HIGH REFRACTIVE INDEX PLASTIC OPTICAL MATERIALS

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Master of Philosophy

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Although, glass was the only lens material for over 600 years, today plastic lenses used for prescription eyewear and sunglasses requiring high abrasion resistance and high quality optical properties have been developed. These first plastic lenses, like CR-39® with a 1.498 refractive index, could not compete with the high index glasses known as flints.

High index plastic lenses are a new lens category, having refractive index from 1.54 (SOLA Spectralite) to even thinner 1.71 high index (Hoya Teslalide). Recently, much interest has been shown in development of new high index polymeric materials. Main target of all these efforts of course is the production of lenses with a very good optical performance. This performance includes high refractive index, low constrigence, good light transmission and UV absorption. Obviously, the outstanding factors defining this performance are refractive index and chromatic aberration.

The refractive index can easily be measured using a light source or a laser beam and computing the minimum deviation angle after the beam refraction through a prism of the material. The chromatic aberration can be determined by evaluating the optical performance of the material itself.

Nowadays, ophthalmic lenses of plastic have become very popular because they are inexpensive, lighter in weight and more resistant to shattering than glass. However plastic lenses generally have less surface hardness and wear resistance, especially materials such as polycarbonate, polyethylmethacrylate, and polyallyldiglycol carbonate which have to be improved by surface coatings and processes such as hard-coating.

At all times we have to consider that spectacle lenses have a psychological function. In that way, what is better for the consumer is not always what is best for the researcher. In order to check out this factor, is essential to look into the performance of these plastic materials in front of the consumer's eye.

Experimental work included testing and estimating refractive index and chromatic performance of various plastic lenses. On one hand, we had to verify and confirm the index of new materials in ophthalmic lenses market and on the other hand to compare different plastic materials about the chromatic dispersion, transparency and yellowness.

Keywords: Plastic lenses, high index, Abbe value, minimum deviation angle, optical performance.

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Chapter 1

General Introduction

1.1 Motivation and Scope of Work

Although the plastics industry has grown rapidly since its inception in the 1940s, the use of plastics as an optical material only really started to pick up in the 1970s and has had a much slower underlying growth than for the commodity industry e.g. packaging, closures, etc. In this industry the advantage of material consistency and uniformity, full three dimensional machining capability and rnass production are exploited to the full.

However, plastics in general are weaker and more costly than traditional materials and people still retain a 'bad image' of them because of their previous misuse. In the past, and to a certain extent today, plastic engineering components have been designed to directly replace components in traditional engineering materials, leading to poor performance and costly reproduction. For effective material substitution, the designer using plastics has to appreciate their benefits as well as their limitations. Today, designs are being produced that are not only unique to plastics but are also out-performing designs in traditional materials

Similar to the above, prejudices prevent consumers trusting plastic lenses. Although they realize benefits such as thinner and lighter design, they worry about clarity and transparency, and the most common question is if plastic lenses harm their eyes or obstruct their vision.

Furthermore, in recent years the industry has confused consumers rather than informing them. Optical properties, like refractive index and Abbe value are not clearly defined by manufacturers (i.e. a given "n" is n_d or n_e ?).

Many people ask themselves why high index plastic lenses must be always multicoated. Another similar question is why high index plastic lenses mainly are designed as aspheric? Is chromatic dispersion more or less affected by the refractive index? What is the relation between Abbe value and chromatic performance of these materials?

This study has been motivated by the above reasons in order to search and estimate the performance of new plastic high index materials and to compare with traditional lens materials.

Consequently, I had to investigate the basic optical properties, such as refractive index and chromatic dispersion. Refractive index deals with the power and 'refractivity' of a lens material. The higher the index, the thinner the lens can be produced. Constringence or Abbe value defines the clarity and transparency of optical material. Nevertheless, the high index materials have reduced Abbe value and as a result chromatic dispersion is higher and the optical performance of these materials is significant reduced.

Chapter 2

Plastic Materials

2.1. Introduction

Since plastics are lightweight, fragmentation-resistant and easy to be dyed in comparison with glasses, they have been developed rapidly in recent years for the application as optical elements such as □lenses□of spectacles and cameras (Kayanoki, 1992). However, the□refractive index□of the normally used resins is less than 1.50, so there is a need to develop new type of optical resins which possess high □refractive index□ and low dispersion (with less chromatic aberration). The best way to raise the □refractive index□of the optical resins is to introduce sulphur element into polymer structure, as the sulphur-containing resins have properties of high □refractive index,□ low dispersion, lightweight ness and good heat stability (Katsumasa,1997; Matsuda,2000).

Epoxy resins possess the advantage of chemical resistance, small shrinkage, good heat resistance and excellent mechanical properties. So, in recent years, they have been used as optical materials for such applications as optical disk matrix, □lenses□ and prisms (Oshima, 1991; Katsumasa, 1997). However, as the □refractive index□ of the conventional epoxy resins is lower, the applications of these resins as optical materials such as □lenses□ where high □refractive index□ is required are limited. So it is necessary to synthesize new optical epoxy resins, which possess high □refractive index,□ good mechanical and good heat properties (Zhanchen, 2000).

2.2. Background of Research - Patent Review

Diethylene glycol bisallyl carbonate resin, polymethylmethacrylate and polycarbonate have been generally known as resins to be used for the optical material such as plastic lenses. However, since the diethylene glycol bisallyl carbonate resin and the polymethylmethacrylate have low refractive indices of 1.49 to 1.50, when these resins are moulded into plastic lenses, they bring about a drawback that the centre thickness, edge thickness and curvature of the lens become greater as compared with those of inorganic optical glass lenses. Further, although the polycarbonate resin has a high refractive index of 1.58 to 1.59, it is liable to cause birefringence in moulding and thus is defective in optical homogeneity. Moreover, because polymethylmethacrylate and polycarbonate are thermoplastic resins of non-cross linked structure, the resins are fused during cutting or grinding and they cannot be considered satisfactory as materials for use in precision optical machinery, optical elements or ophthalmic lenses.

To remedy the above drawbacks of the thermoplastic resins, a method has been so far known which produces resins having a cross linked structure using ethylene glycol dimethacrylate as a cross linking agent, but the resin of such a cross-linked structure has low impact resistance.

Various characteristics are required for transparent synthetic resins as optical materials in addition to the above, and the refractive index is extremely important among them. For example, transparent synthetic resins having a high refractive index, when used as lenses, can be rendered thinner than materials having low refractive indexes to give the same focal distance.

Accordingly, it can reduce the volume of space occupied by lenses in optical assemblies thereby reducing the weight and minimizing the size of optical apparatuses. Furthermore, since transparent synthetic resins have excellent impact resistance as compared with inorganic optical materials such as glass, they can be considered also excellent in durability.

Further, there is also a method of manufacturing a resin of a crosslinked structure by using trimethylol propane tri(meth)acrylate, but the resin material cannot be put to practical use as the optical material since it has a poor transparency being prepared by curing with dispersed metal oxide hydrates.

In order to overcome the foregoing drawbacks, optical materials and optical moulding products using a resin of high refractive index have been developed, for example, for ophthalmic plastic lenses. For producing an optical moulding product such as plastic lenses by using a resin of high refractive index, a process has been adopted of using a cast polymerisation process .This involves casting, into a moulding die, a polymerizable ingredient having halogen atoms such as chlorine or bromine; a nitrogen atom-containing ingredient such as urethane; asulphur atom-containing ingredient such as thiol; or an aromatic ring or the like in the molecule, for example, vinyl monomer, prepolymer or (poly) condensation type monomer.

As materials for optical lenses, resins of high transparency such as acrylic resin, diethylene glycol bis-allylcarbonate resin (e.g. CR-39), polystyrene and polycarbonate have been used. (Kawai et al, 1996). Of these resins diethylene glycol bis-allylcarbonate, which is a thermosetting resin, is most extensively used as a material for spectacle lenses, due to the high transparency, low dispersabillity (quite high Abbe number) and very good heat and impact resistance, although a lens made of this resin has the disadvantage in that the refractive index is as low as 1.50 and its thickness is unavoidably greater than ordinary glass (refractive index 1.523). Further, this type of lens is inferior in abrasion resistance, although a method of coating the surface with an organosilane hard coat film is often used.

Optical lenses have been produced from the polymer of diethylene glycol bis(allyl)-carbonate (DEG-BAC) by thermal curing techniques. These techniques for polymerizing DEG-BAC to produce an optical lens, however, have several disadvantages and drawbacks (Lipscomb, 2001). One of the most significant drawbacks is that it takes approximately 12 hours to produce a lens according to this technique and therefore a lens-forming mould can produce at most two lenses per day.

Moreover, the thermal curing process employs a thermal catalyst so that the polymerizable mixture of DEG-BAC and catalyst will slowly polymerize even while refrigerated. The polymerizable mixture therefore has a very short shelf life and must be used within a short time or it will harden in its container (Lipscomb, 2001). Furthermore, the thermal catalysts utilized in these procedures are quite volatile and dangerous to work with requiring extreme care in handling.

Despite the above-mentioned drawbacks, DEG-BAC polymer exhibits desirable optical and mechanical properties. These properties include high light transmission, high clarity, and a high index of refraction, together with high abrasion and impact resistance. These properties in the past made DEG-BAC one of the leading monomers in the manufacture of high quality lenses, face shields, sun and safety glasses.

Neef(1978) described the formation of a plastic lens by disposing a lens forming material comprising a liquid monomer and a photosensitive initiator into a mould cavity defined in part between a pair of spaced apart moulds each having a lens forming surface facing the cavity and an outer opposed surface, and then directing rays of ultraviolet light against the outer surface of at least one of the moulds to act on the lens forming material in the cavity to produce a lens.

Hungerord and Mullane (1962) and Grandperret (1965) described a method of heating the lens forming material in a mould cavity by an external heat source. Mutzhas (1981) disclosed an apparatus for generating ultraviolet light having a wavelength in the range of 320 to 450 nm for hardening plastics.

Further, due to increasing demand to reduce the weight of spectacle lenses, materials of low specific gravity were actively being studied. For example, the Japanese Patent JP-A-2-238006 (cited in Kawai et al,1996) proposed acrylic resins of high specific gravity (1.31 to 1.35). JP-A-5-215903 (also cited by Kawai et al,1996) proposed a copolymer compound with a low specific gravity, but readily deformable in process of dyeing and hard coating, because of being low in heat resistance.

In 1983 Tarumi et. al. working for Hoya Lens Corp., invented a polyfunctional allyl monomer with excellent physical properties (Tarumi,1983), hardness about H (in pencil test), transmittance about 89%, refractive index 1.568 and reasonable Abbe number of about 34.

In Makino et. Al (1986) introduced an organic glass having a high refractive index and excellent physical properties. This material has as polymerisation initiator, di-isopropyl peroxydicarbonate, giving a refractive index of at least 1.55, according to the patent claim. Sakagami et al (1987) suggested an acrylic copolymer with refractive index 1.58 and Abbe value 28.

Subsequently Fujio et al (1989) presented a novel organic copolymer, a glycol allylcarbonate, that achieves a high refractive index. Furthermore, Suzuki et al (1995) described polystyrenes (refractive Index 1.58, Abbe number 31) and polycarbonates (refractive Index 1.58, Abbe number 30) as thermoplastic resins having high refractive index, but these resins have a large chromatic aberration due to low Abbe number, undesirable low heat resistance and polycarbonate has very low surface hardness.

As an alternative polycarbonate-based and polysulfone-based plastics have been proposed. These plastic materials have a high refractive index of about 1.60 but they have problems in a low light transmittance, deficient optical uniformity and colouring. Unlike CR-39 and other plastic lens materials, polycarbonate (LEXAN® resin) is injection moulded. Heated polycarbonate resin is forced into the lens mould under high pressure. The lens solidifies almost immediately and stresses introduced during moulding become locked permanently into the lens.

Various organic plastic materials have been proposed which are formed of cross-linked polymers, improved the above properties. For example, in 1992 two Japanese patents JP-A-4-202208 and JP-A-4-202209 (cited by Imura et al, 1996) disclosed a polymerizable composition having improved light transmittance, very good optical uniformity and adequate colouring ability.

In order to overcome the above disadvantages, metha-crylate/styrene resins were suggested(JP-A-62-246001, cited by Suzuki et al 1995,1996) .But these are high in the haze rate, low in transparency and heat resistance, and since these resins are thermoplastic resins, there is also a problem in edging ability.

A variety of ophthalmic lenses are described by Evans (2001). Such lenses may comprise a number of different types of materials ranging from inorganic to thermoset plastics, such as allyl diglycol carbonate sold under the (CR-39®), (trademark of PPG Industries, Inc.), to more recent formulations using thermoplastic materials, such as polycarbonate ("PC").

Commonly, polarizers used in hard resin thermoset lenses or polycarbonate thermoplastic lenses are based on polyvinyl alcohol ("PVA") films imbued with a polarizing material. For thermoset lenses, the polarizing film is either adhesively bonded to a lens substrate, or it is placed within a mould assembly or the liquid resin mixture placed around it (sequentially or simultaneously) to form the lens. For thermoplastic lens production, the film is commonly part of a multi-layer construction (often referred to as a wafer) designed for better rigidity and thermal stability. Often this construction involves joining or encapsulating the polarizer with other polymers such as PC or cellulose acetate butyrate ("CAB") by co-extrusion, lamination, calendering, etc.

There are several limitations with these approaches. The common PVA base film is temperature-sensitive and therefore difficult to process with thermoplastics. In thermoplastic lens manufacturing, for example, monomer or polymeric pellets are heated past their softening point (for PC, above 230^{o} C.), and injected into a mould form. Conventional polarizer films comprising PVA or similar polymers cannot withstand these temperatures. For instance, PVA has its glass transition temperature ("T_g ") between 90-95^{o} C., and softens with decomposition at approximately 200^{o} C. Therefore, not only will the PVA film lose its shape, but it will also lose physical integrity (colour, polarization efficiency, mechanical strength, etc.) at typical moulding temperatures.

In addition to the temperature-sensitive film, the dyes or polarizing agents commonly used therein are also temperature-sensitive (Evans, 2001). The temperature-sensitivity of the common polarized film and the dyes or polarizing agents used therein can cause severe non-uniformity or non-reproducibility, adversely affecting either the optical and cosmetic quality of a given lens or lot-to-lot consistency.

2.3. Plastic materials used for Lenses

Ophthalmic lenses of plastic material have become very popular because they are inexpensive, lighter in weight and more resistant to shattering than glass. However, plastic lenses generally have less surface hardness and wear resistance. Therefore, they are usually coated with abrasion resistant coatings.

Generally, plastic lenses have been made from a variety of conventional plastic materials, such as polycarbonate, polyethylmethacrylate, and polyallyl diglycol carbonate. For many decades, the principal optical plastic used for making eyeglasses has been CR-39®, a polycarbonate product of PPG industry.

CR-39® combines the optical properties of glass with the excellent mechanical, thermal, and chemical resistance properties of a thermoset material. It has a refractive Index of 1.498 and an Abbe value of 57.8. It has met to an adequate degree all of the significant requirements as to optical properties, strength, index of refraction, cure time, and compatibility with coating and tinting materials. Although improved over the years, its cost is relatively high, its processing properties require relatively long cure times and the index of refraction is only in a medium range.

Acrylic and polyesters have been given consideration over the years because they are inherently lower cost materials than the polycarbonate. But their properties suitable for spectacle lenses still do not meet current standards.

Lately, some commercial efforts have been reported pertaining to polyester casting materials for spectacle lenses, but these have had little success in the market. Instead, polyester based optical compounds have been offered on a commercial basis.

Commercial material	Refractive Index	Abbe value	Further process
PPG CR-39® monomer	1.498	57.8	....
HIRI® resin	1.56	?	....
PPG CR-307™ Transitions®	1.586	30	hardcoat
Optima Hyper Index 166	1.66	32	aspheric, hardcoat
Pentax Ultra Thin	1.66	32	hardcoat, AR coat
Seiko Super 16	1.6	33	hardcoat
Pentax 1.6	1.6	36	hardcoat
Zeiss Claret 1.6	1.6	36	hardcoat
Signet/Armorlite	1.56	36	hardcoat
Optima 160	1.6	37	aspheric, hardcoat
Essilor Thin&Lite	1.6	37	aspheric, hardcoat
Rodenstock Cosmolite 1.6	1.6	37	hardcoat
Sola Spectralite	1.537	47	hardcoat
Rodenstock Cosmolite	1.5	47	hardcoat
Essilor Thin	1.498	58	hardcoat

Table 2.1. Significant commercial plastic eyeglass lenses and the refractive index and Abbe value of the used plastic materials (*after PPG Ind.*).

2.4. Organic Glass

2.4.1. PLASTIC CR-39

Organic glass is a fully synthetic plastic material available in a vitreous state. It consists of macromolecular organic compounds, which do not follow any principle of periodic arrangement and are hence amorphous. In most cases, duromers are used to produce plastic lenses made of organic glass. Once they have been thermally treated after production, their shape can no longer be changed. A typical feature of the production process is that, when subjected to heat, many molecules (monomers) combine to form giant molecular chains (polymers) as a result of chemical reaction.

The well-known plastic CR-39 is one of the organic materials used for plastic lenses.

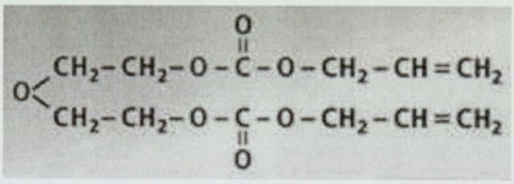


Fig. 2.1. A structural model of CR 39 (*after www.zeiss.com*).

2.4.2 PMMA OR POLY (METHYL METHACRYLATE)

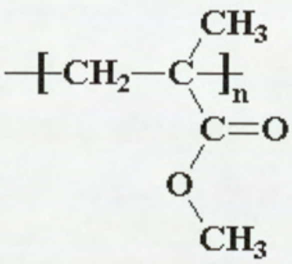


Fig.2.2. Poly (methyl methacrylate) (*after www.usm.edu*).

Poly (methyl methacrylate), also known as PMMA, is a clear plastic used as a shatterproof replacement for glass. The chemical company Rohm and Haas makes windows out of it and calls it Plexiglas. Ineos Acrylics also makes it and calls it Lucite. Lucite is used to make the surfaces of hot tubs, sinks, and the ever-popular one-piece bathtub and shower units, among other articles.

When it comes to making windows, PMMA has another advantage over glass. PMMA is more transparent than glass. When glass windows are made too thick, they become difficult to see through. But PMMA windows can be made as much as 33 cm thick, and they are still perfectly transparent. This makes PMMA a useful material for making large aquariums, whose windows must be thick in order to contain the high pressure of millions of gallons of water. PMMA is also found in paint.

PMMA is a vinyl polymer, made by free radical vinyl polymerization from the monomer methyl methacrylate.

Properties of PMMA

- hard, rigid, transparent
- softening point at 125^{o} C
- tougher than polystyrene but less tough than ABS (acrylobutylstyrene) polymer
- absorbs very little visible light but there is a 4% reflection at each polymer-air interface for normal incident light. Strictly speaking, the term "absorbance" applies only to radiation that is trapped and then usually re-emitted at a lower frequency (heat rather than light.) If you are standing on the other side of a polymer sheet, and you want light to come through the polymer so you can see what is on the other side, than the problem of reflectance must be considered. Since 4% of the light reflects back at the air/polymer interface, and then another 4% is lost at the polymer air interface, only 92% of the light is transmitted. PMMA is a polar material and has a rather high dielectric constant.
- a good electrical insulator at low frequencies but less satisfactory at higher frequencies
- good water resistance
- PMMA prepared by free radical polymerization is amorphous and is therefore soluble in solvents with similar solubility parameters such as benzene, toluene, chloroform, methylene chloride, esters, ethyl acetate, and amyl acetate.

- PMMA has good resistance to alkalis (sodium hydroxide, etc.), aqueous inorganic and dilute acids.
- PMMA has a better resistance to hydrolysis than PMA probably by virtue of the shielding of the methyl group.
- PMMA's outstanding good outdoor weather resistance is marketably superior to other thermoplastics.
- When heated above 200^{o} C, decomposition becomes appreciable and at 350-450^{o} C, a nearly quantitative yield of monomer is readily obtained. Thus, the recovery of monomer from scrap is feasible.
- Because it is a thermoplastic, it can be molten and moulded (at 100 to 150^{o} C) into any desired shape.
- a syndiotactic polymer can be polymerized. At lower temperatures, the stereochemistry of the polymer can be controlled by means of the solvent.

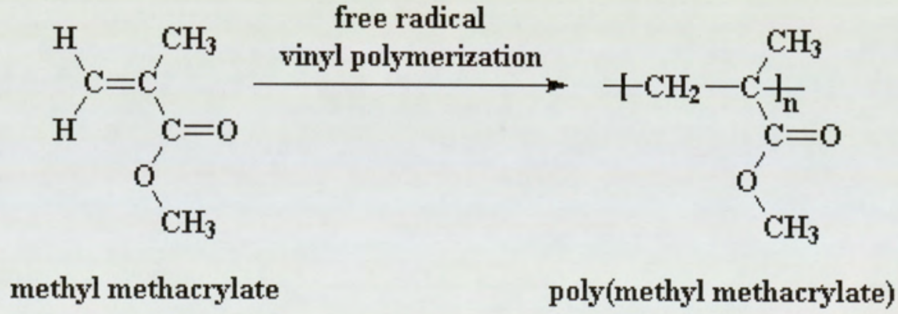


Fig.2.3. Polymerisation of PMMA (*after www.usm.edu*).

2.4.3. High Index Materials

High index lens materials are lighter in weight and thinner than their regular glass or plastic counterparts. This is of particular benefit in high prescriptions. High index lenses are made of materials that are denser, so the same amount of visual correction is taking place using less lens material than traditional plastic or glass requires. "*High index*" means that the lenses are constructed of a plastic or glass material that has a higher index of refraction.

2.4.4. High and Medium Index Plastics Offer Very Light Lenses

2.4.4.1. What Determines How Much a Lens Weighs?

For a given prescription, the weight of a lens is primarily determined by its size, thickness, and the weight of the material used. Frame selection determines the size of the lens while the refractive index of the material and the thinness of the surfacing determine the thickness of the lens. The weight of the material is given by its density. Since spectacle frames play a significant role, lens weight comparisons should only be made on edged lenses and density comparisons cannot provide an accurate representation of lens weights.

2.4.4.2. Total Spectacle Weight must be considered

Though high and medium index materials produce light lenses, the choice of the frame also plays an important role in determining the actual weight experienced by a wearer. Frame weights may vary from 10 grams for a rimless frame to 25 grams for a thick metal frame. Therefore, gain in frame weight could be as important as gain in lens weight. Frame selection is also a key to lighter spectacles for the patient. Considering an average frame weighing 15 grams, high and medium-index lenses offer about 10 to 15 percent reduction in total spectacle weight.

Lens Type	Refractive Index	Specific Gravity	Abbe Number
Air	1.0003	-	-
Water	1.333	1.00	-
Crown Glass	1.52	2.54	58
CR-39®	1.498	1.32	58
Polycarbonate	1.59	1.20	31
High Index	1.54 -1.66	1.21 -1.35	47-32
Diamond	2.417	3.52	-

Table 2.2. Comparison chart of Refractive Index, Specific gravity and Abbe number for different Materials. (*After Blackstock & Associates Optometrists*)

2.4.5. High Index material provides thin lenses

The refractive index of a lens material - its ability to bend light - plays a critical role in the creation of the power and thickness of a lens. For any lens design, the higher the index, the flatter the front and back curvature of the lens surfaces needed for a given optical power. As a result of these flatter curves, the thickness of the lens is automatically reduced. Furthermore, the nature of high-index plastic makes it possible to grind minus-power lenses to a thinner centre thickness than CR-39 while keeping the lens' impact-resistant properties. High-index plastic materials may be surfaced to a 1.5 mm centre thickness in the minus range and still satisfy impact-resistance standards, while CR-39 is generally surfaced to 2.0 mm in the minus range to respect these standards.

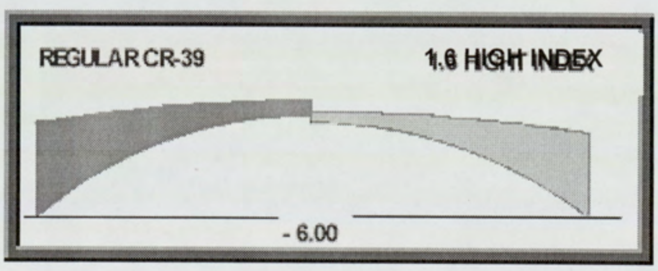


Figure 2.4. Comparison of edge thickness of –6.00 lens. (*After Essilor*)

2.4.6. Chromatism and High index Material

In general, the higher the refractive index of a material, the greater its tendency to disperse light and create rainbow contours of objects seen through a lens periphery. This chromatic dispersion exists in any lens, but is slightly more pronounced in high-index materials. However, it never occurs in the central part of a lens and can only be noticed in the periphery of very high-powered lenses made in very dispersive materials because a strong prismatic effect must be present for it to be noticeable.

The dispersive power of a lens material is characterized by its Abbe value, a number that is directly proportional to its chromatic quality. Abbe numbers for ophthalmic lens materials range between 60 and 30. For example, CR-39, which is considered a low chromatic material, has an Abbe value of 58. Polycarbonate, which is considered highly chromatic, has an Abbe value of 30. Abbe values for high- and medium-index plastic materials fall in the 35 to 45 range.

2.5. Introduction to plastic lens manufacture.

Generally, plastic lenses made from conventional plastic materials such as polycarbonate, poly (methyl methacrylate) and poly (allyl diglycol carbonate) are lighter in weight, higher in impact resistance and lower in cost, and can be produced more rapidly, than conventional glass lenses; and because of this superiority have found extensive use in eyeglasses, cameras, telescopes, etc. Nevertheless, they generally have much lower surface hardness than glass lenses, and this causes the defect that by contact or collision with another object or by scratching, their surfaces are susceptible to damages, which will result in impaired aesthetic appearances and markedly, degraded optical properties.

Various attempts have been made heretofore at removing such a defect of plastic lenses. For example, there is known a method, which comprises coating of the surface of a plastic lens with a silica-type glass material for vacuum deposition, a silicone compound or a melamine compound and then curing the coating to form a film having improved surface hardness. The plastic lens so produced, however, still has various defects. For example, the extent of improvement achieved of its surface hardness is not entirely satisfactory. The adhesion between the coated film and the plastic lens substrate is poor, and cracking is liable to occur in the interface, especially at high temperature and humidity. Furthermore, because the refractive indexes of the coated film and the plastic lens substrate differ from each other at the interface between them, the transmittance of high frequencies decreases and an optical strain tends to occur. Another disadvantage is that it is difficult to adjust the viscosity of the coating agent or control the coating conditions for the formation of a uniform coated film, and consequently, the cost rises or the efficiency of production is reduced.

2.5.1. POLYESTERS

The use of polyester as a material for ophthalmic lenses has been disclosed in various U.S. Patents. Sherr and Bristol (1968) proposed a composition in which polyester is combined with methylmethacrylate and styrene in order to produce an ophthalmic lens. Sherr (1970) disclosed a composition in which specific unsaturated polyester is combined with styrene and ethylene glycol dimethylacrylate (Wolpert,1983). Styrene raises the index of refraction up to 1.52 and ethylene glycol dimethylacrylate reduces the brittleness of the polymer.

Engardio et al (1998) descrribed a number of commercially available polyester resins, which are clear when cast and have a refractive index of approximately 1.56. The density of these various polyester systems are also quite low (on the order of 1.25 g/cc^3). These properties are superior to CR-39 (index 1.498 and density 1.32 g/cc^3).

Polyester resins can be manufactured using different composition to achieve a wide variety of physical properties (hard, soft, rigid, flexible and the like). Typical commercial polyesters include those made from a variety of glycols and acids. Resins made using phthalic anhydride are commonly called "ortho" resins. Those made using isophthalic acid referred to as "iso" resins. Typical iso resins have good scratch resistance but generally are slow to tint. Ortho resins, on the other hand, are generally more scratch-prone, but tint more readily. All of the unsaturated polymers have a propensity to polymerise somewhat non-uniformly causing internal optical distortion or visible “waves”. As previously mentioned, as the portion of styrene is increased, the index of refraction also increases, but also tends to cause formation of optical distortion within the lens.

2.5.2. Polycarbonate or "Poly C" lenses

Polycarbonates are transparent thermoplastics, formed by the condensation of polyphenols with phosgene. They are noteworthy for high-strength and temperature resistance, as well as good electrical resistance and stability. They are stable to water, dilute mineral and organic acids, and are insoluble in aliphatic hydrocarbons, petroleum ether, and most alcohols

Polycarbonate is a material, which has been called a thermoplastic "metal" because of its extremely high impact strength, even greater than that of aluminium. As strong as CR-39 is, polycarbonate can withstand over 5 times the impact energy (DeAngelis, 1997). Among polycarbonate's other advantageous properties over glass and CR-39 are its low specific gravity of 1.20, compared to that of crown glass (2.53) and CR-39 (1.31), and higher refractive index (1.586) compared to crown glass (1.523) and CR-39 (1.498).

Polycarbonate is a material that is considered highly chromatic, and has an Abbe value of 30, whereas Abbe values for high- and medium-index plastic materials fall in the 35 to 45 ranges. Polycarbonate Lenses are more impact resistant than glass, conventional, or high index plastic lenses, and this extra margin of safety makes polycarbonate lenses ideal for children or for safety purposes (sports or safety goggles).

Table 2.3. Properties of Polycarbonates.

Specific gravity	1.2	Volume resistivity ohm-cm	2,1 x 10^{14}
Tensile strength (lb/in^2)	8-10.000	Specific heat cal/^{o}C.g	0.30
Impact strength (lb/in^2) - Izod	2 - 3	Dielectric strength v/mil	400
Hardness R	118	Dielectric constant 6oc	3.2

Table 2.4. Edge thickness comparison (mm). The front base curve, centre thickness and lens diameter are held constant.

REFRACTIVE POWER	CR-39 RESIN	CROWN GLASS	POLYCARBONATE	HY-PER INDEX (1.595)
-2.00 D lens	4.0	3.9	3.7	3.4
-4.00 D lens	6.1	5.9	5.4	5.0
-6.00 D lens	8.1	7.8	7.1	6.6
-8.00 D lens	10.3	9.8	8.8	8.3

2.5.3. A Brief History of Polycarbonate

The use of polycarbonate material dates from 1957 when the material's use became widespread by Bayer, Ciba Geigy, General Electric and Dow Chemicals.

The material became popular for use in baby's milk bottles, furniture, helmet visors and as a cover for record players and food blenders. It also replaced toughened glass in safety lenses. A very important use today is in compact discs

Many millions of pairs of protective lenses have been sold all over the world, thanks to US FDA regulations that require the use of the material for safety reasons. Indeed, early polycarbonate lenses were seen as an inferior but with great impact resistance properties.

Nevertheless, this perception is changing rapidly now, as with better materials they are being seen as a more robust alternative to high-index lenses. This huge US success has not yet been mirrored in Europe, partly due to existing perceptions of the product, which have been based on older, inferior materials.

2.5.4. The Polycarbonate material

Polycarbonate, or specifically polycarbonate of bisphenol A (Fig. 2.5), is a clear plastic used to make shatterproof windows, lightweight eyeglass lenses, and such. General Electric makes this material and sells it as Lexan.

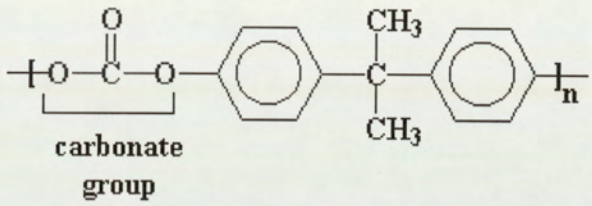


Fig.2.5. Polycarbonate (*after www.usm.edu*).

Polycarbonate gets its name from the carbonate groups in its backbone chain. We call it polycarbonate of bisphenol A because it is made from bisphenol A and phosgene. But for lenses we use a new polycarbonate. It is very different from polycarbonate made of bisphenol A. We make it by starting with next monomer (Fig.2.6).

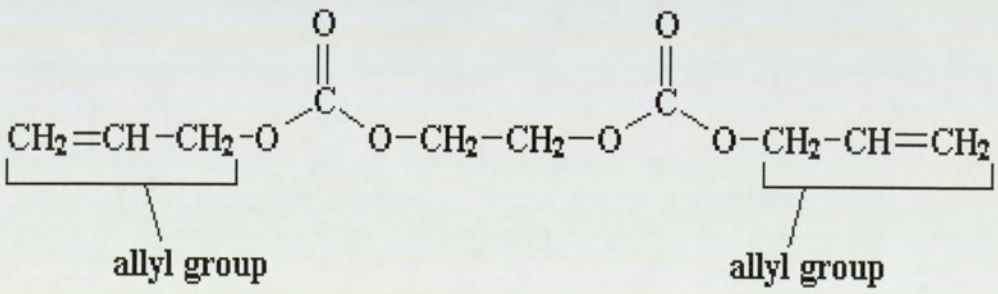


Fig. 2.6. Carbonate polymerisation (*after www.usm.edu*).

It has two allyl groups on the ends. These allyl groups have carbon-carbon double bonds in them. This means they can polymerize by free radical vinyl polymerisation. Of course, there are two allyl groups on each monomer. The two-allyl groups will become parts of different polymer chains. In this way, all the chains will become tied together to form a cross linked material that looks like this:

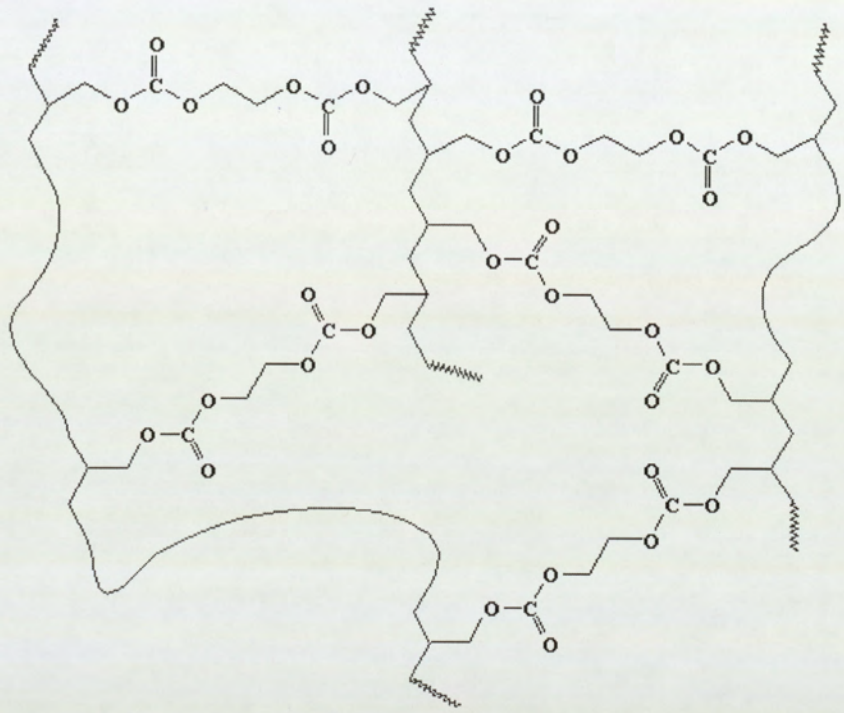


Fig. 2.7. The final structure of poly C (*after www.usm.edu*).

There is a fundamental difference in the two types of polycarbonate described here that I should point out. Polycarbonate of bisphenol A is a thermoplastic. This means it can be moulded when it is hot. But the polycarbonate used in eyeglasses is a thermoset. Thermosets do not melt, and they cannot be remoulded. They are used to make articles that need to be really strong and heat resistant.

2.5.5. The negative perceptions about polycarbonate.

Negative perceptions about polycarbonate lenses fall into three broad categories:

•about the material

It is a fact that as the index of a material rises, its scratch resistance falls. Fortunately, improvements in scratch resistance coatings, specifically designed for high-index lenses, make this an issue of the past and with coatings under development, polycarbonate lenses will be harder than CR39.

Without the proper tools Polycarbonate certainly is a difficult material to edge. The major manufacturers (for example Briot, Weco and Essilor) have machinery that is suited to polycarbonate.

It is true that very occasionally a patient will complain about poor peripheral vision with high-index materials with a low V value. Most lens manufacturers take this into account by limiting the range of available powers. Essilor experience in America shows that among the millions of wearers, only a tiny proportion is aware of any chromatism. Studies show that less than 1% of wearers mentioned vision problems.

• *about the lens geometry*

The first polycarbonate lenses from the USA came with front curves, which were close to best form lenses. Modern polycarbonate lenses are injection moulded, a process, which lends itself well to modern aspheric designs. As a result, the latest versions are especially thin and flat, whether single vision or varifocal.

• *about the surface quality*

The adhesion of multi AR coatings on polycarbonate lenses is now as good as on other substrates and there are strong reasons to use polycarbonate lenses with Multi AR coatings, like any high-index lens.

Table 2.5. A comparison between material, refractive index and Abbe number.

Material	Index	Abbe	Material	Index	Abbe
A.O./UK CR-39	1.53	58	Hoya Hi-Lux2	1.55	-
Essilor Thin	1.498	58	Hoya EYAS	1.60	40
Essilor Ormex	1.561	37	Pentax Ultra Thin	1.66	32
Essilor Ormil	1.6	36	Pentax 1.6	1.6	36
Zeiss Clarlet	1.6	36	Kodak Thin & Lite	1.562	-
Seiko SSV	1.67	32	Kodak White Lite	1.609	-
Seiko maxima	1.60	32	Rodenstock Cosmolite	1.6	37
Seiko Changes	1.55	45	Rodenstock Colormatic	1.52	52
Nikon Lite IV	1.67	32	Polycarbonate	1.586	30
Sola Spectralite	1.537	47			

	Trivex™	CR-39®	PolyC	Mid-Index	Hi-Index
ABBE	43-46	58	29	34-41	32-41
Scratch Resistance (tumble test)	0.6	1.0	0.2	0.3-0.5	0.5
*Impact Resistance (@ 1.0mm)	Pass FDA	Fail	Pass FDA	Fail	Some Pass
Z-87.1 (Draft) Impact Resistance	Pass	Fail	Pass	Fail	Fail
Specific Gravity	1.11	1.32	1.22	1.20-1.34	1.30-1.40
Refractive Index	1.53	1.50	1.59	1.53-1.57	1.59-1.71
Chemical Resistance	Good	Good	Poor	Good	Good

Table 2.6. Properties of Lens Material (*after PPG Industries, Inc.*)

	Trivex™	CR-39®	PolyC	Mid-Index	Hi-Index
Surfacing	Excellent	Very Good	Difficult	Good	Good
Tint Rate	Very Fast	Fast	Non-tintable	Average	Fast
Typical CT	1.0	1.8	1.5	1.5	1.5

Table 2.7. Processing of Lens Material (*after PPG Industries, Inc.*)

Chapter 3

Optical Properties of Plastic Lenses

3.1. Refraction of Light

Refraction (or bending of the light) occurs as light passes from a one medium to another when there is a difference in the index of refraction between the two materials, and is responsible for a variety of familiar phenomena such as the apparent distortion of objects partially submerged in water.

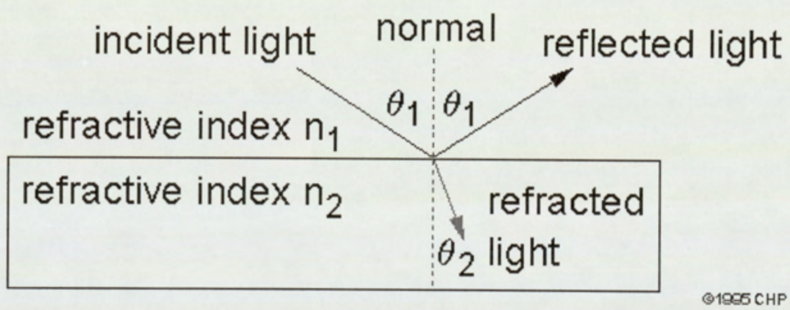


Fig. 3.1. Reflection and refraction of an incident light ray at a surface *(after www.asu.edu)*.

3.2. The Refractive Index

The ratio of the velocity of light in vacuum to the velocity of light in a medium is referred to as the medium's refractive index, denoted by the letter n. The velocity of light in a vacuum is 3.0×10^8 m/s or about 186,000 miles/s. For light, the index of refraction n equals the ratio of the velocities of light in vacuum (c) to that in the medium (v), that is

$$\boxed{n = {}^{c}/_{v}. \qquad (3.1)}$$

The path of light in air incident on and transmitted through a glass plate is shown in Figure 3.2. The angle of the incident ray to the normal is 45° and equals that of the reflected ray. The transmitted ray is refracted at an angle of 28° to the normal and exits the glass at an angle of 45° to the normal, an angle equal to that of the incident ray. This explains why, for example, the image we see through a flat-glass windowpane is unchanged from that seen through an open window.

Light incident normal to a glass plate does not change direction as the transmitted light continues normal to the surface (air/glass interface). The light is not refracted (that is, no change in angle) but the wavelength and velocity do change. Light does reflect as it encounters the air/glass interface (about 4% in this case).

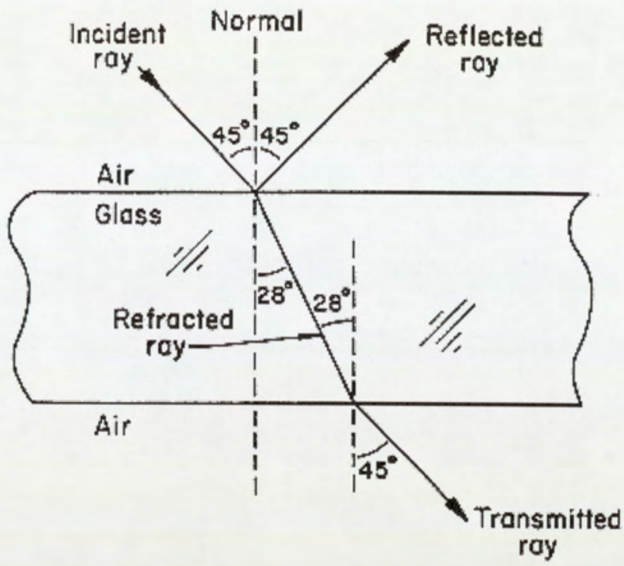


Fig. 3.2. Refraction through a glass plate *(after www.asu.edu).*

The paths of light traversing different media are reversible. The same relations are obeyed in Fig. 3.2, for example, if the light were incident on the bottom of the glass plate.

Refractive index is defined as the relative speed at which light moves through a material with respect to its speed in a vacuum. By convention, the refractive index of a vacuum is defined as having a value of 1.0. The index of refraction, (n), of other transparent materials is defined through the equation (4.1) where c is the speed of light, and V is the velocity of light in that material.

Because the refractive index of a vacuum is defined as 1.0 and a vacuum is devoid of any material, the refractive indices of all transparent materials are therefore greater than 1.0. For most practical purposes, the refractive index of light through air (1.0003) can be used to calculate refractive indices of unknown materials. Refractive indices of some common materials are presented in Table 3.1 below.

Material	Refractive Index
Air	1.0003
Water	1.33
Glycerine	1.47
Immersion Oil	1.515
Glass	1.52
Flint	1.66
Zirkon	1.92
Diamond	2.42
Lead Sulphide	3.91

Table 3.1. . Refractive indices of some common materials *(after www.asu.edu).*

When light passes from a less dense medium (such as air) to a denser medium (such as water), the speed of the wave decreases. Alternatively, when light passes from a denser medium (water) to a less dense medium (air), the speed of the wave increases. The angle of refracted light is dependent upon both the angle of incidence and the composition of the material into which it is entering. We can define the normal as a line perpendicular to the boundary between two substances. Light will pass into the boundary at an angle to the normal and will be refracted according to Snell's Law:

$$n_1 \times \sin(\theta_1) = n_2 \times \sin(\theta_2) \quad (3.2)$$

Where "n" represents the refractive indices of material 1 and material 2 and "θ" are the angles of incidence and refraction relative to the normal. There are several important points that can be drawn from this equation. When n_1 is greater than n_2, the angle of refraction is always smaller than the angle of incidence. Alternatively when "n_2" is greater than "n_1" the angle of refraction is always greater than the angle of incidence.

When the two refractive indices are equal ($n_1 = n_2$), then the light passes through without refraction. The index of refraction varies with the frequency of radiation (or wavelength) of light. This occurs with all transparent media and has been termed dispersion. As the wavelength of light increases, the refractive index decreases. It is the dispersion of light by glass that is responsible for the familiar splitting of light into its component colours by a prism.

When measuring the refractive index of a transparent substance, the particular wavelength used in the measurement must be identified. This is because dispersion is wavelength-dependent as illustrated in Table 3.2 showing dispersion of three independent wavelengths in various media.

Material	Blue (486.1 nm)	Yellow (589.3 nm)	Red (656.3 nm)
Crown Glass	1.524	1.517	1.515
Flint Glass	1.639	1.627	1.622
Water	1.337	1.333	1.331
Cargille Oil	1.530	1.520	1.516
Carbon Disulphide	1.652	1.628	1.618

Table 3.2. Dispersion of three independent wavelengths in various media.

3.3. Refractive Index And Dispersion

For lens designers, the most important difference among glasses is the index of refraction and dispersion (rate of change of index with wavelength). Typically, an optical glass is specified by its index of refraction at a wavelength in the middle of the visible spectrum, usually 587.56 nm (the helium d-line), and by the Abbe number (or v-value), defined as :

$$\boxed{v_d = (n_d - 1)/(n_F - n_C). \qquad (3.3)}$$

The designations F and C stand for 486.1 nm and 656.3 nm, respectively. Here, v_d shows how the index of refraction varies with wavelength. The smaller v_d is, the faster the rate of change is. Glass materials are roughly divided into two categories: crowns and flints. Crown glasses are those with $n_d < 1.60$ and $v_d > 55$, or $n_d > 1.60$ and $v_d > 50$. The others are flint glasses. The refractive index of glass from 365 to 2300 nm can be calculated by using the following formula:

$$\boxed{n = \left(\frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} + 1 \right)^{1/2} \qquad (3.4)}$$

Here λ, the wavelength, must be in μm, and the glass manufacturer gives the constants B_1 through C_3. This equation yields an index value that is accurate to better than $^{1}/1045$ over the entire transmission range, and even better in the visible spectrum.

3.3.1 Chromatic aberration

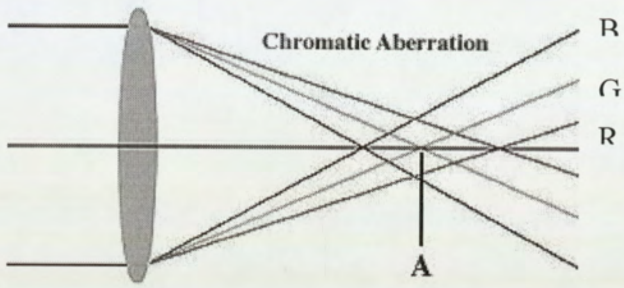


Figure 3.4. Chromatic Aberration. *(after www.fullerton.edu)*

Every optical material will separate white light into a spectrum given the appropriate angle. This is called dispersion. Some types of materials such as flint glasses have a high level of dispersion. Crown glass produces less dispersion for light entering the same angle as flint, and is much more suited for lenses.

In the illustration above, a simple uncorrected lens (assumed to be free of spherical aberration) has split the white light into red, green and blue. If you were to use the green focal point (A), the image would have a blue and red halo around each point. To make an achromat, two lenses are put together to work as a group called a doublet. A positive (convex) lens made of high quality crown glass is combined with a weaker negative (concave) lens that is made of flint glass. The result is that the positive lens controls the focal length of the doublet, while the negative lens is the aberration control.

The negative lens is of much weaker strength than the positive, but has higher dispersion. This brings the blue and the red light back together (B). However, the green light remains uncorrected (A), producing a secondary spectrum consisting of the green and blue-red rays. The distance between the green focal point and the blue-red focal point indicates the quality of the achromat. Typically, most achromats yield about 75 to 80 % of their numerical aperture with practical resolution.

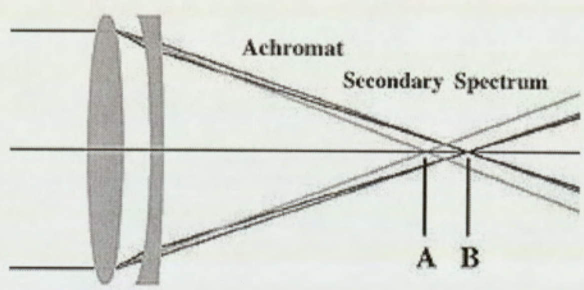


Figure 3.5. Secondary spectrum of an Achromat. *(after www.fullerton.edu)*

Unfortunately,such combinations are not practical for spectacle lenses, as the doublet construction would lead to a lens which was excessively thick and heavy. However, because of the reduced aperture of the eye/spectacle lens system caused by the pupil, and the considerable chromatic aberration exhibited by the human eye, longitudinal chromatic aberration (LCA) is not a significant problem in spectacle lenses.

For a single spectacle lens of power F and made from material of constringence V, the value in dioptres can be calculated (to a first approximation) from:

$$\boxed{LCA = F/V \qquad 3.5}$$

3.3.2 Transverse chromatic aberration

Transverse chromatic aberration (sometimes called lateral colour) is an effect where the lens acts like a prism, giving rise to dispersion of obliquely incident light. Because the prismatic effect of a lens increases with distance from the optical centre, TCA is a problem with oblique gaze through the edge of the lens.

TCA can be estimated (in prism dioptres) by an extension of Prentice's rule, hence for a distance of y cm from the optical centre of a lens:

$$\boxed{TCA = (F/V)y \qquad 3.6}$$

Part II. Experimental Work

Chapter 4

Measurement of Refractive Index

4.1 Refractive Index-Theoretical Approach

One of the important properties of light is the bending of its rays as it passes obliquely from one transparent medium into another. This effect is called refraction.

A light ray incident on an interface between two transparent materials is refracted at an angle determined by the incident angle, θ_1, (measured from the normal to the interface) and indices of refraction, n_1 and n_2, of the two materials. This relationship is known as Snell's Law, and can be written in the form:

$$n_1 \cdot \sin\theta_1 = n_2 \cdot \sin\theta_2 \qquad (4.1)$$

where n_1 and n_2 are the indices of refraction for the two media and θ_1 and θ_2 are the angles that the incident and transmitted rays make with the normal to the surface, respectively. The situation is shown in Fig. 4.1.

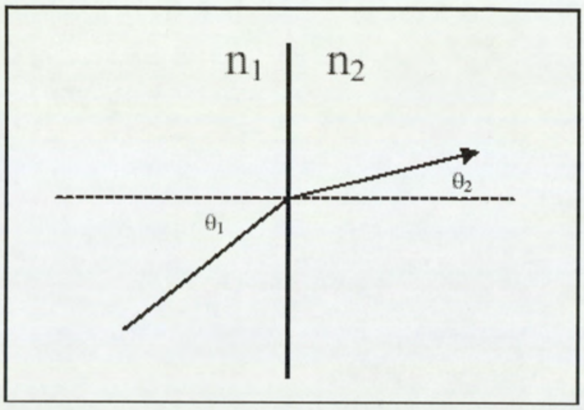


Fig. 4.1. Snell's law.

The index of refraction of a medium for any particular wavelength of light is the ratio of the velocity of light in vacuum to the velocity of light in the medium. The law of refraction, may be stated as:

$$\frac{\sin \alpha}{\sin \beta} = \frac{c'}{c} = \frac{n}{n'} \qquad (4.2)$$

where α is the angle of incidence and β the angle of refraction, n and n' are the indices of refraction for the two media. Note that the index of refraction n' for air is so close to unity that it can be set equal to one for all but the most precise calculations, and will result:

$$n = \frac{\sin \alpha}{\sin \beta} \qquad (4.3)$$

4.1.2. Refractive Index and Dispersion

For lens designers, the most important difference among glasses is the index of refraction and dispersion (rate of change of index with wavelength). Typically, an optical glass is specified by its index of refraction at a wavelength in the middle of the visible spectrum, usually 587.56 nm (the helium d-line), and by the Abbe v-value, defined to be:

$$v_d = (n_d - 1) / (n_F - n_C) \qquad (4.4)$$

The designations F and C stand for 486.1 nm and 656.3 nm, respectively. Here, v_d shows how the index of refraction varies with wavelength. The smaller v_d is, the faster the rate of change is. Glasses are roughly divided into two categories: crowns and flints. Crown glasses are those with $n_d < 1.60$ and $v_d > 55$, or $n_d > 1.60$ and $v_d > 50$. The others are flint glasses. The refractive index of glass from 365 to 2300 nm can be calculated by using the following formula:

$$n = \left\{ \frac{B1\lambda^2}{\lambda^2 - C_1} + \frac{B2\,\lambda^2}{\lambda^2 - C_2} + \frac{B3\lambda^2}{\lambda^2 - C_3} + 1 \right\}^{1/2} \qquad (4.5)$$

Here λ, the wavelength, must be in μm, and the glass manufacturer gives the constants B_1 through C_3. This equation yields an index value that is accurate to better than 1×10^{-5} over the entire transmission range, and even less in the visible spectrum.

Since refractive index is wavelength dependent, the deviation is wavelength dependent; the shorter wavelengths (higher refractive index), are "bent" more than the longer. For greater angular separation between two wavelengths, the prism should be made of a highly dispersive glass, that is one with a rapid change of index with wavelength. You can compare the dispersion of different glasses using the υ (or Abbe) numbers:

$$\boxed{\upsilon_d = \frac{n_d - 1}{n_F - n_C} \qquad (4.6)}$$

Where:

n_d = Refractive index at the Fraunhofer d line, 587.56 nm

n_F = Refractive index at 486.1 nm

n_C = Refractive index at 656.27 nm

$^1/\upsilon_d$ is called the dispersive power. A low Abbe number means a high dispersive power. In general, this translates to a greater angular spread of an emergent spectrum. Table 4.1 lists the Abbe numbers for some glasses:

Table 4.1 Abbe Numbers of some Prism Materials
(*after ORIEL Instruments Catalogue*).

Material	n_d	υ_d
Fused quartz	1.4585	67.8
BK 7	1.5168	64.17
Dense flint glass (Type F2)	1.620	36.37
Very Dense flint glass (Type SF10)	1.728	28.41

4.1.3. Minimum deviation Prism

When white light is shown onto a prism, the light is dispersed into its various spectral components. Given a prism of a material and a monochromatic light source, the light exits the prism bent away from its original direction of propagation by an angle called the angle of deviation (Walker, 2000).

By finding the angle of minimum deviation it is possible to accurately determine the index of refraction for the prism's material at the wavelength of the monochromatic light. Minimum deviation is reached when the deflected ray from the prism, which has been moving in one direction as you rotate the prism, stops and begins moving in the opposite direction. The point at which the beam stops is minimum deviation

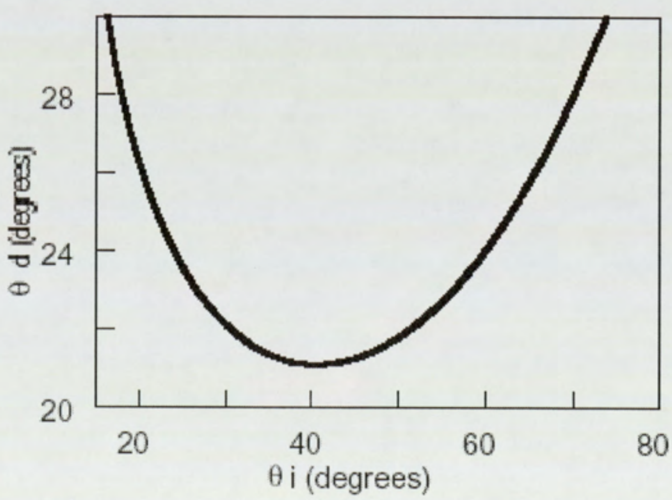


Fig. 4.2. A plot of the deflection angle vs. the incident angle is shown for an equilateral (n=1.3, A=60°) prism with the minimum in θd occurring at θi = 41° (*after. Walker 2000*).

A prism is a wedge-shaped transparent body, which causes incident light to be separated by colour upon exiting. The separation by colour occurs since different colours (corresponding to different wavelengths) of light travel at different speeds in a solid (although at the same speed, namely the speed of light, in a vacuum). As a result, refraction causes the wave fronts of different wavelengths to be deflected different angular amounts. Since "white" light is really a superposition of different wavelengths, the prism therefore has the effect of angularly separating the incident light by colour (Born and Wolf, 1980).

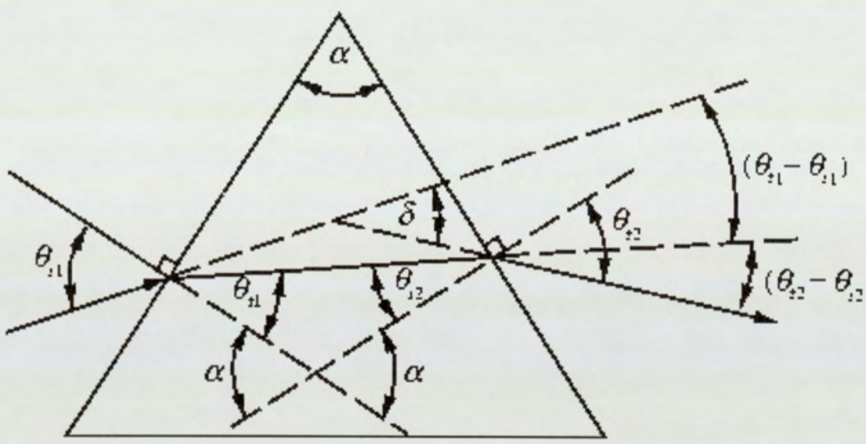


Fig. 4.3. Minimum deviation through a common prism (*after E. W. Weisstein*).

The most common type of prism is a simple isosceles triangular wedge, illustrated above. In the above figure, let the opening angle of the prism be **α**, let light be incident at an angle θ_{i1} to the normal, and let it emerge at an angle θ_{i2} to the normal on the other side. Call the angular deflection of the ray from its original path δ, and define some intermediate angles as shown above. The angular deviation δ caused by a prism is then given by:

$$\delta = (\theta_{i1} - \theta_{t1}) + (\theta_{i2} - \theta_{t2}) \qquad (4.7)$$

From the geometry,

$$\alpha = \theta_{t1} + \theta_{i2} \qquad (4.8)$$

so:

$$\delta = \theta_{i1} + \theta_{t2} - \alpha \qquad (4.9)$$

Let the medium surrounding the prism have index of refraction η_{α}, and assume it is air (or a vacuum), so $\eta_{\alpha} \approx 1$. Let as call the index of refraction of the prism *n*. Then from Snell's law and the above figure,

$$\sin\theta_{t1} = \sin\theta_{i2} \qquad (4.10)$$

It follows that

$$\begin{aligned} \theta_{t2} &= \sin^{-1}(\eta \sin\theta_{i2}) = \sin^{-1}[\eta \sin(\alpha - \theta_{t1})] \\ &= \sin^{-1}(\eta \sin\alpha \cos\theta_{t1} - \eta \sin\theta_{i1} \cos\alpha) \\ &= \sin^{-1}\left(\eta \sin\alpha \sqrt{1-\sin^2\theta_{t1}} - \eta \sin\theta_{i1} \cos\alpha\right) \qquad (4.11) \end{aligned}$$

Using Snell's law once again,

$$n \sin \theta_{t1} = \sin \theta_{i1} \qquad (4.12)$$

so,

$$\theta_{t2} = \sin^{-1}\left(\sin\alpha \sqrt{\eta^2 - \sin^2\theta_{i1}} - \sin\theta_{i1}\cos\alpha\right) \qquad (4.13)$$

$$\delta = \theta_{i1} + \sin^{-1}\left(\sin\alpha \sqrt{\eta^2 - \sin^2\theta_{i1}} - \sin\theta_{i1}\cos\alpha\right) - \alpha \qquad (4.14)$$

But since $n = n^{(\lambda)}$, we have therefore found that the deviation is different for different wavelengths. The minimum deviation with respect to the incidence angle θ_{i1} can be found by differentiating (4.14). However, it turns out to be more convenient to differentiate (4.9).

$$\frac{d\delta}{d\theta_{i_1}} = 1 + \frac{d\theta_{t2}}{d\theta_{i_1}} = 0 \qquad (4.15)$$

$$\frac{d\theta_{t2}}{d\theta_{i_1}} = -1 \qquad (4.16)$$

From (4.8),

$$\frac{d\theta_{i2}}{d\theta_{t2}} = -1 \qquad (4.17)$$

Differentiating Snell's law at each interface gives

$$\cos\theta_{i1}\, d\theta_{i1} = n \cos\theta_{t1}\, d\theta_{t1} \qquad (4.18)$$

and $$\cos\theta_{t2}\, d\theta_{t2} = n \cos\theta_{i2}\, d\theta_{i2} \qquad (4.19)$$

Dividing (4.18) by (4.19) and substituting (4.16) and (4.17) yields

$$\frac{\cos\theta_{i1}}{\cos\theta_{t2}} = \frac{\cos\theta_{t1}}{\cos\theta_{i2}} \qquad (4.20)$$

Using Snell's law,

$$\frac{1 - \sin^2\theta_{i1}}{1 - \sin^2\theta_{t2}} = \frac{\eta^2 - \sin^2\theta_{i1}}{\eta^2 - \sin^2\theta_{t2}} \qquad (4.21)$$

Since $\eta \neq 1$, this requires that

$$\theta_{i1} = \theta_{t2} \qquad (4.22)$$

$$\text{and therefore} \quad \theta_{t1} = \theta_{i2} \qquad (4.23)$$

The index of refraction can therefore be found by determining the minimum deviation angle δ_{min} experimentally, then using it to derive

$$n = \frac{\sin\left[\frac{1}{2}(\delta_{min} + \alpha)\right]}{\sin\left(\frac{1}{2}\alpha\right)} \qquad (4.24)$$

For a prism with normal dispersion, δ decreases with increasing wavelength (from violet to red, as in Fig. 4.4). If the direction of the incident rays is varied, it is found that the magnitude of the deviation varies also, but for one particular angle of incidence the angle of deviation becomes a minimum, δ_{min}.

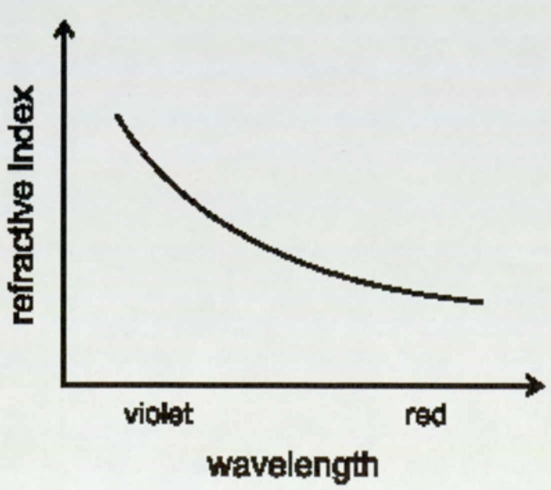


Fig. 4.4: Typical wavelength dependence of the refractive index for normal dispersion (*after Fundamental Physics Lab*).

Figure 4.5. shows the geometry of an incident ray on the surface of an arbitrary prism. As Jenkins and White (1957) point out, the deviation is given by the sum of the deviations at the two surfaces. To determine the refractive index, one needs to measure the prism angle, the deviation angle, and at two other angles the unavailable refracted angles. The minimum deviation method, makes the two angles equal; the normal incidence method makes one of them zero.

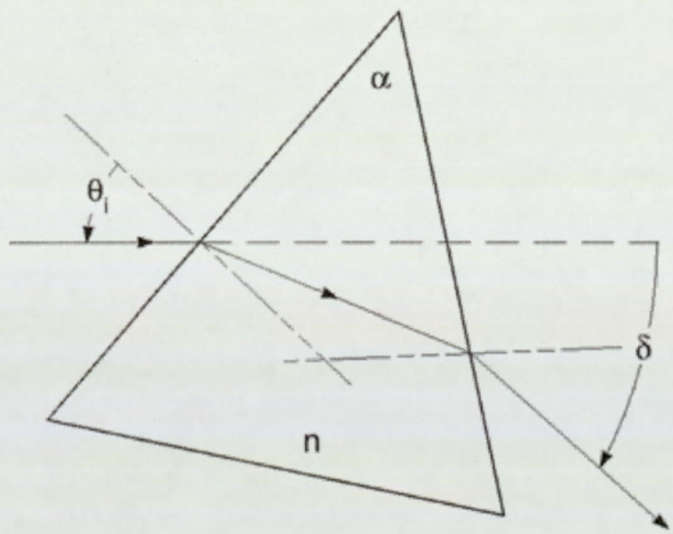


Fig. 4.5. The minimum deviation prism method.

Another view is that at minimum deviation the ray passes perpendicular to the perpendicular bisector of the prism (parallel to the base in most arrangements). The prism used in the normal incidence method may be considered as half the prism used in the minimum deviation method. (Fig. 4.7) The second method seems to be only slightly less accurate than minimum deviation.

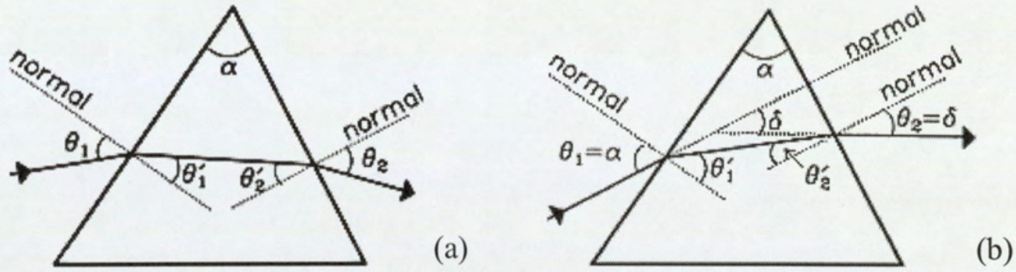


Fig 4.6. General ray diagram (a).The prism in the normal incidence method (b)

Billmeyer (1970). proposed a spectrophotometric method for the estimation of the refractive indices of transparent materials, from measurements of spectral transmittance. Because of serious loss of transmittance due to scattering, mainly in polymers and glasses, it was not so accurate.

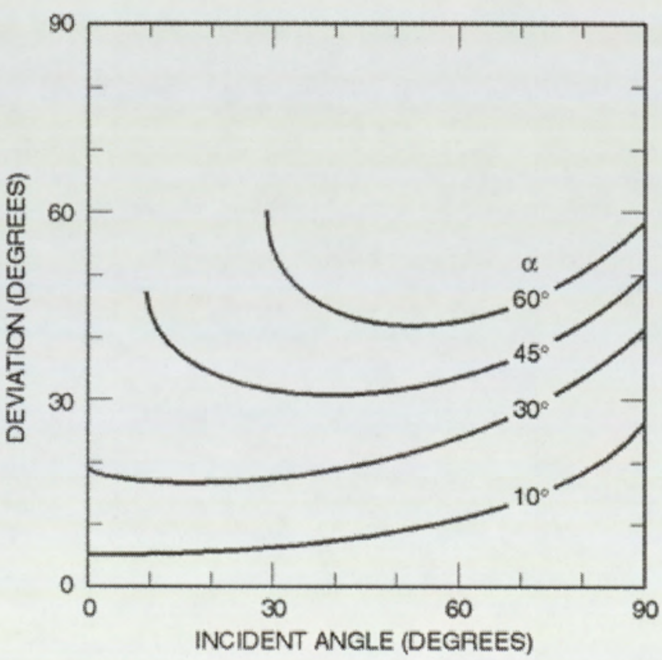


Fig. 4.7. The prism used in the normal incidence method may be considered as half the prism used in the minimum deviation method (*after Jenkins* and *White*).

Another method for measuring the refractive indices of prismatic materials was proposed by Waldenstrëm and Naqvi (1978). This method, called normal-to-the-base incidence, provides all the advantages associated with the classical minimum-deviation method, and is ideally suited for studying the colour dispersion of the prism material.

Nahm et. al. (1996) suggested a white-light interferometer (WLI) to measure the refractive index of some standard optical materials. They used a laser diode of a CD player at 780 nm, as light source and getting samples of 10 mm length they could determine accurately refractive indices up to four decimal places.

Shukla and Malacara (1997) used an interferometer in order to determine the homogeneity of optical materials and to measure the refractive index of simple lenses

4.2. Measurements and results

4.2.1. Prism alignment for index measurement

The centre line of the prism has been set up (as shown in Fig. 4.8). We have done this by putting the corners of the prism precisely on or near one of the scribed circles on the prism table. Its easy to find the zero angle of the apparatus by removing the prism and adjusting the telescope to see the source directly and to centre the bright line on the cross hairs in the eyepiece and read the angle from the table. The prism was placed as shown and the prism mount and the telescope was rotated to find the minimum angle of deviation.

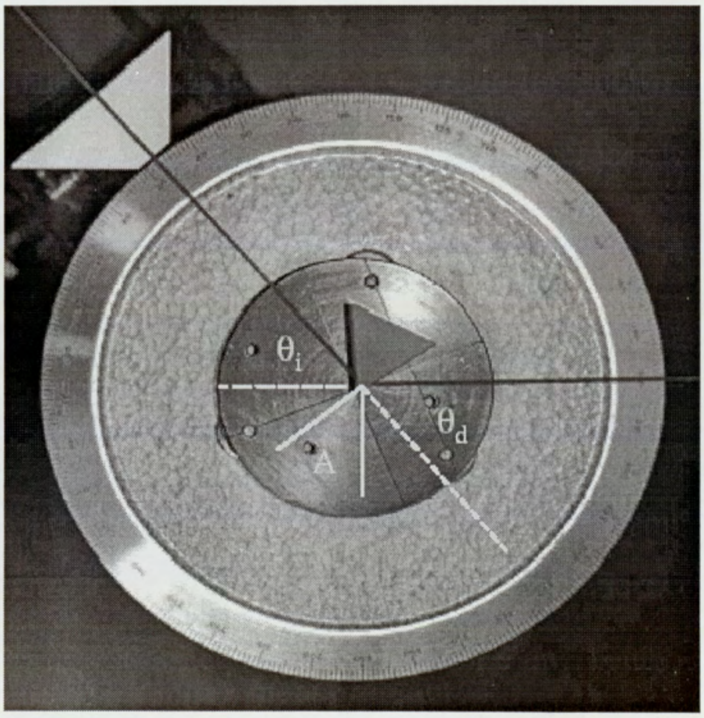


Fig. 4.8. Prism alignment (*after Walker, 2000*).

A rotation stage and a HeNe laser set up on an optical rail (Fig. 5.9). The prism placed on the stage such that its apex is at the stage's centre of rotation (Fig.4.8).

The prism was rotated so that its face was at normal incidence to the laser. The stage is rotated until the minimum deviation angle has reached as indicated by the HeNe deflection (Fig. 4.9). The stationary position was marked (e.g. a millimetre paper on the wall in Fig. 4.9) with tape and calculated the angle of incidence for the prism. The deviation θδ was determined, for the laser beam in the prism at minimum deviation using the law of reflection. Using the angular deviation, θδ, of the refracted beam and the known apex angle, A, with the equation for minimum deviation we determined the index of refraction of prisms of different materials at 632.8nm.

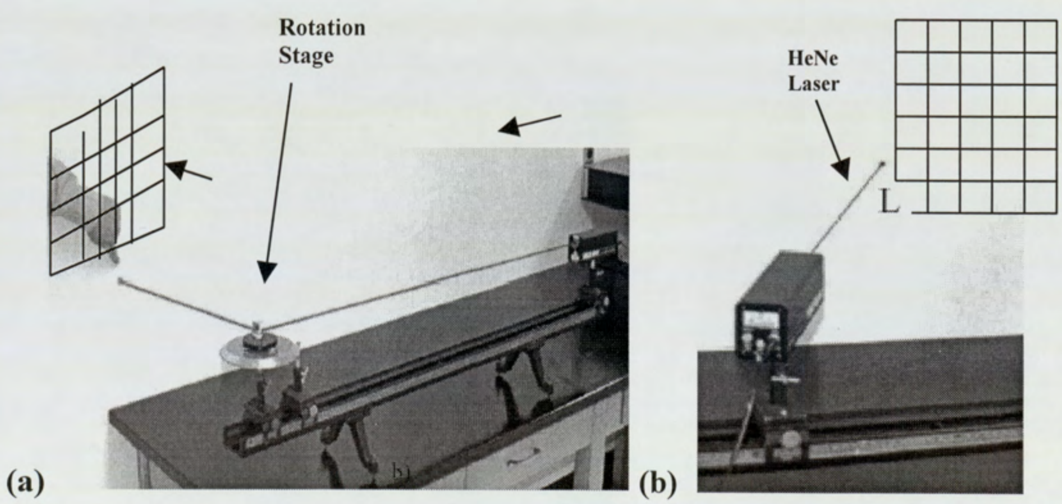


Fig 4.9. (a) Rotation stage and HeNe laser on optical rail

(b) Viewing scattered HeNe 632.8 nm light (L) from the wall.

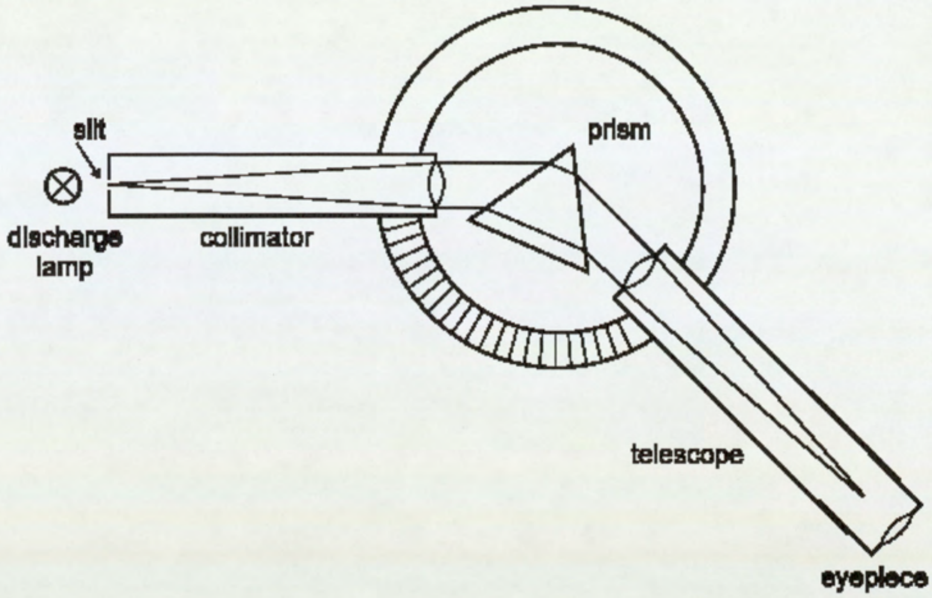


Figure 4.10. Prism spectrometer for the determination of the deviation angle δ_{min}. (*after Yale Physics Lab*)

The measurement is repeated in order to get an estimate of the uncertainty in the index of refraction. The prism is removed between each measurement in order to randomise the possible alignment errors. The “zero” was checked after each measurement to ensure that it hasn’t moved. One can use a prism spectrometer (Fig. 4.10) or even an auxiliary collimator to allow measurements of small angles of incidence (Fig. 4.11)

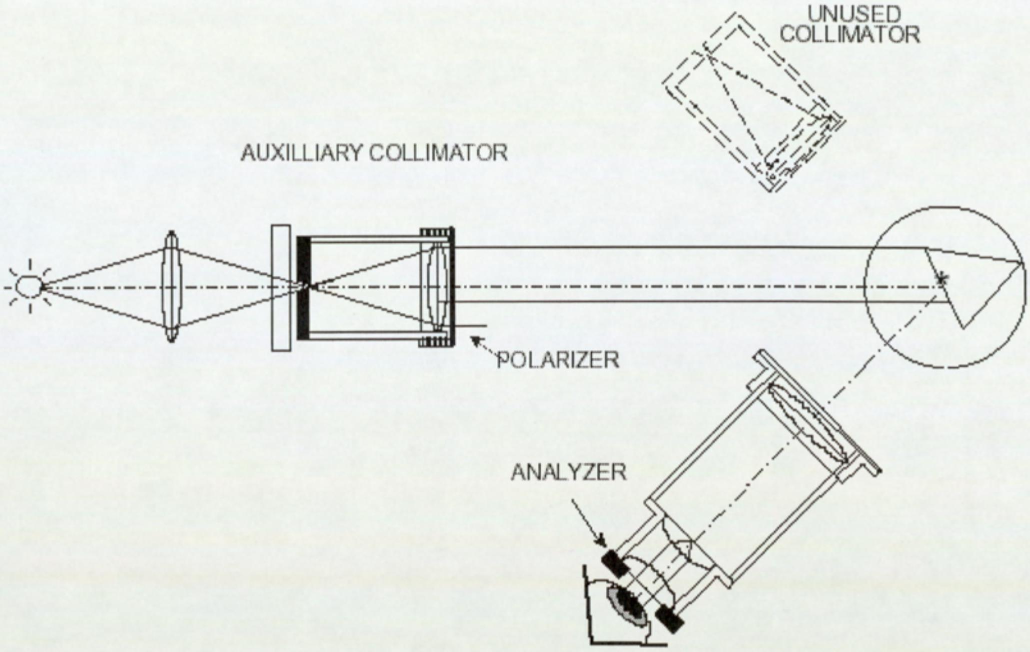
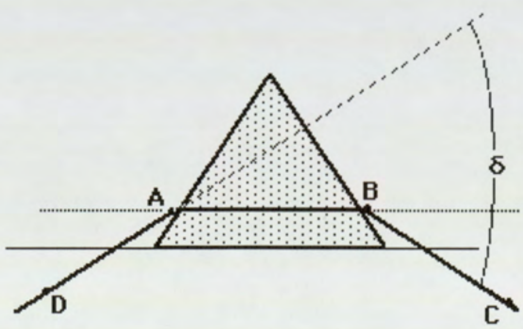


Figure 4.11. Use of auxiliary collimator to allow measurements at small angles of incidence (*after Yale Physics Lab*).

4.2.2. Measuring the Refractive Index

By grinding and polishing an optical material into a prism shape and using it in a spectrometer to give an angle of minimum deviation, it's easy to find the refractive index of it. The method is time consuming and expensive, as a high degree of flatness is required on the incident and emergent faces for good accuracy (Fincham and Freeman, 1974).

To determine the refractive index of the prism it is necessary to measure the angle of minimum deviation. The prism, which usually has a refractive angle of about 60^{o}, is placed with one refracting face making an angle of about 45^{o} with the beam. To find the position of minimum deviation the prism is slowly rotated in the direction that causes the image to move towards the undeviated direction. Following the image a position is found where the image commences to move in the opposite direction. The difference of the readings gives the angle of minimum deviation d and the general formula to compute the index is:



$$\frac{n_{prism}}{n_0} = \frac{\sin \frac{1}{2}(\sigma + \delta)}{\sin \frac{1}{2}\sigma}$$

Fig. 4.12. Measuring the refractive index using a prism

4.2.3. Experimental procedure

In order to achieve accurate measurement of refractive index of the majority of materials, used for plastic lenses and to consider the results to the market proposed indices, we settled on the experimental arrangement, as in Fig.4.13.

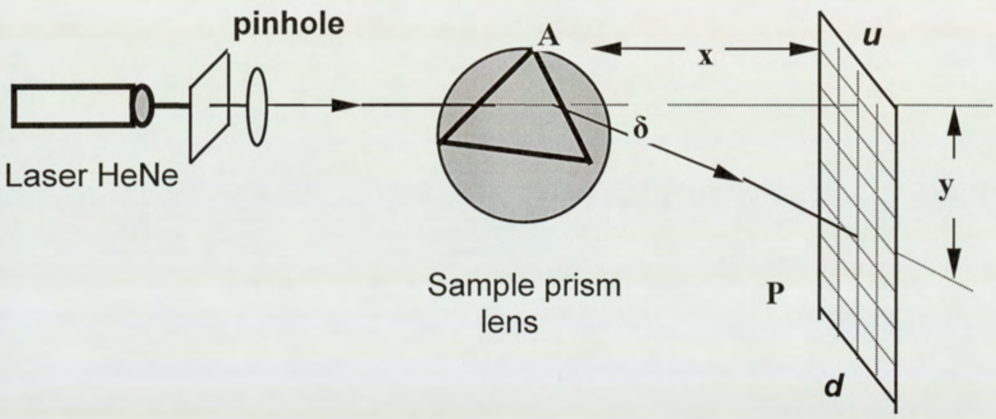


Figure 4.13. Schematic representation of refractive index measurement. After measuring "x" (distance between sample lens and P) and "y" (distance of deviated laser spot on P), calculating tan δ the deviation angle is then computed.

A HeNe laser beam at wavelength of 632.8 nm was used in order to produce monochromatic light. To verify and confirm the wavelength of Laser beam a crown-prism (by Oriel Instr.,) with known "n" values was placed on the rotating disk and measured. A system of pinhole and lens collimator was used to minimise the laser spot diameter at panel P. The sample prism is placed on a rotated table and with one refracting face in position to make an angle of about 45° with the beam. After every recorded measurement prisms were extracted and settled again, in order to minimize the possibility of fault alignment. To find the position of minimum deviation the prism is slowly rotated in the direction that causes the image to move towards the undeviated direction (u). A position is found where the image commences to move in the opposite direction (d). Considering that the prism angle (A) is about 60° and computing from tan δ the deviation angle (δ), we can easily figure out the index of sample prism material.

The next table shows some results after measuring sample prisms. The main drawback on this endeavour was the difficulty in grinding flat and making a very good polish on the prism refractive faces.

Table 4.2. Results of calculated material refractive indices at 632.8 nm.

Sample type	Calculated n_{632}	Market "n_d"	Deviation angle	Commentes
CR-39®	1.50	1,49	37° 04'	
Nikon Hi	1,62	1,60	48° 65'	
HIRI®	1,55	1,56	44° 50'	
Crown Glass	1,56	1,52	54° 54'	
Plexiglas	N/A	1.51	N/A	

4.2.4. Discussion

As mentioned before the first results seem not to be not very accurate. It was obvious that the refractive faces of sample prisms were not very well polished.

Many investigators have studied the optical performance of prisms. Adams at al. (1971) compared the optical distortions between conventional glass and CR-39 (Fresnel) prisms with different base curves of the lens. They showed that conventional glass is slightly better than similarly CR-39 prisms about change of magnification. In this experiment chromatic dispersion did not affect the results due to the use of a monochromatic laser beam. Veronneau-Troutman (1978) showed that reflection from the prism facets induced a second image reflected toward the base of the prism, and Flom and Adams (1982) indicated that diffraction of light by the grooves of the prism produce light dispersion.

So the next step was to make better polished surfaces. All the prisms had to be polished not only by a grinding machine but also by hand. At first special polishing machines (as for prescription lenses) were used, and next special pads (in different thickness) for finishing with powder for this purpose. These were polished by hand movements (left to right) for more than 1 hour and then again to finishing brush for 2 or 3 minutes in order to make the surface as smooth as possible. The new results were more accurate but still there was (probably) insufficient flatness of the refractive surfaces.

Nevertheless, as Werner (1968) describes in a method of high precision refractometry, Tilton (1929,1935) faced the problem using the method of minimum deviation on a prism. Aside from operational errors, errors arising from inhomogeneities in the sample, errors due to inadequate preparation are still exist instrumental and environmental errors. In the next table Werner displays an Average Refractive Index error (dn_{ε}) for 0.2 sec of arc angles measurement and for different refractive indices.

Table 4.3. Average Refractive Index Errors (dn_{ε}) for 0,2 sec of arc Error in Angle Measurement in Minimum Deviation Refractometry*

n	A = 45°	A = 50°	A = 55°	A = 60°
1.50	0.72	0.68	0.64	0.62
1.60	0.88	o.83	0.79	0.77
1.70	1.03	0.97	0.94	0.92
1.80	1.20	1.14	1.10	1.10
1.90	1.36	1.30	1.30	1.30

*Values are to be multiplied by 10^{-6} (*after Werner, 1968*)

The orientation of the prism into the position of minimum deviation is inherently troublesome and imprecise. Every error in orientation produces a positive error in the deviation angle, so that the average error for repeated settings must always differ from zero. According to Werner's work, this is unavoidable, but predictable error ranges from approximately 5.0 min of arc for an index 1.5 and a refractive angle 45° to approximately 3.5 min of arc for an index 1.9 and a refractive angle 65°.

Finally, considerable factors influencing the measurement are also the environmental conditions (temperature, pressure and humidity), as well as the sample temperature.

Chapter 5

Chromatic Performance of Plastic Materials

5.1. Visual Acuity (VA)

To measure the clarity of vision or to assess the visual system's ability to resolve detail, visual acuities should be taken on every patient. Visual acuity depends on the eye's ability to focus images on the retina, the integrity of the eye's neural components, and interpretation of images by the brain.

In the same way we can evaluate the vision quality through different materials (different index and Abbe values) by measuring the vision acuity of same subject looking every time through a lens made of different material.

Adoption of a standard procedure for the measurement of individual differences in acuity, which gives valid and precise measurements and at the same time is simple and practical, requires consideration of the following: selection of the most suitable type of test objects, specification of the range and gradation of the sizes of test objects required, standardization of the brightness of test object and background, as well as other variable factors in the test procedure (Sloan, 1951). Several suggestions have been made for designing standardized VA charts (Bailey and Lovie, 1976; NAS-NRC Committee on Vision, 1980). These include having the same number of letters per row, uniform letter size progression, and constant inter-letter and inter row spaces and the use of letters with nearly equal legibility. Five letters per row has been considered to be most practical (Bailey and Lovie, 1976; Ferris et al., 1982; Strong and Woo, 1985). Letter sizes that follow a geometric progression whose ratio or multiplier is equal to 0.1 log unit or multiples of 1.2589 have been recommended (Bailey and Lovie, 1976;

Westheimer, 1979; NAS-NRC Committee on Vision, 1980). Inter-letter space equal to the breadth of each letter in the row and inter-row space equal to the height of letters in the subjacent row have been recommended (Bailey and Lovie, 1976; NAS-NRC, 1980) and have been used in the design of standard VA charts (Bailey and Lovie, 1976; Taylor, 1978; Ferris et al., 1982; Strong and Woo 1985;).

According to McMonnies and Ho (2000), clinical comparisons of visual acuity between right and left eyes have reduced validity when the same chart is used for both eyes, because the second eye result may be improved by memory of the just completed assessment of the first eye. Similarly, the validity of test - retest assessment of the same eye may be reduced by the introduction of memorisation effects, when the same chart is used on each occasion (Arditi and Cagenello, 1993). Ideally a second test should be completed using an equivalent version of the original chart construction. For example, an equivalent chart can be one that uses the same design but different sequences of the same letters (Raasch et al., 1998). Lack of equivalence of the same nominal lines for different versions of the same chart design may occur when chance combinations of easier or harder letters in particular lines give rise to significantly different total line difficulty (Ferris et al., 1982; Strong and Woo, 1985).

5.1.1. Two common charts for taking VA's

- **Snellen acuity chart –** This is the familiar chart with the single large optotype at the top. It is designed to test the size of letter that a person can read at a standard testing distance of 6 metre or 20 feet. Each letter on the chart has been given a specific size and is notated by a certain number. The bigger the number, the bigger the letter on the chart. 'Normal' acuity of 6/6 or 20/20 is based on the resolution of a gap size of one minute of arc. Thus as one minute subtends 1.75 mm at 6 m, charts are usually constructed on a 5 x 5 grid so that the total height of a letter or symbol will be 8.75 mm.

The visual acuity test measures the smallest letters that you can read on a standardized chart at a distance of 6 metres (20 feet). Visual acuity is expressed as a fraction. The top number refers to the distance you stand from the chart. This is usually 6 m. / 20 feet. The bottom number indicates the distance at which a person with normal eyesight could read the same line you correctly read. The recorded ratio always shows the test distance (in metres or feet) as the numerator and the letter size as the denominator. For example 6/6 (or 20/20) is considered normal. 6/12 (20/40) indicates that the line you correctly read letters at 6m (20 feet), could be read by a person with normal vision at 12 m. (40 feet).

VA = test distance in metres or feet / letter size

This means that a person with 6/6 (20/20) vision can see the bottom 6 letter at a distance of 6 metres. A person with 6/12 (20/40) vision can read the 6 letter at a distance of 12 metres (40 feet), and so on...

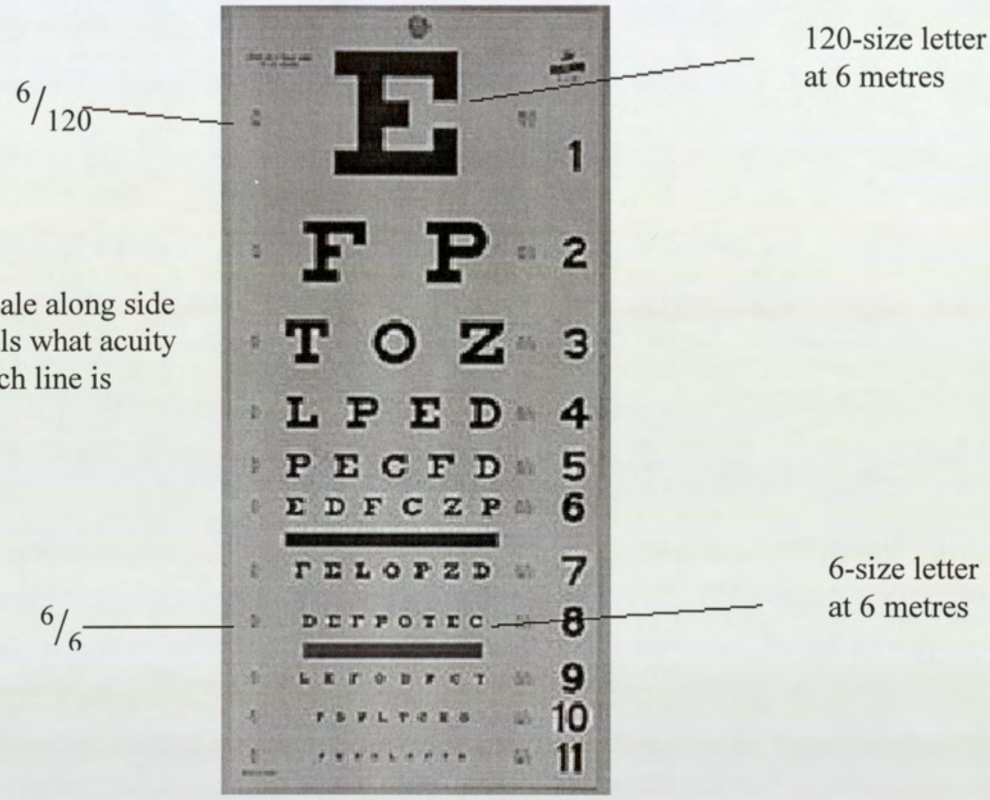


Fig. 5.1. Snellen Acuity Chart

➢ **Bailey-Lovie acuity chart** – This chart is used less frequently than the Snellen chart. This chart differs from the Snellen in that the standard testing distance is 3 metres, instead of 6 metres. Doubling the VA's as described above will put the VA's in the familiar 6/6 format. Another difference is that the Snellen chart has an increasing number of letters per line as the letters get smaller. The Bailey-Lovie chart has a *standard 5 letters* on every line no matter the letter size.

The theory is that with uniform letter and line spacing, the VA's will be a more precise measurement of visual acuity. Regardless of the differences, the VA's are taken in the same manner as the Snellen chart.

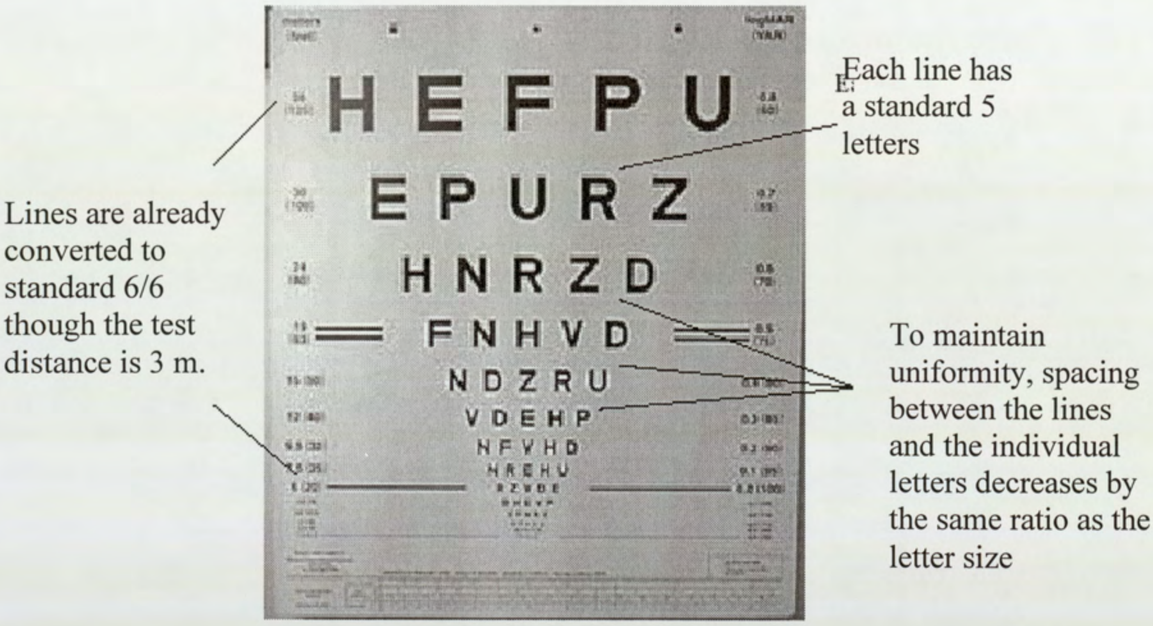


Fig 5.2. Bailey-Lovie acuity chart.

The letters used to construct the Bailey-Lovie charts have been described as having been found by experiment to be of similar legibility (British Standard 4274, 1968) and as being of almost equal legibility (Bailey and Lovie, 1976).

Almost equal letter legibility would enable almost equal line difficulty to be achieved through random combinations of any five of the 10- letter set in each line. In a study using two equivalent versions of the Bailey-Lovie chart, significant differences in letter legibility were demonstrated and the distributions for lines of threshold acuity for each chart were not uniformly proportional (McMonnies and Ho, 2000).

5.2. Contrast Sensitivity

5.2.1. Introduction

When an optometrist tests vision by asking someone to read a row of black letters on a white chart, what is being measured is visual acuity. Acuity is a measure of contrast sensitivity – the upper limit for detecting fine detail at high contrast. Much of what we see in the real world however has a much lower contrast and has an overall shape and form in addition to detail. When one measures an observer's ability to detect objects of different sizes at lower contrasts, the result is a contrast sensitivity function (CSF).

The size of an object can be quantified in terms of the size of its image on the retina, typically in degrees of visual angle. With periodic patterns, such as a sine-wave grating pattern, size is specified in terms of the number of cycles per degree of visual angle (c/deg). This is a measure of the pattern's spatial frequency. A cycle consists of one complete light-dark transition. Lower spatial frequencies correspond to wider bars and higher spatial frequencies correspond to narrower bars. Contrast refers to the difference in luminance between the lightest and darkest points in a cycle.

A CSF is typically obtained by measuring an observer's contrast detection threshold for a number of different grating patterns at different spatial frequencies. The contrast detection threshold is the lowest contrast at which a pattern can be seen. Sensitivity is the reciprocal of the threshold - the lower your threshold, the higher your sensitivity. A CSF is a plot of contrast sensitivity as a function of spatial frequency. One interesting aspect of the CSF is that it peaks at intermediate spatial frequencies, about 3-4 c/deg. In other words, we are best able to detect medium-sized objects when their contrast is low. As you might expect, we see smaller objects less well. The smallest objects that we can detect are around 50 c/deg and they can only be detected if their contrast is very high.

What is somewhat surprising at first is that we also detect larger objects less well. Based on optics alone, the reduced sensitivity to high spatial frequencies is expected, since all optical systems tend to attenuate the contrast of high spatial frequencies. However, an optical system, such as our eye, does not attenuate low spatial frequencies. Our relative insensitivity to low spatial frequencies is due to neural factors, rather than to the optics of the eye.

In its simplest terms, contrast sensitivity refers to the ability of the visual system to distinguish between an object and its background. Contrast describes the difference in the average luminance between 2 visible areas. Contrast sensitivity is the measure of the ability to detect a difference in the luminance between 2 areas. If the 2 areas are adjacent to each other, the ability to detect a difference in luminance is called *spatial* contrast sensitivity. If the areas occur sequentially in time, the ability to detect a difference in luminance is called temporal contrast sensitivity.

5.2.2. The Pelli-Robson Chart

Contrast sensitivity tests with letters as optotypes, such as the Pelli-Robson, are quick, reliable, and repeatable means for studying contrast sensitivity (Rubin, 1988) and are often used in clinical research. (Hirvela, 1995) To ascertain whether a patient has decreased contrast sensitivity, normal values of the test must be available for comparison (Mantyjarvi, 2001)

The Pelli-Robson contrast sensitivity test is a wall chart measuring. 90 X 60 cm (36 X 24 inches) (Figure 6.3). The chart comprises 8 lines of letters with different contrasts. Each line has 6 letters; the first 3 letters (a triplet) on the left have more contrast than the 3 letters on the right. The contrast also decreases downward from line to line. The size of the letters is 4.9 X 4.9 cm (2 X 2 inches). The letters on the left of the top line have the highest contrast, 1 or 100%, and the letters on the right of the bottom line have the lowest contrast, 0.006 or 0.6%. The manufacturer recommends a testing distance of 1 m, which corresponds to a spatial frequency of about 1 cycle per degree (cpd). An addition of +0.75 D can be used if a distance correction is needed (Mantyjarvi,2001).

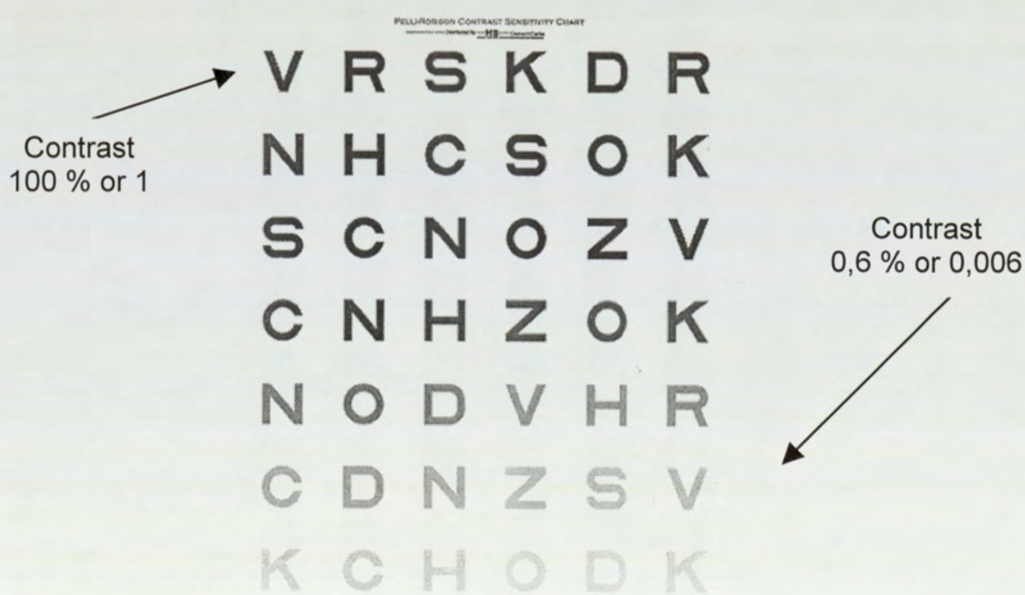


Fig.5.3. The Pelli-Robson Chart (*After Denis Pelli*)

The logarithmic contrast sensitivity value of the last triplet of which at least 2 letters are correctly seen is marked as the result. The luminance of the test should be 85 candelas/m^2 (cd/m^2); the accepted range is 60 to 120 cd/m^2 (Mantyjarvi, 2001).

Contrast sensitivity can be examined using grating tests (eg, the Vistech) or optotype tests (eg, the Pelli-Robson). Grating tests define contrast sensitivity in different sizes of targets as several different cycles per degree. Contrast sensitivity measurements with grating tests usually start at 1.5 cpd and go up to 18.0 cpd (or even higher with computer-based equipment). The range of the contrast levels can be from 3 to 0.004. The results give accurate information about the ability to see contrasts of small and large objects in the real world. The Pelli-Robson test with optotypes (letters) only measures 1 cpd region at a recommended distance, and the examination must be done at different distances if more cycles per degree are needed. The lowest contrast level of the Pelli-Robson test (0.006) is adequate. The Regan test with optotypes (letters) measures several ranges of cycles per degree, but the contrast level is considerably higher than in the grating tests. Therefore, in measuring contrast sensitivity, grating tests would be better and more appropriate to use than optotype charts. (Mantyjarvi, 2001) However, the examination with optotypes at a region of peak sensitivity, such as 3 cpd in the Pelli-Robson chart at 3 m distance, could give important information.

It has been suggested that the scoring on the Pelli-Robson test would be more reliable if the number of all letters correctly seen was used (Elliott, 1990). However, the test's instruction for scoring is to find the last triplet of letters at which at least 2 letters are correctly seen (Mantyjarvi, 2001).

5.2.3. Prisms and vision

Imagine an eye looking at a narrow line object, which emits white light of equal-energy spectrum. When a prism with its base-apex line perpendicular to the line object, is placed before the eye a retinal image consisting of the component wavelengths of the spectrum will be formed.

Thus the line's image has been 'spread' over a portion of the retina. This is due to transverse chromatic aberration, the effects of ocular aberration and diffraction being ignored (El-Kadouri and Charman, 1984). Assuming the spectral sensitivity of the eye to be in accordance with the standard photopic spectral luminous efficiency, the strength of the visual stimulus due to each wavelength will be proportional to the corresponding luminous efficiency value.

The line-spread functions for crown glass prisms of 6 and 12 Δ thus obtained, were shown by El-Kadouri and Charman' (1984). They showed also that a substantial loss of modulation transfer occurs at spatial frequencies < 30 c/deg (the visually significant frequencies), even with 6 Δ prisms (Figure 5.5)

Contrast sensitivity has also been used experimentally to determine the degradation of the retinal image. The results of these experiments (Fonseka and Obstfeld, 1995) showed a loss of modulation transfer, which increased with prism power, and probably also with reducing constringence.

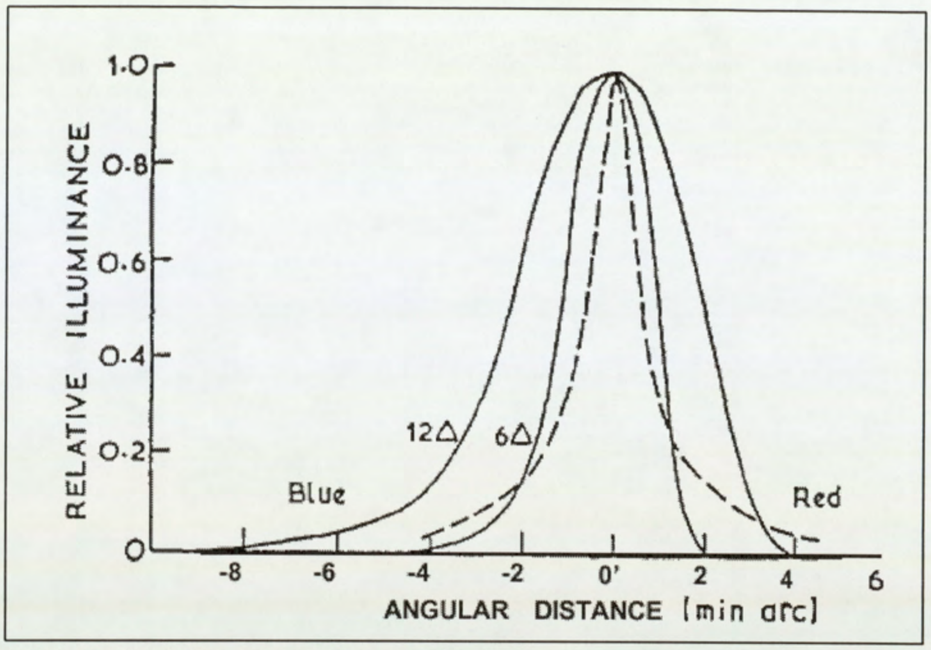


Figure 5.4. Retinal line spread function for transverse chromatic aberration produced by crown glass prisms. Ordinate, angular distance (min arc); abscissa, relative illuminance; dashed line, without prism. *(After Charman and El-Kadouri.1984)*

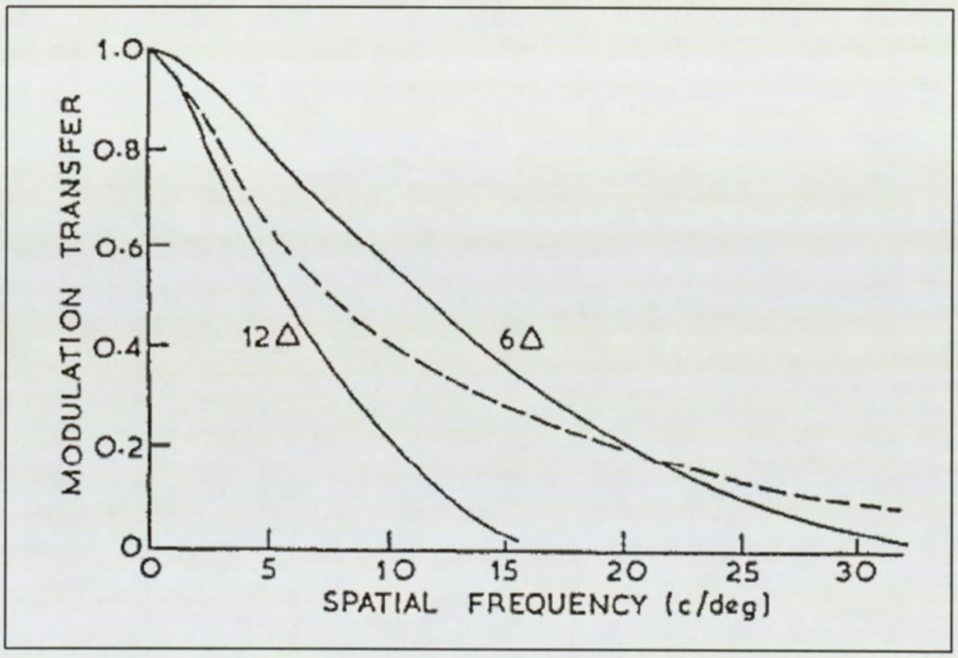


Figure 5.5. Modulation transfer function for prisms. Ordinate, spatial frequency (c/deg); abscissa, modulation transfer; dashed line, for white light *(After Charman and El-Kadouri.1984)*

According to Fonseka, Khosravi in 1988 found a small but statistically insignificant reduction in Snellen letter acuity when a prism was placed before one eye. However, Davis and Clotar(1956), and Meslin and Obrecht (1988) found that when chromatic aberration reaches a value of about 0.1 Δ (which can be caused by a 6 Δ crown glass prism), VA is significantly affected. Jalie (1987) also gave 0.1 Δ as tolerance for transverse chromatic aberration, without quoting evidence

.

5.3. Measuring Visual Acuity

The simplest method for computing the proper average visual acuity from any notation is to convert the value to the LogMAR equivalent and then take the average of the LogMAR values. The easiest way to compute the LogMAR value is to convert to decimal notation and then take the negative of the logarithm, e.g, 6/6 = 1 and the log of 1 is 0, and 6/60 = 0.10 and the negative of the log is +1.0. The average of 0 and +1.0 is 0.5 LogMAR units. Converting back from the logMAR value of 0.5, the corresponding visual acuity is 6/18.9, the correct geometric average.

Corresponding Visual Acuities

Line No.	Snellen Equivalent (feet)	Snellen Equivalent (meters)	Decimal Equivalent (minutes)	Visual Angle	LogMAR* Equivalent
-3	20/10	6/3	2.00	0.50	-0.30
-2	20/12.5	6/3.75	1.60	0.63	-0.20
-1	20/16	6/4.8	1.25	0.80	-0.10
0	20/20	6/6	1.00	1.00	0.00
1	20/25	6/7.5	0.80	1.25	+0.10
2	20/32	6/6.4	0.63	1.60	+0.20
3	20/40	6/12	0.50	2.00	+0.30
4	20/50	6/15	0.40	2.50	+0.40
5	20/63	6/18.9	0.32	3.15	+0.50
6	20/80	6/24	0.25	4.00	+0.60
7	20/100	6/30	0.20	5.00	+0.70
8	20/125	6/37.5	0.16	6.25	+0.80
9	20/160	6/48	0.13	8.00	+0.90
10	20/200	6/60	0.10	10.00	+1.00
11	20/250	6/75	0.08	12.50	+1.10
12	20/320	6/96	0.06	16.00	+1.20
13	20/400	6/120	0.05	20.00	+1.30
.	.	.	.	.	.
.	.	.	.	.	.
20	20/2000†	6/600	0.01	100.00	+2.00
30	20/20000§	6/6000	0.001	1000.00	+3.00

** Log of Minimum Angle of Resolution*
† 20/2000 = count fingers at 2 feet
§ 20/20000 = hand motion at 2 feet

Table 5.1. Corresponding visual acuities (*after Holladay*)

It is common for visual acuity sets to include values in which the patient did not read all of the letters on a single line correctly. Although recording the last line that was read completely or the majority of letters (three out of five) is an acceptable method, it reduces the precision of the measurement —similar to rounding off laboratory measurements.

A more accurate method is to interpolate between the values of the LogMar acuity using the fraction of the number of letters read correctly on a visual acuity line (Hsiu, 1993). For example, suppose our acuity chart had five letters on each visual acuity line and the patient read all of the letters on the 6/15 (LogMar +0.4) line, but only three of the five letters on the 6/12 (LogMar +0.3) line. Three-fifths (3/5 = 0.6) of the way from LogMar +0.4 to +0.3 is LogMar +0.34. The LogMar value of +0.34 is the correct value for this patient's visual acuity.

For studies that involve large databases, where converting these values manually is tedious, there are published formulas that allow direct conversion from the Snellen acuity value to the interpolated LogMar value 0.6 These formulas only work if there are an equal number of letters on a line, as there are on the Bailey-Lovie (1976) visual acuity chart and other standardized charts.

Unfortunately, if the number of letters on the acuity chart is not equal on each line (as occurs on many projected and wall charts), then a table must be created that shows the conversion interpolation for each line, and a single formula is not possible.

Visual Acuity Data Set for Seven Theoretical Eyes

Eye No.	Measured Visual Acuity*	Snellen Equivalent	Decimal Equivalent	LogMAR Equivalent
1	20/10	20/10	2.0	-0.30
2	20/10-2	20/10-2	2.0-2	-0.26
3	20/40	20/40	0.5	+0.30
4	20/40+3	20/40+3	0.5+3	+0.24
5	20/200	20/200	0.1	+1.00
6	CF† at 2 ft	20/2000	0.01	+2.00
7	HM§ at 2 ft	20/20000	0.001	+3.00
Mean		20/142	0.141	+0.85
Standard deviation		± 11.5 lines	± 11.5 lines	±0.115

** Bailey-Lovie visual acuity chart with five letters on each line*
† Count fingers
§ Hand motion

Table 5.2. Visual acuity data for theoretical eyes (*after Holladay*)

5.4. Materials and subjects

- **Bailey-Lovie chart**

Thirty male and female subjects ranging in age 18 to 30 years were selected. Subjects had no ocular abnormality by direct ophthalmoscope, no reported systemic abnormality and were taking no ocular or systemic medications. Subjects with any visual complaints were excluded. Contact lens wearers were accepted. Subjects had no suppression as tested by viewing targets simultaneously seen through polarising filters. Central or eccentric fixation was not checked. However, the logMAR acuity of either eyes could not be worse than 0.2 (i.e. Snellen notation of 6/9.5) so as to eliminate amblyopic subjects (Millodot, 1993).

Each subject was refracted; the monocular subjective prescription to "maximum acuity" without balancing was recorded for each eye. With the prescription in a trial frame (fig. 5.6), monocular VA was recorded using a Snellen type chart at 6 m., converted to logMAR visual acuity and *the* values were recorded to the nearest letter. Four Snellen charts with different combinations of letters were used to eliminate the possibility of correct identification of letters by memory. The subject's head was fixed using a headrest and he/she was reminded to keep both eyes open throughout the test.

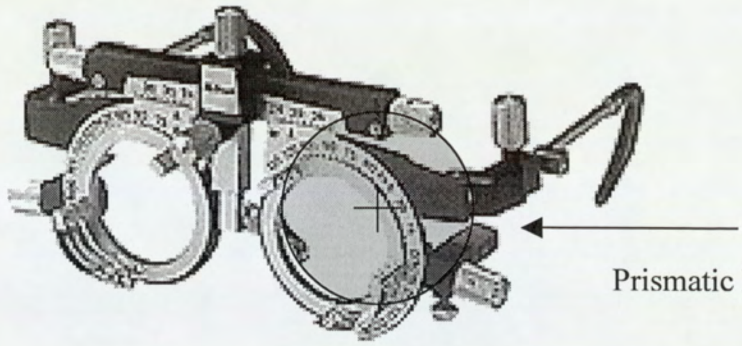


Fig. 5.6. Lens edged to round shape and placed on trial frame.

Initially, forty subjects were examined altogether; data of ten were excluded because of unstable responses and/or because fewer than six reversals were obtained. The mean age of thirty accepted subjects was 22.48 (Standard Deviation 1.82) years. Seventeen were females and the remainder were males.

- **Pelli-Robson chart**

Seven subjects, who were naïve to the purpose of the experiment, participated in the study after giving informed consent. All subjects were carefully at first refracted at 4 m, the usual viewing distance. To determine the subjective refraction we used the typical clinical approach of highest plus/lowest minus spherical power commensurate with maximal visual acuity, careful cross-cylinder determination of correcting cylinder power and axis while viewing concentric ring targets and binocular balancing to reduce any accommodation. Though there is the possibility of errors in the determination of the subjective refraction (Rosenfield and Chiu,1995), our confidence in the determination of the appropriate refractive correction was verified by measurements of ocular aberrations of the subjects (Strang et al., 1999).

During contrast sensitivity measurements each subject was seated, the non checked eye patched, head and eye movements were not restrained and contact lenses were worn, if needed.. Subjects monocularly viewed the contrast sensitivity chart. Pupils of the subjects' eyes, measured using comparison hemi-circles ruler with 0.5 mm increments, ranged between 3 and 6 mm under average room illuminance of 40 lux used in most experiments. Contrast sensitivity was measured with best correction.

As the letter size on a Pelli–Robson letter contrast chart (Pelli *et al.*, 1988) is fixed; we altered the spatial frequency content of the letters by altering the distance of the subject from the chart. The two-dimensional spatial frequency spectrum of letter targets is relatively complex. An important feature of these spectra is the "fundamental" peak of the familiar square-wave spectrum, which is related to the width of the bars or strokes composing the letters. For example, at 1 m the fundamental peak is at approximately 1 cpd, and at 4 m it is at about 3.6 cpd (Woods et al., 2000).

Letter contrast sensitivity was measured using the Pelli-Robson Chart (Pelli et al., 1988) under the recommended conditions and at a working distance of one metre. Subjects were required to identify the letters and were encouraged to look at a line of letters for at least 20-30 s and forced to guess when they were not sure, as scoring depends upon a forced choice paradigm. Letter contrast sensitivity was determined where each letter counted as 0.05 log units as recommended by Elliott et al. (1991) and confusions between the letters 0 and C were ignored.

5.4.1. Lenses

Twenty-two lenses made from 8 different plastic materials were obtained from our suppliers. The following specifications were requested: power +6.00D; edged to round shape (38 mm. in diameter) and decentred in order to produce a 9^{Δ} prism in front of the subjects' eye, after placing in the trial frame. To avoid defocus a minus equal lens (-6.00) was used in the trial frame to neutralise the focal power of the prism lens.

It was confirmed by inspection that all lenses met these specifications. The lenses were coded and tested in a different random order in each phase of the experiment.

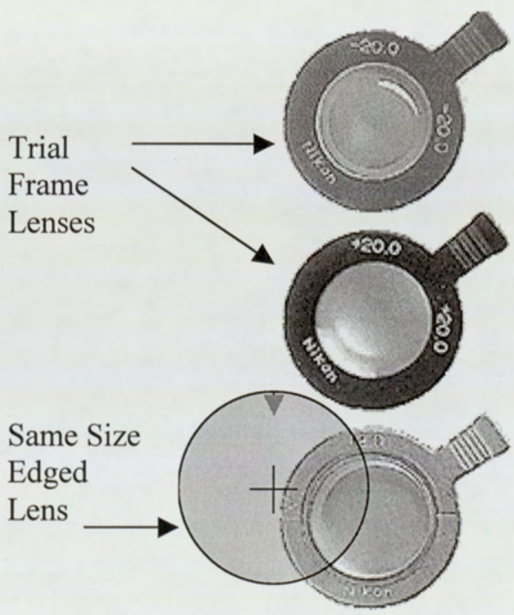


Fig. 5.7 Lenses edged to round shape in order to be placed in trial frame.

5.4.2. Repeatability

Measurements of every subject were repeated four times on Bailey-Lovie and Pelli Robson charts, for each lens used in the experiment .

5.4.3. Chart Projector

VA was measured with letter charts' wall-display using a Nikon NP-3S chart projector. The acuity charts consisted of high contrast black letters on a white background. Each row consisted of five letters (No 4 and 5 on Fig.6.9) and, from top to bottom, decreased in size by a constant factor (0.1 log unit per row).

Letter sequence was varied from trial to trial to discourage learning effects. Testing was conducted in an otherwise dark room at a distance of 6 m. Each subject was instructed to start from the top of each chart and read down as far as possible, and was encouraged to guess when unsure. Scoring was conducted by letter with a precision of 0.02 log units (0.1 log units per five letter row). VA was scored as the log of the minimum angle of resolution (logMAR).

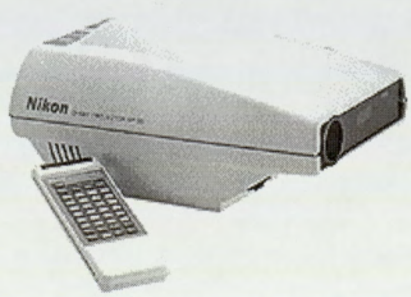


Fig.5.8. Nikon NP-3S chart projector.

Fig. 5.9 Frames used by Nikon NP-3S projector.

5.5. Results and Discussion

- **Bailey-Lovie chart**

		Sola CR-39	Sola . Asph.	Essilor Ormex	Essilor Poly-C	Pentax– HIX	Pentax Asph	–Hoya Teslalid
		1.498	1.54	1.56	1.59	1.60	1.67	1.71
Subject A/A - Sex	**VA Cor**	**VA 1**	**VA 2**	**VA 3**	**VA 4**	**VA 5**	**VA 6**	**VA 7**
1 M	0	0.2	0.2	0.2	0.32	0.24	0.24	0.26
2 M	0	0.2	0.2	0.18	0.26	0.28	0.22	0.26
3 F	0.16	0.3	0.24	0.3	0.34	0.36	0.24	0.32
4 M	0.16	0.16	0.2	0.2	0.32	0.34	0.32	0.34
5 M	0.02	0.1	0.2	0.3	0.4	0.42	0.32	0.36
6 M	0.02	0.1	0.16	0.16	0.22	0.24	0.3	0.32
7 F	0	0.16	0.2	0.22	0.3	0.32	0.32	0.38
8 F	0.1	0.2	0.28	0.24	0.32	0.34	0.32	0.34
9 F	0.06	0.16	0.24	0.2	0.24	0.26	0.24	0.3
10 M	0.16	0.16	0.24	0.2	0.26	0.26	0.24	0.26
11 M	0.02	0.1	0.1	0.16	0.2	0.22	0.22	0.24
12 M	0	0.2	0.2	0.2	0.24	0.22	0.22	0.32
13 F	0.1	0.24	0.2	0.2	0.2	0.24	0.2	0.2
14 M	0	0.2	0.16	0.2	0.2	0.2	0.2	0.24
15 M	0.01	0.16	0.16	0.22	0.3	0.26	0.24	0.32
16 F	0	0.1	0.1	0.16	0.22	0.16	0.22	0.24
17 F	0.16	0.1	0.16	0.2	0.3	0.21	0.3	0.3
18 M	0	0.1	0.1	0.16	0.22	0.16	0.2	0.22
19 M	0.16	0.16	0.2	0.16	0.22	0.2	0.24	0.21
20 F	0.1	0.16	0.2	0.16	0.3	0.2	0.24	0.2
21 M	0	0.1	0.16	0.16	0.21	0.2	0.2	0.21
22 F	0	0.2	0.22	0.2	0.3	0.24	0.32	0.24
23 M	0	0.1	0.1	0.16	0.2	0.16	0.2	0.2
24 F	0.1	0.16	0.16	0.2	0.24	0.2	0.3	0.32
25 M	0.1	0.16	0.16	0.2	0.2	0.2	0.2	0.22
26 F	0.1	0.2	0.2	0.2	0.3	0.22	0.24	0.24
27 M	0	0.2	0.21	0.16	0.24	0.22	0.24	0.24
28 M	0.16	0.2	0.16	0.2	0.22	0.2	0.22	0.16
29 F	0	0.1	0.16	0.2	0.2	0.16	0.2	0.16
30 F	0.06	0.16	0.22	0.16	0.16	0.16	0.2	0.2

Table 5.3 Results for 30 subjects' VA measurement after samples (VA1-7) and without sample lens (VA cor.)

TradeNames	nD	ρ (gr.cm-^{3})	Abbe
Low Index	1.498	1.32	58
Sola 1.5	**1.498**	**1.32**	**58**
Zeiss Clarlet 1.5	**1.501**	**1.32**	**58**
Essilor Orma	**1.50**	**1.28**	**58**
Hoya HiLux	**1.50**	**1.32**	**58**
Pentax Superlite	**1.498**	**1.32**	**59**
Nikon LH i	**1.498**	**1.32**	**58.7**
Medium Index	1.54	1.21	47
Spectralite ASL	*1.54*	*1.21*	*47*
Middle Index	1.56	1.25	37
Sola Mid. Index	**1.56**	**1.27**	**36**
Nikon LH ii	**1.56**	**1.17**	**41**
Hoya Hilux ii Asph	*1.56*	*1.25*	*37*
Essilor Ormex	**1.56**	**1.23**	**37**
Poly-C Mid.Index	1.59	1.20	31
Pentax PC ASAR	*1.59*	*1.20*	*31*
Essilor Airwear	**1.59**	**1.20**	**31**
Mid-High Index	1.60	1.34	36
Pentax 1.6 HIX	**1.60**	**1.34**	**36**
Zeiss Clarlet 1.6	**1.60**	**1.34**	**36**
Hoya EYAS	*1.60*	*1.32*	*41*
Sola Estilite	**1.60**	**1.34**	**36**
Nikon LH iii	**1.60**	**1.34**	**36**
Essilor Ormil	**1.60**	**1.36**	**36**
High Index	1.67	1.20	32
Essilor Stylis	**1.67**	**1.36**	**32**
Pentax HIX Asph	*1.67*	*1.35*	*32*
Nikon LH iv	**1.67**	**1.35**	**32**
Sola SupHi Asph	*1.67*	*1.35*	*32*
Zeiss Clarlet 1.67 As	*1.67*	*1.36*	*32*
Very High Index	1.71	1.40	36
Hoya Teslalid	**1.71**	**1.40**	**36**

Table 5.4. Commercial plastic lenses used for samples lenses.
(Lenses in *Italics* are of aspheric design).

In table 5.3. the full results of this study are presented. In first column included all 30 (males+females) subjects in range the follow the test. All the samples (as presented in table 5.4.) selected randomly for every subject.

Before entering the test all subjects had an interview and their VA was recorded. Some of them wore contact lenses and the test took place over the contact lenses.

The records of the prior interview and the test results entered up to a special form (questionnaire) for later analysis.

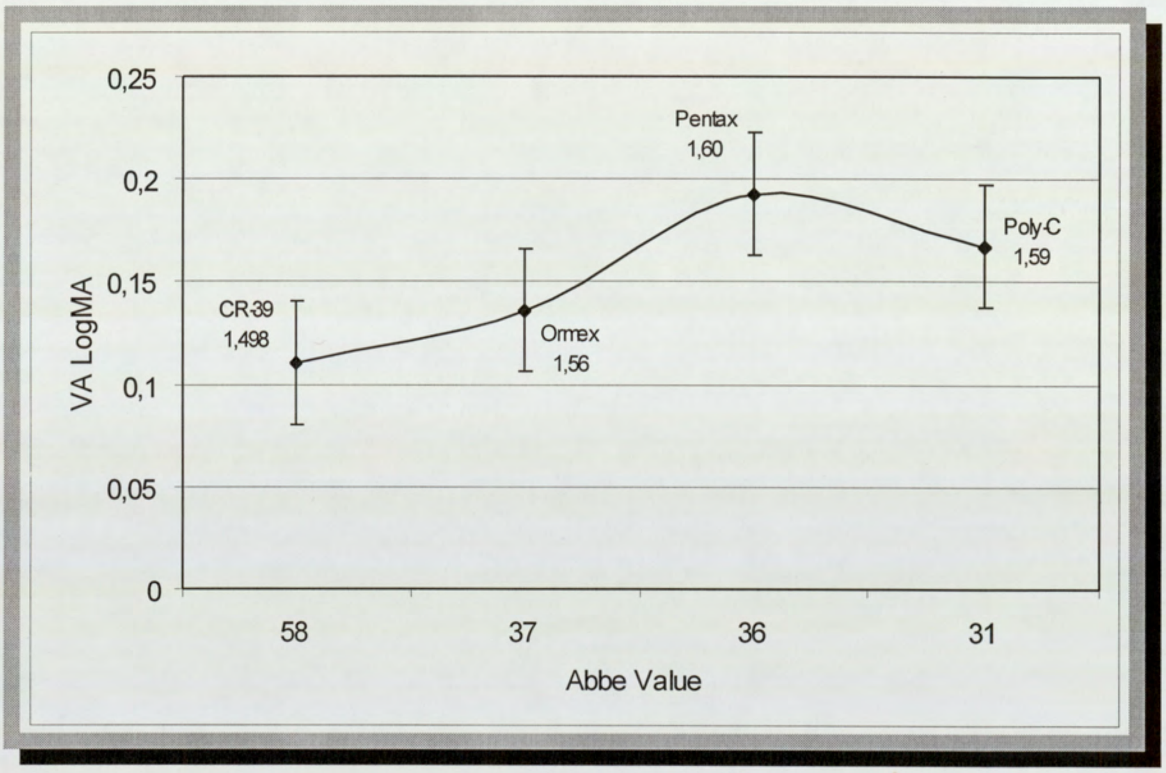


Fig.5.10. Correlation between Visual Acuity and Abbe number in Plastic Lenses.

In Figure 5.10 we observe a significant decline of visual acuity in correlation to higher index plastic lenses like Ormex (1,56) and Pentax (1,60). Against to what we expected from a lens such as Polycarbonate having an Abbe value of about 31, we notice that its performance comes better than Pentax but still worse than Ormex.

In Figure 5.11 we observe a similar graph of Visual Acuity decline (in LogMAR units) but concerning Aspheric design lenses. The inclination presents a steeper decline and a performance a little better than non-aspheric design lenses.

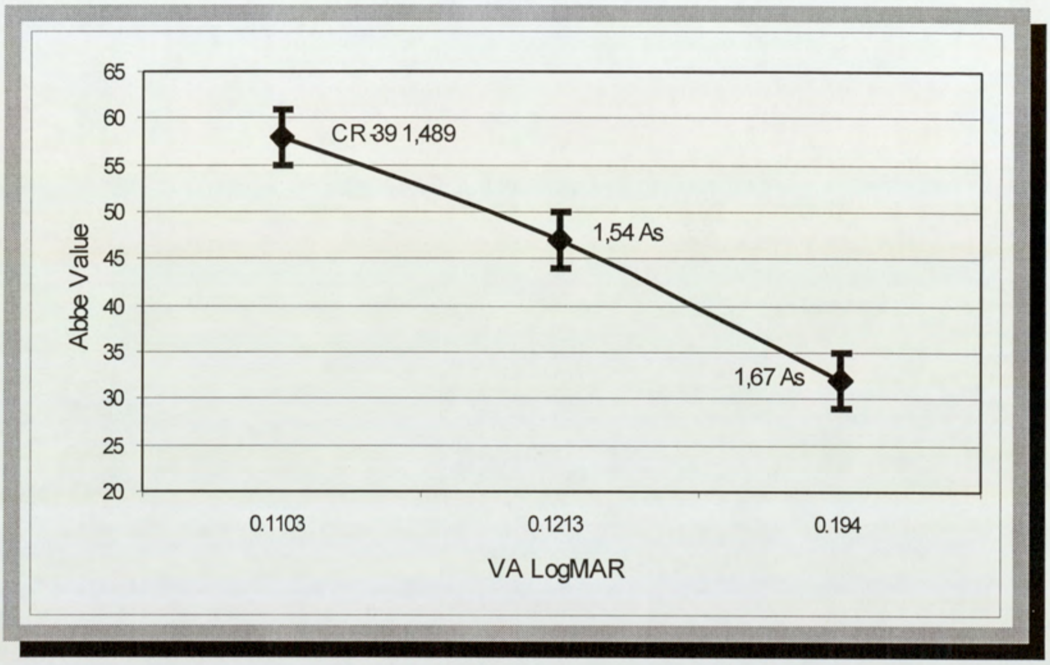


Fig. 5.11. Correlation between Abbe Value and Visual Acuity reduction for Aspheric Plastic Lenses

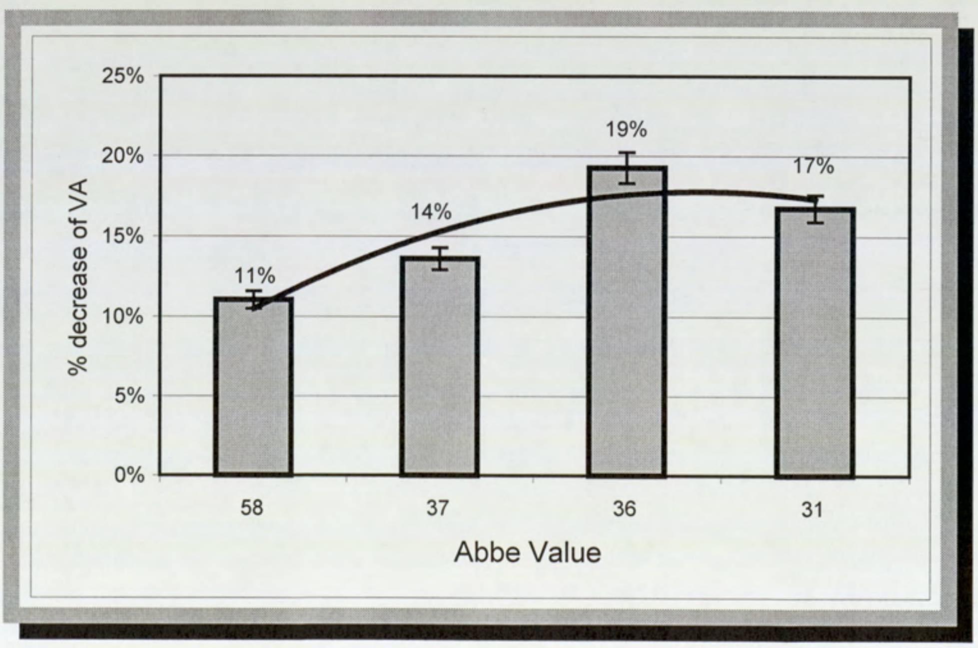


Fig 5.12. Comparison of % Visual Acuity decrease and Abbe Value

The significance of the differences in the lens material in relation to the visual acuity (as shown in Table 5.3) was assessed by analysis of variance:

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.276158	6	0.046026	17.31843	3.8E-16	2.143452
Within Groups	0.539503	203	0.002658			
Total	0.815661	209				

This shows a highly significant difference ($p<0.01\%$) between the different materials and their effect on Bailey-Lovie visual acuity.

- **Pelli-Robson chart**

		Sola CR-39	Sola . Asph.	Essilor Ormex	Essilor Poly-C	Pentax– HIX	Pentax –Asph	Hoya Teslalid
		1.498	1.54	1.56	1.59	1.60	1.67	1.71
Subject A/A	Contrast Norm. Cor.	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**	**Sample 6**	**Sample 7**
1	1.65	1.50	*1.35*	1.35	1.20	1.20	*1.20*	1.20
2	1.50	1.35	*1.35*	1.20	1.20	1.20	*1.05*	1.05
3	1.65	1.50	*1.35*	1.35	1.20	1.20	*1.20*	1.20
4	1.50	1.35	*1.20*	1.20	1.20	1.20	*1.05*	1.05
5	1.65	1.50	*1.35*	1.35	1.20	1.20	*1.20*	1.20
6	1.80	1.65	*1.50*	1.50	1.35	1.35	*1.25*	1.25
7	1.65	1.50	*1.35*	1.20	1.20	1.20	*1.20*	1.20

Table 5.5 Results for 7 subjects' logarithmic contrast sensitivity samples (1-7) and without sample lens (contrast norm cor.) at 1 m.

In the laboratory, contrast sensitivity is usually measured psycho-physically, using patches of grating (bars) that vary over a wide range of sizes (spatial frequencies). Typically, the gratings are computer generated and displayed on a computer screen or cathode ray tube. This allows the experimenter to construct a contrast sensitivity function. However, this study was not for clinical screening, but mainly for material determination purposes where the contrast sensitivity function is inefficient and difficult to interpret. Moreover, the typical laboratory test for it requires sophisticated and specialized equipment.

Ideally, a contrast sensitivity test for material performance determination should satisfy several criteria. It should be simple to administer, requiring no sophisticated electronic or computer equipment, well standardized, reliable, valid, sensitive to visual loss, and relatively insensitive to changes in focus, viewing distance, and illumination. It should provide a single score that is meaningful and can easily be compared with extensive normative data and should provide information about visual function not captured by other tests (such as high contrast acuity).

The currently available test that best meets the requirements laid out above is the Pelli-Robson chart (Pelli et al.,1988). This test measures contrast sensitivity for a single (large) letter size. Specifically, the chart uses Sloan letters (6 per line), arranged in groups whose contrast varies from high to low. The chart is simple to use, because the subject simply reads the letters, starting with the highest contrast, until she or he misses two or three letters in a single group. Each group has three letters of the same contrast level, so there are three trials per contrast level. The subject is assigned a score based on the contrast of the last group in which two or three letters were correctly read. The score, a single number, is a measure of the subject's log contrast sensitivity. Thus a score of 2 means that the subject was able to read at least two of the three letters with a contrast of 1 percent (contrast sensitivity = 100 percent or log 2).

The Pelli-Robson chart is quick and easy to administer. Because it is based on reading letters, it can be easily administered to anyone who is literate; however, it is not useful with nonverbal individuals or those who are unfamiliar with the alphabet.. It is simple, efficient, and provides user-friendly information by providing a single number to describe the observer's contrast sensitivity. The chart has been extensively normed and validated, and there is now an extensive literature on the reliability and validity of the test.

It is actually a measure of the height of the contrast sensitivity function, similar to measuring contrast sensitivity for a luminance edge. Thus, it should be sensitive to losses that affect low and medium spatial frequencies, losses that might not be evident for high-contrast acuity, thus providing information not captured by acuity testing. The Pelli-Robson chart provides a graded index of performance (log contrast sensitivity),

In the instructions, most contrast sensitivity tests recommend a luminance level at which to administer the test. In the Pelli-Robson test, the recommended luminance is 85 cd/m^2. However, under photopic conditions, contrast sensitivity results on the Pelli-Robson were almost the same at luminance ranging from 7 to 514 cd/m^2 (Zhang et al., 1989). In this study the luminance level was exactly 100 cd/m^2 and the room level at about 20 cd/m^2.

The results for the seven subjects measured on the Pelli-Robson chart are shown in Table 5.5. The effect of the reduced Abbe number arising from the increase in refractive index was assessed by means of analysis of variance (ANOVA), with the following results:

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.548163	6	0.091361	12.69976	4.04E-08	2.323993
Within Groups	0.302143	42	0.007194			
Total	0.850306	48				

This indicates a highly significant difference (<0.01%) between the different lens materials, as measured by contrast sensitivity testing.

%	logCS	PELLI - ROBSON		logCS	%
100	0.00	**V R S**	K D R	0.15	75
50	0.30	**N H C**	**S O K**	0.45	35,5
25	0.60	S C N	O Z V	0.75	18
12,5	0.90	C N H	Z O K	1.05	9
6	1.20	N O D	V H R	1.35	4.5
3	1.50	C D N	Z S V	1.65	2.2
1,6	1.80	K C H	O D K	1.95	1.1
0.8	2.10	H S Z	D S N	2.25	0.56

Table 5.6 Part of the result paper of the Pelli-Robson contrast sensitivity test. The numbers on both sides give the logarithmic contrast sensitivity corresponding to the neighboring group of 3 letters. For instance, the number 0.60 next to the letters SCN (*Mantyjarvi, 2000*) indicates a contrast of $1/10^{0.60} = 0.25$ or contrast of 25% for those letters.

- **Relation to Other Measures**

Contrast sensitivity measures provide information that is related to, but is also distinct from, high-contrast visual acuity measures. For example, a number of studies have reported that the correlation between high-contrast acuity and contrast sensitivity is of the order of 0.5 to 0.6 (Rubin, West, et al., 1997). It is widely believed that letter contrast sensitivity (as assessed by Pelli-Robson) reflects the contrast sensitivity near the peak of the contrast sensitivity function, while high-contrast letter acuity probably reflects sensitivity at high spatial frequencies.

Does contrast sensitivity provide a unique measure of disability? It subsumes visual acuity. Thus an individual with visual acuity poorer than 20/200 is likely to have reduced contrast sensitivity, and one with a visual acuity of 20/40 or better is unlikely to have significantly reduced contrast sensitivity. However, between those limits (acuity between about 20/50 and 20/100), contrast sensitivity may distinguish individuals with visual impairment from those with no impairment; in other words is evident that it will affect their contrast sensitivity scores. For example, people with multiple sclerosis (Regan, 1991b) or visual pathway disorders (Elliott, 1998) may show significant contrast sensitivity loss with little visual acuity loss and, so in order to evaluate the performance using visual acuity is very important to be sure about the subjects' visual health.

5.6 Conclusion

The hypothesis of this research was that the higher the index the more the chromatic aberration. The conclusion based on the discussion above is that this hypothesis is quite correct.

However, many important conclusions were obtained through this research. First, that the measurement of the refractive index of a lens is not a very easy task. Many factors affect the accuracy of measurement, like good polishing, control of temperature and the use of monochromatic light in order to reduce the errors of measurement

This was seen through the minimum deviation method. We used a monochromatic laser beam in order to avoid diffraction, or double reflection beams of prism facets. After very good polishing of the prism faces finally we made the most reliable measurements. Practically speaking, we can estimate the refractive index of about every optical material.

On the other hand, chromatic aberration, as was expected, reduces visual acuity. Of course in aspheric design we notice a slight improvement, but still far from CR-39. The high and low contrast acuity loss when wearing prisms is mainly the result of distortion and chromatic aberration. The distortion effect has been studied by Adams et al. (1971), and the chromatic dispersion by Woo et al. (1986). Additional factors such as reflection from the prism facets, secondary refraction at the prism facet bases, diffraction of light by the grooves in Fresnel prisms, observers' direction of gaze and prism area variations (Veronneau-Troutman, 1978) are potential causes for a greater acuity reduction with the prism.

Therefore, the greater high and low contrast acuity reduction with prisms in this study, is mainly the result of chromatic dispersion than of reflection from the prism facets, secondary refraction at the prism facet bases and diffraction of light by the grooves. And that is because mainly the prisms are of the same power and size, worn at the same distance and the only difference is the Abbe value due to the material.

The advantage of measuring a CSF, as opposed to a simple measure of acuity, is that it describes how the visual system performs at lower contrasts and at a range of spatial frequencies. The measurement of acuity provides only one point on the CSF. So we can be more accurate to visual acuity decline due to the material of lenses used.

Measurement of CSF reduction with prism does need care. As shown by Tang and Charman (1992), if gratings are used, then there is a considerable reduction in CSF if the prism base is perpendicular to the grating. If the prism base is parallel to the 'lines' of the grating, then the effect is much reduced. Thus there is a great advantage is using targets such as the Pelli-Robson chart where there is not the same orientation specificity.

The goal of this research was to attempt an evaluation of the optical performance of plastic lenses in correlation to the high refractive index and consequently the chromatic dispersion of the material, and in that I think we were successful. The experiments performed in the study confirmed that as the index of refraction increases (consequently the Abbe decreases) there is a consequent trend to reduced visual performance.

5.7 Future Work

Although we can measure the optical characteristics of lens materials, it still does not tell us what the real impact is on the wearer. It might be thought that a material with an Abbe value of 30 would be half as successful from the wearer's point of view as one with a value of 60. However anecdotal evidence does not support this hypothesis, and reports of optical problems being noted by wearers of high index lenses are limited. But this does not mean they do not occur.

The problem is that transverse chromtic aberration induced by a low Abbe number is just one of a number of aberrations to which spectacle lenses are prone. The wearer may simply experience blur through the periphery of the lens without realising the cause, and therefore the symptoms described to the optician can be confusing. Furthermore, single vision lens wearers can easily develop a coping strategy where they simply turn their head for clearer vision through a point on the lens free from obvious aberration.

Perhaps the lens wearers of most interest are users of bifocal or progressive lenses. Here, the near zones of the lenses are typically some distance from the optical centre of the major portion, and hence prone to transverse chromatic aberration.

Thus the proposed next experiment would be to compare a group of presbyopes with two versions of the same design of progressive lens. One would be normal index CR39, the other a high index material with a low Abbe number. The ideal comparison would be Polycarbonate, as that has a low Abbe number without a large change in refractive index. Hence the overall lens design in the two materials would be similar. Near vision contrast sensitivity testing would then give a good indication of the effect of chromatic blur.

In conclusion, it is perhaps ironic that high refractive index materials were developed when large aperture spectacle frames were fashionable. With small frames currently being fashionable, there is now very little requirement for such materials in the vast majority of prescriptions. But no doubt fashion will turn again to large frames, and these lens materials will then come into their own.

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