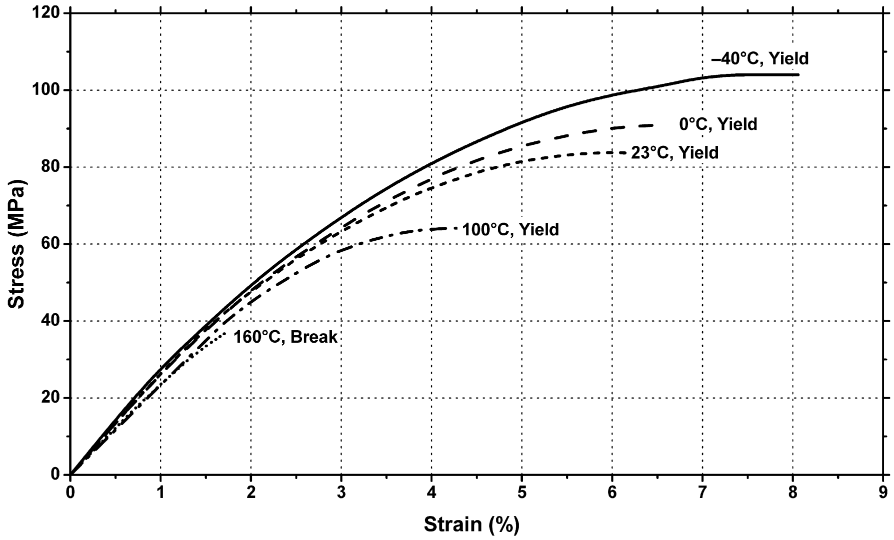


Figure 10.62 Stress vs. strain at several temperatures for BASF Ultrason® E 1010—low viscosity, unreinforced PES resin (conditioned at 50% RH).

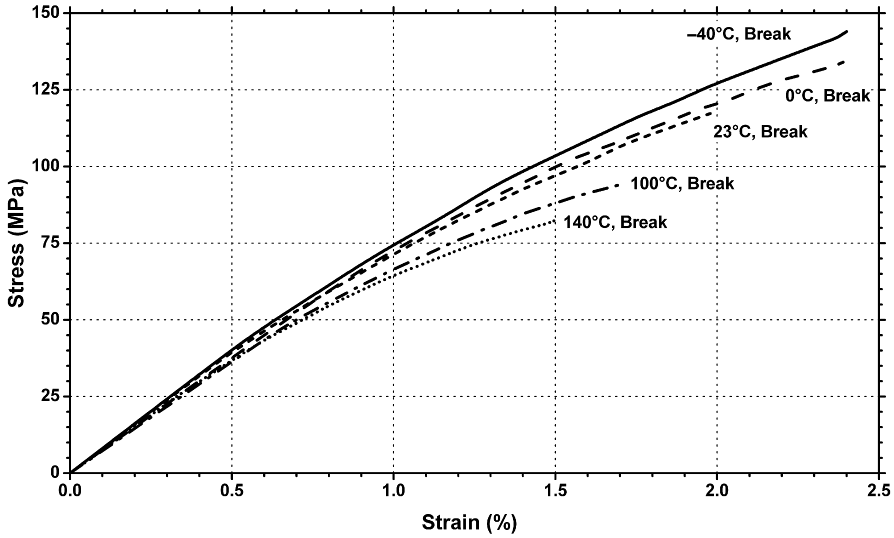


Figure 10.63 Stress vs. strain at several temperatures for BASF Ultrason® E 2010 G4—medium viscosity, 20% glass fiber-reinforced PES resin (conditioned at 50% RH).

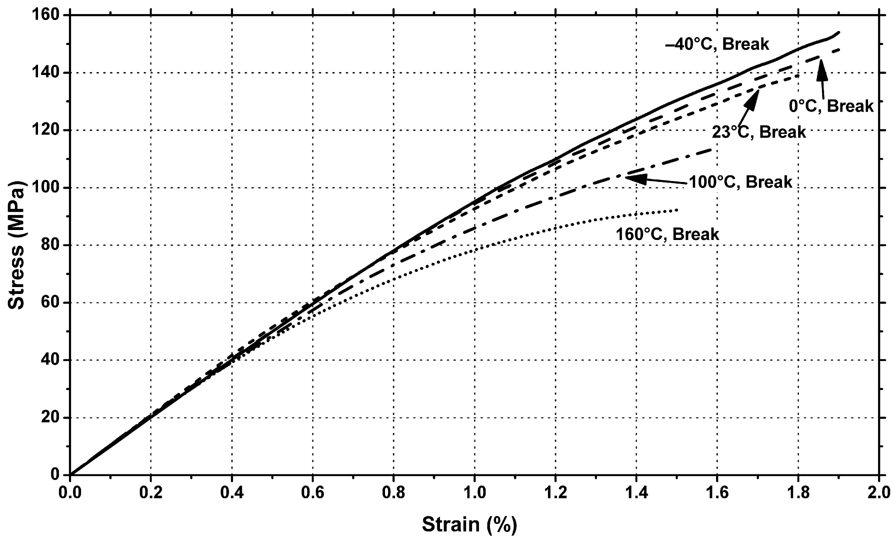


Figure 10.64 Stress vs. strain at several temperatures for BASF Ultrason® E 2010 G6—medium viscosity, 30% glass fiber-reinforced PES resin (conditioned at 50% RH).

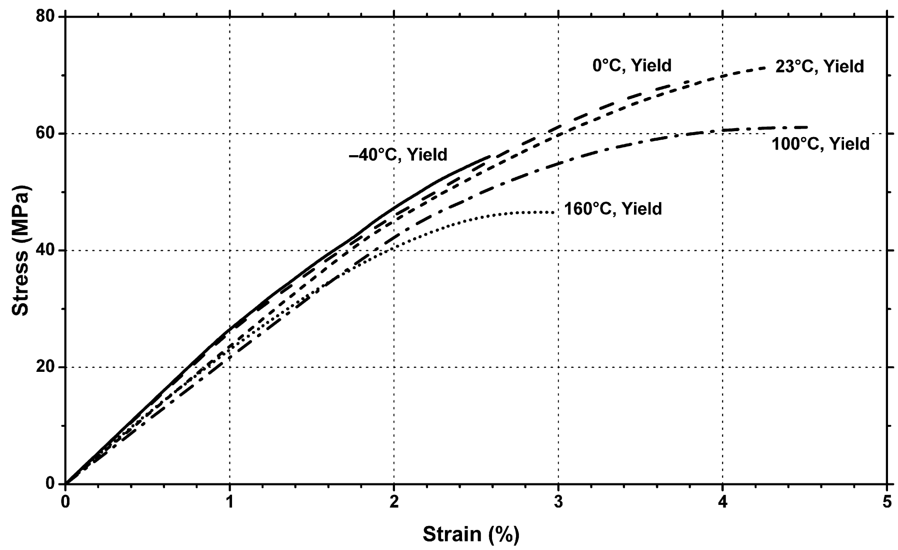


Figure 10.65 Stress vs. strain at several temperatures for BASF Ultrason® E 2010—medium viscosity, unreinforced PES resin (conditioned at 50% RH).

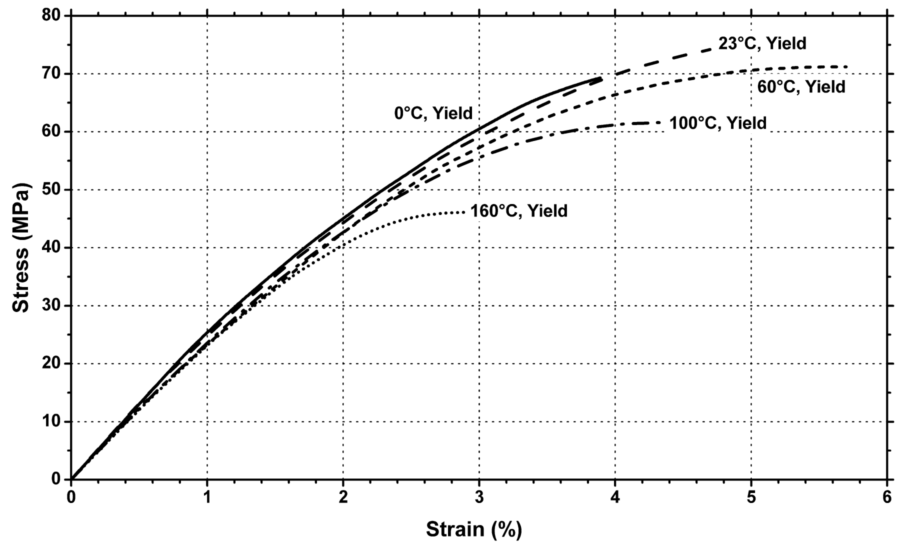


Figure 10.66 Stress vs. strain at several temperatures for BASF Ultrason® E 3010—high viscosity, unreinforced PES resin (conditioned at 50% RH).

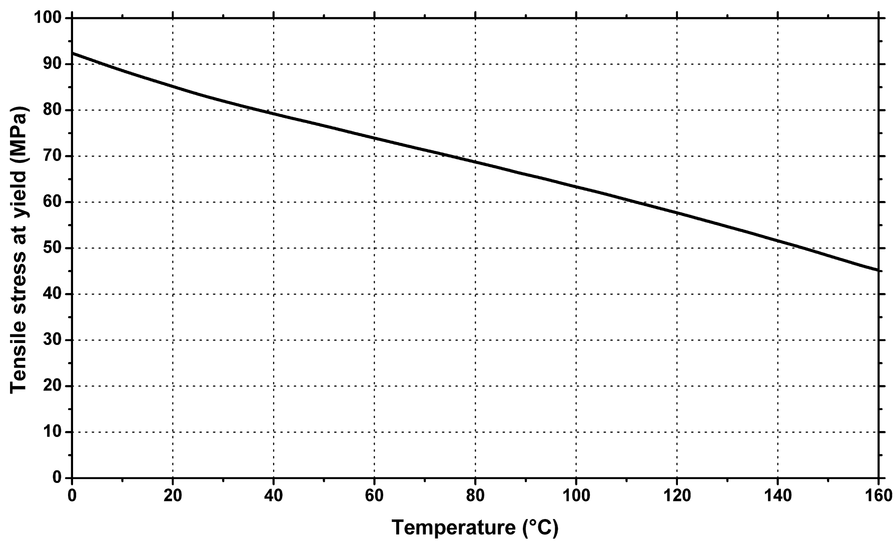


Figure 10.67 Temperature dependence of the tensile stress at yield (dry) of BASF Ultrason® E 3010 PES resin [6].

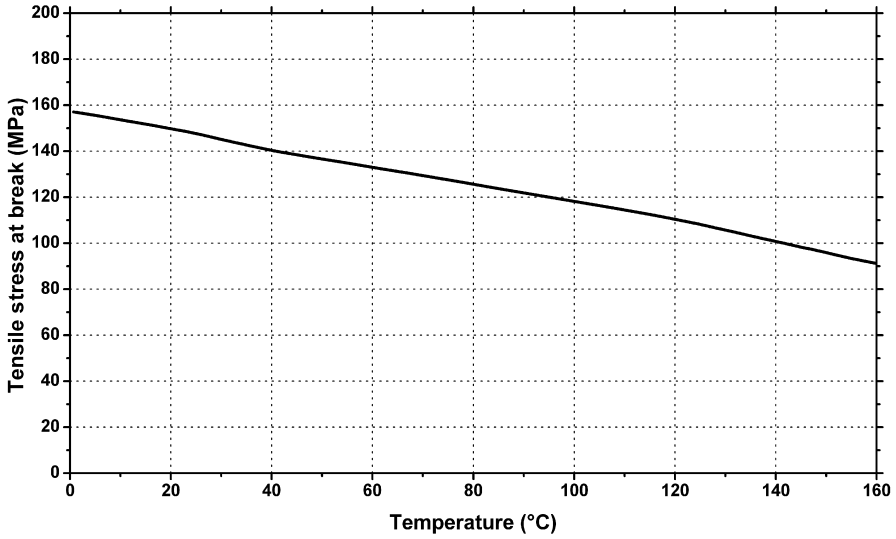


Figure 10.68 Temperature dependence of the tensile stress at break (dry) of BASF Ultrason® E 2010 G6 30% glass fiber PES resin [6].

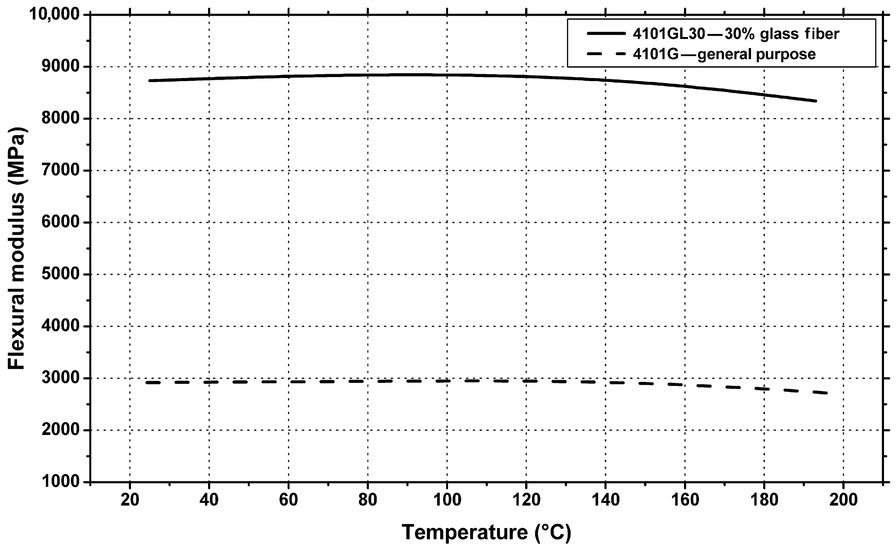


Figure 10.69 Flexural modulus vs. temperature for Sumitomo Chemical Sumika Excel® PES resins [7].

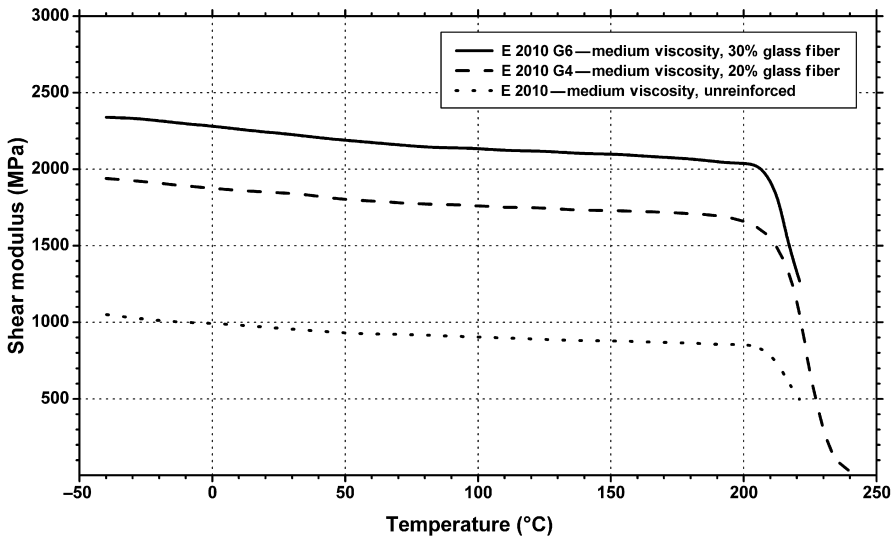


Figure 10.70 Shear modulus vs. temperature for BASF Ultrason® E 2010—medium viscosity PES resins (dry as molded).

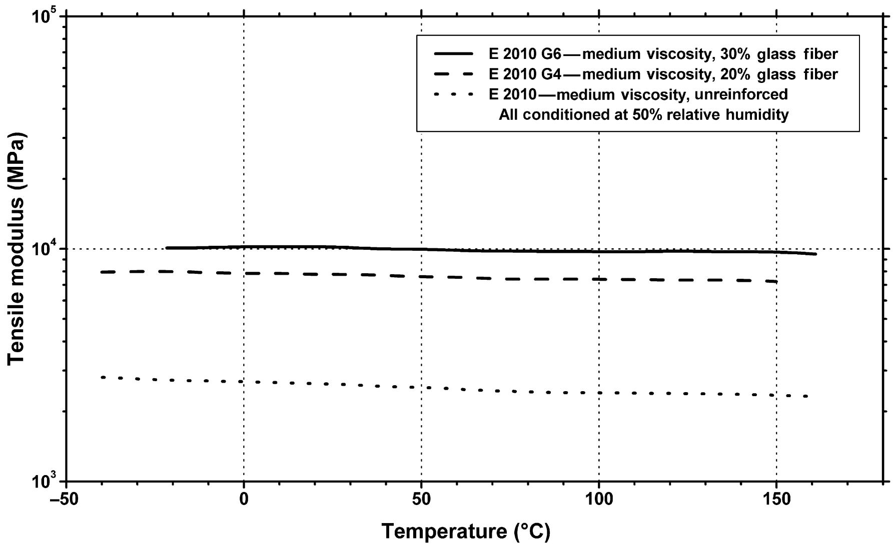


Figure 10.71 Tensile modulus vs. temperature for BASF Ultrason® E 2010—medium viscosity PES resins (conditioned at 50% RH).

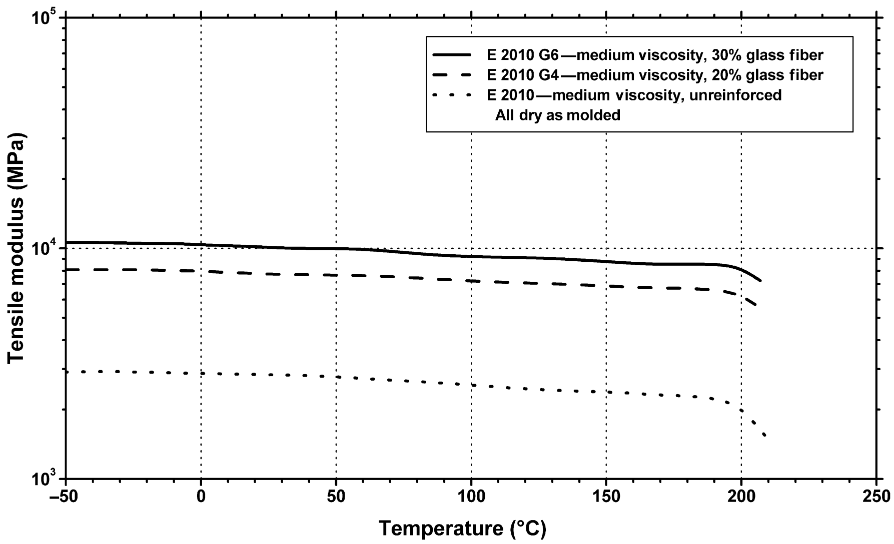


Figure 10.72 Tensile modulus vs. temperature for BASF Ultrason® E 2010—medium viscosity PES resins (dry as molded).

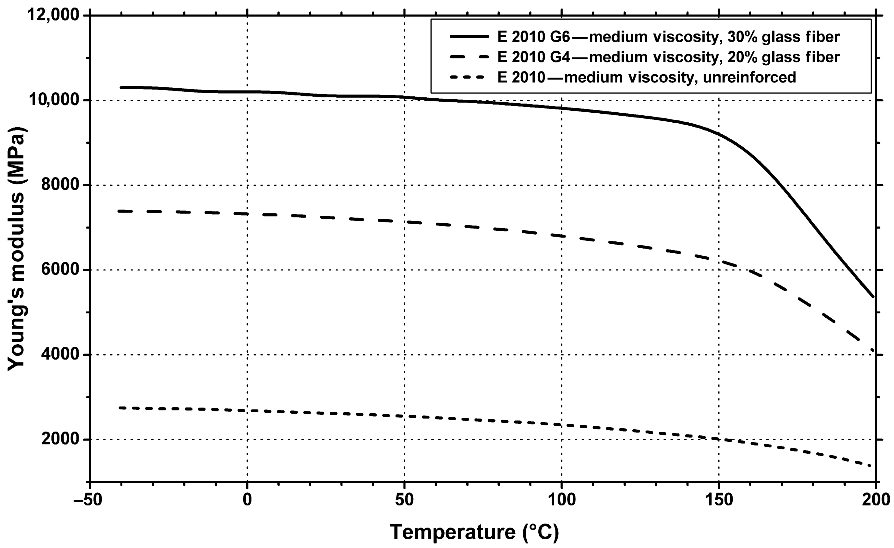


Figure 10.73 Young's modulus vs. temperature for BASF Ultrason® E 2010—medium viscosity PES resins.

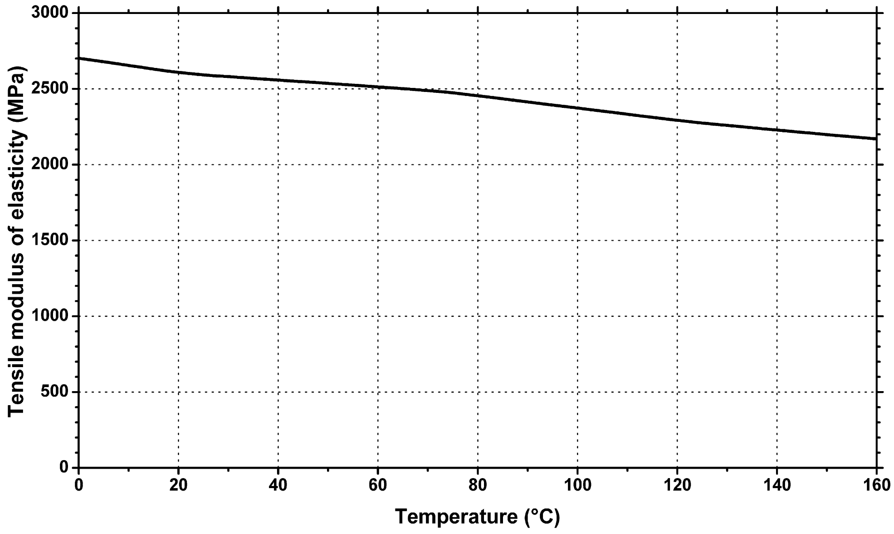


Figure 10.74 Modulus of elasticity (according to ISO 527) as a function of temperature (dry) of BASF Ultrason® E 3010 PES resin [6].

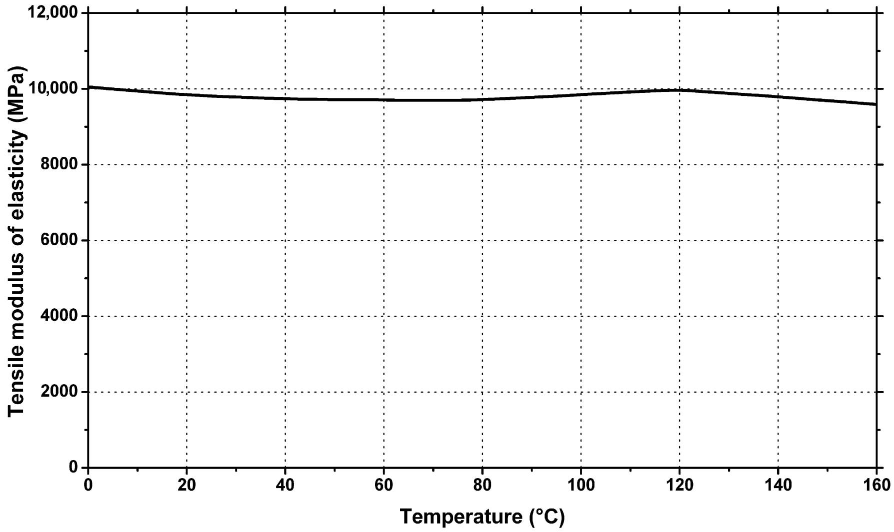


Figure 10.75 Modulus of elasticity (according to ISO 527) as a function of temperature (dry) of BASF Ultrason® E 2010 G6 30% glass fiber PES resin [6].

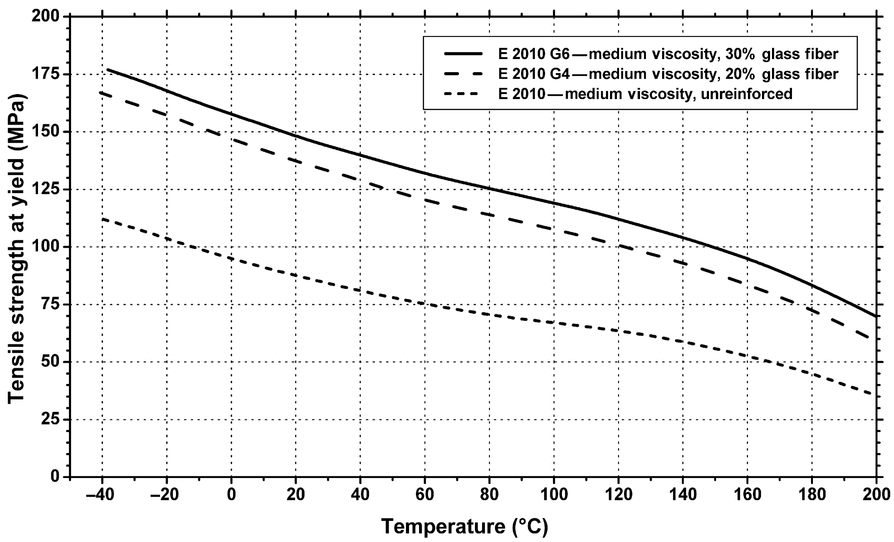


Figure 10.76 Tensile strength vs. temperature for BASF Ultrason® E 2010—medium viscosity PES resins.

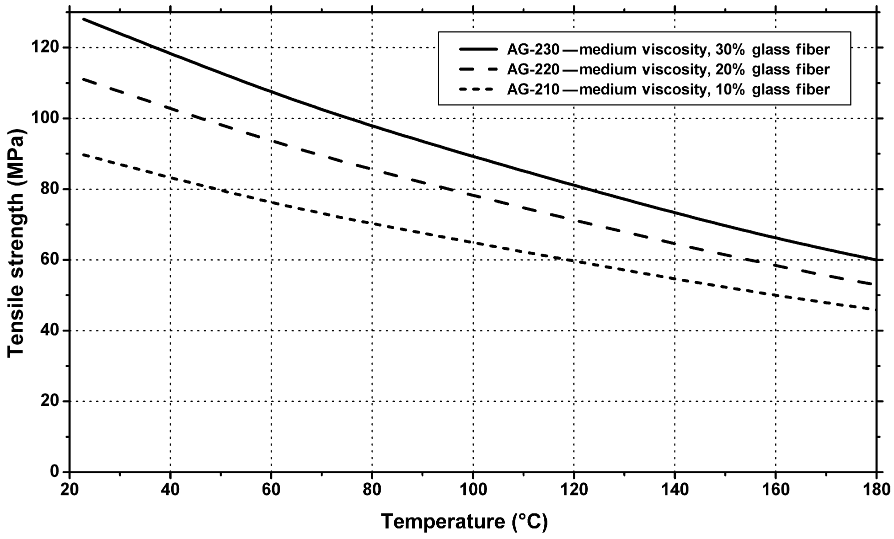


Figure 10.77 Tensile strength vs. temperature for Solvay Radel® A PES resins with different amounts of glass fiber filler.

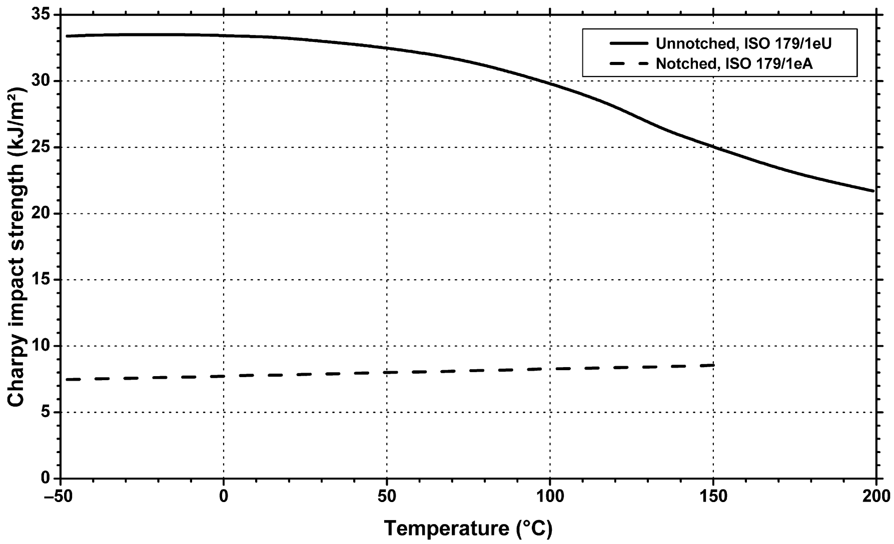


Figure 10.78 Charpy impact strength vs. temperature for BASF Ultrason® E 2010 G4—medium viscosity, 20% glass fiber-reinforced PES resins.

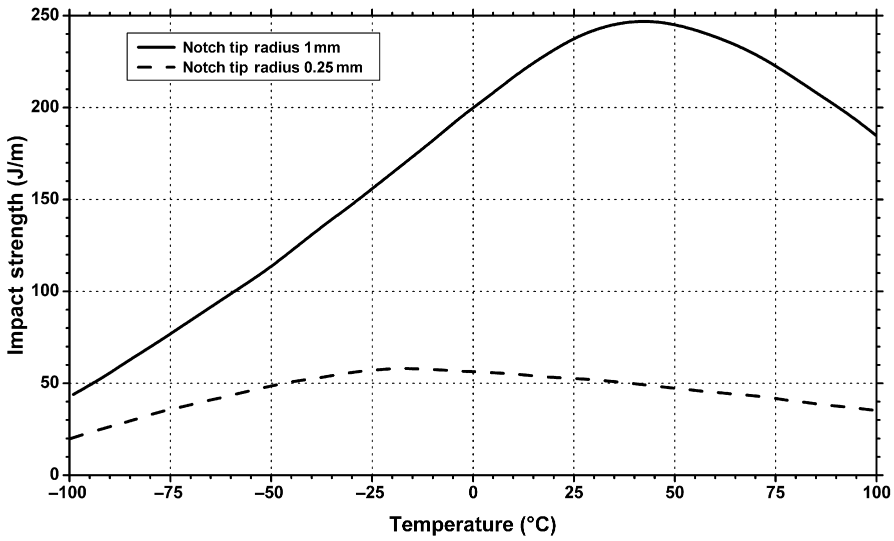


Figure 10.79 Charpy impact strength vs. temperature for Sumitomo Chemical Sumika Excel® 4800G—high viscosity, general-purpose PES resin [7].

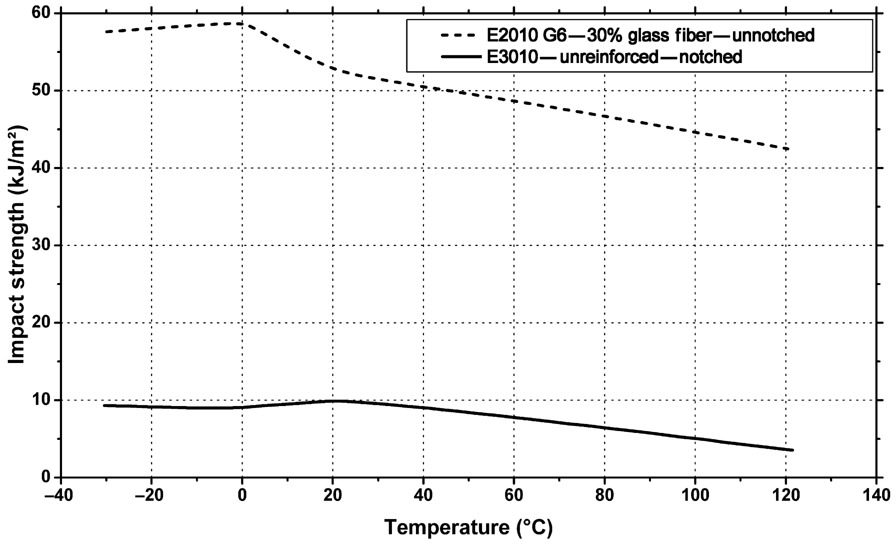


Figure 10.80 Impact strength as a function of temperature for BASF Ultrason® PES resins [6].

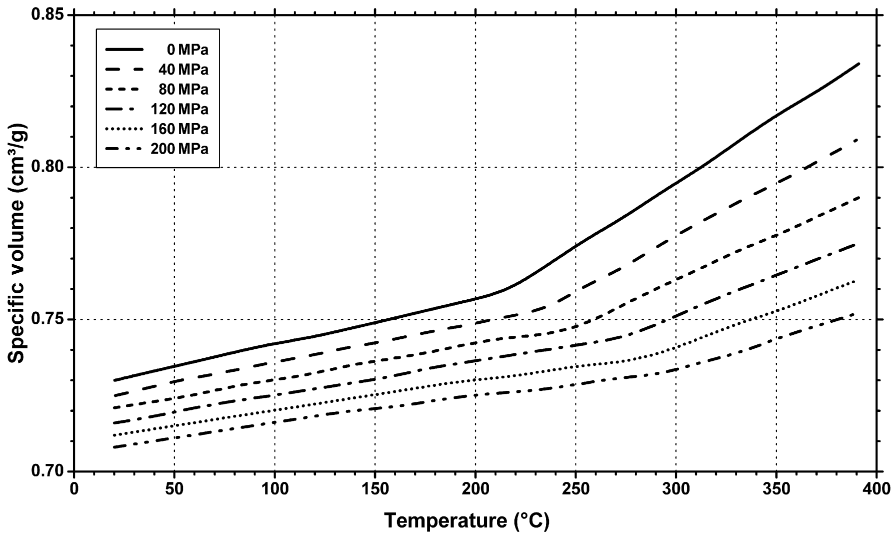


Figure 10.81 Specific volume as a function of temperature and pressure (PVT) of BASF Ultrason® E 1010—low viscosity, unreinforced PES resin.

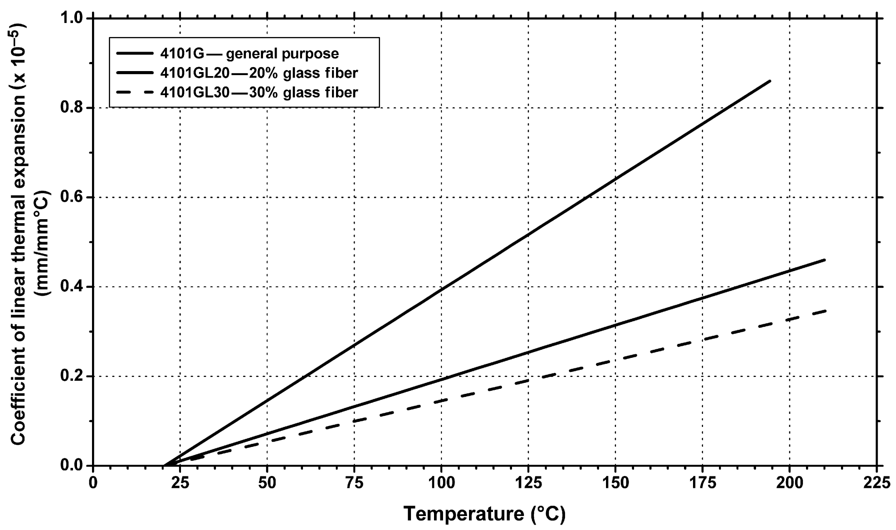


Figure 10.82 Coefficient of linear thermal expansion vs. temperature for Sumitomo Chemical Sumika Excel® PES resins.

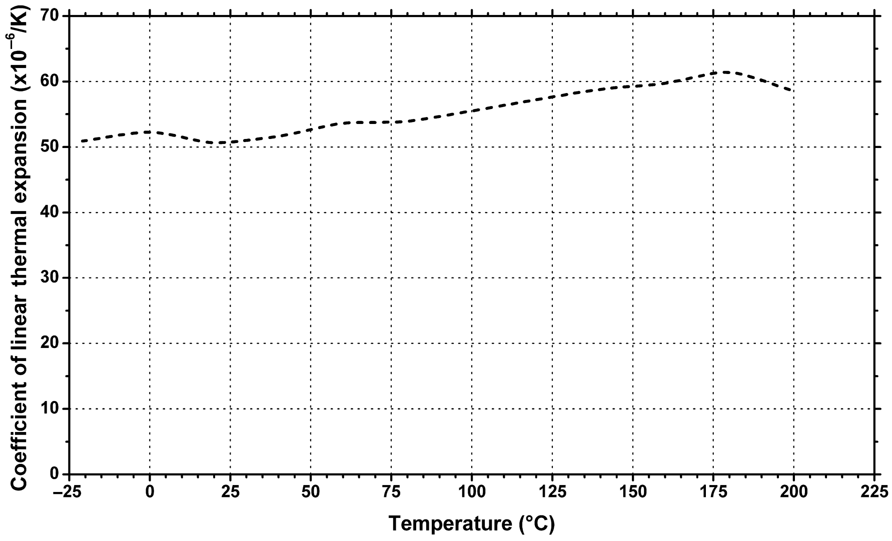


Figure 10.83 Coefficient of linear thermal expansion according to DIN 53752 of BASF Ultrason® E 2010 PES resin [6].

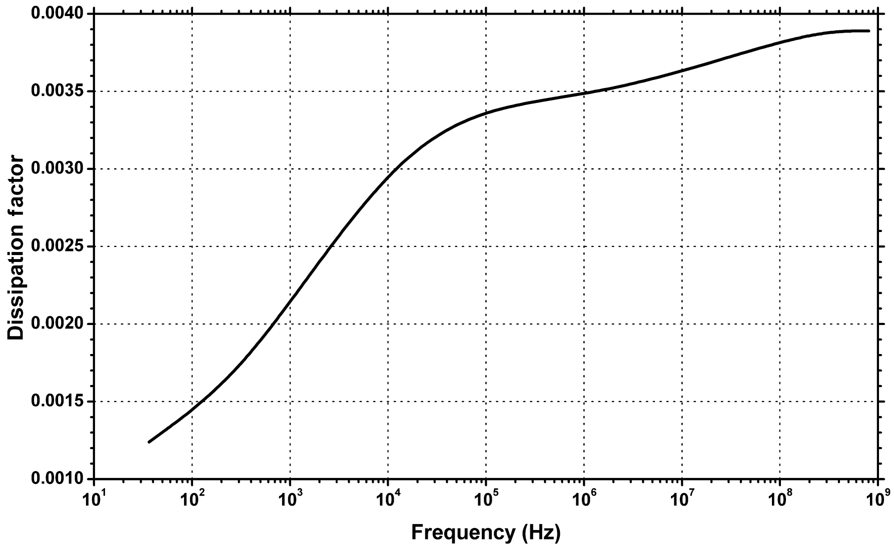


Figure 10.84 Dissipation factor vs. frequency for Sumitomo Chemical Sumika Excel® 4800G—high viscosity, general-purpose PES resin [7].

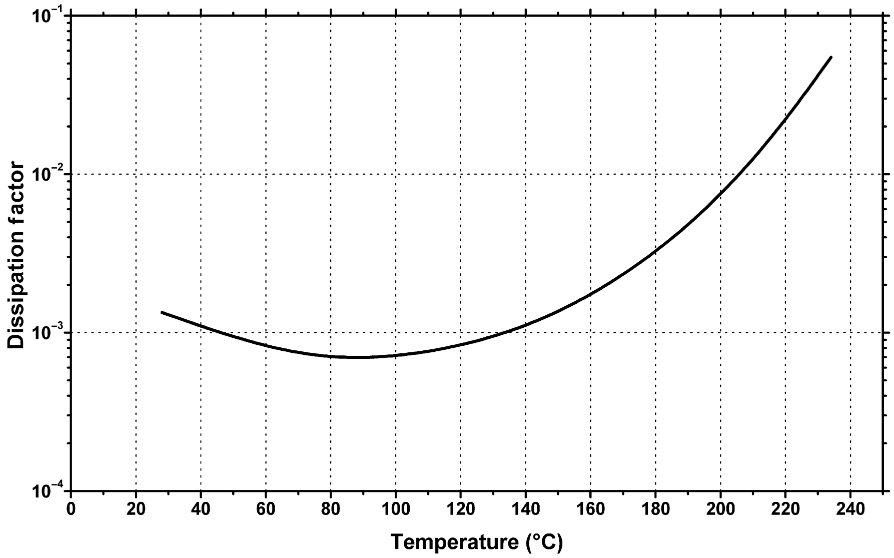


Figure 10.85 Dissipation factor vs. temperature for Sumitomo Chemical Sumika Excel® 4800G—high viscosity, general-purpose PES resin [7].

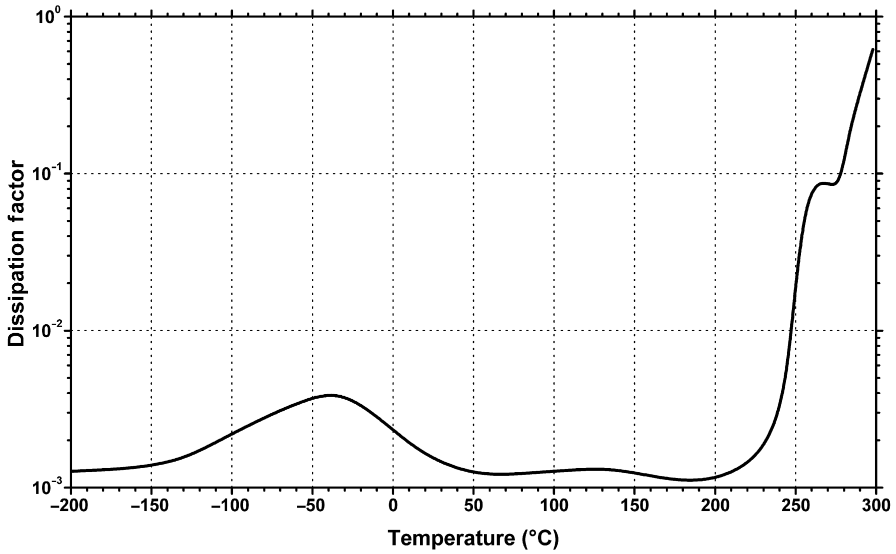


Figure 10.86 Dissipation factor vs. temperature at 1 kHz for BASF Ultrason® E 2010—medium viscosity, unreinforced PES resin [6].

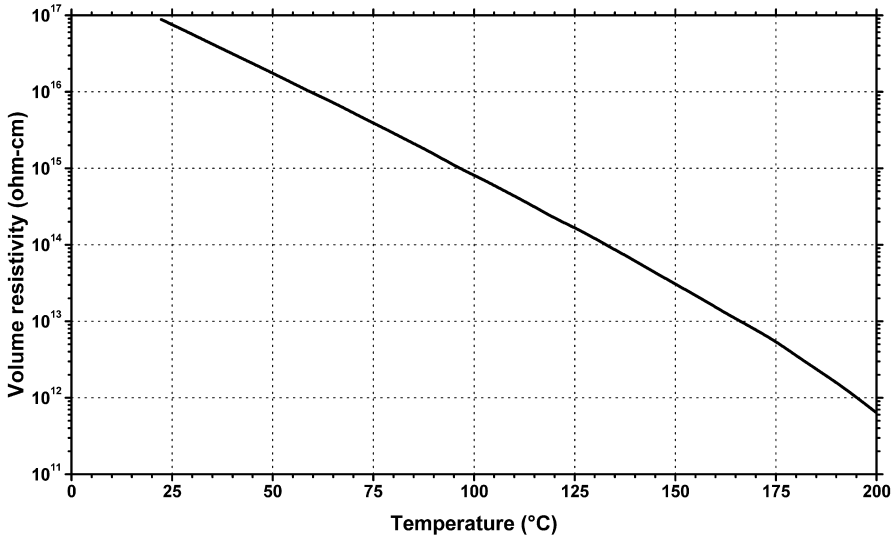


Figure 10.87 Volume resistivity vs. temperature for Sumitomo Chemical Sumika Excel® 4800G—high viscosity, general-purpose PES resin [7].

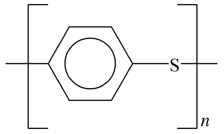


Figure 10.88 Structure of PPS.

- High molecular weight (HMW) linear PPS has a molecular weight about double of that of regular PPS. The higher molecular weight improves elongation and impact strength.
- HMW branched PPS has not only higher molecular weight than regular PPS but also polymer chain branches along the main molecule backbone. This provides improved mechanical properties.

PPS properties are summarized as follows:

- Continuous use temperature of 220°C
- Excellent dimensional properties
- Transparent
- Improved impact strength and toughness as compared to PES
- Excellent hydrolytic stability
- High stress cracking resistance
- Good chemical resistance
- Good surface release properties
- Expected continuous temperature of 180°C

Manufacturers and trade names: Dinippon Ink, Chevron Phillips Ryton®, Celanese Fortron®, Toray Torelina®.

Applications and uses: *automotive*: coolant, fuel, braking, transmission, engine, electrical and lighting components engine mounts; *electrical*: connectors, sockets, bobbins, relays, optical pickups, housings; *industrial and consumer*: hair straightener housings, hard disk drive components, chemical pumps, turbo charger air ducts, piping for down-hole oilfield applications, pump and motor parts, sensors, thermostats, blower housings, hot water manifolds, nonstick cookware coatings.

The data for PPS plastics are given in Tables 10.12−10.19 and shown in Figures 10.89−10.116.

Table 10.12 Nominal Elongation at Break of Chevron Phillips Chemical Ryton® PPS and Xtel® PPS Alloy Compounds from −40°C to 200°C [8]

	Elongation at Break in % at Temperature						
Product Code	**−40°C**	**23°C**	**50°C**	**75°C**	**100°C**	**150°C**	**200°C**
Ryton® R-4-200BL	1.4	1.5	1.4	1.4	1.9	3.4	3.0
Ryton® R-4-220BL	1.4	1.4	1.4	1.4	2.0	3.3	3.0
Ryton® R-7-120BL	1.0	0.8	0.8	0.9	1.4	2.7	3.0
Ryton® R-7-220BL	1.1	1.0	1.1	1.1	1.4	2.3	2.2
Ryton® BR111BL	1.0	1.0	0.9	0.9	1.6	2.5	2.3
Ryton® BR42B	1.8	1.7	1.6	1.8	2.5	3.5	3.8
Xtel® XE5030BL	2.0	2.0	1.8	1.8	3.3	4.4	3.8
Xtel® XE4050BL	1.9	1.9	1.8	1.7	3.1	5.3	4.9
Xtel® XK2340	1.4	1.8	2.1	2.3	2.8	3.4	3.9

Note*: Test Method: ISO 527, Test Specimen Molding Conditions: Melt Temperature 315–343°C; Mold Temperature 135°C.*

Table 10.13 Nominal Flexural Modulus of Chevron Phillips Chemical Ryton® PPS and Xtel® PPS Alloy Compounds from −40°C to 200°C [8]

	Flexural Modulus in GPa at Temperature						
Product Code	**−40°C**	**23°C**	**50°C**	**75°C**	**100°C**	**150°C**	**200°C**
Ryton® R-4-200BL	15	14	16	15	11	6.0	5.0
Ryton® R-4-220BL	14	14	14	13	10	6.0	5.0
Ryton® R-7-120BL	19	19	18	17	–	7.0	6.5
Ryton® R-7-220BL	19	19	18	18	14	8.5	7.5
Ryton® BR111BL	19	19	18	18	14	7.5	6.5
Ryton® BR42B	14	14	13	13	10	6.5	5.5
Xtel® XE5030BL	10	9.0	9.0	8.5	6.0	3.5	2.0
Xtel® XE4050BL	10	9.5	8.5	8.5	6.5	3.5	2.5
Xtel® XK2340	14	12	10	9.0	7.5	6.0	5.5

Note*: Test Method: ISO 178, Test Specimen Molding Conditions: Melt Temperature 315–343°C; Mold Temperature 135°C.*

Table 10.14 Nominal Tensile Modulus of Chevron Phillips Chemical Ryton® PPS and Xtel® PPS Alloy Compounds from −40°C to 200°C [8]

Product Code	Tensile Modulus in GPa at Temperature						
	−40°C	23°C	50°C	75°C	100°C	150°C	200°C
Ryton® R-4-200BL	16	14	14	14	12	7.0	5.0
Ryton® R-4-220BL	15	14	14	14	11	6.0	5.5
Ryton® R-7-120BL	21	19	18	17	16	7.0	6.5
Ryton® R-7-220BL	17	17	16	16	12	8.0	7.0
Ryton® BR111BL	20	21	20	20	15	8.5	7.5
Ryton® BR42B	17	16	16	15	12	7.5	6.0
Xtel® XE5030BL	10	10	10	10	7.0	4.0	3.5
Xtel® XE4050BL	12	11	11	10	7.5	4.0	3.5
Xtel® XK2340	18	15	12	11	9.5	7.5	7.0

Note: *Test Method: ISO 527, Test Specimen Molding Conditions: Melt Temperature 315–343°C; Mold Temperature 135°C.*

Table 10.15 Nominal Flexural Strength of Chevron Phillips Chemical Ryton® PPS and Xtel® PPS Alloy Compounds from −40°C to 200°C [8]

Product Code	Flexural Strength in MPa at Temperature						
	−40°C	23°C	50°C	75°C	100°C	150°C	200°C
Ryton® R-4-200BL	300	280	265	245	190	110	80
Ryton® R-4-220BL	270	250	240	225	180	110	85
Ryton® R-7-120BL	240	210	200	200	175	110	80
Ryton® R-7-220BL	265	240	210	205	175	115	90
Ryton® BR111BL	250	230	210	195	165	100	75
Ryton® BR42B	310	275	250	230	180	120	85
Xtel® XE5030BL	240	195	175	165	120	75	55
Xtel® XE4050BL	255	190	170	150	115	75	55
Xtel® XK2340	275	265	220	195	175	135	110

Note: *Test Method: ISO 178, Test Specimen Molding Conditions: Melt Temperature 315–343°C; Mold Temperature 135°C.*

10.4 Polysulfone (PSU)

PSU is a rigid, strong, tough, high temperature amorphous thermoplastic. The structure of PSU is shown in Figure 10.117. Its CAS number is 25135-51-7.

Its properties are summarized as follows:

- High thermal stability
- High toughness and strength
- Good environmental stress crack resistance
- Inherent fire resistance
- Transparence

Manufacturers and trade names: Solvay Advanced Polymers Udel®, BASF Ultrason® S.

Applications and uses: analytical instrumentation, surgical and medical devices, semiconductor process equipment components.

Table 10.16 Nominal Tensile Strength of Chevron Phillips Chemical Ryton® PPS and Xtel® PPS Alloy Compounds from −40°C to 200°C [8]

Product Code	Tensile Strength in MPa at Temperature						
	−40°C	23°C	50°C	75°C	100°C	150°C	200°C
Ryton® R-4-200BL	195	180	160	140	105	65	45
Ryton® R-4-220BL	190	175	160	145	110	65	50
Ryton® R-7-120BL	175	135	120	120	100	70	50
Ryton® R-7-220BL	185	160	150	140	115	80	60
Ryton® BR111BL	180	155	140	125	110	70	45
Ryton® BR42B	220	190	165	155	120	75	55
Xtel® XE5030BL	160	130	110	95	75	45	35
Xtel® XE4050BL	175	130	110	95	75	50	40
Xtel® XK2340	205	195	165	140	120	90	75

Note*: Test Method: ISO 527, Test Specimen Molding Conditions: Melt Temperature 315–343°C; Mold Temperature 135°C.*

Table 10.17 Nominal Compressive Strength of Chevron Phillips Chemical Ryton® PPS and Xtel® PPS Alloy Compounds from −40°C to 200°C [8]

Product Code	Compressive Strength in MPa at Temperature						
	−40°C	23°C	50°C	75°C	100°C	150°C	200°C
Ryton® R-4-200BL	340	275	270	240	195	90	70
Ryton® R-7-120BL	–	260	250	275	195	110	70
Ryton® BR111BL	350	295	270	275	215	125	80
Ryton® BR42B	–	255	240	240	160	90	65
Xtel® XE5030BL	275	205	–	–	110	55	–
Xtel® XE4050BL	275	190	–	–	105	55	–
Xtel® XK2340	320	255	–	–	140	95	–

Test Method: ASTM D695, Test Specimen Molding Conditions: Melt Temperature 315–343°C; Mold Temperature 135°C.

Table 10.18 Nominal Unnotched Izod Impact Strength of Chevron Phillips Chemical Ryton® PPS and Xtel® PPS Alloy Compounds from −40°C to 200°C [8]

Product Code	Unnotched Izod Impact Strength in kJ/m^2 at Temperature						
	−40°C	23°C	50°C	75°C	100°C	150°C	200°C
Ryton® R-4-200BL	33	35	36	37	31	30	27
Ryton® R-4-220BL	28	30	–	–	–	28	–
Ryton® R-7-120BL	15	15	14	15	15	14	15
Ryton® R-7-220BL	20	20	–	–	–	22	–
Ryton® BR111BL	22	20	20	21	19	20	18
Ryton® BR42B	37	40	39	35	36	35	30
Xtel® XE5030BL	50	45	45	43	43	37	34
Xtel® XE4050BL	41	35	32	33	33	30	27
Xtel® XK2340	26	35	31	26	27	28	27

Note*: Test Method: ISO 180/U, Test Specimen Molding Conditions: Melt Temperature 315–343°C; Mold Temperature 135°C.*

Table 10.19 Nominal Notched Izod Impact Strength of Chevron Phillips Chemical Ryton® PPS and Xtel® PPS Alloy Compounds from −40°C to 200°C [8]

Product Code	Notched Izod Impact Strength in kJ/m² at Temperature						
	−40°C	23°C	50°C	75°C	100°C	150°C	200°C
Ryton® R-4-200BL	7.8	8.0	8.0	8.2	8.0	9.5	13
Ryton® R-4-220BL	7.9	7.5	–	–	–	9.7	–
Ryton® R-7-120BL	5.6	5.5	5.7	6.8	5.7	6.7	6.2
Ryton® R-7-220BL	9.9	8.0	–	–	–	7.5	–
Ryton® BR111BL	8.1	6.5	5.8	8.8	4.9	7.6	6.2
Ryton® BR42B	11	9.5	9.1	10	10	14	13
Xtel® XE5030BL	7.4	9.5	10	11	12	15	17
Xtel® XE4050BL	6.2	8.0	8.6	8.7	9.0	11	12
Xtel® XK2340	9.7	8.5	9.3	10	10	13	20

Note: *Test Method: ISO 180/A, Test Specimen Molding Conditions: Melt Temperature 315–343°C; Mold Temperature 135°C.*

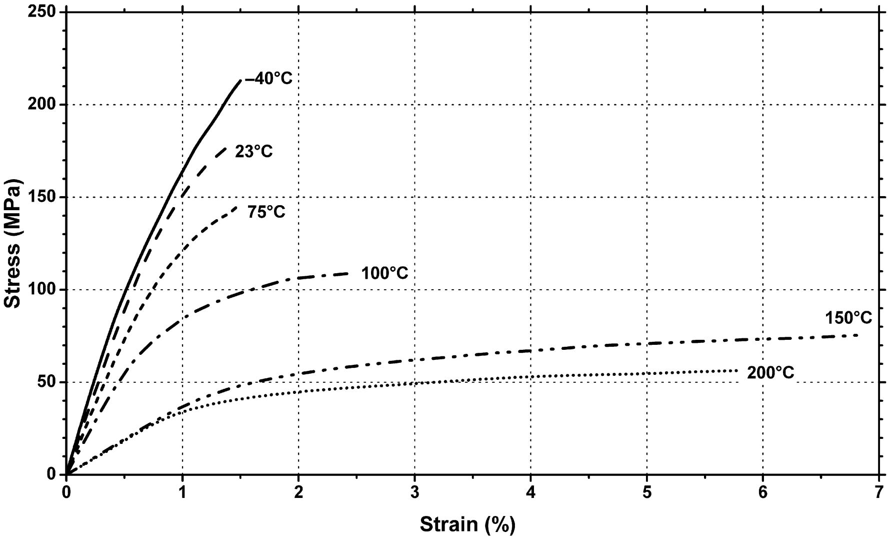


Figure 10.89 Stress vs. strain at several temperatures for Chevron Phillips Chemical Ryton® BR42B—40% glass fiber-filled, low friction PPS resin [9].

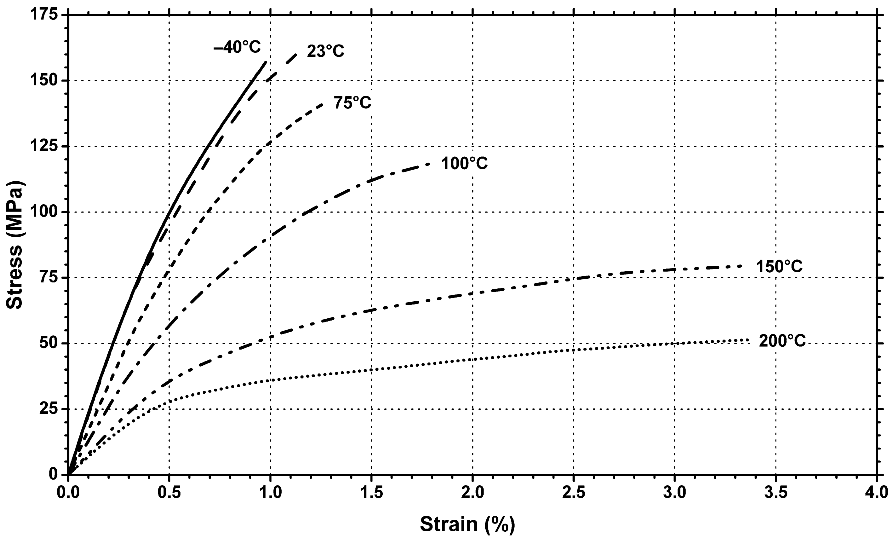


Figure 10.90 Stress vs. strain at several temperatures for Chevron Phillips Chemical Ryton® BR111—40% glass/mineral-filled PPS resin [9].

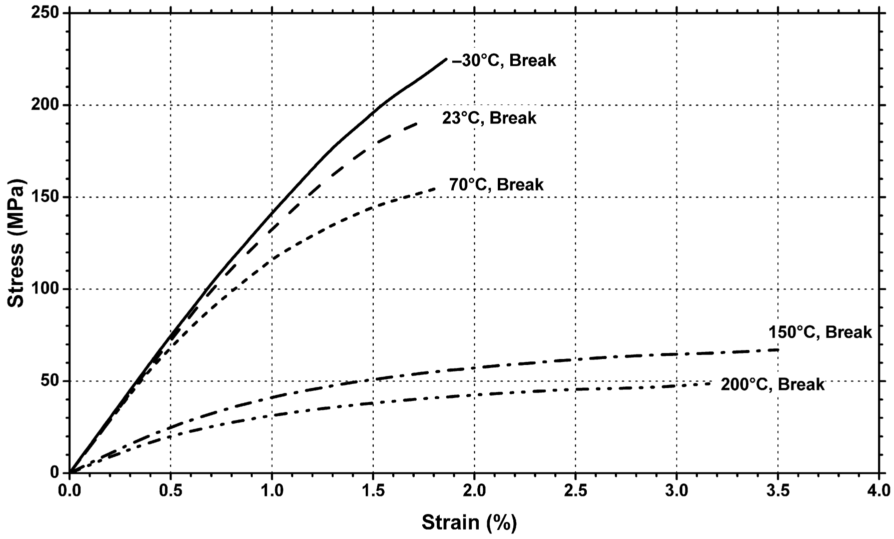


Figure 10.91 Stress vs. strain at several temperatures for Celanese Fortron® 1140L4—40% glass fiber-filled, medium melt viscosity PPS resin.

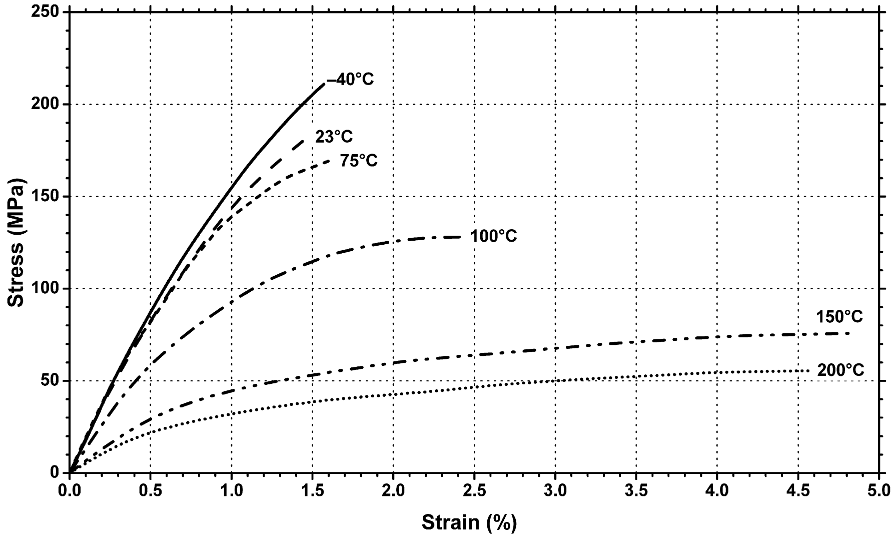


Figure 10.92 Stress vs. strain at several temperatures for Chevron Phillips Chemical Ryton® R-4-200BL—40% glass fiber-filled, high-strength PPS resin [9].

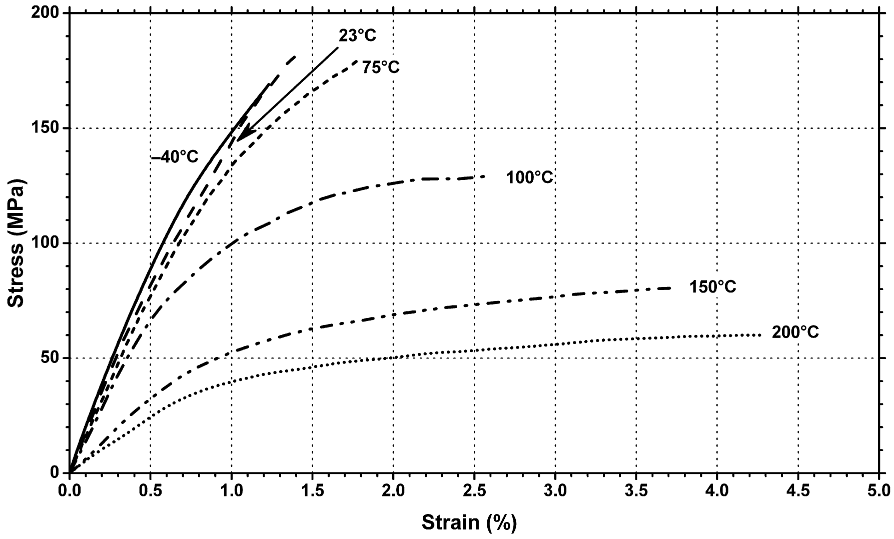


Figure 10.93 Stress vs. strain at several temperatures for Chevron Phillips Chemical Ryton® R-4-230NA—40% glass fiber-filled, high flow PPS resin [9].

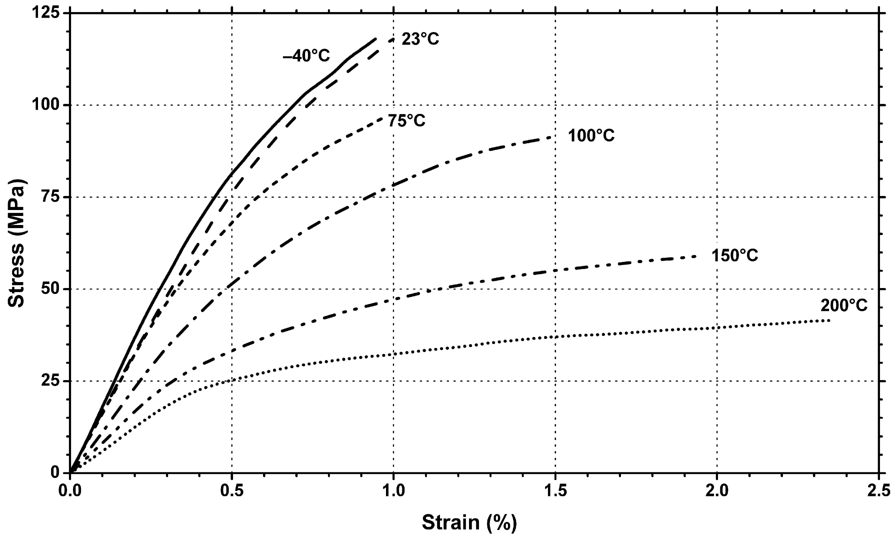


Figure 10.94 Stress vs. strain at several temperatures for Chevron Phillips Chemical Ryton® R-7-120BL—65% glass fiber/mineral-filled, arc resistant PPS resin [9].

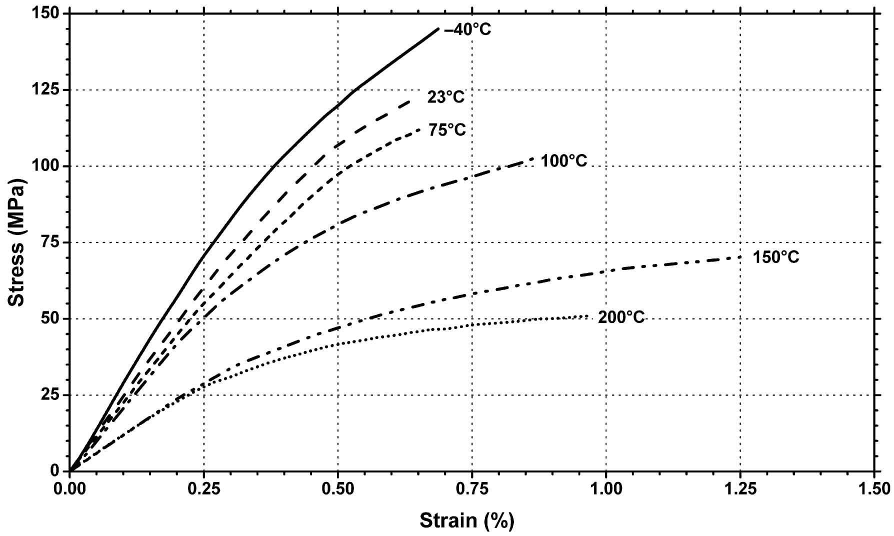


Figure 10.95 Stress vs. strain at several temperatures for Chevron Phillips Chemical Ryton® R-10-110BL—65% glass fiber/mineral-filled, lower cost PPS resin [9].

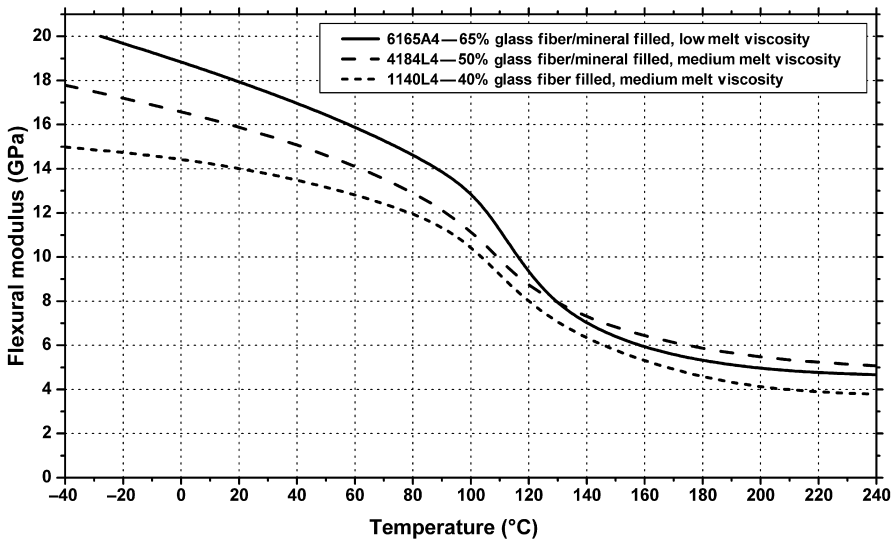


Figure 10.96 Flexural modulus vs. temperature for Celanese Fortron® glass fiber-filled PPS resins [10].

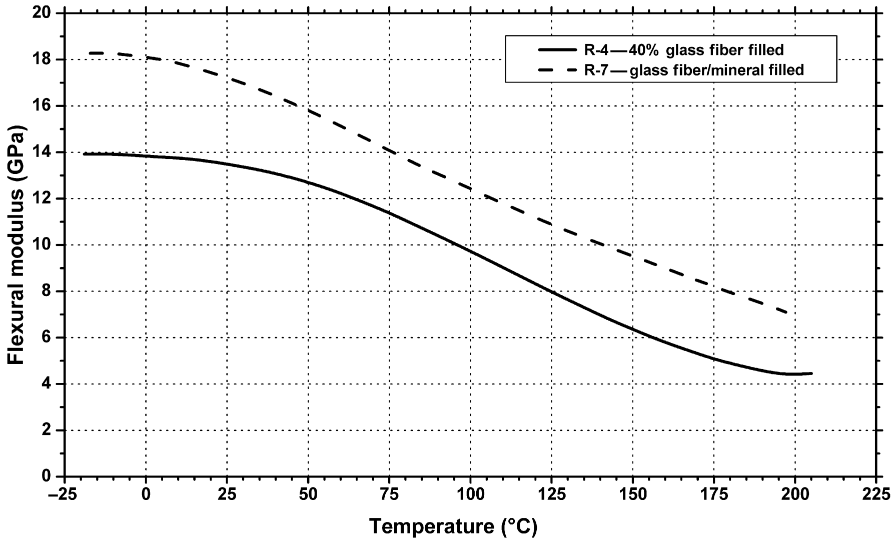


Figure 10.97 Flexural modulus vs. temperature for Chevron Phillips Chemical Ryton® PPS resins [11].

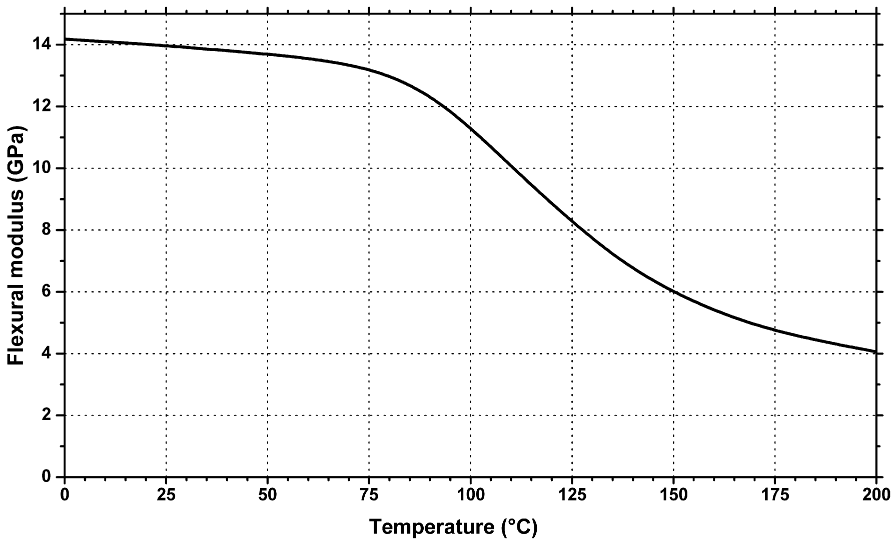


Figure 10.98 Flexural modulus vs. temperature for Toray Resin Company Torelina® A504—40% glass fiber-filled, standard grade PPS resin [12].

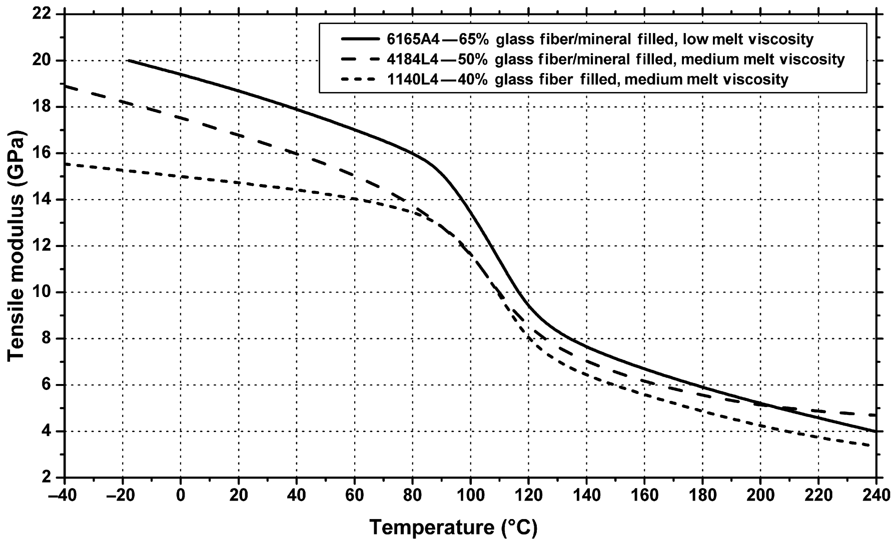


Figure 10.99 Tensile modulus vs. temperature for Celanese Fortron® filled PPS resins [10].

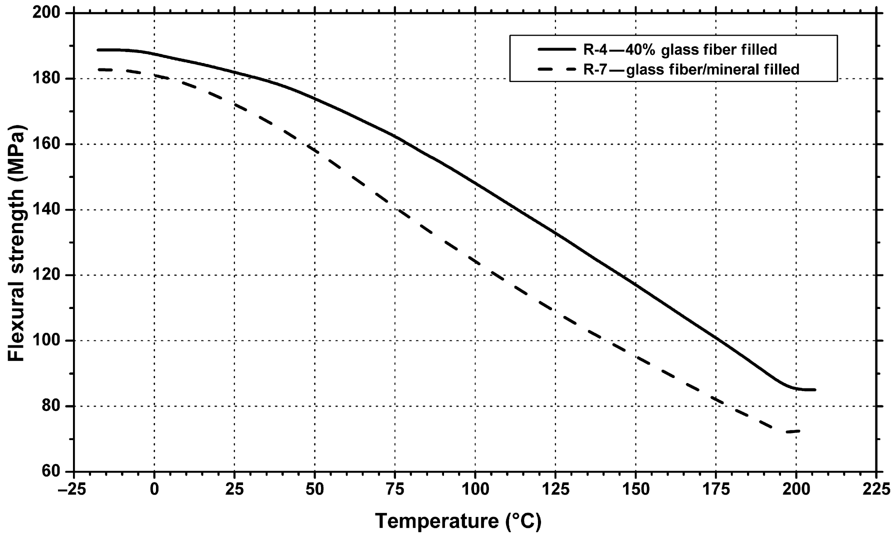


Figure 10.100 Flexural strength vs. temperature for Chevron Phillips Chemical Ryton® PPS resins [11].

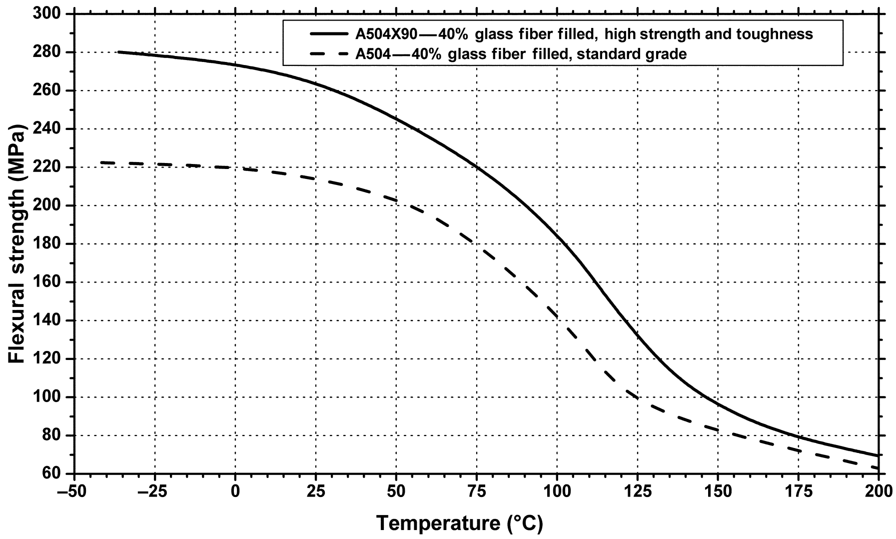


Figure 10.101 Flexural strength vs. temperature for Toray Resin Company Torelina® PPS resins [12].

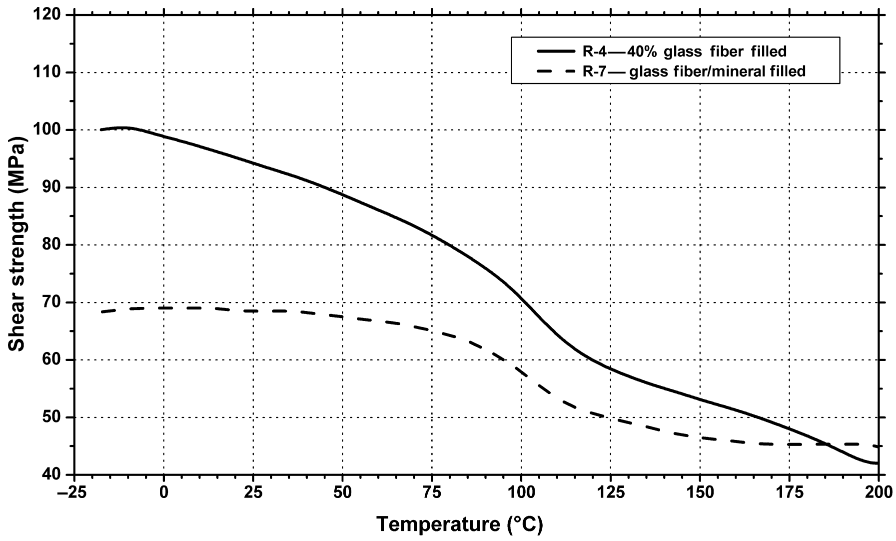


Figure 10.102 Shear strength vs. temperature for Chevron Phillips Chemical Ryton® PPS resins [11].

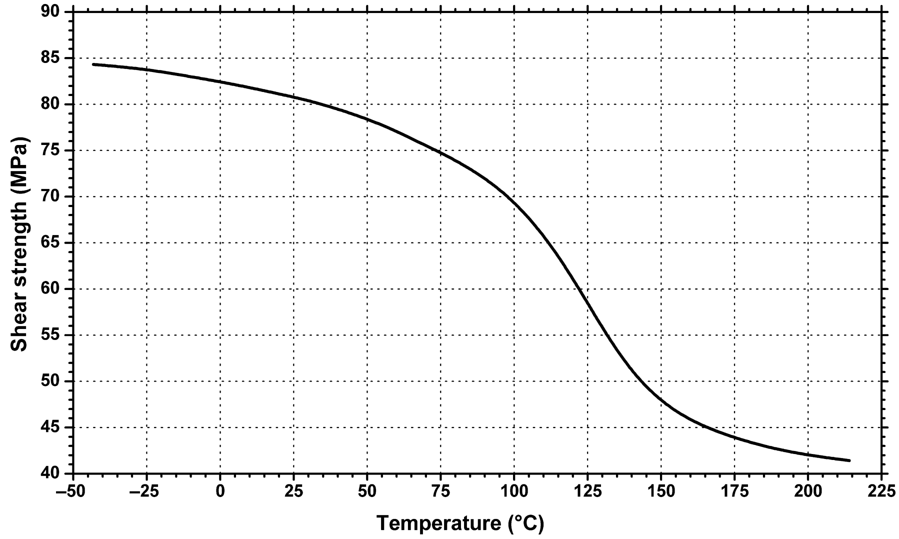


Figure 10.103 Shear strength vs. temperature for Toray Resin Company Torelina® A504—40% glass fiber-filled, standard grade PPS resin.

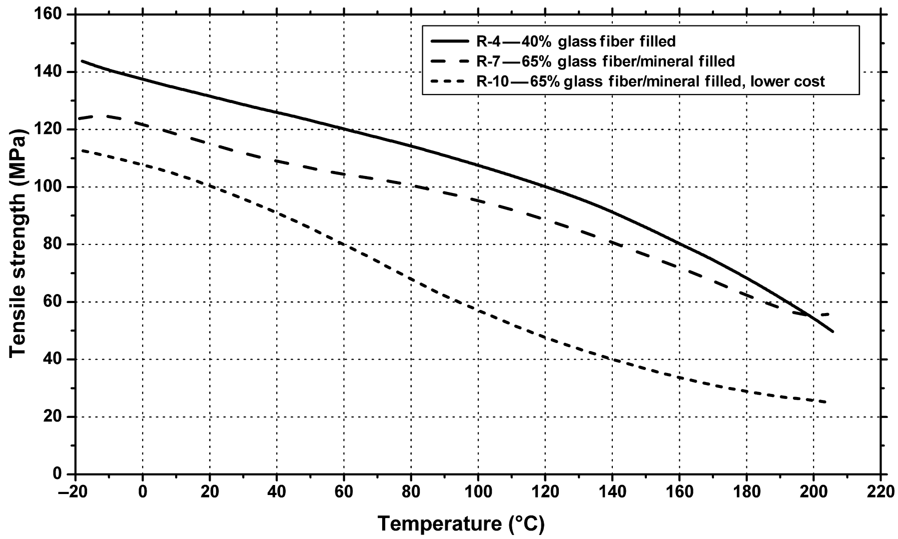


Figure 10.104 Tensile strength vs. temperature for Chevron Phillips Chemical Ryton® PPS resins [11].

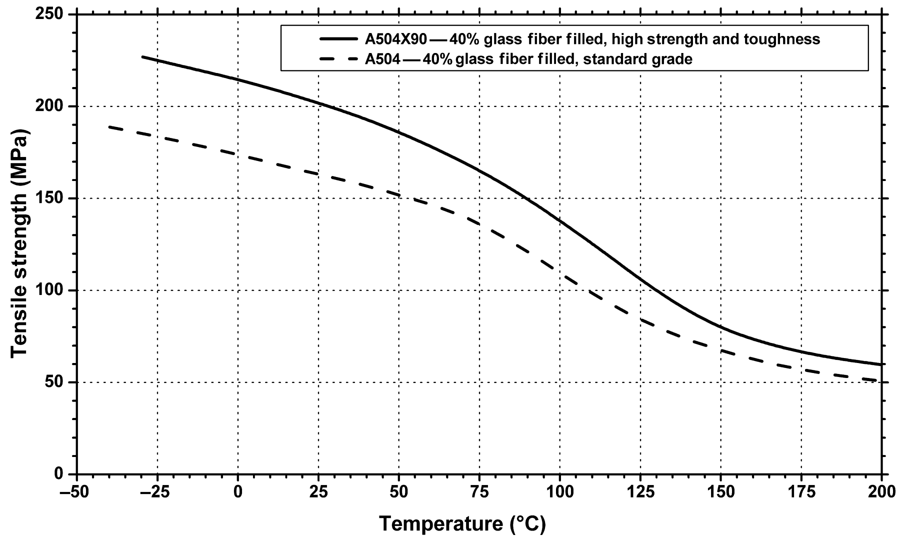


Figure 10.105 Tensile strength vs. temperature for Toray Resin Company Torelina® PPS resins [12].

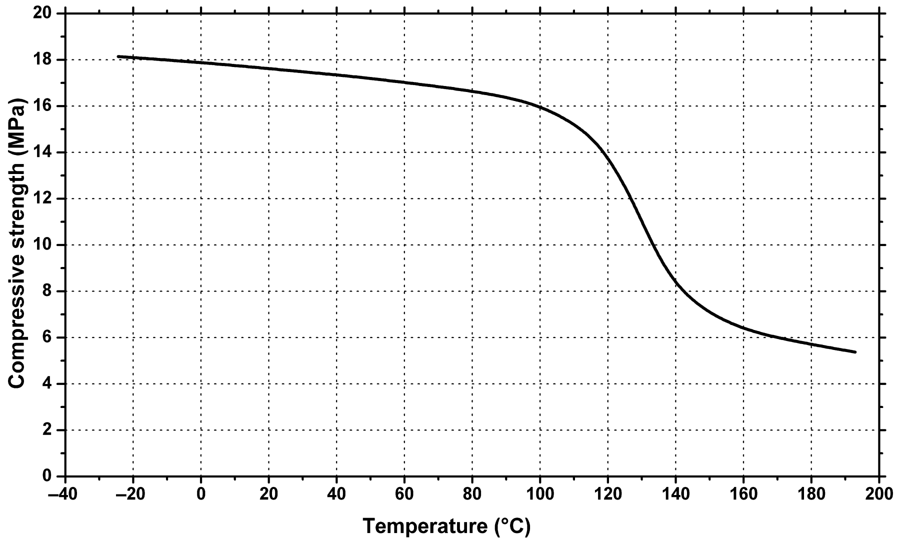


Figure 10.106 Compressive strength vs. temperature for Toray Resin Company Torelina® A504—40% glass fiber-filled, standard grade PPS resin [12].

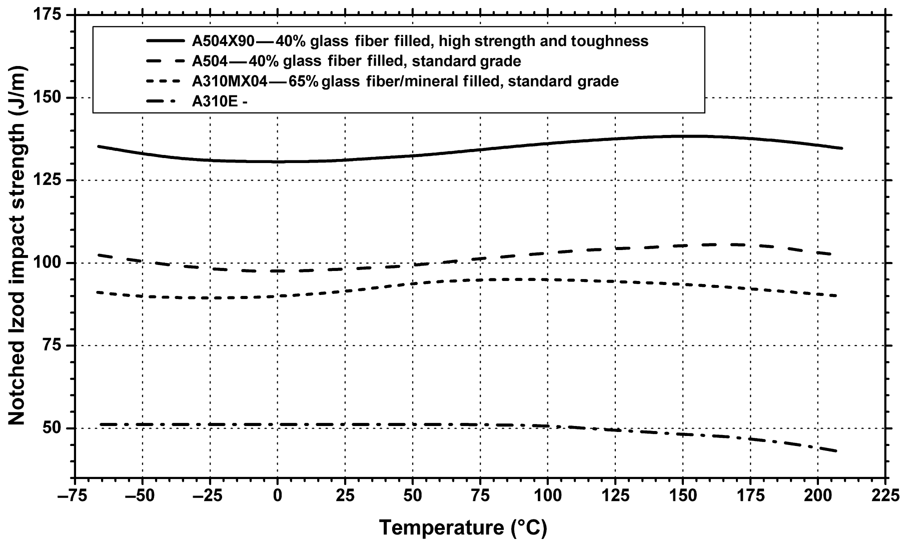


Figure 10.107 Notched Izod impact strength vs. temperature for Toray Resin Company Torelina® PPS resins [12].

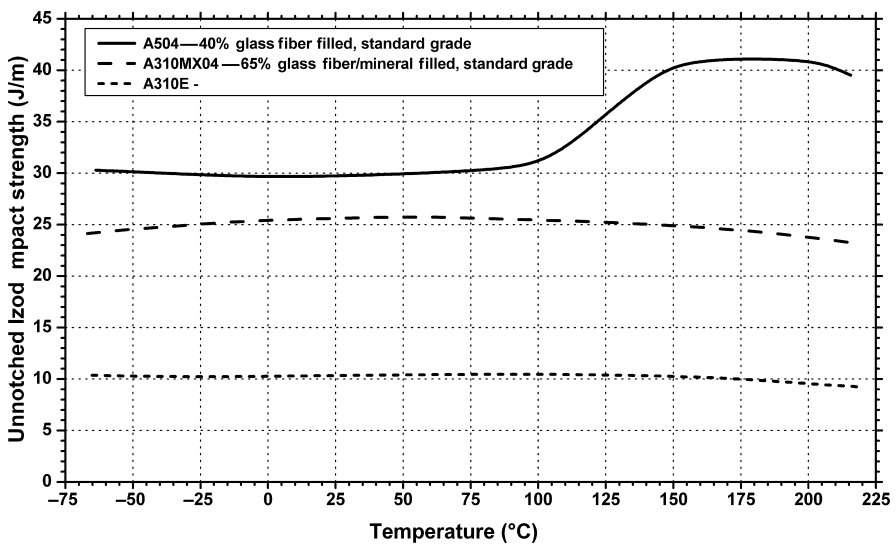


Figure 10.108 Unnotched Izod impact strength vs. temperature for Toray Resin Company Torelina® PPS resins [12].

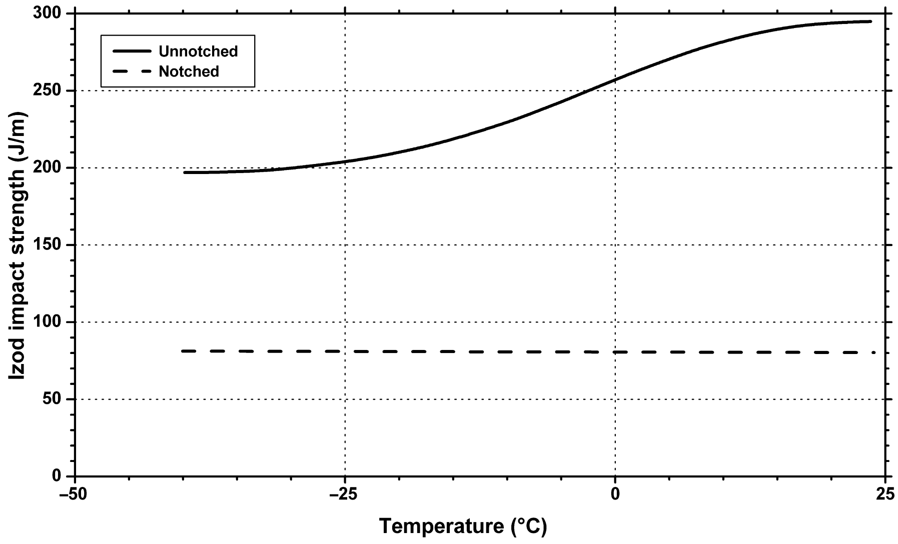


Figure 10.109 Izod impact strength vs. low temperature for Chevron Phillips Chemical Ryton® R-4—40% glass fiber-filled, high-strength PPS resin [11].

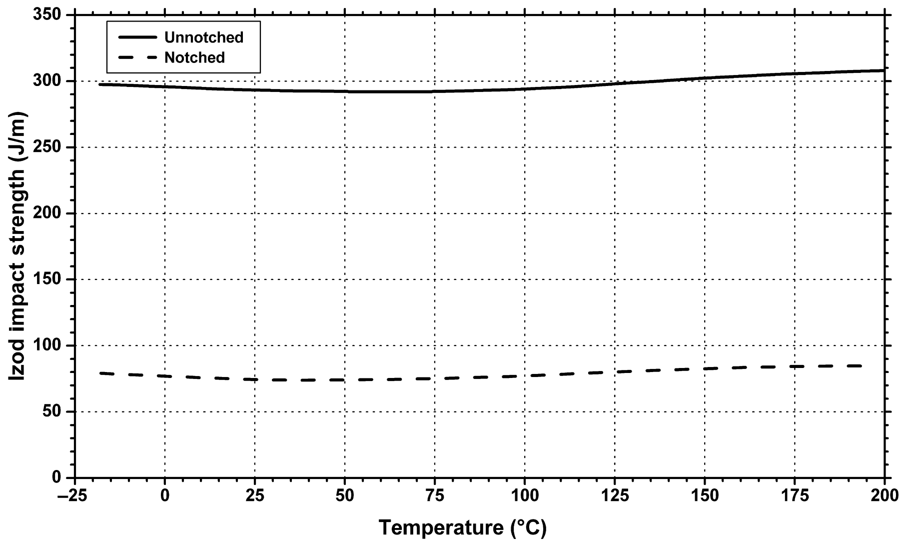


Figure 10.110 Izod impact strength vs. high temperature for Chevron Phillips Chemical Ryton® R-4—40% glass fiber-filled, high-strength PPS resin [11].

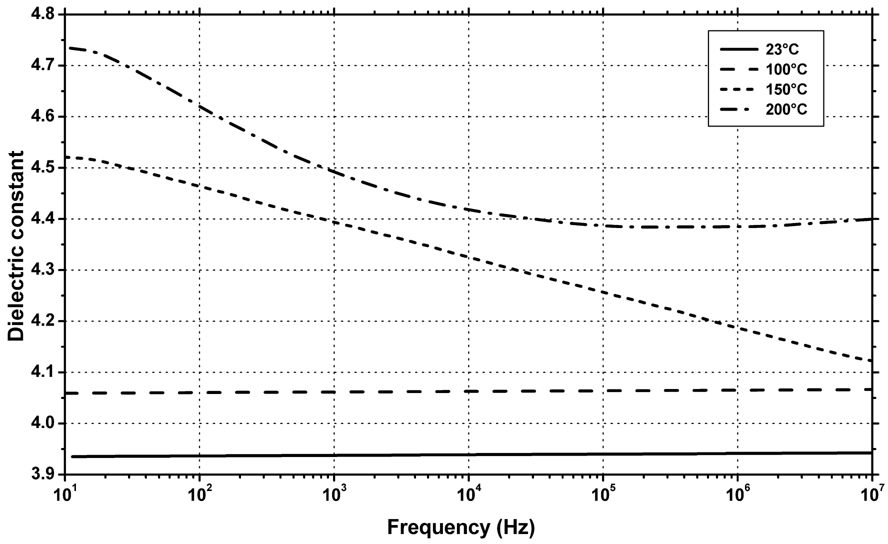


Figure 10.111 Dielectric constant vs. frequency and temperature for Chevron Phillips Chemical Ryton® R-4—40% glass fiber-filled, high-strength PPS resin [13].

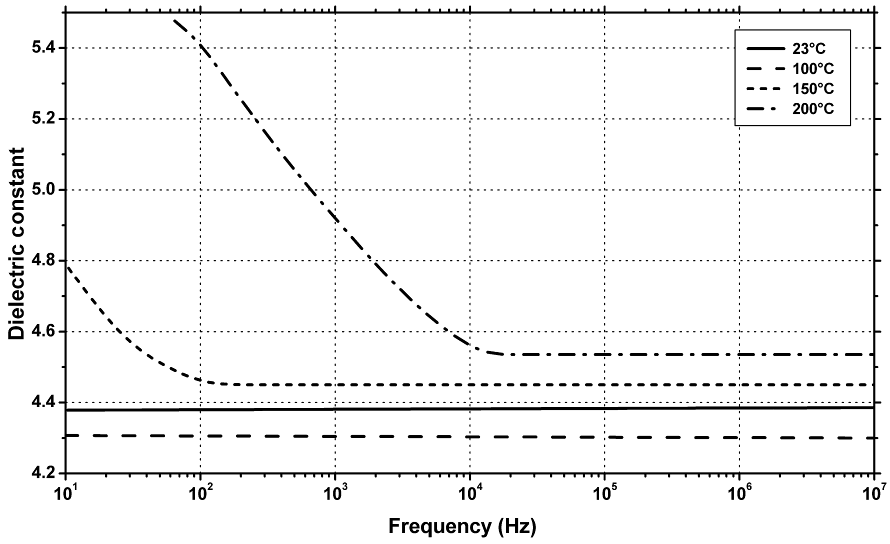


Figure 10.112 Dielectric constant vs. frequency and temperature for Chevron Phillips Chemical Ryton® R-7—65% glass fiber/mineral-filled PPS resin [13].

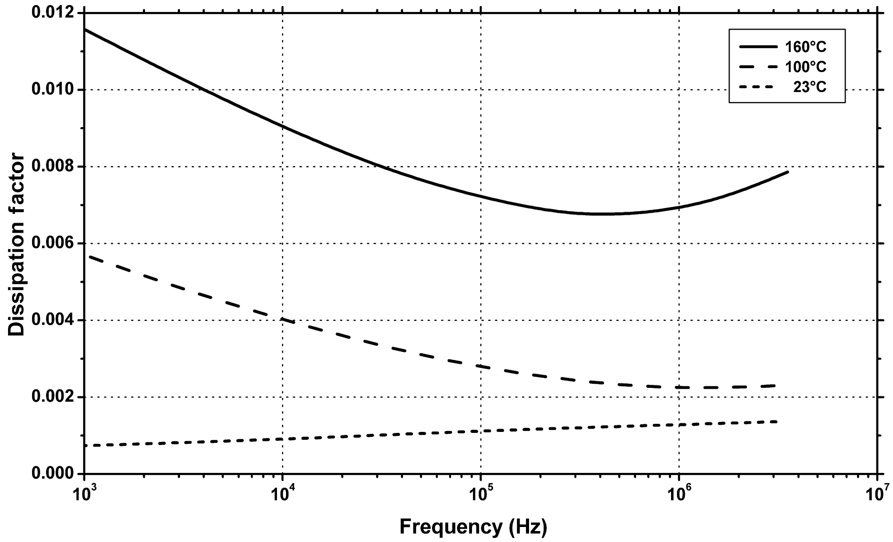


Figure 10.113 Dissipation factor vs. frequency at several temperatures for Celanese Fortron® 1140L4—40% glass fiber-filled, medium melt viscosity PPS resin [10].

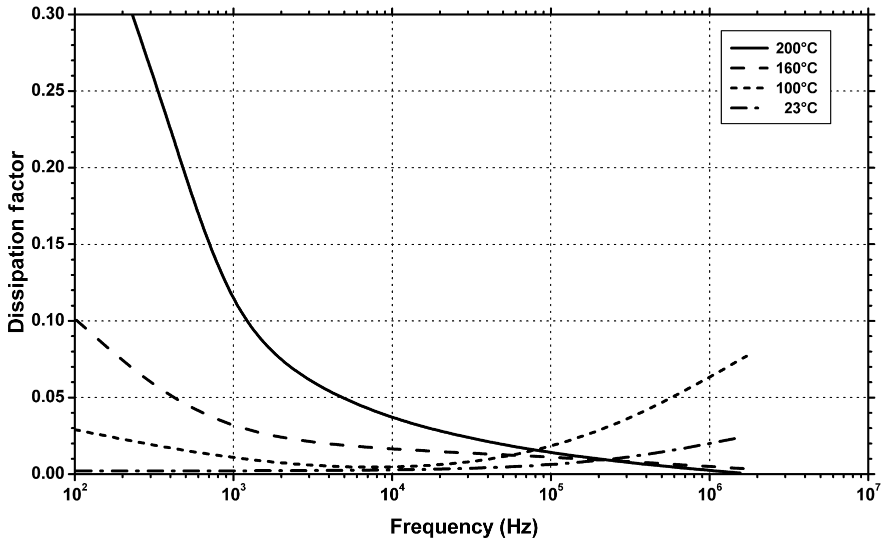


Figure 10.114 Dissipation factor vs. frequency at several temperatures for Celanese Fortron® 6160B4—60% glass fiber/mineral-filled PPS resin [10].

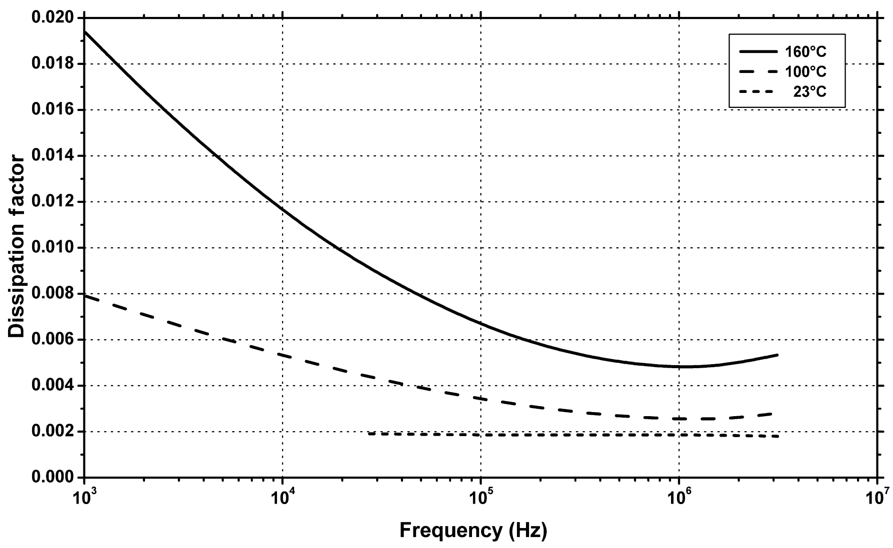


Figure 10.115 Dissipation factor vs. frequency at several temperatures for Celanese Fortron® 6165A4—65% glass fiber/mineral-filled, low melt viscosity PPS resin [10].

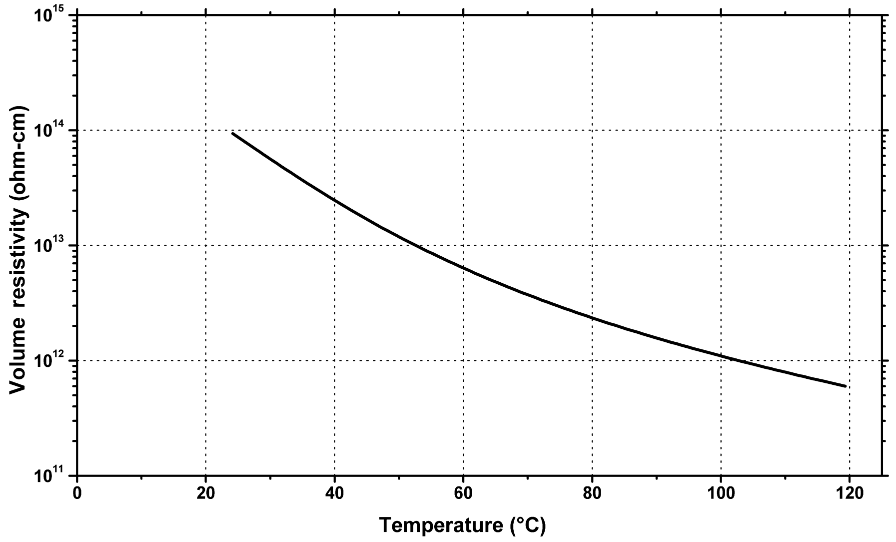


Figure 10.116 Volume resistivity vs. temperature for Celanese Fortron® 1140L4—40% glass fiber-filled, medium melt viscosity PPS resin.

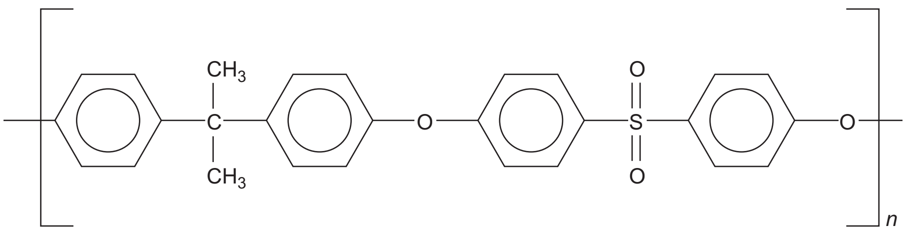


Figure 10.117 Structure of PSU.

The data for PSU plastics are shown in Figures 10.118–10.144.

10.5 Polyphenylsulfone (PPSU)

Polyphenylsulfone (PPSU) is a rigid, strong, tough, high temperature amorphous thermoplastic. It has a high heat deflection temperature of 405°F (207°C). It can withstand continuous exposure to heat and still absorb tremendous impact without cracking or breaking. It is inherently flame retardant and offers exceptional resistance to bases and other chemicals. The structure of PPSU is shown in Figure 10.145.

Its properties are summarized as follows:

- High deflection temperatures
- Steam sterilizable with high retention of impact properties

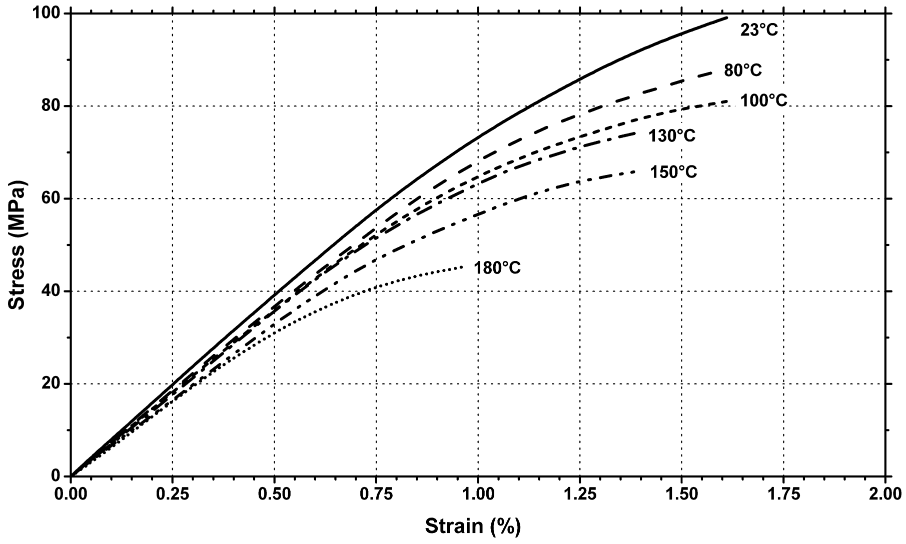


Figure 10.118 Stress vs. strain at several temperatures for Solvay Advanced Polymers Udel® GF-130—30% glass fiber-reinforced PSU resin.

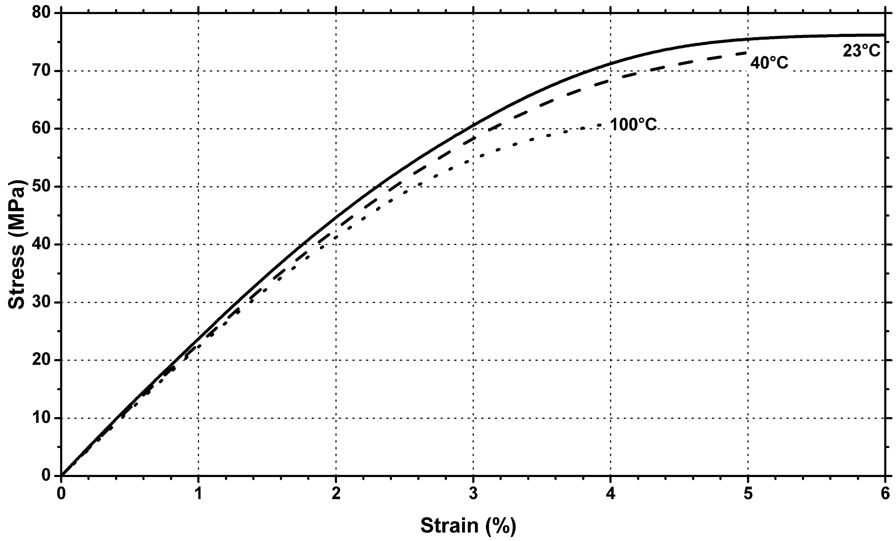


Figure 10.119 Stress vs. strain at several temperatures for Solvay Advanced Polymers Udel® P-1700—unreinforced, mid-viscosity PSU resin.

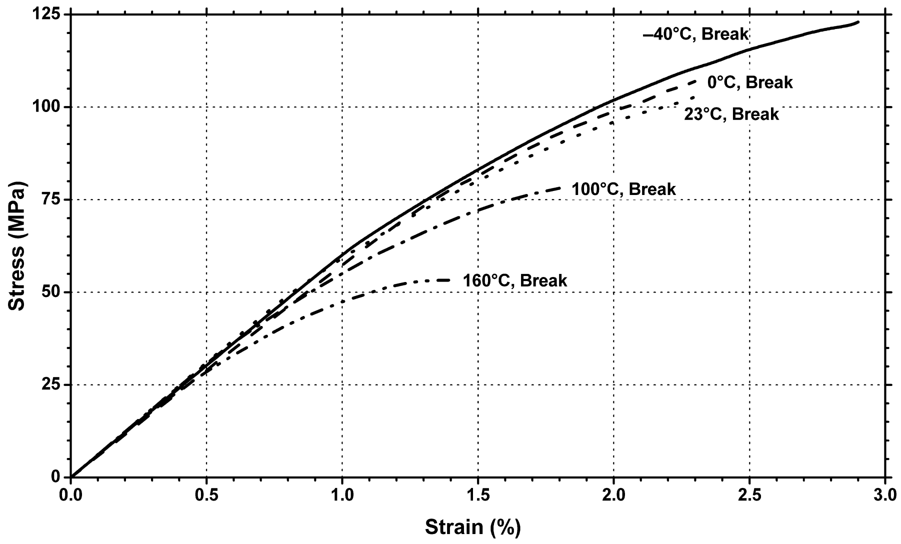


Figure 10.120 Stress vs. strain at several temperatures for BASF Ultrason® S 2010 G4—20% glass-reinforced, medium viscosity PSU resin.

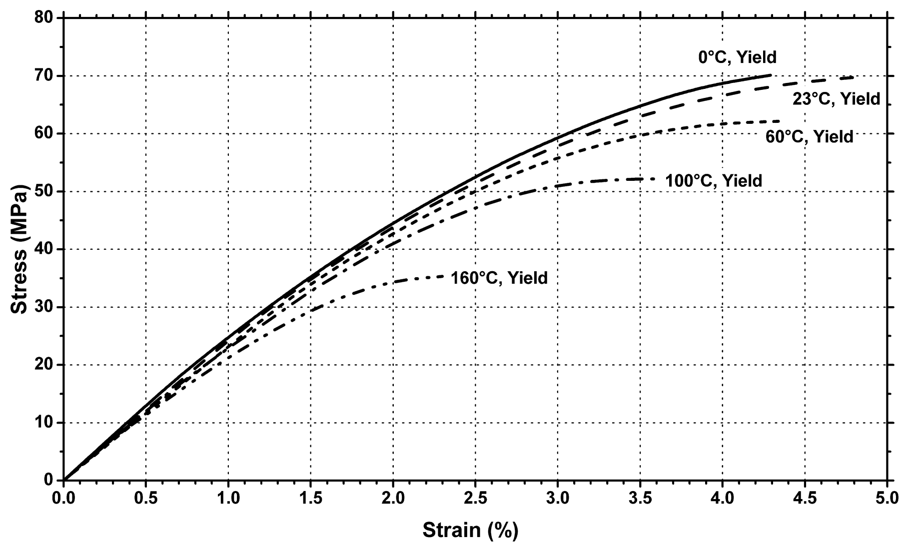


Figure 10.121 Stress vs. strain at several temperatures for BASF Ultrason® S 2010—unreinforced, medium viscosity PSU resin.

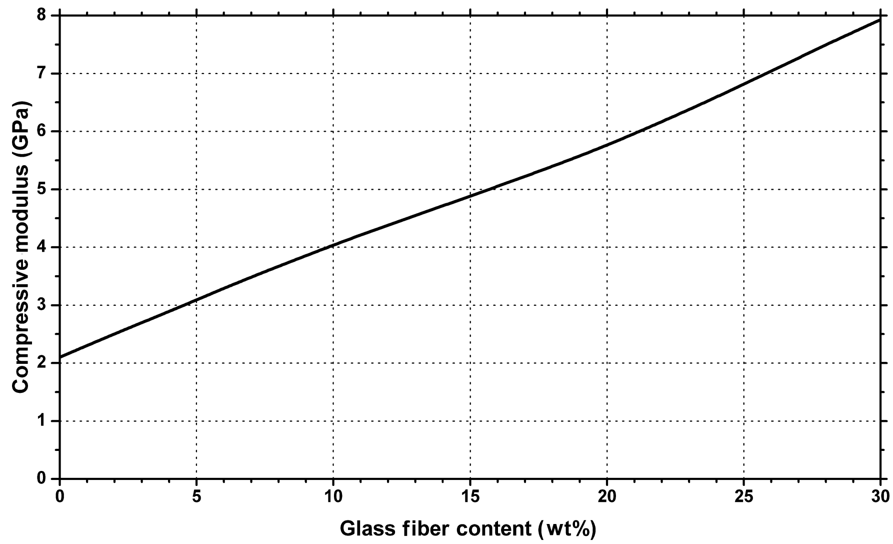


Figure 10.122 Compressive modulus vs. glass fiber content for Solvay Advanced Polymers Udel® PSU resins [14].

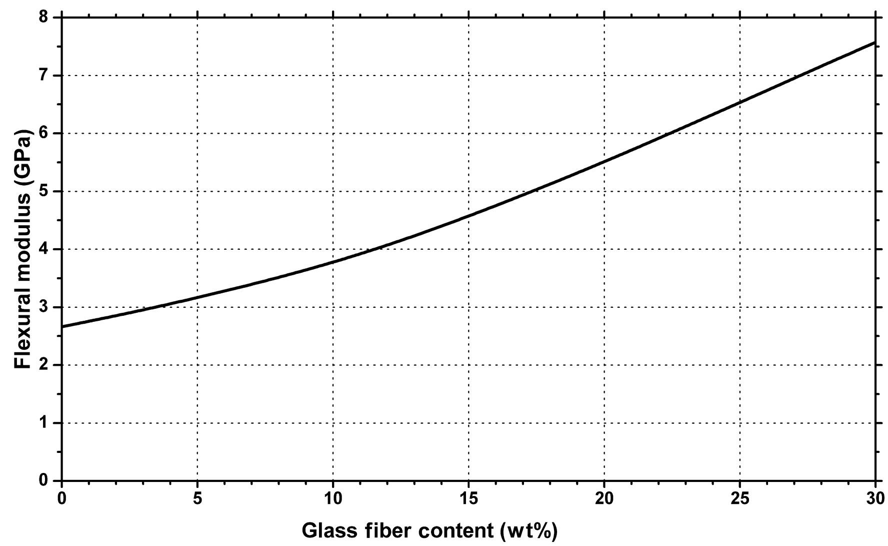


Figure 10.123 Flexural modulus vs. glass fiber content for Solvay Advanced Polymers Udel® PSU resins [14].

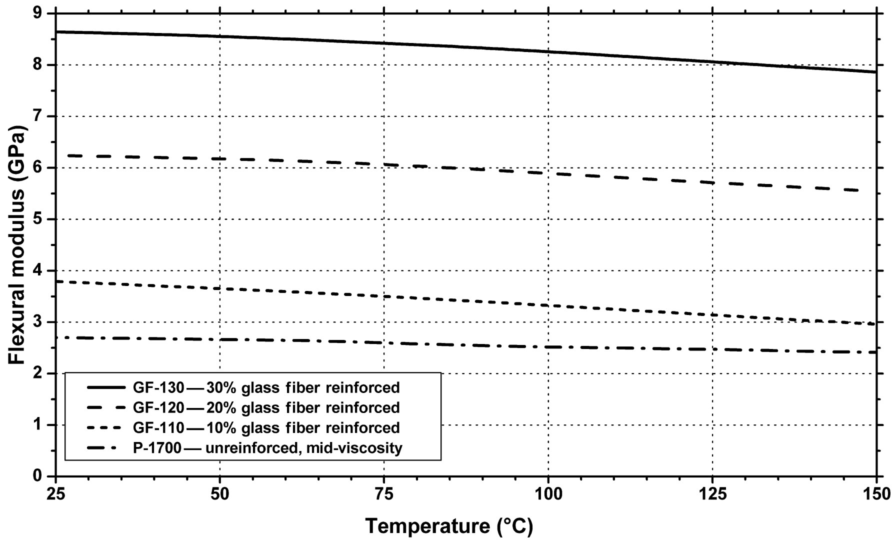


Figure 10.124 Flexural modulus vs. temperature for Solvay Advanced Polymers Udel® PSU resins [14].

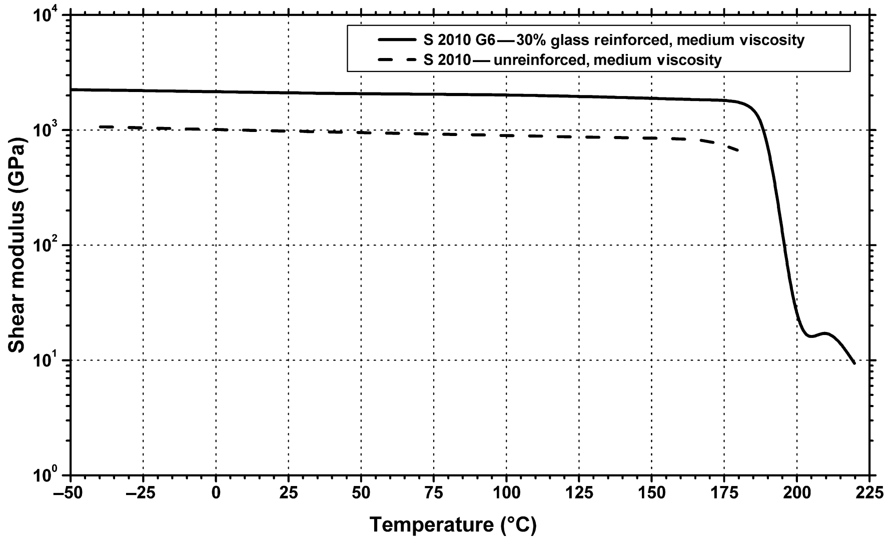


Figure 10.125 Shear modulus vs. temperature for BASF Ultrason® S PSU resins [14].

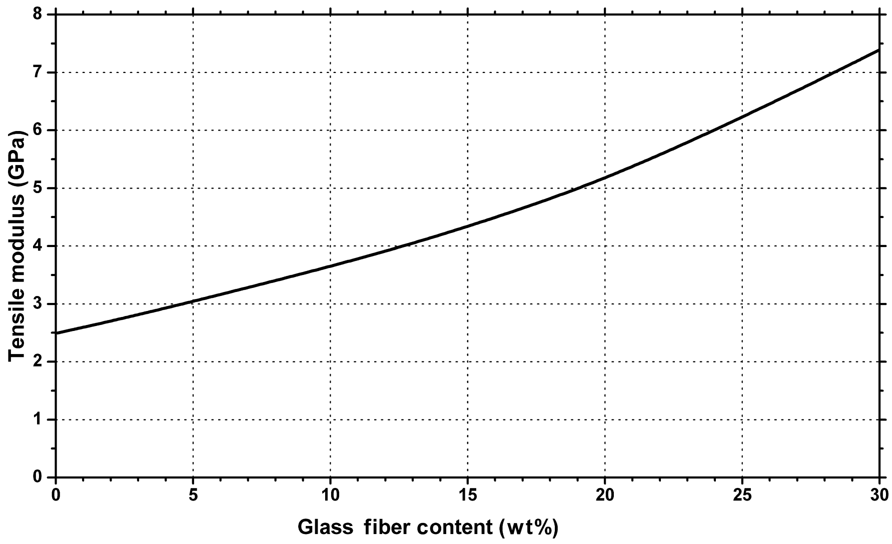


Figure 10.126 Tensile modulus vs. glass fiber content for Solvay Advanced Polymers Udel® PSU resins [14].

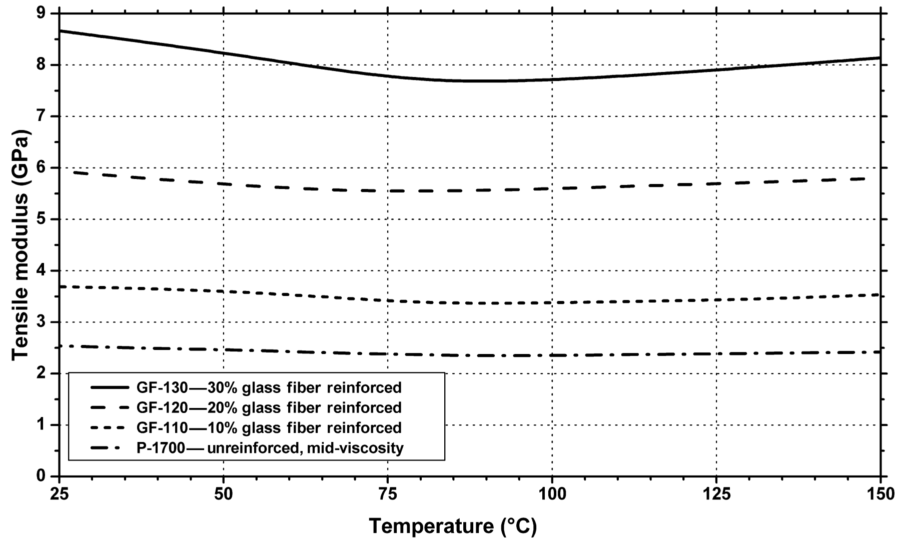


Figure 10.127 Tensile modulus vs. temperature for Solvay Advanced Polymers Udel® PSU resins [14].

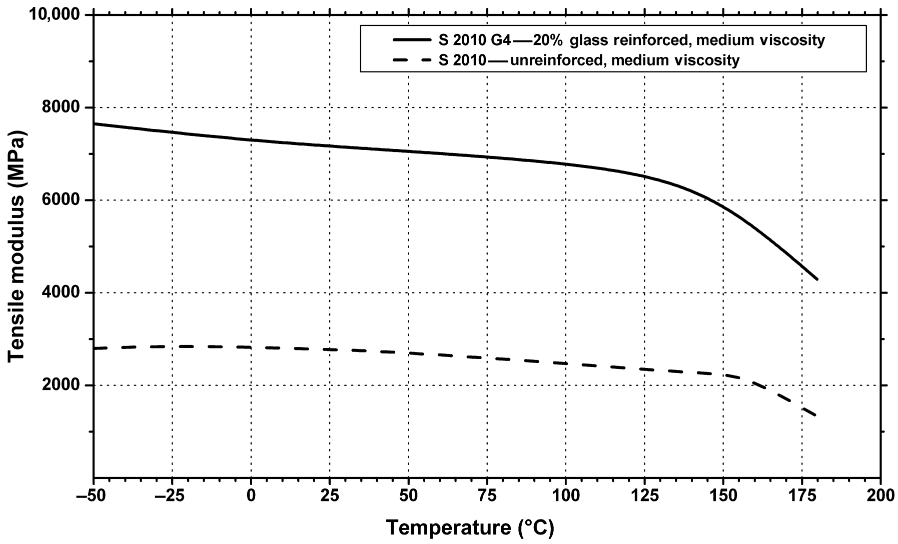


Figure 10.128 Tensile modulus vs. temperature for BASF Ultrason® S PSU resins.

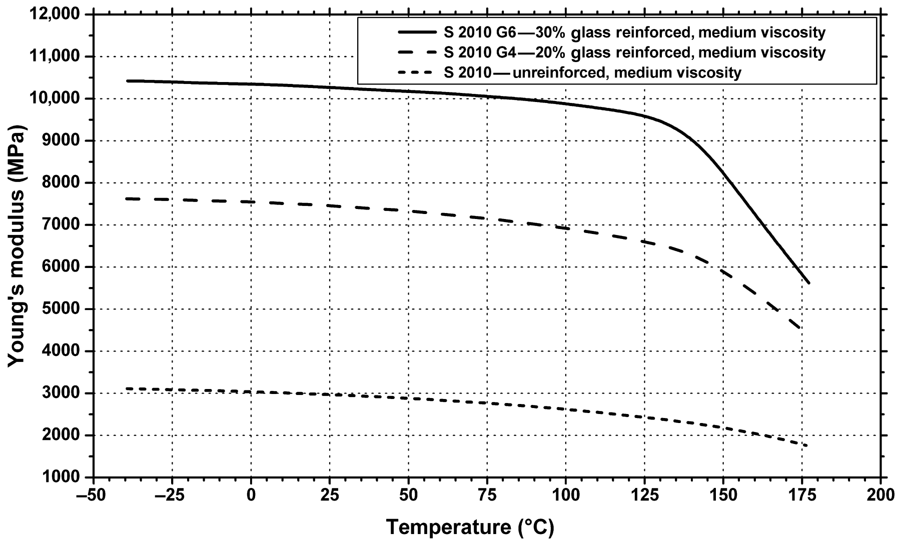


Figure 10.129 Young's modulus vs. temperature for BASF Ultrason® S PSU resins.

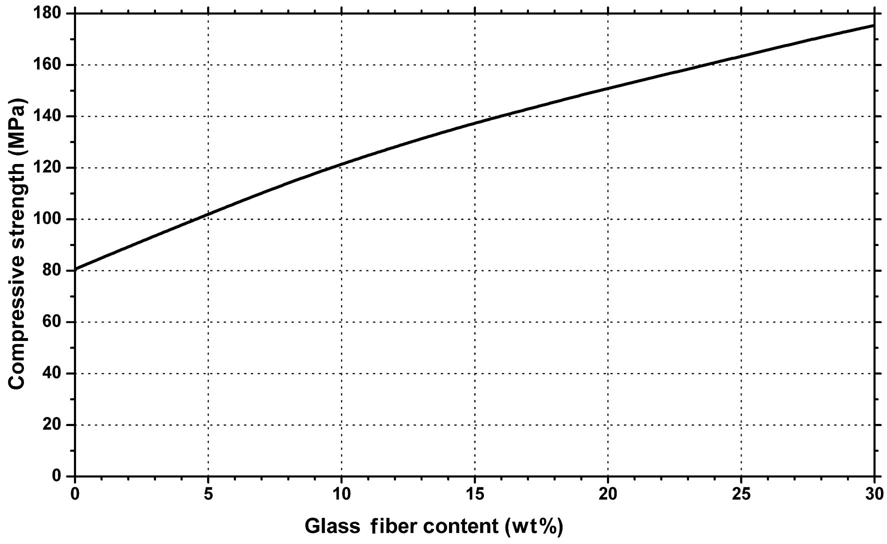


Figure 10.130 Compressive strength vs. glass fiber content for Solvay Advanced Polymers Udel® PSU resins [14].

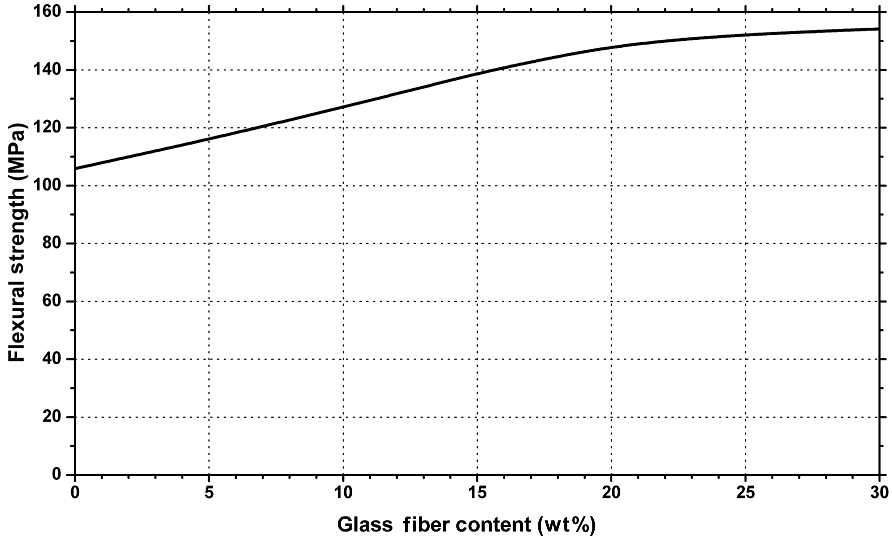


Figure 10.131 Flexural strength vs. glass fiber content for Solvay Advanced Polymers Udel® PSU resins [14].

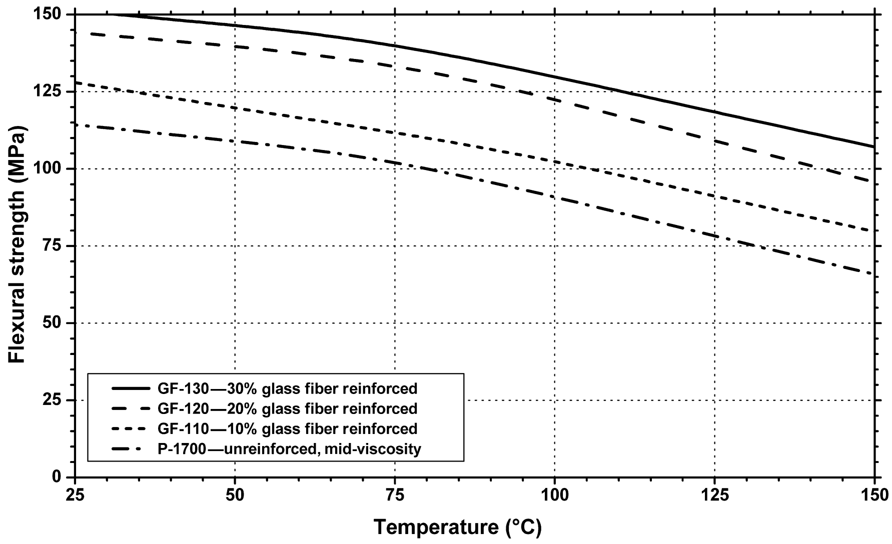


Figure 10.132 Flexural strength vs. temperature for Solvay Advanced Polymers Udel® PSU resins [14].

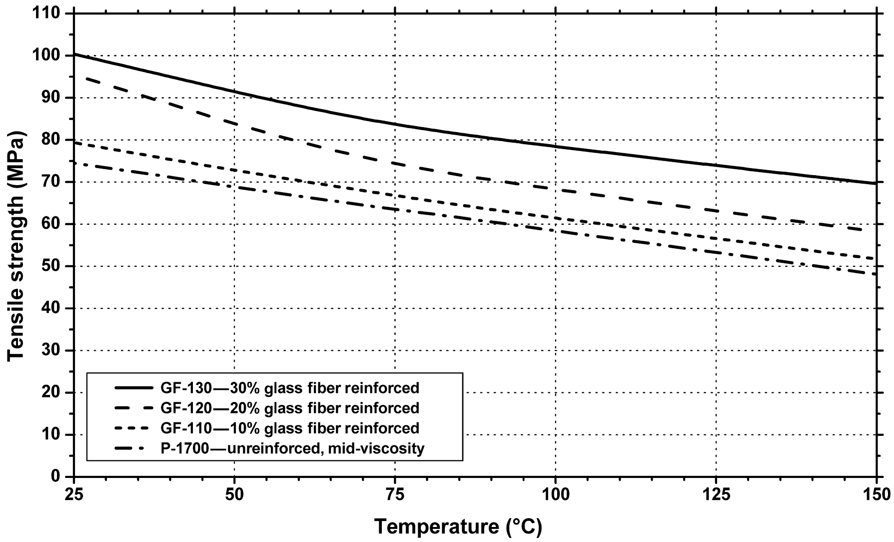


Figure 10.133 Tensile strength vs. temperature for Solvay Advanced Polymers Udel® PSU resins [14].

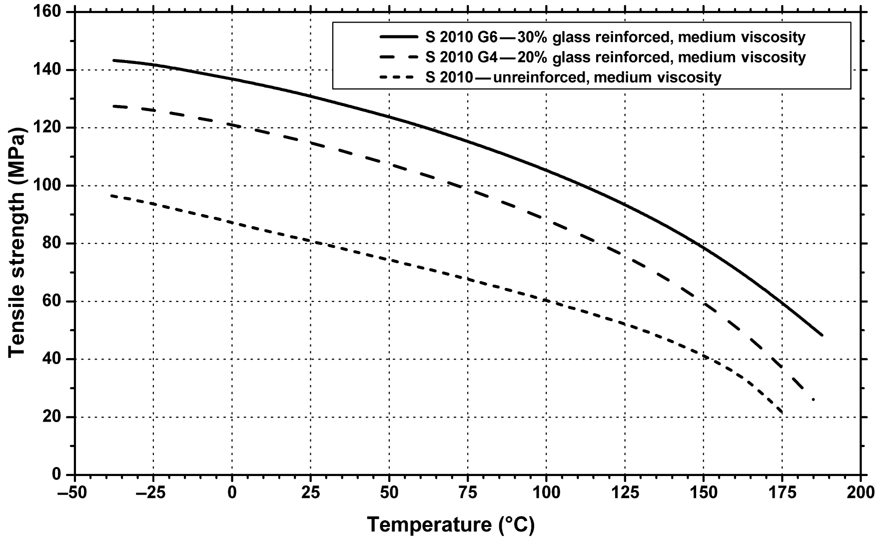


Figure 10.134 Tensile strength vs. temperature for BASF Ultrason® S PSU resins.

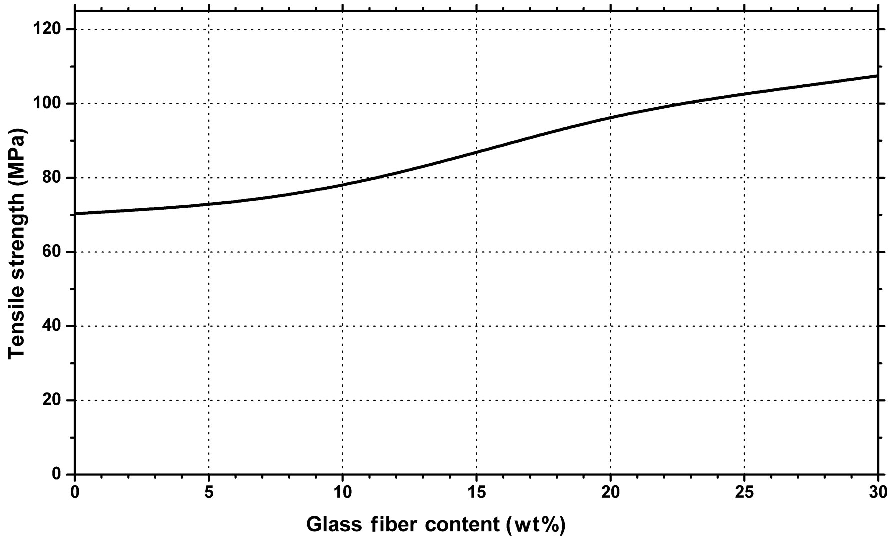


Figure 10.135 Tensile strength vs. glass fiber content for Solvay Advanced Polymers Udel® PSU resins [14].

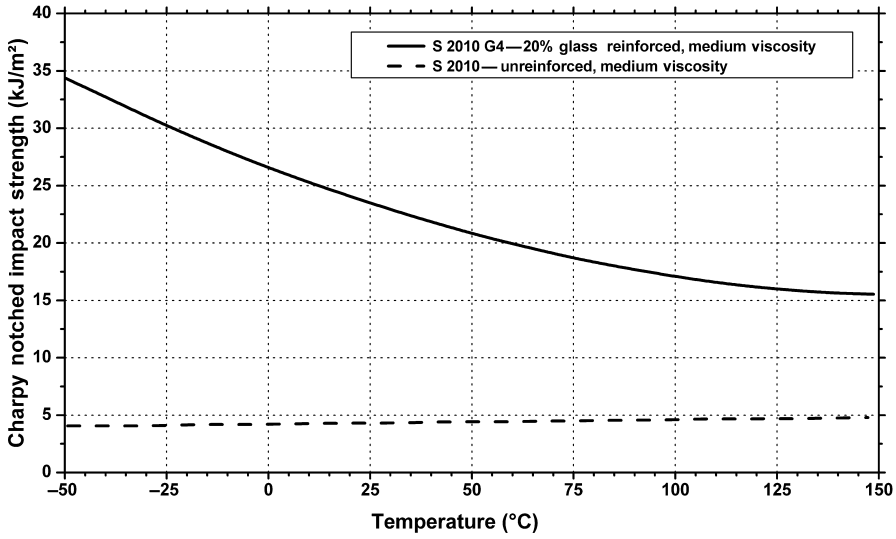


Figure 10.136 Charpy notched impact strength vs. temperature for BASF Ultrason® S 2010 PSU resins [15].

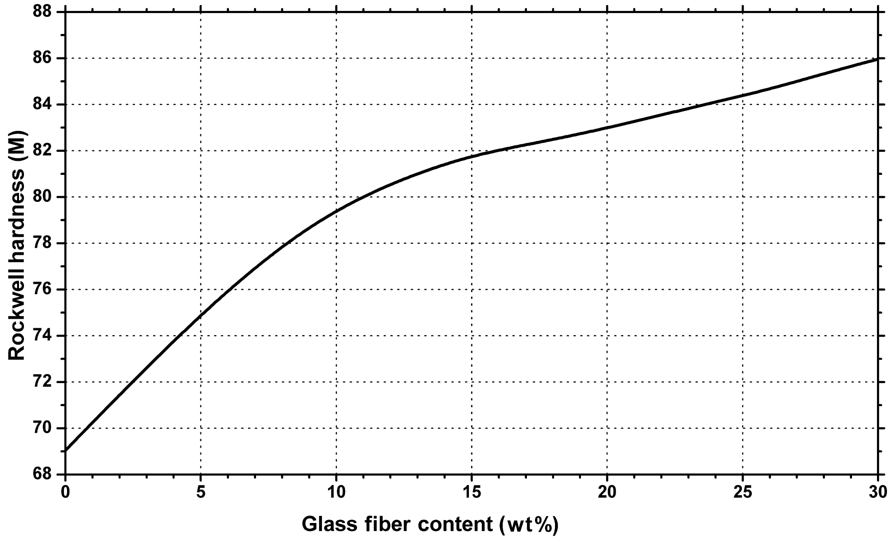


Figure 10.137 Rockwell hardness vs. glass fiber content for Solvay Advanced Polymers Udel® PSU resins [14].

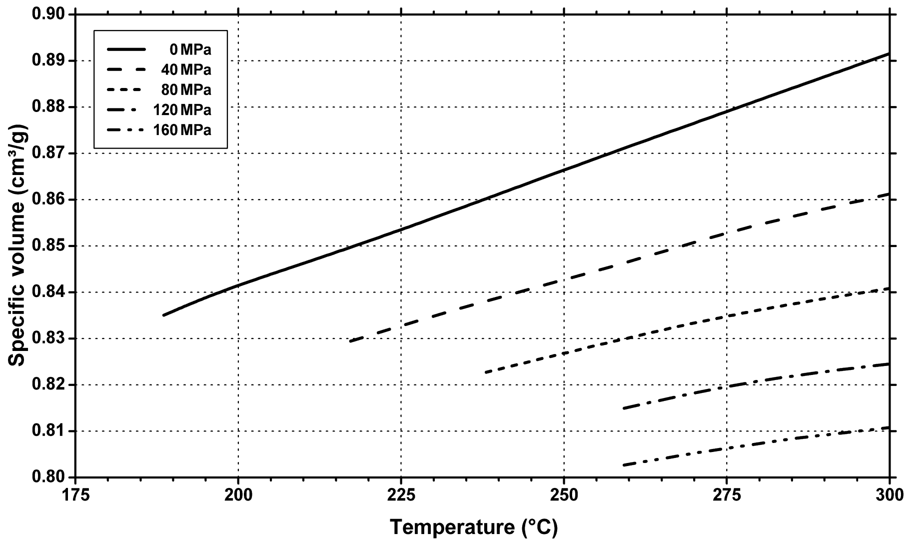


Figure 10.138 Specific volume as a function of temperature and pressure (PVT) of Solvay Advanced Polymers Udel® PSU resin [14].

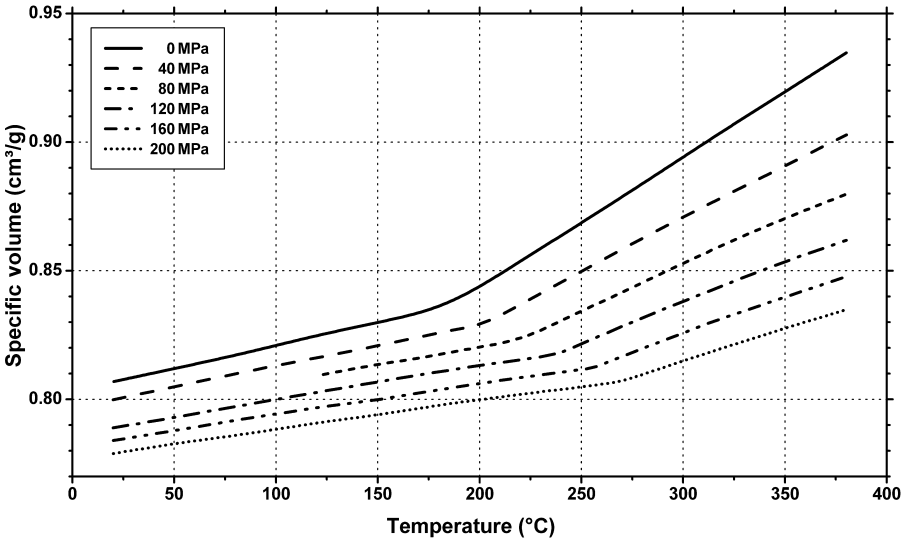


Figure 10.139 Specific volume as a function of temperature and pressure (PVT) of BASF Ultrason® S 2010—unreinforced, medium viscosity PSU resin.

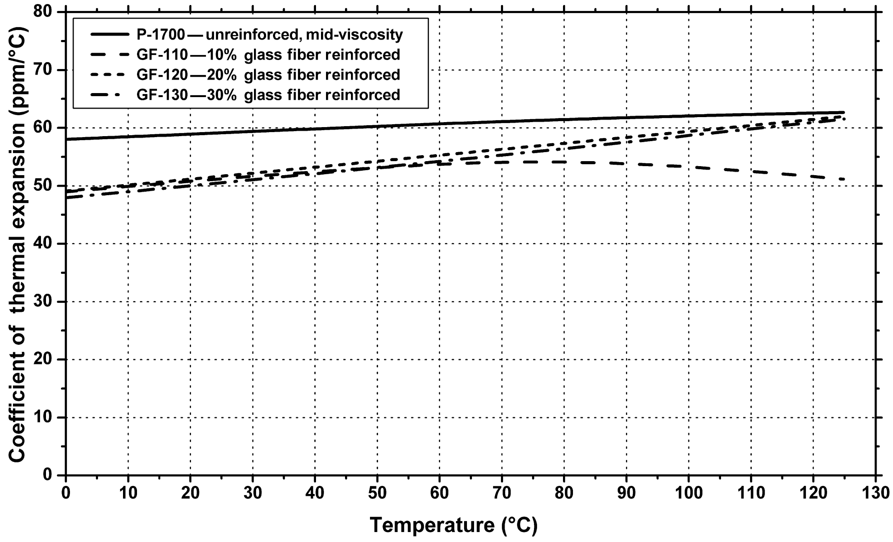


Figure 10.140 Coefficient of thermal expansion (cross flow direction) vs. temperature for Solvay Advanced Polymers Udel® PSU resins [14].

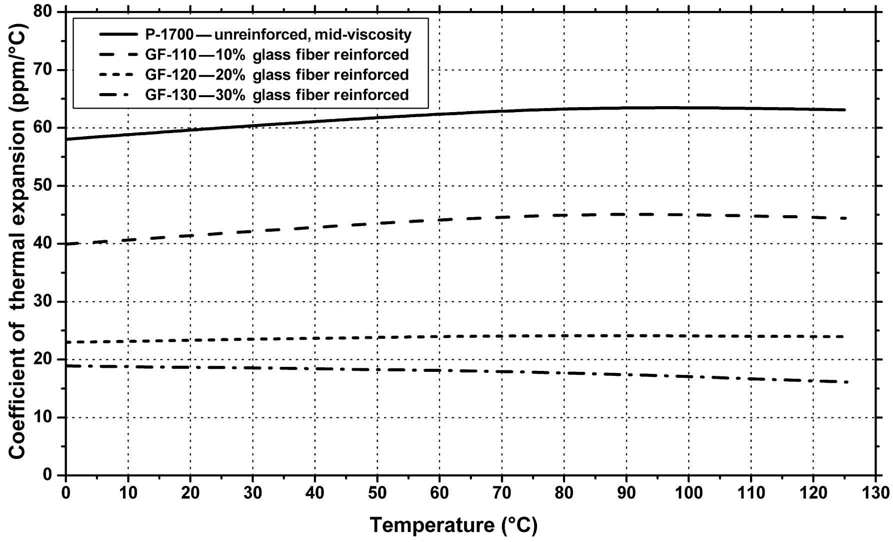


Figure 10.141 Coefficient of thermal expansion (flow direction) vs. temperature for Solvay Advanced Polymers Udel® PSU resins [14].

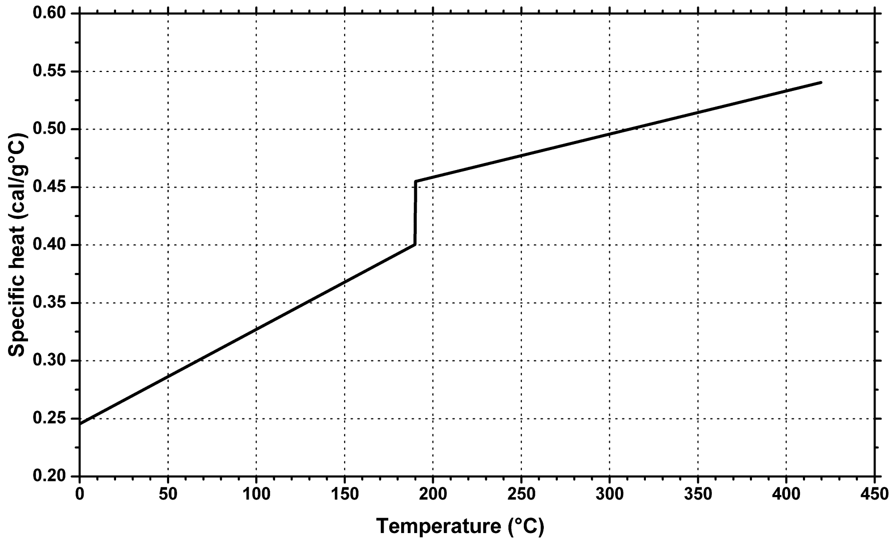


Figure 10.142 Specific heat vs. temperature for Solvay Advanced Polymers Udel® PSU resin [14].

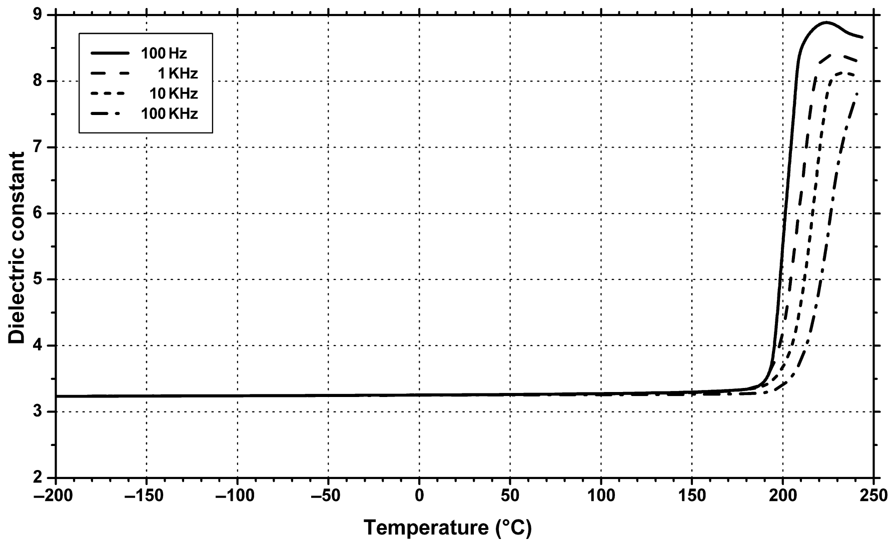


Figure 10.143 Dielectric constant vs. temperature and frequency for Ultrason® S 2010—unreinforced, medium viscosity PSU resins [15].

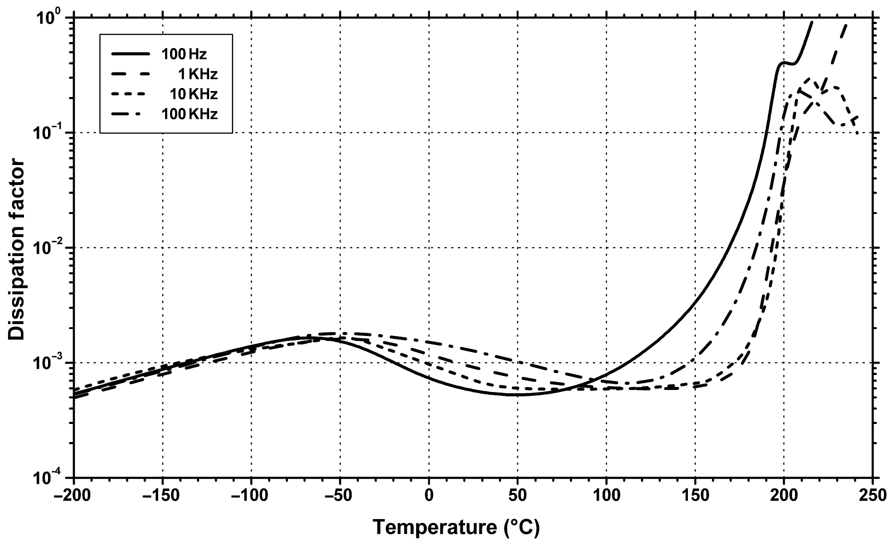


Figure 10.144 Dissipation factor vs. temperature and frequency for Ultrason® S 2010—unreinforced, medium viscosity PSU resins [15].

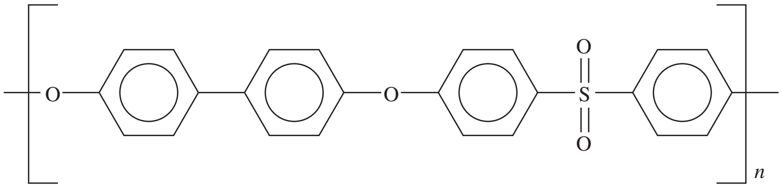


Figure 10.145 The structure of PPSU.

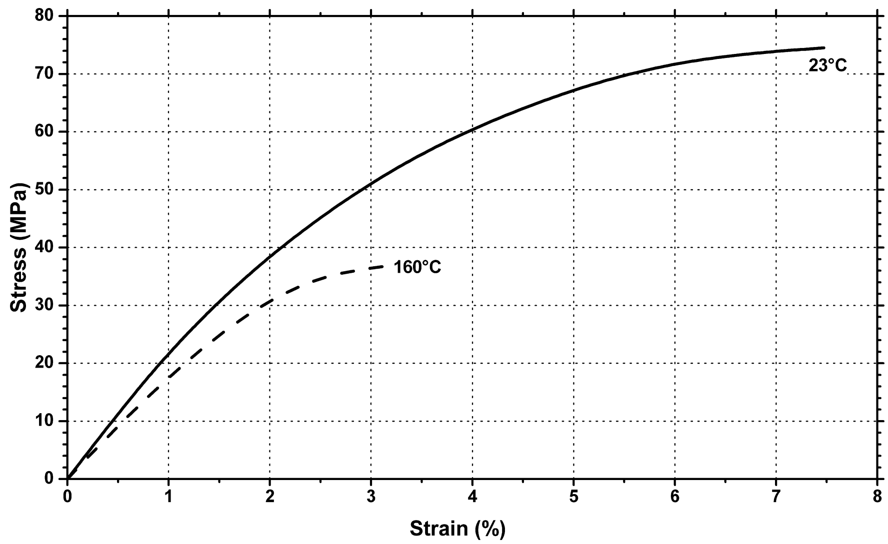


Figure 10.146 Stress–strain diagram (according to ISO 527) up to the yield point, at 23°C and 160°C for BASF Ultrason® P 3010 PPSU [6].

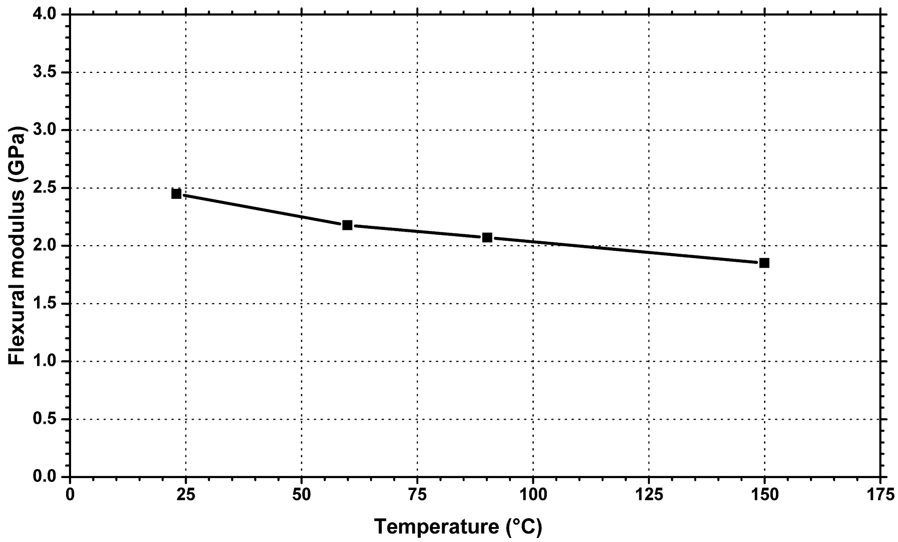


Figure 10.147 Flexural modulus vs. temperature for Solvay Radel® R unfilled PPSU [16].

- Inherently flame retardant
- Excellent thermal stability making films suitable
- For applications where very low shrink at high temperatures is needed
- Good electrical properties

Manufacturers and trade names: Solvay Advanced Plastics Radel® R, Evonik Industries Europlex®, BASF Ultrason® P.

Applications and uses: electrical/electronic, aircraft interiors, and automotive industry.

The data for PPSU plastics are shown in Figures 10.146–10.154.

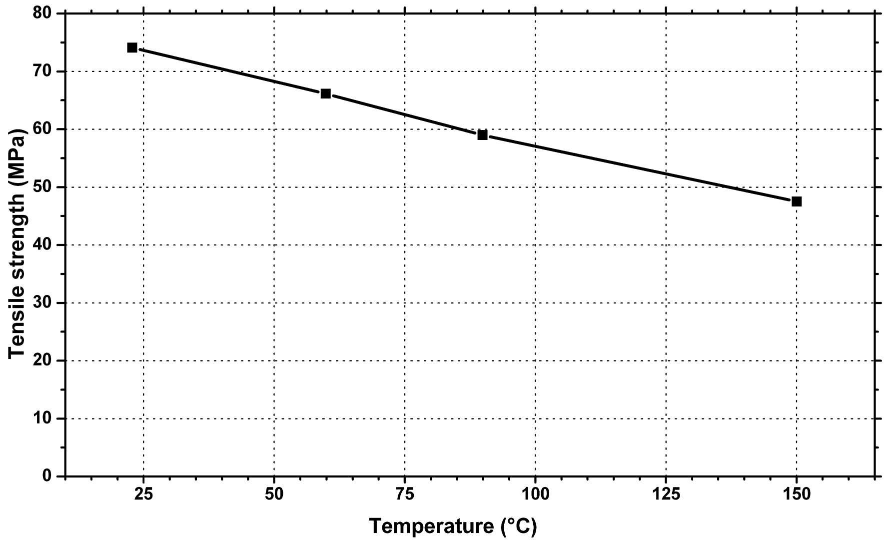


Figure 10.148 Tensile strength vs. temperature for Solvay Radel® R unfilled PPSU [16].

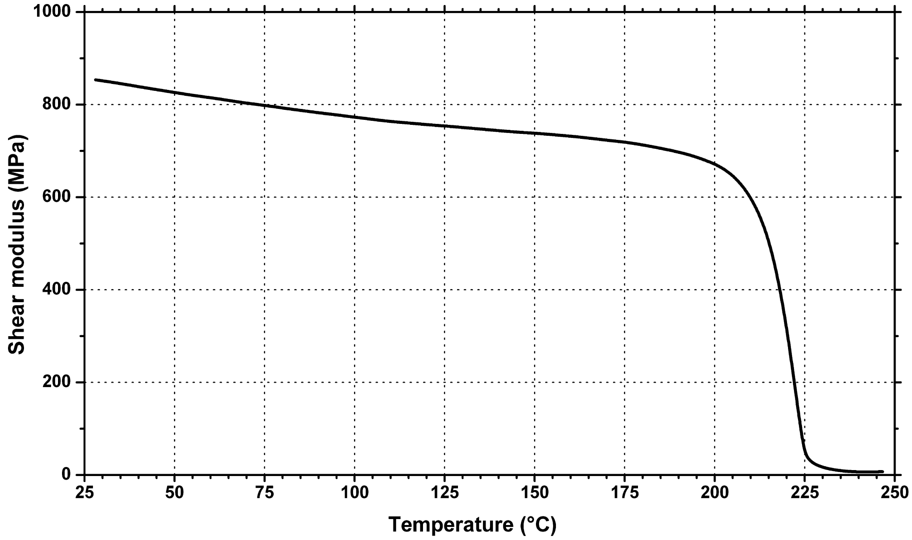


Figure 10.149 Shear modulus vs. temperature according to ISO 6721 for BASF Ultrason® P 3010 PPSU [6].

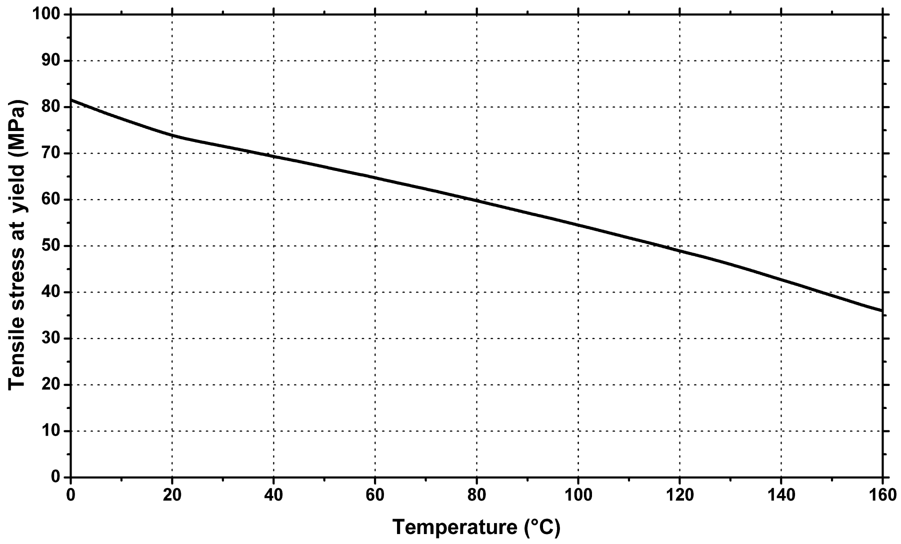


Figure 10.150 Temperature dependence of the tensile stress at yield (dry) of BASF Ultrason® P 3010 PPSU [6].

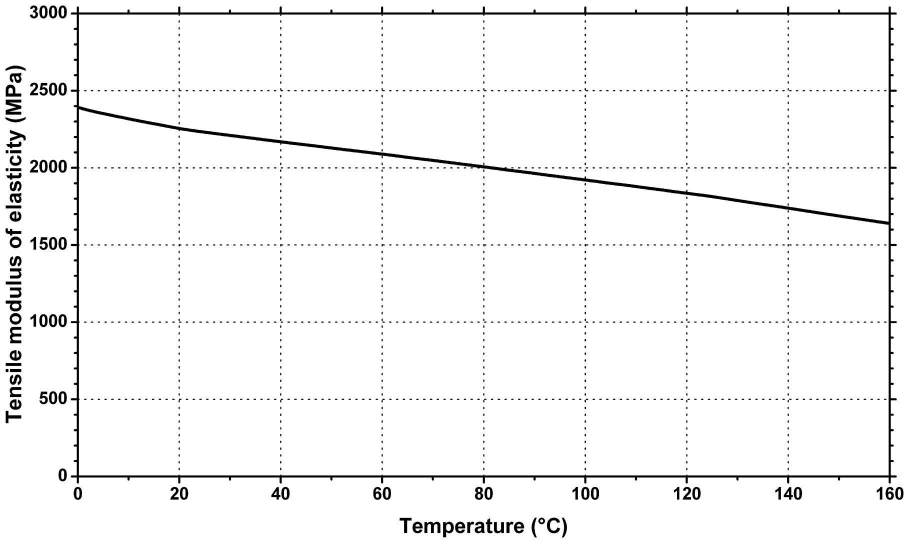


Figure 10.151 Modulus of elasticity (according to ISO 527) as a function of temperature (dry) of BASF Ultrason® P 3010 PPSU [6].

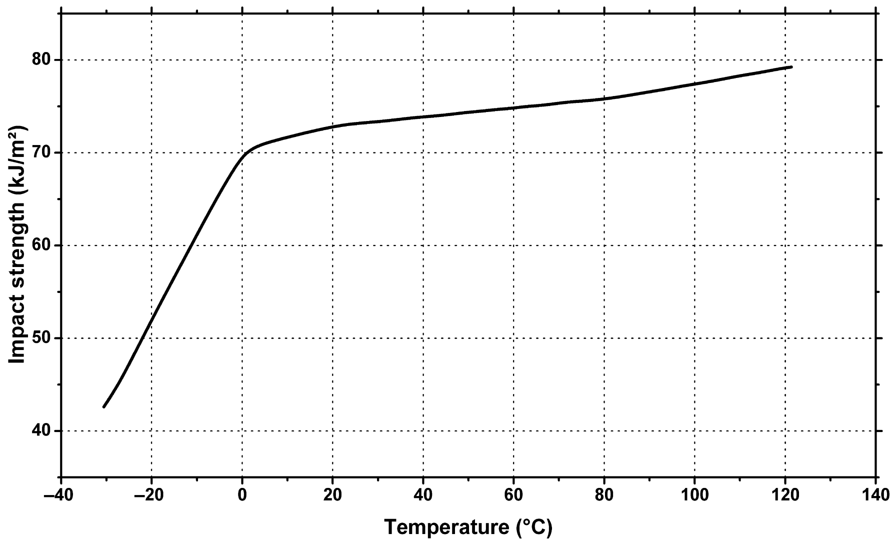


Figure 10.152 Impact strength as a function of temperature (unnotched according to ISO 179/1eU) of BASF Ultrason® P 3010 PPSU [6].

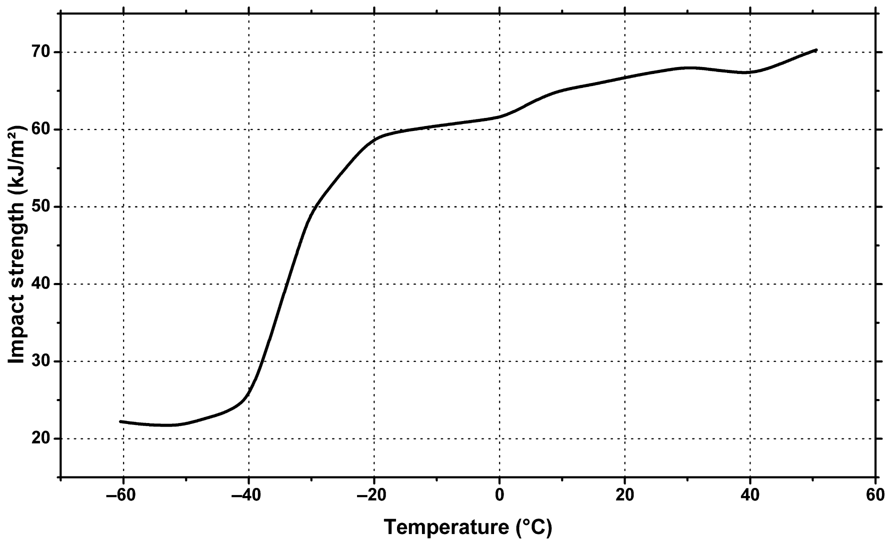


Figure 10.153 Notched impact strength as a function of temperature (ISO 179/1eA) of BASF Ultrason® P 3010 PPSU [6].

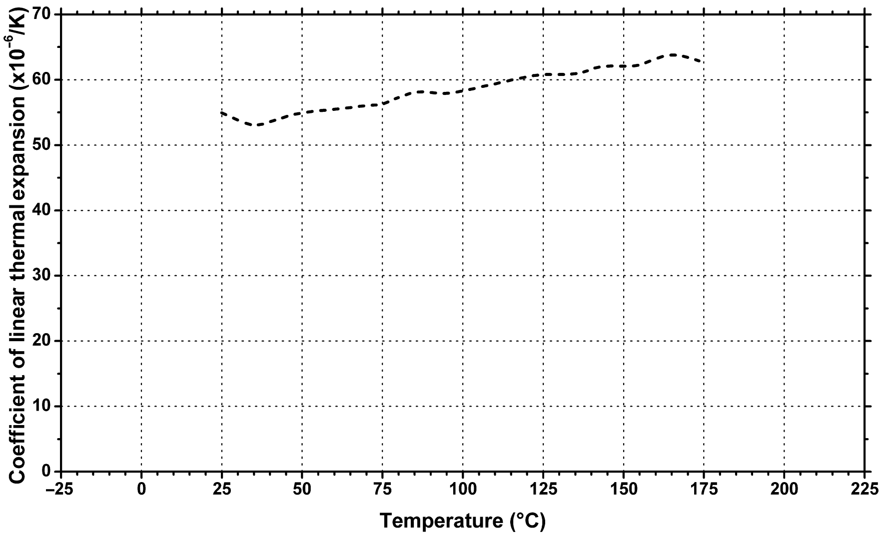


Figure 10.154 Coefficient of linear thermal expansion according to DIN 53752 of BASF Ultrason® P 3010 PPSU [6].

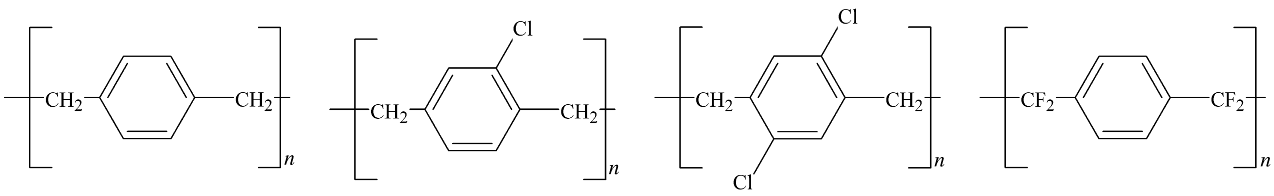


Figure 10.155 Structures of the Parylene polymer molecules.

10.6 Parylene (Poly(*p*-xylylene))

Parylene is the generic name for members of a series of polymers. The basic member of the series, called Parylene N, is poly(*para*-xylylene), a completely linear, highly crystalline material. The structures of four Parylene types are shown in Figure 10.155.

Parylene polymers are not manufactured and sold directly. They are deposited from the vapor phase by a process which in some respects resembles vacuum metalizing. Parylene polymers are formed at a pressure of about 0.1 torr from a reactive dimmer in the gaseous or vapor state. Unlike vacuum metalizing, the deposition is not line of sight, and all sides of an object to be encapsulated are uniformly impinged by the gaseous monomer. Due to the uniqueness of the vapor phase deposition, Parylene polymers can be formed as structurally continuous films from as thin as a fraction of a micrometer to as thick as several mils.

The first step is the vaporization of the solid dimer at approximately 150°C. The second step is the quantitative cleavage (pyrolysis) of the dimer vapor at the two methylene–methylene bonds at about 680°C to yield the stable monomeric diradical, *para*-xylylene. Finally, the monomeric vapor enters the room temperature deposition chamber where it spontaneously polymerizes on the substrate. The substrate temperature never rises more than a few degrees above ambient.

Parylene is used as a coating on electronics ranging from advanced military and aerospace electronics to general-purpose industrial products, medical devices ranging from silicone tubes to advanced coronary stents, synthetic rubber products ranging from medical grade silicone rubber to ethylene propylene diene monomer rubber (EPDM).

The manufacturer of coating equipment and starting materials is Para Tech Coating, Inc. They also offer coating services.

Manufacturers and trade names: Para Tech Coating, Inc. Parylene

Applications and uses: *electronics*: circuit boards, sensors, integrated circuits/hybrids, MEM devices, motor assemblies, coil forms, silicon wafers; *medical*: needles, prosthetic devices,

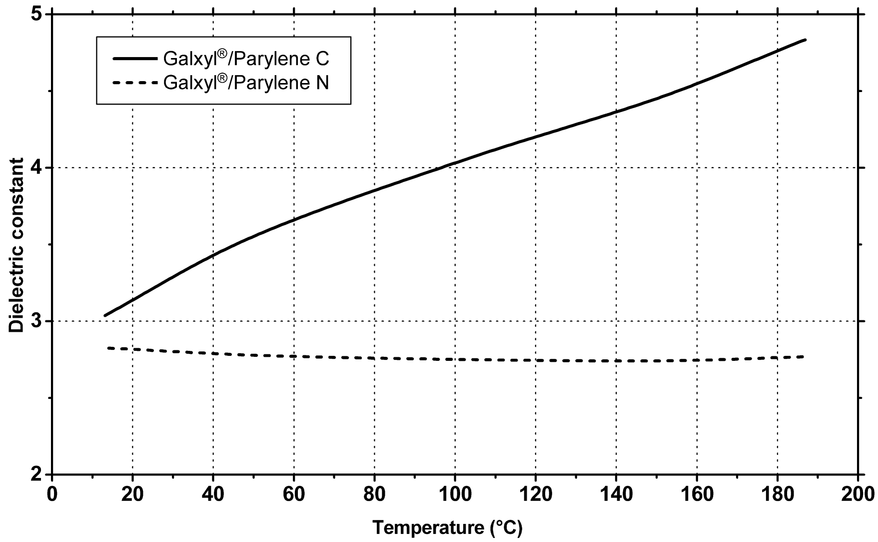


Figure 10.156 Dielectric constant vs. temperature for Galxyl® Parylene films [17].

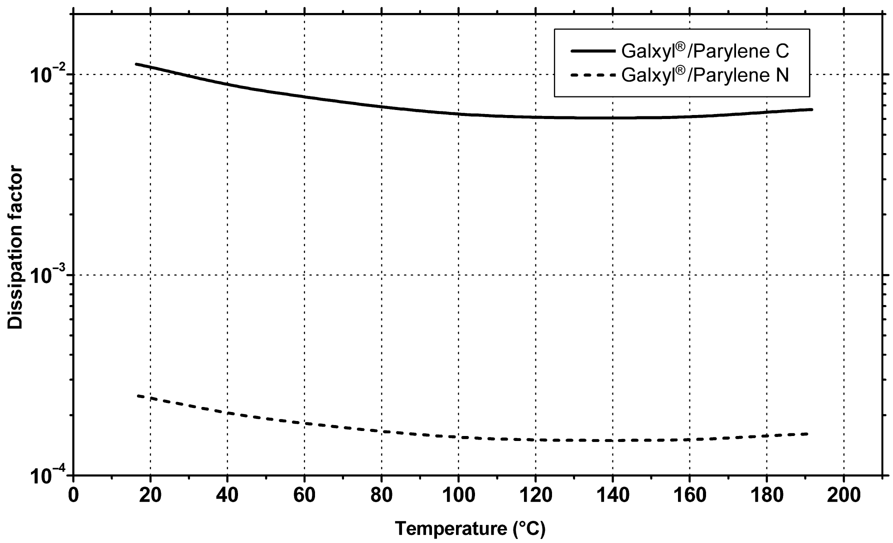


Figure 10.157 Dissipation factor vs. temperature for Galxyl® Parylene films [17].

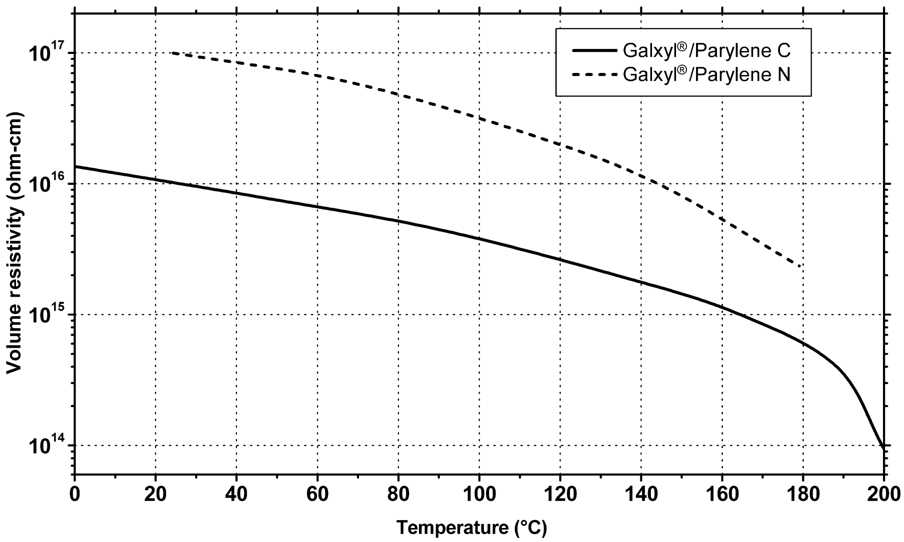


Figure 10.158 Volume resistivity vs. temperature for Galxyl® Parylene films [17].

implantable components, catheter, electrodes, stents, epidural probes, cannula assemblies; *aerospace*: deep space vision systems, navigation and controls, optical devices, satellite and spacecraft devices, flight deck controls.

The data for Parylene plastics are shown in Figures 10.156–10.158.

References

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[2] Victrex® Materials Properties Guide. Victrex; 2012.
[3] Technical Bulletin, Tensile properties AvaSpire® PAEK. Solvay; 2012.
[4] Technical Bulletin, Compressive properties AvaSpire® PAEK. Solvay; 2012.
[5] Technical Bulletin, Flexural properties AvaSpire® PAEK. Solvay; 2012.
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