THE PROPERTIES OF GLASS

An eBook that reviews the thermal, optical, and mechanical properties of glass, and how they influence both the design and performance of glass components and lenses.

TABLE OF CONTENTS

This eBook will teach you the basics of the thermal, mechanical, and optical properties of glass, including how they can influence both the design and performance of glass components and lenses. We also compare the properties of common transparent materials and share guidelines for selecting the best material for your application.

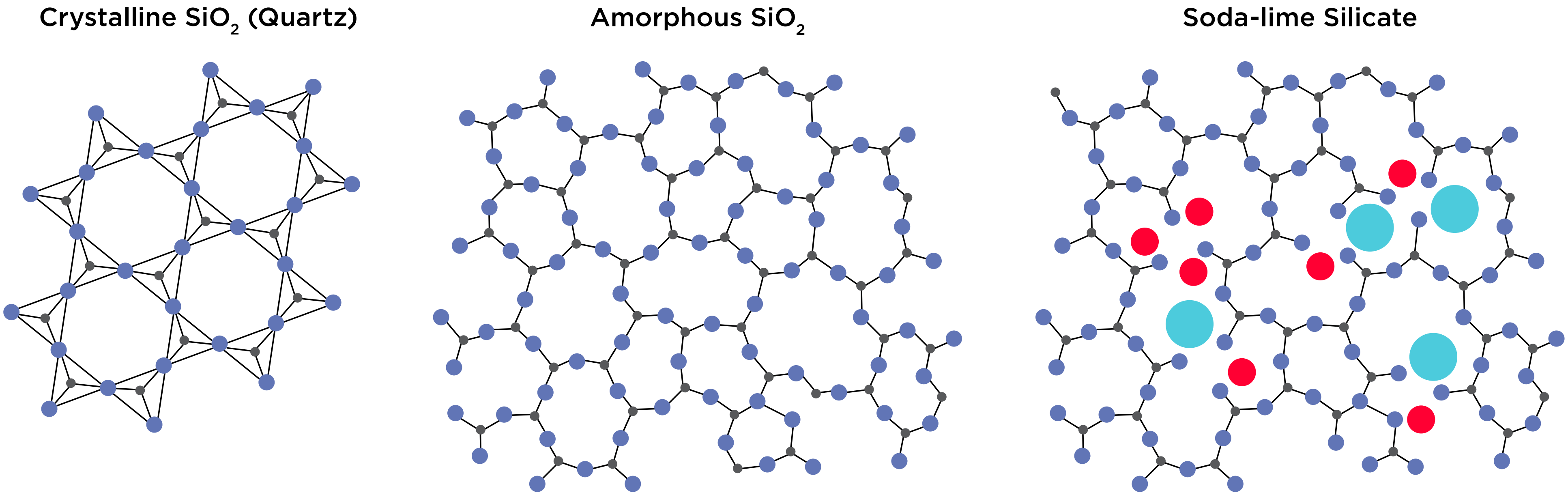
WHAT IS GLASS?

Glass is an amorphous material; unlike a crystalline material, it has no long-range structural order. The molecules that act as the building blocks of a glass network are oxides such as SiO_2, B_2O_3, or Na_2O. These are randomly oriented and interconnected. And it is this network connectivity, as well as the chemical composition and oxides present, which determines glass properties.

WHAT IS GLASS?

Consider the SiO_2 molecule. This oxide is present in nearly every glass composition that is commercially available; additionally, beach sand is primarily composed of crystalline SiO_2. The crystalline form of SiO_2 is a mineral known as quartz. It can also be melted into an amorphous glass, called fused quartz or fused silica. Even though the structural building block of the two materials is the same, the optical, thermal, and mechanical properties are different. This is because the arrangement of SiO_2 molecules in the two materials differ. The properties of fused silica are changed even further when additional oxides, such as CaO or Na_2O, are introduced into the glass and alter the structural network. The bond-model representation below shows the structural differences between crystalline quartz, fused silica, and soda-lime silicate glass.

The chemical composition of a glass greatly contributes to its properties and characteristics. We can vary the amount of different oxides in the glass network, which changes how the molecules interact and connect with one another. By controlling how much of each oxide is present, we are able to engineer and fine-tune glass compositions for their properties.



Crystalline SiO_2 (Quartz)

Amorphous SiO_2

Soda-lime Silicate

● Calcium ● Sodium ● Oxygen • Silicon

Schematic drawing of a 2-dimensional structure for crystalline quartz, a pure glassformer, and a soda-lime silicate glass. A fourth oxygen would be located above each silicon in the 3-dimensional structure.

HOW IS GLASS MADE?

Glasses are commonly made by melting raw materials at a high temperature and cooling the melt quickly enough to form a glass. The starting materials, usually crystalline or glassy powders, are mixed together according to a "recipe." Common glasses can have a wide range of oxides present in their glass network. For example, fused silica is composed solely of SiO_2 while borosilicates are often made up of ten or more different starting materials. Each oxide present in the glass has a specific role to play—either as a network former, property modifier, fluxing agent, or colorant.

Once the starting materials have been weighed according to the glass recipe, the batch is then heated to its melting temperature (upwards of 1200°C) to form a homogeneous viscous liquid. At this point, depending on the manufacturing technique, the molten glass is manipulated and shaped into its desired final form.

WHAT ARE COMMON GLASS TYPES?

There are three glass types commonly used for technical glass products: borosilicates, soda-lime silicates, and phosphates. At first, it may seem difficult to decide which glass is best for a particular application. Answering a few questions will help guide you to the right glass type. For example, is it more important to have high thermal shock resistance or chemical resistance? Often, it depends on the environment the glass will be exposed to as well as the performance specifications required.

In this eBook, we will discuss the thermal, mechanical, and optical properties of glass and how they can influence both the design and performance of glass components and lenses.

Borosilicate

Borosilicate glasses are primarily composed of SiO_2 and B_2O_3. These glasses tend to have high network connectivity, which leads to excellent glass properties. They have good thermal shock resistance and can withstand extreme thermal cycling with minimal effect. They are also durable materials with high abrasion and chemical resistances.

Soda-lime Silicate

Soda-lime silicate glasses are primarily composed of SiO_2, Na_2O and CaO. The introduction of calcium and sodium oxides into a silicate glass tends to break up the network connectivity slightly. This means that they are easier to melt and form, but that they are also less durable and less thermal shock resistant than silicates or borosilicates. Still, the durability can be improved through thermal and chemical strengthening.

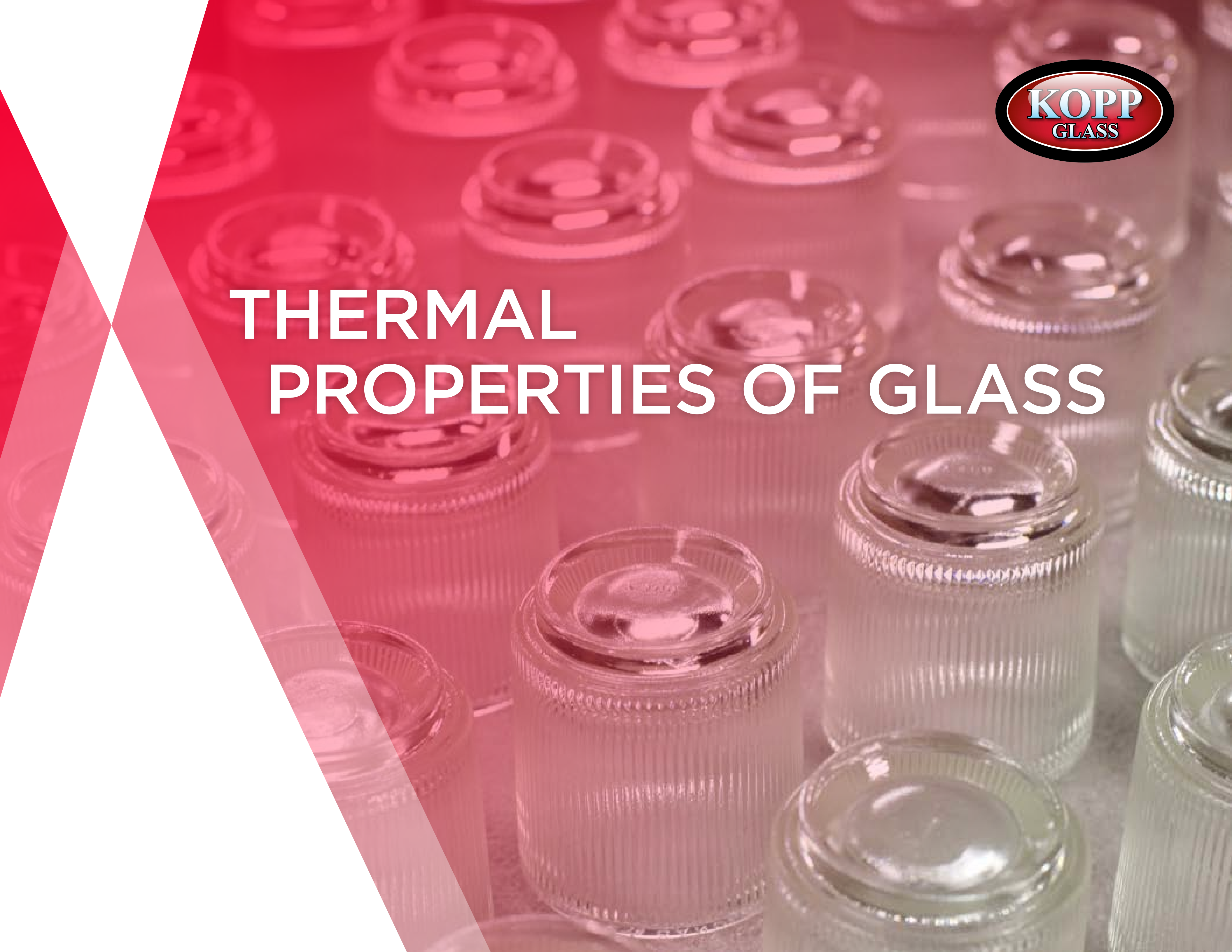
Phosphate

Phosphate glasses are primarily composed of P_2O_5. The bonds in P_2O_5 are much weaker than those in SiO_2 glasses. This means that the chemical and abrasion resistance of phosphates is lower than that of soda-lime silicates or borosilicates. It also means that phosphates melt at a much lower temperature than other glasses. They typically have high homogeneity and good optical properties. Plus, they are well-suited for doping with various colorants, including transition metal ions and rare earth oxides.

COMMON GLASS TYPES: PROPERTY OVERVIEW

Glass	Borosilicate	Soda-lime silica	Phosphate
Primary Oxides	SiO_2, B_2O_3	SiO_2, Na_2O, CaO	P_2O_5
Applications	» Industrial equipment » Exterior lighting » Laboratory and kitchen glassware	» Food and beverage containers » Windows » Lamp envelopes	» NVIS (cockpit lighting) » Bone scaffolds » Optical fibers » Heat absorbers
Thermal Profile	Good thermal shock resistance, and can withstand thermal cycling	Good to average thermal shock resistance, and can withstand thermal cycling	Poorly suited for applications requiring thermal resistance
Mechanical profile	High resistance to abrasion, impact, and tensile fracture	Average resistance to abrasion, impact, and tensile fracture	Low to average resistance to abrasion, impact, and tensile fracture
Chemical Profile	High resistance to most chemical environments	Average resistance to most chemical environments	Low resistance to most chemical environments
Optical Profile	Excellent transmission of light at UV, visible, and near-IR wavelengths	Excellent transmission of light at UV, visible, and near-IR wavelengths	Excellent transmission of light at UV, visible, and near-IR wavelengths

THERMAL PROPERTIES OF GLASS



WHAT YOU NEED TO KNOW: KEY TAKEAWAYS

It is critical to have a thorough understanding of glass thermal properties when designing a glass lens or component. When exposed to sudden or even gradual changes in temperature, improperly designed glass lenses will perform poorly and can even fail. Their thermal properties determine how they will perform in different operating conditions; this information will help you select a glass composition that will perform best for your application and environment.

Coefficient of Thermal Expansion (CTE)

Glasses will expand by a small amount when heated. If this is not properly accounted for, it can result in residual stresses in your lens. Generally speaking, glasses with lower CTE can better withstand thermal stresses.

Thermal Conductivity

Thermal conductivity tells you how well a material conducts heat. Most glasses have fairly low thermal conductivities, meaning that they act more like thermal insulators than like heat sinks.

Thermal Shock Resistance

If your lens or component undergoes rapid temperature changes, then your glass needs to have high thermal shock resistance to prevent it from breaking.

Specific Heat

Specific heat tells you how much heat is needed to raise the temperature of a glass. Specific heat, combined with knowledge of a glass' thermal conductivity, can give you an idea of how quickly your lens will reach thermal equilibrium.

Heat Processing

Glass products need to be annealed by the glass manufacturer in order to remove the internal stresses that develop from rapid cooling. In other instances, manufacturers introduce a controlled amount of compressive and tensile stress in the glass by heat-strengthening or tempering the piece; this will improve the thermal and mechanical resistances of the glass.

COEFFICIENT OF LINEAR THERMAL EXPANSION

The coefficient of thermal expansion (CTE) is a measure of how much volume changes as a material is heated or cooled. It is defined by

$$\beta = \frac{1}{V}\left(\frac{\partial V}{\partial T}\right)$$

where *V* and *T* are volume and temperature, and its units are 1/°C. For isotropic amorphous materials, such as glass, that have small thermal expansions, the linear coefficient is accurately described by

$$\alpha = \frac{\beta}{3} = \frac{1}{L}\left(\frac{\partial L}{\partial T}\right)$$

where *L* is the length of the glass.

IN APPLICATION

If heat is unevenly applied to a glass, different areas of the glass will expand by varying amounts and internal stresses will develop. This could result in glass fracture or failure.

In applications where glasses are closely installed with other materials, their thermal expansions need to match. For example, in stage lighting, glass lenses are tightly fitted into metal fixtures. If the expansions of the materials are not taken into consideration, and adequate space is not provided, then the glass could crack and fail due to applied stress from the fixture.

In another example, ceramic enamel is frequently applied to glass lenses to block unwanted light. However, the CTE for the enamel must be similar to that of the glass, or the enamel will crack and chip.

THERMAL SHOCK RESISTANCE

The thermal shock resistance of a glass indicates how likely it is to break when its temperature suddenly changes. It is defined as the maximum change in temperature (ΔT) that a glass can withstand upon rapid heating or cooling. It can be related to other glass properties by

$$\Delta T = \frac{\sigma(1-\nu)}{E\alpha}$$

where σ is the internal stress necessary to cause cracking or failure, ν is Poisson's ratio, *E* is Young's modulus and α is the coefficient of linear thermal expansion of the glass.

IN APPLICATION

Thermal shock testing is a method used to indicate the ability for glass lenses or components to withstand large changes in temperature when installed in their operating environment. For example, glass lenses used with high power lighting often become hot during use and can experience rapid cooling when exposed to rain, snow, or other environmental factors. In these dynamic environments, it is critical to select the correct type of glass to ensure the lens' ability to withstand thermal shock.

Thermal shock resistance of specific parts is often tested by taking heated glass lenses and rapidly cooling them through methods such as immersion in an ice bath or exposure to water droplets.

The thermal shock resistance of a glass can be improved by thermally or chemically strengthening processes. These processes introduce compressive stresses at the glass surface and increase their resistance to sudden impacts or temperature changes. We'll expand on heat-strengthening in an upcoming section.

THERMAL CONDUCTIVITY

Thermal conductivity represents how well a glass conducts or transfers heat. It is defined as:

$$K = -\frac{q}{A\left(\frac{dT}{dx}\right)}$$

where q is the heat flow measured in Watts (or J/s), A is the cross-sectional area of the glass, and dT/dx is the temperature gradient applied to the glass. A good thermal conductor will allow heat to travel through the material very quickly, much like good electrical conductors will allow for faster charge movement.

SPECIFIC HEAT

The specific heat of a glass is the heat needed to raise the temperature of the glass by 1°C per unit weight:

$$C = \frac{Q}{m\Delta T}$$

where Q is heat, m is mass and T is temperature. If the thermal conductivity shows how much heat will flow through a material, the specific heat shows how quickly heat will raise the temperature of a glass.

THERMAL CONDUCTIVITY & SPECIFIC HEAT

MATERIAL COMPARISON

Thermal conductivity and specific heat can be important considerations for applications where the lens or component operates at a high temperature. Take a look at the table to the right, and compare the values for thermal conductivity and specific heat of some common transparent materials, as well as for the metal aluminum.

Compared to any metal, glasses and polymers such as soda-lime silicates, borosilicates, acrylics, polycarbonates, and silicones have much lower thermal conductivities. This means that they act more like thermal insulators than like thermal conductors and that it will take time for heat to travel through these transparent materials.

An example of these properties in an application would be estimating how much the temperature of a glass lens and a plastic lens will increase due to the heat output of your bulb. You need to consider the specific heat of the materials, as well as the mass of the part. The material choice and therefore temperature of your lens in an application can be critical in determining important optical requirements for the lens like chromaticity and transmission as these properties can be temperature dependent.

Material	Thermal Conductivity W/(m.C)	Specific Heat J/(kg.C)
Acrylic	0.2	1450
Polycarbonate	0.2	1200
Silicone cast resin	0.2	1175
Soda-lime silicate glass	1.0	675
Borosilicate glass	1.0	750
Aluminum	205	900

HEAT PROCESSING

Glass manufacturers must have a sound knowledge of key processing temperatures; this information helps ensure production efficiency as well as high-quality products. It also guides the temperature parameters for annealing, tempering, and heat-strengthening of glass. But it is also important for application design so that the right glass is chosen for a specific job. If a glass lens is going to be used in a high-temperature environment, like the lens for a spotlight, it has to be able to withstand the operating temperature of the bulb without losing its desired shape. A brief overview of annealing, heat strengthening, and tempering is given below.

Annealing Temperature

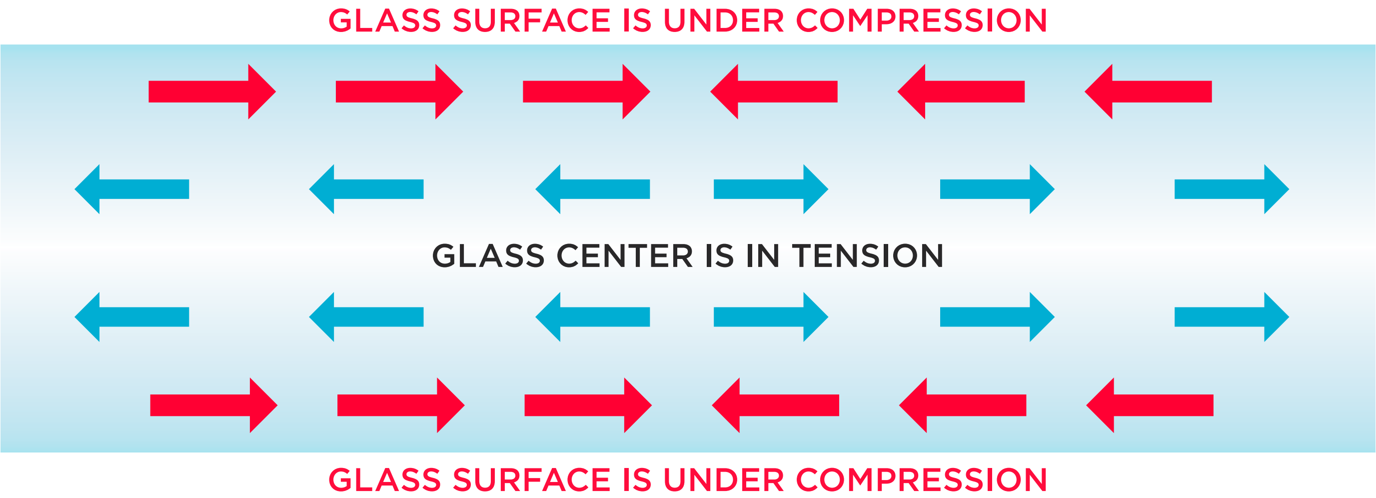
In technical glass production, molten glass is pressed, and it rapidly cools as it is removed from the mold. This rapid cooling creates internal stresses within the glass piece. When the glass finally cools to room temperature, stresses in the glass can potentially cause spontaneous breakage. Glass annealing is a controlled process of slowly cooling glass to relieve these internal stresses. First, the glass is heated to its annealing point; the temperature at which the residual stresses in a glass are reduced over a matter of minutes. It is then slowly cooled to room temperature. To ensure maximum stress removal, each product design requires a unique annealing schedule that takes into consideration the glass composition, coefficient of thermal expansion, and thickness. Following production, glass lenses can be inspected with equipment like a polariscope to ensure well annealed, minimally stressed glasses.

HEAT PROCESSING

Heat Strengthening and Tempering

Conversely, there are times when you want to introduce stress in a controlled way to improve a glass' thermal and mechanical properties. Glass can be heat-strengthened or tempered through a controlled heating and cooling process.

This is accomplished by first heating the glass above its glass transition temperature. Next, the external surface of the glass is rapidly cooled. Because the inner material cools at a slower rate compared to the outer material, the thermal differential creates compressive stress on the glass surface and tensile stress at the inner layer of the glass. According to the standard ASTM C1048, a heat-strengthened glass has a surface compression of 3500 to 7500 psi, while a tempered glass must have a surface compression of at least 10,000 psi. The compressive layer is responsible for improving the thermal and mechanical resistance of the glass; any shock or impact would have to overcome this stress before catastrophic failure could occur.



Surface compression improves the thermal shock resistance, as well as mechnical resistance of a glass.

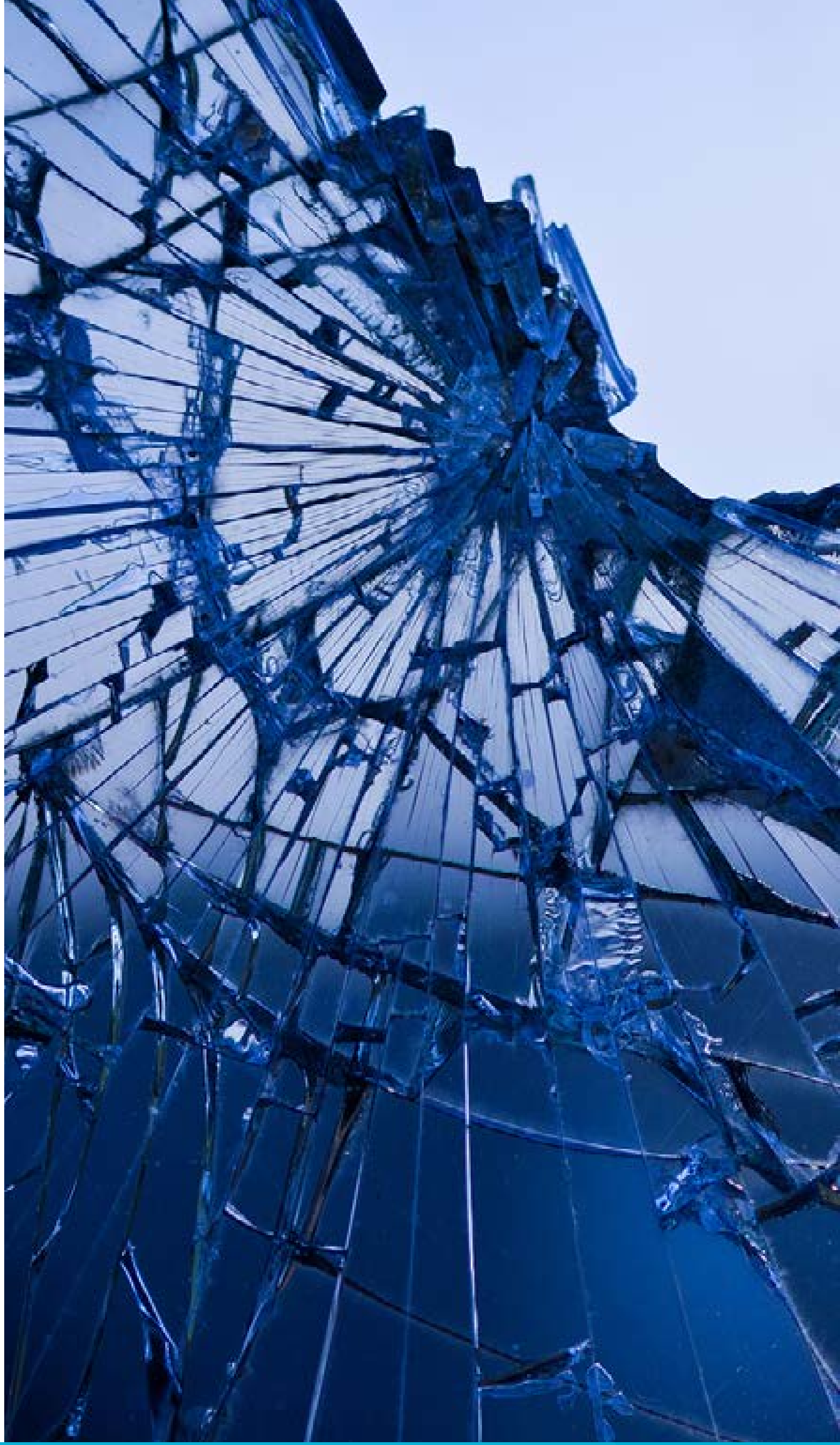
MECHANICAL PROPERTIES OF GLASS

MECHANICAL PROPERTIES OF GLASS

DESIGN TO SURVIVE STRESS, IMPACT, AND ABRASION

When designing a lens or component for a harsh environment, you need to choose a material that is resistant to pressure, abrasion, and impact. Some applications, such as exterior aircraft lighting, can push a material to its limits. Exterior aircraft lenses are exposed to smog, dust, and other air pollutants at very high speeds; the resulting impacts can degrade the lens surface, sometimes to the point where they are no longer able to meet transmission requirements.

Proper material selection for a lens, filter, or other optical system component is crucial for successful product design. The material's physical properties determine its ability to resist damage and prevent failure. In this section, we review the mechanical and chemical properties of glasses, including elastic moduli, strength, hardness, impact resistance, and chemical resistance, and demonstrate their effect on different applications.



WHAT YOU NEED TO KNOW: KEY TAKEAWAYS

Elastic Properties

When you apply stress to a glass, it expands and contracts on a very small scale. The elastic moduli of a glass tell you how much it will deform under applied stress, and in what direction it will deform.

Strength

The strength of a material tells you how much stress it can stand before breaking. In glasses and other materials, this value depends on a variety of factors, such as composition, shape, and even surface finish.

Hardness

Hardness is the ability of a material to resist being scratched, fractured, or permanently deformed by the sharp edges of another material. If you know the hardness of a glass, you get a sense of its resistance to abrasion.

Impact Resistance

Impact resistance measures the ability of a glass to resist being fractured and to retain surface quality after being hit. This value is improved with higher values of strength, hardness, and toughness.

Chemical Resistance

Liquids such as hydrofluoric acid, jet fuel, and salt water can etch at the surface of a transparent material. If your lens is exposed to these and other chemicals, you need to choose a glass with high chemical resistance to maintain transmission.

MECHANICAL PROPERTY OVERVIEW

TRANSPARENT MATERIAL COMPARISON

Property	Unit	KOPP Borosilicate	Borosilicate	Soda-lime silicate	Phosphate	Quartz	Acrylic	Poly-carbonate	Silicone
Density	g/cm^3	2.33	2.23	2.52	2.86	2.20	1.2	1.2	1.5
Tensile Strength	MPa	60	70	40	65	70	70	75	11
Hardness	Moh's	5.5	5.5	5.5	5	6	3	3	2
Brittleness	-	Yes	Yes	Yes	Yes	Yes	No	No	No
Young's Modulus	GPa	65	65	70	60	72	3	2	0.002
Abrasion Resistance	-	High	High	Med	Med	Very High	Med	Med	Med
Impact Resistance	-	Med	Med	Med	Med	Med	High	High	High
Chemical Resistance	-	High	High	Med	Low	Very High	Low	Low	Med

STRESS, STRAIN, AND ELASTIC PROPERTIES

You may be surprised to learn that glass is an elastic material on the atomic level. This means that under stress, glass will deform due to the nature of its atomic bonding structure. However, this change is not permanent and when the stress is removed, the glass reverts to its original form. The stress on a glass is defined by force applied to a unit area,

$$\sigma = \frac{F}{A}$$

Applied stress can be homogeneous, meaning uniform across the entire glass sample, or there can be a stress gradient where one area experiences more stress than another area. The strain, e, describes the deformation of the glass. It is the fractional change in length due to compression or tension stresses,

$$e = \frac{\Delta L}{L}$$

The elastic nature of glass is described by its elastic moduli. These moduli tell you a lot about how much a glass will deform under stress and in what direction it will deform. They are defined by the relationships between different directional elements of stress and strain.

3 IMPORTANT ELASTIC MODULI TO KNOW

Since glass is an isotropic material, which means that the bulk properties are independent of direction (unlike many crystalline materials), if you know at least two of the elastic moduli mentioned below, you can determine any of the others.

$$Y = \frac{\sigma_x}{e_x}$$

Young's modulus:
The modulus *Y* is a measure of the stiffness of a glass. Larger values of *Y* indicate stiffer glasses which will not deform as much under applied stress.

$$\nu = -\frac{e_y}{e_x}$$

Poisson's ratio:
Poisson's ratio, *ν*, indicates the relationship between elongation and contraction of a material when stress is applied in one direction. The material will typically elongate in length in the direction of the applied tensile stress and contract in dimension in the perpendicular direction.

$$G = \frac{\sigma_{xy}}{e_{xy}}$$

Shear modulus:
The shear modulus, *G*, relates shear stress and shear strain. It is an indication of the rigidity of a glass.

STRESS, STRAIN, & ELASTIC PROPERTIES

IN APPLICATION

It's important to understand that while glass is elastic in nature, it is also a very stiff material. This means that for typical stresses applied to glass, the resulting strain is very small. So for most applications, stress applied to a glass piece will not cause it to shift out of its dimensional specifications.

Knowledge of Young's modulus can be very useful in predicting the strength or impact resistance of a glass piece. For example, if you are designing a lens that needs to withstand large pressures without breaking, such as an exterior submarine light, or a runway lens that will be exposed to impact from gravel and hail.

All other things held equal, a glass with a higher Young's modulus is a better choice, since it will be more resistant to failure from both consistent pressure and sudden impact. This will be discussed in more detail in the following sections.

STRENGTH

The strength of a material is the amount of stress that it can withstand before fracturing. For a perfect theoretical glass, the strength is defined as

$$\sigma_m = \left(\frac{\gamma_f E}{a_0}\right)^{1/2}$$

where γf is the energy of the fractured surface, *E* is Young's modulus, and a_o is the distance between atoms in the glass. This typically ends up being on the order of GPa (gigapascals (10^9 Pa). In practice, however, glasses typically have strengths much lower, in the range of 14-70 MPa (megapascals, or 10^6 Pa). This is because no glass is as perfect as theoretically possible and small flaws are always present in real glass structures. Accounting for these imperfections, the strength is rewritten as

$$\sigma_m = \frac{1}{2}\left(\frac{\gamma_f E}{c}\right)^{1/2}$$

where *c* is the size of the flaw. The strength is greatly reduced for flaws larger than the interatomic distance a_o. Even if the flaw is as small as 4 microns, the strength is decreased by approximately a factor of 200.

For most finished glass products, including polished glass, molded glass, and float glass, surfaces are finished to a quality on the order of microns. What this means is that there are flaws present on the glass surface with a size of about a micron. Therefore, surface finish is one of the main reasons for the actual strength of a glass to be on the order of MPa.

STRENGTH

IN APPLICATION

When selecting glass as the material for your application, knowing the strength of the glass will help ensure it can withstand applied stress and meet specific pressure requirements. Glassware used in naval applications such as navigation, warning, or signal lights must pass hydrostatic pressure tests according to the military standard MIL-DTL-24560A. For example, the glass lenses installed in exterior submarine lighting are required to withstand pressures of 10-15MPa.

Glasses most commonly fail from flaws at the surface when tensile (think pulling apart) stresses are applied. To test the strength of a glass, the ASTM C158 Standard: Test Methods for Strength of Glass by Flexure is often used. This method uses a three or four point bend test to determine the strength of a glass and can be used to predict application strength. Should a glass need the ability to withstand greater stress, chemical and heat strengthening processes can be used to increase its strength.

HARDNESS

Hardness is the ability of a material to resist being scratched, fractured, or permanently deformed by the sharp edges of another material. In other words, it is a measure of a material's resistance to abrasion. While you might sometimes hear strength and hardness discussed interchangeably, they are in fact separate properties. Strength refers to the resistance of a bulk material to applied pressure, while hardness refers to the resistance of a surface to small, sharp projectiles.

You can measure the hardness of a glass by using a scratch test (Mohs scale) or an indentation test (Vicker's hardness). However, both of these tests are performed only at single points on a material's surface. Often it is more useful to measure the abrasion resistance of an entire surface. The Taber method is often used to determine the abrasion resistance of an entire surface, where two rough wheels rotate on either side of the material and simulate abrasion. The falling sand test is another common abrasion resistance test, where the surface of a material is struck with sand, silicon carbide, or other small particles, at known quantities and rates to gage abrasion resistance. Watch our video to learn more about abrasion testing and how different materials compare.

IN APPLICATION

Glass lenses that are installed in outdoor environments, such as exterior aircraft lighting, are often subject to abrasive conditions. When designing a lens for such a harsh environment, it is important to know how the surface of your material will wear, since abrasion can adversely affect performance. For example, when the surface of a transparent material is abraded, light transmission decreases. When the surface accumulates enough scratches, the part could shift out of the required optical specification range. It's also critical to remember that small surface flaws created by abrasion can affect the strength of the glass lens and lead to premature failure, as we discussed in the previous section.

When designing for an application that requires high strength, high transmission, and abrasion resistance in the face of extreme conditions, it is best to choose a hard glass.

Read our blog article to learn more about the effects of abrasion on transmission and to see how glass offers significantly higher abrasion resistance compared to other materials like plastics.

IMPACT RESISTANCE

Glass is often required to withstand not only continuous stress or surface abrasion but also impact. Impact is typically defined as a large force that is applied instantaneously to one spot on the material. Glasses are said to be resistant to impact if both they retain their surface quality and resist fracture.

Impact resistance is improved with higher values of strength, hardness, and toughness. A material can be strong and tough but not necessarily hard, meaning that an impact would mar the surface but not break the material. Or conversely, the material could exhibit high hardness but not be strong and tough, meaning that an impact would not abrade the surface but the material could still fracture internally. In contrast to other materials, glasses are typically strong, hard, and tough, which leads to high impact resistance. Additionally, heat strengthening and chemical strengthening mechanisms can be used to improve the inherent impact resistance of the glass.

IN APPLICATION

The impact requirements of a glass part depend strongly on its application; a glass fit for one application may fail in another. Pebbles and gravel are often kicked up on the airfield runway by an airplane's wheels; runway lighting systems must be able to withstand these impacts without failure. In contrast, in-ground pavement lights are subject to different environmental impacts and as a result, have different impact requirements.

Commonly, lenses or glass components may need to adhere to specific impact requirements or standards for their application. For example, a glass lens for a helipad light must adhere to MIL-DTL-24560A(SH) and be able to withstand impact-without damage-from a three-pound steel ball dropped on the center of the glassware from a height of two feet. Meeting this and similar standards requires the proper combination of lens design, glass composition selection, and additional heat-strengthening processes.

CHEMICAL RESISTANCE

The chemical resistance of a glass is a measure of its durability when it is exposed to or immersed in applicable chemicals. It is important to understand how glasses react to acids and bases, but it is equally important to know whether they degrade in water or even humidity in the air. Typically, only the surface layer of glass is affected by exposure to water or other liquids, but some of the more exotic glass compositions, such as phosphates or chalcogenides, can degrade or even dissolve over time due to humidity in the air.

Most commercial glasses, including silica, soda-lime silicates, and borosilicates, have high chemical durability. This is due to these glasses having strong bonds between atoms and high network connectivity. For less durable glass compositions, like phosphates, degradation occurs when the glass is exposed to a chemical that causes the weaker network bonds to break.

There is no hard and fast rule when it comes to performing chemical durability tests. Glasses can be immersed in water, acids, bases, or any other fluid of interest. Measurements can be done on bulk or ground glass samples. Tests can be closed, where the liquid is constant, or open, where the liquid (and dissolved glass) is continually replaced. Weathering tests can also be performed, where glass is exposed to water vapor and weight loss is measured. So when reviewing design specifications, it is important to know and determine appropriate test parameters to fully understand a glass' ability to withstand applicable chemical attack.

IN APPLICATION

Before you can select a material for an application, you need to know what environmental conditions it will be exposed to. For example, exterior aircraft lenses can be exposed to a variety of harsh chemicals such as deicing fluids, petroleum based fuels, hydraulic fluids, and air pollutants. Materials chosen for these lenses must be highly resistant to these chemicals in order to prevent degradation and failure. In another example, lighting fixtures installed in coastal regions are often exposed to high humidity and air salinity. To reduce constant lens replacement and maintenance costs, it is best to choose a material—like glass—that will withstand this environment and retain high transmission.

In some stringent applications, the lens or filter material may be required to withstand certain environmental conditions, such as resistance to humidity. For example, glasses used in night vision imaging system (NVIS) applications need to pass the humidity test outlined in MIL-STD-810E. Here, the surface degradation of a glass is tracked as a function of time and relative humidity at a constant temperature.

OPTICAL PROPERTIES OF GLASS

HOW LIGHT AND GLASS INTERACT

We often hear from engineers who are evaluating the impact of a design change from one lens material to another. For example, they may be switching from an existing polycarbonate lens design to glass due to concerns about durability in harsh environments. They ask “Can I use my existing lens design with the new glass material? Will the resulting light output have the same chromaticity, distribution, and intensity?” The answers to these questions are partially rooted in understanding the optical properties of materials.

The optical properties of a material determine how it will interact with light. Today, most engineers use advanced software tools to simulate the properties of a material and their impact on optical performance. Still, familiarity with a few fundamental optical properties will help engineers pick the right material for their application. In this section, we review refractive index, wavelength dependency, transmission, and absorption and discuss how these properties impact product design.

WHAT YOU NEED TO KNOW: KEY TAKEAWAYS

Refractive Index

The index of refraction determines how much light is reflected and transmitted at a glass-air interface, and also the angle at which it's refracted. It is used in ray tracing programs to determine light path and output.

Absorption, Transmission, and Reflection

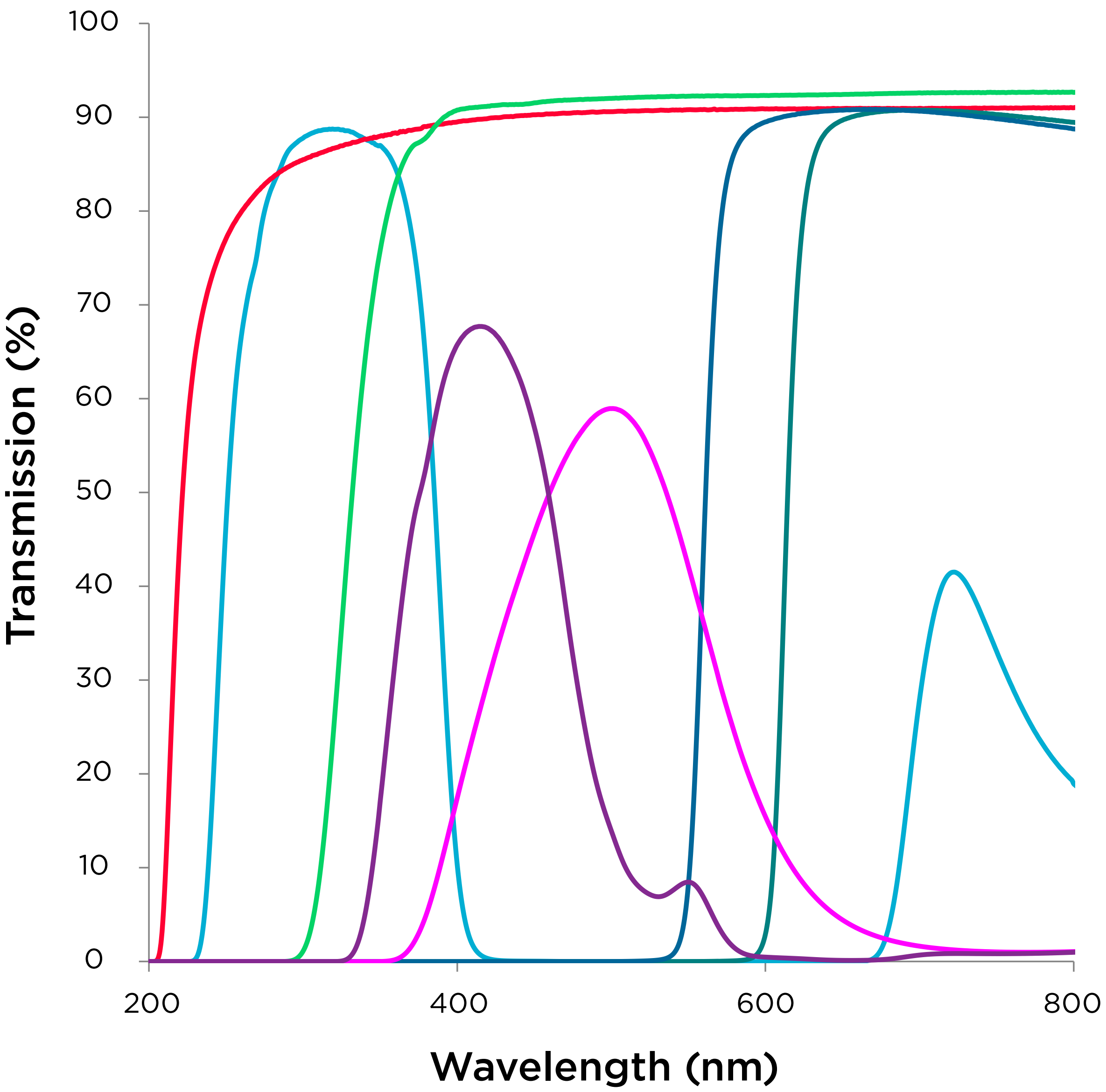
Absorption is the reduction of light as it travels through a material. Conversely, transmission is the amount of light that makes it through. Reflection for transparent materials usually occurs at the surface and is a function of wavelength and index of refraction.

Chromaticity

The perceived color of a glass is determined by the output of the light source, the transmission of the glass, and the human eye response. This is objectively described by a three-coordinate chromaticity value; many applications specify a narrow range for this value.

Property	KOPP Borosilicate	Borosilicate	Soda-lime silicate	Phosphate	Quartz	Acrylic	Poly-carbonate	Silicone
Transmission	UV, Visible, near-IR	UV, Visible, near-IR	UV, Visible, near-IR	UV, Visible, near-IR	UV, Visible, near-IR	UVA, Visible, near-IR	Visible, near-IR	UV, Visible, near-IR
Refractive Index	1.49	1.51	1.52	1.55	1.46	1.49	1.58	1.41
UV Resistance	High	High	High	High	High	Med	Low	High

GLASS TRANSMISSION EXAMPLES



Glass compositions can be engineered to either transmit or absorb specific wavelengths of light. The plot to the left demonstrates the transmission spectrum of various glass compositions, spanning from the ultraviolet to infrared regions of the electromagnetic spectrum.

The following sections discuss the specific properties that control what wavelengths are transmitted, and why.

REFRACTIVE INDEX

You're probably familiar with the concept of "traveling at the speed of light", but did you know that the speed of light can change? Light's speed is reduced when it travels through a medium due to the interaction of photons with electrons. Typically, higher electron densities in a material result in lower velocities. This is why light travels fast in glass, faster in water, and fastest in a vacuum. The *refractive index (n)* of a material is defined as the ratio of the speed of light in a vacuum to that of light in the material.

When a beam of light hits a glass surface, part of the beam is reflected, and part is transmitted. The index of refraction of the glass determines not only how much light is reflected and transmitted, but also its *refracted angle* in the glass. The angle of transmission can be calculated using Snell's law:

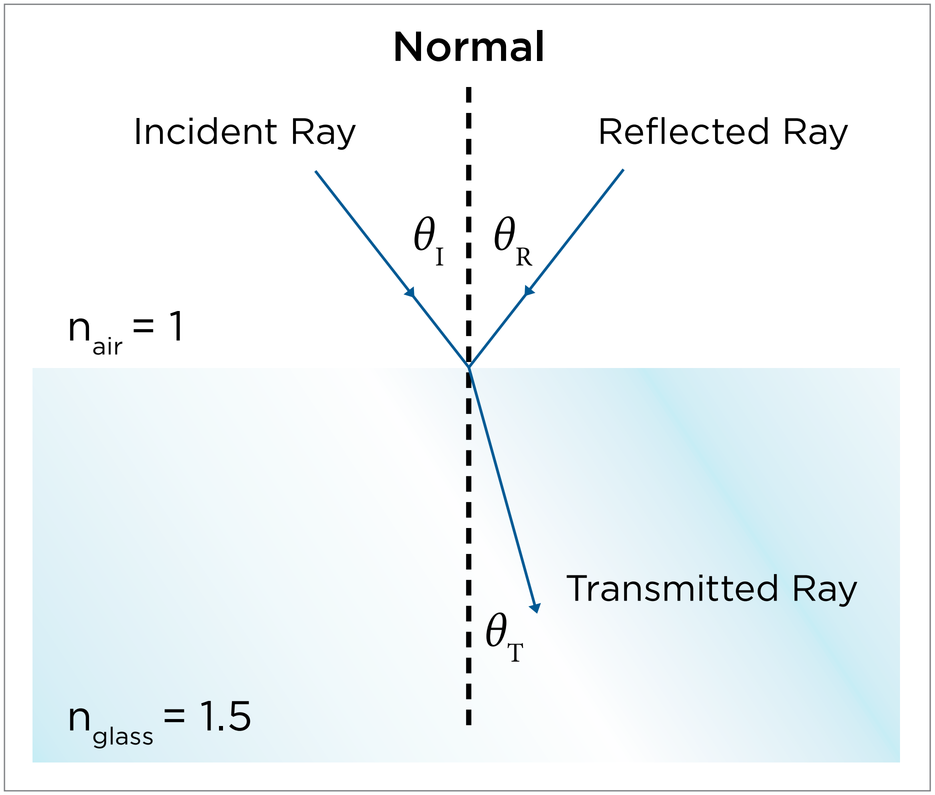
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Larger indices of refraction in glass result in greater differences between the angle of incidence and transmission of light. The reflection of light at the surface occurs due to an instantaneous change in refractive index between glass and its surrounding medium.

For normal incidence (Θ_i = 0°), the amount of light reflected is found by

$$R = 100 \times \left(\frac{n_{air} - n_{glass}}{n_{air} + n_{glass}}\right)^2$$

For most glasses with a refractive index of 1.5, reflection losses at the surface result in an approximate 4% decrease in light intensity.



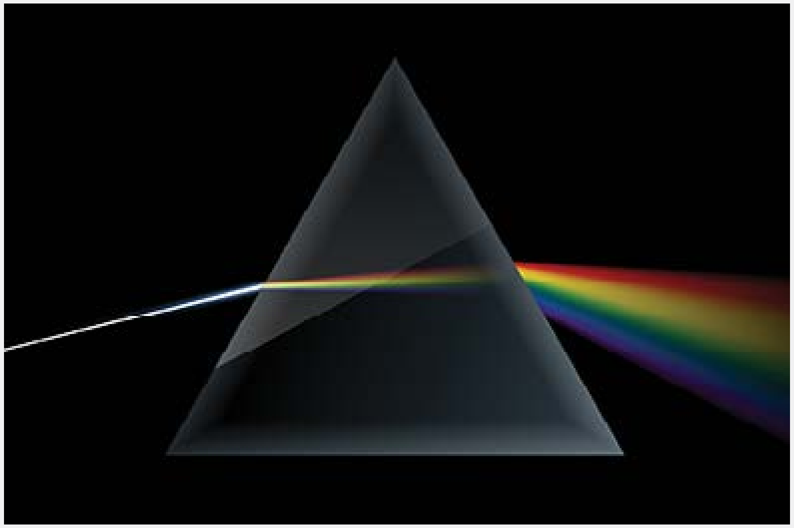
Light that is incident on a glass surface will be reflected at an angle equal to the angle of incidence and transmitted according to Snell's law. For normal incidence, approximately 4 % of the light is reflected; this value is determined by the refractive index of the glass.

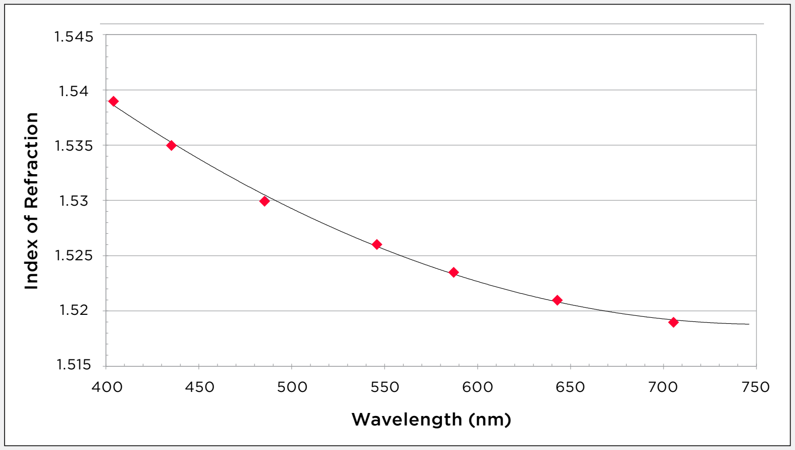
REFRACTIVE INDEX

It’s important to know the refractive index of most glasses is wavelength dependent: it increases as the wavelength of incident light gets shorter. The dispersion of the refractive index is often visually shown using the example of white light splitting while traveling through a prism. Mathematically, it is described using the empirical Cauchy equation,

$$n(\lambda) \approx A + {}^{B}/_{\lambda^2} + {}^{C}/_{\lambda^4} + \cdots$$

Here A, B, and C are constants specific to the glass composition. This relationship works well for visible wavelengths, but often does not accurately describe ultraviolet or infrared behavior.





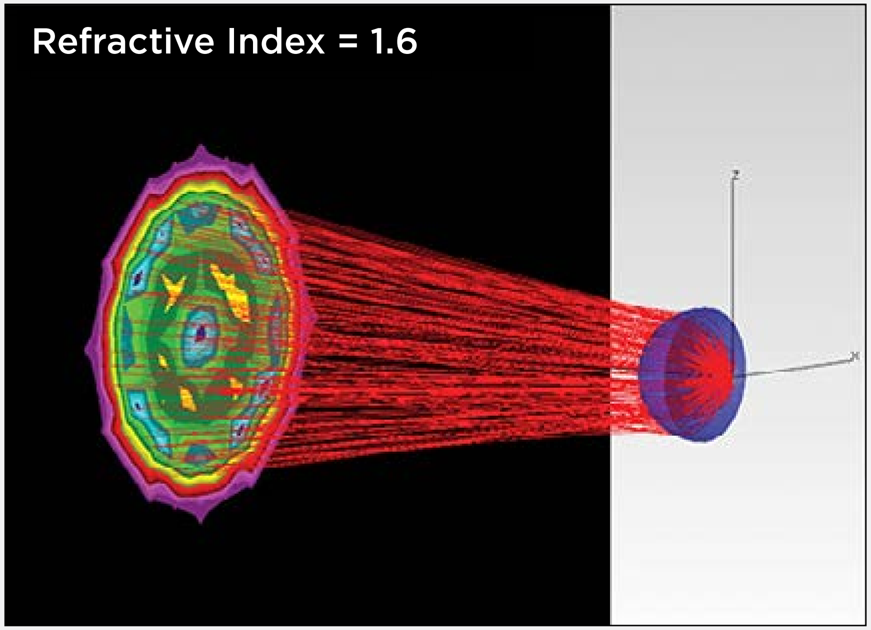
The index of refraction for a glass material changing over the visible wavelength spectrum. The use of an optical prism shows the effect of this change index across the visible spectrum as white light is split into individual wavelengths and colors.

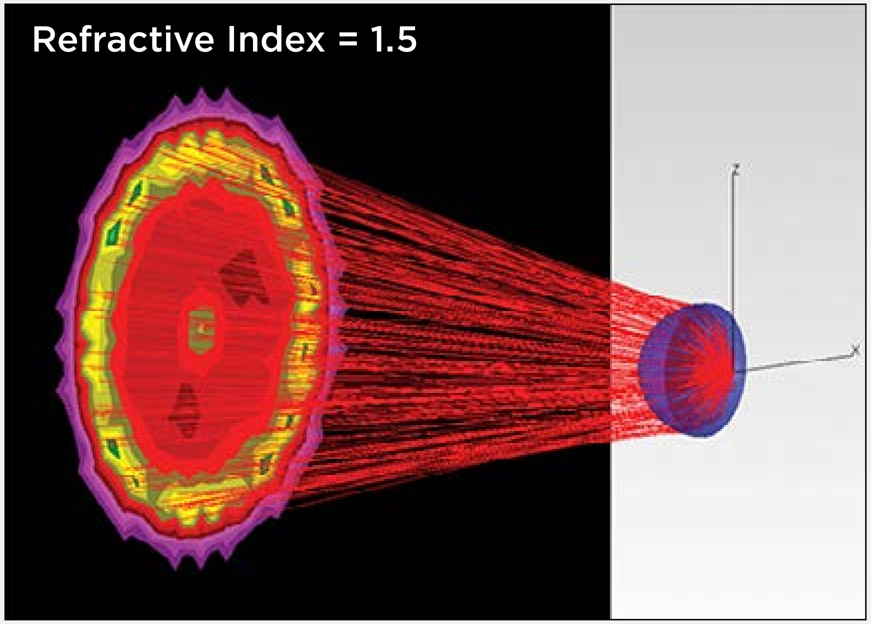
REFRACTIVE INDEX

IN APPLICATION

When designing a lens that transmits light, you need to consider the material's refractive index. Even a small change in the refractive index can affect the distribution of the transmitted light. This can be seen in the example below, where light travels through two identically shaped plano-convex lenses with different refractive indices.

The luminous intensity distribution on the bottom is produced by a glass lens with a typical refractive index of 1.5. Displayed on the top is a lens with a refractive index of 1.6. It could be made from a higher index of refraction glass or plastic, such as polycarbonate. For the specific lens example shown, using a glass with a smaller refractive index will distribute light across a larger surface area while using a glass with a larger refractive index will focus the light onto a smaller surface area. Understanding this optical property will provide you with one more tool to help you select the right material and achieve your desired performance results.


Refractive Index = 1.6


Refractive Index = 1.5

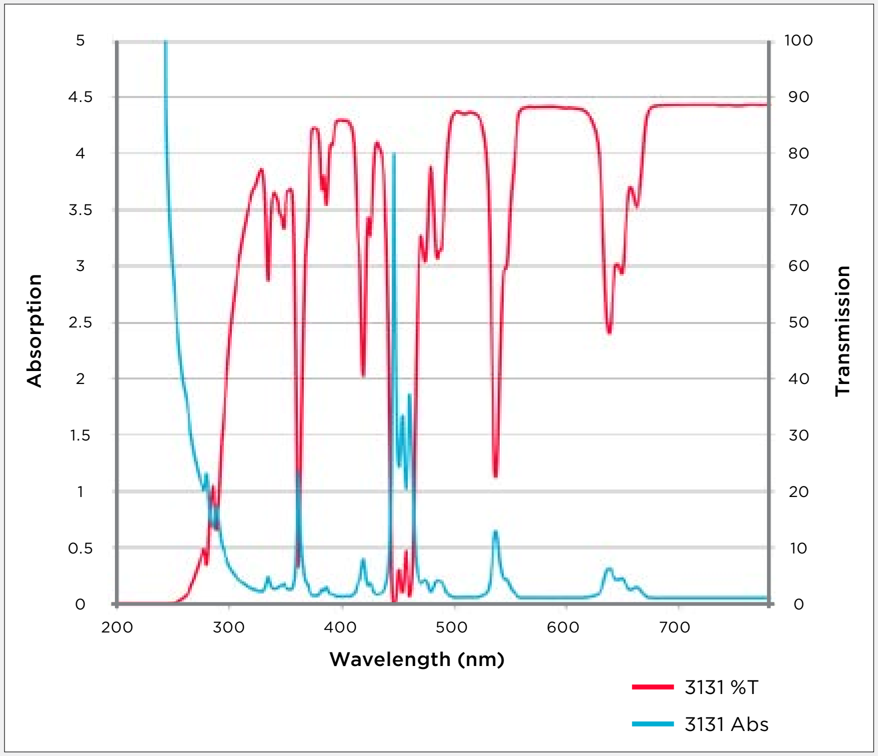
ABSORPTION

When light travels through a glass, the intensity of the light is typically reduced. This absorption happens when the energy of a photon of light matches the energy needed to excite an electron within the glass to its higher energy state, and the photon is absorbed by the glass.

The absorbance of a glass, shown in the figure above as a function of wavelength, is often used to describe the decrease in intensity of light as it travels through the glass. It is defined as

$$A = -\log\frac{I}{I_0}$$

This value depends on the composition and thickness of the glass as well as the wavelength of incident light.



The absorption spectrum of a glass varies by composition. Glasses with standard absorption peaks in their spectra, such as Kopp Glass' 3131 filter plotted here, can be used to calibrate spectrophotometers. Large absorption peaks corresponds to decreases in the transmission spectra.

ABSORPTION

IN APPLICATION

Rare earth glass filters are often used to calibrate the absorption and transmittance of spectrophotometers. These glasses absorb light at very specific wavelengths, which enable the calibration of well-characterized absorption peaks across the ultraviolet, visible, and infrared spectrums.

In some applications, it is beneficial to reduce light output in equal parts across all wavelengths. Neutral density filters, for example, absorb all wavelengths nearly equally and are often used in photography to reduce the intensity of light without affecting the color. They're also used to attenuate lasers and other light sources where the power can't be adjusted or reduced.

TRANSMISSION / TRANSMITTANCE

Any light that is not absorbed by a glass or reflected at its surface will be transmitted through the glass. It is often very important to know exactly how much light will pass through a glass at specified wavelengths. Often, glasses are discussed in terms of their transmittance or transmission. The same information is provided by both of these terms, but transmission is reported with ranges from 0 % to 100 % and transmittance from 0 to 1.

Transmission is calculated from the intensity of incident light I_0 and the intensity of light leaving the glass I:

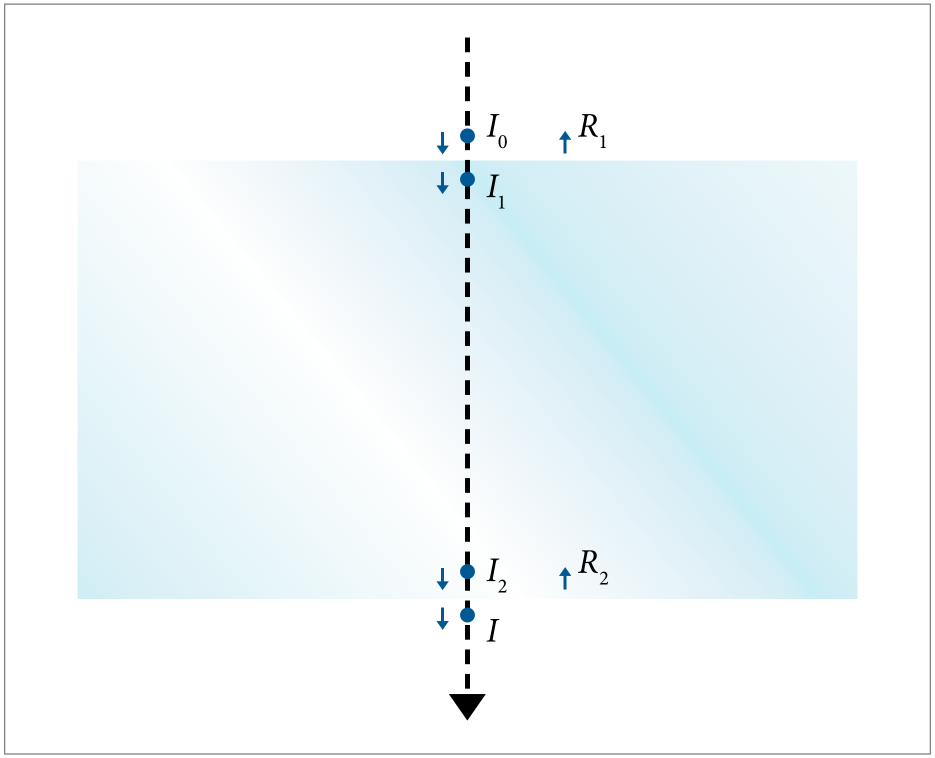
$$\%T = 100 \times \frac{I}{I_0}$$

For a typical clear class, the transmission of light is around 92%; this value is less than 100% due to the reflection of light at the surfaces of the glass as well as the absorption loss of light within the material.

The internal transmittance, on the other hand, does not include reflection losses. It is determined from the light intensity just after entering the glass, I_1, and just before exiting the glass, I_2:

$$\tau_i = \frac{I_2}{I_1}$$

Internal transmittance values are typically near 1.0 for a clear glass since the only loss accounted for with this value is from the absorption of light through the material.



TRANSMISSION / TRANSMITTANCE

IN APPLICATION

The reporting of transmittance values of a material can vary depending on the application or common industry nomenclature. While most industrial glasses report optical properties as transmission, values for filter glasses are typically given as internal transmittance. This is because filter glasses may be treated with anti-reflective coatings to prevent intensity losses at the glass surface. For example, a glass filter which has an external transmittance of 0.92 at 589.2 nm might have a much higher internal transmittance of 0.98, as is the case with our 3131 filter.

When reviewing a glass property sheet and designing a part, it's important to know if the industry specifications you're trying to meet are for external transmission or internal transmittance. For instance, many of the Federal Aviation Administration (FAA) specifications for airport and aerospace applications have requirements that are provided in transmission. SAE Aerospace Standard AS 25050 requires specific transmission ratios for the different colored ware. Depending on the transmission level, various grades (A-D) are assigned to the ware.

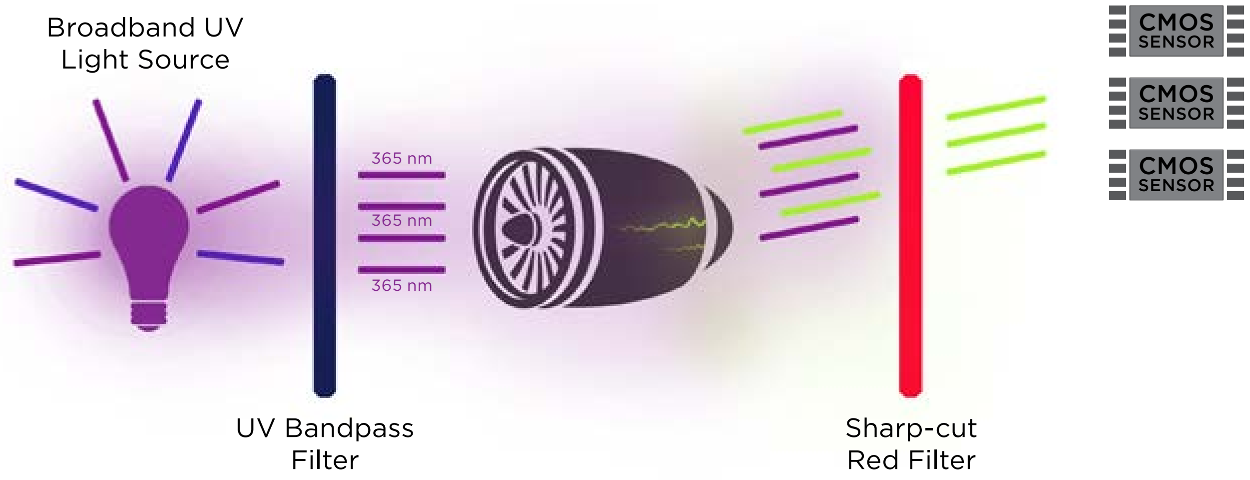
TRANSMISSION / TRANSMITTANCE

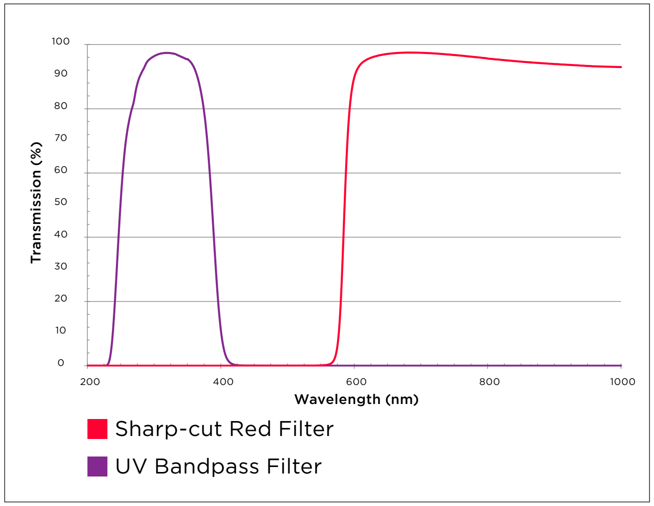
IN APPLICATION: CASE STUDY

Glass filters with tightly controlled transmission and absorption spectra can be used in a variety of applications. For instance, bandpass, longpass, and shortpass filters with cut-ons/offs in transmission are commonly used in non-destructive testing and sensor-based applications.

The figure below illustrates the concepts and benefits of using absorption filters with tightly controlled and tailorable transmission properties. A UV bandpass filter is used in combination with a broadband UV light source, like an arc lamp, to transmit UV light output while absorbing all visible light. The UV light causes fluorescence of a targeted material, like a powder or liquid, which can then be detected by a sensor. This type of fluorescent dye is commonly used to detect cracks in industrial equipment and components, like aircraft turbines.

In front of the sensor pictured below is a sharp-cut red filter glass, which helps absorb UV light from the light source but allows passage of the longer wave fluorescence. A configuration like this enables the sensor to detect the maximum amount of signal while minimizing noise produced by the UV light.





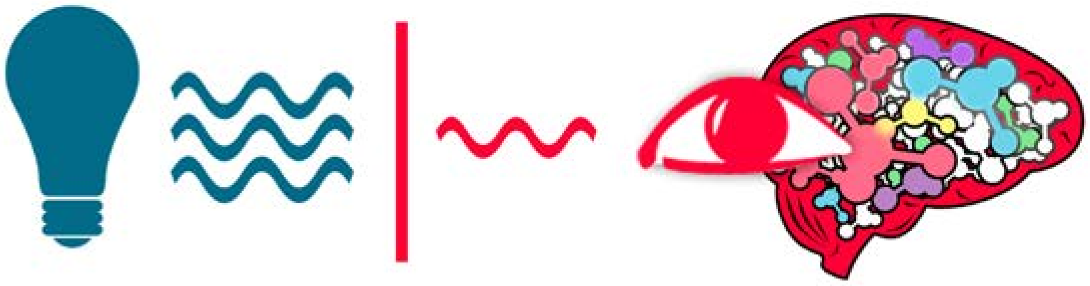
CHROMATICITY

The color of light emitted from a light fixture can be described by its chromaticity, which is a three-coordinate value. Three factors will determine the chromaticity of a light fixture: the light source, the transmission of the lens or cover material, and the human eye.

The spectral power distribution of the light output from a fixture is weighted by each of the three color-matching functions and then integrated over visible light wavelengths. The result is three tristimulus values that give an objective description of the color. Within the CIE 1931 color space, these values are X, Y, and Z. These values are then normalized to give the chromaticity of the light, (x, y, z).

The CIE 1931 color space, mapped on the next page, is particularly informative, since the tristimulus values describe red (x), green (y), and blue (z) wavelengths of light and the Y value gives an indication of the photopic transmission of the glass.

Other color spaces include CIE 1964 and CIELAB, CIELUV, RGB, and HSB. It should be noted that most color spaces can be converted between one another through the use of mathematical expressions. However, most signal lighting specifications use either CIE 1931 or CIE 1964 chromaticity values.



LIGHT SOURCE + LENS MATERIAL TRANSMISSION + HUMAN EYE RESPONSE

= CHROMATICITY

CHROMATICITY

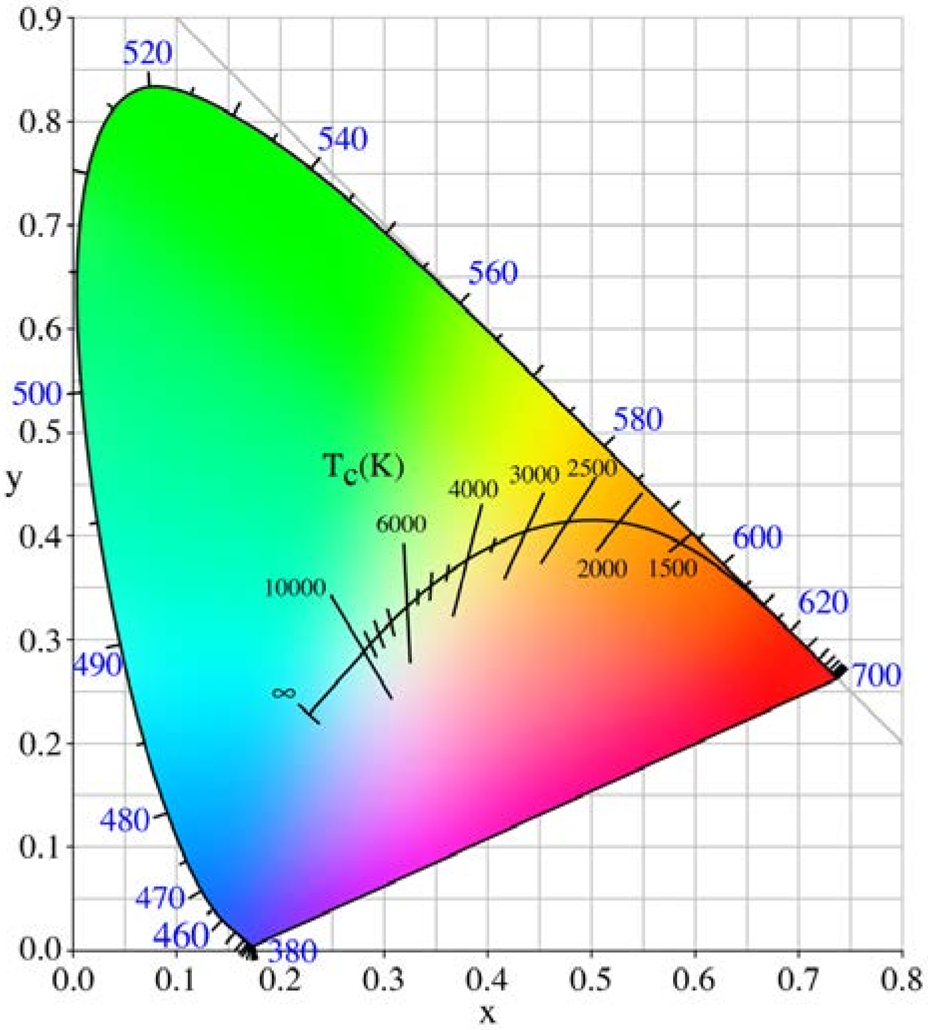
The chromaticity of glass is often defined according to the CIE 1931, or CIEXYZ, color space. This allows color to be defined numerically. To determine the chromaticity coordinates, you need to know the spectral power distribution of your light source, S(λ), the transmission spectrum of your lens, T(λ), and the color matching functions of the observer, $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$. The tristimulus values are then calculated from

$$X = k \int_{380}^{780} S(\lambda)T(\lambda)\bar{x}(\lambda)d\lambda,$$

$$Y = k \int_{380}^{780} S(\lambda)T(\lambda)\bar{y}(\lambda)d\lambda,$$

$$Z = k \int_{380}^{780} S(\lambda)T(\lambda)\bar{z}(\lambda)d\lambda\,,$$

where $k = 100 / \int_{380}^{780} S(\lambda)\,\bar{y}(\lambda)d\lambda$ is a weighting factor that allows Y to be 100 for a perfectly diffusing lens. The tristimulus values are then normalized to yield the commonly presented chromaticity coordinate (x,y,z).



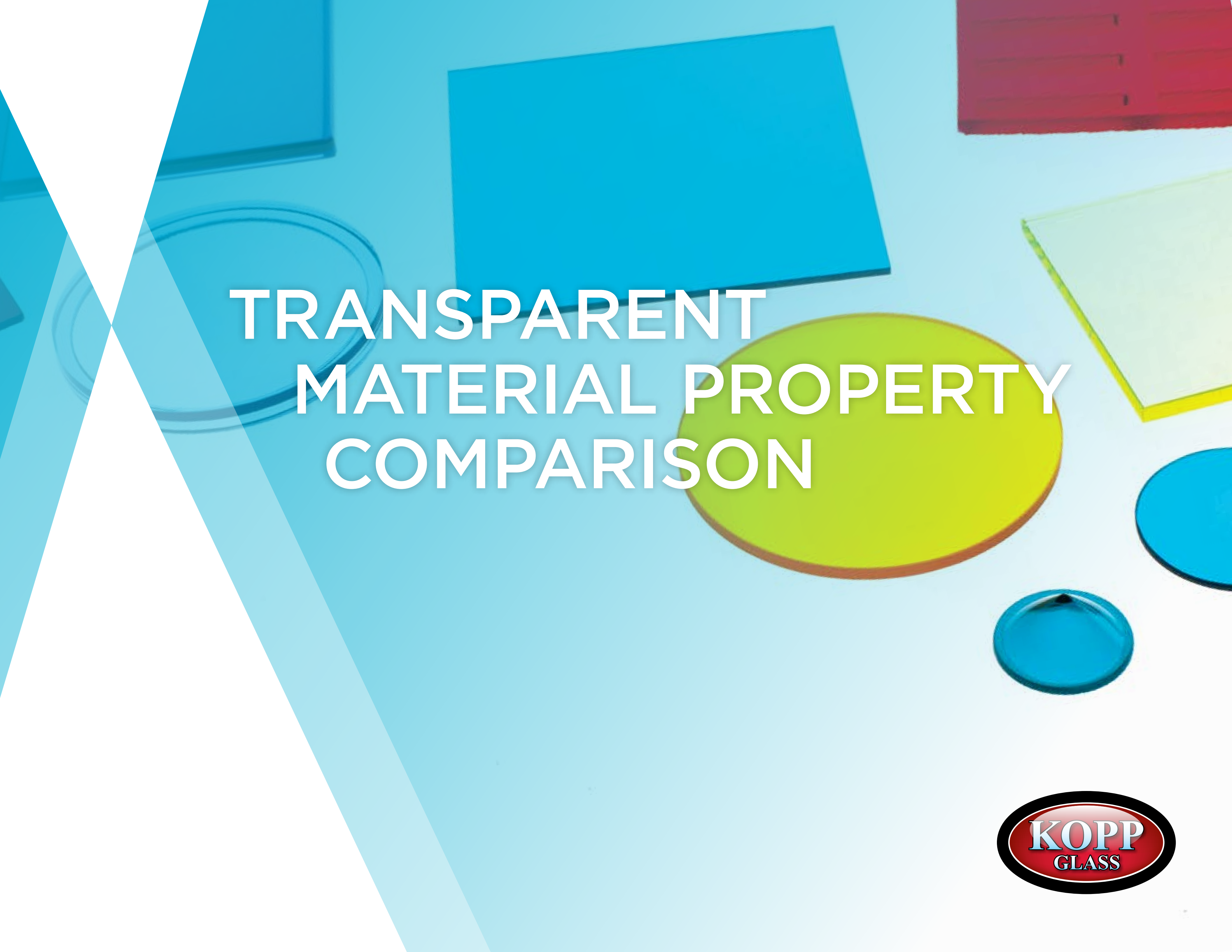
DESIGNING TO MEET CHROMATICITY SPECIFICATIONS

The lighting industry is rapidly evolving; in this fast-paced, competitive environment, it's critical to embrace new technologies, such as LEDs. Otherwise, you run the risk of obsolescence. But before making heavy investments into LED technology, their impact needs to be fully understood. You must evaluate all parts of the chromaticity equation—source, lens, and specifications—before you make the switch. You may need to change your lens, or even adhere to different specifications for varying light sources.

As shown in the previous section, when a light source is changed, there are no guarantees that the chromaticity will be the same—or remain within specification. The specifications you need to meet may be different as well. This is true of airport runway and obstruction lighting; if a fixture uses an incandescent bulb, it must meet SAE-AS25050A color requirements. However, when using a light source other than an incandescent or xenon bulb, the requirements will be outlined in Engineering Brief 67D.

Often, global lighting standards for chromaticity are used to ensure reliability, consistency, and safety in aerospace and transportation applications. These include specifications from the International Civil Aviation Organization (ICAO), the Federal Aviation Administration (FAA), the Institute of Transportation Engineers (ITE), the Association of American Railroads (AAR), and the Defense Logistics Agency (Mil) among others.

To make the transition to LEDs as simple and informed as possible, work with your suppliers. You'll be able to reap the benefits that LEDs provide while staying within specification.



TRANSPARENT MATERIAL PROPERTY COMPARISON

KOPP GLASS

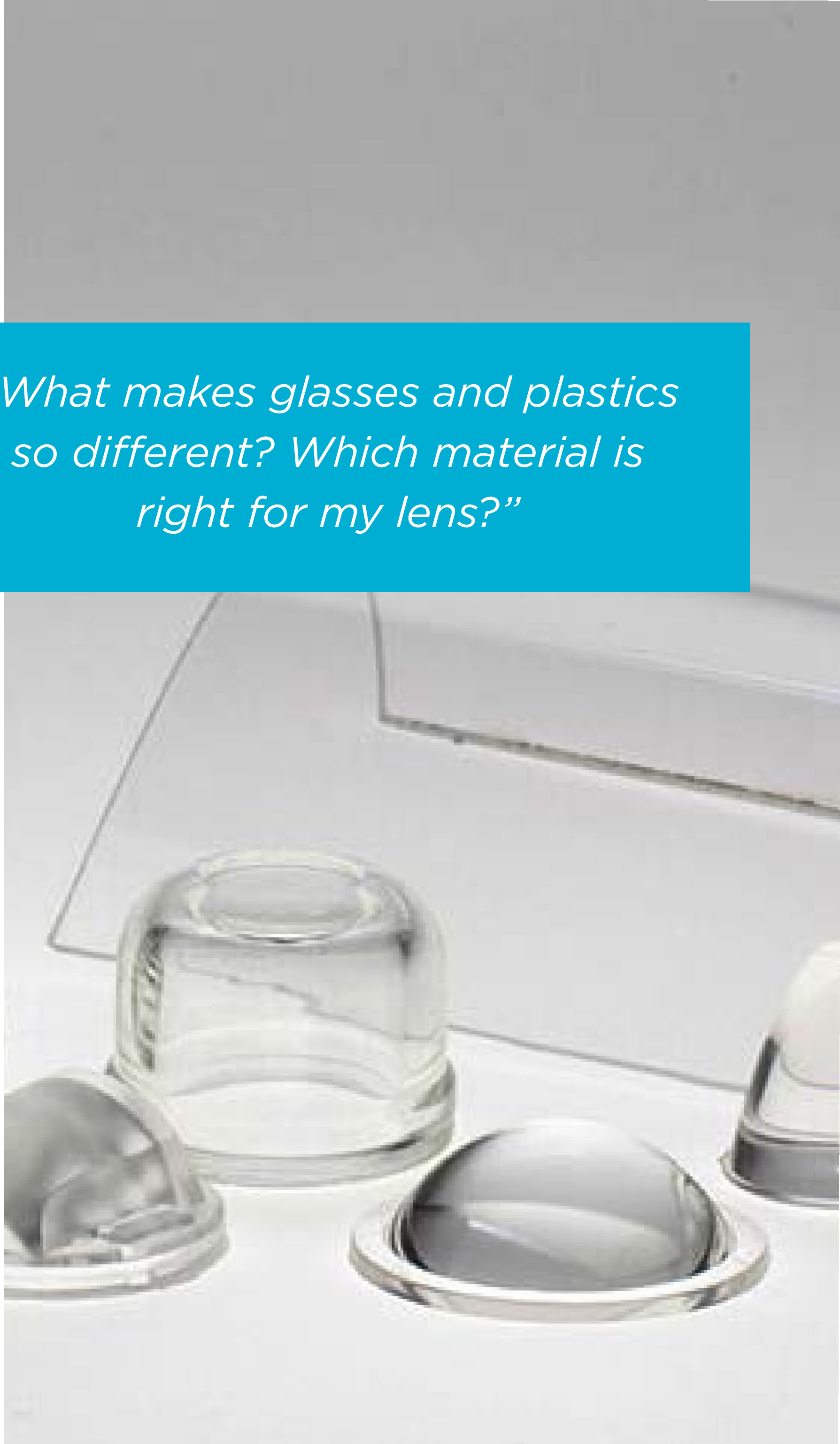
HOW TO CHOOSE THE BEST TRANSPARENT MATERIAL

There are many transparent materials out there for you to consider when designing a lens for a lighting application. Take a look at the image to the right; these different transparent materials all look fairly similar don’t they? You may be asking yourself “What makes glasses and plastics so different? Which material is right for my lens?” To answer these questions, you need to look not only at the material properties but also consider everything from your lens’ operating environment, the transmission requirements of your application, to the durability needs and expected lifetime of your part.

To help make your selection a little bit easier, we compared some of the mechanical, optical, and thermal properties of common transparent materials. The table on the following page contains generalized properties that are representative of common glass types, polycarbonates, optical silicone materials, and fused silica.

Keep in mind that properties will vary depending on the specific type and composition of the material that you select, and can often be tailored to meet the requirements of your application.

> *“What makes glasses and plastics so different? Which material is right for my lens?”*



OPTICAL + MECHANICAL + THERMAL

TRANSPARENT MATERIAL COMPARISON

Property	Unit	KOPP Borosilicate	Borosilicate	Soda-lime silicate	Phosphate	Quartz	Acrylic	Poly-carbonate	Silicone
Transmission	-	UV-nIR	UV-nIR	UV-nIR	UV-nIR	UV-nIR	UVA-nIR	Vis-nIR	UV-nIR
Refractive Index	-	1.49	1.51	1.52	1.55	1.46	1.49	1.58	1.41
Density	g/cm^3	2.33	2.23	2.52	2.86	2.20	1.2	1.2	1.5
Tensile Strength	MPa	60	70	40	65	70	70	75	11
Hardness	Moh's	5.5	5.5	5.5	5	6	3	3	2
Brittleness	-	Yes	Yes	Yes	Yes	Yes	No	No	No
Young's Modulus	GPa	65	65	70	60	72	3	2	0.002
Abrasion Resistance	-	High	High	Med	Med	Very High	Med	Med	Med
Impact Resistance	-	Med	Med	Med	Med	Med	High	High	High
CTE	E^{-7}/°C	43	33	80	100	5	720	650	2750
Annealing Temperature	°C	525	560	525	525	1040	*	*	*
Operating Temperature	°C	410	410	410	350	790	70	130	200
Chemical Resistance	-	High	High	Med	Low	Very High	Low	Low	Med
UV Resistance	-	High	High	High	High	High	Med	Low	High

GUIDELINES FOR SELECTING THE BEST TRANSPARENT MATERIAL

When it comes to transparent materials, there is no one-size-fits-all solution. Every lighting fixture has its own set of requirements and operating environment that will influence your selection. It is important to understand the temperature range, light output, and durability requirements for your optical lens. Once you know these operating conditions, you can choose a material that will best meet your performance needs. When selecting a material, you should:

1 **IDENTIFY**
Outline the operating parameters for your light fixture.

2 **PRIORITIZE**
List properties from most important to least important.

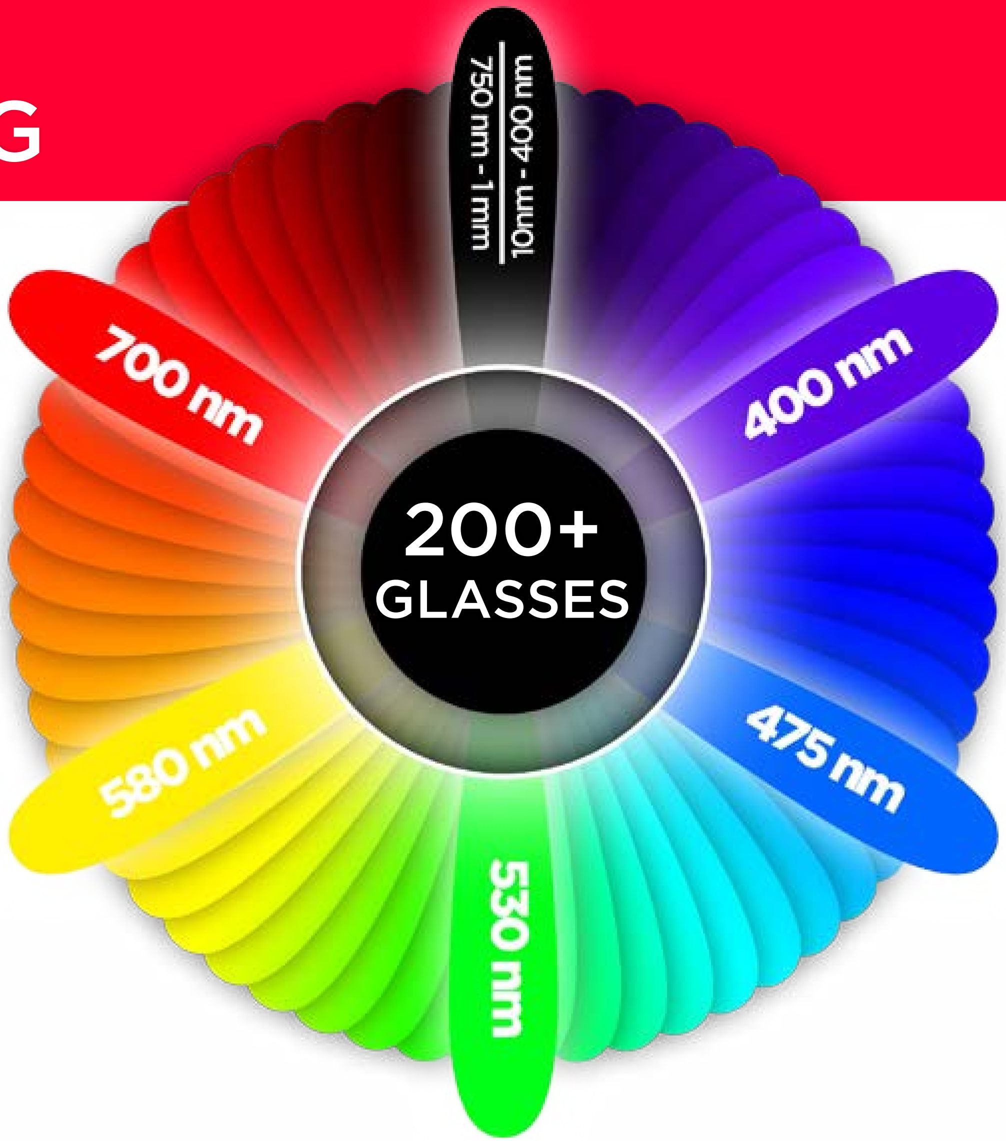
3 **ANALYZE**
Be aware of the advantages and limitations of each material.

4 **COMMUNICATE**
Work with a manufacturer as early as possible. They will be able to help you select a material that meets your performance requirements while helping you to optimize your design for manufacturing thus reducing costs.

EXPLORE
OUR GLASS CATALOG

Now that you've learned about the thermal, mechanical, and optical properties of glass, put your knowledge to the test and explore our glass catalog and glass spec sheets.

Our catalog includes more than 200 different glass compositions with spectral capabilities extending from the ultraviolet to infrared regions of the electromagnetic spectrum.



EXPLORE GLASS CATALOG

KOPP GLASS