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Division of Building Research, National Research Council Canada

CBD 157

Properties and Behaviour of Plastics

Originally published 1973

A. Blaga

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Plastics are relatively new as building materials and their properties are very different from those of traditional ones such as concrete and metal. It is essential that designers and users understand their characteristics in order to ensure proper performance in new applications. This Digest will discuss their general properties and mechanical behaviour.

Density

The density of most plastics is considerably lower than that of metals, a useful feature where reduction in weight is required for it makes a number of plastics stronger than metals on a weight basis. On a volume basis, however, the opposite is normally true. Polymers and plastics generally have densities in the range 0.83 to 2.5 g/cm³, although some, such as foamed plastics, have densities as low as 0.01 g/cm³ and filled plastics have densities as high as 3.5 g/cm³.

Thermal and Electrical Properties

As organic materials, polymers and plastics have, with few exceptions, much lower heat resistance than metals, particularly in the presence of oxygen. Among the common polymers, one exception is tetrafluoroethylene which has very high heat stability owing to the fact that it has only C-C and C-F bonds, both very stable. When heated through a range of temperatures, thermoplastic materials slowly change from more or less rigid solids to highly viscous liquids. Although thermosetting materials do not appreciably soften with heat, excessive or prolonged heating will result in overhardening, contraction, charring, or disintegration. Plastics have coefficients of thermal expansion (4 to 20 x 10⁻⁵/°C; 2 to 11 x 10⁻⁵/°F) considerably higher than those of common metals (1.0 to 2.5 x 10⁻⁵/°C; 0.6 to 1.4 x 10⁻⁵/°F). Polymers and derived plastics are generally good electrical insulators and some, such as polytetrafluoroethylene, are excellent.

Fire Resistance

Plastics show a wide range of behaviour in fire: some ignite, some are self-extinguishing, others are slow- to fast-burning. Flammability depends on the polymer and other constituents such as fillers, reinforcing materials, plasticizers, or fire-retardant additives.

Halogen-containing polymers like PVC or chlorinated PVC are inherently flame retardant; with heating, they liberate halogen gases that interrupt the free radical oxidation chain reaction. The

addition of most plasticizers to PVC, however, makes it flammable. The fire resistance properties of plastics can be improved by incorporating appropriate additives (CBD 154) or using polymers with built-in fire resistance.

The products of combustion of most plastics are similar to those of wood, paper and fabrics because their chemical constituents are essentially similar. Products of combustion, however, depend not only on the chemical nature of the material but also on the conditions under which it burns. For example, with sufficient air the main combustion products of most plastics, woods and fabrics are (harmless) carbon dioxide and water, but if there is an oxygen deficiency large volumes of toxic carbon monoxide and smoke are formed. In addition, fire-retardant plastics rapidly produce dense smoke that is not easily cleared by ventilation; and if plastics contain combined chlorine, fluorine, nitrogen and sulphur (or their derivatives) these elements or their derivatives will also be present in the smoke.

Appearance

Many polymers are inherently transparent, some are translucent, a few opaque. Similarly, derived plastics show a range of optical properties, depending upon the compounding ingredients. Rigid amorphous polymers free of fillers and other impurities are isotropic to visible light and have high clarity approaching that of glass, particularly when they are fabricated so as to avoid orientation of molecules and flow. Poly(methyl methacrylate) is a good example of this type of polymer.

Blends of impact-grade plastics and those based on crystalline polymers, on the other hand, are usually composed of intermixed solid phases of different densities and this makes them translucent to opaque. For example, in some thick polyethylene articles the crystalline material has a much greater density (about 1.01) than have the amorphous regions (0.84 to 0.85) so that the article is opaque. Polymers and plastics can also be rendered translucent or opaque by deliberate incorporation of appropriate amounts of certain pigments or fillers.

Mechanical Behaviour

Polymeric materials are chiefly valuable for their mechanical properties. In comparison with metals, polymers and plastics have low moduli and high strength to weight ratios. Articles and structures made from plastics show a wide variation of impact strength, covering the whole range from very tough to very brittle.

The essential difference between the deformational behaviour of polymeric materials and metals of construction is that in polymeric material strain depends not only on the magnitude of the stress but also on the length of time during which it is applied. Creep effects in polymers and plastics may be significant even at room temperature, whereas in metals they are not important at temperatures below 500°C. Furthermore, the mechanical properties of polymeric materials are much more dependent on temperature and rate of application of stress than are those of metals. They can also be affected by previous history, that is, by their method of fabrication, post-treatment, and the age of the finished article.

Polymeric materials do not obey Hooke's law but exhibit so-called viscoelastic behaviour. The prefix "visco" means that the material has some of the features of a viscous liquid, implying time dependence. According to this behaviour, the deformational response of amorphous polymeric materials to nondestructive (relatively small) stresses may be of three kinds, differing in the way they depend upon time under load: instantaneous (or Hookean) elasticity, delayed or retarded elasticity (high elasticity), and viscous flow.

Instantaneous or Hookean elasticity. Under very rapid loading the material behaves like an elastic solid, so that the ratio of stress to strain is constant and independent of time. On the molecular level, instantaneous elasticity involves a slight deformation of valence bonds by stretching and bending as well as changes in the distances between neighbouring chains. This takes place at temperatures below the glass-transition temperature (T_g), where every polymer chain is trapped in one of its many possible arrangements.

Delayed elasticity. Under slower rates of loading the ratio of stress to strain depends on time; strains may become large but they are recoverable if the load is removed. Delayed elastic behaviour corresponds to changes in the conformation of molecules and takes place in the vicinity of the glass-transition or above it. Above T_g , the polymer is in a rubbery state. Normally, the molecules take up a random, coiled or zigzag arrangement (conformation) as a result of free rotation about single bonds in the chain backbone. On application of stress, the molecules tend to uncoil or unfold, and in the absence of crystallization the polymer may be stretched until the molecules assume a fully stretched conformation. With some rubbery polymers subjected to tensile stress, elongations as high as 1200 per cent are possible. On removal of stress, the molecules assume the coiled or zigzag conformation once again. Neither stretching nor recovery of the polymeric mass is instantaneous.

Viscous flow. Under very slow rates of loading some of the strain may be irrecoverable, indicating that the material has deformed in part like a viscous liquid rather than as a solid. viscous flow is the result of slow displacement of entire polymer chains in relation to their neighbours. Crosslinked or network polymers do not undergo viscous flow, which is prevented by the cross-links between chains.

The deformational response to stress of crystalline polymers is considerably more complex than that of amorphous polymers. Most crystalline polymers contain amorphous regions (CBD 154) that show viscoelastic behaviour. Far below T_g molecular mobility of the crystalline polymer will be essentially absent and the material will behave as a hard elastic solid. Above the melting temperature (T_m) the polymer will no longer be crystalline and will behave as an amorphous viscoelastic liquid. Between T_g and T_m , and somewhat below T_g , which is usually the range of temperature at which these materials are used, the response to stress is complex.

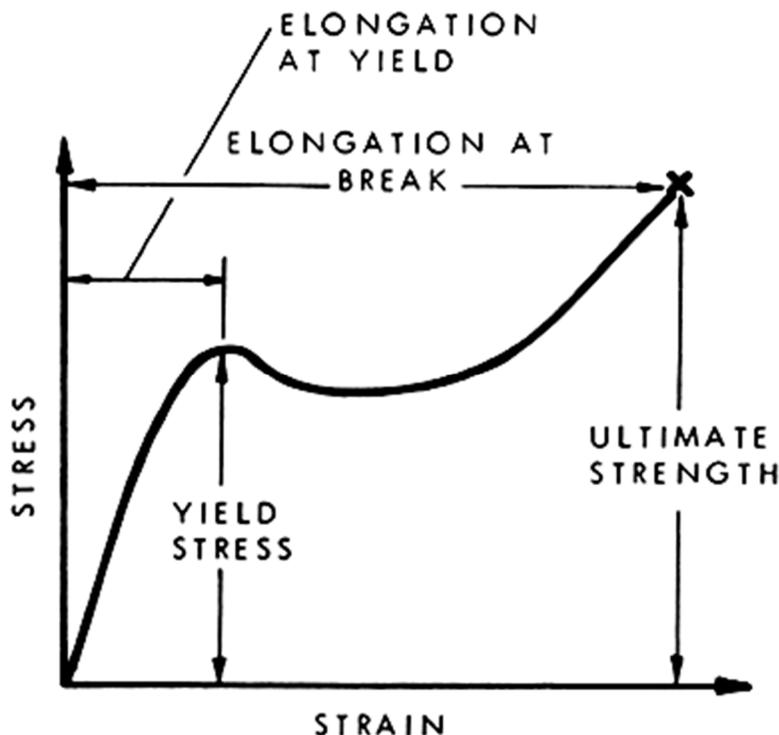


Figure 1. Generalized tensile stress-strain curve for polymeric materials.

Ultimate mechanical properties. Engineering applications of plastics are governed by strain considerations to a greater extent than are applications of other materials. The designer using polymeric materials must therefore understand their mechanical behaviour with respect to the maximum permissible strains to avoid failure. As for most materials, a simple tensile stress-strain curve provides a good start towards understanding the mechanical behaviour of a

particular plastic or polymer. This curve is usually established by continuously measuring the force developed as the sample is elongated at constant rate of extension until it breaks. Portions of the curve (Figure 1) represent the stress-strain behaviour of any plastic and are used to define several useful quantities. The initial slope provides a value for Young's modulus (or the modulus of elasticity) which is a measure of stiffness. The curve also gives yield stress, and strength and elongation at break. The area under the curve or work to break is a rough indication of the toughness of the polymeric material. The stress at the knee in the curve (known as the yield point) is a measure of the strength of the material and of its resistance to permanent deformation. The stress at the breaking point, commonly known as ultimate strength, is a measure of the force required to fracture the material completely. Stress-strain behaviour for four typical classes of polymeric material is shown in Figure 2.

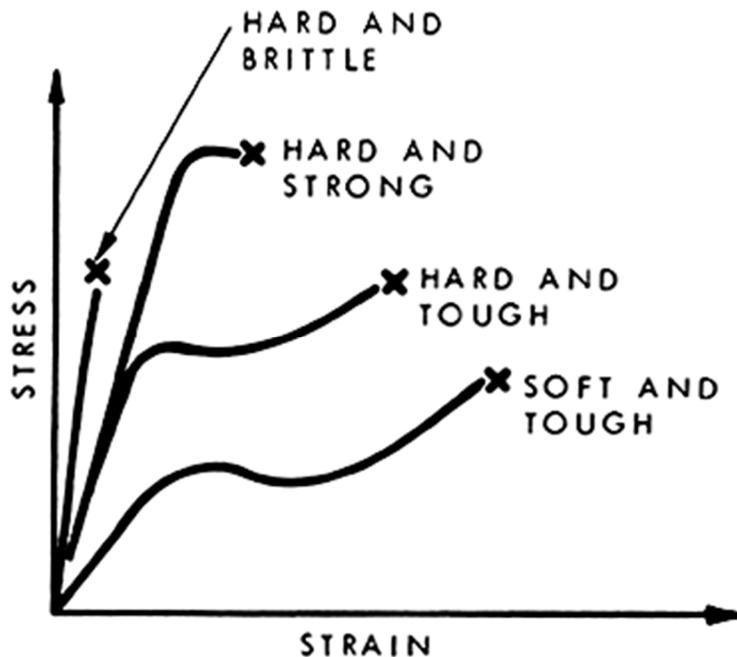


Figure 2. Tensile stress-strain curves for four types of polymeric material.

A hard brittle material such as an amorphous polymer far below its T_g usually has an initial slope indicative of very high modulus, moderate strength, a low elongation at break, and a low area under the stress-strain curve (Figure 2). Typical values of modulus and tensile strength are 500,000 and 10,000 psi, respectively; typical elongation is about 2 per cent. Generally, such materials exhibit elastic deformation up to the point of fracture, which is a brittle fracture. Polymeric materials showing hard brittle behaviour at room temperature or below are polystyrene, poly(methyl methacrylate) and many phenolformaldehyde resins.

Hard and strong polymers have high modulus of elasticity, high strength, and elongation at break of approximately 5 per cent. The shape of the curve often suggests that the material has broken where a yield point might be expected. This type of curve is characteristic of some rigid poly(vinyl chloride) formulations and polystyrene polyblends.

Hard, tough behaviour is shown by polymers such as cellulose acetate, cellulose nitrate and nylons; they have high yield points and high modulus, high strengths and large elongations. Most polymers of this group show cold-drawing or "necking" during the stretching process. Cold-drawing is important in synthetic fibre technology, and is used to develop strength.

Polymeric materials that are soft and tough show low modulus and yield values, moderate strength at break, and very high elongation ranging from 20 to 1000 per cent. This type of stress-strain curve is characteristic of plasticized PVC and rubbers (elastomers). The stress-strain behaviour of the various groups of polymeric materials is summarized in Table I.

Table I. Characteristic Features of Stress-Strain Behavior of Polymers

Examples and Characteristics of Polymeric Materials	Type of Polymeric Material			
	Hard & Brittle	Hard & Strong	Hard & Tough	Soft & Tough
	PS, PMMA, Phenolics	Rigid PVC, PS poly-blends	PE, PTFE	Flexible PVC, Rubbers
Modulus	High	High	High	Low
Yield Stress	None	High	High	Low
Ultimate Strength	Mod.	High	High	Mod.
Elongation at Break	Low	Mod.	High	High

PS = polystyrene;
 PMMA = poly(methyl methacrylate);
 PVC = poly(vinyl chloride);
 PE = polyethylene;
 PTFE = polytetrafluoroethylene.

Impact strength. Impact strength is a measure of toughness or resistance to breakage under high velocity impact conditions. From this point of view, polymeric materials under normal conditions of use are thought to be either brittle or tough. For example, polystyrene, poly(methyl methacrylate) and unmodified, unplasticized PVC are usually rated as brittle, breaking with a sharp fracture; plasticized PVC's are considered to be tough. In general, polymeric materials are either brittle or tough, depending on the temperature and rate of impact, i.e., rate of deformation. Impact strength of polymers and derived plastics depends upon the position of the glass transition temperature (T_g) with respect to room temperature and ease of crystallization. Far below the glass-transition, amorphous polymers break with a brittle fracture, but they become tougher as the service temperature approaches T_g . Above T_g , amorphous polymers are in a rubbery state so that the term impact ceases to have any significance.

Chemical and Weathering Resistance

The chemical resistance of polymeric materials depends on the nature of the polymer constituent and formulation, so that specific information on behaviour in a given environment is best obtained from the material manufacturer. In general, polymers and plastics are resistant to weak acids, weak alkali, salt solutions, and water, although some polyesters and polyamides may hydrolyze in acid and alkali. Strong oxidizing acids may attack plastics, resulting in discoloration or embrittlement; most polymers and plastics are affected by organic liquids. For example, fuels, oils and various organic solvents may attack plastics, causing swelling, softening and dissolution. Resistance to these agents depends on temperature and the composition of the plastic.

Most plastics may be used as corrosion-resistant materials. In view of the considerable variation in their resistance to various environments, however, care should be exercised in the selection of the best suitable plastic material for corrosion resistance in specific situations. Polymeric materials vary widely in their resistance to outdoor weathering, in particular to solar radiation. Some polymers and the corresponding plastics have displayed outstanding weather resistance, whereas others have performed very poorly. Most commercial plastic compounds, however, can now be formulated to have fairly good weathering resistance.