

2.3

Thermoplastics – Properties

J. D. Muzzy

Georgia Institute of Technology, Atlanta, GA, USA

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2.3.1 INTRODUCTION

The primary objective of this chapter is to present representative properties of thermoplastics. First, some general comparisons with thermosetting matrices are presented since most high performance composites have thermosetting matrices. Next, eleven groups are established for dividing the presentation of 40 different types of thermoplastics. Then the properties of these thermoplastic types are presented.

Not all types of thermoplastics are included in this chapter. Thermoplastic rubbers have been excluded since these rubbers have low elastic moduli. Usually the reason for reinforcing a thermoplastic is to increase its stiffness and strength. From this perspective a thermoplastic rubber represents a low starting point. If the property desired is high impact strength or durability, then reinforcing a thermoplastic rubber should be considered.

2.3.2 GENERAL FEATURES

The mechanical properties of polymers are sensitive to temperature changes. Figure 1 illustrates the change in modulus with respect to temperature for an amorphous thermoplastic. Below its glass transition temperature (T_g) the modulus is relatively constant with a value close to 2.8 GPa (0.4 msi). As the temperature increases above T_g the modulus drops roughly three orders of magnitude to 0.28 GPa (0.4 ksi) as the polymer becomes rubbery. If the molecular weight of the

polymer is high, the polymer becomes a viscoelastic fluid about 100°C above its glass transition temperature. At this temperature the polymer can be processed as a melt.

A crystalline thermoplastic has a modulus similar to an amorphous thermoplastic if both are below their T_g . As shown in Figure 2, above T_g a crystalline polymer has an intermediate modulus depending on the degree of crystallinity present. This crystallinity disappears during melting, leading to a rapid drop in modulus as the polymer becomes a viscoelastic fluid.

In comparing crystalline polymers and thermosetting polymers a similar trend is observed above T_g . For thermosets the modulus above T_g is dependent on the crosslink density, as shown in Figure 3. However, crosslinks are permanent covalent bonds which cannot be "melted" like polymer crystals. From this perspective, crystalline polymers have thermally reversible crosslinks which enable them to be melt processed.

When polymers are reinforced, the modulus is raised, as shown in Figure 4. The transition temperatures, T_g and T_m , are not changed significantly. However, the heat deflection temperature (HDT) determined according to ASTM D 648 can change substantially, particularly in reinforced crystalline polymers. In accordance with ASTM D 648, a flexural test sample is subjected to a stress of 0.46 Mpa (66 psi) or 1.8 MPa (264 psi) while the sample is heated at 2°C/min. When the deflection reaches 0.25 mm the HDT has been attained. These conditions correspond to apparent flexural moduli of 0.9 GPa and 3.6 GPa for stresses of 0.46 MPa (66 psi) and 1.8 MPa (264 psi) respectively. These moduli are shown as horizontal lines in Figure 4. Thus, a large increase in HDT for a crystalline polymer through reinforcement is due to raising its modulus above the HDT lines in Figure 4.

Usually there are some performance differences between thermoplastic and thermosetting matrices. As shown in the following property tables, thermoplastics often have tensile strengths and moduli, which are less than those of many thermosets. In many cases this tendency is due to the T_g of the thermoplastic being close to or below room temperature. In contrast, these same thermoplastics often have very high strains to failure compared to thermosets. This high failure strain capability also leads to high fracture toughness and high impact strength. Because thermoplastics are not crosslinked they often exhibit high creep strains.

Compared to thermosetting composites, achieving good interfacial adhesion in thermoplastic composites can be more challenging. The combination of high melt viscosities and the lack of reactive groups make it difficult for a thermoplastic to wet and bond to reinforcing fibers. Often the reinforcing fibers must be coated (sized) with hybrid polymers, sometimes called compatibilizers, which can associate with the fibers well and blend with the matrix. Alternatively, the compatibilizers migrate to the fiber-matrix interface. A common example is the use of maleated polypropylene in glass/polypropylene composites. The maleic anhydride graft is expected to associate with the glass fibers well while the more extensive propylene component of this graft copolymer blends with the polypropylene matrix.

Since thermoplastics are fully polymerized before they are combined with reinforcing fibers the glass transition temperature and melting temperature are fully developed. Consequently, the thermoplastic must be melted at high temperature in order to wet the fiber. Furthermore, once

the thermoplastic is melted, its viscosity is orders of magnitude higher than the low molecular weight prepolymers used in thermoset composite processing. Thus, combining thermoplastic matrices with reinforcements and insuring good fiber wetout and bonding is a significant technical challenge.

Since thermoplastics aren't cured during the fabrication of parts, rapid cycle times can be realized. The ultimate limitation on cycle time is the heat transfer required to solidify the thermoplastic. For thin cross-sections cycle times in the range of seconds are possible. However, many thermoplastic preforms consist of unconsolidated commingled fibers or powder coated fibers. In these cases the time required to complete fiber wetout would extend the cycle time. In these cases cycle times are in the range of minutes. In contrast, the cure times for some thermosets can be hours long.

2.3.3 GUIDELINES FOR SELECTION OF POLYMERS AND PROPERTIES

There are well over fifty types of thermoplastics based on chemical structure and more than ten thousand specific grades of thermoplastics available commercially. In addition to chemical structure these grades are distinctive based on molecular weight, molecular weight distribution, fillers, additives and reinforcements. The number of thermoplastic types presented in Table 1 has been reduced to forty by eliminating rubbery thermoplastics. In addition, the forty types are presented in groups with similar chemical structures. In many cases the thermoplastics within a group will have similar properties. The chapter sections for these groups are listed in Table 1 as a guide.

Most of the letter abbreviations listed in Table 1 are well known for the different types of polymers. Due to the long names for many of these different polymer types only the abbreviations are listed in the ensuing tables.

The price and transition temperatures for thermoplastics are often considered their most critical attributes. Therefore these properties are presented in Table 1. The costs reported for specific types of thermoplastics in this chapter are as of January, 2000 (Anon., 2000). They are list prices for large volume orders. Because the primary feedstocks of lower cost polymers are sensitive to fluctuations in the price of natural gas and oil, *Plastics Technology* (Anon., 2000) publishes current prices every month. Specialty resins are less sensitive to these feedstock cost variations.

The transition temperatures are from multiple sources (Brandrup, 1999, Graff, 1993, Rodriguez, 1996). Typical values of these transition temperatures are presented rather than the range of values found in the literature. The amorphous thermoplastics would be used in applications limited to service temperatures below the polymer's glass transition temperature, T_g . Crystalline polymers can be used above their glass transition temperatures, sometimes approaching within 30 or 40°C of their melting temperatures. In some critical applications crystalline polymers are not specified for applications exceeding their glass transition temperatures.

In this chapter the properties presented are often for multiple grades of a particular type of thermoplastic (Graff, 1993, Rodriguez, 1996, Matweb, Waterman and Ashby, 1991). Since the focus of this chapter is on distinguishing grades of thermoplastics before reinforcement, grades

with significant quantities of fillers, additives and reinforcements are excluded. For a particular type of thermoplastic, like polypropylene, there are still many grades available based on molecular weight, molecular weight distribution and copolymer content. Therefore a range of properties associated with these variables is presented. An important criterion used for selecting these grades is the suitability of the grade for injection molding. Compared to extrusion grade resins, injection molding resins usually have a lower molecular weight. To facilitate incorporating reinforcements low molecular weight polymers, which have lower viscosities, are preferred.

A consistent set of standard tests has been used to present properties. There are corresponding ISO standards for most of these ASTM standards.

Table 2 presents the ranges in processing temperature, specific gravity and water absorption for the different types of thermoplastics. The processing temperature ranges are from manufacturer's recommendations and are not the results of a specific ASTM standard. The processing methods considered are primarily injection molding and extrusion where the residence times in the melt state are short. If longer melt processing times are envisioned then lower processing temperatures should be emphasized.

In most cases the range in specific gravity for a particular type of polymer is not great. A wide range in specific gravity usually reflects variations in chemical composition; however, in some cases this variation is due to the presence of fillers or plasticizers. While the intent has been to exclude such filled or plasticized grades of polymers in these tables, some may have been included inadvertently.

The range in 24-hour water absorption is reported in Table 2. While the weight percent water absorbed at saturation might be more useful, it isn't reported as frequently as the 24-hour absorption. The low values for each type of polymer are probably a better indication of the behavior of neat polymer. Much higher values may reflect the presence of moisture sensitive additives.

Table 3 is limited to tensile properties obtained by one standard test method. The wide range in strengths and moduli is due most often to changes in chemical composition or crystallinity for a particular type of polymer. Another reason for the large ranges is variations in test specimen molding conditions, leading to differences in molecular orientation and residual stresses. Elongation at break can vary substantially for the same reasons, particularly in specimens that yield and draw. Thus, any elongation at break exceeding 10 % is likely to show wide variations.

Table 4 presents flexural and impact properties. For a specific type of polymer the range in flexural and impact properties often is broad for the same reasons a broad range is found in tensile properties. In most cases the flexural strengths and moduli are somewhat higher than the corresponding tensile properties. Compressive properties have not been presented since they aren't measured as frequently.

The notched Izod impact strength was selected for presentation since it is reported most frequently. There is insufficient information available for all these polymers to report ranges in fracture toughness.

The thermal properties in Table 5 include heat deflection temperature, coefficient of thermal expansion and thermal conductivity. Only the higher stress (1.8 Mpa, 264 psi) heat deflection temperature is presented because the results at the lower stress level are similar. The coefficient of thermal expansion (CTE) is presented since the polymers have much higher CTEs than most of the reinforcing fibers. The data on thermal conductivity is somewhat limited. Based on the data reviewed thermal conductivity does not vary substantially for the set of polymers considered.

The electrical properties presented in Table 6 include dielectric constant, dissipation factor and dielectric strength. For printed circuit boards a low dielectric constant and low dissipation factor are sought. For electrical insulators high dielectric strengths are preferred. Most polymers absorb energy to varying degrees as a function of frequency; hence, a range in dissipation factor is common. Dissipation factors are small compared to dielectric constants for most polymers. In Table 6 the dissipation factors have been multiplied by 1,000 for clarity in presentation. The dielectric constants and dissipation factors reported in Table 6 often were obtained at both low and high frequencies. For a number thermoplastic types presented electrical applications are not common; hence, manufacturers don't always report electrical properties.

2.3.4 THERMOPLASTIC GROUPS

2.3.4.1 Polyolefins

The primary types of thermoplastics in this group are presented in Table 1. Their repeat structures are shown in Figure 5. Polyethylene and polypropylene are produced in large quantities. For example, the worldwide production of polypropylene in 1998 exceeded 20 million metric tons (American Plastics Council, 2000).

The first two polymers in Table 1 are polyethylenes. Low density polyethylene (LDPE)[#1] contains branches or comonomer components. Because of these disruptions in chain regularity, LDPE has a much lower crystallinity than high density polyethylene (HDPE)[#2] and hence, a lower density. One consequence of this lower density is a lower modulus, which means LDPE is not often selected as a matrix for composites. One exception is polyethylene fiber reinforced polyethylene. Since LDPE has a lower melting point than the ultra high molecular weight polyethylene used to make polyethylene fibers (~140 °C), it is possible to consolidate LDPE without melting the fibers.

Since HDPE is highly crystalline and nonpolar it is quite inert. It absorbs very little water and is not attacked by most acids, bases or solvents. For these reasons it is often used in containers, such as milk bottles. Since HDPE is relatively inert it is difficult to achieve good interfacial adhesion in composites. Often maleic anhydride grafted polyethylene is added to HDPE to improve interfacial adhesion to the reinforcing fibers.

Polypropylene (PP)[#3] is used as a matrix in numerous composite products. Its appeal is both low density and low cost. Because polypropylene is semi-crystalline, its heat distortion temperature increases significantly from 55° C to 130°C with the addition of 20 wt% glass fiber reinforcement (Matweb). Since polypropylene is non-polar, it absorbs very little water. Due to its glass transition temperature below room temperature, it exhibits good impact strength. Because of these properties polypropylene is used 90% of the time in glass mat thermoplastic (GMT) sheet material for compression molding. Short and long fiber-reinforced polypropylene made by melt impregnation is available from many sources for injection molding applications. Continuous fiber reinforced polypropylene containing >50 vol % fiber is usually made by powder coating (Applied Fiber Systems, 2000) or commingling polypropylene with reinforcing fibers (Vetrotex, 2000).

2.3.4.2 Styrenics

Unlike the polyolefins, the styrene family consists primarily of amorphous polymers due to irregularities in their repeat structures. Consequently, the styrene family relies on having glass transition temperatures above room temperature in order to be structurally useful. All the styrenes have densities greater than the polyolefins and most cost more. In general, the strengths and moduli of the styrenes exceed the polyolefins. Their heat deflection temperatures are close to their glass transition temperatures.

Polystyrene (PS)[#4] has many attractive properties for consideration as a composite matrix: it has a low density, modest T_g , high modulus, and virtually no water absorption. However, it is brittle and sensitive to solvent attack. To improve its toughness, butadiene is added, normally as a discrete separate phase. To improve its chemical resistance, acrylonitrile is added. To achieve higher temperature performance, maleic anhydride is incorporated as a comonomer. The result is the family of polymers depicted in Figure 6.

Syndiotactic polystyrene has not been listed in the tables because there is only one supplier and apparently the unreinforced grade is not marketed. The polymer is partially crystalline with a melting point of 250 °C. Thus, composites can be made from syndiotactic polystyrene, which have high heat deflection temperatures.

High impact polystyrene (HIPS)[#5] has a continuous phase of polystyrene and a discrete phase consisting primarily of butadiene. The amount of the discrete phase can vary substantially, leading to wide variations in impact strength, as shown in Table 4, depending on composition. Unfortunately, substantial improvements in impact strength also lead to drops in tensile strength and modulus.

By adding acrylonitrile to styrene and butadiene the terpolymer, ABS [#7], is obtained. This polymer has a rubbery discrete phase based on the butadiene present. The styrene and acrylonitrile are primarily in the continuous phase. The polar acrylonitrile component hydrogen bonds with itself, leading to improved chemical resistance. Since the amounts of all three constituents can vary significantly, the range of properties among ABS grades is quite broad.

If strength, stiffness and chemical resistance are important then butadiene can be dropped, leading to styrene/acrolonitrile copolymers (SAN) [#7]. While these copolymers have fairly low impact strengths, their tensile and flexural properties exceed polystyrene.

A copolymer of styrene and methyl methacrylate (an acrylic), S/A [#8], is a useful alternative to SAN since it has better thermal stability in the melt and often-lower viscosity. The properties of SAN and S/A are quite close; however, SAN generally has better chemical resistance.

The final polymer included in the styrene family is a copolymer of styrene and maleic anhydride, SMA [#9]. Due to its higher glass transition temperature, it has somewhat higher service temperature capabilities compared to the other styrenics. Furthermore, the maleic anhydride comonomer should improve interfacial adhesion to the reinforcing fibers.

2.3.4.3 Vinyls

The dominant polymer among the vinyls is polyvinyl chloride, PVC [#10]. Since PVC is inexpensive and readily extended with low cost fillers, it is the sold more than any other polymer. PVC has tensile and flexural properties similar to many of the styrene family. Unless it is filled, it is inherently tough. Due to the pendant chlorine shown in Figure 7, it is non-flammable. However, when PVC degrades, particularly when it is processed at too high a temperature, hydrochloric acid is released. Also due to the presence of chlorine, PVC has a comparatively high density. Because it is non-flammable and environmentally durable, PVC is used in numerous outdoor applications, such as gutters, siding and shutters on homes.

Since the glass transition temperature of PVC is 85 °C, it is not suitable for hot water pipe. Chlorinated PVC, CPVC [#11] has enough additional chlorine to obtain a glass transition temperature of 100 °C, making it suitable for hot water pipe. The general properties of CPVC are attractive for many composite applications. However, its density is quite high.

A crystalline vinyl not listed in the tables is polyvinylidene chloride, PVDC. Since PVDC crystallizes it has better solvent resistance than PVC or CPVC. PVC and CPVC dissolve in chlorinated and aromatic hydrocarbons.

2.3.4.4 Acrylics

Polymethyl methacrylate, PMMA [#12], is best known for its clarity and good weather resistance. Since it is an amorphous polymer with a glass transition of 100 °C, like CPVC, most of its properties are close to CPVC. The primary differences are lower density, lower impact strength and easier processing. Compared to the vinyls, PMMA has a higher degradation temperature; hence, it is easier to process. Due to the presence of the methacrylate group, as shown in Figure 7, PMMA can associate with reinforcing fibers well. PMMA is sensitive to many solvents. It will craze when exposed to some alcohols and detergents and will be attacked by strong acids.

In order to improve the impact strength of PMMA, it has been alloyed with PVC, designated as PVC/Acrylic blend [#13]. The improvement in impact strength is impressive. The primary

difficulty with these blends is finding low viscosity grades which can be readily combined with reinforcing fibers.

2.3.4.5 Fluoropolymers

The fluoropolymers are noted for their environmental and chemical resistance. This resistance is attributed to the stability of the carbon-fluorine bonds illustrated in Figure 8 as well as the crystallinity of the fluoropolymers selected for presentation in the tables. All the fluoropolymers are expensive due to the difficulty in synthesizing their monomers. They are all high density, due to the presence of fluorine, and absorb very little water. They are all low modulus but possess good impact properties. They all have low coefficients of friction and are all non-flammable.

Polytetrafluoroethylene, PTFE [#15], is the best known fluorocarbon. A limited processing temperature range is indicated for PTFE because it degrades just above its melting temperature and usually has a very high viscosity. It can be solidified slowly by sintering below its melting temperature. It is the most chemically inert fluorocarbon. Due to this characteristic it is extremely difficult to achieve good adhesion between PTFE and reinforcing fibers.

Polychlorotrifluoroethylene, CTFE [#14] has a much lower melting point than PTFE because one fluorine has been replaced with chlorine in the repeating unit. Therefore CTFE can be melt processed; however, it is very expensive.

Polyvinylidene fluoride, PVDF, [#16], also can be melt processed and is considerably less expensive than CTFE. Since it has carbon-hydrogen bonds it is not as chemically inert as the other fluorocarbons included in the tables. Since it has excellent weathering properties it is often used as a protective barrier.

2.3.4.6 Polyesters

The polyesters all have the ester group in their repeat structures as shown in Figure 9. Due to this ester group polyesters are subject to hydrolysis at high temperature. Therefore, they must be extremely dry when they are processed in the melt. There are many types of polyesters which cover a wide range of properties. Only commercially well established polyesters are presented here. Most of the polyesters in Table 3 are crystalline with high melting temperatures. They have high densities compared to polyolefins but low densities compared to the fluorocarbons. They absorb a moderate amount of water. Their mechanical properties can vary substantially, as illustrated by the five types presented in the tables.

Polyethylene terephthalate, PET [#17] is the lowest cost, highest volume polyester produced, even compared to thermosetting polyesters. It is best known in textile applications and for bottles for carbonated beverages. The melt viscosity of PET is low compared to most polypropylenes; hence, it is relatively easy to combine with reinforcements. Based on its relatively low cost it is often considered as an alternative to polypropylene composites when higher service temperatures are needed. Compared to polypropylene PET provides a stiffer, stronger matrix.

The use of PET in packaging has spurred the development of copolymers such as PETG [#18]. PETG incorporates some cyclohexane dimethanol in place of ethylene glycol during polymerization with terephthalic acid. This change lowers the rate of crystallization or eliminates the development of crystallinity.. For composite considerations PETG has a somewhat higher glass transition temperature, better impact strength and less water absorption.

Polybutylene terephthalate, PBT [#19], is used frequently for injection molding applications. Due to the two extra methylene groups in its repeat structure compared to PET, as shown in Figure 9, PBT absorbs less water and has better impact strength than PET.

Polyarylate, PAR [#20], is an amorphous copolyester. Consequently, PAR can be processed at lower temperatures than the crystalline polyesters. PAR is made from a mixture of aromatic diacids in order to avoid the development of crystallinity. The repeat structure for PAR shown in Figure 9 is based on terephthalic acid and bisphenol A. Isophthalic and orthophthalic acid are used to break up regularity in the chain structure. Some aromatic diols, such as the bisphenol A diol shown in Figure 9, are included in the formulation to achieve glass transition temperatures above 100 °C. The properties of different grades of PAR can vary significantly due to the variety of monomers used to make PAR.

Liquid crystal polyesters, LCP [#21] are similar to PAR in that aromatic groups in the repeat structure are emphasized. However, regularity in the repeat structure also is emphasized in order to develop crystalline structures with high melting points. In LCP a two dimensional crystalline state exists in the melt which facilitates polymer chain orientation in processing as well as the retention of polymer chain orientation during solidification. Consequently, molded LCP is highly oriented leading to exceptionally high mechanical properties and a low CTE in the direction of flow. In essence, LCP is a “self-reinforced” composite. Due to their high melting temperatures and the presence of liquid crystals in the melt, LC polymers are viscous and somewhat difficult to combine with reinforcing fibers. LC polymers are available as fibers, which can be used as reinforcements in other matrices.

2.3.4.7 Polyamides (Nylons)

There are a wide variety of nylons available commercially and many types are reinforced. The repeat structures of the nylons presented in the tables are shown in Figure 10. Most nylons are crystalline and have relatively low melt viscosities. Also, the nylons adhere well to reinforcing fibers. Due to these features nylons are good candidates for reinforcement.

The primary nylons in use, nylon 6 [#22] and nylon 66 [#23], are quite similar. Nylon 66 has slightly higher transition temperatures compared to nylon 6. Both types have excellent strength, stiffness and toughness. They are self-lubricating and exhibit good abrasion resistance.

Both nylon 6 and 66 have good chemical resistance. However, they are sensitive to strong acids and absorb significant quantities of water. The absorption of water leads to lower strength and modulus and higher impact strength. Nylon expands due to the absorption of water. The properties reported in the tables, except for water absorption, are “dry, as-molded” properties.

The suppliers of nylons also report nylon properties after equilibration at 50 % relative humidity (Matweb).

Since the other nylons in the tables are less prevalent, they are more expensive. Nylon 11 [#24] and nylon 12 [#25] have extra methylene linkages between amide groups; hence, compared to nylon 6 they are more flexible, tougher and absorb less water. Nylons 6, 11 and 12 can be polymerized "*in situ*"; hence, they have been explored for resin transfer molding and pultrusion processing (Luisier, 1999).

Polyphthalamide, PPA [#26], has been designed for higher service temperature applications since it melts at 310 °C. It is copolyester since "R" in Figure 10 can be aliphatic as well as aromatic. With 33 % short glass fiber its heat deflection temperature exceeds 280 °C (Graff, 1993). PPA must be processed above 300 °C where the risk of thermal degradation is high. The viscosity of PPA melts is usually higher than nylon 66. PPA absorbs less water than nylon 66 and is slightly stiffer and stronger. It has a similar impact strength.

The properties, as well as the cost, of polyamideimide, PAI [#27] are impressive. Unfortunately, PAI has a very high viscosity in its processing temperature range. It is usually solidified by sintering. PAI has a very high tensile strength and modulus combined with a good elongation to break, leading to high impact strength. Even without reinforcement its heat deflection temperature exceeds 275 °C. Since PAI contains an imide group it is shown in Figure 11. An amide group is included in PAI to facilitate processing>

There are many more nylons which are suitable as matrices for composites. Commercial types include nylons 4, 69, 610, and 612. Also, there are many copolymers, including partially aromatic copolymers, which are amorphous and have a glass transition exceeding 100 °C. Additional information can be found in references (Graff, 1993, Matweb, Waterman and Ashby, 1991).

2.3.4.8 Polyimides

Compared to the amide group in polyamides, the imide group in polyimides is much more rigid, leading to high transition temperatures for polyimides. Many linear polyimides degrade before their melting temperatures are reached; hence, they have to be processed from solution or converted into polymer *in situ*. Even a modified polyimide like PAI is difficult to process.

In polyether imide, PEI [#28], an ether bond is included in the backbone, as shown in Figure 11, in order to have a polyimide that can be processed as a melt. Due to its irregular structure, PEI is amorphous. The polymer has a relatively high glass transition temperature. Most grades of PEI are quite viscous. PEI is often selected for composite applications because of its high service temperature, toughness, good interfacial adhesion and non-flammable behavior.

The properties presented for polyimide, PI [#29], are for a number of chemically different polyimides. The transition temperatures for specific grades can be significantly different from the values presented in Table 3. Only a few can be processed as melts. Their prices are much

higher than PEI. Their physical and mechanical properties often exceed PEI. Their service temperature capabilities are very high compared to other commercial polymers.

2.3.4.9 Polyethers

All polyethers contain oxygen bonded to carbon in their backbone as illustrated in Figure 12. This ether group imparts flexibility which makes melt processing easier. Many have aromatic segments in their backbone to increase the transition temperatures of the polyethers. There is a wide variety of chemical types in the polyether family. Only a few of the commercially successful polyethers are presented here.

Polyacetals, POM [#30], also called polyoxymethylene, are polymerized from formaldehyde. POM homopolymer can thermally degrade by unzipping back to formaldehyde; hence copolymers and special terminal groups are incorporated to minimize this threat. POM polymers are highly crystalline and fairly dense. POM is chemically resistant, except for strong acids. POM is stiff, strong and tough. It also has a low coefficient of friction and is often specified for self-lubricating gears. POM has a low melt viscosity which facilitates reinforcement.

Polycarbonate, PC [#31], is best known for its toughness and clarity. The carbonate group provides two ether linkages in the backbone which provide molecular flexibility well below PC's glass transition temperature. The bisphenol A group in polycarbonate, which is present in many epoxies and vinyl esters, imparts both rigidity and toughness. If moisture is present when PC is melt processed, it degrades rapidly. Hence drying before processing is critical. PC is used in many polymer blends, including PBT and PEI. In addition, high service temperature versions of PC are available which are still tough but have glass transition temperatures above 200 °C.

Polyphenylene oxide, PPO [#32], is not used alone since it would be too hard to process. The properties presented in the tables are blends of PPO with polystyrene, which are miscible. A wide range of compositions is available commercially, leading to a range of glass transition temperatures as well as a range of mechanical properties. PPO adds chemical resistance, reduces flammability, increases toughness and raises the heat deflection temperature of the blend. The densities of PPO blends are fairly low.

Polyaryletherketone, PAEK [#33], and Polyetheretherketone, PEEK [#34], are crystalline polymers with melting points above 300 °C in order to provide high service temperatures. Their structures, shown in Figure 12, are quite similar. Both types have ether and ketone groups as well as aromatic groups to achieve high melting points. PEEK has twice as many ether groups compared to ketone groups, leading to the use of two ethers and only one ketone in its name. Substituting ketone groups for ether groups can increase the melting point of PAEK. However, this substitution makes PAEK more difficult to process.

PEEK's use in advanced thermoplastic composites is well known since it is the matrix for APC 2, initially sold as a unidirectional tape containing 60 vol % carbon fiber (Cogswell, 1992). The appeal of PEEK is its high strength, high modulus, high impact strength, good fiber adhesion, excellent chemical resistance and non-flammability. Unfortunately, it is also quite expensive.

2.3.4.10 Sulfur Containing Polymers

Sulfur and sulfone groups are similar to oxygen and ketone groups placed in the backbone of aromatic polymers; hence, many of the structures in Figure 13 look like structures in Figure 12. Sulfur in the backbone provides flexibility, like ether linkages, whereas sulfone is much more rigid.

Polyphenylene sulfide, PPS [#35], is similar to PPO; however, it is crystalline and some low viscosity grades are available. Hence, it is used extensively as a homopolymer. It is used frequently as a composite matrix. It has excellent chemical resistance, low moisture absorption and high strength and stiffness. Without modification its impact strength is low. Due to its high melting point and good electrical properties it is used in a variety of electronic applications. It is non-flammable.

The remaining sulfur based polymers presented are all sulfones which are amorphous with high glass transition temperatures. All have good strength and stiffness. Polysulfone, PSF [#36], has the lowest glass transition temperature of the three types and is the easiest to process. It is often used in microwave cookware since it has a low dielectric loss factor at high frequency. Polyethersulfone, PES [#37], and polyarylsulfone, PAS [#38], are fairly similar in performance. While PAS with higher glass transitions can be synthesized, the ability to melt process PAS is lost because sulfur dioxide is generated at high processing temperatures. All these sulfone polymers are non-flammable.

2.3.4.11 Additional Thermoplastics

Acrylonitrile copolymer, ANC [#39], is similar to SAN but contains more acrylonitrile. Also, the comonomers aren't limited to styrene. This type polymer was first developed for bottling carbonated beverages. It has a modest cost and good strength, stiffness and toughness.

Thermoplastic polyurethane, TPU [#40], is usually a rubbery material; however, versions are available which are rigid above room temperature. This TPU adheres well to fibers and is often reinforced. It is unusual in that some chemical disassociation occurs in the melt, leading to a very low viscosity melt by thermoplastic standards. The structure shown in Figure 14 includes two generic groups, "R" and "R'", Both aliphatic and aromatic segments would be used for "R" and "R'". The specific structures for "R" and "R'" often are kept confidential.

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TABLES

1. Thermoplastic selling prices and transition temperatures
2. General Properties
3. Tensile properties
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Table 1, Part A
Thermoplastic Selling Prices and Transition Temperatures

Section	Type	Abbrev.	Prices		Transition Temperatures		
			\$/lb	\$/kg	Tg (°C)	Tm (°C)	
2.3.4.1	Polyolefins						
	1	Polyethylene, Low density	LDPE	0.41	0.90	-90	120
	2	Polyethylene, High density	HDPE	0.39	0.86	-30	135
	3	Polypropylene	PP	0.28	0.62	-20	165
2.3.4.2	Styrenics						
	4	Polystyrene, "crystal"	PS	0.39	0.86	100	am*
	5	Polystyrene, Impact Mod.	HIPS	0.44	0.97	100	am*
	6	Acrylonitrile/Butadiene/Sty.	ABS	0.90	1.98	100	am*
	7	Styrene/Acrylonitrile	SAN	0.87	1.91	110	am*
	8	Styrene/Acrylic	S/A	1.10	2.42	100	am*
	9	Styrene/ Maleic Anhydride	SMA	1.13	2.48	115	am*
2.3.4.3	Vinyls						
	10	Polyvinyl Chloride	PVC	0.37	0.82	85	am*
	11	Chlorinated PVC	CPVC	1.19	2.62	100	am*
2.3.4.4	Acrylics						
	12	Polymethylmethacrylate	PMMA	0.85	1.87	100	am*
	13	PVC/Acrylic Blend	PVC/MA	1.50	3.31	90	am*
2.3.4.5	Fluoropolymers						
	14	Polychlorotrifluoroethylene	CTFE	45.00	99.18	30	235
	15	Polytetrafluoroethylene	PTFE	7.00	15.43	27	325
	16	Polyvinylidene fluoride	PVDF	6.75	14.88	-30	170
2.3.4.6	Polyesters						
	17	Polyethylene terephthalate	PET	0.54	1.19	80	250
	18	Polyester, PETG	PETG	0.98	2.16	80	am
	19	Polybutylene terphthalate	PBT	1.45	3.20		235

*am = amorphous

Table 1, Part B
Thermoplastic Selling Prices and Transition Temperatures

Section	Type	Abbrev.	Prices		Transition Temperatures		
			\$/lb	\$/kg	Tg (°C)	Tm (°C)	
2.3.4.6	Polyesters, continued						
	20	Polyarylate	PAR	2.40	5.29	190	am*
	21	Liquid Crystal Polyester	LCP	12.00	26.45		400
2.3.4.7	Polyamides (Nylons)						
	22	Nylon Type 6	N6	1.30	2.87	60	220
	23	Nylon Type 66	N66	1.40	3.07	70	260
	24	Nylon Type 11	N11	3.35	7.38	-70	185
	25	Nylon Type 12	N12	3.30	7.26		190
	26	Polyphthalamide	PPA				310
	27	Polyamideimide	PAI	26.10	57.52	275	am*
2.3.4.8	Polyimides						
	28	Polyetherimide	PEI	6.41	14.13	215	am*
	29	Polyimide	PI			320	385
2.3.4.9	Polyethers						
	30	Polyacetal	POM	1.25	2.76	-75	175
	31	Polycarbonate	PC	1.55	3.42	150	am*
	32	Polyphenylene oxide blend	PPO	1.80	3.97	110-190	am*
	33	Polyaryletherketone	PAEK	29.50	65.02	138	320-380
	34	Polyetheretherketone	PEEK	33.00	72.73	145	335
2.3.4.10	Sulfur Containing Polymers						
	35	Polyphenylene sulfide	PPS			90	285
	36	Polysulfone	PSF	4.40	9.70	190	am*
	37	Polyethersulfone	PES	4.40	9.70	225	am*
	38	Polyarylsulfone	PAS	4.40	9.70	220	am*
2.3.4.11	Additional Thermoplastics						
	39	Acrylonitrile copolymer	ANC	1.25	2.76	95	am*
	40	Polyurethane	TPU	2.10	4.63		am*

am* = amorphous

Table 2, Part A
General Properties

#	Type	Processing Temperature				Specific Gravity		Water Absorption	
		Low °C	High °F	Low °C	High °F	D 792 Low	D 792 High	D 570 Low %	D 570 High %
Polyolefins									
1	LDPE	149	300	316	600	0.92	0.95	0.01	0.03
2	HDPE	177	350	274	525	0.95	0.97	0.00	0.00
3	PP	191	375	288	550	0.90	0.91	0.01	0.03
Styrenics									
4	PS	149	300	260	500	1.04	1.05	0.01	0.03
5	HIPS	177	350	274	525	1.03	1.06	0.05	0.07
6	ABS	163	325	274	525	1.03	1.06	0.20	0.45
7	SAN	149	300	288	550	1.06	1.08	0.15	0.25
8	S/A	191	375	246	475	1.08	1.13	0.11	0.17
9	SMA	204	400	266	510	1.05	1.08	0.10	0.10
Vinyls									
10	PVC	141	285	213	415	1.30	1.58	0.04	0.40
11	CPVC	177	350	227	440	1.48	1.58	0.02	0.15
Acrylics									
12	PMMA	149	300	260	500	1.17	1.20	0.10	0.40
13	PVC/MA	177	350	210	410	1.26	1.35	0.09	0.16
Fluoropolymers									
14	CTFE	238	460	349	660	2.08	2.27	0.00	0.00
15	PTFE	316	600	349	660	2.14	2.20	0.00	0.01
16	PVDF	182	360	288	550	1.76	1.78	0.03	0.06
Polyesters									
17	PET	227	440	349	660	1.29	1.40	0.10	0.20
18	PETG	232	450	293	560	1.27	1.28	0.07	0.13
19	PBT	224	435	274	525	1.30	1.38	0.06	0.09

Table 2, Part B
General Properties

#	Type	Processing Temperature				Specific Gravity		Water Absorption	
		Low °C	High °F	Low °C	High °F	D 792 Low	D 792 High	D 570 Low %	D 570 High %
Polyesters, continued									
20	PAR	204	400	316	600	1.21	1.26	0.20	0.27
21	LCP	282	540	410	770	1.35	1.84	0.00	0.09
Polyamides (Nylons)									
22	N6	227	440	288	550	1.12	1.14	1.60	2.00
23	N66	260	500	327	620	1.13	1.15	1.00	1.50
24	N11	199	390	271	520	1.03	1.05	0.30	0.40
25	N12	179	355	274	525	1.01	1.02	0.25	0.30
26	PPA	321	610	349	660	1.17	1.17	0.81	0.81
27	PAI	316	600	371	700	1.42	1.42	0.17	0.33
Polyimides									
28	PEI	338	640	371	700	1.26	1.27	0.10	0.30
29	PI	329	625	393	740	1.33	1.43	0.24	0.40
Polyethers									
30	POM	171	340	243	470	1.39	1.42	0.20	0.25
31	PC	271	520	293	560	1.20	1.20	0.12	0.19
32	PPO	218	425	274	525	1.04	1.09	0.06	0.12
33	PAEK	379	715	429	805	1.30		0.10	0.10
34	PEEK	316	600	399	750	1.30	1.32	0.10	0.14
Sulfur Containing Polymers									
35	PPS	310	590	338	640	1.35		0.01	0.07
36	PSF	329	625	399	750	1.24	1.25	0.30	
37	PES	310	590	399	750	1.37	1.46	0.40	0.70
38	PAS	327	620	427	800	1.29	1.37	1.10	1.10
Additional Thermoplastics									
39	ANC	193	380	216	420	1.15		0.20	
40	TPU	221	430	266	510	1.20	1.22	0.13	0.19

Table 3, Part A
Tensile Properties

#	Type	Tensile Strength at Break D 638				Elongation at Break D 638		Tensile Modulus D 638			
		Low Mpa	ksi	High Mpa	ksi	Low %	High %	Low GPa	ksi	High GPa	ksi
Polyolefins											
1	LDPE	8.3	1.2	32.1	4.6	50	970	0.17	25	0.70	100
2	HDPE	22.1	3.2	31.4	4.5	10	1200	1.08	155	1.10	158
3	PP	31.0	4.5	41.9	6.0	100	600	1.15	165	1.57	225
Styrenics											
4	PS	35.9	5.2	52.4	7.5	1	3	2.31	330	3.32	475
5	HIPS	13.1	1.9	43.3	6.2	20	65	1.12	160	2.58	370
6	ABS	37.9	5.5	52.4	7.5	5	60	2.10	300	2.79	400
7	SAN	69.0	10.0	83.1	11.9	2	3	3.32	475	3.91	560
8	S/A	55.8	8.1	70.5	10.1	2	5	3.07	440	3.63	520
9	SMA	55.8	8.1	56.6	8.1	2	30	2.37	340	2.72	390
Vinyls											
10	PVC	40.7	5.9	52.4	7.5	40	80	2.44	350	4.19	600
11	CPVC	46.9	6.8	62.9	9.0	4	100	2.37	340	3.32	475
Acrylics											
12	PMMA	48.3	7.0	73.3	10.5	2	6	2.27	325	3.28	470
13	PVC/M	44.1	6.4	48.9	7.0	35	100	2.37	340	2.58	370
Fluoropolymers											
14	CTFE	31.0	4.5	41.9	6.0	80	250	1.05	150	2.10	300
15	PTFE	13.8	2.0	34.9	5.0	200	400	0.41	58	0.56	80
16	PVDF	24.1	3.5	51.0	7.3	12	600	0.56	80	1.40	200
Polyesters											
17	PET	48.3	7.0	73.3	10.5	30	300	2.79	400	4.19	600
18	PETG	24.8	3.6	41.9	6.0	15	130	2.10	300		
19	PBT	56.5	8.2			50	300	1.96	280	3.04	435

Table 3, Part B
Tensile Properties

#	Type	Tensile Strength at Break				Elongation at Break		Tensile Modulus			
		D 638		High		D 638		D 638		High	
		Low	ksi	Mpa	ksi	Low	High	Low	ksi	GPa	ksi
		Mpa				%	%	GPa			
Polyesters, continued											
20	PAR	69.0	10.0	76.1	10.9	8	100	2.06	295	2.24	320
21	LCP	109.6	15.9	188.6	27.0	1	5	9.78	1400	19.56	2800
Polyamides (Nylons)											
22	N6	41.4	6.0	167.6	24.0	20	100	2.65	380	3.25	465
23	N66	51.7	7.5	95.7	13.7	15	80	1.61	230	3.84	550
24	N11	55.2	8.0	66.4	9.5	100	300	1.29	185	1.29	185
25	N12	35.2	5.1	69.9	10.0	120	350	0.25	36	1.40	200
26	PPA	85.5	12.4	105.5	15.1	3		3.75	537		
27	PAI	75.8	11.0	160.0	22.9	2	15	2.51	360	4.89	700
Polyimides											
28	PEI	62.1	9.0	150.2	21.5	5	90	2.72	390	4.02	575
29	PI	72.4	10.5	119.4	17.1	4	10	2.10	300	4.02	575
Polyethers											
30	POM	66.9	9.7	69.9	10.0	10	75	2.79	400	3.63	520
31	PC	62.7	9.1	73.3	10.5	110	150	2.20	315	2.41	345
32	PPO	49.0	7.1	66.4	9.5	50	60	2.48	355	2.65	380
33	PAEK	93.1	13.5			50		3.63	520	4.05	580
34	PEEK	70.3	10.2	104.8	15.0	15	30	3.63	520		
Sulfur Containing Polymers											
35	PPS	48.3	7.0	87.3	12.5	1	4	3.28	470	3.42	490
36	PSF	60.0	8.7	74.7	10.7	50	100	2.51	360	2.72	390
37	PES	68.3	9.9	100.6	14.4	40	80	2.44	350	2.86	410
38	PAS	62.1	9.0	100.6	14.4	7	60	2.17	310	2.79	400
Additional Thermoplastics											
39	ANC					3	4	3.49	500	3.84	550
40	TPU	49.6	7.2	69.9	10.0	60	180	1.33	190	2.17	310

Table 4, Part A
Flexural and Impact Properties

#	Type	Flexural Strength				Flexural Modulus				Izod Impact Strength D 256			
		D 790		D 790		D 790		D 790		Low		High	
		Low	High	Low	High	Low	High	Low	High	J/cm	ft-lb/in	J/cm	ft-lb/in
		MPa	ksi	MPa	ksi	GPa	ksi	GPa	ksi				
Polyolefins													
1	LDPE	41	5.8	41	5.8	0.24	35	0.73	105	0.5	1.0	No Break	
2	HDPE	35	5.0	49	7.0	1.01	145	1.57	225	0.2	0.4	2.1	4.0
3	PP	42	6.0	56	8.0	1.19	170	1.75	250	0.2	0.4	0.7	1.4
Styrenics													
4	PS	70	10.0	102	14.6	2.65	380	3.42	490	0.2	0.4	0.2	0.5
5	HIPS	23	3.3	70	10.0	1.12	160	2.72	390	0.5	1.0	3.7	7.0
6	ABS	50	7.1	91	13.0	2.17	310	2.79	400	1.6	3.0	3.2	6.0
7	SAN	77	11.0	133	19.0	3.49	500	4.26	610	0.2	0.4	0.3	0.6
8	S/A	98	14.1	112	16.0	3.14	450	3.21	460	0.2	0.3	0.2	0.4
9	SMA	56	8.0	99	14.2	2.24	320	3.28	470	0.2	0.4	2.0	3.7
Vinyls													
10	PVC	70	10.0	112	16.0	2.10	300	3.49	500	0.2	0.4	11.7	22.0
11	CPVC	101	14.5	119	17.0	2.65	380	3.14	450	0.5	1.0	3.0	5.6
Acrylics													
12	PMMA	73	10.5	133	19.0	2.27	325	3.21	460	0.1	0.2	0.2	0.4
13	PVC/M	72	10.3	77	11.0	2.44	350	2.65	380	0.5	1.0	6.4	12.0
Fluoropolymers													
14	CTFE	52	7.4	77	11.0	1.19	170	1.40	200	1.3	2.5	2.7	5.0
15	PTFE	21	3.0	45	6.5	0.35	50	0.70	100	1.3	2.5	2.1	4.0
16	PVDF	49	7.0	96	13.7	0.84	120	1.82	260	1.5	2.8	42.7	80.0
Polyesters													
17	PET	84	12.0	126	18.0	2.44	350	3.14	450	0.1	0.3	0.4	0.7
18	PETG	66	9.4	74	10.6	2.10	300	2.24	320	0.7	1.3	1.0	1.9
19	PBT	84	12.0	117	16.7	2.31	330	2.79	400	0.4	0.7	0.5	1.0

Table 4, Part B
Flexural and Impact Properties

#	Type	Flexural Strength				Flexural Modulus				Izod Impact Strength			
		D 790		D 790		D 790		D 790		D 256		D 256	
		Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
		MPa	ksi	MPa	ksi	GPa	ksi	GPa	ksi	J/cm	ft-lb/in	J/cm	ft-lb/in
Polyesters, continued													
20	PAR	74	10.6	103	14.7	2.10	300	2.34	335	0.7	1.3	2.1	4.0
21	LCP	133	19.0	248	35.5	12.36	1770	18.86	2700	0.9	1.7	5.3	10.0
Polyamides (Nylons)													
22	N6	70	10.0	112	16.0	2.72	390	2.86	410	0.3	0.6	1.2	2.2
23	N66	125	17.9	136	19.5	2.86	410	3.28	470	0.3	0.6	0.5	1.0
24	N11	91	13.0			0.31	44	1.26	180	0.4	0.8	4.3	8.0
25	N12	10	1.4	57	8.1	0.19	27	1.33	190	0.5	1.0	No Break	
26	PPA	142	20.3	161	23.0	3.32	475	3.77	540	0.2	0.4	0.5	1.0
27	PAI	136	19.5	244	34.9	4.12	590	5.10	730	0.3	0.5	1.4	2.7
Polyimides													
28	PEI	84	12.0	154	22.0	2.79	400	3.49	500	0.3	0.6	2.1	4.0
29	PI	84	12.0	201	28.8	3.00	430	4.05	580	0.4	0.8	0.9	1.7
Polyethers													
30	POM	91	13.0	119	17.0	2.58	370	3.42	490	0.4	0.8	1.2	2.3
31	PC	84	12.0	105	15.0	2.31	330	2.50	358	6.4	12.0	8.5	16.0
32	PPO	66	9.5	98	14.0	2.31	330	2.79	400	2.1	4.0	2.7	5.1
33	PAEK	131	18.8	171	24.5	3.70	530			0.9	1.6	1.4	2.7
34	PEEK	112	16.0			3.70	530	3.91	560	0.9	1.6	6.4	12.0
Sulfur Containing Polymers													
35	PPS	98	14.0	147	21.0	3.84	550	4.19	600	0.2	0.4	0.3	0.50
36	PSF	108	15.4	122	17.5	2.69	385	2.72	390	0.6	1.2	0.7	1.3
37	PES	112	16.0	131	18.7	2.51	360	3.49	500	0.6	1.2	No Break	
38	PAS	112	16.0	129	18.5	2.31	330	2.79	400	0.8	1.5	6.4	12.0
Additional Thermoplastics													
39	ANC	98	14.0			3.35	480			1.3	2.5		
40	TPU	71	10.2	105	15.0	1.64	235	2.31	330	0.8	1.5	1.3	2.4

Table 5, Part A
Thermal Properties

#	Type	Heat Deflection Temperature D 648 @ 1.8 MPa (264 psi)				Coef. of Thermal Expansion, Linear D 696		Thermal Conductivity C 177	
		Low °C	High °F	Low °C	High °F	Low Microns/meter/°K	High	Low W/(meter-°K)	High
Polyolefins									
1	LDPE	38	100	44	112	27	220	0.34	
2	HDPE	79	175	91	196	59	110	0.46	0.50
3	PP	49	120	60	140	81	100	0.12	0.20
Styrenics									
4	PS	76	169	94	202	50	83	0.08	0.13
5	HIPS	77	170	96	205	44		0.04	0.12
6	ABS	93	200	104	220	80	100	0.18	0.32
7	SAN	101	214	104	220	65	68	0.12	0.13
8	S/A	96	205	99	210	40	72		
9	SMA	101	214	118	245	80		0.17	
Vinyls									
10	PVC	60	140	77	170	50	100	0.15	0.21
11	CPVC	94	202	112	234	62	78	0.13	0.14
Acrylics									
12	PMMA	68	155	100	212	50	90	0.17	0.25
13	PVC/MA	75	167	85	185	44	79	0.15	
Fluoropolymers									
14	CTFE	126	258			36	70	0.20	0.22
15	PTFE	46	115	90	194	70	120	0.24	0.27
16	PVDF	54	129	118	244	70	142	0.10	0.13
Polyesters									
17	PET	21	70	66	150	60	80	0.14	0.15
18	PETG	63	145	66	151	51	67	0.20	0.33
19	PBT	50	122	85	185	60	95	0.18	0.29

Table 5, Part B
Thermal Properties

#	Type	Heat Deflection Temperature D 648 @ 1.8 MPa (264 psi)				Coef. of Thermal Expansion, Linear D 696		Thermal Conductivity C 177	
		Low °C	High °F	Low °C	High °F	Low Microns/meter/°K	High	Low W/(meter-°K)	High
Polyesters, continued									
20	PAR	110	230	174	345	63			
21	LCP	180	356	355	671	5	7	0.08	
Polyamides (Nylons)									
22	N6	68	155	95	203	50	83	0.20	0.30
23	N66	75	167	104	220	80	110	0.20	0.30
24	N11	40	104	60	140	100		0.34	0.35
25	N12	35	95	70	158	61	100	0.25	0.35
26	PPA	120	248	170	338	54		0.07	
27	PAI	275	527	280	536	25	60	0.26	0.53
Polyimides									
28	PEI	193	380	232	450	47	56	0.07	0.16
29	PI	238	460	360	680	45	90	0.10	0.30
Polyethers									
30	POM	85	185	136	277	65	110	0.23	0.30
31	PC	121	250	132	270	60	70	0.18	0.21
32	PPO	107	225	149	300	33	77	0.22	0.23
33	PAEK	162	323	170	338	41	44	0.30	
34	PEEK	160	320			40	47		
Sulphur Containing Polymers									
35	PPS	100	212	135	275	27	49	0.08	0.29
36	PSF	174	345	174	345	56		0.26	
37	PES	195	383	232	450	31	70	0.13	0.27
38	PAS	204	400	271	520	31	85	0.19	
Additional Thermoplastics									
39	ANC	66	151	66	151	66		0.26	
40	TPU	70	158	91	195	62	76	0.25	

Table 6, Part A
Electrical Properties

#	Type	Dielectric Constant D 150		Dissipation Factor D 150		Dielectric Strength D 149	
		Low	High	Low (x 10 ⁺³)	High (x 10 ⁺³)	Low kV/mm	High kV/mm
Polyolefins							
1	LDPE	2.3	2.4	0.2	0.5	19	150
2	HDPE	2.3	2.4	0.5		18	20
3	PP	2.1	2.6	0.5	2	24	28
Styrenics							
4	PS	2.4	2.7	0.1	0.6	20	28
5	HIPS	2.4	4.8	0.4	2	12	24
6	ABS	2.4	2.9	5	9	14	19
7	SAN	2.6	3.4	6	12	16	20
8	S/A	3.3	3.7	40	50	18	20
9	SMA	2.5	3.3	1		12	20
Vinyls							
10	PVC	2.8	3.6	7	20	14	20
11	CPVC	2.8	3.6	30	75	48	60
Acrylics							
12	PMMA	2.2	3.9	30	50	18	60
13	PVC/MA	3.4	3.9	2		17	19
Fluoropolymers							
14	CTFE	2.3	2.7	20		20	24
15	PTFE	2	2.1	0.1	0.3	18	100
16	PVDF	6.4	10	18	50	10	11
Polyesters							
17	PET	3.6	4.2	15	30	18	20
18	PETG	2.4	2.6	5	20	15	16
19	PBT	2.8	3.8	1	20	17	22

Table 6, Part B
Electrical Properties

#	Type	Dielectric Constant D 150		Dissipation Factor D 150		Dielectric Strength D 149	
		Low	High	Low (x 10 ⁺³)	High (x 10 ⁺³)	Low kV/mm	High
Polyesters, continued							
20	PAR	2.6	3.1	0.1	22	16	17
21	LCP	4.2		13		24	39
Polyamides (Nylons)							
22	N6	2.9	3.2	10	20	12	16
23	N66	3.4	4	14	40	16	25
24	N11	3.7	3.8	20	30	25	29
25	N12	3.1	4.1	30	40	18	
26	PPA	4.3		27		21	
27	PAI	4.2	7.3	6	71	23	24
Polyimides							
28	PEI	2.8	3.7	1.3	4	20	33
29	PI	3.4	3.6	1.8	5	22	28
Polyethers							
30	POM	3.7	3.9	1	6	20	
31	PC	3	3.2	0.9	1	15	16
32	PPO	2.6	2.7	0.4	0.7	16	27
33	PAEK					14	
34	PEEK	3.2		2			
Sulphur Containing Polymers							
35	PPS	3.1		0.5		15	18
36	PSF	3		3.4	8	15	17
37	PES	3.5	4.1	1	14	15	80
38	PAS	3.5	3.9	3		14	15
Additional Thermoplastics							
39	ANC					9	10
40	TPU	3.9	6.4	11	84	16	19

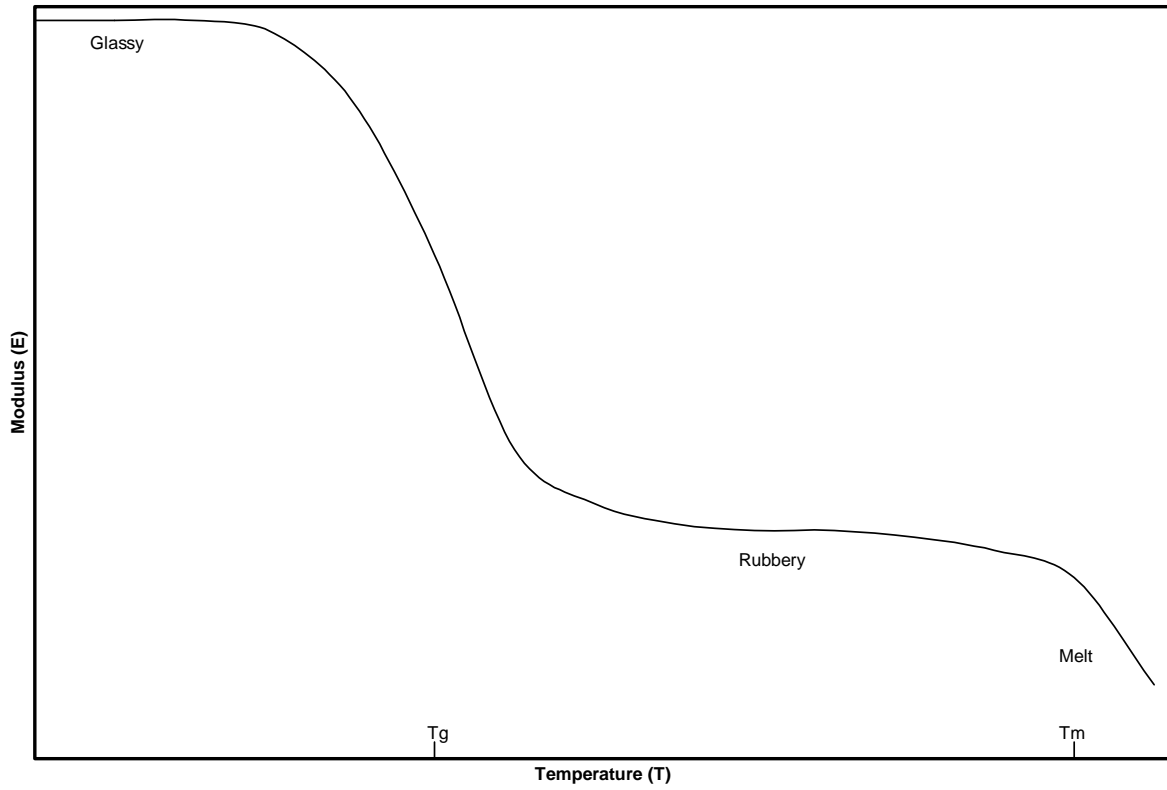


Figure 1 Modulus versus temperature for an amorphous thermoplastic

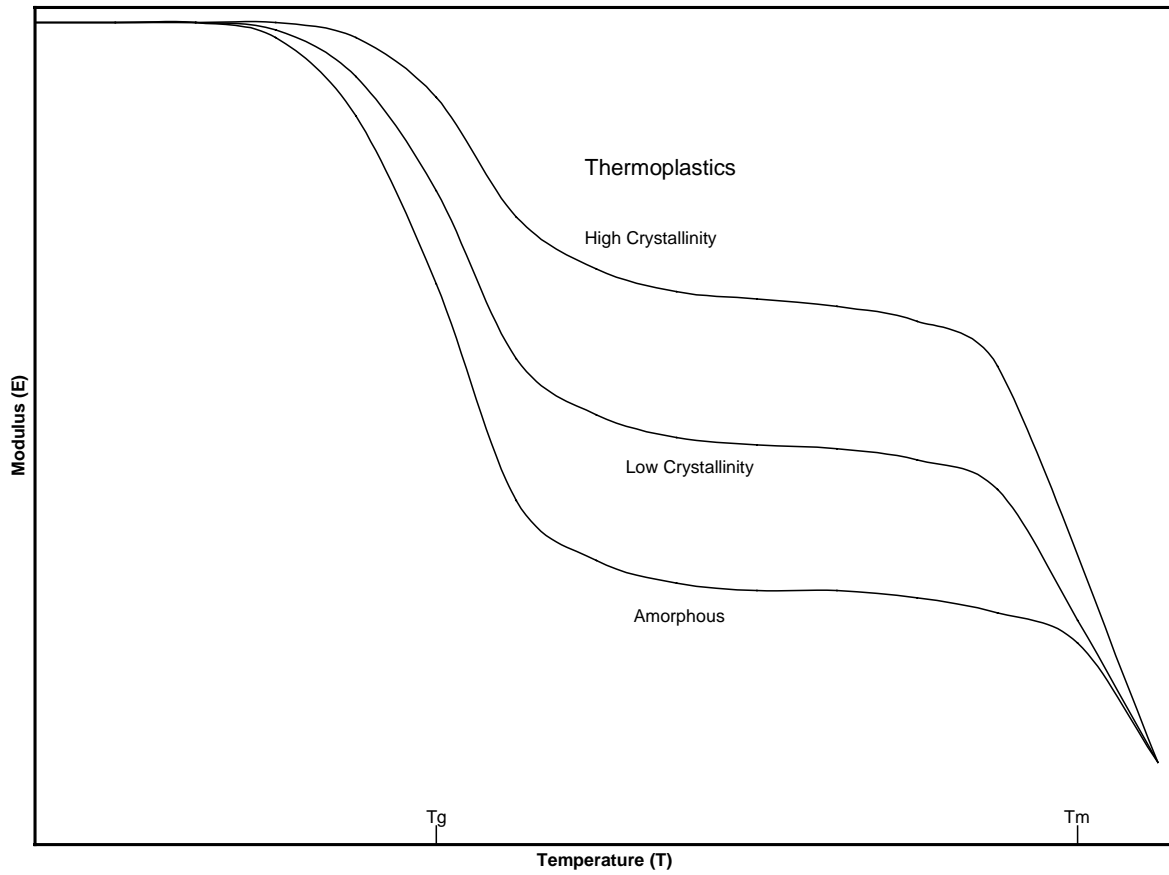


Figure 2. Modulus versus temperature for crystalline thermoplastics

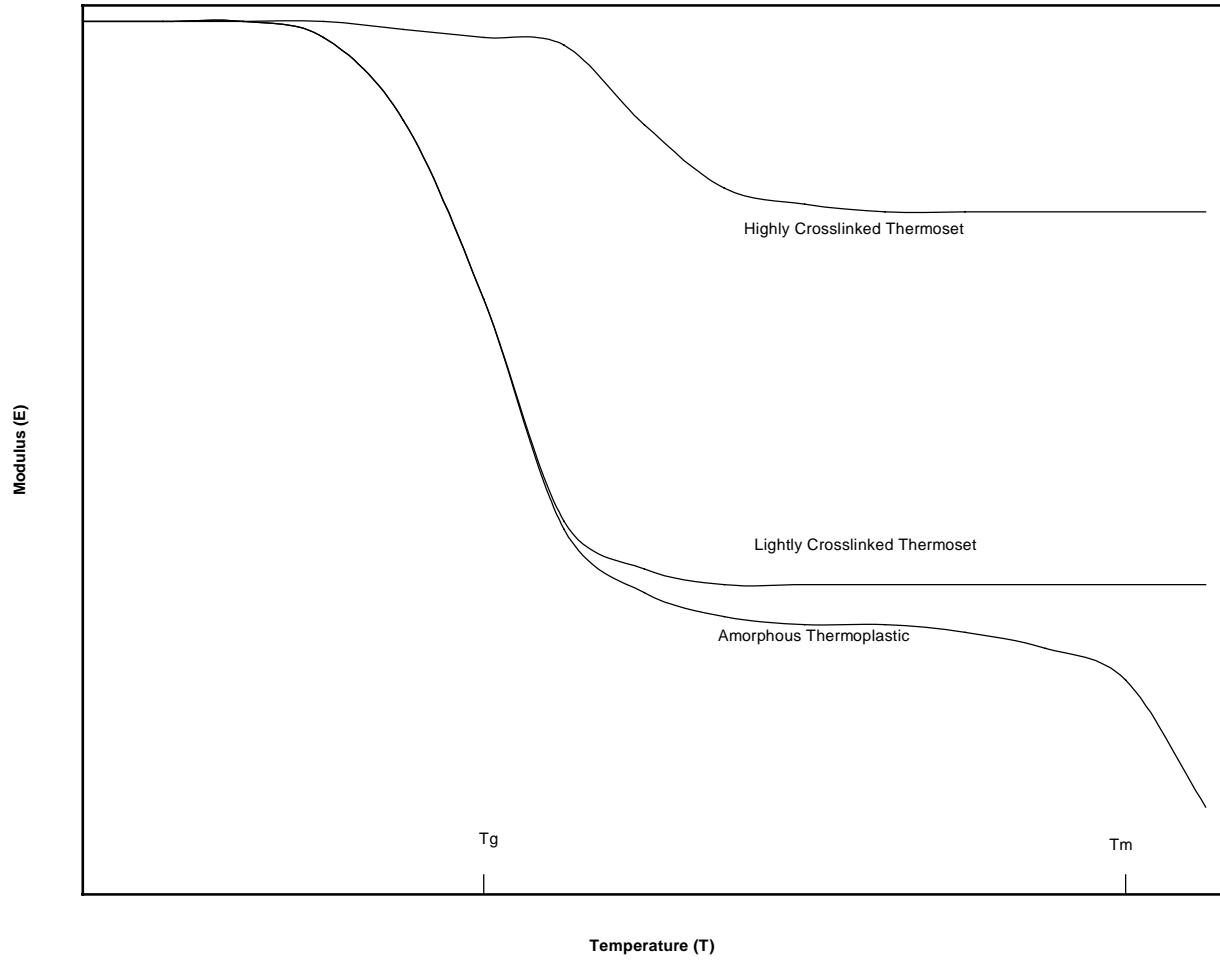


Figure 3. Modulus versus temperature for thermosetting resins

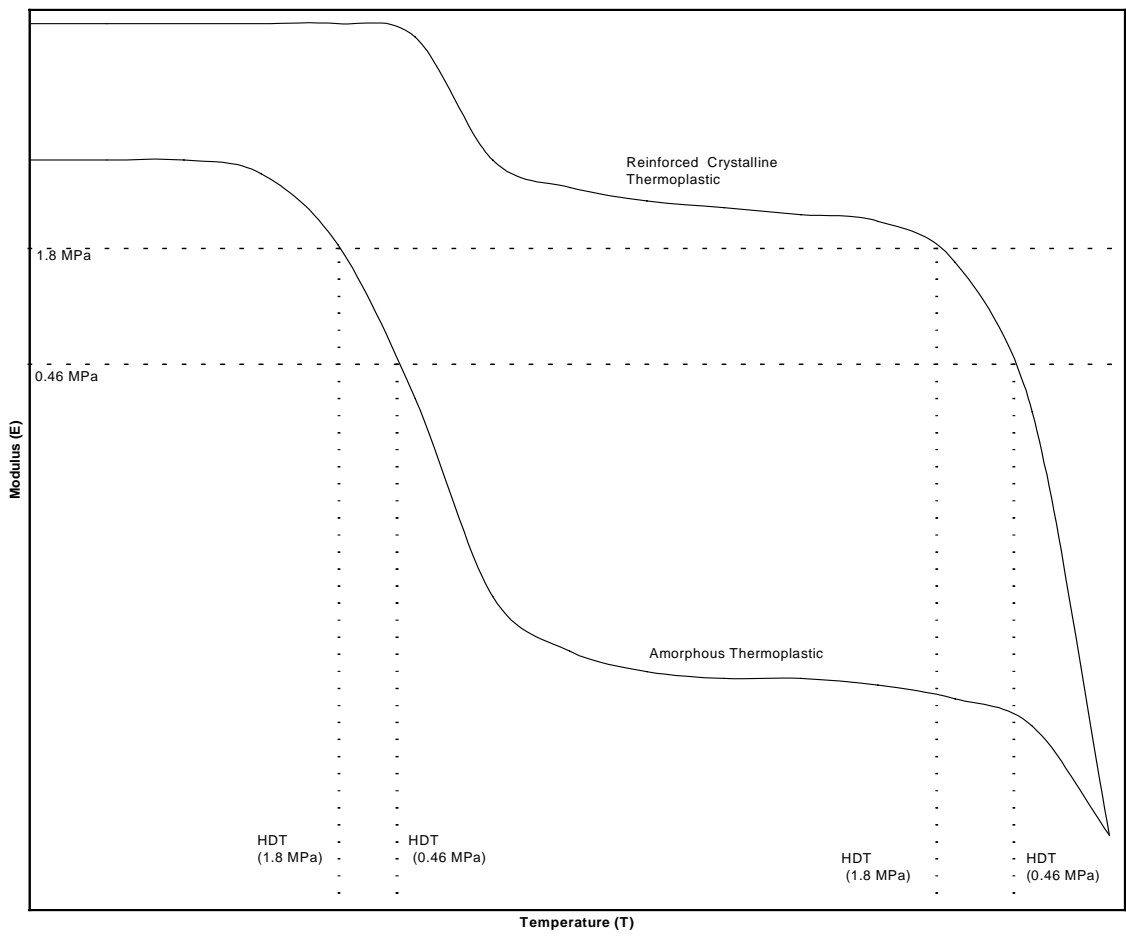
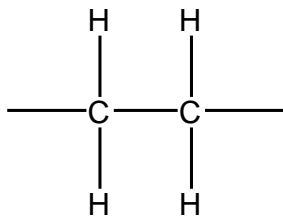


Figure 4 Modulus versus temperature for a reinforced crystalline thermoplastic

Polyethylene



PP

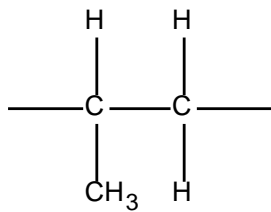
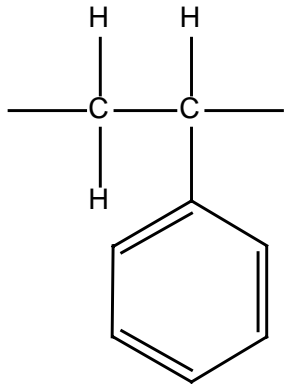
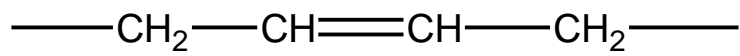


Figure 5 Chemical structures of polyolefin repeating units.

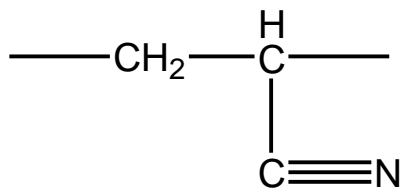
Polystyrene



Butadiene



Acrylonitrile



Maleic anhydride

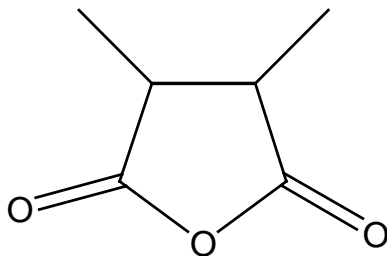
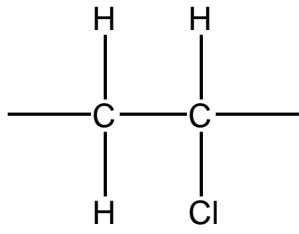


Figure 6. Chemical Structures of Styrenics

PVC



PMMA

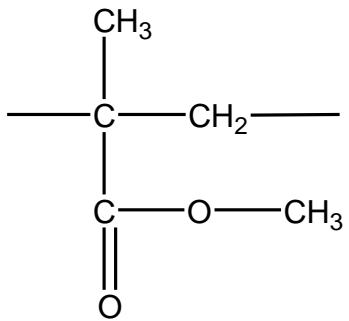
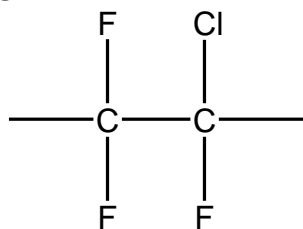
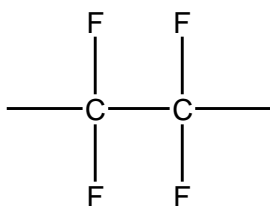


Figure 7 Chemical Structures of PVC and PMMA

CTFE



PTFE



PVDF

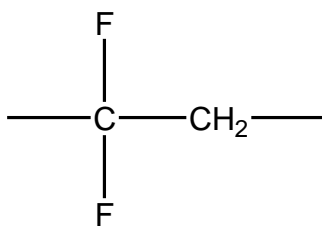
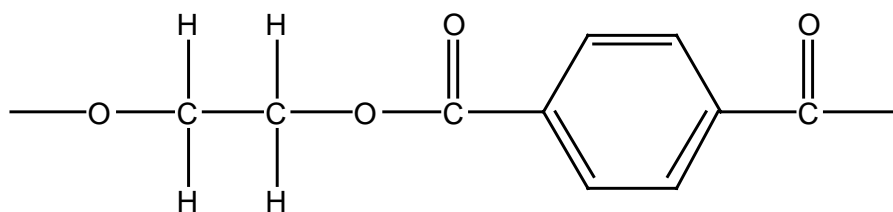
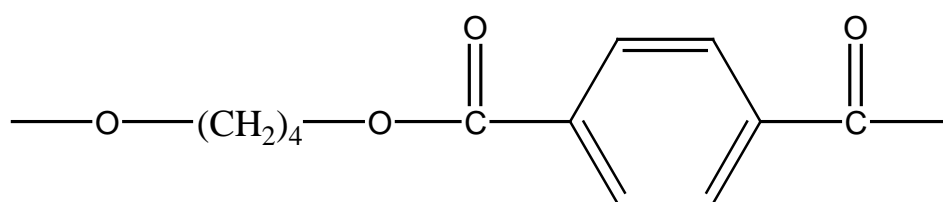


Figure 8 Fluoropolymer chemical structures

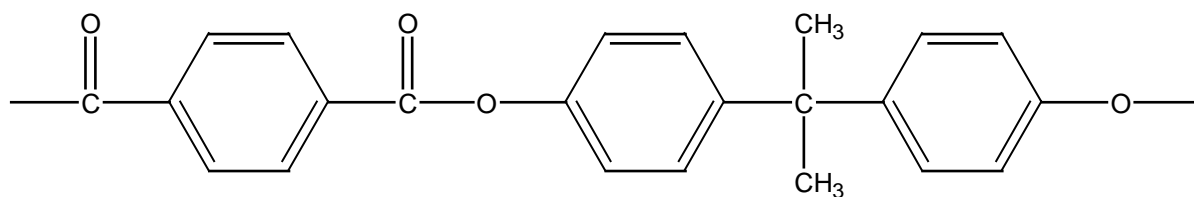
PET



PBT



PAR



LCP

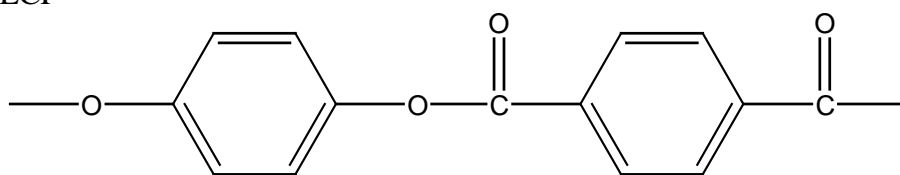
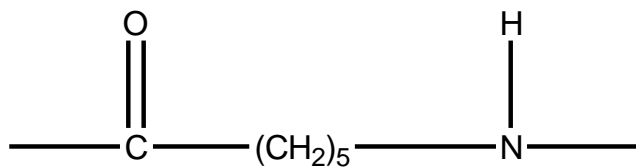
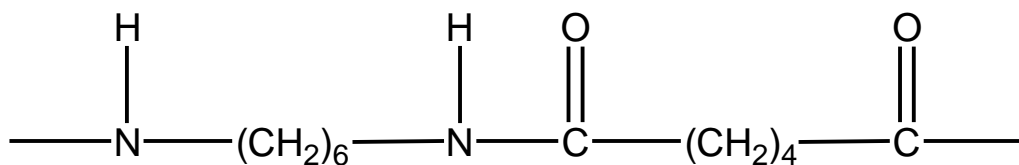


Figure 9. Polyester chemical structures

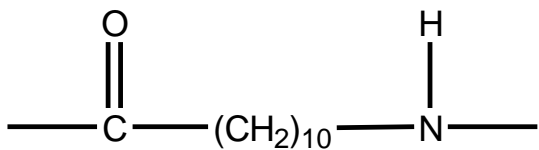
N6



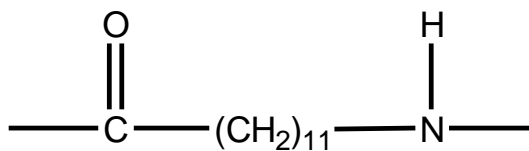
Nylon 66



N11



N12



PPA

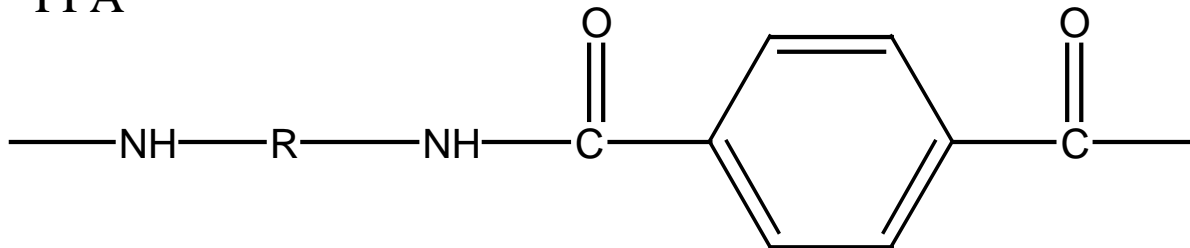
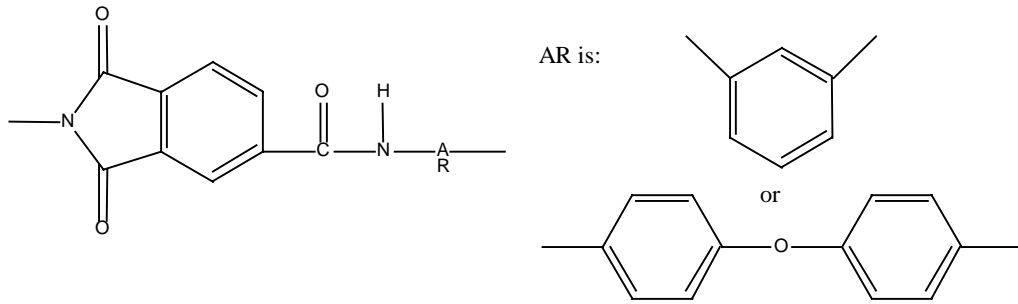
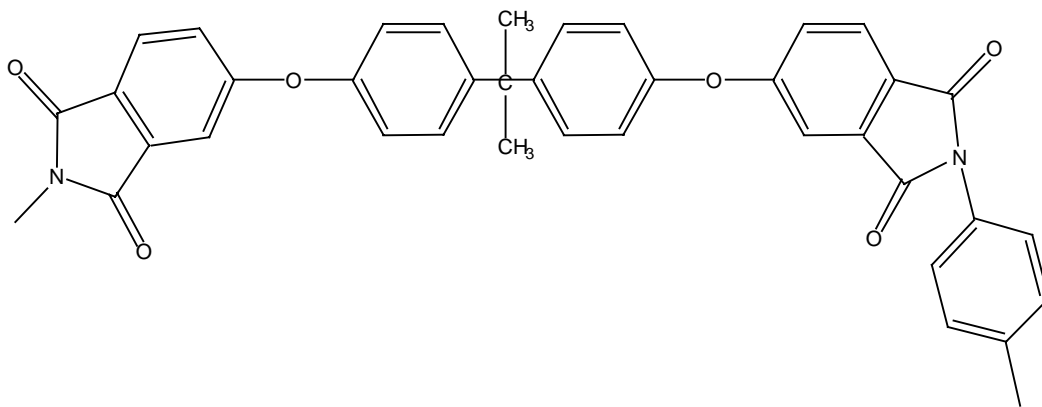


Figure 10 Polyamide chemical structures

Poly amide imide



Polyetherimide



PI

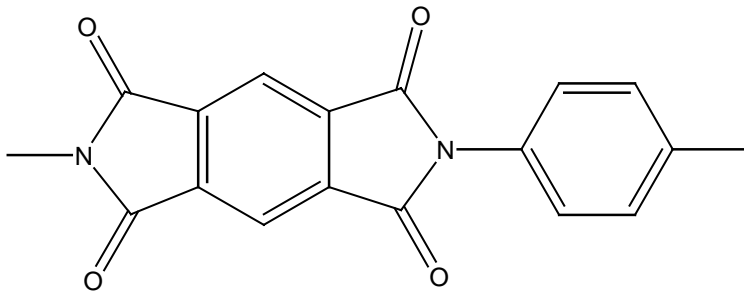
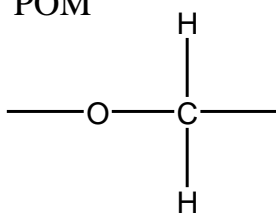
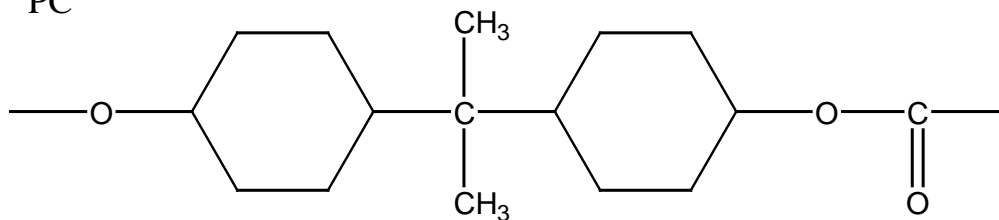


Figure 11 Polyimide chemical structures

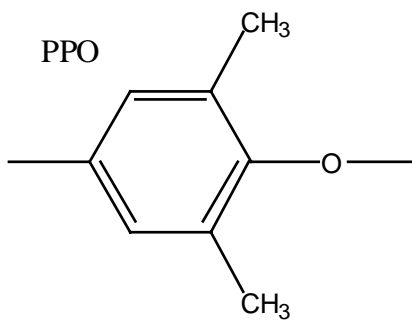
POM



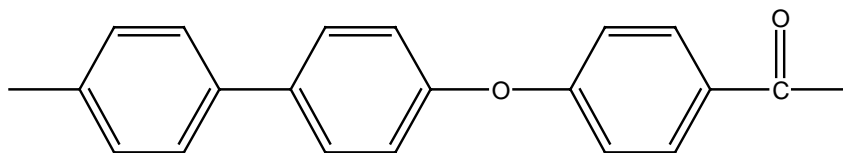
PC



PPO



PAEK



PEEK

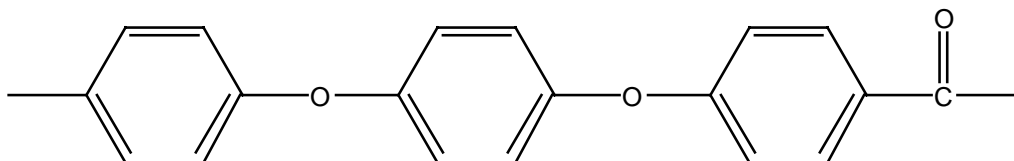
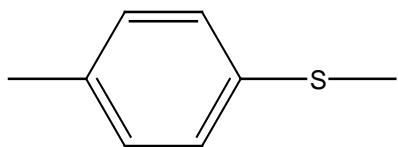
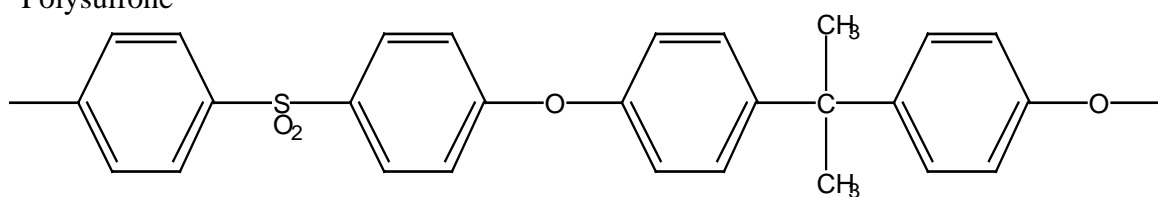


Figure 12. Polyether chemical structures

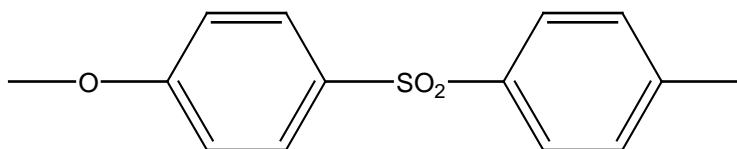
PPS



Polysulfone



PES



Polyarylsulfone

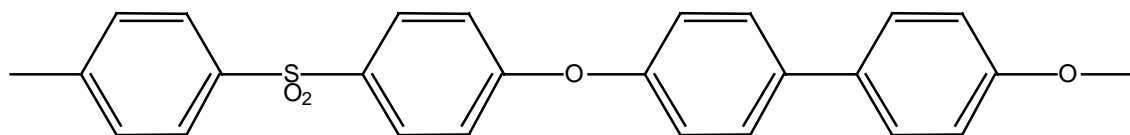


Figure 13 Chemical Structures of sulfur containing polymers

Polyurethane

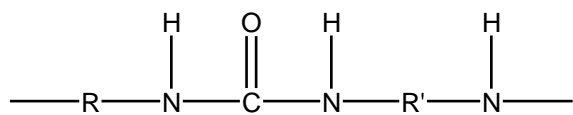


Figure 14 Chemical structure of a polyurethane