

4

Electrical and Optical Properties

As polymer materials have developed, their excellent and sometimes outstanding dielectric properties have guaranteed their widespread use as insulants in electrical and electronic engineering. In the nineteenth and early twentieth centuries electrical apparatus relied on wood, cotton sleeving, natural waxes and resins and later ebonite as insulating materials. Today a number of polymers including PTFE, PE, PVC, EP and MF offer an unrivalled combination of cost, ease of processing and electrical performance. These materials have played a most important part in the evolution of electrical components and equipment. Most electrical properties are determined largely by primary chemical structure, and are relatively insensitive to microstructure. In consequence the electrical behaviour of polymers is generally less varied than the mechanical behaviour. The same can be said of the optical properties, which nevertheless govern a variety of engineering end-uses.

4.1 Behaviour in a Steady (d.c.) Electric Field

The electrical properties of a material may be investigated by considering its response to imposed electric fields of various strengths and frequencies, just as the mechanical properties may be defined through the response to static and cyclic stress. We consider first the behaviour of polymers in steady (d.c.) electric fields.

Figure 4.1 shows the range of *volume resistivity* ρ found in electrical engineering materials. Polymers as a class have the very high electrical resistivity characteristic of insulators. To quote resistivities in this way implies that Ohm's law is obeyed and that the conduction current $I = AE/\rho$, where E is the electric field strength and A the cross-sectional area of the material. However, it is

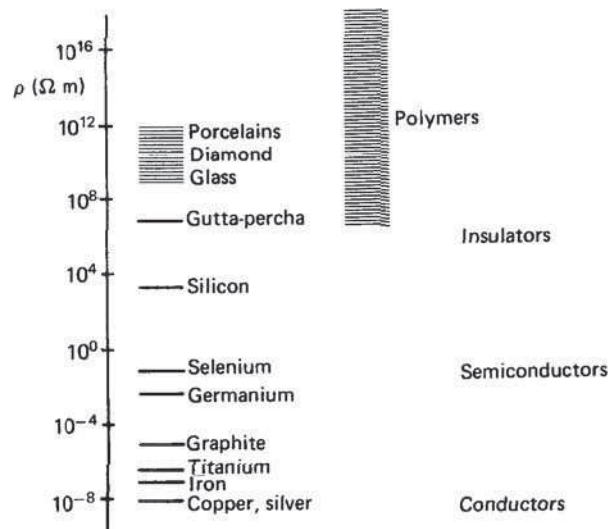


Figure 4.1 Volume resistivity ρ of electrical engineering materials

difficult to measure steady d.c. conduction in high performance insulants such as PTFE, where ρ may exceed $10^{16} \Omega \cdot m$. The volume resistivity measured by standard test methods increases steadily with time. One-minute values of ρ are frequently quoted, but curves such as those of figure 4.2 showing how ρ changes with time of electrification present the d.c. conduction behaviour more

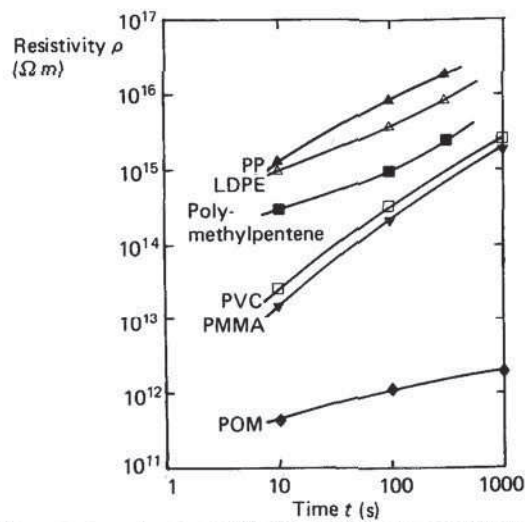


Figure 4.2 Changes in volume resistivity ρ with elapsed time for selected polymers

satisfactorily. Conduction in the surface layers of a polymer material is often sensitive to ambient humidity and surface contamination. The *surface resistivity* is determined from the flow of current between two electrodes in contact with one surface of a thin specimen of polymer material.

The extremely low values of current at typical working voltages implied by the high values of ρ show the absence in polymers of any large number of charge carriers such as exist in metals and to a less extent in semiconductors. The valency electrons in polymer molecules (with a few exceptions) are localised in covalent bonds between pairs of atoms. The small currents which are observed to flow in weak fields arise from the movement of electrically charged species present as structural defects and impurities. The concentration of defects increases as the temperature rises, so that the resistivity falls — figure 4.3(a). Exposure to ionising radiation and absorption of water or plasticiser can also lead to an increase in the concentration of charge carriers with an accompanying increase in conductivity — figure 4.3(b).

The high conductivity of graphite (figure 4.1) demonstrates that polymeric materials are not invariably insulators. The conductivity of graphite (which is a form of pure carbon) arises directly from its chemical and electronic structure. In the solid the carbon atoms lie in parallel stacked layers — see figure 1.8(a). Within each layer the C atoms are bonded in hexagonal rings to form a continuous network of primary chemical bonds. However, a quarter of all the valency electrons in such a fused ring structure are not localised between pairs of atoms, but are delocalised, much as they are in metals, and are free to carry a

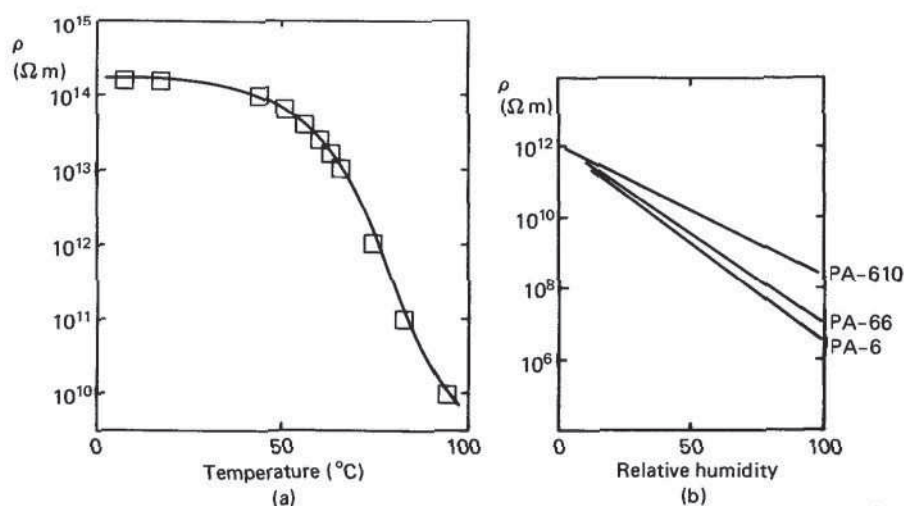


Figure 4.3 (a) Volume resistivity ρ of unplasticised PVC between 0 and 100 °C (all values measured after 60 s electrification). (b) Steady-state volume resistivity ρ of polyamides: dependence on relative humidity at room temperature

conduction current. The conductivity of graphite is much higher parallel to the layers than perpendicular to them because the delocalisation is essentially confined to the individual layers. Carbon fibre and other forms of polymeric carbon with unsaturated structures show similar high conductivity. In sharp contrast diamond, which is another form of pure carbon but which contains only localised electron pair bonds, is a dielectric. The hydrocarbon polymer polyacetylene has some electron delocalisation along the chain and is a semiconductor with a resistivity of about 10^3 ohm m. It is likely that commercially important engineering polymers with intrinsic conductivity or semiconductor or photoconductor properties will be developed.

In a perfect insulator no steady current flows in a static electric field, but energy is stored in the material as a result of dielectric polarisation. The effect is analogous to the storage of mechanical energy in a perfect elastic material, and arises through the displacement of electric charge. Some polarisation occurs in all materials through small displacements of electrons and nuclei within individual atoms, but larger effects arise if the solid contains permanent dipoles (from polar bonds or asymmetric groups of atoms) which tend to orient themselves in the direction of the externally imposed field. At normal electric field strengths the dielectric polarisation is proportional to the field strength, and we are able to define an important linear property of the material the *relative permittivity* (or dielectric constant), ϵ_r . ϵ_r is the ratio ϵ/ϵ_0 of the permittivity of the material to the permittivity of a vacuum. The permittivity determines the size of the force acting between a pair of electric charges separated by the dielectric material – figure 4.4(a). The capacitance C of a parallel plate capacitor is proportional to the relative permittivity of the medium between the plates. The energy stored by a capacitor charged at voltage V is $\frac{1}{2} CV^2$ and therefore the energy stored by a dielectric in an electric field increases with its permittivity.

The d.c. relative permittivities of selected polymers are listed in table 4.1. The values are determined largely by the nature and arrangement of the bonds in the primary structure. In polymers such as PE, PP and PTFE there is no dipole in the mer because of symmetry. Furthermore both bonding and non-bonding electrons are tightly held and displaced little by external fields. These materials exhibit very little dielectric polarisation, and as a result ϵ_r is low. Polar polymers such as PMMA, PVC and notably PVDF possess higher values of ϵ_r .

The insulating property of any dielectric breaks down in sufficiently strong electric fields. However, in polymers the *dielectric* (or *electric*) *strength* may be as high as 1000 MV/m. An upper limit on dielectric strength is set by the ionisation energies of electrons in covalent bonds within the polymer primary structure. Purely electrical or *intrinsic breakdown* occurs when appreciable numbers of electrons are detached from their parent molecules and accelerate in the electric field to cause secondary ionisation and avalanching. Breakdown of this kind runs its course extremely rapidly and the breakdown voltage does not depend greatly on temperature.

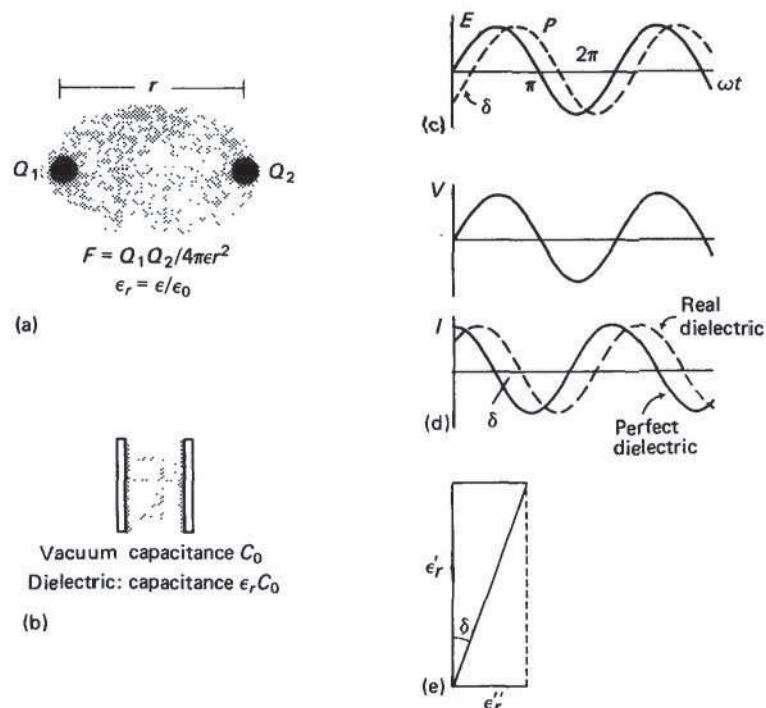


Figure 4.4 Relative permittivity ϵ_r . (a) Screening of electric charges Q_1 and Q_2 by a dielectric of permittivity ϵ . (b) Capacitance of a parallel plate condenser with dielectric. (c)–(e) Response of a dielectric in an alternating electric field. (c) Polarisation response P in a sinusoidal electric field E . (d) Voltage–current relation of a perfect (lossless) and of a real dielectric, showing phase angle δ . (e) Real and imaginary parts of the complex relative permittivity ϵ_r^*

Dielectric breakdown may occur at lower electric field strengths for several reasons. If power dissipated in the dielectric is not lost to the surroundings the rising temperature may bring about *thermal breakdown*. Breakdown voltage in this case depends on heat loss, and hence on the geometry of the specimen and the ambient temperature. In some materials, such as PE above 50 °C, the polymer becomes severely compressed in intense electric fields, and failure may occur through mechanical collapse. Surface contamination (for example by dust and moisture) may lead to local breakdown by *tracking*, a mode of failure in which carbon conducting paths are formed across the surface by localised pyrolysis of polymer. Polymer materials differ greatly in their tendency to fail by tracking, PTFE and PE/PP elastomer (EPM) having particularly good resistance to tracking. Alternatively, discharge through air or vacuum from an electrode to the polymer surface may cause erosion of the material; if the solid polymer contains voids (as in the case of sintered granular PTFE) such discharge erosion may penetrate through the material, and reduce the dielectric strength considerably. Standard

TABLE 4.1
D.C. relative permittivity (dielectric constant)
of selected polymers

	ϵ_r'
PE	2.3
PP	2.3
Polymethylpentene	2.1
POM copolymer	3.8
PMMA	3.8
PVC	3.8
PTFE	2.1
EPDM	3.1
Chlorosulphonated PE (CSM elastomer)	8–10
Urethane elastomer (AU, EU)	9
PVDF	9–13

tests for dielectric strength do exist, but measured breakdown voltages should be regarded as markedly dependent on test and specimen conditions.

4.2 Behaviour in an Alternating (a.c.) Electric Field

In section 3.11 we examined the linear mechanical stress response of a polymer material to a cyclic strain. Stress lags strain by a phase angle δ . We defined a complex compliance $D^* = D' - iD''$, and showed that $D''/D' = \tan \delta$, the loss tangent. The dynamic mechanical behaviour of the material is described by the frequency dependence of D^* .

In a similar way the linear response of a dielectric to an alternating electric field is described by the use of a complex relative permittivity $\epsilon_r^* = \epsilon_r' - i\epsilon_r''$. The ratio ϵ_r''/ϵ_r' is the dielectric loss tangent $\tan \delta$ (known also as the dissipation factor). δ is the phase lag between the electric field and the polarisation of the dielectric — figure 4.4(c). In a perfect dielectric (which behaves as a pure capacitance) the phase angle between current and voltage is $\pi/2$. In real dielectrics, δ is not zero, and current leads voltage by $(\pi/2 - \delta)$. $\sin \delta$ is known as the *power factor*. Finally we note that $\epsilon_r'' = \epsilon_r' \tan \delta$ is the *dielectric loss index* of the material.

The a.c. electrical properties of polymers are thus commonly and conveniently expressed in the form of relative permittivity ϵ_r' and loss tangent ϵ_r''/ϵ_r' data as functions of frequency (and temperature). Data may extend from d.c. or low audiofrequency (30 Hz) in half-decade steps to high radiofrequency (1000 MHz) — see figure 4.5. In pure homogeneous nonpolar polymers, the polarisation arises

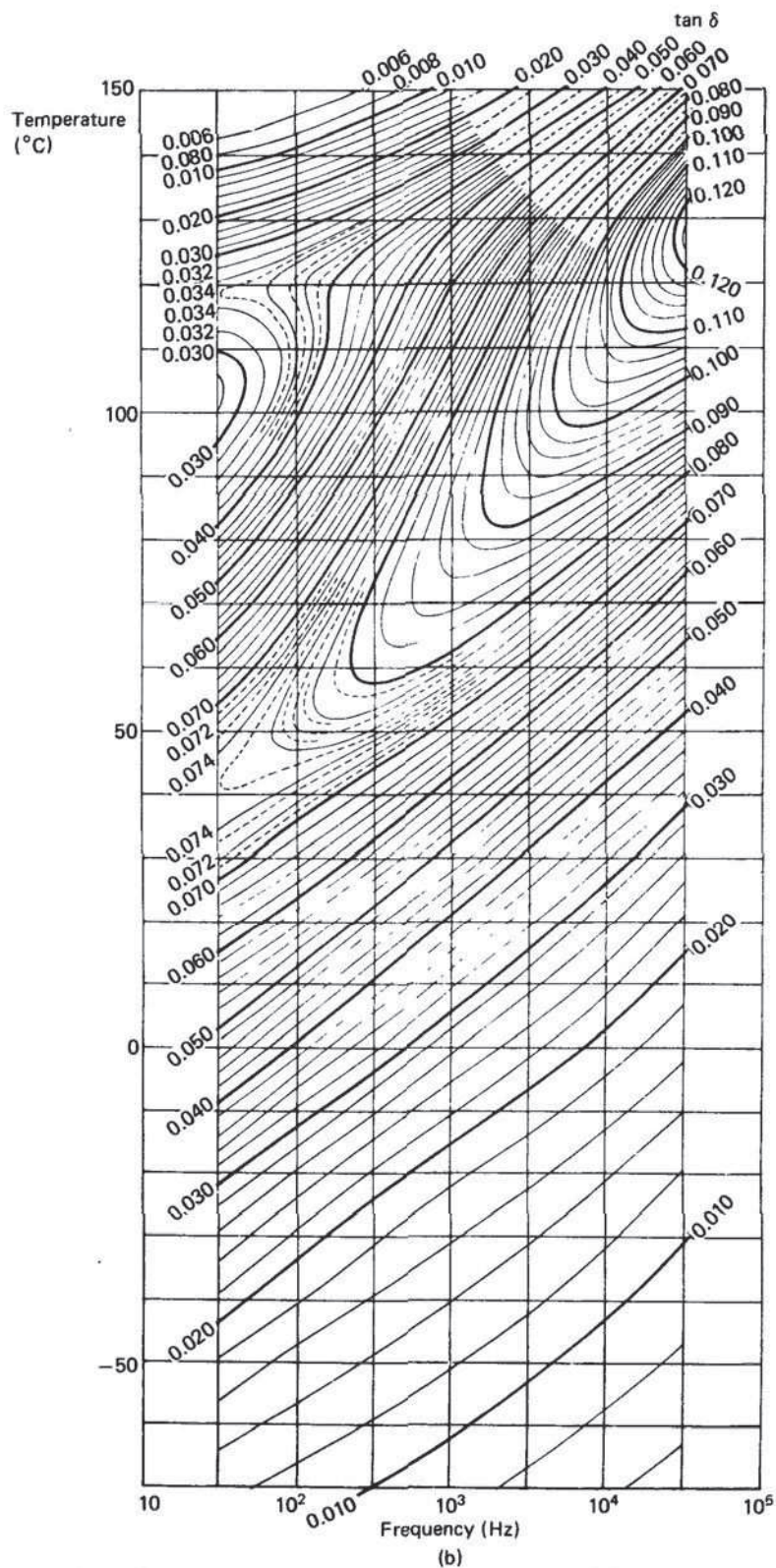


Figure 4.5 Frequency and temperature dependence of (a) permittivity and (b) loss tangent of PMMA (cast sheet, dry) (Data from ICI Ltd)

almost entirely from displacements of electrons and nuclei. These redistributions occur extremely rapidly, in picoseconds or less, and the polarisation response follows the alternating electric field without lag up to high radiofrequencies and beyond. As a result polymers of this type, notably PTFE and PE, show little frequency dependence of ϵ'_r and extremely low loss tangents with no loss peaks. In homogeneous PTFE $\tan \delta$ may be as small as 10^{-5} , and since $\tan \delta \approx \delta$ for small δ the loss tangent (or loss angle) is often expressed in microradians. The loss tangents of pure PE and PTFE are so low that they may be sharply increased by very small concentrations of impurities and additives, or by physical heterogeneity. PEs synthesised by different processes may show different loss characteristics depending on the number of CO impurities incorporated in the chain. Sintered granular PTFE shows a loss peak which is absent in material of high crystallinity — figure 4.6(a). PTFE with a high filler content may have a loss tangent as high as 0.1 in damp conditions.

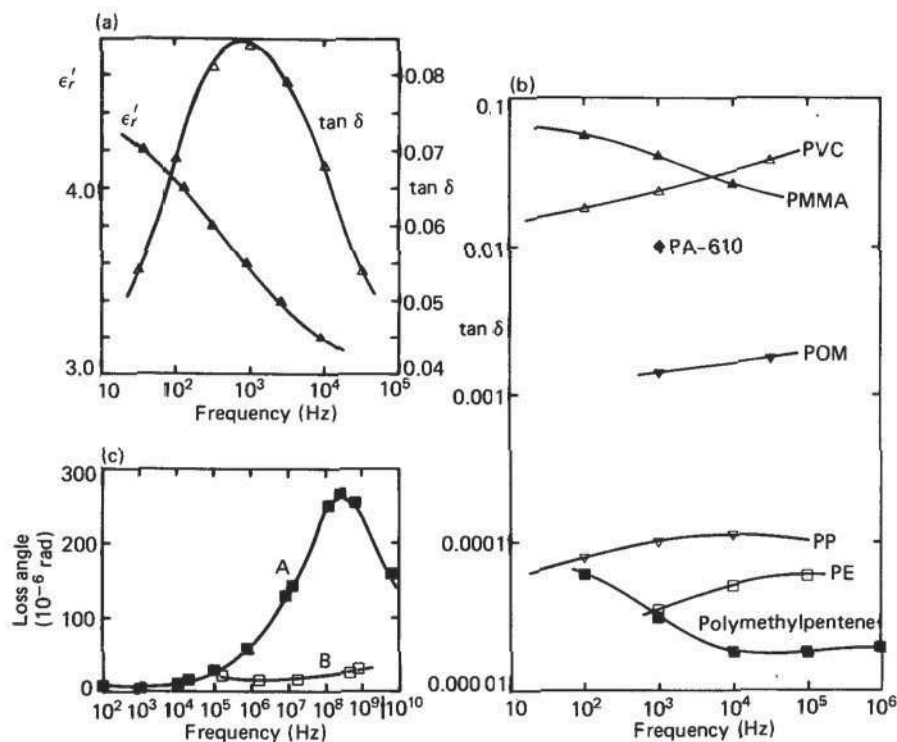


Figure 4.6 (a) Frequency dependence of the relative permittivity and loss tangent of PMMA at 70 °C. (b) Frequency dependence of loss tangents of polar and nonpolar polymers at 20 °C. (c) Dependence of loss tangent on frequency for two PTFE materials: sintered granular PTFE, crystallinity 60 per cent (A); unsintered coagulated dispersion polymer, 93 per cent crystallinity (B) (Data from ICI Ltd)

The loss tangents of polar polymer materials are generally much higher than those of nonpolar polymers — figure 4.6(b). As figure 4.6(c) shows, loss peaks are observed at frequencies corresponding to the relaxation times for dipole reorientation and the positions of these loss peaks can often be correlated with known structural transitions, such as T_g and T_m . The permittivity and loss in the vicinity of a loss peak may be markedly affected by changes in temperature.

The extremely low dielectric loss of PE and PTFE make these outstanding materials for high frequency electronic devices and components. The lossy polymers such as PVC are valuable insulants (for example as cable sheathing) in low frequency applications. At higher frequencies dielectric heating (and the possibility at high voltages of thermal breakdown) may become serious in high loss polymers.

A heated polymer polarised in a very strong electric field and then cooled may retain its polarisation indefinitely. Such a polarised dielectric is the electrostatic counterpart of a magnet, and is known as an *electret*. Polymeric electrets can be prepared with field strengths of 30 kV/cm, showing little loss of strength over periods of several years. Electrets bearing a net electric charge stable for long periods can be made from suitable polymer materials carrying metal foil on one face. Such foil-electrets are used, for example, in microphones.

Finally, we mention the static electrification or triboelectric charging of polymers by contact or friction. The high resistivity of polymers allows large electrostatic charges to accumulate. This has many troublesome consequences (as in textile manufacture and use) and is occasionally hazardous. The study of how triboelectric charging depends on polymer structure is in its infancy, but table 4.2 shows a *triboelectric series* which indicates the sign of the electrostatic

TABLE 4.2
Triboelectric series

Positive end	wool
	PA
	cellulose
	cotton
	silk
	CA
	PMMA
	PVAL
	PETP
	PAN
	PVC
	PVDC
	PE
Negative end	PTFE

charge acquired by contact between pairs of dissimilar polymers. *Antistatic* formulations of polymers have much reduced resistivities so that electrostatic charge may be dissipated by leakage currents.

4.3 Optical Properties

The highest a.c. electrical frequencies we have discussed fall within the short radiowave and microwave regions of the electromagnetic spectrum. The transmission and absorption of radiation by the polymer dielectric are determined by the quantities ϵ'_r and ϵ''_r . Even higher frequencies bring us into the infrared and visible parts of the spectrum, that is, to optical phenomena. In the rest of this chapter we discuss the transmission, scattering and absorption of light by polymer materials.

There is an important underlying continuity in the electrical and optical behaviour of materials; for example, the optical *refractive index* n and the high frequency permittivity are linked in electromagnetic theory by the relation $n = (\epsilon'_r)^{1/2}$. At optical frequencies as at lower a.c. frequencies absorption of radiation occurs by irreversible non-radiative loss processes. As we shall see, absorption of optical radiation occurs by excitation of bond vibrations (infrared) and rearrangements of electrons within molecules (visible and ultraviolet). Even so we should not overstress the internal connections between electrical and optical properties, which in practice are usually considered separately and have distinct terminologies. In addition we shall see that *scattering* phenomena play a major part in determining optical properties. Light scattering is a manifestation of optical diffraction processes, which occur prominently in polymer materials having microstructural features of dimensions comparable with optical wavelengths (0.5 μm). Diffraction effects within materials are rarely important at electrical a.c. frequencies because of the much greater associated wavelengths.

4.4 Colour and Infrared Absorption

Very few pure polymers absorb radiation in the visible spectrum, that is, roughly between 380 and 760 nm. Thus most polymers are colourless. The only exceptions are some thermosets and elastomers, including PF, some polyurethanes, epoxies and furan resins, which absorb more or less strongly at the blue end of the spectrum and consequently appear brownish when viewed by transmitted or reflected light. These substances contain alternating double and single covalent bonds or aromatic rings which act as *chromophores*, absorbing light at frequencies corresponding to the excitation energies of bonding electrons. Graphite and the other polymeric carbons which have fused ring structures and which appear intensely black exhibit this absorption throughout the visible spectrum in extreme form. Deliberately coloured polymer materials are

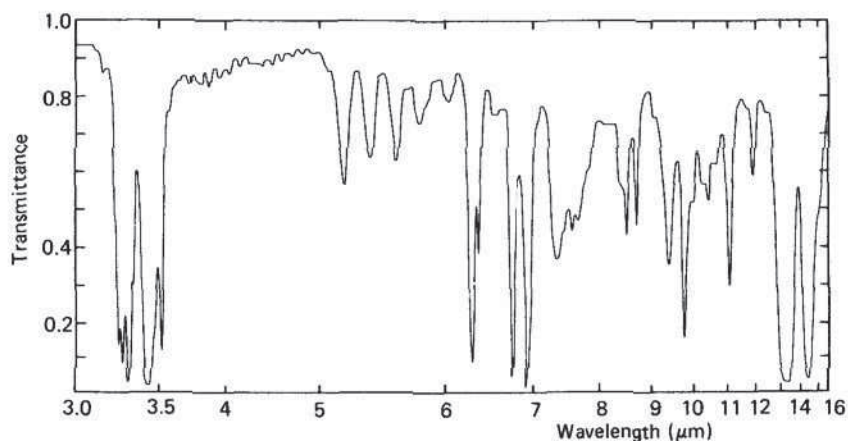


Figure 4.7 Infrared spectrum of polystyrene measured in transmission

invariably produced by incorporating as additives either finely divided coloured solids (pigments) or soluble coloured substances (dyes). The colours of solid polymers are fully defined by their spectra, measured either by transmission or reflection as appropriate. It is often more useful for purposes of specification to refer to colours by using the CIE trichromatic system of colour measurement.

Although many polymers show no absorption of radiation at visible wavelengths, they invariably absorb strongly at certain frequencies in the infrared. The infrared (transmission or reflectance) spectrum of a polymer is determined by its molecular structure. Infrared spectroscopy is one of the most powerful methods of polymer analysis, enabling polymer materials of unknown composition to be identified very rapidly from small samples. Figure 4.7 shows the infrared spectrum of polystyrene PS. The sharply defined absorption peaks correspond to various modes of vibration of individual chemical bonds, and give the analytical chemist detailed information about the primary molecular structure. The infrared spectrum is a fingerprint which allows even closely similar materials such as the various polyamides to be distinguished.

4.5 Refraction

The visual appearance and optical performance of a polymer material depends, apart from colour, on the nature of its surface and its light transmission properties. We follow the recommendations of BS 4618 : Section 5.3 : 1972 and consider in turn *refraction*, *transparency*, *gloss* and *light transfer*.

The optical phenomena which occur when a ray of light strikes the plane surface of a colourless transparent material, figure 4.8(a), are governed by the refractive index n . Snell's law relates the angle r to the angle i ; Fresnel's equation

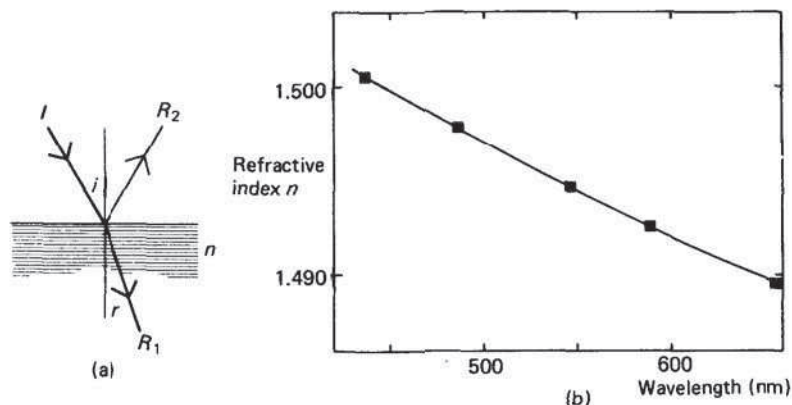


Figure 4.8 (a) Refraction and reflection at the surface of a transparent solid. (b) Variation with wavelength of the refractive index n of PMMA

allows the intensities and polarisations of the refracted and reflected rays R_1 and R_2 to be calculated from n and i . n varies with wavelength and accurate determinations are made with monochromatic light at specified wavelengths, using selected lines from the atomic emission spectra of elements contained in discharge lamps. The wavelength dependence of the refractive index, figure 4.8(b), which leads to refractive dispersion of white light is expressed in terms of the *reciprocal dispersive power* V_d of the material

$$V_d = \frac{n(d) - 1}{n(F) - n(C)}$$

where d denotes the helium emission line at 587.6 nm; and F and C denote hydrogen lines at 486.1 and 656.3 nm.

Table 4.3 lists the refractive indices of a number of polymers. More precise data for polymers which find use as optical materials are given in table 4.4 which includes for comparison two optical glasses.

Refractive index is determined by the extent to which the electronic structure of the polymer molecules is deformed by the optical frequency electric field of the radiation. If a material is structurally isotropic, as in the case of unstressed amorphous polymers, then it is also optically isotropic, and a single refractive index characterises the refraction behaviour. In crystals and other anisotropic materials the refractive index takes different values along different principal axes, and the material is said to be doubly refracting or *birefringent*. Amorphous materials under deformation develop birefringence as molecules become aligned. Similar effects arise in flowing polymer melts. The study of birefringence is thus a very useful method of exploring the microstructural effects of deformation. One particularly important technical application of stress-induced birefringence in

TABLE 4.3
Refractive index of selected polymers

	Refractive index
PTFE	1.35
PCTFE	1.42–1.43
PVDF	1.42
CA	1.48–1.50
POM	1.48
PMMA	1.49
PP	1.49
PF	1.5–1.7
EP	1.5–1.6
LDPE	1.51
PAN	1.52
NR	1.52
PA	1.53–1.55
HDPE	1.54
PVC	1.54–1.55
UF	1.54–1.56
CR	1.55
PS	1.59
PC	1.59
PVDC	1.60–1.63

TABLE 4.4
Refractive index $n(d)$ and reciprocal dispersive power V_d
of optical materials

	$n(d)$	V_d
PS	1.591	31.0
PC	1.586	29.9
PMMA	1.492 6	59.3
Allyl diglycol carbonate	1.498	53.6
Polymethylpentene	1.465 4	44.9
SAN	1.569	35.7
Borosilicate crown glass	1.509 7	64.4
Dense flint glass	1.620 5	36.2

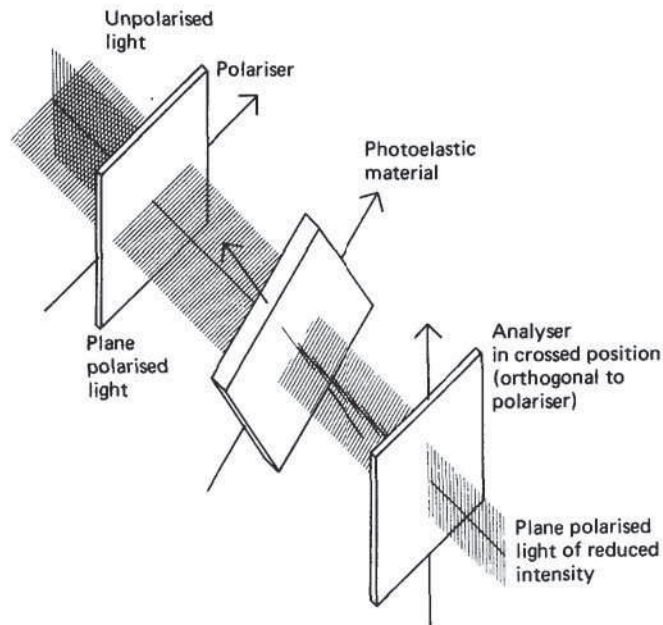


Figure 4.9 Principle of photoelastic stress analysis (see text)

polymer materials is in *photoelastic stress analysis*, a method of investigating complex stress distributions in engineering components and structures.

Figure 4.9 summarises the principle of a simple photoelastic analysis. The component under examination is modelled in a stress-free polymer material either by moulding or machining. The model component is then loaded and viewed by transmitted light between crossed polaroids. Birefringence induced by the internal stress field generates two components of the refracted ray which travel at different speeds, and may thus produce interference effects. For example, variations in stress within the component give rise to a fringe pattern from which the principal stress lines can be obtained. The value of photoelastic analysis depends almost entirely on the availability of polymeric materials (notably epoxies, polyesters, PC, PS and PMMA) with a suitable combination of mechanical and optical properties. The change Δn in refractive index produced by a stress P defines the *stress-optical coefficient* C of the material by the relation $\Delta n = CP$ (table 4.5).

4.6 Transparency

Colourless polymeric materials range from highly transparent to opaque. Loss of transparency arises from light scattering processes within the material, which distort and attenuate the transmitted image. Figure 4.10(a) shows a light ray I

TABLE 4.5
Stress-optical coefficient C of commonly used
photoelastic materials

	$10^{12} C(\text{m}^2 \text{N}^{-1})$
Selected EP resins	55
PMMA	-4.7
PC	78
Polyurethane elastomer	3500

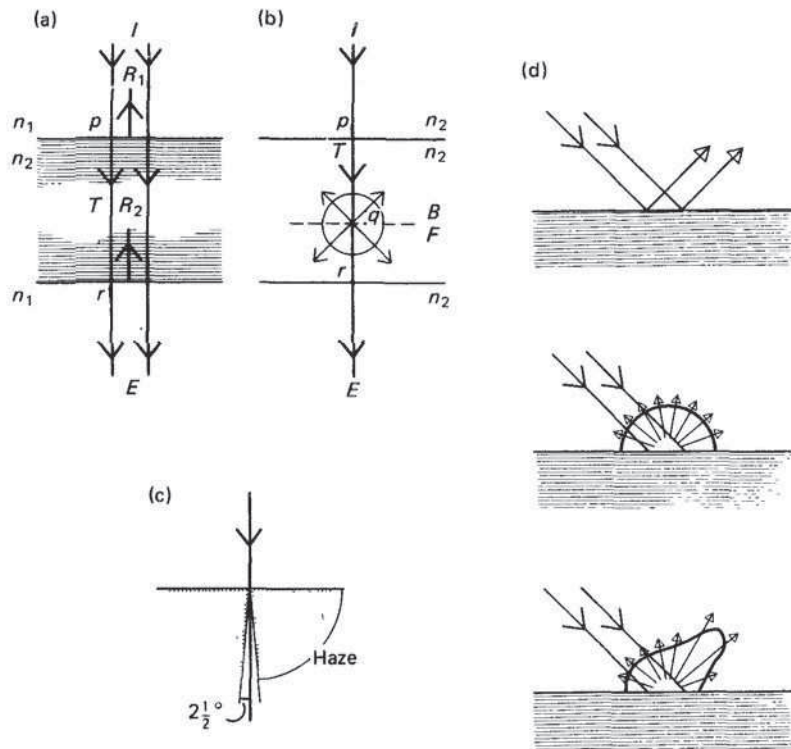


Figure 4.10 (a) Reflection and (b) scattering of light on transmission through a transparent medium. (c) Haze produced by wide-angle forward scattering of light. (d) Gloss: (from the top) specular reflection; perfect diffuse reflection; intermediate behaviour. The polar envelope shows the angular distribution of reflected light intensity

striking a plane surface at right angles. A small fraction of the incident flux is reflected back from the surface at the point of incidence p . The ratio of reflected to transmitted flux is calculated by Fresnel's equation and for normal incidence $\phi(R_1)/\phi(T) = (n_2 - n_1)^2 / 4n_1n_2$. At an air-polymer interface, with $n_2 = 1.5$, about 4 per cent of the incident flux is reflected. If the air is replaced by a transparent liquid having the same refractive index as the polymer the surface reflection at p (and also at r) is eliminated — figure 4.10(b).

If the material is non-absorbing and optically homogeneous and isotropic the transmitted ray propagates without loss of intensity. In real materials the transmitted ray may lose some intensity as it travels forward as the result of scattering from refractive index inhomogeneities within the material figure 4.10(b). Such scattering is akin to the ray splitting which occurs at the surface at p and which is repeated whenever the ray encounters a change of refractive index δn_2 at points q within the material. The angular distribution of the scattered light is unlikely to be simple, but it is useful to speak of back-scattered and forward-scattered components B and F of the total flux. In figure 4.10(b) we have $\phi(I) = \phi(B) + \phi(F) + \phi(E)$, where E is the undeviated emergent ray. The *direct transmission factor* T of the material is determined as the ratio $\phi(E)/\phi(I)$. For weakly scattering colourless materials T decreases exponentially with the sample thickness l , and therefore $\ln T = -\sigma l$, where σ is the *scattering coefficient*.

The effect of scattering is to reduce the contrast between light and dark parts of the object viewed through the transparent polymer, and thus to produce haze or milkiness in the transmitted image. The direct transmission factor, the *total transmitted flux* ϕ_t , i.e. the sum of $\phi(F)$ and $\phi(E)$, and the *forward-scattered fraction* $\phi(F)/\phi_t$ can be determined photometrically.

Besides haze, scattering may produce loss of *clarity* so that distinct features of the object can no longer be distinguished in the transmitted image. Loss of clarity is caused by forward scattering at angles very close to the undeviated beam, since it arises from confusion of light rays diverging from the object at the limits of the angular resolution of the eye. Haze on the other hand is associated with scattering over a wide range of angles. A quantitative measure of haze is obtained in an ASTM standard test from the total forward-scattered flux, *excluding* that within $2\frac{1}{2}$ degrees of the undeviated ray — see figure 4.10(c).

In polymer materials heterogeneity of refractive index can arise from differences of density in amorphous and crystalline regions within the polymer itself, or from solid particles incorporated as pigments or fillers, or from voids. The degree of scattering depends strongly on the variation of refractive index ($\pm \delta n_2$) and on the size of the heterogeneities. The most efficient scattering occurs when the scattering centres are comparable in dimensions with the wavelength of light. The scattering of light in pigmented polymer films has been extensively studied in connection with the optical properties of paints (see section 6.8). Crystalline polymers are normally translucent or opaque unless it happens (as in polymethylpentene) that there is little difference in the refractive indices of crystalline and amorphous regions or (as in cellulose triacetate) that

TABLE 4.6
Selected optical properties of some engineering polymers

	PP	LDPE (rapidly cooled film)	Polymethyl- pentene (modified)	PA (nylon 66)	PMMA	PVC*	PTFE
Refractive index n (546.1 nm)	1.505	1.516	1.472	—	1.495	—	—
Refractive index n (589.3 nm)	—	—	1.465	1.448	—	1.542	1.325
Temperature coefficient of refractive index ($10^4 \, dn/dT$)(K $^{-1}$)	—	−2.4	−2.4	—	−1.0	−1.1	—
Direct transmission factor T (%) (normalised to 1 mm sample thickness)	11	45	99	0	99	94	0
Scattering coefficient $10^{-2} \, \sigma$ (m $^{-1}$)	21.5	8.3	0.11	100	0.01	0.6	80

* Optical properties vary widely between grades.

the spherulites are exceptionally small. It is frequently possible to enhance the transparency of polymer materials by assisted nucleation or by rapid cooling from the melt, both means of decreasing the spherulite size. Stretching is also an effective way of increasing transparency, since spherulites are transformed into oriented fibrils which scatter light less effectively.

4.7 Gloss

'Gloss' is a term applied to the surface optical character of a material, whether transparent or opaque. A perfect mirror-like surface, a specular reflector, shows one extreme of behaviour – figure 4.10(d). At the other extreme, a highly scattering surface (a perfect diffuse reflector) reflects light equally in all directions at all angles of incidence.

The gloss of real surfaces is most completely described by the angular intensity distribution of reflected light for one or more angles of incidence. A somewhat simpler index of surface appearance is the *direct reflection factor*, the ratio of the flux reflected at the specular angle to the incident flux, for angles of incidence from 0 to 90 degrees.

Table 4.6 collates optical data on a number of engineering polymers.

4.8 Light Transfer

Strongly scattering translucent materials (optical 'diffusers') are unable to transmit useful images but nevertheless may transmit appreciable amounts of diffuse light. Their optical characteristics are most simply expressed through the *total transmission factor T* (or *luminous transmittance*) for normal incidence, which is defined as $[\phi(F) + \phi(E)] / \phi(I)$.

Suggestions for Reading

Electrical Properties

ASTM D149–81, *Dielectric breakdown voltage and dielectric strength of solid electrical insulating materials at commercial power frequencies* (American Society for Testing and Materials, Philadelphia, Pa.).

ASTM D150–81, *A-C loss characteristics and permittivity (dielectric constant) of solid electrical insulating materials* (American Society for Testing and Materials, Philadelphia, Pa.).

ASTM D257–78, *D-C resistance or conductance of insulating materials* (American Society for Testing and Materials, Philadelphia, Pa.).

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