

## Getting the Most Out of Your Data

By Michael Sepe

### INTRODUCTION

Back in 1992, Suzie Witzler of [Injection Molding Magazine](#) and Mike Kmetz of [IDES](#) had an idea to publish plastics processing and performance information in hand-sized reference books that could be conveniently referred to on shop floors to help process and select plastic materials.

Over the years, data grew so extensively that the books are now much thicker and more difficult to place in your back pocket. IDES now provides a service throughout the plastics industry known as [Prospector](#) that provides many powerful search methods to access data sheets and information on more than 67,000 plastic materials from 600 global resin suppliers. Unique characteristics include methods for searching on over 400 material properties (for example; tensile strength, notched Izod impact, flexural modulus, etc...), comparing materials side-by-side, searching by auto spec for automotive approved plastics, finding alternative resins, and displaying multi-point design data.

The following is an excerpt from the [3rd Edition of Pocket Performance Specs for Thermoplastics](#), written by our friend [Michael Sepe](#). We invite you to register for a free account to Prospector to reference the plastics data referred to throughout this book: [www.ides.com/pse](http://www.ides.com/pse)

## Getting the Most Out of Your Data

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There are now more than 67,000 grades of plastic material commercially available. Over half of these are captured in this book. In addition, the Supplier and Tradename Directories provide the increasingly necessary service of identifying the companies that remain involved in the manufacture of various resin families. With mergers and acquisitions continuing to take place at a furious pace in the plastics industry, keeping track of the shifting capabilities of the material suppliers is extremely challenging without such a guide.

As the introduction suggests, this compilation is intended as a screening tool for identifying materials that may be suitable for an application. All efforts to compile data from such a large industry must be limited at some point, and this one is no exception. It focuses on twelve properties that are generally considered to be of the greatest importance. More detailed property tables provided by a material supplier might contain as many as 64 properties, although few suppliers run the tests necessary to provide values for all of these properties. The reason is quite simple. According to one estimate, it can require as much as \$15,000 to run the tests needed to fill in all of the blanks.

But the real problem with the way property data is presented in our industry goes much deeper than a few empty spaces on a property chart. The shortcomings lie with the tabular format itself. Virtually all properties listed in a data sheet are measured at room temperature, defined as 73°F (23°C). Most of these properties change as functions of temperature. Therefore, applications that must function at temperatures above or below room temperature will be different from the values given in a data sheet. Furthermore, the values selected for reporting typically represent on point, or at best a small region of behavior on a curve that is rich with detail about the material's performance. A test for tensile properties, for example, generates a comprehensive picture of the behavior of a material. The yield and break strength that are highlighted in supplier data sheets represent two points on that complex curve. They are not particularly useful to the designer or engineer charged with the responsibility of selecting a material, because they represent catastrophic overload rather than a sensible limit for successful long-term performance. However, these points are easily identified and placed into a table; therefore, they get our attention.

The preference for single-point tabular data is compelling. It is easy to evaluate and understand. Comparisons are simple to make. In the age of computerized databases, sorting and cataloging according to these numbers becomes a quick and painless task, and this is precisely the problem. It becomes so simple that it makes the process of material selection appear to be nothing more than a trivial numbers game. Yet every year many applications fail because the selected material is not equal to the stresses and strains of the application environment. This problem has become epidemic as sourcing has become global and cost reduction has become the order of the day.

The alternative of providing curves instead of tables is also problematic. If we were to include one graph for each property listed in this book, it would no longer be a practical tool that you could carry with you. But if these numbers really are just a place to start, then the logical question to ask is: Where are we going as we translate these numbers into realistic expectations for our applications? To put it in more hard-headed economic terms, how do we make sure that we do not spend too much on a material but at the same time ensure that we spend enough? And how do we accomplish this without making the material selection process so time consuming that it eats up an inordinate portion of the product development time line?



I have spent a good portion of my career in the plastics industry trying to popularize the more complex data sets that truly give a complete picture of material behavior. What I have discovered is that once you have seen the broader range of material performance, the isolated data points are much more meaningful. If a few simple rules of polymer classification are understood, there are general patterns of behavior that can be used to approximate the larger picture using data points like the ones in this reference as a starting point. So the purpose of this piece is to provide the user of this manual with tools that can turn the numbers in these tables into an approximation of the bigger picture. We will discuss the twelve properties in the tables, focus on the strengths and weaknesses of the test, and consider the particularly important effects of changing temperature.

### Specific Gravity

We start our review with one of the few properties where a single number provides an adequate description of a property. This is not to suggest that specific gravity does not change with temperature, but the effect is relatively minor until the material reaches the softening or melting point, and it is seldom a determining factor in part performance. There are a couple of benefits to knowing the specific gravity of a material. One of these has to do with the weight of the molded part. For a given volume of material, a compound with a lower specific gravity will produce a part with a lower weight. To put this another way, a given weight of raw material will make more parts in a resin with a lower specific gravity. This is important because while processors buy material by the pound or the kilogram, end users buy by the cubic inch or cubic centimeter.

Specific gravity considerations also come into play in industries where weight savings is a key value-added feature. In the automotive industry, one of the key benefits of metal-to-plastic conversion is the fuel economy benefit of changing from steel, with a specific gravity of approximately 7, or aluminum, with a specific gravity of 2.7, to a polymer where the specific gravity usually ranges from 1-2. In aerospace this is an even more important consideration. Often engineers work in terms of strength-to-weight ratios. Obviously, specific gravity is the key to the weight portion of this calculation. In high-performance markets, this factor is one of the reasons that the much more expensive carbon fiber is chosen over glass fiber. For example, this book shows that a 40% carbon fiber-reinforced polycarbonate is almost 7% lighter than the same polymer compounded with 40% glass but at the same time is 50% stiffer (modulus) and over 25% stronger (at room temperature, of course). Higher specific gravity materials can also wipe out an apparent cost saving. For example, replacing a \$2.00/lb material with one that cost \$1.60/lb may appear to an excellent decision until we realize that the "higher-priced" material has a specific gravity of 1.24 while the new material has a specific gravity of 1.57.

### Melt Flow Rate

The melt flow rate is a property determined by a specific ASTM test that expresses the flow rate of a polymer under specific standard conditions. The unit of measure used to express the result is a mass per unit time, grams/10 minutes. Since it employs a constant load, it is a constant shear stress test, not a constant shear rate test. Therefore, it resembles a pressure-limited molding process and is particularly sensitive to small changes in molecular weight. Consequently, many material suppliers use melt flow rate as a specification to distinguish between grades of material based on differences in average molecular weight and to monitor the uniformity of a given grade of material from lot to lot. Grades with higher average molecular weights have lower melt flow rate values. Higher average molecular weights also result in better properties and in greater resistance to flow. Commodity materials such as polyethylene, polypropylene, and polystyrene rely heavily on the melt flow rate





specification. Some engineering polymers such as polycarbonate also make use of this specification. Lower melt flow rate grades are considered to be higher-performance materials while higher melt flow rate grades have somewhat reduced properties but are designed for easier processing, particularly in demanding thin-walled parts.

The significance of the melt flow rate test has historically been misunderstood by a large segment of the industry. Many processors place a disproportionate emphasis on melt flow rate because they believe that it accurately reflects differences in processability. It is certainly true that for a given set of processing conditions a polypropylene with a melt flow rate of 20 grams/10 minutes will flow farther or fill a given part geometry with less pressure than a polypropylene with a melt flow rate of 3 grams/10 minutes. But the numbers suggest that the 20-melt material will require 5 times less pressure to fill the same part or will flow five times farther in an open-ended geometry such as a spiral flow channel. However, practical experience shows that this does not happen, because the melt flow rate test is conducted at very low shear rates where the measured viscosity values are at their highest. As a polymer melt moves with increasing speed, the viscosity of the material declines rapidly, an effect known as shear thinning. This resulting viscosity reduction tends to occur more rapidly in higher molecular-weight materials. At a shear rate more typical of the injection molding process, the viscosity of both polypropylenes declines by a factor of approximately 100-200 compared to the viscosity measured during the melt flow rate test. At this higher velocity, the viscosity of the 4-melt grade is only 40% greater, not the 400% suggested by the melt flow rate numbers.

While materials from a given family tend to shear thin in similar fashion, behavior between polymer families can be drastically different. For example, the viscosity of a 4-melt flow rate polypropylene may be reduced by a factor of 100 over a given range of shear rates, while the viscosity of a 4-melt flow polycarbonate may only decline by a factor of five over the same range. Consequently, there can be no expectation that the two materials with the same melt flow rate will behave in the similar fashion when molding a particular part. There is also the subtle factor of melt density. A given volume of polycarbonate weighs approximately 30% more than the same volume of polypropylene. Therefore, a polypropylene with the same melt flow rate as a polycarbonate actually has a lower viscosity, since it takes more polypropylene to produce a given weight.

Even within a given material family, the melt flow rate numbers are only useful for comparison purposes when they are generated at the same test conditions. As the table of melt flow rate test conditions shows, there are more than fifty sets of test conditions used to generate these results. While many of these are material specific, there are several materials where a number of different conditions may be used at the discretion of the material suppliers. For example, ABS materials may be tested under condition G (200°C/5.0 kg), condition I (230°C, 3.8 kg), condition V (210°C, 2.16 kg), or condition AL (220°C/10.0 kg). Testing the same material under these various conditions will produce results that, at the extremes, may differ by more than a factor of 10. Therefore, it is very important to read the fine print when comparing materials using this property.

### Flexural Modulus

This is the first of the solid-state performance-based properties that we will discuss. By definition, *modulus* is the ratio of stress to strain. In the early stages of a test for tensile or flexural properties, this relationship is linear, and the resulting stress-strain plot is therefore a straight line. The slope of that line represents the modulus. While this publication ([Pocket Performance Specs for Thermoplastics](#)) focuses on flexural modulus, the good news is that for homogeneous materials, measurements of tensile, flexural, and compressive modulus all produce nearly the same value. The problem with a property like modulus is that it changes with temperature - increasing at lower temperatures and decreasing at higher





temperatures. While every material has its own unique modulus/temperature plot, these plots tend to fall into two general categories depending upon whether the base polymer in the compound is amorphous or semi-crystalline. Here are the rules governing each class.

In amorphous polymers the modulus is relatively constant over a broad temperature range. Once the material reaches a particular critical temperature region, the material will begin to soften, and the modulus will decline suddenly over a narrow temperature region. At the conclusion of this softening process, the material will have lost over 99% of its room-temperature stiffness, and it will no longer possess useful load-bearing properties. The narrow temperature region where this sudden decline in modulus occurs is known as the glass transition. This term has nothing to do with whether there is glass filler in the material. The term comes from the structural resemblance that amorphous polymers have to glass. Glass is a rigid material that is transparent because it has no well-defined order at the molecular level, no crystal structure. Therefore, it does not melt in the traditional sense. But once the temperature reaches a certain point, glass becomes a viscous fluid that will flow and can be shaped. This temperature region represents a transition from a hard and rigid material to a soft and pliable one. All amorphous polymers follow a similar behavior; they differ primarily in their glass transition temperature (T<sub>g</sub>). Polystyrene and PVC have relatively low glass transition temperatures, while those of polyetherimide and polyethersulfone are much higher. Later we will discuss how to approximate the T<sub>g</sub> of a material using the properties in this book - *Pocket Specs for Thermoplastics*.

For the moment, let's follow an amorphous material from room temperature through its softening point to illustrate the relationship of temperature to modulus. If we look at a material such as unfilled polycarbonate, we will see that almost all general-purpose unfilled grades of polycarbonate have room-temperature modulus values of 330-350 kpsi. As the temperature of any of these materials is increased, the modulus will decline very gradually over a relatively large temperature range. At 130°C (266°F), an unfilled polycarbonate will maintain 80% of its room-temperature stiffness, having lost the other 20% in a nearly linear fashion. Between 130°C-160°C (266°F-320°F) the modulus drops sharply, and when a new plateau is established, less than 1% of the room-temperature stiffness remains. An inspection of an actual curve for materials in this family will show that the T<sub>g</sub> ranges from 145-155°C (293-311°F), depending upon the exact grade. The process of drastic decline covers a region approximately 20°C (54°F) wide. Above and below this transition, the modulus is nearly constant with temperature.

If we look at a glass fiber-reinforced grade, we will notice that the room-temperature modulus has increased significantly. For example, a 20% glass-reinforced polycarbonate will have a room-temperature modulus of 800 kpsi. A compound with 40% glass fiber will exhibit a modulus at room temperature of 1400 kpsi. Whatever the modulus may be at room temperature, we can expect the same temperature-dependent behavior we outlined for the unfilled material. The room-temperature value will initially decline very gradually. In the region leading up to the glass transition, the glass fiber-reinforced materials actually retain 90-95% of their room-temperature stiffness as opposed to the unfilled polymer. Then, suddenly, the modulus will decline to 1-2% of room-temperature values over the same temperature region given for the unfilled material. The presence of the filler does not change the softening temperature; it only ensures that the material will be stiffer until it reaches that softening point.

The behavior for the semi-crystalline material is somewhat more complex but can still be summarized in some simple general rules that will allow a user of this book to expand upon the significance of the room-temperature values provided in the tables. Semi-crystalline polymers consist of well-ordered crystalline domains distributed in a matrix of amorphous material. The amorphous regions have a glass transition, but because of the crystal structure, the onset of the glass transition does not result in complete softening. Instead, a substantial modulus reduction occurs, and then a new plateau develops that is maintained until the crystal structure reaches its melting point. So, whereas amorphous materials soften in one step, semi-crystalline materials do so in two.



Let's look at a semi-crystalline material, PBT polyester. We will start with an unfilled material, [Valox 325](#), as an example. This book gives a room temperature flexural modulus of 340 kpsi. Here is what happens to Valox 325 as the temperature increases. The room-temperature modulus of the material is maintained until the glass transition is reached. The glass transition region begins at 50°C (122°F). Across a narrow temperature region between 50-90°C (122-194°F) the material loses 80% of its room-temperature modulus. A new plateau is established at 70 kpsi. Between the end of the glass transition and the onset of crystal melting, (90-210°C or 194-410°F) the modulus declines in a nearly linear fashion from 70 kpsi to approximately 15 kpsi. Melting occurs at 220-225°C (428-437°F). All unfilled semi-crystalline materials with glass transitions above room-temperature follow essentially this same pattern - a region of relative stability from room-temperature to the glass transition, a decline of 80-90% through the glass transition, and a new region of very gradual decline from the end of the glass transition to the onset of melting. All you would need to draw a reasonable estimate of the actual curve would be the room-temperature modulus, the glass transition temperature, and the melting point of the polymer.

If we add a filler or reinforcement, the shape of the curve does not change. As with amorphous materials, the presence of a filler does not alter the transition temperatures, but it does stiffen the material both above and below the glass transition. To get an idea of how the filler affects the properties of the polymer, we can look at Valox 420, a 30% glass fiber-reinforced PBT. The addition of the glass fiber raises the room-temperature modulus to 1100 kpsi. The modulus still exhibits a reasonably stable plateau between room temperature and 50°C. The material still goes through the glass transition region between 50-90°C where the modulus declines rapidly, and the material still exhibits a gradual rate of decline between the end of the glass transition region and the melting point. The big difference between the unfilled and the 30% glass-reinforced grade is that at the conclusion of the glass transition the modulus of the glass-reinforced material has only declined by 50% from room temperature instead of 80%. This same general pattern will be observed for all highly reinforced semi-crystalline materials with glass transition temperatures above room temperature.

One more example helps amplify this pattern. A dry-as-molded unfilled nylon 6, such as [Capron 8202](#), has a flexural modulus of 410 kpsi. Our 80% rule suggests that at the conclusion of the glass transition, which is near 100°C for the entire family of nylon 6 materials, the modulus should be 82 kpsi. Believe it or not, an actual scan of modulus versus temperature shows that the modulus at 100°C for Capron 8202 is 82.4 kpsi. Between 100°C and 210°C, which is just 10°C from the crystalline melting point, the modulus declines in nearly linear fashion by only another 50 kpsi. In other words it is nearly constant between the end of the glass transition and the onset of crystal melting. The 33% glass fiber-reinforced analog, Capron 8233, has a dry-as-molded room-temperature modulus of 1300 kpsi. Once again the glass transition region starts near 50°C and concludes by 100°C. Our 50% rule predicts that the modulus at 100°C will be 650 kpsi. In actuality it is 635 kpsi.

There is an important point to be made here regarding the use of reinforced materials. Commercially, there are far more grades of filled and reinforced semi-crystalline materials than there are amorphous materials. The preceding discussion helps illustrate the reason for this. In amorphous materials, no matter how much reinforcement is added to the polymer, the compound still loses its useful load-bearing properties once it passes through the glass transition. Therefore, all of the benefits of reinforcement pertain only to the temperature region below T<sub>g</sub>. In semi-crystalline materials, the advantages exist both below and above the T<sub>g</sub>. More importantly, because the presence of high levels of reinforcement reduces the modulus depleting effects of the glass transition, the benefits of reinforcement are far greater above T<sub>g</sub> than below. For example, at room temperature Capron 8233 is approximately three times stiffer than Capron 8202. However, at 100°C the modulus of the 33% glass-reinforced grade is nearly eight times higher than for the unfilled grade.



There are a few semi-crystalline materials in which these predictable patterns appear to break down. Notable exceptions to these rules are polyethylenes, polypropylenes, and acetals. Modulus versus temperature plots do not appear to contain the simple plateau regions punctuated by a sudden, sharp decline. Instead, these materials show a single extended, almost linear decline from room temperature up to the melting point. The reason for this apparent violation is quite simple. The glass transition regions for these families of materials are below room temperature. In the case of polyethylenes and acetals, in fact, the glass transition regions occur at extremely low temperatures. If these materials are cooled below  $-130^{\circ}\text{C}$  ( $-202^{\circ}\text{F}$ ), the modulus versus temperature plots look similar to those for the materials we have discussed above. An examination of curves for these materials also shows that the percentage decline in modulus while passing through the glass transition is only 60-70% rather than the 80-90% mentioned above. This is because these families of materials are more crystalline, and the higher degree of crystallinity reduces the decline in modulus associated with the glass transition.

We have established that a great deal of information can be deduced about the temperature-dependent behavior of modulus if we know the room-temperature modulus, the glass transition temperature, and for semi-crystalline materials the melting point. The room-temperature modulus can be obtained from this reference. But where do we obtain the temperatures? Regrettably, very few data sheets quote a value for  $T_g$  or  $T_m$ . There is more good news. We can estimate these two temperatures from a property that is provided in this reference. This property is the deflection temperature under load (DTUL). In order to maintain the continuity of our discussion, we will skip over to the two columns of data that attempt to treat the question of elevated temperature performance. The property itself is not very useful, but we can use it to gain some insights into very important characteristics of plastic materials.

### Deflection Temperature Under Load (DTUL)

Two columns are devoted to this property because the deflection temperature under load is measured at two standardized stress levels, 66 psi and 264 psi. The ISO 75 standard that is the equivalent to ASTM D 648 has actually added a third stress level, 1160 psi. However, this new method has yet to catch on in a big way in North America. This is probably because as the fixed stress level used in the test increases, the measured DTUL values decline. No material supplier likes to be the first to publish values that make it appear that its materials are losing capability.

To understand the relationship between stress level, DTUL, and the important transitions of  $T_g$  and  $T_m$ , it is important to appreciate what the test is measuring. The apparatus used to measure DTUL is a three-point bending fixture. A load is placed in the middle of the sample in order to generate a constant stress, and the temperature is increased until a specific deformation is obtained. In other words, the DTUL is the temperature at which a specific stress produces a specific strain. Remembering that stress divided by strain is modulus; we have the conclusion that the DTUL results represent the temperatures at which a material achieves particular modulus values. In 1978, a very smart man by the name of Mike Takemori took the time to calculate what those modulus values actually are. His work showed that the modulus associated with the DTUL at 66 psi was 29 kpsi, while the modulus associated with the 264 psi stress was 116 kpsi.

This is where we fall back on the understanding of the temperature-dependence of modulus that we discussed in the previous section. We know that the modulus of an amorphous material declines very little from room-temperature until the material approaches its glass transition. We also know that once the glass transition region has been attained, all amorphous materials, regardless of whether they are unfilled or highly reinforced,





lose more than 99% of their room-temperature modulus over a narrow temperature region. This means that even a material like a 50% glass-fiber reinforced polyetherimide (PEI), with a room-temperature modulus of 2000 kpsi, will decline to a level below 29 kpsi as it passes through T<sub>g</sub>. In addition, the sharp decline in modulus in the glass transition region dictates that the material will pass through both benchmark modulus values in a narrow temperature region. Therefore, both DTUL values will be closely related to the T<sub>g</sub> of the polymer. For example, a 40% glass fiber-reinforced PEI has a DTUL at 66 psi of 420°F (215°C) and a DTUL at 264 psi of 415°F (213°C). The T<sub>g</sub> of PEI is between 421-432°F (216-222°C), depending on the method of measurement. Unfilled PEI has DTUL values that are only slightly lower: 410°F (210°C) at 66psi and 392°F (200°C) at 264 psi. This pattern holds for virtually all amorphous materials. Therefore, the T<sub>g</sub> for an amorphous material can be estimated very closely simply by adding a few degrees to the DTUL values. The DTUL values for a highly reinforced grade will be particularly close to the T<sub>g</sub> for a given amorphous polymer. As might be expected, the rules for semi-crystalline materials are somewhat different and are more dependent upon the presence or absence of a filler. Let's start with unfilled semi-crystalline materials that have glass transition temperatures above room temperature. This includes most families of semi-crystalline materials with the significant exceptions that have been mentioned previously: polyethylenes, polypropylenes, and acetals. A review of the modulus values for unfilled semi-crystalline materials will show that virtually all materials in this category have room-temperature modulus values between 300 kpsi and 450 kpsi. Remember that as a material of this type passes through its glass transition, it will lose approximately 80% of its room-temperature modulus. This will leave the material at the end of its glass transition with a modulus of 60-90 kpsi. In other words, these materials are guaranteed to pass through the modulus associated with the DTUL at 264 psi. Furthermore, because the rate of change is greatest within the glass transition region, the crossover point will almost certainly occur somewhere during the glass transition.

Various techniques are used to measure and assign an exact temperature to the T<sub>g</sub>. Because we are concerned here with the effects of the glass transition on modulus, we will refer to the values obtained using dynamic mechanical analysis (DMA). This is a technique that continuously measures modulus as a function of temperature. Given the relationship between the T<sub>g</sub> and modulus, we should expect that the T<sub>g</sub> should be very close to the DTUL at 264 psi for unfilled semi-crystalline materials. If we go back to the examples of unfilled PBT polyester and dry-as-molded nylon 6, we will see that this is the case. The T<sub>g</sub> of an unfilled PBT polyester like Valox 325 is 60°C (140°F). The DTUL at 264 psi for this material is 55°C (130°F). The T<sub>g</sub> of an unfilled nylon 6 such as Capron 8202 is 72°C (162°F). The DTUL at 264 psi for the same grade of material is 65°C (149°F). These are not coincidences; they reflect a fundamental relationship between the continuous change of modulus with temperature and the essential points where our short-term measurement techniques intersect these continuous data sets.

So for many unfilled semi-crystalline materials, the DTUL at 264 psi provides us with a tool for estimating the T<sub>g</sub>, one of the two key phase changes that a semi-crystalline material undergoes as it is heated. For the second major event, the melting point, we need to rely on the behavior of filled grades. Here we can use the DTUL at either stress level, although if both numbers are available, the point at 66 psi will get us closer to the true crystalline melting point. As we discussed previously, the presence of fillers in a semi-crystalline material increases the room-temperature modulus and decreases the degree of decline associated with the glass transition. This combination of improvements in stiffness takes the entire modulus curve above the critical modulus of 116 kpsi until the material gets very close to the melting point. To illustrate this, look at the properties listed for even a material with a low level of reinforcement, such as [Celanex](#), a 13% glass fiber-reinforced PBT polyester. The room-temperature modulus of this grade is 800 kpsi, and the glass transition, which occurs near 150 crystalline, will only reduce the modulus by about 65% to 280 kpsi. This is still well above the modulus of 116 kpsi that is associated with the DTUL at 264 psi. So with filled semi-crystalline materials, the modulus remains above the DTUL benchmark as the material passes through the glass transition. The continued gradual decline in modulus that







occurs in the region above the T<sub>g</sub> will bring the modulus closer to this critical point, but the DTUL value at 264 psi for this material shows that the temperature must rise to 180°C (365°F) before this point is reached. The temperature must climb still higher to 214°C (417°F) before the modulus of 29 kpsi associated with the DTUL at 66 psi is attained. The crystalline melting point is only 11°C (20°F) higher than this last DTUL.

As the level of reinforcement or filler increases, the differences between the two DTUL values become smaller, and they both approach the melting point more closely. This is because the high level of filler keeps the modulus of the compound elevated until just before the polymer becomes molten. We can see this principle if we look at Celanex 2400, a 40% glass fiber-reinforced grade of the same PBT polyester. For this material the DTUL at 264 psi is 209°C (408°F) and the DTUL at 66 psi is 223°C (433°F). The crystalline melting point is 225°C (437°F). This rule for estimating the crystalline melting point works so well that it even applies to those exception families, the polypropylenes and acetals.

So with this discussion we have shown how combining single point data involving room-temperature flexural modulus, the two DTUL values, and a rudimentary knowledge of polymer structure can allow us to make educated guesses about the modulus of a material across a wide range of temperatures for which we have no direct measurements. Some materials, in particular polymer blends, will appear to violate these rules because the temperature-dependent behavior of blends is far more complex and more difficult to generalize. However, we have nonetheless made huge strides in increasing the utility of the tabular data. We are now ready to move back over to the left side of the table and discuss measurements of strength.

### Tensile Strength and Elongation

The tensile stress-strain curve is one of the most valuable tools for capturing a broad range of behavior in a polymer. The initial portion of the curve is a straight-line relationship between stress and strain and is called the elastic region. Gradually, the relationship begins to deviate from linear behavior as plastic deformation begins to take place. The plot becomes a curve as smaller increases in stress are required to produce the same incremental increase in strain. At some point all materials will respond in one of two ways. If the material is very rigid and brittle, tensile specimens will fail outright, splitting abruptly into two pieces. The stress level at this point is defined by terms such as *ultimate tensile strength* or *tensile strength at break*. Very stiff materials such as highly filled polymers follow this behavior. Brittle unreinforced materials such as general-purpose polystyrene and SAN also exhibit this response. If the material is softer and more ductile, it will continue to stretch to the point where no additional stress is required to produce additional strain. The slope of the stress-strain curve becomes zero, and this point is known as the yield point. The stress at this peak is reported as the *tensile strength at yield*. The material may continue to stretch for some distance before ultimate failure occurs. The degree of extension that occurs between yield and break is a relative measure of the ductility or impact resistance of the material. It is almost impossible to discuss tensile strength without at the same time treating the subject of strain or elongation.

The first item of importance in reading the values from the tables is to note the letter that accompanies the value. A 'Y' means *yield* and suggests that the material exhibits some extension beyond this point. A 'B' means that the stress level reported for a given material causes a sudden failure or break. Ductile materials will also have an elongation at break; however, the value will be much higher than those typically associated with yield. For example, a ductile material such as polyethylene may report a 1000% elongation to break. This material will also have an elongation at yield, probably at a strain level of 10-15%. It may simply not be reported by the supplier. As the temperature of a material increases, the peak tensile strength, whether it is at yield or at break, will decline. As the temperature decreases, the tensile strength will rise. Perhaps of greater



importance, a material that is brittle at room temperature will at some point become more ductile as temperature increases. Therefore, at the same time that the peak stress at yield or at break is declining, the strain at break is increasing. For example, an impact-modified nylon 6/6 is strong but brittle at -40°C (-40°F) with a peak tensile strength of 15,000 psi but an elongation to break of less than 15%. At room temperature the peak strength of this same material decreases to 9500 psi, but the elongation to failure exceeds 70%.

The manner in which peak tensile strength changes with temperature is less predictable than in the case of the modulus. If we plot peak tensile strength versus temperature for a variety of compounds, we tend to find behavior that is almost linear, regardless of whether the compound is semi-crystalline or amorphous, filled or unfilled. The rate of decline can be difficult to predict based on structure. There is, however, a general trend that stronger materials lose their strength at a faster rate. For example an unfilled ABS may lose 300 psi for every rise of 10°F. An unfilled acetal copolymer, which is nearly 70% stronger at room temperature, will decline by approximately 500 psi per 10°F increase. A glass-filled acetal copolymer has twice the room-temperature tensile strength of the unfilled material but loses 700 psi for every 10°F rise. The linear pattern is not as reliable as the behavior outlined above for the modulus. For example, at the high-end of the temperature region there is a tendency for the decline in tensile strength to slow. And for some semi-crystalline materials there may be a relatively sudden decline in strength that coincides with the glass transition.

Further complicating matters is the difference in the rate of decline for materials that may seem to be more or less equivalent. For example, a 33% glass fiber-reinforced nylon 6/6, a polyphthalamide (PPA) with the same glass-fiber loading, and a 40% glass fiber-reinforced PPS are all high-strength, high-modulus materials with good chemical resistance. At room temperature, both of the polyamide materials have superior tensile strength-27,000 psi for the nylon 6/6 and 32,000 for the PPA as opposed to 22,000 for the PPS. However, the rate of decline is substantially greater for the polyamides. By the time the temperature reaches 100°C (212°F), the PPS has caught up to the nylon 6/6. At 200°C (392°F) the PPA and the PPS have the same tensile strength. For this reason, estimates of the temperature dependence at peak strength are most easily made if two or three data points can be found. This makes a determination of the approximately linear relationship much easier.

Before we move on to the next property, it is important to highlight a place on the tensile stress-strain curve that does lend itself to tabular reporting but never appears on a data sheet. This is the proportional limit. As its name would suggest, this is the highest stress level on the stress-strain curve where the stress-strain curve is still linear. Above this stress level, sustained loading will result in increasing amounts of permanent deformation or creep, even though the yield or break stress has not been achieved. Many design manuals will refer to an upper working stress limit as 50% of the proportional limit, but then quantitative data on this proportional limit is curiously absent. Here again, a general rule or pattern will help. For most materials, the proportional limit occurs at a strain of approximately 1%. We already know that the stress and strain are in proportion up to this point, and this proportionality is expressed as the modulus. Since stress is the product of the modulus and the strain, the proportional limit can be estimated with a reasonable degree of certainty simply by multiplying the modulus from the book by 0.01.

There are exceptions to this rule, particularly in the soft, ductile materials like unfilled polyethylene and polypropylene where the strain at the proportional limit may be as low as 0.4%. For materials like these, the estimates of the proportional limit have to be reduced even further. It is also important to note that as the temperature of a material rises, and it becomes softer and more ductile, the strain at the proportional limit will decline. For example, the proportional limit strain for a 30% glass fiber-reinforced PET polyester like [Rynite 530](#) is approximately 1% at room temperature.

However, at 93°C (200°F), which is above the glass transition, it has declined to 0.5%. Since the modulus is also declining as the temperature increases, it is easy to understand why the design limits for sustained or repeated cyclic loading decrease faster than the modulus itself.

If designers and engineers seek a general rule for relating yield or break strength to the proportional limit, it must take into account the rigidity of the material. Very rigid and brittle materials maintain linear stress-strain behavior until they approach the point of ultimate failure. Many of these materials have elongation to break values between 1% and 1.5% and may have a proportional limit almost equal to the peak stress at break. For less rigid systems that have some capacity for yield, the proportional limit will be between one-third and one-half of the peak strength. For very soft, ductile materials such as unfilled polyethylene and polypropylene, the proportional limit may be as low as 20-25% of the yield stress.

## Elongation

As we discussed previously, elongation is a good relative indicator of ductility. High levels of elongation, most of which occurs after yield, indicate good energy-absorbing capabilities. These values are normally associated with impact resistance. Since polymeric materials become more ductile with rising temperature, increasing temperature will result in increasing elongation at break. It may have little to no effect on elongation at yield. In materials where grades are distinguished by molecular weight, elongation at break is often the best indicator of the improved ductility that comes with higher molecular weight. For example, [Celcon M25, M90, and M270](#) are three acetal copolymers with different average molecular weights. This is indicated by their melt flow rates, 2.5, 9.0, and 27.0 grams/10 minutes, respectively. All three of these grades have the same tensile strength at yield and the same flexural modulus, even though the average molecular weight of M25 is nearly twice that of M270. However, the elongation at break value for M25 is 75%, while it is only 40% for M270. It should be no surprise that the result for M90 is between these two extremes at 60%.

Any modification of composition that increases ductility will increase elongation to break values. Conversely, any change in composition that

Properties <sup>1</sup>					
Physical	Test Standard	Units (English)	Celcon® M25	Celcon® M90	Celcon® M270
Density -Specific Gravity	ASTM D792	sp gr 23/23°C	1.41	1.41	1.41
Melt Flow Rate (190°C/2.16 kg - E)	ASTM D1238	g/10 min	2.50	9.00	27.0
Mold Shrink, Linear-Flow	ASTM D965	in/in	0.022	0.022	0.022
Mold Shrink, Linear-Trans	ASTM D965	in/in	0.018	0.018	0.018
Water Absorption @ Equil (50% RH, 73 °F)	ASTM D570	%	0.10	0.10	--
Water Absorption @ 24 hrs	ASTM D570	%	0.20	0.22	0.22
Water Absorption @ Sat.	ASTM D570	%	0.80	0.80	0.80
Mechanical	Test Standard	Units (English)	Celcon® M25	Celcon® M90	Celcon® M270
Tensile Modulus	ASTM D638	psi	410000	410000	410000
Tensile Strength @ Yield	ASTM D638				
(73 °F)		psi	8800	8800	--
(-40 °F)		psi	13700	13700	--
(160 °F)		psi	5000	5000	--
--		psi	--	--	8800
Tensile Elongation @ Brk	ASTM D638				
(73 °F)		%	75	60	--
(-40 °F)		%	30	20	--
(160 °F)		%	250	250	--
--		%	--	--	40
Flexural Modulus	ASTM D790				
(73 °F)		psi	375000	375000	--
(160 °F)		psi	180000	180000	--
(220 °F)		psi	100000	100000	--
--		psi	--	--	375000
Flexural Strength @ Yield	ASTM D790	psi	--	--	13000
Flexural Strength @ Break	ASTM D790	psi	13000	13000	--
Compressive Strength	ASTM D695	psi	16000	16000	4500
Shear Strength	ASTM D732	psi	7700	7700	7700
Coef. of Friction	ASTM D1894				
(vs. Metal - Static)			0.15	0.15	--
(vs. Itself - Static)			0.35	0.35	--



increases stiffness will decrease elongation to break properties. Impact-modified nylon 6 will have an elongation to break of 200-250%, while a standard grade of general-purpose material will break at 25-50% strain. Adding glass fiber will drop the elongation to break to values between 1% and 3.5%, depending upon the amount of glass fiber. As we will see below, the elongation to break can be a much better gauge of practical toughness than the classical impact test properties.

Beyond the general trend of increasing elongation to break with increasing temperature, it is difficult to quantify the relationship for a broad range of materials. The only clear rule that can be offered here is that if a change in temperature takes a material through a key transition, the elongation to break values will change more rapidly than they do in temperature regions where no transition is present. Take as an example a 33% glass fiber-reinforced nylon 6/6. The glass transition temperature of this material is 75°C (167°F), and the glass transition region covers a temperature region between 50-95°C (122-203°F). Since we already know that such a transition reduces the modulus of the material by approximately 50%, we would expect that across this temperature region there would be a detectable step change in the ductility of the material. The elongation to break values confirm this. Between -40°F and 73°F, a range of 113°F, the elongation to break for this type of material only increases from 2% to 3%. But from 73°F to 200°F, which represents a comparable temperature rise, the elongation to break value increases from 3% to 7.5%. Beyond the glass transition, in the region between 200°F and 300°F, the property only increases from 7.5% to 8%.

For amorphous materials the glass transition represents complete softening; therefore, it is never encountered while measuring solid state properties. Remembering that the modulus of most amorphous materials declines gradually with temperature, we can expect a corresponding gradual increase in elongation to break as temperature rises. For materials where these measurements have been made, we see exactly this pattern of behavior. As an example, consider a high-heat modified phenylene ether (PPE) with an elongation to break at room temperature of 40%. At 60°C (140°F) this value increases to 50%, and at 100°C (212°F) it rises to 60%. Conversely, if the temperature is reduced to 20°F (-7°C) the elongation to break drops to 30%. This again reflects the change in real ductility that the material undergoes as a function of temperature.

### Notched Izod Impact

Since impact properties are closely related to elongation at break, it is appropriate that we discuss the notched Izod impact test at this point. The notched Izod test was adopted from the metals industry at a time when no one had a clear idea of how to perform impact property evaluations on plastic materials. The debate goes on regarding the best tools for measuring impact resistance, but we know a lot more today than we did sixty years ago. Our continuing reliance on the notched Izod impact test does not reflect that growing body of knowledge. But as with the other properties in this book, a great deal can be learned if we look at the bigger picture.

First, it is productive to examine what the notched Izod test measures. The samples used in this test contain an intentionally created flaw, a notch with a corner radius of 0.010". Almost all plastic materials are notch sensitive at some point, but for some materials like polycarbonate, the critical notch radius is below 0.010". These materials do very well in the notched Izod test, giving values of 12-16 ft-lbs/inch. For other materials, like dry-as-molded nylon 6, the critical notch radius is larger than 0.010"; therefore, the Izod test will produce very unflattering results, usually hovering around 1.0 ft-lbs/inch. Therefore, it is important to understand that the notched Izod test measures notch sensitivity. There is some value in this. As much as plastic design manuals caution against the use of sharp corners, tool construction details often result in sharp corners. In addition,





environmental damage such as non-catastrophic impact or chemical attack causes flaws in a product that represent notches. It is therefore important to assess notch sensitivity.

Since elongation to break is related to true ductility, we can expect that increasing temperature will also raise impact resistance as it increases ultimate elongation. For most materials this is what we observe. The rate of increase will depend on the effect of the rising temperature on the individual material. A tough, amorphous material such as modified PPE exhibits a steady increase in notched Izod impact that is almost a mirror image of the modulus versus temperature curve. In the sub-ambient temperature region, a particular grade of modified PPE nearly doubles in notched Izod impact from 1.8 ft-lbs/inch at -40°C (-40°F) to 3.5 ft-lbs/inch at room temperature. As the temperature continues to climb, the value doubles again to 7 ft-lbs/inch at 65°C (149°F).

A much more interesting phenomenon is something called ductile-to-brittle transition temperature (DBTT). Many materials exhibit a sudden change from ductile to brittle behavior across a narrow temperature range. Because the notched Izod test magnifies the sensitivity of a material to impact stresses, it tends to highlight these transitions particularly well. It is especially important to be aware of the DBTT for materials that are extremely tough at room temperature, such as a polycarbonate. It is well documented that unreinforced polycarbonate materials have among the highest notched Izod properties. However, somewhere between -20°F and +20°F the values drop from 15-17 ft-lbs/inch to 2-3 ft-lbs/inch. For any particular grade the change spans a very narrow range of 5-10°F, with the exact DBTT dependent upon the average molecular weight. Lower melt-flow-rate materials perform better in this respect, which at this point should come as no surprise.

For other materials the DBTT is less well documented because it occurs above room temperature. In these cases the material is typically thought of as brittle because under standard test conditions the impact test values are low. However, they improve dramatically just above room temperature. Polymethylpentene is a good example of this behavior. At room temperature these materials appear very brittle, with notched Izod impact values of 0.5-1.5 ft-lbs/inch. However, between 23°C (73°F) and 60°C (140°F) the impact resistance increases to over 20 ft-lbs/inch. The notched Izod impact of some impact-modified PVC grades triples over the interval of a few degrees near room temperature. Many polypropylene materials exhibit the same behavior.

When we look at reinforced materials, particularly those with a polymer matrix that is fairly brittle, some surprising behavior emerges. For example, a 20% glass fiber-reinforced SMA has a room temperature notched Izod impact strength of 2.6 ft-lbs/inch. This declines in essentially linear fashion to 2.6 ft-lbs/inch at -23°C (-10°F). However, as the temperature drops farther, the value starts to rise. At -40°C (-40°F) the notched Izod impact strength rises to 2.8 ft-lbs/inch-higher than the room-temperature value. An indiscriminating review of these data suggests that below a certain temperature this material actually becomes more impact resistant. This points out a problem that the notched Izod test shares with other impact test techniques. The total energy to break is a combination of energy to crack initiation and energy to propagate the crack to complete failure. The first event is very dependent upon the stiffness of the material, while the second event is a measure of true ductility, sometimes referred to as energy management. This means that very stiff materials can exhibit reasonably good total energy to break values even if they are relatively brittle in nature. The contribution of the energy to crack initiation is exaggerated in the notched Izod test because the samples are prepared in a manner that maximizes orientation across the notch. Glass fiber-reinforced materials, therefore, tend to provide numbers that are unrealistically high, particularly for notch-sensitive materials like nylons and PBT polyester.





Inflated notched Izod impact numbers can be detected by using the elongation to break values as a reality check. For example, the notched Izod impact strength for an unfilled nylon 6/6 such as [Zytel 103](#) is only 1 ft-lb/inch in the dry-as-molded state. The glass fiber-reinforced analog, Zytel 70G33L, has a notched Izod impact resistance of 2.2 ft-lbs/inch. However, the elongation to break for the unfilled material is 55%, while the strain to break for the 33% glass-filled material is only 3%. When these two indicators are this contradictory, it is a sign that the Izod result is exaggerated by the modulus of the compound. The reality is that the introduction of fillers and reinforcements reduces ductility, regardless of what the notched Izod values show. Ductile amorphous materials tend to more accurately reflect the effect of added reinforcement. Most grades of unfilled polycarbonate, for example, have a notched Izod impact strength of 12-17 ft-lbs/inch. The values for glass fiber-reinforced grades range from 2-2.5 ft-lbs/inch.

This problem of overstated impact resistance becomes even greater when long-glass fiber materials are considered. Short glass fibers are approximately 1-1.5 mm in length in molded parts. However, well-molded specimens made from long-glass fiber-reinforced materials will have average fiber lengths of 6 mm. When these longer fibers are oriented across the notch, there is a greater likelihood that more fibers will span the notch area, making the crack zone that much stronger and stiffer. This does not necessarily translate to greater ductility, but it does guarantee that the numbers will be higher in the notched Izod test. A good example comes from the polypropylene family. Unreinforced polypropylenes tend to be very notch sensitive. Most homopolymers have notched Izod impact values below 0.5 ft-lbs/inch, and even most copolymers fall below 2 ft-lbs/inch. Short glass fiber-reinforced materials tend to range between 1-2 ft-lbs/inch. But long-glass fiber-reinforced polypropylenes report notched Izod impact results as high as 4-6 ft-lbs/inch. However, other types of impact tests that rely on a falling dart and do not induce a pre-stressed condition show that the improvement in damage resistance from using long glass over short glass is approximately 20-25% rather than the 100-200% suggested by the notched Izod test.

The notched Izod test could be made more useful if the mode of specimen failure were simply added to the table. The test recognizes four different failure modes: complete break, hinged break, partial break, and no break. Simply adding a notation similar to the designations of yield and break used for tensile tests would lend a greater sense of reality to the numbers.

### Hardness

This is a fairly straightforward property and has its greatest significance in the elastomer families where surface hardness is measured on the Shore A or Shore D scales and has traditionally been a specification because so many important properties are related to hardness in rubber-like materials. Tensile properties, compression set, abrasion resistance, and tactile properties all vary as a function of surface hardness. It is fairly simple to predict that hardness declines with rising temperature.

### UL Flammability

The UL subject 94 tests governing flammability are very specific in the way they are conducted and in the manner in which ratings are assigned. While it is important to understand that everything burns if the temperature is sufficiently high, the flammability ratings do distinguish between materials that are self-extinguishing once a flame source has been removed and those that are not. Two very important aspects of the flammability testing should be emphasized here. First, the results are very dependent upon sample thickness. Some materials can only achieve a





self-extinguishing rating at thicknesses of 3/16" to 1/4", while others establish this same capability at thicknesses as low as 1/32", making them suitable for use in markets where thin-wall designs are common. Second, some materials can only achieve self-extinguishing ratings with the use of additives. These additives are often less stable than the base polymer and may, because of their chemistry, compromise other properties and eliminate them from consideration for applications requiring contact with food and potable water. Polypropylenes, ABS, and polyesters are among the families that represent this class of materials. Other polymers, because of their chemical makeup, are inherently flame-retardant. Therefore, they require no additives that might reduce impact strength or increase density.

### Coefficient of Linear Thermal Expansion (CLTE)

Most materials, including plastics, expand as they increase in temperature. The degree to which this dimensional change occurs is captured by the CLTE, which expresses this dimensional change relative to a standard dimension and a temperature change. The slope of the line representing dimensional change as a function of temperature is CLTE. The standard test to measure this property is conducted from -30°C to +30°C (-22°F to 86°F) because in this temperature range the value is relatively constant for almost all materials. It therefore lends itself to tabular reporting. There are a couple of simple rules that can be used to expand the significance of this measurement.

For amorphous materials the CLTE tends to be fairly constant, not only between the temperature limits prescribed by the test but also up to the glass transition temperature. For semi-crystalline materials that have a glass transition temperature above 30°C, the values reported in the data tables tend to be correct for all temperatures below the glass transition. However, above the T<sub>g</sub> the CLTE will abruptly increase by a factor of 3-5. Since semi-crystalline materials are intended for use at temperatures above T<sub>g</sub>, it is important that this increase be factored into any calculations of required clearances in assemblies. For those semi-crystalline materials where the T<sub>g</sub> is below 30°C (polypropylenes, polyethylenes, and acetals), the CLTE may show a gradual increase as the temperature rises above 30°C. The rate of this increase will depend on the amount and type of filler present (if any) in the material and the orientation of that filler relative to the direction in which the expansion is measured.

### **Summary**

We have attempted to provide a brief discussion of the broader picture into which the data provided in this book fits. It is simply not practical to provide a pocket-sized guide that captures all of the possible property combinations that the various materials in this book might present. However, a few general rules can be employed to increase the utility of these data points far beyond their normal use. No test is perfect, and when different tests appear to provide contradictory indications, the problem of understanding what is really taking place with a given material becomes much more difficult. Ironically, once we understand the bigger picture, these single points are much more significant than when they stand alone.







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## Biography

[Michael Sepe](#) has worked in the plastics industry since 1975 in a variety of roles involving both manufacturing and research and development. Currently he is the Technical Director at Dickten & Masch Mfg. in southeastern Wisconsin where he runs the analytical laboratory. He also is involved in qualifying new materials and manufacturing processes and he trains the technical staff in polymer properties and processing and their relationship to final part performance. From 1994-1999 he taught the injection molding apprenticeship program at Waukesha County Technical College where he re-designed the curriculum and authored a new text for the course.

He has presented over 25 ANTEC papers, has written several book chapters on the testing of plastic materials. He authors a bimonthly column for Injection Molding Magazine titled "The Materials Analyst" on the practical aspects of using testing techniques to solve manufacturing problems. He teaches a variety of short courses for the University of Wisconsin and Penn State - Erie and gives in-plant seminars to designers and engineers on material selection, processing, and troubleshooting.

