MECHANICAL PROPERTIES

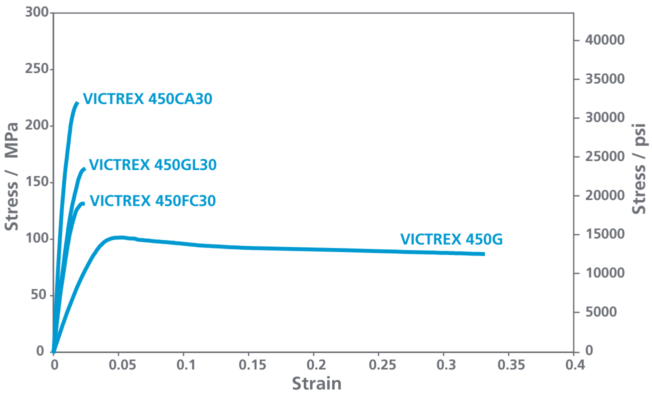
VICTREX PEEK is widely regarded as the highest performance material processable using conventional thermoplastic processing equipment.

TENSILE PROPERTIES

The tensile properties of VICTREX PEEK exceed those of most engineering thermoplastics. A comparative tensile plot of VICTREX PEEK materials is shown in Figure 2, where stress is defined as the applied force divided by the original cross-sectional area and the strain as the extension per unit length of the sample.

The initial part of each trace in Figure 2 is approximated to be linear and by definition is equivalent to the tensile modulus. Due to the viscoelastic nature of VICTREX PEEK, a range of values for tensile properties may be obtained by testing at different strain rates or temperatures. Therefore, evaluations of the tensile parameters contained in the data table were conducted in accordance with the ASTM D638 testing standard with strain rates set at either 5 or 50 mm min^{-1} (0.2 or 2.0 in min^{-1}).

Figure 2: Typical Stress Versus Strain Curves for VICTREX PEEK Materials

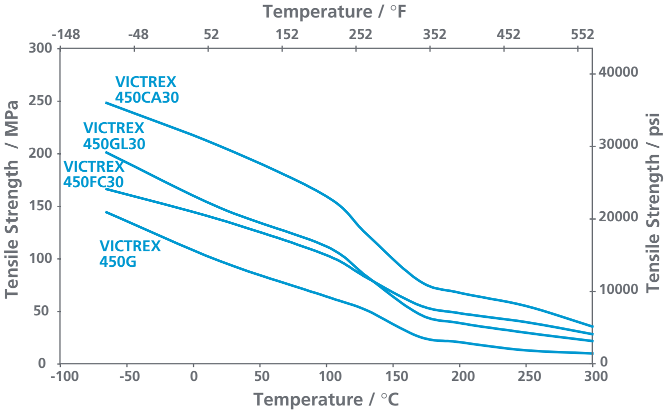


VICTREX PEEK is used to form structural components which experience or continually operate at high temperatures. Figure 3 shows a plot of tensile strength versus temperature for VICTREX PEEK materials and demonstrates a high retention of mechanical properties over a wide temperature range.

FLEXURAL PROPERTIES

VICTREX PEEK and the high-performance compounds based on VICTREX PEEK exhibit outstanding flexural performance over a wide temperature range. Due to the viscoelasticity of these materials, evaluations were performed using a defined deformation rate three point bending test (standards ISO 178 and ASTM D790) with the results plotted versus temperature in Figures 4 and 5.

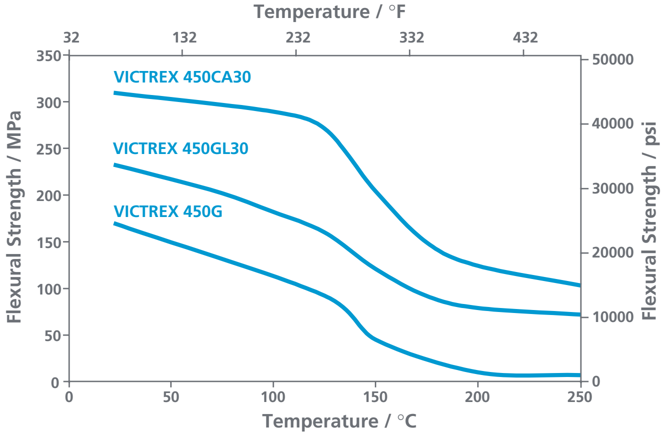
Figure 3: Tensile Strength Versus Temperature for VICTREX PEEK Materials

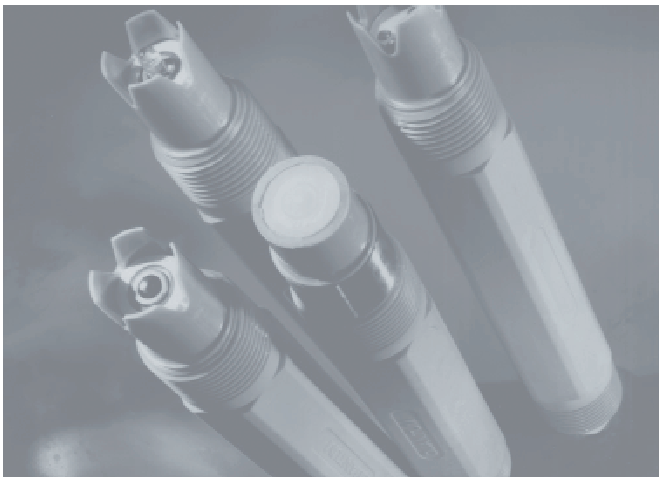


Flexural strength has been defined as the maximum stress sustained by the test specimen during bending, and flexural modulus as the ratio of stress to strain difference at pre-defined strain values.

The data plotted in Figures 4 and 5 define the exceptional temperature range over which VICTREX PEEK can be used as a structural material. However, flexural strength measurements made above 200°C (392°F) are subject to error as the yield point of these materials is greater than the 5% strain specified in the test standard. Above this value, a linear stress to strain relationship cannot be assumed for the calculation of flexural properties.

Figure 4: Flexural Strength Versus Temperature for VICTREX PEEK Materials





VICTREX PEEK was selected for the sensor housing and structural components because of its outstanding combination of properties.

Figure 5: Flexural Modulus Versus Temperature for VICTREX PEEK Materials

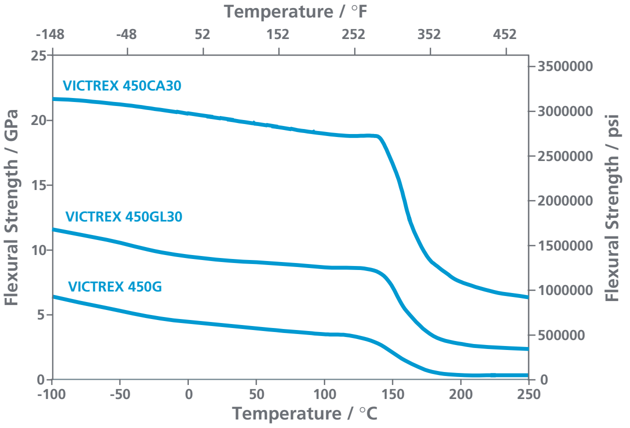


Figure 6: Tensile Strain Versus Time for VICTREX 450G at 23°C (73°F)

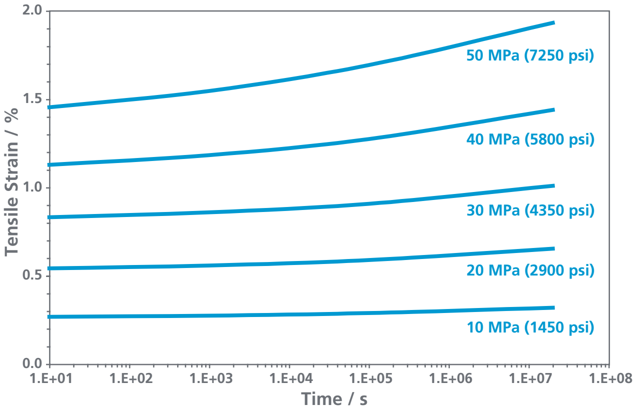
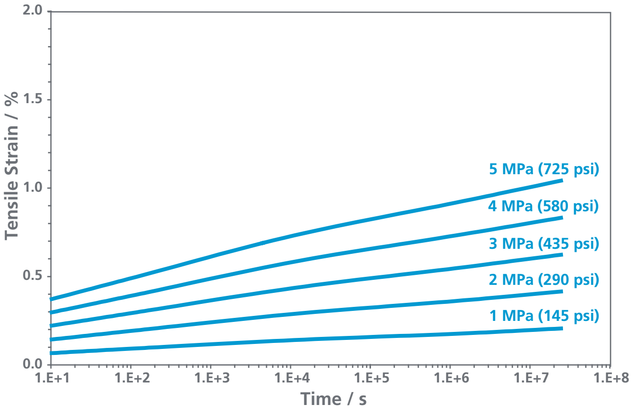


Figure 7: Tensile Strain Versus Time for VICTREX 450G at 150°C (302°F)

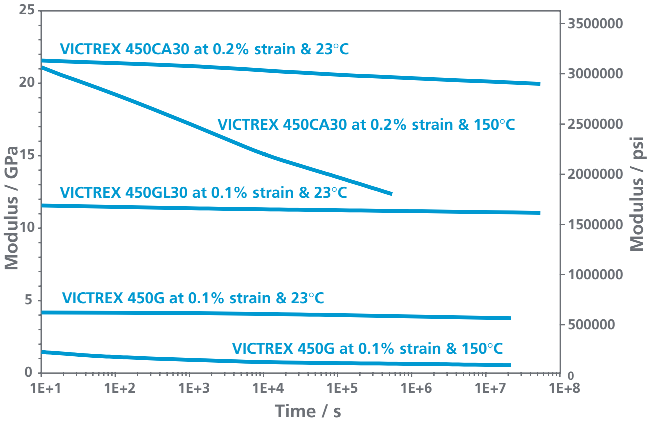


CREEP PROPERTIES

Creep may be defined as the deformation observed in a sample versus time under a constant applied stress. VICTREX PEEK has outstanding creep resistance for an engineering thermoplastic material and may sustain large stresses over a useful service life without significant time induced extension. Figures 6 and 7 display the creep behavior of VICTREX 450G with respect to applied stress, time and temperature.

The magnitude of stress, time and temperature required to induce accurately measurable (> 0.5%) strains is exceptionally large for an unfilled polymer. Values of creep modulus may be calculated from such data and used as a measure of resistance to creep deformation. The creep moduli for some of the high performance compounds from the VICTREX PEEK grade range are plotted against time in Figure 8.

Figure 8: Creep Modulus Versus Time for VICTREX PEEK at 23°C (73°F) and 150°C (302°F)



From the data in Figure 8 it is clear that reinforcement significantly enhances the excellent creep resistance of VICTREX PEEK and that the carbon fiber based compounds (CA30) are the highest performance materials tested.

If analogous plots to Figures 6 and 7 are constructed for VICTREX 450CA30 (Figures 9 and 10), the time dependent strain behavior over experimentally practicable lifetimes may be evaluated. From the data shown in Figure 9 it is clear that there is little measurable creep at ambient temperatures even for the highest values of stress [80 MPa (11,600 psi)] applied to the VICTREX 450CA30 samples.

At elevated temperatures (Figure 10), under the same applied stresses, small but measurable time dependent strains are observed. Although the creep resistance of natural VICTREX PEEK is outstanding for an unfilled material, VICTREX 450CA30 can be used to make structural components which will withstand continual loading over a wide temperature range.

Figure 9: Tensile Strain Versus Time for VICTREX 450CA30 at 23°C (73°F)

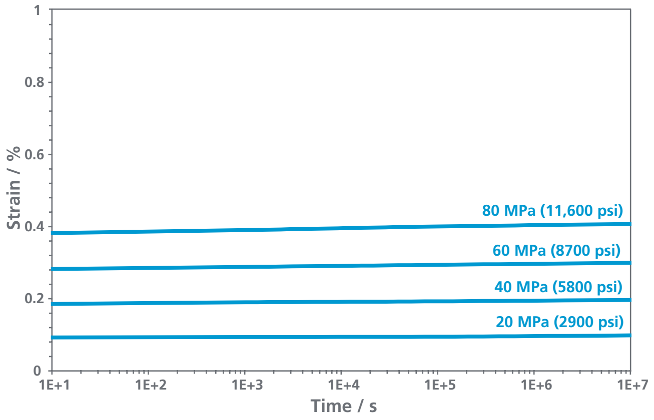
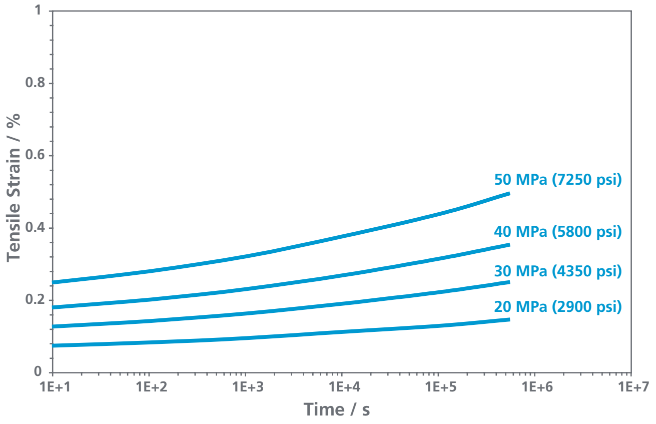


Figure 10: Tensile Strain Versus Time for VICTREX 450CA30 at 150°C (302°F)



CREEP RUPTURE

The performance of thermoplastic materials under a constant applied stress may also be considered in terms of creep rupture. Creep rupture indicates the maximum loading a material will sustain for a given period before it fails, where failure is defined as brittle or necking deformation. Figure 11 shows tensile creep rupture data versus time for natural and reinforced VICTREX PEEK materials.

Figure 11: Creep Rupture for VICTREX PEEK Materials at 23°C (73°F)

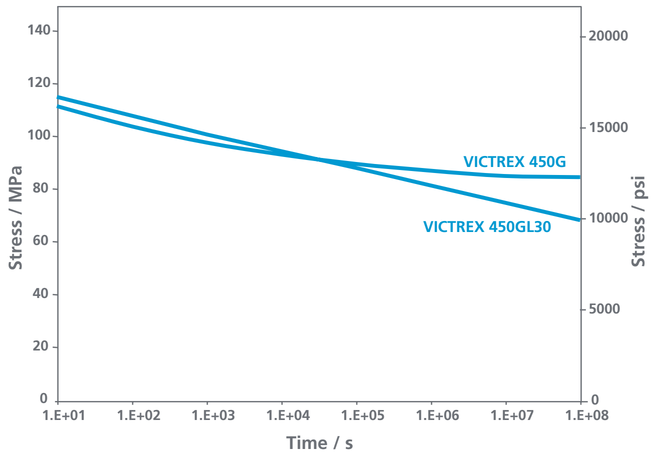


Figure 11 shows that there is little difference between the grades at ambient temperatures over the time-scale tested. Therefore, experiments were performed at elevated temperatures (Figure 12).

Figure 12: Creep Rupture for VICTREX PEEK Materials at 150°C (302°F)

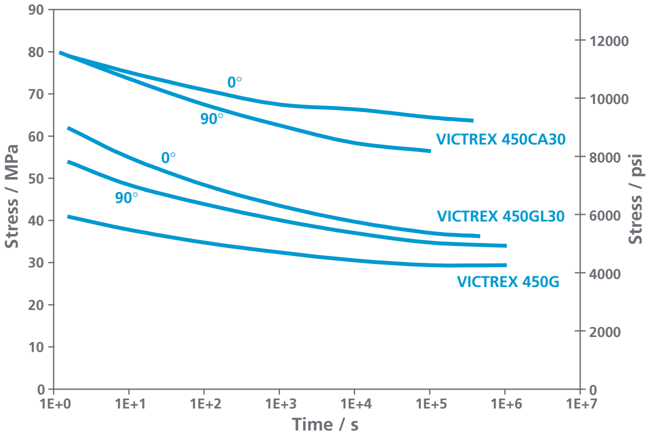


Figure 12 shows the effect of fiber reinforcement and orientation for VICTREX PEEK materials. The angles indicate the direction of testing with respect to melt flow. VICTREX 450CA30 exhibits superior creep rupture performance over the other materials tested and to most high performance thermoplastics. Therefore, VICTREX 450CA30 materials are often used to form components which experience permanent loading at high temperatures.

FATIGUE PROPERTIES

Fatigue may be defined as the reduction in mechanical properties during continued cyclic loading. In these experiments, a tensile sample is stressed to a predefined limit and released to zero tension repeatedly at a given frequency using a square waveform. After a certain number of cycles, samples undergo either brittle failure or plastic deformation. The failure mechanism is often dependent on the extent of localized heating that occurs within the sample during testing and has been shown to vary with frequency.

Figure 13 shows the maximum number of cycles that natural VICTREX PEEK materials can withstand under fatigue stress at ambient temperatures.

Figure 13: Fatigue Stress Versus Cycles to Failure for VICTREX PEEK Materials at 23°C (73°F) at 0.5 Hz

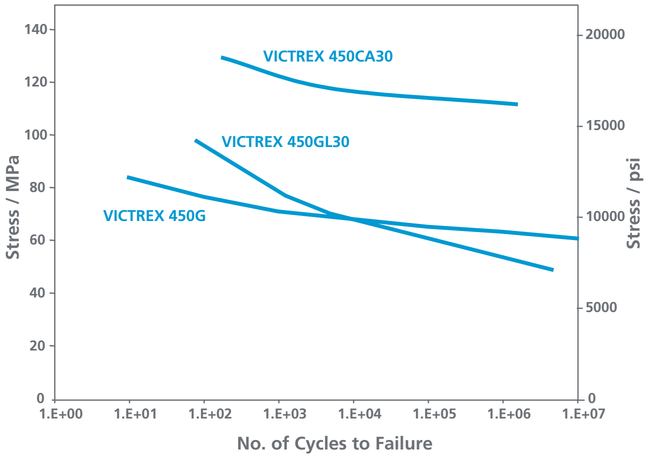
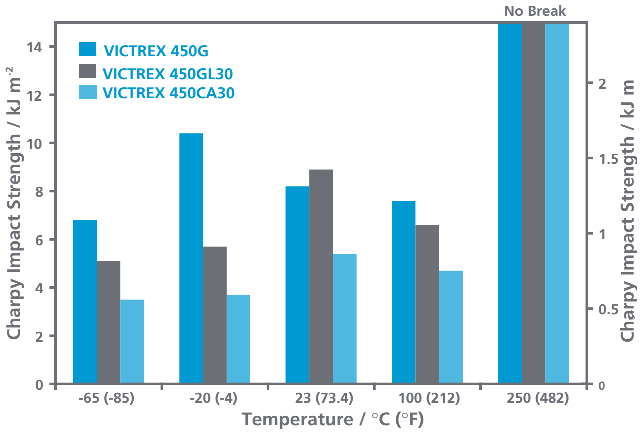


Figure 13 clearly shows that the excellent fatigue resistance of VICTREX 450G is enhanced by both glass and carbon fiber reinforcement. Independent studies have shown that these compounds feature the optimum level of reinforcement for improved fatigue and mechanical performance.

IMPACT PROPERTIES

Impact testing may be classified according to the energy imparted to the impactor prior to contact with the material. Low energy studies are performed using a pendulum geometry, whereas higher energy failures are evaluated using falling weight apparatus. The impact properties of a material are strongly dependent on test geometry (notch radius and position), temperature, impact speed and the condition of the sample (surface defects). Therefore, in an attempt to unify these variables, measurements are often made in accordance with one of the testing standards.

Figure 14: Charpy Impact Strength Versus Temperature for VICTREX PEEK Materials

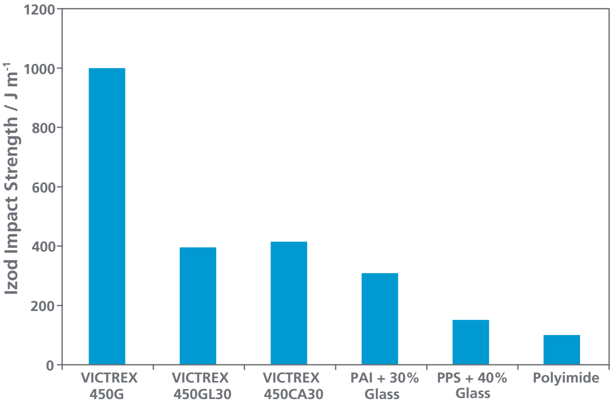


The impact strength of VICTREX PEEK materials was evaluated using the Charpy test protocol (ISO 179, 0.25 mm notch radius) and is shown at various temperatures in Figure 14.

The data in Figure 14 show that there is little reduction in the impact properties of these materials at subambient temperatures. All VICTREX PEEK samples tested above 100°C (212°F) could not be broken using the forces and pendulum distances specified in the test standard.

Comparative studies of the impact strengths of some high performance materials are shown in Figures 15 and 16 (ASTM D256).

Figure 15: Unnotched Izod Impact Strength at 23°C (73°F) for Various High Performance Materials



The bar chart shown in Figure 15 allows comparisons to be made between VICTREX PEEK materials and other high performance compounds. Natural VICTREX 450G has the highest unnotched impact strength and remains unbroken under the Izod test conditions.

Figure 16: Notched Izod Impact Strength at 23°C (73°F) for Various High Performance Materials

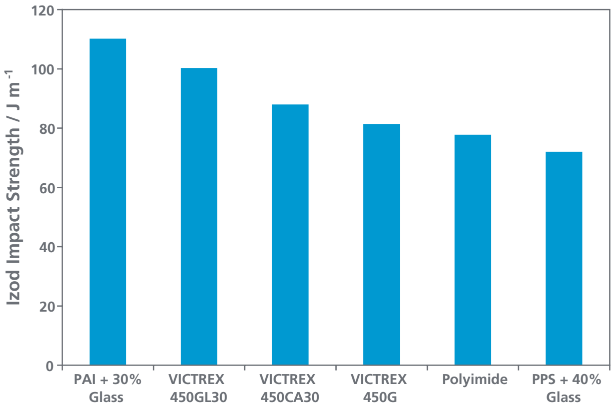


Figure 16 shows the effects on the impact strength of notching various materials. The geometry of the notch has been shown to be critical to the measured impact strength. Therefore, in component design, molded notches or acute angles should be avoided.

Instrumented falling weight techniques are used to evaluate higher energy impacts by monitoring the forces and displacements required to destructively test a sample.

Figure 17: Falling Weight Impact Failure Energy Versus Temperature for VICTREX PEEK Materials

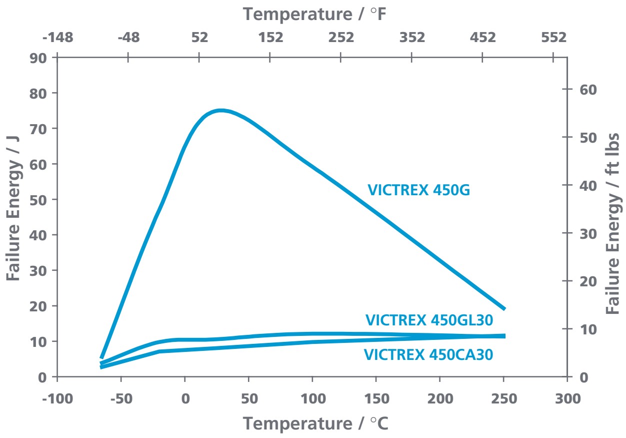


Figure 17 shows the energy to failure of VICTREX PEEK and compounds versus temperature to failure.

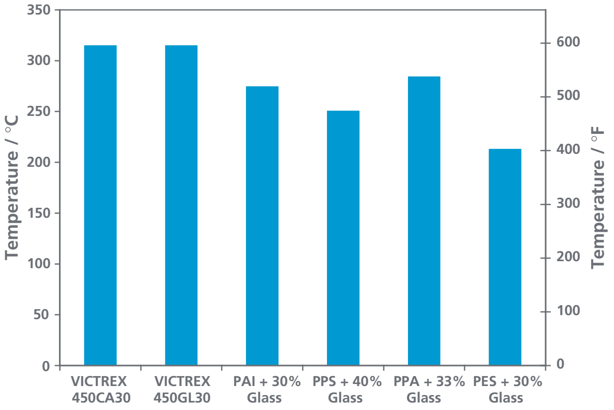
THERMAL PROPERTIES

VICTREX PEEK has a glass transition temperature of 143°C (289°F) and, because it is a semi-crystalline thermoplastic, retains a high degree of mechanical properties close to its melting temperature of 343°C (649°F).

HEAT DEFLECTION TEMPERATURES

The short term thermal performance of a material may be characterized by determining the Heat Deflection Temperature (HDT, ISO 75). This involves measuring the temperature at which a defined deformation is observed in a sample under constant applied stress. A comparative chart of high performance materials using ISO 75 HDT values (Figure 18) for a defined applied stress of 1.8 MPa (264 psi) shows that VICTREX PEEK compounds are superior to the other materials tested.

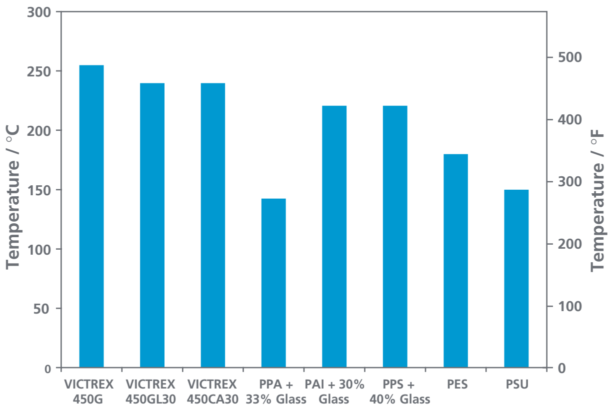
Figure 18: Heat Deflection Temperature for a Range of High Performance Materials



CONTINUOUS USE TEMPERATURE

Polymeric materials are subject to chemical modification (often oxidation) at elevated temperatures. These effects may be evaluated by measuring the Continuous Use Temperature (CUT) otherwise known as the Relative Thermal Index (RTI) as defined by Underwriters Laboratories (UL 746B). This test determines the temperature at which 50% of material properties are retained after a conditioning period of 100,000 hours. The UL RTI rating for natural VICTREX PEEK is charted against other engineering materials in Figure 19 (page 13).

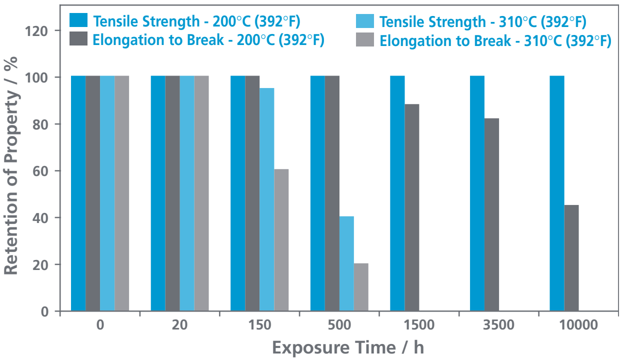
Figure 19: Relative Thermal Index (RTI) for a Range of High Performance Materials



HEAT AGING

As part of the Underwriters Laboratories evaluation of the physical performance of polymeric materials with respect to temperature, heat aging experiments are performed. These involve conditioning specimens for a pre-defined time at a constant temperature and subsequently measuring their tensile properties. The retention of these properties is calculated with respect to a control and is used as a measure of the thermal aging performance. The outstanding percentage retention of tensile strength and elongation to break for natural VICTREX PEEK is plotted versus conditioning time in Figure 20.

Figure 20: Tensile Strength and Elongation to Break Versus Conditioning Time for VICTREX 450G as Determined by Underwriters Laboratories



FLAMMABILITY AND COMBUSTION PROPERTIES

In a fire, the thermal and chemical environment is changing constantly. Therefore, it is difficult to simulate the conditions experienced by a material in a fire situation. The four commonly accepted variables are flammability, ignitability, smoke and toxic gas emission. The chemical structure of the VICTREX PEEK is highly stable- and requires no flame retardant additives to achieve low flammability and ignitability values. The composition and inherent purity of VICTREX PEEK results in excellent smoke and toxicity performance.

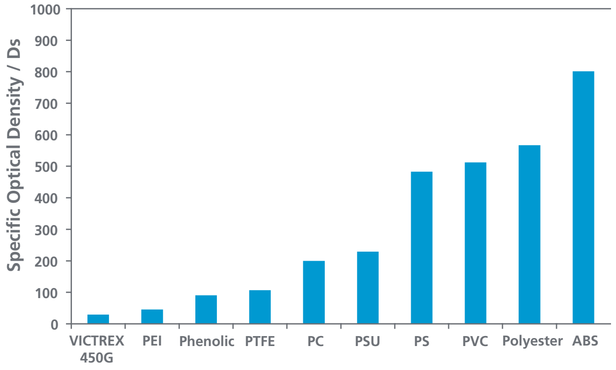
FLAMMABILITY

The flammability of a material may be defined as the ability to sustain a flame upon ignition from a high energy source in a mixture of oxygen and nitrogen. The recognized standard for the measurement of flammability is the Underwriters Laboratories test UL94. This involves the ignition of a vertical specimen of defined geometry and measures the time for the material to self-extinguish. The average time from a repeated ignition sequence is used to classify the material. Natural VICTREX 450G has been rated as V-0 [1.5 mm (0.059 in) thickness] which is the best possible rating for flame retardancy.

SMOKE EMISSION

The current standard for the measurement of smoke produced by the combustion of plastic materials is ASTM E662. This uses the National Bureau of Standards (NBS) smoke chamber to measure the obscuration of visible light by smoke generated from the combustion of a standard geometry sample in units of specific optical density. The test may be carried out with either continuous ignition (flaming) or interrupted ignition (non-flaming). A comparative bar chart of the specific optical density for a range of engineering plastics is shown in Figure 21.

Figure 21: Specific Optical Density for a Range of Engineering Thermoplastics Measured in Flaming Mode for 3.2 mm (0.126 in) Thick Samples



The data in Figure 21 show that natural VICTREX PEEK has the lowest value of specific optical density of all the materials tested.

TOXIC GAS EMISSION

The emission of toxic gases during combustion of a polymer cannot be considered purely as a function of the material. The component geometry, heat release, conditions of the fire, and the synergistic effects of any toxic gases affect the potential hazard of the material in an actual fire situation. VICTREX PEEK, like many organic materials, produces mainly carbon dioxide and carbon monoxide upon pyrolysis. The extremely low concentrations of toxic gases emitted have been evaluated using the Aircraft Standards (BSS 7239, ATS1000/ABD0031). This procedure involves the complete combustion of a 100 g (0.22 lb) sample in a 1 m^3 (35.3 ft^3) volume and subsequent analysis of the toxic gases evolved. The toxicity index is defined as the summation of the concentration of gases present normalized against the fatal human dose for a 30 minute exposure. VICTREX 450G gives a 0.22 toxicity index with no acid gases detected.

ELECTRICAL PROPERTIES

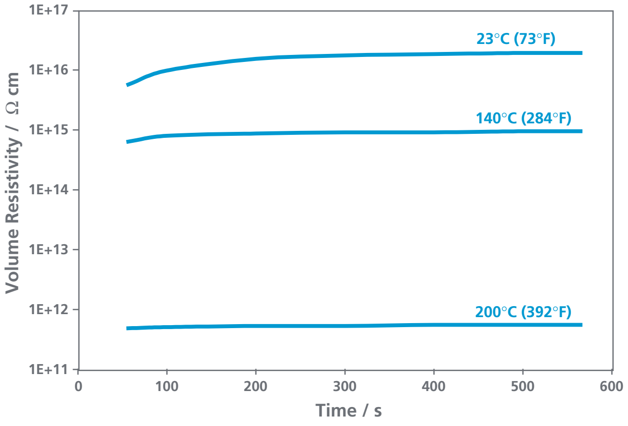
VICTREX PEEK is often used as an electrical insulator with outstanding thermal, physical and environmental resistance.

VOLUME RESISTIVITY

Volume resistance and resistivity values are used as aids in choosing insulating materials for specific applications. The volume resistance of a material is defined as the ratio of the direct voltage field strength applied between electrodes placed on opposite faces of a specimen and the steady-state current between those electrodes. Resistivity may be defined as the volume resistance normalized to a cubical unit volume.

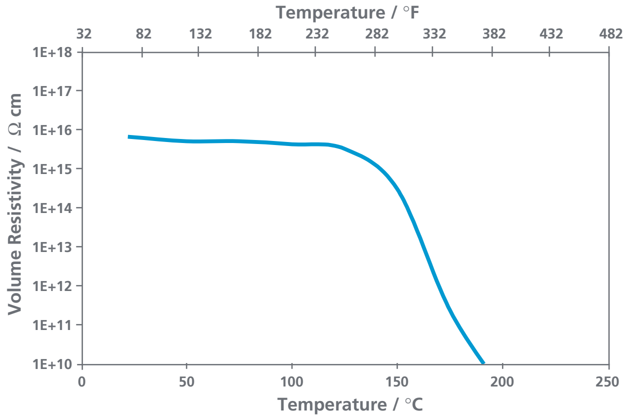
As with all insulating materials, the change in resistivity with temperature, humidity, component geometry and time may be significant and must be evaluated when designing for operating conditions. When a direct voltage is applied between electrodes in contact with a specimen, the current through the specimen decreases asymptotically towards a steady-state value. The change in current versus time may be due to dielectric polarization and the sweep of mobile-ions to the electrodes. These effects are plotted in terms of volume resistivity versus electrification time in Figure 22.

Figure 22: Volume Resistivity Versus Electrification Time for VICTREX 450G



The larger the volume resistivity of a material, the longer the time required to reach the steady-state current. Natural VICTREX 450G has an IEC 93 value of 6.5×10^{16} Ω cm at ambient temperatures, measured using a steady-state current value for 1000 s applied voltage. Using the same experimental technique, the volume resistivity of VICTREX 450G is plotted versus temperature in Figure 23. This shows that high values for the volume resistance of natural VICTREX PEEK are retained over a wide temperature range.

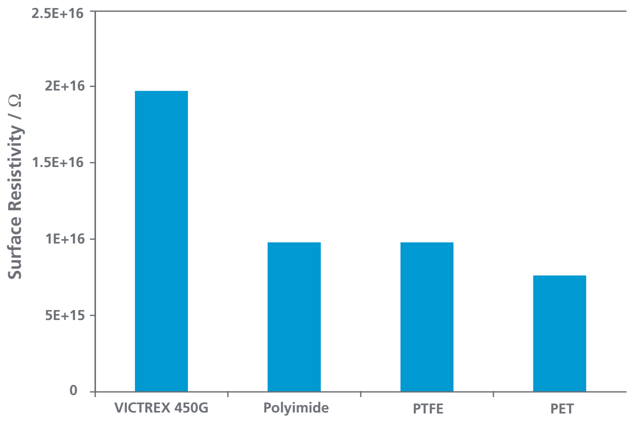
Figure 23: Volume Resistivity Versus Temperature for VICTREX 450G



SURFACE RESISTIVITY

The surface resistance of a material is defined as the ratio of the voltage applied between two electrodes forming a square geometry on the surface of a specimen and the current which flows between them. The value of surface resistivity for a material is independent of the area over which it is measured. The units of surface resistivity are the Ohm (Ω), although it is common practice to quote values in units of ohm per square. A comparative bar chart of surface resistivities for some high performance engineering polymers at ambient temperatures is shown in Figure 24. This shows that natural VICTREX 450G has a surface resistivity typical of high performance materials.

Figure 24: Surface Resistivities for Various Engineering Polymers Tested at 25°C (77°F) with 50% Humidity



RELATIVE PERMITTIVITY AND DIELECTRIC DISSIPATION FACTOR

VICTREX PEEK can be used to form components which support and insulate electronic devices. Often these components experience alternating potential-field strengths at various frequencies over wide temperature and environmental changes. The material response to these changes may be evaluated using IEC 250. This standard test evaluates the relative permittivity of a material and relates sinusoidal potential-field changes to a complex permittivity and a dielectric dissipation factor (tan δ). The permittivity of a material (ε_r) is defined as the ratio of the capacitance of a capacitor in which the space between and around is filled with that material (C_x) and the capacitance of the same electrode system in a vacuum (C_{vac}).

$$\varepsilon_r = C_x / C_{vac}$$

The relative permittivity in an alternating current forms the complex relationship,

$$\varepsilon_r^* = \varepsilon_r' - j\varepsilon_r''$$

where ε_r' is the storage permittivity, j is a complex number and ε_r'' is the imaginary loss permittivity. When such a potential difference is applied to a viscoelastic material the finite response time induced by the material means that there is a phase-lag (δ) in the measured capacitance. This phase-lag may be described by the relationship,

$$C_x = C_o (\sin \omega t + \delta)$$

where C_o is the maximum capacitance measured. Therefore, an expression for the viscoelastic phase lag (tan δ) can be derived from consideration of the storage and loss permittivities.

$$\tan \delta = \varepsilon_r'' / \varepsilon_r'$$

Low values of tan δ are desirable for component operating conditions as this implies that the material will continuously insulate without excessive losses. The value of tan δ over wide temperature and frequency ranges is shown in Figures 25 and 26 respectively.

From the data reported in Figure 25, natural VICTREX PEEK has a typical loss-tangent profile compared with other high performance materials over the temperature range tested.

The comparative plot shown in Figure 26 displays the excellent electrical performance of natural VICTREX PEEK over nine decades of applied frequency. Although many of the electrical properties of the material are described as typical of thermoplastic materials, VICTREX PEEK retains these excellent insulating properties over a wide range of temperature and frequency.

Figure 25: Loss Tangent of VICTREX 450G at Temperatures Between 23°C (73°F) and 250°C (482°F) at Frequencies Between 50 Hz and 100 MHz

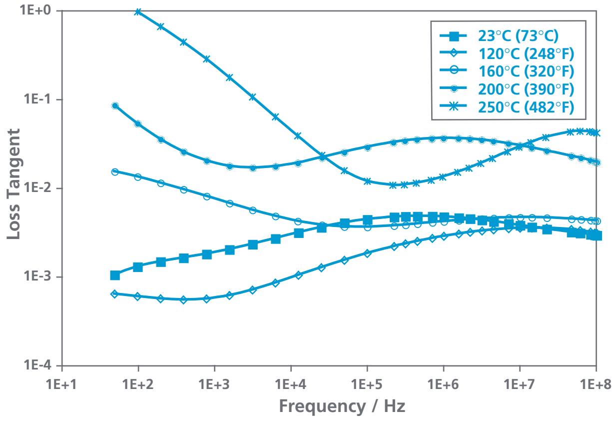
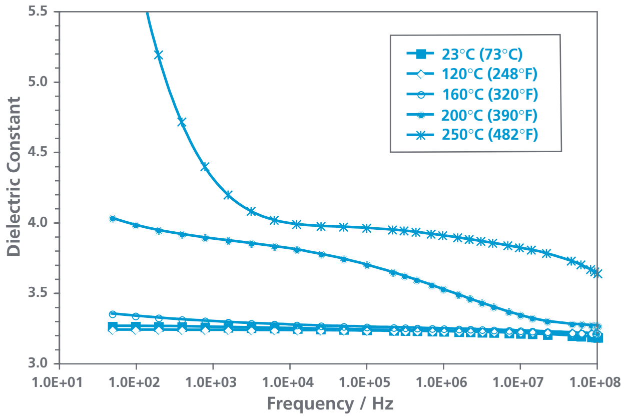


Figure 26: Relative Permittivity of VICTREX 450G at Temperatures Between 23°C (73°F) and 250°C (482°F) at Frequencies Between 50 Hz and 100 MHz



TRIBOLOGY

Tribology may be defined as the interaction of contacting surfaces under an applied load in relative motion. If the surface of a material is viewed on a microscopic scale, a seemingly smooth finish is, in fact, a series of asperities. Therefore, if two materials are then placed in contact and moved relative to one another, the asperities of both surfaces collide. The removal of asperities may be considered as wear, and resistance to the motion as a frictional force. VICTREX PEEK, and compounds based on VICTREX PEEK, are used to form tribological components due to their outstanding resistance to wear under high pressure (p) and high velocity (v) conditions. The friction and wear behavior of a material may be evaluated using one of several test geometries. The data given in this publication were generated in unlubricated conditions using an AMSLER pad on ring test rig. The rotating disc used in this apparatus was 60 mm (2.36 in) in diameter with a 6 mm (0.236 in) depth and was ground to a 0.4 µm R_a surface finish.

WEAR

The useful life of components which function in tribologically demanding environments is governed by the wear. The performance of a material may be quantified by evaluating either the specific wear rate (υ_{sp}).

$$\upsilon_{sp} = \frac{V}{F \cdot D}$$

where V represents the volumetric loss of the sample, F the force applied and D the total sliding distance, or the specific wear factor (k),

$$k = \frac{dh}{dt} \cdot \frac{1}{p \cdot v}$$

where dh/dt represents the rate of height loss measured in the sample. The lower the wear rate or wear factor, the more resistant a material is to tribological interactions. Figure 27 shows a comparative wear factor bar chart of some of the materials commonly used in demanding tribological situations. These data show that VICTREX 450FC30 has an extremely low wear factor for a thermoplastic material.

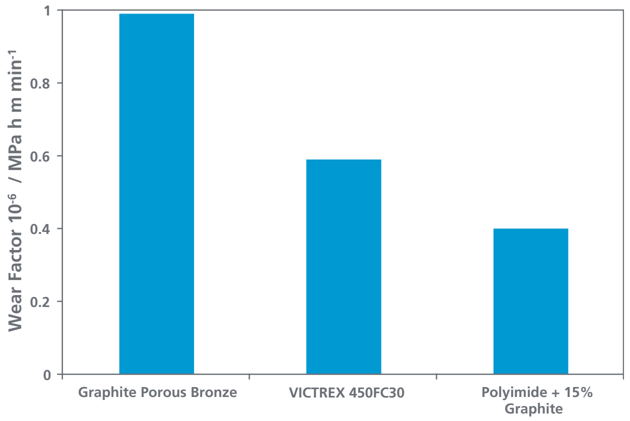
FRICTION

The friction of a sliding tribological contact may be defined as the tangential force (F) required to move a slider over a counterface,

$$F = \mu N$$

where N represents the normal force and μ is the coefficient of friction. Values of μ quoted for polymers vary with the thermal characteristics of the material and experimental conditions. Therefore, the value of μ and F may vary for VICTREX PEEK components which experience ‘real-life’ tribological contacts. This variable force may be considered in terms of two elements: a deformation term involving the dissipation of energy in a local area of asperity contact, and an adhesion term originating from the contact of the slider and the counterface.

Figure 27: Wear Factor at 200°C (390°F), with 3 m s^{-1} (600 ft min^{-1}) and 20 kg (44 lb) Load for some of the Highest Tribological Performance Materials



VICTREX 450FC30, a special tribological grade, contains optimum levels of PTFE and graphite to reduce and maintain the coefficient of friction at a low value. In addition, the carbon fiber reinforcement enhances the mechanical and thermal performance of the material. A comparative bar chart of high tribological performance materials is shown in Figure 28.

Figure 28: Coefficient of Friction for a Range of Materials at 200°C (390°F), with v = 3 m s^{-1} (600 ft min^{-1}) and 20 kg (44 lb) Load