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Materials for Optical Systems

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3.1 Introduction

Any optical system, of necessity, consists of many components, often fabricated from and joined by a variety of materials. The choice of materials depends on the system performance requirements and many other factors including size, weight, mechanical loading, environment, number of systems required, and, of course, cost. This chapter provides both a discussion of the importance of various properties and figures of merit, and a listing of many of them. Typical application requirements for the various classes of materials are given along with brief discussions of selection methods and cost comparisons. A discussion of dimensional stability is deferred to Chapters 4 and 10.

3.2 Applications

In general, materials for optical systems include almost all available materials, the choice depending on the requirements of the particular application. For simplicity, these materials can be divided into four applications categories: refractors, reflectors, structural components, and adhesives. Typical applications are discussed below.

Refractors

The refractors are generally defined as those optical elements which are transmissive to light. These may include image-forming lenses, which generally have one or both surfaces curved to a spherical or aspherical shape. Another class of transmissive optical elements includes optical windows, which are commonly used at the front end of an optical system to protect and seal the critical components of an optical assembly from adverse environmental effects such as dirt, dust, and humidity. Usually, optical windows are plane-parallel plates of optical quality glass, but sometimes a small wedge may be introduced between the two surfaces to correct the errors introduced by the window itself. In some applications involving large field of view, optical windows are shaped like a shell or dome with a significant curvature. Although optical windows are not a part of the image-forming optics, these can have a significant effect on the wavefront and image quality of the system if they have a significant thickness and are located in a converging or diverging beam. Therefore, the selection of an appropriate material and thickness of the windows is critical to optimize the performance of the system. Another important class of refractive optics includes filters, which are extensively employed in photography, spectrometers, and other chemical analysis equipment. Such absorption filters may be made of glass or optical grade plastics. The glass absorption filters with multilayer coatings can be designed to isolate specific transmission bands in environmental monitoring instruments to detect the presence of specific gases and chemicals.

The choice of material used for making refractors depends on the wavelength and application. Although hundreds of optical glasses are available from major manufacturers in the U.S. and Europe, only 50 or so are most commonly used for making refracting components. Most of the other glasses tend to stain, have poor machinability or thermal properties, or are too expensive. The commonly used glasses are available in various formulations of SiO_2 plus small amounts of the oxides and fluorides of barium, boron, calcium, lanthanum, sodium, and potassium. A number of lightweight glasses have also been developed for head-mounted displays, binoculars, and other airborne and space applications, where the overall weight of the system may be critical. Most of these lightweight glasses also have good hardness and better resistance to acids and alkalis.

The transmission of different glasses varies greatly over the spectral region from UV to IR. The crown glasses have good transmission at shorter wavelengths, while flints have good transmission in the near-IR region. Fused silica, Schott Ultran 30, and a few crystals transmit well in the near-UV region between 200 and 350 nm. A large variety of synthetic crystalline materials are available for UV and IR applications. These materials include alkali halides (KCl, NaCl, LiF, etc.) and alkaline earth halides (BaF_2, MgF_2, etc.), oxides (quartz, fused silica, etc.), semiconductors (Si, GaAs, Ge, diamond, etc.), and calcogenides (CdTe, ZnS, ZnSe, etc). New optical quality plastics are becoming more readily available. Plastics are lightweight, have low fabrication cost, and are resistant to mechanical shock and vibrations. The plastics do have low scratch resistance and softening temperature, and may be difficult to coat. They often exhibit birefringence due to stresses from the molding process. The plastics, in general, have low refractive index and not as many optical grade plastics are available as compared to glasses. Some of the commonly used polymers are polycarbonates, acrylics, and polystyrenes.

Reflectors

Reflective components are all mirrors, but include scanners, reflecting prisms, diffraction gratings, and other specialized components. The reflecting surface of a mirror can be bare, as for certain infrared telescopes of beryllium, or have an optical coating for specific wavelengths. All glass mirrors are coated. A mirror consists then of the reflective surface and the substrate that supports it. That substrate can be anything from a simple plane-parallel flat disk to a lightweighted, off-axis asphere of nonsymmetrical geometric form. They range in size from millimeters to meters and can be made from glasses, ceramics, metals, composites, or plastics. The classical reflective optical system, such as an astronomical telescope, usually consists of glass mirrors and a metal support structure. For light weight, whether for space applications or thermal considerations, the glass can be lightweighted, or other materials such as aluminum (Al) or silicon carbide (SiC) can be used. The

Hubble Space Telescope has a lightweight ULE™ fused silica (ULE™*) primary mirror, a Zerodur®** secondary, and a graphite/epoxy (Gr/Ep) structure. For ultralightweight systems, typically for space applications, beryllium (Be) or metal matrix composites can be used for both the mirrors and structure.

For high heat load applications, such as synchrotron or laser optics, actively cooled mirrors of copper (Cu), molybdenum (Mo), silicon (Si), or SiC are usually specified. These mirrors are fabricated with internal cooling channels, the complexity of which depends on the incident heat flux. Cooled mirrors have also been successfully fabricated with internal heat pipes. For lower heat loads, the low expansion materials such as ULE™, Zerodur®, or invar can be used. Heat absorption is minimized with high efficiency optical coatings and/or by using the optical surface at grazing incidence.

At the opposite end of the temperature scale, cryogenic mirrors are typically fabricated from fused quartz/fused silica. Beryllium and SiC are also an option, because of their unique properties. The Infrared Astronomical Satellite (IRAS) was a cryogenic all-Be system that successfully provided a far-infrared survey of the galaxies.

For production systems where cost is critical, replicated optics are popular. These mirrors are manufactured with Al or glass substrates on which a thin polymer layer forms the mirror surface and is pulled, with the optical coating already in place, from a polished master surface. This technique is used extensively for small aspheric mirrors and for diffraction gratings. In the latter application, a master grating is ruled into a metal surface, often plated or otherwise consisting of deposited gold (Au) or Al.

Structural Components

While optical components, both reflective and refractive, may have to be designed as structures, the components referred to here are those that mechanically support and connect the optical components. Typical examples are optical benches, metering structures, mounting hardware, lens housings, fasteners, etc. These components must be relatively stiff, dimensionally stable (but not necessarily to the same tolerance as optical components), and should be thermally matched to the optics in both expansion and conductivity.

In many production systems that are used primarily at room temperature, Al is the preferred material because of low cost and fabricability. Wrought products such as rod, bar, tube, plate, or extrusions are used as well as castings. For systems where weight is critical, such as space systems or inertia-critical systems, Be and Gr/Ep are the preferred materials. Metal matrix composites (MMCs) can provide intermediate properties and can be cost effective in production applications. While Gr/Ep has become a common material in optical structures, each application requires a custom design and fabrication process. As with the MMCs, production quantities can be cost effective for demanding applications. For extremely stable and/or controlled expansion applications such as optical benches and metering structures, the low expansion materials such as invar and graphite epoxy composites are most often used, but Zerodur is also used in critical metering applications.

Fastening of structural components can be accomplished in many ways. All metals, including Be and the MMCs, can be attached with conventional fasteners such as screws. Some, such as Al, Cu, and steels, can be brazed or welded as well. Others like Be and Mo can be brazed, but just about all materials can be adhesively bonded.

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[*] ULE™ is a registered trademark of the Corning Glass Works, Corning, NY.

[**] Zerodur® is a registered trademark of Schott Glaswerke, Mainz, Germany.

Adhesives and Cements

Adhesives can either be structural or optical. Structural adhesives have no optical requirements and are used strictly to mechanically attach components to each other such as a baffle to a support structure or a lens to its housing. When used in optical applications, even in the supporting structures, adhesives should have low thermal expansion and relatively low residual stress due to shrinkage during curing. Optical cements are part of the optical train since they are in the light path where they join refractive components such as cemented doublets, and as such must have high transmission and index homogeneity.

A structure in which optical and mechanical components are secured together by adhesives as opposed to tradition fasteners is lighter in weight and usually less expensive to fabricate because the machining of threaded and through holes for screws is not required. Moreover, the required machining tolerances (flatness, parallelism, etc.) for the bonded components are, in general, much looser compared to parts that must be rigidly bolted together. Also, bonded joints are flexible to a degree, thereby providing a better stress distribution under high loads, damping in vibration and shock environments, and allowing differential expansion between parts made from dissimilar materials. The silicone elastomers can also be used for sealing and damping. All adhesives have good shear strength, but have lower strength in tension and peel modes.[1]

Adhesives and cements are formulated from many different polymers. The most common structural adhesives are epoxies, polyurethanes, modified acrylics, cyanoacrylates, and anaerobics. Silicones are used in structural applications where resiliency is required, such as for joining of materials with disparate thermal expansions.

Optical cements can be epoxies, silicones, or other polymers. They can be thermosets, i.e., two-part systems, thermoplastics that are heated to a liquid state and applied, photosetting, e.g., UV curing, or solvent loss cements. The latter are seldom used in modern optical systems because of the stress induced in the components by shrinkage during and after curing.

3.3 Properties

Important Properties and Figures of Merit

Important properties vary with the type of material: refractor, reflector, structure, or adhesive. For all materials, the properties fall into four categories: physical, mechanical, thermal, and optical. The most significant of these properties are discussed here, and those properties more appropriate for a specific type of material are discusssed under that section. All material properties vary with temperature, some in a linear fashion, but most nonlinear. For systems that operate at temperatures other than room temperature, great care is required in selecting and matching materials in order to ensure that the system will meet specifications over the required temperature range.

General references for properties include *Handbook of Optics,* 2nd ed., Vol. 2;[2] *The Infrared Handbook*, 2nd ed.;[3] *Handbook of Infrared Optical Materials*;[4] *CRC Handbook of Laser Science and Technology,* Vol. 4, Part 2;[5] *ASM Handbook*, Vol. 1 and 2 (early printings are titled Metals Handbook, 10th ed.);[6,7] and *Engineered Materials Handbook,* Vol. 1 to 4.[8-11]

Physical

For all materials under consideration here, the physical properties of interest are mass density ρ, electrical conductivity, and/or electrical resistivity. Electrical conductivity is inversely proportional to electrical resistivity and for most materials, one or the other is normally reported. These properties vary with temperature, but density varies slowly.

Mechanical

The design of optical components often involves some structural aspects where mechanical properties can be used as a basis for comparison. Deflection in any application is a function of five parameters: support conditions, materials, structural efficiency of the design, size (i.e., diameter), and loading. For static conditions, deflection is proportional to the fourth power of diameter of a circular plate, while for dynamic conditions it is proportional to the fifth power. This means that for many large components, keeping edge roll-off allowables to a minimum is essential for good performance.

The easiest of the five parameters to control is the material, the subject of this chapter. The important mechanical properties include elastic and/or plastic, strength, and fracture. Figures of merit for structural efficiency are used to rapidly compare materials for a given structural application, particularly in the design of lightweight reflective systems.

The elastic properties of crystalline materials can be described by a 6 × 6 matrix of constants called elastic stiffness constants.[12] From these constants, the elastic properties of the material: Young's modulus E (the elastic modulus in tension), bulk modulus K, modulus of rigidity G (also called shear modulus), and Poisson's ratio ν, can be calculated. The constants, and consequently the properties, vary as functions of temperature. Young's modulus of elasticity is the measure of stiffness or rigidity of a material; the ratio of stress, in the completely elastic region, to the corresponding strain. Bulk modulus is the measure of resistance to change in volume; the ratio of hydrostatic stress to the corresponding change in volume. Shear modulus, or modulus of rigidity, is the ratio of shear stress to the corresponding shear strain under completely elastic conditions. Poisson's ratio is the ratio of the absolute value of the rate of transverse (lateral) strain to the corresponding axial strain resulting from uniformly distributed axial stress in the elastic deformation region. For isotropic materials, the properties are interrelated by the following equations:

$$G = \frac{E}{2(1+\nu)} \tag{1}$$

$$K = \frac{E}{3(1-2\nu)} \tag{2}$$

A group of structural figures of merit, all utilizing combinations of density and Young's modulus, have been used to compare the structural efficiency of materials. The most commonly used term is specific stiffness, E/ρ. For many applications, a simple comparison of specific stiffness shows that the highest structural efficiency material will have the lowest mass or self-weight deflection for identical geometry. For more realistic comparisons, other related proportionality factors are more appropriate. For example, ρ^3/E should be compared if mass is a specified parameter and minimum self-weight deflection is desired. The optimum geometries for each material are appropriate with this factor as they are with $(\rho^3/E)^{1/2}$, the factor to be compared when self-weight deflection is specified in a mass-critical application. For most applications, the resonant frequency of a mirror is an important design consideration and since natural frequency is proportional to the square root of specific stiffness, a simple comparison is also possible. More detailed discussions of design issues are given in Chapters 2 and 5.

Mechanical strength and fracture properties are important for structural aspects of the optical system. The components in the system must be able to support loads with no permanent deformation within the limits set by the error budget and certainly with no fracture. For ductile materials, the yield and/or microyield strength may be most important, but for brittle or near-brittle materials fracture toughness and/or modulus of rupture are more significant. A listing of definitions for each of these and other related terms follows:

Creep strength — the stress that will cause a given time-dependent plastic strain in a creep test for a given time

Ductility — the ability of a material to deform plastically before fracture

Fatigue strength — the maximum stress that can be sustained for a specific number of cycles without failure

Fracture toughness — a generic term for measures of resistance to extension of a crack

Hardness — a measure of the resistance of a material to surface indentation

Microcreep strength — the stress that will cause 1 ppm of permanent strain in a given time, usually less than the microyield strength

Microstrain — a deformation of 10^{-6} m/m (1 ppm)

Microyield strength — the stress that will cause 1 ppm of permanent strain in a short time; also called precision elastic limit, PEL

Ultimate strength — the maximum stress a material can withstand without fracture

Yield strength — the stress at which a material exhibits a specified deviation from elastic behavior (proportionality of stress and strain), usually 2×10^{-3} m/m (0.2%)

Hysteresis is a term that has more than one meaning. In terms of mechanical behavior, it is the time-dependent strain from an applied mechanical or thermal load, also referred to as anelasticity. In this case, removal of the load causes the strain to eventually return to zero. It also refers to the accumulated strain when a component is subjected to cyclic loading and unloading, a factor in fatigue failures. Another use of the word refers to the residual plastic strain in a component that has been thermally or mechanically cycled. This type of hysteresis is due to combined applied and residual stresses that exceed the microyield strength of the material. Further discussion of residual stress and hysteresis is given in Chapter 4.

Thermal

The significant thermal properties are coefficient of linear thermal expansion α (or CTE), thermal conductivity k, and specific heat C_p. Diffusivity D, a derived property equal to $k/\rho C_p$, is also important. All of these properties vary with temperature, α and C_p tending to vary directly with temperature and k and D varying inversely.

Thermal expansion is a generic term for a change in length for a specific temperature change, but there are more precise terms that describe specific aspects of this material property.[13] CTE is the most generally applicable version and is defined as:

$$\alpha \equiv \frac{1}{L}\frac{\Delta L}{\Delta T} \tag{3}$$

Many materials are also anisotropic in thermal expansion. This is particularly true in polycrystalline materials and fiber-reinforced composites. Lower CTE is better for optical system performance as it minimizes the effect of thermal gradients on dimensional changes of components. It is important to match CTE of adjacent components to minimize thermally induced strain in the system.

Thermal conductivity is the quantity of heat transmitted per unit of time through a unit of area per unit of temperature gradient. Higher thermal conductivity is desirable to minimize temperature gradients when there is a heat source in or close to the optical system. Specific heat, also called heat capacity per unit mass, is the quantity of heat required to change the temperature of a unit mass of material 1° under conditions of constant pressure. A material with high specific heat requires more heat to cause a temperature change that might cause a distortion. High specific heat also means that more energy is required to force a temperature change (e.g., in cooling an infrared telescope assembly to cryogenic temperatures). Thermal diffusivity determines the rate at which a nonuniform temperature distribution reaches equilibrium.

The two common thermal figures of merit are the steady-state and transient distortion coefficients, α/k and α/D. The former is a measure of the total thermal displacement for a given steady-state thermal input. The latter indicates the time for a thermal distortion to dissipate per unit of temperature gradient. Note that for actively cooled mirror applications such as laser mirrors, there is no appropriate figure of merit, since the single most important factor is the coefficient of linear thermal expansion, α.

Optical

Optical properties of solids are complex tensors, and as such will not be described in depth here. For a more complete treatise, see Wooten[14] or Born and Wolf.[15]

The most important optical property used in geometric optics is the index of refraction, n. The index of refraction is the ratio of the velocity of light in a vacuum to that in the material. In its general form it is a complex quantity expressed as:

$$\bar{n} = n - ik \tag{4}$$

where n is the real index and k is the imaginary part, called the index of absorption or extinction coefficient. For normal incidence, only the real part is important in optical design. For isotropic and cubic materials, there is one index, but for more complex crystals, the index varies with crystallographic direction. For an in-depth treatment of the optical properties of crystals and glasses see Tropf et al.[16]

The index of refraction varies with wavelength, temperature, and applied stress. The variation of refractive index with wavelength is called dispersion. The index of all transmitting materials increases with decreasing wavelength as shown in Figure 3.1. One way to characterize the dispersion, as devised for optical glasses, is with the Abbé number, ν_d, where:

$$\nu_d = \frac{n_d - 1}{n_F - n_C} \tag{5}$$

The subscripts d, F, and C refer to the wavelengths for the emission lines of hydrogen and helium at 587.56, 486.13, and 656.27, respectively. There are other dispersion parameters, such as partial dispersions, that are discussed in more detail in Yoder[1] and in optical glass catalogues.

The variation of refractive index with temperature, dn/dT, is positive for most glasses, but negative for a few. When combined with CTE, the change in optical path length with temperature can be obtained from the thermo-optical constant G, equal to $\alpha(n - 1) + dn/dT$. The change in path length is then $t \cdot G \cdot \Delta T$, where t is the mechanical thickness of the element. Note that a material can be athermal if α and dn/dT have opposite signs.

Properties of Refractive Materials

The refractive materials commonly used for making lenses, prisms, optical windows, and filters can be broadly classified into three distinct categories, namely: glasses, optical crystals, and plastics and semiconductor materials. The physical, mechanical, and thermal properties of selected materials, which are most commonly used for optical and mechanical components, are covered in the subsequent sections. To keep the material property tables concise, only the nominal values at room temperature are listed, and therefore must only be used for preliminary evaluation and comparison purposes. Since the mechanical and thermal properties of materials can vary from one manufacturer to another and even from lot to lot for the same material from the same manufacturer, it is advisable to contact the manufacturer for obtaining more exact values of these properties for critical applications.

The optical properties of materials such as refractive index, Abbe value, reflectivity and transmittance, and variations of these properties as funtion of wavelength and temperature have deliberately been left out of these tables to avoid duplication of property tables from other sources. Some excellent and comprehensive references for optical properties of materials are *Handbook of Optics*,[2] *The Infrared Handbook*, 2nd ed.,[3] and Yoder.[1]

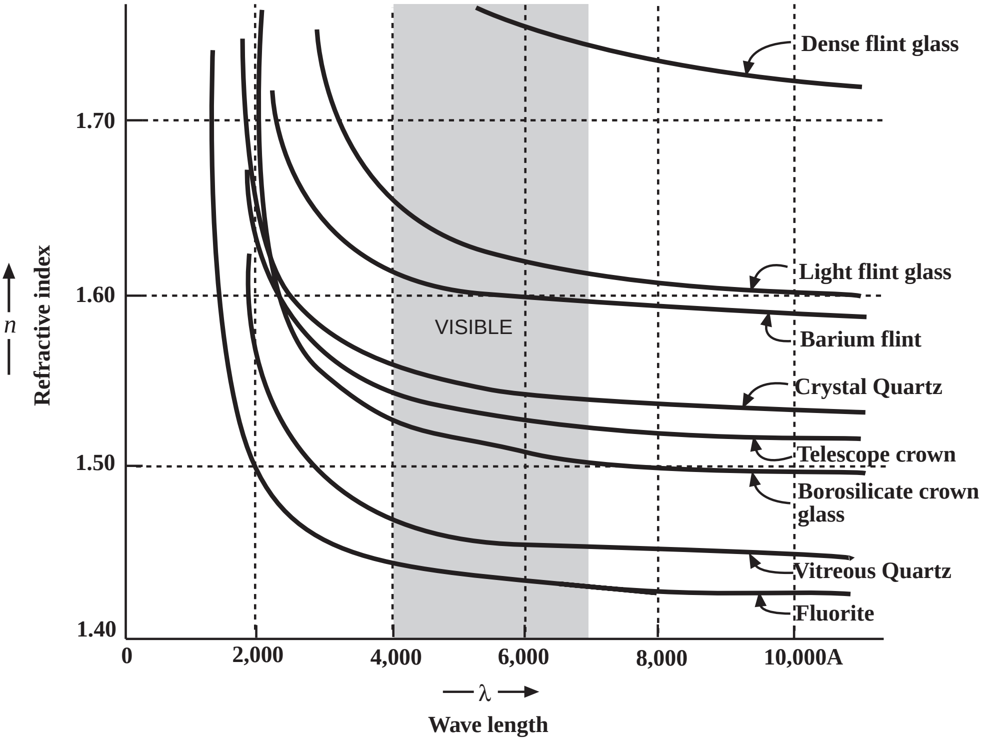

FIGURE 3.1 Dispersion curves for several materials commonly used for refracting optical components.

Glasses

Glasses are the most commonly used class of refracting material in optical systems. The most important property of a particular glass is its ability to transmit light over a desired range of wavelengths. An optical designer would primarily select a particular type of glass, which would have maximum transmission over the entire spectral region for which the instrument is being designed. Although the mechanical properties of the glass being used in a system may be of secondary importance, they do play a critical role in ensuring dependable performance during operation. Mechanical and thermal properties of the selected refractive materials such as density, elastic modulus, microyield strength, coefficient of thermal expansion, and thermal conductivity are of special significance if the designed optical system must be lightweight, rugged, and capable of retaining its performance over a large temperature range. Therefore, rather than selecting a particular glass merely on the basis of its optical properties, due consideration must also be given to its mechanical, and thermal properties before finalizing the choice. Table 3.1 lists physical, mechanical and thermal properties of selected optical and specialty glasses which are most commonly used in a majority of the optical systems.[1,17] For a clear explanation of the various terms used in describing the properties of optical glasses, see Marker[18] and the catalog Schott Optical Glass.[19]

There is a difference between fused silica and fused quartz, or quartzglass.[20] Fused silica is manufactured by the pyrolytic decomposition of reactive gases and usually has high water content and no metallic impurities. Fused quartz is made by fusing crystalline quartz to form a glass. Fused quartz has some level of metallic impurities that can cause UV fluorescence, and the water content depends on the firing method. Fused quartz can have some granularity, a residual of the original

TABLE 3.1 Properties of Selected Optical Glasses

Glass Code	Schott Type	Density ρ (g/cm^3)	Young's Modulus E (Gpa)	Poisson's Ratio υ	Knoop Hardness HK	Thermal Expansion α (ppm/K)	Specific Heat C_p (J/kg K)	Thermal Conductivity k or λ (W/m K)
487 704	FK 5	2.45	62	0.232	520	9.2	808	0.925
517 642	BK 7	2.51	82	0.206	610	7.1	858	1.114
518 651	PK 2	2.51	84	0.209	640	6.9	736	0.755
522 595	K 5	2.59	71	0.224	530	8.2	783	0.950
523 515	KF 9	2.71	67	0.202	490	6.8	720	1.160
532 488	LLF 6	2.81	63	0.203	470	7.5	700	1.000
540 597	BaK 2	2.86	71	0.233	530	8.0	708	0.715
548 458	LLF 1	2.94	60	0.208	450	8.1	650	0.738
573 576	BaK 1	3.19	73	0.252	530	7.6	687	0.795
575 415	LF 7	3.20	58	0.213	440	7.9	660	0.879
589 613	SK 5	3.30	84	0.256	590	5.5	560	0.990
617 366	F4	3.58	56	0.222	420	8.3	553	0.768
620 364	F 2	3.61	57	0.220	420	8.2	557	0.780
620 603	SK 16	3.58	89	0.264	600	6.3	578	0.818
626 390	BaSF 1	3.66	62	0.242	460	8.5	553	0.741
636 353	F 6	3.76	57	0.224	410	8.5	510	0.755
648 339	SF 2	3.86	55	0.227	410	8.4	498	0.735
651 559	LaK N22	3.73	90	0.266	600	6.6	550	0.797
652 449	BaF 51	3.42	89	0.266	590	8.4	620	0.870
658 509	SSK N5	3.71	88	0.278	590	6.8	574	0.773
670 471	BaF N10	3.76	89	0.281	590	6.8	595	0.798
673 322	SF 5	4.07	56	0.233	410	8.2	488	0.738
699 301	SF 15	4.06	60	0.235	420	7.9	464	0.741
702 410	BaSF 52	3.96	86	0.283	550	5.2	540	0.737
717 295	SF 1	4.46	56	0.232	390	8.1	415	0.702
717 480	LaF 3	4.14	95	0.286	580	7.6	465	0.690
720 504	LaK 10	3.81	111	0.288	720	5.7	580	0.840
740 282	SF 3	4.64	56	0.236	380	8.4	423	0.706
744 448	LaF 2	4.34	93	0.289	560	8.1	480	0.648
750 350	LaF N7	4.38	80	0.280	520	5.3	440	0.770
755 276	SF 4	4.79	56	0.241	390	8.0	410	0.650
785 258	SF 11	4.74	66	0.235	450	6.1	431	0.737

Source: Schott Glass Technologies, Inc., Duryea, PA.

quartz crystal structure. Properties of these silica materials depend to some extent on their thermal history, and therefore nominally identical materials will have slightly different n and α from different manufacturers.

Crystals and Semiconductors

Optical crystals and ceramics are widely used in broadband optical systems and include both synthetic and naturally occurring materials. Optical crystal materials are available as single and polycrystalline forms. The polycrystalline form of a material consists of small, randomly oriented individual crystals, and are manufactured by various methods such as by hot pressing of powders, sintering, and chemical vapor deposition (CVD). On the other hand, single crystals are typically grown from dissolved and molten materials. Polycrystalline materials, in general, have higher strength and hardness as compared to single crystal materials.[16] Polycrystalline materials generally have isotropic properties while single crystals have directionally dependent anisotropic properties.

Optical crystals are widely used in infrared applications but there are a number of crystals which have good tranmission over a wide band from ultraviolet (UV) to far-infrared (IR) wavelengths; e.g., CaF_2 and LiF are extensively used for achromitized lenses in far-UV to mid-IR (0.11 to 10 μm) applications. CaF_2 has the best strength and moisture resistance of all fluoride crystals and has a very low thermo-optic coefficient.

Another very useful material for high temperature application is sapphire, which is the single crystal form of aluminum oxide. It has high strength and hardness, and excellent thermal shock resistance. It is widely used in specialized optical systems subjected to severe environments. Another useful naturally occurring optical crystal is quartz, which is commonly used for UV prisms and windows and in IR applications to 4 µm. Quartz and sapphire are also grown artificially to improve transmission by controlling the amount of impurities. The thermal properties, such as CTE, of these materials are direction dependent and quite sensitive to thermal shock.[21]

Silicon and germanium (Ge) are extensively used in IR systems for lenses, windows, and domes. Silicon is very suitable for missile domes because of its good mechanical and thermal properties. Germanium is quite hard but is susceptible to brittle fracture. Both materials have high index of refraction and are therefore very suitable for making multiple lens assemblies to keep the thicknesses and weight within reasonable limits. Due to the high index of these materials, efficient antireflection coatings are required to minimize internal reflection losses. The optical properties of Ge, such as index of refraction and absorption, are quite sensitive to temperature. Table 3.2 lists optical, physical, mechanical, and thermal properties of selected crystalline materials, while Tables 3.3 and 3.4 list the same properties for IR-transmitting materials. A more extensive list of materials and properties can be found in Tropf.[16]

TABLE 3.2 Properties of Selected Alkali Halide Crystalline Materials

Material Name and Symbol	Useful Spectral Range (µm)	Refractive Index n at λ (µm)	Density ρ (g/cm³)	Young's Modulus E (GPa)	Poisson's Ratio υ	Thermal Expansion coeff. α (ppm/K)	Specific Heat C_p (J/kg K)	Thermal Conductivity k (W/mM)
Barium fluoride, BaF_2	0.13–15	1.463 (0.6) 1.458 (3.8) 1.449 (5.3) 1.396 (10.6)	4.89	53	0.343	6.7 at 75 K 19.9 at 300 K 24.7 at 500 K	402	11.7
Calcium fluoride, CaF_2	0.13–10	1.431 (0.7) 1.420 (2.7) 1.411 (3.8) 1.395 (5.3)	3.18	96	0.28	18.9	854	10
Calcium fluoride, CaF (Kodak Irtran 3)	0.15–11.8	1.434 (0.6) 1.407 (4.3)	3.18	99		18.9	853	9.7
Potassium chloride, KCI	0.21–25	1.474 (2.7) 1.472 (3.8) 1.469 (5.3) 1.454 (10.6)	1.98	30	0.216	37.1	678	6.7
Lithium fluoride, LiF	0.12–8.5	1.394 (0.5) 1.367 (3.0) 1.327 (5.0)	2.63	65	0.33	5.5	1548	11.3
Magnesium fluoride, MgF_2	0.15–9.6	1.384 (0.4)o 1.356 (3.8)o 1.333 (5.3)o	3.18	169	0.308	14.0 (P) 8.9 (N)	1004	21
Magnesium fluoride, (Kodak Irtran 1)	0.6–8	1.378 (1.0) 1.364 (3.0) 1.337 (5.0)	3.18	73	0.25–0.36	10.7	502	14.6
Sodium chloride, NaCl	0.17–18	1.525 (2.7) 1.522 (3.8) 1.517 (5.3) 1.488 (10.6)	2.16	40	0.28	39.6	837	6.5

Source: Adapted from Yoder, P.R., Jr. 1993. *Optomechanical Systems Design*, 2nd ed., pp. 108–109. Marcel Dekker, New York.

TABLE 3.3 Properties of Selected IR Materials

Material Name and Symbol	Useful Spectral Range (μm)	Refractive Index n at λ (μm)	Density ρ (g/cm^3)	Young's Modulus E (GPa)	Poisson's Ratio υ	Thermal Expansion coeff. α (ppm/K)	Specific Heat C_p (J/kg K)	Thermal Conductivity k (W/mK)
Semiconductors								
Diamond C	0.25–200	2.382 (2.5) 2.381 (5.0) 2.381 (10.6)	3.51	1050	0.16	–0.1 at 25 K 0.8 at 293 K 5.8 at 1600 K	108	2600
Gallium arsenide, GaAs	1–16	3.1 (10.6)	5.32	83	0.31	5.7	326	48–55
	1.8–23	4.055 (2.7) 4.026 (3.8) 4.015 (5.3) 4.00 (10.6)	5.33	104	0.278	5.7–6.0	310	59
Silicon, SI	1.2–15	3.436 (2.7) 3.427 (3.8) 3.422 (5.3) 3.148 (10.6)	2.329	131	0.22	2.7–3.1	53	150–163
Calcogenides								
Cadmium telluride, CdTe	0.9–15	2.682 (6) 2.650 (10) 2.637 (14)	5.85	37	0.41	5.9 at 300 K	234	6.3
Zinc sulfide, ZnS (Raytheon Standard grade)	0.5–12	2.36 (0.6) 2.257 (3.0) 2.246 (5.0) 2.192 (10.6)	4.08	75	0.29	4.6 at 173 K 6.6 at 273 K 7.7 at 473 K	469	17 at 296 K
Zinc sulfide, ZnS (Kodak Irtran 2)	0.5–14	2.37 (0.6) 2.249 (4.3)	4.09	96	0.25–0.36	6.6	962	15.4
Zinc selenide, ZnSe (Raytheon CVD Raytran)	0.6–20	2.61 (0.6) 2.438 (3.0) 2.429 (5.0) 2.403 (10.6) 2.376 (14)	5.27	70	0.28	5.6 at 163 K 7.1 at 273 K 8.3 at 473K	339 at 0296 K	18 at 300 K
Zinc selenide, ZnSe (Kodak Irtran 4)	0.5–20	2.485 (1.0) 2.440 (3.0) 2.432 (5.0) 2.418 (8.0) 2.407 (10.0) 2.394 (12.0)	5.27	71		7.7	335	

Source: Adapted from Yoder, P.R., Jr. 1993. *Optomechanical Systems Design*, 2nd ed., pp. 112–115. Marcel Dekker, New York.

Plastics

Optical plastics are used in a small fraction of optical systems as compared to optical glasses and crystal materials. The largest market for plastic optics is the high volume consumer items such as ophthalmic lenses (eyeglasses) and low end camera, microscope, and binocular lenses. The number of optical plastics available is quite limited as compared to the number of optical glasses. The optical plastics can be classified into two broad categories: thermoplastics and thermosets. The term thermoplastic means a material which flows when heated, but there are some thermoplastics that do not flow when heated. Thermoset plastics can be set by heating these materials. Thermoplastics, or linear plastics as they are sometimes called, do not undergo any chemical change during the molding process and therefore can be remolded several times without affecting their properties. On the other hand, thermosets, also known as cross-linked plastics, start with a linear polmer chain, which gets cross-linked permanently in the presence of heat during molding.[22]

TABLE 3.4 Properties of Selected IR-Transmitting Glasses and Other Oxide Materials

Material Name and Symbol	Useful Spectral Range (µm)	Refractive Index n at λ (µm)	Density ρ (g/cm³)	Young's Modulus E (GPa)	Poisson's Ratio υ	Thermal Expansion coeff. α (ppm/K)	Specific Heat C_p (J/kg K)	Thermal Conductivity k (W/mK)
Calcium alumino-silicate (Schott IRG 11)	0.5–5	1.684 (0.55) 1.635 (3.3) 1.608 (4.6)	3.12	108	0.284	8.2 at 293–573 K	749 at 293–373 K	1.13
Calcium alumino-silicate (Corning 9753)	0.6–4.2	1.61 (0.5) 1.57 (2.5)	2.798	99	0.28	5.95 at 293–573 K	837 at 373 K	2.5 at 373 K
Calcium alumino-silicate (Schott IRGN6)	0.4–4.5	1.592 (0.55) 1.562 (2.3) 1.521 (4.3)	2.81	103	0.276	6.3 at 293–573 K	808 at 293–373K	1.36
Fluoro phosphate (Schott IRG9)	0.4–4	1.488 (0.55) 1.469 (2.3) 1.458 (3.3)	3.63	77	0.288	6.1 at 293–573 K	694 at 293–373 K	0.88
Germanate (Corning 9754)	0.4–5	1.67 (0.5) 1.63 (2.5) 1.61 (4.0)	3.581	84	0.290	6.2 at 293–573 K	544	1.0
Germanate (Schott IRG 2)	0.4–5	1.899 (0.55) 1.841 (2.3) 1.825 (3.3)	5.00	96	0.282	8.8 at 293–573 K	452 at 293–373 K	0.91
Lanthanum-dense flint (Schott IRG3)	0.4–4	1.851 (0.55) 1.796 (2.3) 1.776 (3.3)	4.47	100	0.287	8.1 at 293–573 K		0.87
Lead silicate (Schott IRG7)	0.4–4	1.573 (0.55) 1.534 (2.3) 1.516 (3.3)	3.06	60	0.216	9.6 at 293–573 K	632 at 293–373 K	0.73
Magnesium oxide, MgO_2 (Kodak Irtran 5)	0.2–6	1.723 (1.0) 1.692 (3.0) 1.637 (5.0)	3.58	332	0.2	11.5	879	50
Sapphire, Al_2O_3	0.15–7.5	1684 (3.8) 1.586 (5.8)	3.97	400	0.27	5.6 (P) 5.0 (N)	753	25–33
Silica, fused, SiO_2 (Corning 7940)	0.15–3.6	1.566 (0.19) 1.460 (0.55) 1.433 (2.3) 1.412 (3.3)	2.202	73	0.17	–0.6 at 73 K 0.52 at 278–308 K 0.57 at 273–473 K	108.8	13.8

Source: Adapted from Yoder, P.R., Jr. 1993. *Optomechanical Systems Design*, 2nd ed., pp. 110–111. Marcel Dekker, New York.

The most widely used optical plastic is acrylic, specifically known as polymethyl methacrylate (PMMA). It is a low-cost plastic that can be easily molded, machined, and polished, and has the best combination of optical properties. It has a low thermal conductivity and a high linear coefficient of thermal expansion (70 ppm/K), which is eight to ten times greater than that of typical optical glass. It has a shrinkage of 0.2 to 0.6% and a good optical memory, which is the ability to return to its original shape after exposure to heat. Acrylic has very good transmission (92%) and low internal scattering, and its refractive index varies from 1.483 for $\lambda = 1$ µm to 1.510 for $\lambda =$ 380 nm. The index varies from about 1.492 to 1.480 over a temperature range of 20 to 90°C.[22]

Polystyrene is a second common optical plastic that can be combined with acrylic to obtain highly corrected achromatic lens designs. Its index of refraction is 1.590 and transmission is about 90%. It can be easily injection molded and it is the lowest cost optical plastic. It has a lower moisture absorption than acrylic, but it is more difficult to machine and polish as compared to acrylic.

Polycarbonate is another widely used optical plastic for ophthalmic lenses, street lights, and automotive tail light lenses due to its high durability and impact resistance. It is more expensive than acrylic and styrene because it is more difficult to mold, machine, and polish, and it scratches easily. Its refractive index ranges from 1.560 to 1.654, and the transmission is about 85%. It retains its performance over a broad range of temperature (–137 to 121°C).

The only thermoset optical plastic used is allyl diglycol carbonate (ADC), commonly known as CR 39. It is extensively used in making cast ophthalmic lenses, which are subsequently machined and polished, which makes it more expensive. It cannot be injection molded. It has excellent optical and mechanical properties such as clarity, impact, and abrasion resistance. It can withstand continuous temperature up to 100°C, and up to 150°C for short periods, but it also has a high shrinkage rate of up to 14%.[22]

Other less commonly used optical copolymers of styrene and acrylic include methyl methacrylate styrene (NAS), styrene acrylonitrile (SAN), methyl pentene (TPX), and clear acrylonitrile butadiene styrene (ABS). Table 3.5 lists physical, mechanical, and thermal properties of some of the optical plastics discussed here. A more detailed discussion of optical properties and design and fabrication methods for plastic lenses can be found in Lytle[23] and Welham.[24]

TABLE 3.5 Selected Properties of Optical Plastics

Material	Density (gm/cc) ρ	CTE (ppm/K) α	Max. Service Temp (°C) T_v	Thermal Conductivity k	Water Absorption (%) A	Luminous Transmittance (%)
P-methylmethacrylate (acrylic)	1.18	6.0	85	4–6	0.3	92
P-styrene	1.05	6.4–6.7	80	2.4–3.3	0.03	88
Methyl methacrylate styrene (NAS)	1.13	5.6	85	4.5	0.15	90
Styrene acrylonitrile (SAN)	1.07	6.4	75	2.8	0.28	88
P-carbonate	1.25	6.7	120	4.7	0.2–0.3	89
P-methyl pentene (TPX)	0.835	11.7	115	4.0	0.01	90
P-amide (Nylon)	1.185	8.2	80	5.1–5.8	1.5–3.0	
P-arylate	1.21	6.3		7.1	0.26	
P-sulfone	1.24	2.5	160	2.8	0.1–0.6	
P-styrene co-butadiene	1.01	7.8–12			0.08	
P-cyclohexyl methacrylate	1.11					
P-allyl diglycol carbonate (ADC)	1.32		100	4.9		93
Cellulose acetate butyrate	1.20			4.0–8.0		
P-ethersulfone	1.37	5.5	200	3.2–4.4		
P-chloro-trifluoroethelyne	2.2	4.7	200	6.2	0.003	
P-vinylidene fluoride	1.78	7.4–13	150		0.05	
P-etherimide	1.27	5.6	170		0.25	

Source: Adapted from Lytle, J.D. 1995. *Handbook of Optics*, Vol. 2, 2nd ed., p. 34.1. McGraw-Hill, New York; and Wolpert, H.D. 1988. *Engineered Materials Handbook*, Vol. 2, pp. 481–486. ASM International, Metals Park, OH.

Properties of Mirror and Structural Materials

A number of metals, ceramics, and composites can be used for making the substrates of mirrors and the structural components of an optical system including the housings, optical benches, and metering structures. Table 3.6 lists physical, mechanical, and thermal properties of a number of commonly used mirror and structural materials at room temperature. Some temperature dependencies for these materials are given in Chapter 2, but for a more comprehensive treatment, see Paquin.[25] An examination of the table shows that there is no one material that is best in all categories. Choice of a material for a particular application is always a trade-off.

Table 3.7 lists some of the more important figures of merit for these same materials. The thermal properties and consequently the distortion coefficients are strongly temperature dependent and care should be taken to ensure that appropriate values are used if the mirror application is other than at room temperature. These figures of merit can be used for selecting one or more materials best suited for a particular application during the preliminary design phase. For example, if the weight of an optical system has to be minimized for a given deflection, then a quick look at the

TABLE 3.6 Properties of Selected Mirror and Structural Materials

	ρ Density (g/cm^3)	E Young's Modulus (GPa)	ν Poisson's Ratio	K_{Ic} Fracture Toughness (MPa[m]$^{1/2}$)	MYS Microyield Strength (MPa)	α Thermal Expansion (10^{-6}/K)	k Thermal Conductivity (W/m K)	Cp Specific Heat (W sec/kg K)	D Thermal Diffusivity (10^{-6} m^2/sec)
Preferred		Large	Small	Large	Large	Small	Large		Large
Pyrex 7740	2.23	63	0.2			3.3	1.13	1050	0.65
Fused silica	2.19	72	0.17	<1.0	—	0.5	1.4	750	0.85
ULE fused silica	2.21	67	0.17			0.03	1.31	766	0.78
Zerodur	2.53	91	0.24			0.05	1.64	821	0.77
Aluminum: 6061	2.70	68	0.33	—	140.	22.5	167.	896	69.
MMC: 30% SiC/Al	2.91	117	0.29	>10.	>200.	12.4	123.	870	57.
Beryllium: I-70-H	1.85	287	0.043	12.	35.	11.3	216.	1925	57.2
Beryllium: I-220-H	1.85	287	0.043	12.	50.	11.3	216.	1925	57.2
Copper: OFC	8.94	117	0.343	—	12.	16.5	391.	385	115.5
Invar 36	8.05	141	0.259	—	41.	1.0	10.4	515	2.6
Super Invar	8.13	148	0.26	—	41.	0.3	10.5	515	2.5
Molybdenum	10.21	324	0.293	—	280.	5.0	140.	247	55.5
Silicon	2.33	131	0.42	1.0	—	2.6	156.	710	94.3
SiC: HP alpha	3.2	455	0.14	5.2	—	2.4	155.	650	74.5
SiC: CVD beta	3.21	465	0.21	2.7	—	2.4	198.	733	84.2
SiC: RB-30% Si	2.89	330	0.24	2.5	—	2.5	155.	670	80.0
Stainless steel: 304	8.00	193	0.27	—	65.	14.7	16.2	500	4.1
Stainless steel: 416	7.80	215	0.283	—	—	8.5	24.9	460	6.9
Titanium: 6Al4V	4.43	114	0.31	—	50.	8.8	7.3	560	2.9
Gr/Ep (GY-70/×30)	1.78	93	—			0.02	35.0		

numbers in the ρ/E column reveals that SiC and beryllium may be the best materials for such an application, while the mirror substrate or structure made out of aluminum or titanium would have the maximum weight. It must be emphasized that the final selection of a material for a particular application must also be based on a number of other factors such as fabrication cost, microyield strength, and thermal properties.

Properties of Adhesives and Cements

When using optical cements and adhesives in optical systems, a number of their characteristics and properties must be considered carefully, including shrinkage, outgassing, shear and peel strengths, and curing time and temperature. Tables in the following sections list physical, mechanical, and thermal properties of a number of commonly used structural adhesives and optical cements at room temperature. These properties' values are nominal values and therefore must be used for comparison and preliminary design purposes. For critical applications, it is advisable to obtain the latest data and specification sheets from the manufacturers.

Structural Adhesives

Structural adhesives and elastomers can be used to bond structural components to each other or to bond optical components such as mirrors and lenses to their cells or mounts. The three main classes of structural adhesives are epoxies, urethanes, and cyanoacrylate adhesives. The thermosetting epoxy adhesives have high bonding strengths and good thermal properties. The epoxies are available in one- or two-part types, and some are room temperature curable. The urethanes or polyurethanes have fairly high strength and can be used to bond together a variety of materials.

TABLE 3.7 Figures of Merit for Selected Mirror and Structural Materials

	Weight and Self-Weight Deflection Proportionality Factors				Thermal Distortion Coefficients	
	$(E/\rho)^{1/2}$ Resonant Frequency for Same Geometry (arb. units)	ρ/E Mass or Deflection for Same Geometry (arb. units)	ρ^3/E Deflection for Same Mass (arb. units)	$(\rho^3/E)^{1/2}$ Mass for Same Deflection (arb. units)	α/k Steady State (μm/W)	α/D Transient (sec/m^2 K)
Preferred	Large	Small	Small	Small	Small	Small
Pyrex	5.3	3.53	1.76	0.420	2.92	5.08
Fused silica	5.7	3.04	1.46	0.382	0.36	0.59
ULE fused silica	5.5	3.30	1.61	0.401	0.02	0.04
Zerodur	6.0	2.78	1.78	0.422	0.03	0.07
Aluminum: 6061	5.0	3.97	2.90	0.538	0.13	0.33
MMC: 30% SiC/Al	6.3	2.49	2.11	0.459	0.10	0.22
Beryllium: I-70-H	12.5	0.64	0.22	0.149	0.05	0.20
Beryllium: I-220-H	12.5	0.64	0.22	0.149	0.05	0.20
Copper: OFC	3.6	7.64	61.1	2.471	0.53	0.14
Invar 36	4.2	5.71	37.0	1.924	0.10	0.38
Super Invar	4.3	5.49	36.3	1.906	0.03	0.12
Molybdenum	5.6	3.15	32.8	1.812	0.04	0.09
Silicon	7.5	1.78	0.97	0.311	0.02	0.03
SiC: HP alpha	11.9	0.70	0.72	0.268	0.02	0.03
SiC: CVD	12.0	0.69	0.71	0.267	0.02	0.03
SiC: RB-30% Si	10.7	0.88	0.73	0.270	0.01	0.03
Stainless steel: 304	4.9	4.15	26.5	1.629	0.91	3.68
Stainless steel: 416	5.2	3.63	22.1	1.486	0.34	1.23
Titanium: 6Al4V	5.1	3.89	7.63	0.873	1.21	3.03

They are flexible and therefore susceptable to creep and not suitable for high temperature (>100°C) applications, but are well suited for cryogenic applications.

The one-part cyanoacrylate adhesives have low viscosity and are suitable for bonding smooth surfaces with very thin bond joints. They have cure times of less than 30 sec, so proper fixturing is a requirement and care must be taken to protect the skin from accidental bonding. These materials outgas more than other adhesives and are suitable for applications where the humidity is low and the temperatue stays belows 70°C. The key physical, mechanical, and thermal properties of some commonly used structural adhesives in optical applications are listed in Table 3.8.[1]

The two-part room temperature vulcanizing rubbers (RTVs) available from GE and Dow Corning are extensively used to bond mirrors, lenses, filters, and optical windows to their mounts. These silicone rubber elastomers are inert chemically and can tolerate a temperature variation of –80 to 200°C or more. The two main reasons for their popularity are the low cost and ability to accommodate differential thermal expansion between high-expansion metal mounts and low-expansion optical elements. Since a fairly thick bond layer of RTV is needed, the edges or diameters of the optical elements and their mounts do not need to be machined to close tolerances, thereby reducing their fabrication cost. Moreover, retainers, clips, and screws for securing the optics in their mounts are also eliminated resulting in a much simpler design. RTV is resilient and allows for the differential expansion between the optic and its metal mount when the ambient temperatrure changes, without introducing any adverse stresses in the optic. The key physical, mechanical, and thermal properties of some commonly used silicone rubber-type elastomers in optical applications are listed in Table 3.9.[1]

Optical Cements

Optical cements are the adhesives used for bonding the refracting optical elements to each other. Therefore, these adhesives must have good transmission and homogeneity over the desired spectral wavelengths in addition to the desirable mechanical properties such as low shrinkage and outgas-

TABLE 3.8 Properties of Representative Structural Adhesives

Material	Mfr. Code[a]	Recommended Cure (time at °C)	Cured Joint Strength (MPa[psi] at °C)	Temperature Range of Use (°C)	Thermal Expansion Coeff. (ppm/°C at °C)	Recommended Joint Thickness (mm)	Density at 25°C (g/cm^3)
One-part epoxies	3M	40 min at 121	13.8 (2000) at 24	–55 to 177			
2214Hi-Temp[b]			20.7 (3000) at 82				
Two-part epoxies	SL	7 days at 25	14.5 (2099) at 25		0.381 ± 0.025		
Milbond			6.8 (992) at 70				
EC-2216B/A	3M	Fix: 2 hr at 65	17.2 (2500) at 24	–55 to 150	102 at 0–40	0.102 ± 0.025	
Gray		Full: 7 days at 75	2.8 (400) at 82		134 at 40–80		
Translucent		Fix: 6 hr at 65	8.3 (1200) at 24		81 at 50–0	0.102 ± 0.025	
		Full: 30 days at 75	1.4 (200) at 82		207 at 60–150		
27A/B	EC	24 hr at 25	13.8 (2000)	–65 to 105			
45	EC	24 hr at 25	21.4 (3100)	–40 to 90			1.34–1.18
324	L	Fix: 3 min at 20	10.3 (1500)	–54 to 135	12.6 (7.0)	>1.0 (0.040)	1.1
		Full: 24 hr at 20					
3532B/A	3M	3 days at 24	13.8 (2000) at 24				
			2.1 (300) at 82				
UV — curable	EC	UV cure: 15 sec at 200		–25 to 125		<3.2 (0.125)	1.04
UV-900		W/in.; heat cure:					
		10 min at 120					
349		Fix: 20 sec at 0.25	5.2 (750)	–54 to 130			
		Full: 36 sec at 0.25 gap					
460	L	Fix: 1 min at 22	12.1 (1750)	–54 to 71	100 (56)	0.100 max	1.06
		Full: 7 days at 22					

[a] Mfr. code: 3M, SL = Summers Laboratories; EC = Emerson & Cummings; L = Loctite.

[b] Also available in varieties with higher density, greater flexibility, or increased electrical resistivity.

Source: Adapted from Yoder, P.R., Jr. 1993. *Optomechanical Systems Design*, 2nd ed., pp. 144–146. Marcel Dekker, New York.

TABLE 3.9 Properties of Representative Elastomeric Sealants

Material	Mfr. Code[a]	Suggested Cure Time at °C	Elastomer Tensile Strength, MPa (psi)	Temperature Range of Use (°C [°F])	Thermal Expansion Coeff. (ppm/°C)	Density at 25°C (g/cm^3)	Shrinkage after 3 Days at 25°C (%)
732	DC	24 hr at 25	2.2 (325)	–55 to 200	310	1.04	
RTV112	GE	3 days at 2	2.2 (325)	<204 (400)	270 293	1.05	1.0
NUVA-SIL	L	UV cure 1 min or 7 days at 25	3.8 (550)	–70 to 260	167	1.35	0.4
3112	DC		4.5 (650)	–55 to 250	300	1.02	0.25
93–500	DC	7 days at 25 4 hr at 65	69 (100)	–55 to 155			
RTV88	GE	<24 hr at 25	5.9 (850)	–54 to 260	210	1.48	0.6
RTV8111	GE	<24 hr at 25	2.4 (350)	–54 to 204	250	1.18	0.6
RTV8262	GE	<24 hr at 25	5.2 (750)	–54 to 260	210	1.47	0.6

[a] Mfr. code: 3M = 3M Company; DC = Dow Corning; GE = General Electric; L = Loctite.

Source: Adapted from Yoder, P.R., Jr. 1993. *Optomechanical Systems Design*, 2nd ed., pp. 148–149. Marcel Dekker, New York.

sing, good strength and stability, and resistance to adverse environmental effects such as humidity, temperature variations, and UV exposure. The optical cements come in four basic types: solvent loss, thermoplastic, thermosetting, and photosetting cements.

The solvent-loss cements, such as Canada balsam, have a high viscosity and are heat cured by elimination of solvent to a refractive index ~1.53. They have a poor bond strength and can introduce distortion in the bonded optical surfaces due to high shrinkage on curing and are, therefore, seldom used in precision optical systems. The thermoplastic cements, such as cellulose carpate with n ~ 1.48, are colorless or lightly colored solids that liquify when heated to about 120°C. Their principle advantage is that the bonded elements can be separated by applying heat, which is easy and risk free. The thermosetting cements are two-part adhesives, which can be cured at room temperature by addition of an appropriate catalyst. The room temperature curing time for this type of adhesive varies from 3 to 7 days. The cure time can be reduced to a few hours with a low elevated temperature cure, typically 70°C. Summer's C-59, M-69, F-65, RD3 to 74, Lens Bond's, and Kodak's Eastman HE-80 are some of the commercially available thermosetting cements with n of ~1.55.[1]

Photosetting optical cements are generally one-part clear adhesives that are cured by exposure to UV light of 250 to 380 nm wavelength. These cements are suitable for bonding small low-mass optics that have transmission in this spectral region. Bondline thickness must be kept small to prevent excessive stress due to shrinkage. Norland's NOA-61 (n = 1.56) and Summer's UV-69 (n = 1.55) and UV-74 are some of the UV-curing optical cements available. A two-step curing process, a short exposure for 20 sec, followed by a long exposure of up to 60 min, is used for some of these cements. The bonded parts can be gently handled and cleaned, or debonded if needed, after the short exposure. Once the adhesive is fully cured after the long exposure, it becomes quite difficult to separate the parts. The entire area of the bond joint must be completely exposed to a uniform intensity UV illumination to obtain complete curing of the joint to prevent surface distortions. If feasible, the strength of the bond joint can be improved by heating the bonded parts to 40°C.

Typical properties of optical cements are shown in Table 3.10. For specific properties, manufacturer's data sheets should be obtained.

TABLE 3.10 Typical Properties of Optical Cements

Refractive index n after cure	1.48–1.56
Thermal expansion coefficient	
27 to 100°C	63 ppm/°C (35 ppm/°F)
100 to –200°C	56 ppm/°C (31 ppm/°F)
Young's modulus E	430 GPa (62×10^6 lb/in.^{2})
Shear strength	360 GPa (5200 lb/in.^{2})
Specific heat K	837 J/kg K (0.2–0.4 BTU/lb °F)
Water absorption (bulk material)	0.3% after 24 hr at 25°C
Shrinkage during cure	Approximately 6%
Viscosity	200–320 cps
Density	1.22 g/cm^3 (0.044 lb/in.^{3})
Hardness (shore D)	Approximately 90
Total mass loss in vacuum	3–6%

Source: Adapted from Yoder, P.R., Jr. 1993. *Optomechanical Systems Design*, 2nd ed., p. 137. Marcel Dekker, New York.

3.4 Material Selection Criteria

Material selection for any particular optical system is a trade-off process that starts at the initial design stage and involves the system performance and environmental specifications, structural and optical designs, material properties of candidate materials, and potential substrate and optical fabrication methods. A discussion of selection of material candidates is included in Section 10.4 of Chapter 10.

A schematic diagram of the trade-off process for lightweight metal mirrors is given in Figure 3.2 as an example of the interactive process that includes material selection. The process is basically one of addressing a number of options that may meet the requirements and performing rough analyses to narrow the choices. More detailed analyses can then determine the best choice of material, structural design, and fabrication methods. The process is iterative and multidisciplinary, with continuous feedback to continually refine the choices.

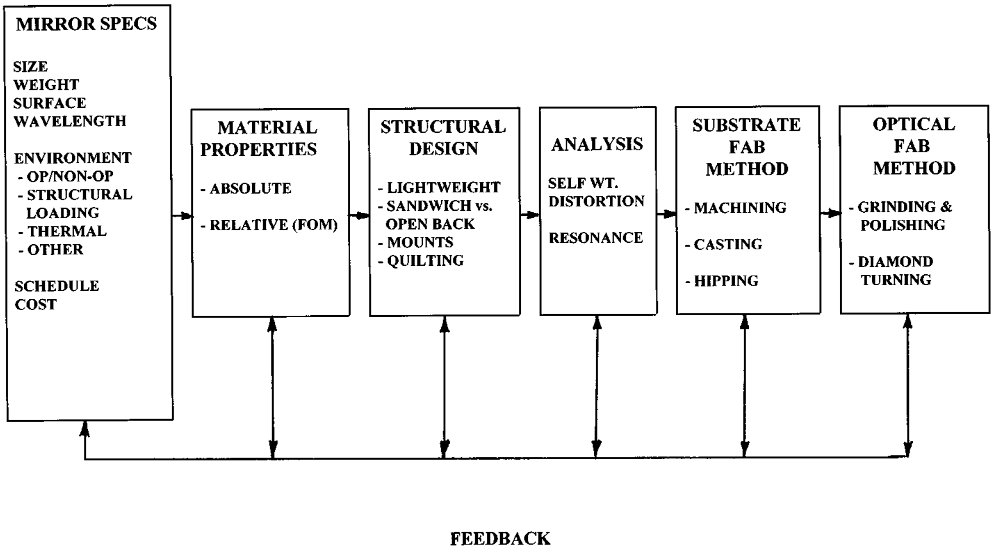

FIGURE 3.2 Schematic diagram showing trade-off process for material selection and structural design of a lightweight mirror.

3.5 Summary

This chapter provides guidelines for use of materials in optical systems by providing a description of the types of materials used — refractors, reflectors, structural, and adhesives — typical applications of each type, and detailed descriptions and properties of the most representative of each type.

After a brief introduction, typical applications are discussed with the materials commonly used for each type of application. Under refractors, the various types of glasses, crystals, and other materials are discussed for typical applications in various wavelength ranges. Reflectors include all types of mirrors from 8-m astronomical telescopes to small scanners and cooled mirrors, with the range of materials typically used for each. Structural components can be metals, ceramics, or composites and some typical examples are discussed. Athermalization of the optical system is accomplished through use of matched expansion materials for optics and structures. Structural adhesives and optical cements with their typical requirements for most applications are discussed.

Definitions of the important properties and figures of merit and their relevance to optical systems are given. Tables of properties of the most used reflector, refractor, and structural materials are given with sources for more extensive property data including the temperature dependence of properties.

A brief discussion of material selection methods completes the chapter.

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