Studies on Impact Resistance of Spectacle Lens Materials

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Introduction:

The Canadian Standards Association (CSA) Z94.3-07 ballistic impact test for industrial lenses, tests the ability of a lens material to withstand the impact of a 6.4 mm diameter steel ball travelling at a speed of 46.5 ± 0.5 m/s. The specific testing is waived if the lens made of various materials meets a minimum centre thickness requirement. New lens materials, like Hi-Vex, are not included in this list. The first study compared the breakage speed of Hi-Vex lenses to CR39 lenses at different conditioned temperatures.

In the process of carrying out the literature review, it became apparent that the definition of lens failure varied. This led to the question as to how naïve individuals may interpret a National Standard definition of lens failure after being impacted by a missile. Naïve subjects were asked to classify impacted lenses as either pass or fail based on the written CSA Z94.3-07 failure criterion.

Purpose:

Study 1: To investigate the impact resistance of a mid-index plastic lens material Hi-Vex (n=1.56) at different temperatures.

Study 2: To investigate if people actually understood what the CSA classifies as a failed lens.

Methods:

Study 1: Two groups of plano hard coated lenses were tested: CR39 and Hi-Vex. Lenses were ordered with 3mm centre thickness, cut to 50mm diameter and edged to achieve the Hide-a-Bevel® which was in agreement with the CSA requirement for prescription industrial safety lenses and frames. A pneumatic gun was used to propel a 6.35mm steel ball at the centre of each lens. Impact speed was varied using the Zippy Estimation by Sequential Testing (ZEST) protocol to determine the threshold breakage speed. Combined uncertainties as defined in the International organization for standardization (ISO) Guide to the

expression of uncertainty in measurement were used to determine the statistical significance of all comparisons of the data sets.

Study 2: Ten graduate students from the School of Optometry and ten patients from the general public were given 25 spectacle lenses that had been subjected to the ballistic impact test. They were asked to classify the lenses as either a pass or fail after reading the definition of a failure under the ballistic impact test in CSA Z94.3-07 clause 6.1.3.1. Lenses were presented to the participants in the same order. The responses of both groups of participants were compared to the classification of two experienced researchers who agreed on 100% of the lens outcomes.

Results:

Study 1: The threshold breakage speeds of the industrial thickness Hi-Vex and CR39 lenses at 24°C were 50.88m/s and 50.64 m/s and at -29°C, 52.57m/s and 52.56 m/s respectively. Both comparisons were not statistically significant. The corresponding threshold breakage speeds for Hi-Vex and CR39 lenses at -49°C were 66.38m/s and 49.66m/s and at 50°C were 57.01m/s and 53.54m/s respectively. Both comparisons were statistically significant.

Study 2: There were only two lenses in which all participants agreed with the outcome. These lenses were failed lenses. The naïve subjects were more likely to classify a lens that passed as a failure than a failed lens as a pass. This trend was more obvious in the general public results although the results across the various lenses for the graduate students and general public were not statistically different.

Conclusions:

Study 1: We found that the mean breakage speeds of the Hi-Vex and CR39 lenses were greater than the level required of eye protector lenses by the Standards American National Standards institute (ANSI) Z87.1-2010 and CSA Z94.3-07. Hi-Vex was also superior to CR39 at more extreme temperatures with a threshold breakage speed of 57.01±3.51m/s at 50°C and 66.38±4.00m/s at -49°C. Although its impact resistance was less than that of both Trivex and Polycarbonate lenses, Hi-Vex may provide an acceptable level of impact protection in industrial settings. This is the first study to concomitantly assess impact resistance of a new lens material as well as compare the impact resistance at various temperatures.

Study 2: Simply reading the definition of a lens failure is insufficient. Some type of training with actual lenses may be necessary. Whether revising the text of the Standard or repeating the instructions several times would reduce this problem is uncertain. Both the graduate students and general public tended to be more conservative in their classification of failure. If there were any visible damage to the lens as a result of the impact, at least one person would classify the lens as a failure regardless of whether the damage met the CSA definition. This result suggests that the vision care community and CSA may need to educate the public on the meaning of impact resistance of eye protectors.

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Dedication

I dedicate this thesis to God Almighty; I could not have done this without you!

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in	Inches
cm	Centimetres
m	Metres
mg	Milligrams
mm	Millimetres
m/s	Metres per second
g	Gram
kg	Kilograms
J	Joules
°C	Centigrade
°F	Fahrenheit
%	Percentage
DS	Dioptres sphere
D	Dioptres

Chapter 1

General Introduction

The first principle in safety engineering is to remove the hazard at the source. If this is impossible to achieve, then the person exposed to the hazard should be outfitted with personal protective equipment (PPE) that reduces the probability of injury from the hazard. For eye protection, this usually involves wearing some type of spectacle or shield that is impact resistant. Impact resistance of a spectacle lens material and protective eyewear has been defined in several ways. Silberstein (1964) defined impact resistance as the ability of a lens material to resist the force of a flying particle. Impact resistance has also been referred to as fracture resistance or penetration resistance (Corzine *et al* 1996, Rychwalski *et al* 2003). Stephens (1993) stated that impact resistance could be expressed as the amount of stress that must be applied to the lens material before it fractures or breaks. The common feature that is present in these definitions is the ability of the lens material to resist breakage and penetration by objects striking or compressing the lens material, thereby protecting the eye (Wigglesworth 1971).

Most eye injuries have been shown to occur either at work or at home (Dain *et al* 2012). These injuries often occur from flying objects, which could be large and slow moving or small and fast moving. Dain *et al* (2012) stated that either form of hazard could be found in the work place or home. For the purpose of impact resistance testing, spectacle lens materials could be divided into two main categories: dress lenses worn every day and industrial safety lenses worn for occupational eye protection (Stephens 1993). One would expect that the impact resistance requirements for the industrial setting would be different from dress lenses because of the nature of the hazards.

This thesis will focus on two lens materials and identify factors that could affect impact resistance of these materials. The first part of the introduction of this thesis reviews the nature of hazards in the home and work place. The next section identifies the variety of impact resistance testing methods and the third section discusses how different lens materials and designs affect impact resistance. The research for this thesis was divided into two studies. The first study focused on two of the factors that could affect impact resistance -temperature and lens material. The second study was on the interpretation and application of the lens failure criteria that were set out in CSA Z94.3-07.

1.1 The nature of ocular hazards in the home and work place.

Major causes of eye injury could be grouped into two categories: those caused by slow moving, high mass objects and those caused by fast moving, low mass objects. According to Prevent Blindness America (2011), "The average home is full of dangers that often go unnoticed. Accidents involving common household products cause 125,000 eye injuries each year." Others have stated that "Ninety percent of these eye injures can be prevented through understanding, safety practices and the use of proper eye protection" (Vinger *et al* 1997, Matter *et al* 2007). Most of the spectacle lens injuries occurring in non-industrial settings occur as a result of relatively large objects and low velocity impacts. Keeney *et al* (1972) reported that most of the eye injuries due to fragments of broken frames and lenses hitting the eye in non-industrial accidents were caused by impact of low velocity, high mass objects (Fatt *et al* 1976, Corzine *et al* 1996). Table 1.1 summarizes frequency of objects or mechanisms causing non-industrial spectacle breakage leading to eye trauma (Keeney *et al* 1972, Keeney and Renaldo 1973, Stephens 1993).

Cause	Number	Percentage
Rocks	73	24.5
Sports	53	17.8
Baseball	(22)	
Basketball	(8)	
Golf ball	(5)	
Other balls	(8)	
Fishing weights	(4)	
Hockey stick	(1)	
Archery bow	(1)	
Plastic hockey puck	(1)	
Spinning top	(1)	
Boomerang	(1)	
Golf club	(1)	
Auto crashes	28	9.4
Falls	25	8.4
Flying objects	20	6.7
Assaults	18	6.0
BB pellets	16	5.4
Running collisions	12	4.0
Tree branches	7	2.3
Total	298	100%

Table 1-1 Causes of broken spectacle lenses in non-industrial eye trauma. Eye injuries occurred in 157 of the 298 cases. Modified from Keeney *et al* (1972) and Stephens (1993)

Work related eye injuries are still common. Over 2,000 people injure their eyes at work daily with 10-20 % of the injuries causing a temporary or permanent vision loss. The more disturbing finding is approximately 90% of all workplace eye injuries could be avoided by wearing proper safety eyewear

(Prevent Blindness America 2011, McMahon and Beckerman 2007, Rychwalski *et al* 2003, Sinclair *et al* 2006, Vinger *et al* 1997). In the work place, eye injuries could occur from impact from flying objects (bits of metal, glass) and there could be possibility of damage to the eyes from various forms of harmful optical radiation, chemicals or any combination of these or other hazards (Silberstein 1962, Prevent Blindness America 2011, Ritzmann *et al* 1992).

McBride (1949) studied 50 consecutive cases of intraocular foreign bodies in the work place. He discovered that the most common accidents resulting in ocular foreign body injury were caused by high-speed flying steel particles resulting from striking metal objects with a hammer. The sizes of the ocular foreign bodies were also mostly less than 3mm; however, the foreign bodies were over 5mm in four cases.

1.2 Impact resistance testing

There are three methods for testing the impact resistance of spectacle lens materials. They are the ballistic, drop ball and static load tests. Ideally, the missile used for impact testing would resemble the actual hazard in terms of shape, material, size, mass, and velocity (McBride 1949). The drop ball and static load tests were designed to test the effect of slow moving high mass objects on spectacle lens materials (Innes 1982), whereas the ballistic test was designed to evaluate the impact resistance to fast moving low mass objects (Corzine *et al* 1996).

Impact resistance testing using these methods can be done in two ways: "The impacting energy is either increased until a given lens breaks on repeated testing, or a sample of identical lenses tested consecutively" (Stephens 1993). In the latter method, each lens is tested once and the energy of impact is increased or decreased from lens to lens to determine the threshold for breakage (Stephens 1993). This method of testing is preferred because it is often difficult to impact the same site on a single lens repeatedly (Stephens 1993, Oliver and Chou 1993). Below is a brief description of each test for impact resistance.

1.2.1 Drop ball test

The drop ball test tests the ability of a lens to withstand being hit by a steel ball of diameter 5/8 in dropped from a height of 50 in. The steel ball should weigh 15.88 g (Stephens 1993). During drop ball testing, the ophthalmic lens is placed on a mount and not restricted in anyway. The steel ball is dropped on the convex side of the lens material (Corzine *et al* 1996). Impact resistance is recorded as either the drop height or the impact energy that leads to failure of the lens material (Stephens 1993). In other to determine the threshold breakage, the energy of the ball striking the lens has to be increased. This could be done by either increasing the height or size of the ball (Stephens 1993).

1.2.2 Static load test

This test simulates impact from high mass slow moving objects (Scaief 1975, Innes 1982). The static load test involves testing a lens material through an increase in the amount of stress applied until breakage occurs (Innes1982). In the static set up, an increasing load is applied on the lens front surface and the energy that results in lens fracture is the measure of the impact resistance. One advantage of this test is that because the load is distributed evenly throughout the lens material and mount, the lens receives the full amount of the measured load. This test is most repeatable with glass lenses. Deformability of the material makes the test unreliable for most plastics (Corzine *et al* 1996; Diallo *et al* 2001).

1.2.3 Ballistic test

The ballistic test is a high-speed test in which a small projectile is fired at the lens by compressed gas discharge from an air cannon (Rose and Stewart 1957, Innes 1982), and is said to simulate the hazard from perforating injuries caused by small objects (Wigglesworth 1971).

Material type	Scratch Resistant Coating		Anti-Reflective Coating	Scratch Resistant and Anti-Reflective Coating	Tints Solid/gradient
	1 side	2 sides			
Glass (chemically hardened or heat treated)	-	-	N/A	-	N/A
CR39 (allyl resins)	3.0	3.0	N/A	N/A	N/A
Polycarbonate	2.0	2.0	-	2.0	2.0
Trivex	2.5	2.5	-	2.5	2.5
Photochromic					
Glass	-	-	N/A	-	N/A
CR39	3.0	3.0	N/A	N/A	N/A
Polycarbonate	2.0	2.0	-	2.0	2.0
Polarized					
Glass	-	-	N/A	-	N/A
CR39	3.0	3.0	N/A	N/A	N/A
Polycarbonate	2.0	2.0	-	2.0	2.0

Table 1-2 Modified from Table 5 of CSA Z94.3-07 Canadian Standards Association (CSA) specification for minimum thickness of lens materials in mm (Canadian Standards Association 2007).

Key:

Tint = Any colour of tint, including solid or gradient, but not including pre-tinted (through and through) material. Pre-tinted materials fall under material type.

N/A = Not applicable due to the inability of the material type to meet the minimum impact requirements, regardless of minimum thickness

\- = Not available in this form

The Canadian Standards Association (CSA) Z94.3-07 ballistic impact test for industrial lenses, tests the ability of a lens material to withstand the impact of a 6.4 mm diameter steel ball travelling at a speed of 46.5 ± 0.5 m/s (Canadian Standards Association 2007). In clause 6.1.3.1.2 of the Standard a lens is said to have failed if it cracks through its entire thickness into two or more separate pieces, or if any lens material visible to normal or corrected to normal vision, including a laminar layer, if any, becomes detached from the ocular surface. Table 1.2 is taken from clause 12.2.2.4.2.1 of the CSA Z94.3-07 and shows prescription lens materials and thicknesses deemed to meet the standard.

1.3 Factors that affect impact resistance of spectacle lens materials

Factors that could affect impact resistance of ophthalmic lens materials include the power of the lens, type of lens material, laboratory surface coatings, centre thickness and temperature. Below is a brief description of each factor and reports on studies that have been done using one or more of the impact tests.

1.3.1 Centre thickness

1.3.1.1 Centre thickness and the drop ball test

Although the United States Food and Drug Administration (FDA) has no minimum thickness requirement for the dress lenses, it does require lenses to pass the drop ball test using a 5/8in ball dropped from 1.27m. However most lenses have centre thickness between 1.5mm to 2mm (Stephens 1993). This result is likely due to the fact that most studies on lens materials showed that lenses thinner than 1.5 to 2mm will not pass the drop ball test (Stephens 1993).

1.3.1.2 Centre thickness and the ballistic test

Chou *et al* (2011a) carried out a study on the resistance of selected plano plastic lenses to ballistic impact. Table 1.3 below shows tested lenses with refractive indices and centre thicknesses. The lenses were obtained in lots of 20 and flat edged to a diameter of 50mm. Lenses were hard coated, uncoated, coated with an unspecified anti-reflective (AR) coat or Hi Vision coated. The Hi Vision coat is a proprietary AR hard coat. The ballistic missile test was used to test for mean breakage speed. The material with the highest mean breakage speed of 87.6±5.0m/s was the Trivex-based Trilogy AR hard coated lenses with a refractive index n=1.53 and centre thickness of 2.0mm and the material with the lowest mean breakage speed of 29.5±1.9m/s was Hoya EYAS Hi Vision coated n= 1.60 and centre thickness of 1.9mm. Looking at similar lens materials and coatings, Hoyas EYAS with Hi Vision coat and a centre thickness of 3.0mm had a mean breakage speed of 39.6±2.2m/s. This indicates that the greater the centre thickness, the higher the impact resistance. They generally discovered that mid index materials of similar thicknesses showed varying levels of impact resistance as shown in Table 1-3. The mean breakage speed of 2.5mm thick Hoya Phoenix with hard coat (53.2±3.1m/s) and 2.5mm Hoya EYAS with Hi Vision coat (36.0±2.1m/s) might indicate that material type and form of lens coating might affect impact resistance more than the centre thickness of a material.

Lens material	Refractive index	Centre thickness (mm)	Mean threshold velocity±1 standard deviation. (m/s)
Hoya EYAS HV	1.60	1.9	29.5 ±1.9
Hoya EYAS HV	1.60	2.5	36.0 ± 2.1
Hoya EYAS HV	1.60	3.0	39.6 ±2.2
Hoya Phoenix HC	1.53	2.0	49.2 ± 3.4
Hoya Phoenix HC	1.53	2.5	53.2 ± 3.1
Hoya Phoenix HC	1.53	3.0	60.8 ± 3.4
Hoya Phoenix HC	1.53	2.0	51.2 ± 3.0
Nikon 1.67 HC	1.67	3.0	58.0 ± 3.4
Nikon 1.67 HC	1.67	3.5	61.6 ± 3.4
Younger Trilogy HC	1.53	2.0	55.7 ± 3.4
Younger Trilogy HC	1.53	2.5	53.1±3.2
Younger Trilogy HC	1.53	2.9	67.8 ± 4.2
Younger Trilogy AR HC	1.53	2.0	87.6 ± 5.0
Nikon 1.67 HC	1.67	2.0	39.6 ± 3.8
CR39 uncoated	1.498	2.0	52.5 ± 3.2
CR39 uncoated	1.498	3.0	59.3 ± 3.5
CR39 uncoated	1.498	3.5	48.6 ± 2.9
CR39 Permagard	1.498	2.0	38.6 ± 2.1

Key: HC=Hard coat AR=Anti-reflective coating HV=HiVision coating

Table 1-3 Table extracted from Chou *et al* (2011a)

1.3.1.3 Centre thickness studies done using other missiles

Johnson and Good (1996) studied ophthalmic lens retention in safety frames. This was because of a report on an ocular industrial injury where the patient was injured when the polycarbonate lens was dislodged from the eyewire of a metal safety frame. The aim of their study was to test if polycarbonate lenses were easily displaced at lower centre thicknesses. Plano polycarbonate lenses of 1.6 mm, 2.0 mm, 2.4 mm and 3.2 mm centre thickness were tested in safety frames using a blunt object of 500 g mass. The blunt object was a 1in diameter brass rod with a round tip of approximately 2 in radius and this was used to simulate low velocity impact. Based on their study, they discovered that the 1.6 mm thick polycarbonate lenses were more easily displaced from the frame. They concluded that polycarbonate industrial lenses should have a minimum thickness of 2 mm.

Chou *et al* (2005) also studied the effect of multiple antireflective coatings (MAR) and centre thickness on resistance of polycarbonate spectacle lenses to penetration by pointed missiles. In this study four groups of surfaced plano polycarbonate lenses were investigated. Two of the groups had a scratch-resistant (SR) coating applied to both surfaces. One of these groups had a 2 mm centre thickness and the other had a 3 mm centre thickness. The other two groups of 2 mm and 3 mm thick lenses had a MAR coating applied over the SR coating. A missile consisting of an industrial sewing machine needle mounted in a cylindrical aluminum carrier was used to impact the lenses.

It was discovered that the sharp missiles were able to pierce the lenses at speeds between 29.6 m/s and 46.2 m/s. The thinner lenses and lenses with the MAR coating had the lowest impact resistance. It was concluded that the presence of the MAR and reduced lens thickness contributed to the decreased impact resistance.

1.3.1.4 Centre thickness of a lens and the static load test

To my knowledge there are no studies on the effect of centre thickness on impact resistance done with the static load test.

1.3.2 Power of a lens

Since the power of the lens determines centre thickness, one might say the two factors act dependently on impact resistance. Hyperopic lenses are expected to be stronger than the myopic lenses since they have greater centre thicknesses than edge thickness (Vinger and Woods 2000). This might also mean that they are more easily dislodged from an eyewire than myopic lenses. The following studies describe the effect of power on impact resistance and in some cases the centre thickness and power of the lens material are discussed.

1.3.2.1 Power of a lens and the drop ball test

Citek *et al* (2011) studied the impact resistance of dress spectacle lenses ordered via the internet in order to evaluate the safety and compliance of the prescription lenses. Lenses were ordered from computers that could not be traced back to the authors address. Lenses were ordered specifically for research purposes and were not given out to clients. Lenses were plastic with indices of 1.50, 1.56, 1.60, 1.67 and polycarbonate. Prescriptions ranged from -4.00 to +2.25 DS, cylinder powers ranged from -0.25 to -2.25DC, axis was from 30° to 150°, and add powers ranged from +1.50 to +2.25D. A total of 400 lenses were ordered and they received 312 hard resin lenses with a refractive index of 1.56, 48 lenses with refractive index of either 1.56 or 1.58 that were not identified, 28 polycarbonate and 12 unidentified lenses with refractive index of either 1.60 or 1.61. The lenses either had a scratch resistant coating or an antireflective coating. Centre thickness ranged from 0.96 to 3.31mm. Lenses were mounted either in a metal frame or plastic frame and testing was done in an independent lab with the drop ball set up. All the polycarbonate lenses passed the drop ball test. Thirty-one out of 162 (19.1%) myopic and myopic astigmatic lenses failed the drop ball impact test while 21 out of 118 (17.8%) hyperopic and hyperopic astigmatic lenses failed. Based on the confidence interval using the binomial distribution this differences were not statistically significant. However, centre thickness for the hyperopic prescriptions ranged from 1.51mm-3.31mm and for the myopic prescriptions, 0.96 mm to 2.89 mm. Regardless of the prescription, the probability of the lens breaking was higher when the thickness was below 1.9 mm. This might indicate that the centre thickness played an important role in improving the impact resistance of the prescription lens.

1.3.2.2 Power of a lens and the ballistic test

There were few studies published which systematically examined the effect of lens power on impact resistance to ballistic missiles. One study did examine of the impact resistance of plano and –4.00 DS Transitions Plus™ lenses (Chou and Fong 1995). Their study also examined the effect of near addition design and lens coatings. The impact resistance test was for the complete spectacle to be mounted on the head form and it had to withstand the impact of a 6.4mm steel ball at 18m/s. A lens was said to have failed if it fractured, cracked with loss of 30mg of material, deformed or was penetrated by the missile. A housing failure was defined as lens dislodgement and/or cracked or fractured frame component.

- Twenty uncoated lenses made up of fifteen plano single vision lenses, five plano bifocal lenses.
- Sixteen Dura™ coated lenses made up of four plano single vision lenses, four plano straight top bifocal lenses, four plano progressive addition lenses (PAL) and four -4.00DS PAL. Dura coating is a form of proprietary hard coat used on lenses.
- Twenty Super shield™ coated lenses made up of four plano single vision lenses, four plano bifocal lenses, two plano PAL and two -4.00DS PALs. Super shield coating is another form of proprietary hard coat used on lenses.
- Twelve spin coated lenses made up of four plano single vision lenses, four plano bifocal lenses, two plano PAL and two -4.00DS PALs.

The PAL had a maximum reading addition of +2.00D. All lenses were edged to fit a metal industrial spectacle frame. The centre thickness was approximately 2mm for all the lenses except the -4.00DS

PAL that were about 4.7mm thick. All lenses passed the single hit from the steel ball travelling at 18±0.70 m/s (Chou and Fong 1995). They also concluded that front surface configuration caused by different lens designs did not affect impact resistance under their test condition at that time. Their results also indicated that, as long as a minimum centre thickness was maintained, the power of low to moderate minus power lenses did not affect the impact resistance of plastic lenses to missiles traveling at 18 m/s.

1.3.2.3 Power of a lens and the static test

To the author's knowledge there are no studies on the effect of power of a lens on impact resistance using the static method of assessment.

1.3.2.4 Power of a lens and studies found using other missiles

Bryant (1969) studied dress and industrial thickness glass and plano CR39 lenses. There were forty lenses in total. Of these lenses five were industrial prescription glass with a mean centre thickness of 3.03 mm, five dress thickness prescription glass with a mean centre thickness of 2.33 mm, five industrial thickness plano CR39 with mean centre thickness of 3.28 mm and ten prescription dress thickness single vision CR39. Of the ten CR39 single vision lenses five were -1.00 DS with a centre thickness of 1.81mm and five were -5.00 DS with a mean centre thickness of 1.69 mm. The aim was to identify the energy just sufficient to fracture the glass and plastic lens materials using the non-spherical objects. The lenses were mounted in plastic safety frames. Non-spherical impacting missiles differing in weight and configurations were used - a 5/8 in diameter steel cap screw weighing 20.62 g and a 5/8 in diameter steel nut with a hole closed on one side weighing 13.39 g. An archery bow that was strung with a standard nylon bowstring was used to propel the missiles. The archery bow was placed on a mounting in a wooden enclosure and in a horizontal orientation. All lenses were hit with the cap screw. The first notable result was that there was no significant difference amongst the fracture energies of either missile type at comparable angles and locations of impacts on similar lenses (Bryant

1969). The second result was, as expected the centre thickness decreased with increasing minus power in both material and so it is difficult to determine whether any change in impact resistance is due to the form of the lenses, centre thickness or a combination of the two factors. Nevertheless, the plano CR39 with a centre thickness of 3.28 mm had the highest impact energy at 2.39 J, whereas the -5.00DS CR39 lenses of centre thickness 1.69 mm had the lowest fracture energy of 1.26 J for the plastic lenses (Bryant 1969). Glass lenses broke at approximately half the energy level as the plastic lenses.

Vinger and Woods (2000) studied 641 plano and prescription polycarbonate lenses. Prescription lenses were either -3.00 DS or +3.00 DS. Impacting missiles were a 500 g high mass steel projectile, a 6.35 mm steel ball and a sports ball delivered by gravity, nitrogen powered air gun or an air cannon respectively. Plano lenses had the least impact energy compared to the -3.00 DS or +3.00 DS lenses of the same thickness. For any lens thickness, the -3.00 DS lenses were heavier than the +3.00 DS lenses, which were heavier than the plano lenses. They concluded that the plano lenses were more susceptible to lens failure especially if the centre thickness was less than 1.8 mm.

1.3.3 Lens material

1.3.3.1 Lens material and the drop ball test

Dain *et al* (1995) studied the impact resistance of high index (range of refractive index was not given) hard resin prescription lenses using the drop ball test. Samples of uncut prescription lenses in CR39 and high index resin were obtained from three sources. All lenses were edged. The drop ball test was done with a 16 mm diameter ball dropped from 1.27 m and if they passed at that height, the lenses were hit with a 22 mm diameter ball dropped from a height of 2.4 m. If the lens passed the drop ball test at both heights, it was hit with a 6 mm diameter ball starting at a speed of 25 m/s and rising in steps of 10 m/s until failure. All CR39 lenses were identical in their impact protection properties. On the other hand, the high index hard resin lenses ordered from the three suppliers behaved differently in impact resistance with one batch fracturing at less than half the energy, the second fractured at about

80 % the energy and the third showed increased impact resistance requiring about twice to three times the energy compared with CR39. Dain *et al* (1995) concluded that all high index hard resin lenses should not be considered equivalent.

1.3.3.2 Lens material and the static load test

To the author's knowledge there are no studies using the static load test.

1.3.3.3 Lens materials and studies found with other missiles

Polycarbonate materials are considered to be the most impact resistant material to be used for dress and industrial safety spectacle lenses (Chou *et al* 2005); however, the material is not indestructible. In a study to evaluate the penetration resistance of common spectacle and safety lens materials to high velocity projectiles, Rychwalski *et al* (2003) compared glass, polycarbonates, high index plastic and safety lens by striking them with BBs, pellets and 0.22 caliber projectiles. The maximum velocity for each of the projectiles was 221m/s, 210m/s and 290m/s respectively. The BB threshold for the glass lenses was 84.0m/s and 107.7m/s for the high index lenses. All polycarbonate lenses were not penetrated by the BBs or pellets but by the 0.22 caliber projectile. In their study, the polycarbonate lenses had the lowest centre thickness of 1.6±0.5mm. Due to the survival of the polycarbonate lenses at that thickness, they concluded that they could be excluded from the rule of minimum dress thickness of 2mm.

Vinger *et al* 1997 studied seven lenses with center thickness ranging from 1mm to 2.2mm made of high-index plastic, allyl resin plastic, heat tempered glass, chemically tempered glass and polycarbonate, and four 3.0mm centre thickness lenses made up of allyl resin plastic, heat-tempered glass, chemically tempered glass, and polycarbonate. All lenses were tested for impact resistance to 5 types of projectiles (air gun pellets, golf balls, tennis balls, lacrosse balls, and baseballs). The aim was to determine the impact energy required to shatter these lenses. The authors stated that all lenses were chosen to be -3.00DS since the incidence of eye injuries caused by spectacle lens failure was found to be greater in myopic patients. The impact test set up simulated sports injury and other forms of accidents. It was discovered based on 348 lens impacts, dress thickness and industrial lenses made from glass, allyl resin plastic, and high-index plastic shattered at impact energies less than those expected to be encountered from the test projectiles during their routine use. Polycarbonate lenses demonstrated resistance to impact for all tested projectiles exceeding the impact potential expected during routine use (Vinger *et al* 1997). This might indicate the importance of material type on impact resistance speed above prescription and centre thickness.

1.3.4 Coatings

1.3.4.1 Lens coatings and the drop ball test

To the author's knowledge there are no studies on the effect of lens coatings on impact resistance done with the drop ball test.

1.3.4.2 Lens coatings and the ballistic test

Chou and Fong (1995) studied the effect of surface coatings on impact resistance of Transitions Plus™ lenses using the CSA ballistic test for industrial eye protectors. Of the 60 lenses, 20 were uncoated, 16 had the Dura™ coat applied to both surfaces, 12 had Super shield™ coating applied to the front surface only, and 12 had a spin coating applied to the front surface. The impact speed of the steel ball was 18 ±0.70 m/s. All lenses were edged to fit a metal industrial spectacle frame and were placed on an anthropomorphic head form. All the lenses passed at this speed. They were then subjected to either 50 consecutive hits at 18m/s (until lens failure), or a single impact at 46.5m/s. While none of the Dura™ or Super shield™ coated lenses failed under multiple impacts, two uncoated lenses broke after at least 5 hits and 2 spin coated lenses developed starburst cracks after the third and thirteenth hits respectively. All lenses tested at 46.5m/s failed. All lenses but one (this failed by dislodgement from the frame on impact) were penetrated by the missile. The authors concluded that surface treatment did not affect impact resistance after a single hit by a blunt missile with moderate speed. Under multiple impacts, the uncoated or spin coated lenses became less durable with 2 failures among 17 for the former and 2 failures among 4 lenses tested for the latter. Though the numbers are too small to apply statistical tests of significance, they suggest that coatings may affect the durability of that lens material after multiple impacts (Chou and Fong 1995).

Chou and Hovis (2000) studied the durability of coated CR39 industrial lenses using the ballistic missile test. Twelve groups of CR39 lenses with various scratch-resistant (SR) or combinations of scratch-resistant and antireflective (SR-AR) coatings were mounted in metal industrial spectacle frames. Eight groups had various forms of dip coatings, 3 groups had various forms of in-mold coating and the last group was uncoated. All but two of the lens groups were of industrial thickness (3 mm). The ZEST protocol developed by King-Smith *et al* (1993) was used to determine the mean threshold breakage speed and standard deviation for each group of lenses. The ZEST algorithm is based on the ascending and descending staircase psychophysical method for determining thresholds. A lens was considered to have failed if it broke into two or more fragments, if it cracked, or if it lost material from either surface. Uncoated lenses had the highest impact speed for lens breakage. All lenses, except the groups with dip coating scratch resistant and anti-reflective coated lenses, passed the blunt impact at a speed at 18m/s. At 46m/s, only the uncoated and those with SR coating passed, but the lenses with AR coating did not pass. Application of a SR coating resulted in a decrease in impact breakage speed from 63.97 m/s to between 51.55m/s and 59.53m/s for most lens groups. Lenses with combined AR and SR coating resulted in severe reduction of the threshold breakage speeds to between 16.89m/s and 25.09m/s. They concluded that for industrial safety, CR39 hard-coated lenses could be used since the coating moderately reduced impact resistance. However the antireflective lenses did not fare well and so they discouraged using AR coated CR39 industrial lenses (Chou and Hovis 2000). Their findings were similar to Corzine *et al* (1996) and Rychwalski *et al* (2003) findings in which the anti-reflective coated lenses had the least impact resistance.

1.3.4.3 Lens coatings and the static load test

Corzine *et al* (1996) studied the effect of coatings on fracture resistance of coated and uncoated CR39 ophthalmic lenses using the static load tester. The lenses were 35uncoated CR39 lenses, 35 CR39 lenses prepared for anti-reflective coating but not actually coated, 35 CR39 anti-reflective coated, and 35 lenses with a two-sided factory scratch resistant coating. During testing, a thin sheet of Mylar ™ was placed between the lens and the steel ball to prevent flattening defects in the ball. The mean fracture energy was highest for the AR prepared lenses that were not coated, next was the uncoated lenses, followed by the two sided scratch resistance coatings and then the AR coated lenses. The static load values for the uncoated lenses were significantly higher than values for the coated lenses. These results were in qualitative agreement with the ballistic test results from Chou and Hovis (2000). The other interesting finding was that the lenses with the scratch resistant coating were thicker than the uncoated lenses.

1.3.4.4 Lens coatings and studies done using other missiles

Because the three tests for impact resistance- drop ball, static load, and ballistic test- test for impact strength using blunt missiles, Chou *et al* 2005 carried out a study using sharp pointed missiles impacted on 2mm and 3mm thick polycarbonate lenses with different surface coatings. The missile was a Singer sharp industrial sewing machine needle (Chou *et al* 2005). The sharp needles were actually able to pierce the 2mm lenses at 29.6m/s and the 3mm lenses at 46.2m/s. For the thinner lenses and lenses with the multiple layer antireflective (MAR) coating, threshold penetration speed was lower. This study showed that a pointed missile could penetrate a lens material that was considered highly impact resistant to blunt missiles. The study concluded that since the reduced thickness lenses with the MAR coating had lower impact energies, they should not be used for industrial safety lenses when there is a potential for penetrating eye injury from sharp missiles in a work setting (Chou *et al* 2005).

1.3.5 Temperature

1.3.5.1 Temperature of a lens and the drop ball test

To the author's knowledge there are no studies on the effect of temperature on impact resistance done with the drop ball test.

1.3.5.2 Temperature of a lens and the ballistic test

Keeney and Renaldo (1973) hypothesized that impact resistance increases with increasing temperature. Chou and Fong (1993) studied the impact resistance of plano CR39 and polycarbonate spectacle lenses at -10°C. Plano power finished CR39 with a centre thickness of 1.8mm and polycarbonate lenses with a centre thickness of 2.0mm were mounted in metal frames and stored overnight at a temperature of -10°C. The metal frame with the lens was placed on a head form. The combination was subjected to the ballistic test with the 6.5mm steel ball propelled from an air gun using either:

- 50 consecutive impacts or to lens failure at 18m/s or
- Single impact at 46m/s.

They concluded that at moderate speed, there is little loss of impact resistance or durability by the materials at -10°C.

Chou *et al* (2011b) carried out a study to investigate the effect of impact resistance of CR39, Trivex and Polycarbonate lenses at low temperatures. Plano lenses with centre thickness of 2.2mm and 3mm were ordered for each lens material. The ballistic missile test was used in this study and lenses were conditioned to -29°C and another batch tested at room temperature 22°C. As a result of the increased rigidity of the frozen lens material, those conditioned to -29°C showed significant reductions in impact resistance after exposure to low temperatures. The greatest effect was seen in 3.0mm polycarbonate which at 22°C could not be broken in the ballistic set up at the maximum possible speed of 100 m/s, but showed a breakage velocity of 79.4m/s at -29°C.

1.3.5.3 Temperature of a lens and the static load test

To the author's knowledge there are no studies on the effect of temperature on impact resistance done with the static load test.

1.3.5.4 Temperature of a lens and studies done using other missiles

Polycarbonate shields were discovered to lose impact resistance at decreased temperature. In 2008, a study was done on new football face shields to determine the impact speed and effect of being hit by baseballs projected by an air cannon (Baker *et al* 2008). The effect of temperature on impact resistance was also assessed. Two brands of new face shields (Nike and Oakley) with thicknesses of 2.83mm and 2.36mm were tested. During impact resistance testing, the full assembly of helmet and face shield was mounted on a head form and secured with the chinstrap. 5 new shields were cooled to -10°C for an hour and tested. There was no failure (complete fracture) with speeds up to 54m/s. The authors repeated the study in 2011 with 5 used helmet shields from the same manufacturers used in 2008. The shields were cooled to -10°C for an hour. Four of the 5 face shields broke into multiple fragments at impact speeds between 58 and 59 m/s, with pieces projected towards the eye of the head form. It was concluded that polycarbonate football face shields lose their impact resistance with usage and lower temperatures may further reduce the impact resistance of polycarbonate shield. (Zimmerman *et al* 2011)

Howes *et al* (1981) studied the impact resistance of plano CR39 lenses at 20°C, -50°C and 100°C. CR39 samples were 50mm diameter disc and 2mm thick with optical quality surface finish. Since the strength of lenses is likely to be affected by the presence of flaws or cracks, resistance to cracking under any load is important. In this study, the authors concentrated on crack initiation resistance that might lead to failure. Lens damage was considered to be any kind of cracking. The impact test set up was made up of a spherically tipped metal dart of variable mass released from a fixed height to fall freely onto a peripherally supported circular disc specimen. The impacting mass could be varied since the head of the impact was a 1mm diameter tungsten carbide sphere mounted on a steel support that could be screwed onto different lengths of steel bar. The velocity of impact was varied from 0.75m/s to 5m/s. A microscope was used after each test to determine if a ring crack had formed or not. During this test, ring cracks were never found on the CR39 at room temperature or at -50°C. However, peripheral cracks were observed at -50°C. The impact energy at room temperature was 12mJ, and at 100°C 45mJ. Results on the impact energies were only reported for the room temperature and the higher temperature. At -50 °C, the nature of the cracks changed but we were not given any value at that temperature so we do not know what to conclude from that. Howes *et al* (1981) stated that the increase in impact energy at higher temperatures is expected as a result of the softening of the plastic which modifies deformation characteristics thereby leading to increased resistance to cracking.

Chapter 2

Classifying a failed lens

2.1 Description of failure in impact resistance testing

Failure of spectacle lenses during impact resistance studies has been described in a variety of ways, including one or more of fracture of lens material, lens material broken into two, cracked lens or loss of material from either side (Chou and Hovis 2003, Chou *et al* 2011a, Baker *et al* 2008). Other terminologies used to describe lens failure are lens material dislodgement, shattering or perforation (Vinger and Woods 2000). The fact that different studies identify lens failure with different terminologies suggests that examiners are interpreting failure based on their understanding or interpretation of whatever Standard the researcher used during their study. This could be problematic. CSA Z94.3-07, Clause 6.1.3.1 defines lens failure as "a crack through its entire thickness into two or more separate pieces, or if any lens material visible to normal or corrected-to-normal vision, including a laminar layer, if any, becomes detached from the ocular surface" (Canadian Standards Association 2007). Since no pictorial exemplar for lens failure exists in the CSA clause, it is possible individuals could set their own criteria based on their reading of the definition.

2.2 Perception/rating of spectacle lens failure

To the author's knowledge there are no studies comparing observer's ratings of lens failures. However, two studies were found comparing observers ranking on lens surface damage. In a study by Honson *et al* (1986), a visual ranking was used to judge the amount of abrasion present in a group of lenses. Ten types of lenses, including glass, coated and uncoated CR39, crystallite and coated and uncoated polycarbonates were studied. Between two and five samples were obtained for each lens type. The lens under study was placed against a backdrop of black felt under fluorescent illumination. Lenses were ranked thrice by two observers in a masked fashion for the severity of abrasion and results were averaged for lens type. The glass lens was ranked with the least amount of abrasion. The researchers expected that the lens with the most abrasion would scatter the most light. This was confirmed with a Tektronics J16 digital photometer with a luminance probe mounted on a tripod and directed to the abraded portion of the lens. The light reflected from a particular section could then be measured as the amount of scattered light in each lens. Glass scattered the least light and so was expected to have the least abrasion as predicted by the observers. On the other hand, the uncoated CR39 seemed to scatter less light than the crystallite group. Despite this, the observers ranked the uncoated CR39 as more abraded than the crystallite that scattered more light (Honson *et al* 1986). This study shows that individual perception of lens quality or damage may not necessarily reflect the real extent of lens damage.

Chou and Hovis (2003) did a study to determine the effect of coatings on impact resistance of CR39 industrial plano lenses to ballistic impacts and abrasion from fine particles. After the lenses had been hit and depending on whether they survived the initial hit, one pair of lenses from each group was tested for abrasion resistance with the falling sand method. The falling sand method is one of several tests that have been used to rate the abrasion resistance of ophthalmic lens surfaces. Although samples placed on the tester turntable should be flat, the samples used for this study were cut from ophthalmic lenses with, approximately, a 6 D base curve. Thus, this abrasion method could have exaggerated the wear and tear on lens surfaces from cleaning and handling. The reference glass samples used in the test were also convex, so this eliminated sample surface shape as a factor.

According to the EN-168 protocol at that time, abrasion resistance is evaluated by measuring the amount of light scattered by the lens. Because the researchers lacked access to the required equipment for this evaluation method, a visual comparison method was used to rate the haze of the abraded samples relative to the glass references. This was a qualitative measure of backscattered light. Rating values lower than the glass reference indicated that the sample was noticeably more transparent than the glass sample. The abrasion resistance was then ranked by the degree of haze observed by three independent observers. Unfortunately there was no data to indicate agreement between the observers' ranking. Lenses were viewed against a black background at an illumination of 350lux. Though observers were blind to lens material type during testing, it is possible that the presence of the reference glass lens made it easier for them to judge the abrasion resistance of the lenses given. This might mean that having an exemplar would help with classifying lenses.

Winder *et al* (1998) carried out a survey of eye safety knowledge and attitudes of mine workers to awareness of importance of eye safety at work. A total of 236 mineworkers completed the questionnaire. When the miners were asked if they were aware of any rules on eye protection operating at that time and if the rules were written down in a manual, 76% of miners were aware of written rules for eye protection. The rest of the miners answered that they did not know, or could not remember, whether written policies existed in their mines. Written rules actually existed at that time and were displayed at locations or jobs where eye protection should be worn. This might be an issue of lack of attention in training programs or an issue of forgetting what written rules and policies state. Although a large number of respondents indicated that they had seen the written rules, a number of responses indicated that they "can't remember". These responses, according to Winder *et al* (1998), indicate inadequate attention of workers to the details of eye hazard recognition and eye protection practices.

Lombardi *et al* (2009) studied factors influencing workers use of personal protective eye wear (PPE). The aim was to identify factors that influence workers decision to wear PPE and the barriers that exist in preventing their use. Workers and supervisors from construction, manufacturing or service/ retail industries were questioned. Participants were 18 to 70 years of age and had potential exposure to occupational eye injury hazards. Lombardi *et al* (2009) identified that some complained that "the eyewear were scratched and they felt dirt or grease may affect the usage and inhibit their usage". Of the people questioned, 85.7% also suggested that lack of enforcement affected their decision to wear their PPE. When asked for suggestions on ways to increase the PPE usage, 100% suggested the use of training and videos to encourage use, while 85% suggested the use of enforcement or reinforcement. They may also need to be reminded of policies that exist in the work place regarding PPE usage (Lombardi *et al* 2009). These might indicate the need for safety training programs in addition to those provided by the employers.

Chapter 3

Impact resistance study

3.1 Purpose

The purpose of this study was to determine the impact resistance of a mid-index organic lens material, Hi-Vex (n=1.56), at different temperatures. The outcome of this study would determine if the 3mm Hi-Vex could be used for safety eyewear. If new lens materials with higher refractive index can be shown to have better optical quality and comparable impact resistance to polycarbonate lenses, this would expand the choice of safety lens materials available. An expanded choice may make industrial and sports eye protectors more acceptable to the Canadian public and therefore enhance public safety. The results from this study will be submitted to the Canadian Standards Association for inclusion in the next edition of the Z94.3 standard. This study was designed with the following objective:

- To determine the impact resistance of ophthalmic lens material with refractive index 1.56 relative to CR39 lenses at 24°C, -29°C, -49°C and 50°C.

3.2 General approach

Lens materials were CR39 (n=1.498) and a mid-index organic lens Hi-Vex (n=1.56). Mean breakage speed was compared within and between both lens materials at 4 temperatures. The ballistic impact test was used with the Zippy estimation by sequential testing (ZEST) programme developed by King-Smith *et al* (1993) to estimate the threshold breakage speed for each lens material at each temperature. The ZEST protocol developed by King-Smith *et al* (1993) was used to determine the mean threshold breakage speed and standard deviation for each group of lenses. The long-term goal was to determine the impact resistance for the new lens material and the effect of temperature change on impact resistance.

3.3 Inclusion Criteria

Hard coated CR39 and hard coated Hi-Vex lenses ordered from Centennial Optical Limited, Toronto, Ontario, Canada, through the optical dispensary at the School of Optometry and Vision Science, University of Waterloo, Ontario, Canada. Lenses were plano with a nominal centre thickness of 3mm. All lenses were cut to 50mm diameter and edged to achieve the Hide-a-Bevel® form.

3.4 Procedure

Lenses were inspected with the Ronchi grating test, which is a quick qualitative method to evaluate overall optical quality of a lens by the presence and absence of waves and distortions in an illuminated grid. The centre thickness and refractive power of each lens were checked for accuracy using the Vernier calipers and focimeter at room temperature. The mean and standard deviation of each batch of lenses was calculated.

Amongst the 80 lenses for each material, 20 lenses were frozen to -29°C for four hours; another 20 lenses were frozen to -49°C for four hours; another twenty heated up to 50°C for four hours and the last batch of 20 were tested at room temperature 24°C. To achieve the temperature of -29°C, lenses were placed in a deep freezer set to a temperature of -29°C. To achieve the temperature of -49°C, 1kg of dry ice was used to freeze the lenses in a Styrofoam container. The temperature was monitored with a remote sensing thermometer. To achieve the temperature at 50°C, lenses were placed in an incubator set to the desired temperature.

Each lens was placed into the lens mount. The speed of the air gun was changed by adjusting the air valve. The initial test velocity used was based on existing data on ballistic impact resistance. To achieve the desired missile speed, the pressure was adjusted in the air gun system to propel a steel ball with diameter 6.4mm at the centre of the lens. The ZEST program was used to determine a nominal speed for subsequent impacts. The criteria for lens failure were in accordance with the CSA criteria. The ZEST computer program is based on the ascending and descending staircase psychophysical method for determining thresholds (King-Smith *et al*, 1993). After each hit, the lens was inspected for breakage, cracking or loss of material and recorded as observed. The lens was then replaced with a new unused sample for testing at higher speed. The speed for the ball was adjusted based on the performance of the previous sample lens. If the lens broke, the speed was reduced and if it did not break it was increased. A threshold mean impact speed and standard deviation was then calculated with the ZEST program for each material and test condition.

3.5 Statistical Analysis

Statistical decisions on lens performance were based on the International Organization for Standardization (2008) ISO Guide to the expression of uncertainty in measurement (GUM) method using means and combined uncertainties of the data. To compare pairs of means (mean1 and mean2), the combined uncertainties (U1 and U2) were compared with the difference in the mean to give an En ratio.

$$En = \frac{mean_1 - mean_2}{\sqrt{(U_1^2 + U_2^2)}}$$

Absolute values of En ≥ 1.0 indicate significantly different values between samples. International Organization for Standardization (2008).

3.6 Results

The means and standard deviations of the lens thicknesses and mean powers of individual lens properties are listed in Appendix A and B. Appendix C shows ZEST parameters and output for the CR39 and Hi-Vex lenses tested. Table 3-1 shows comparison between each lens material power measured at room temperature for lenses of the same material assigned to the different temperature conditions. There was no significant difference for any comparison.

Comparison of hot and cold lenses to the room temperature lenses.	**CR39 or Hi-Vex assigned to 24°C**			**CR39 or Hi-Vex assigned to other temperature conditions**			**Comparison**
	Mean lens power	**Standard deviation**	**Standard uncertainty** U_1^2	**Mean lens power**	**Standard deviation**	**Standard uncertainty** U_2^2	**En ratio**
CR39 24°C vs CR39 -29°C	0.012	0.066	0.000871	-0.012	0.066	0.00087	0.57
CR39 24°C vs CR39 -49°C	0.012	0.066	0.000871	-0.018	0.070	0.00098	0.70
CR39 24°C vs CR39 50°C	0.012	0.066	0.000871	0.03	0.053	0.00056	-0.47
Hi-Vex 24°C vs Hi-Vex -29°C	0.012	0.066	0.000871	-0.03	0.094	0.00177	0.82
Hi-Vex 24°C vs Hi-Vex -49°C	0.012	0.066	0.000871	0.018	0.058	0.00067	-0.15
Hi-Vex 24°C vs Hi-Vex 50°C	0.012	0.066	0.000871	0.006	0.047	0.00044	0.16

Table 3-1 GUM tests of significance comparing the lens power between each lens material assigned to 24°C and the three temperature conditions. These lens powers were all measured at room temperature.

Table 3-2 compares lens material power assigned to the four temperature conditions. The mean power between lens materials was not significantly different for any comparison.

Comparison of both materials at the four temperature conditions.	**Hi-Vex assigned to various temperatures**			**CR39 assigned to various temperatures**			
	Mean lens power	**Standard deviation**	**Standard uncertainty** U_1^2	**Mean lens power**	**Standard deviation**	**Standard uncertainty** U_2^2	**En ratio**
Hi-Vex -29°C vs CR39 -29°C	-0.03	0.094	0.0018	-0.012	0.066	0.0009	-0.35
Hi-Vex 24°C vs CR39 24°C	0.012	0.066	0.0009	0.012	0.066	0.0009	0
Hi-Vex 50°C vs CR39 50°C	0.006	0.047	0.0004	0.03	0.053	0.0006	-0.76
Hi-Vex - 49°C vs CR39 -49°C	0.018	0.058	0.0007	-0.018	0.070	0.00098	0.88

Table 3-2 GUM tests of significance comparing the lens power between each lens material assigned to the four temperature conditions. The powers were all measured at room temperature.

Table 3-3 shows the comparison of centre thicknesses for the lenses assigned to the different temperatures relative to the room temperature group within each material. All but three comparisons were significantly different. These were the comparisons between the CR39 at room temperature and the -49°C group, comparison between the Hi-Vex at room temperature and the -49°C group and between the Hi-Vex at room temperature and the 50°C group. For the other comparisons, the lenses assigned to the room temperature condition were significantly thicker than the lenses assigned to the other temperatures within each material.

Comparison of hot and cold lenses to the room temperature lenses.	**CR39 or Hi-Vex assigned to 24°C**			**CR39 or Hi-Vex assigned to other temperature conditions**			**Comparison**
	Mean lens thickness	**Standard deviation**	**Standard uncertainty** U_1^2	**Mean lens thickness**	**Standard deviation**	**Standard uncertainty** U_2^2	**En ratio**
CR39 24°C vs CR39 -29°C	3.15	0.06	0.00072	3.10	0.01	2.42E-05	1.83
CR39 24°C vs CR39 -49°C	3.15	0.06	0.00072	3.13	0.06	0.00072	0.53
CR39 24°C vs CR39 50°C	3.15	0.06	0.00072	3.05	0.07	0.00090	2.49
Hi-Vex 24°C vs Hi-Vex -29°C	3.22	0.05	0.0005	3.02	0.04	0.00027	7.18
Hi-Vex 24°C vs Hi-Vex -49°C	3.22	0.05	0.0005	3.25	0.08	0.00128	-0.71
Hi-Vex 24°C vs Hi-Vex 50°C	3.22	0.05	0.0005	3.23	0.04	0.00039	-0.33

Table 3-3 GUM tests of significance comparing centre thickness between each lens material assigned to 24°C and those assigned to the three temperature conditions. All measurements were done at room temperature.

Table 3-4 also shows the comparisons of centre thickness between lens materials assigned to the same temperature condition. With the exception of one temperature condition, the Hi-Vex lenses were significantly thicker than the CR39 assigned to the same temperature. The exception was the -29°C condition where the CR39 lenses were significantly thicker than the Hi-Vex lenses.

Comparison of both materials at the four temperature conditions.	**Hi-Vex assigned to various temperatures**			**CR39 assigned to various temperatures**			
	Mean lens thickness	**Standard deviation**	**Standard uncertainty** U_1^2	**Mean lens thickness**	**Standard deviation**	**Standard uncertainty** U_2^2	**En ratio**
Hi-Vex -29°C vs CR39 -29°C	3.02	0.037	0.00027	3.10	0.01	2.42E-05	-4.63
Hi-Vex 24°C vs CR39 24°C	3.22	0.055	0.00060	3.15	0.06	0.00072	2.00
Hi-Vex 50°C vs CR39 50°C	3.23	0.044	0.00039	3.05	0.07	0.00090	5.02
Hi-Vex - 49°C vs CR39 -49°C	3.25	0.08	0.0013	3.13	0.06	0.00072	2.68

Table 3-4 GUM tests of significance comparing both centre thickness of each Lens material at the four temperature condition.

Although there were statistically significant differences between centre thicknesses, the largest difference was only 0.2 mm. Based on data from Chou *et al* (2011a), the difference in mean breakage speed for 0.2 mm difference in centre thickness would be 1.72 m/s for CR39 and 2.32 m/s for materials similar to Hi-Vex. Thus, if there was a significant difference in centre thickness between any two lens groups and this difference was the only factor influencing breakage speed, then one would expect a difference in mean breakage speed of approximately 2 m/s.

Figure 3.1 shows mean velocities and standard deviations for each lens material and temperature. Lens with the highest and lowest impact breakage speed was Hi-Vex at -49°C and CR39 at -49°C respectively. For all temperature conditions tested, Hi-Vex had the higher breakage speed.

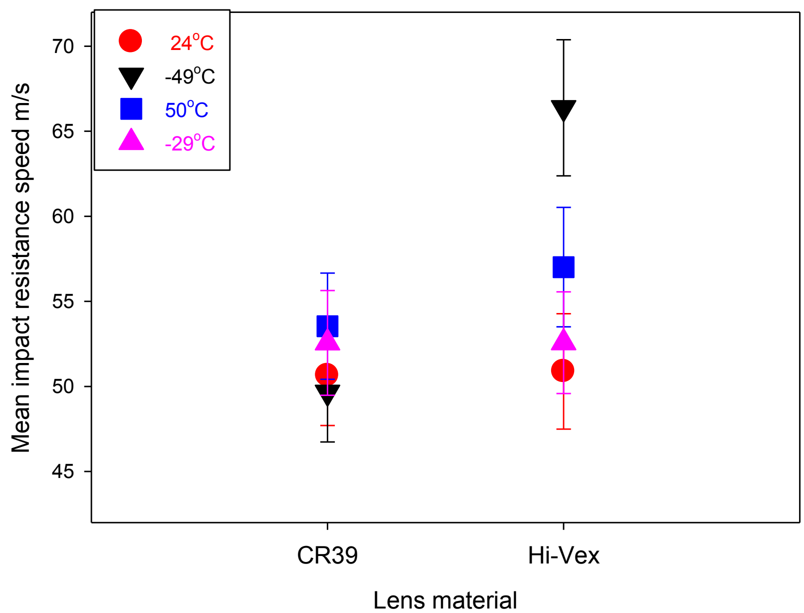


Figure 3-1 Mean impact velocities (m/s) and standard deviations of the lens material at each temperature.

Table 3-5 shows comparison of each material at room temperature conditions to the other temperature conditions for each material. One result that was common to both materials was that mean breakage speeds were significantly higher 50° C than at room temperature. The increase in breakage speed at this temperature was greater for the Hi-Vex material. The Hi-Vex material also had a significantly higher breakage speed at the other temperature extreme of -49°C, but not -29°C. The breakage speed for CR39 was significantly higher at -29° C, but not at -49°C compared to room temperature values. The difference at -29° C was relatively small and suggestive that centre thickness differences could have played a role. However, the room temperature lenses were actually the thicker lenses, on average, and they had the lower breakage speed. If centre thickness did play a role at this temperature, then it is likely that the difference between the breakage speeds shown in Table 3-5 is less than the value would have been if the centre thickness were equal, because the room temperature lens was thicker but had a lower breakage speed compared to the -29°C group. Note that the centre thicknesses between the room temperature lenses and the -49°C where statistically identical and so it is unlikely that differences in centre thickness for these groups of lenses affected the mean breakage speed.

Comparison of hot and cold lenses to the room temperature lenses.	**CR39 or Hi-Vex assigned to 24**°C			**CR39 or Hi-Vex assigned to other temperature conditions**			**Comparison**
	Mean breakage speed	**Standard deviation**	**Standard uncertainty** U_1^2	**Mean breakage speed**	**Standard deviation**	**Standard uncertainty** U_2^2	**En ratio**
CR39 24°C vs CR39 -29°C	50.64	2.94	1.73	52.56	3.08	1.90	-1.01
CR39 24°C vs CR39 -49°C	50.64	2.94	1.73	49.66	2.92	1.71	0.53
CR39 24°C vs CR39 50°C	50.64	2.94	1.73	53.54	3.12	1.95	-1.51
Hi-Vex 24°C vs Hi-Vex -29°C	50.88	3.39	2.30	52.57	2.99	1.79	-0.84
Hi-Vex 24°C vs Hi-Vex -49°C	50.88	3.39	2.30	66.38	4	3.2	-6.61
Hi-Vex 24°C vs Hi-Vex 50°C	50.88	3.39	2.30	57.01	3.51	2.46	-2.81

Table 3-5 GUM tests of significance comparing mean breakage speed of each Lens material at 24°C with those assigned to the three temperature conditions.

Table 3-6 shows comparison of both materials at the four temperature conditions. It was only at the extreme temperatures that the impact speeds were significantly different. The Hi-Vex material had significantly higher impact speeds at -49°C and 50°C than the CR39 lenses. Although the Hi-Vex lenses assigned to these temperatures were thicker than the CR39 lenses, the difference in breakage speeds was greater than 2m/s benchmark based on Chou et al's results.

Comparison of both materials at the four temperature conditions.	**Hi-Vex assigned to various temperatures**			**CR39 assigned to various temperatures**			
	Mean Breakage Speed m/s	**Standard deviation**	**Standard uncertainty** U_1^2	**Mean Breakage Speed m/s**	**Standard deviation**	**Standard uncertainty** U_2^2	**En ratio**
Hi-Vex -29°C vs CR39 -29°C	52.57	2.99	1.79	52.56	3.08	1.90	0.005
Hi-Vex 24°C vs CR39 24°C	50.88	3.39	2.30	50.64	2.94	1.73	0.12
Hi-Vex 50°C vs CR39 50°C	57.01	3.51	2.46	53.54	3.12	1.95	1.65
Hi-Vex - 49°C vs CR39 -49°C	66.38	4	3.2	49.66	2.92	1.71	7.55

Table 3-6 GUM tests of significance comparing mean breakage speed between each Lens material assigned to the four temperature conditions.

3.7 Discussion

This is the first study to report on the impact resistance of the Hi-Vex lens material and how temperature affects its impact resistance at different temperatures. The average impact speed for failure of the Hi-Vex lenses at room temperature and -29^{o}C was not significantly different from the CR39 lenses at the same temperatures. The breakage speeds ranged from 50 to 52 m/s. This range is also similar to the hard coated CR39 breakage speeds found in previous studies (Chou *et al* 2005, Chou and Hovis 2003). Other mid-index lens materials also appear to behave similarly to CR39 in ballistic impact testing done at room temperature. In a study by Chou and Hovis (2006) the mean breakage speed of a material similar to the Hi-Vex (plastic with an n=1.53) had breakage speed ranging from 50m/s to 62m/s.

In terms of impact resistance, the Hi-Vex material performed better at the extreme temperature conditions of 50°C and -49°C. The Hi-Vex lens had significantly higher breakage speeds at these temperatures when compared to its room temperature value and the CR39 material. Interestingly the CR39 lenses only showed a small but a significant, increase in breakage speed at -29^{o}C when compared to its room temperature value, but not at the -49 ^{o}C. The higher breakage speeds of the Hi-Vex material at the cold temperatures were probably related to the material. Gloor (1947) stated that certain plasticizers such as mineral oil could promote low temperature impact strength and perhaps an increased intrinsic viscosity was improved. Further studies could be done to look at the viscosity of lens materials at subzero temperature. Also the Hi-Vex Lenses performed better at 50 ^{o}C. This could be a result of the softening of the material at that temperature making it more flexible before breaking on impact. Conversely at -49^{o}C, the material is becoming more rigid and more prone to brittle failure as we have seen.

The CR39 data showed that mean breakage speed of CR39 at 24°C and -29°C was 50.64±2.94m/s and 52.56±3.08m/s. These breakage speeds for CR39 were lower than the mean speed of 59.3±3.5m/s with the ballistic test reported by Chou *et al* (2011a) for 3mm CR39 uncoated lenses at room temperature, but higher than found in other studies. Chou *et al* (2011b) reported an impact speed of 39.61±0.093m/s and 37.99±1.97m/s at 22°C and -29°C respectively. This was significantly different using the GUM analysis. Table 3-7 below shows this comparison.

Comparison	CR39 from current study			CR39 from Chou et al's study			
	Mean speed m/s	**Standard deviation**	**Standard uncertainty**	**Mean speed m/s**	**Standard deviation**	**Standard uncertainty**	**En ratio**
CR39 3.1mm -29°C current study vs Chou *et al* CR39 3.3 mm -29°C	52.56	3.08	1.90	37.99	1.97	0.62	9.18
CR39 3.15mm 24°C current study vs Chou *et al* CR39 3.3 mm 22°C	50.64	2.94	1.73	39.61	0.09	0.001	8.39

Table 3-7 Comparison of current CR39 mean breakage speed with previous study by Chou *et al* 2011b).

The differences may be attributed to the different sources of the lenses. The CR39 lenses used for this study were a different brand compared to Chou *et al*'s study (2011b) and there could be differences in the impact breakage speed that were due to differences in the hard coat or batch-to-batch variations in both the hard coat or polymerization processes (Chou, private communication). This was not the first time that a particular lens material from different suppliers has behaved differently when tested. In Dain *et al* (1995) the impact resistance of high index hard resin prescription lenses was studied using the drop ball test. Lens samples that were made up of uncut prescription lenses in CR39 and high index resin were obtained from three sources. Although all the CR39 lenses were identical in their impact protection properties, the hard resin lenses ordered from three suppliers behaved differently with one batch fracturing at less than half the energy, the second fractured at about 80 percent the energy and the third showed increased impact resistance requiring about twice to three times the energy compared with CR39. Dain *et al* (1995) concluded that all high index hard resin lenses should not be considered equivalent (Dain *et al* 1995). It is possible differences in the manufacturing process at different locations could affect impact resistance quality of a lens sample.

Furthermore, Chou and Hovis (2003) in their study on the durability of coated CR39 industrial lenses discovered that with the ballistic set up two CR39 lens materials with similar characteristics ordered from different suppliers/manufactures behaved differently. The CR39 were 3mm thick and had dip coating proprietary scratch resistance coating on them. One of them fractured at a speed of 57.28 ±3.35m/s and the other at 42.78±2.52m/s. Both lenses were tested with the CSA ballistic set up at a speed of 18m/s and if they survived they were subjected to 46.5m/s. Both brands of CR39 survived the 18m/s speed test but just one of them passed the 46.5m/s test. This result further supports our findings that similar lens materials ordered from different manufactures or suppliers can behave differently in terms of their impact resistance.

The variation in the mean breakage speeds reported by the different studies show that the values for CR39 do vary and for some samples the breakage speed is below the CSA requirement even though the lens had the required centre thickness and acceptable coatings. These unpublished results, in particular, suggest that the CSA practice of approving lens material based on centre thickness should be reviewed.

The present study shows that when subjected to the CSA ballistic impact test, hard coated Hi-Vex lenses of 3mm thickness met or exceeded the CSA requirements for impact resistance. None of the lenses tested broke at a speed less than 46m/s. Table 3-8 shows the mean breakage speeds and centre thickness for each lens material and at each temperature condition. Hi-Vex lenses tested at -49°C had the highest mean breakage speed of 66.38m/s. Table 3-8 compares the threshold breakage speed and threshold impact energy with the energy levels associated with the ANSI drop ball and CSA ballistic impact requirements for industrial spectacle lenses. The mean impact energy for this group of lenses was uniformly above the impact energy for the CSA high speed ballistic impact resistance test and the ANSI 1 in drop ball test.

Lens group	**Mean breakage speed (m/s)**	**Impact energy (J)**
CR39 -49°C	49.66±2.92	**1.25**
CR39 24°C	50.64±2.94	**1.30**
Hi-Vex 24°C	50.88±3.39	**1.31**
Hi-Vex -29°C	52.57±2.99	**1.40**
CR39 -29°C	52.56±3.08	**1.40**
CR39 50°C	53.54±3.12	**1.45**
Hi-Vex 50°C	57.01±3.51	**1.65**
Hi-Vex -49°C	66.38±4.00	**2.24**
The data below were not measured		
1in drop ball (ANSI Z87.1)	**N/A**	**0.80**
Ballistic test (CSA Z94.3-07, ANSI Z87.1)	**46.5**	**1.10**

Table 3-8 Results by speed and impact energy for each lens at the various temperatures, the corresponding breakage speed and impact energy are shown for the ANSI standard and CSA Standard. The ANSI and CSA tests are done at room temperature.

Although our results indicate that these lenses are suitable for use in occupational, sports, and leisure activities where there is a high risk of exposure to high-speed flying particles, the Hi-Vex material did have an impact breakage speed that was below Trivex and polycarbonate. There also remains the issue as to whether the repeatability in the breakage speeds remains above the CSA requirements for different batches of the Hi-Vex material and surface treatments.

Chapter 4

Perception of spectacle lens failure based on the criteria of Canadian Standards Association Z94.3-07 Standard

4.1 Purpose

This study was designed to compare the perception of spectacle lens failure among individuals after reading the CSA criteria for lens failure.

4.2 General approach

Participants were graduate students in the Vision Science program and patients at the public clinic located in the School of Optometry and Vision Science, University of Waterloo. Both groups were naïve to impact resistance testing and terminologies. They were instructed to classify each lens of a batch of impacted spectacle lenses as either pass or fail based on the text of the CSA standard. Their results were compared to the classifications by two researchers experienced in the interpretation of lens failures. The goal was to identify if simply reading the definition of a lens failure was sufficient for different groups of subjects.

4.3 Inclusion criteria

- Graduate students from the Vision Science program, at the School of Optometry and Vision Science Waterloo, ON, Canada.
- Patients visiting the Public Clinic at the School of Optometry and Vision Science, University of Waterloo ON, Canada.
- Participants must have no knowledge or experience of impact resistance testing or terminologies.

4.4 Procedure

Ten graduate students and 10 patients from the public were shown 25 spectacle lenses that had been subjected to ballistic impact. They were asked to classify the lenses as either a pass or fail after reading the definition of a failure under the ballistic impact test in the Canadian Standards Association Standard CSA Z94.3-07, clause 6.1.3.1. Lenses were presented to the participants in the same order. Participants were not allowed to ask questions on how to interpret the criteria while classifying the lenses. The responses of both groups of participants were compared to the classification of two researchers experienced in interpretation of the Standard and who agreed on 100% of the lens outcomes.

4.5 Results

The characteristics of all twenty-five lenses and the researchers' point of view are displayed in Appendix D. There were twelve passed lenses and thirteen failed lenses according to the researchers' classification. Figure 4-1 shows the percentage agreement of the graduate students and public for each lens classified as passed. There was only one lens (lens 8) where all the subjects in one group, the graduate students, agreed with the researches as to whether the lens passed. For the rest of the lenses, both the graduate students and public classified the lenses as a failure instead of a pass.

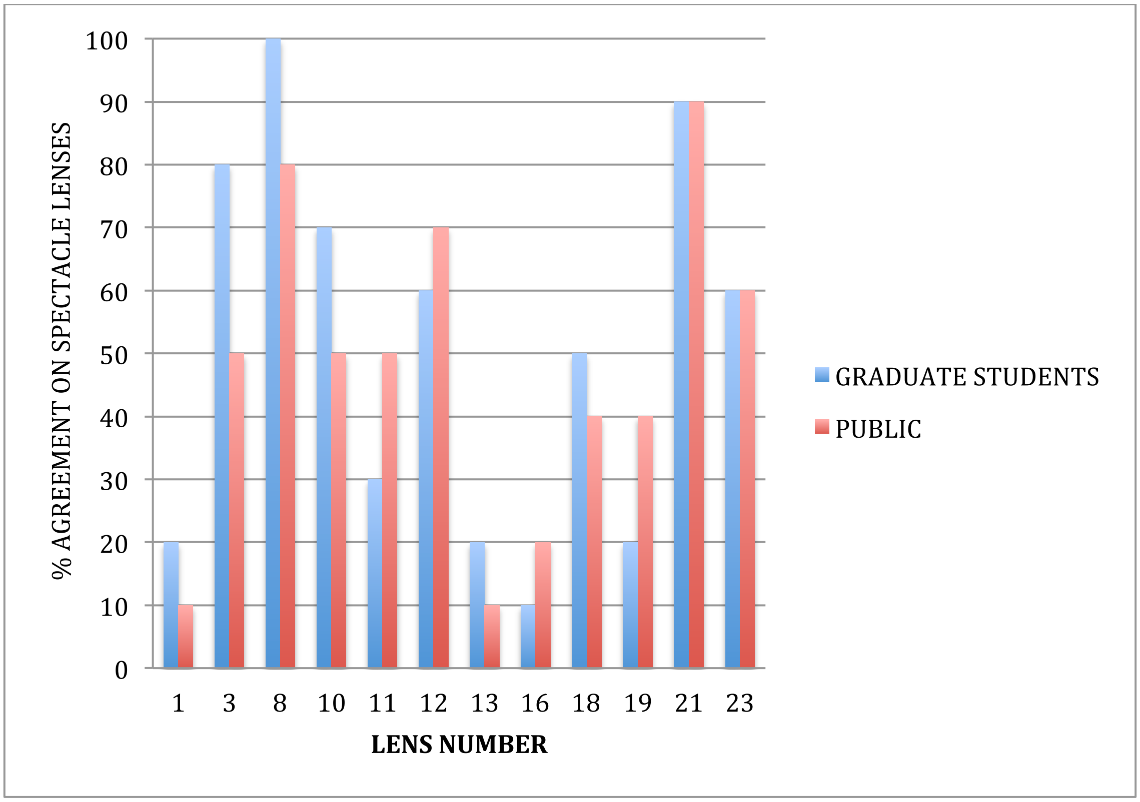


Figure 4-1 Percentage agreement of the graduate students and public with the researchers results on lenses that passed the requirement.

There was no statistically significant difference between the graduate students and public as to the overall frequency in rating the lenses as a pass (Mann-Whitney U Statistic= 65.500 P = 0.727). To further understand the characteristics of the lenses in this group and why the participants had difficulty classifying them, we divided the agreement into lenses that fell within specific percentages and arrived at low (10-40%), moderate (50-80%) and high agreement (90-100%).

Table 4-1 shows these sample lenses from the groups classified as low, moderate and high agreement. From the characteristic of the lenses, we found that it was more likely for the participants to agree with the researchers on passed lenses when there was either a single dent or crack in the lens. An example is found in Lens 8 shown in Table 4-1. When there appeared to be more than one crack, participants classified it as a fail though the lens was still in one piece with no loss of material. An example is Lens 1 shown also in Table 4-1.

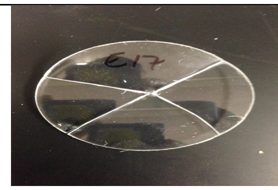
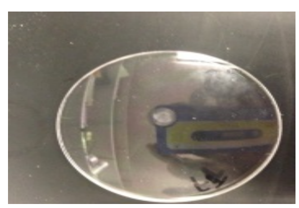
LENS NUMBER	AGREEMENT CATEGORY	SAMPLE LENS OF THE GROUP	COMMENT
1,11,13,16,19	10-40%	 LENS 1	All lenses had cracks through them thought the lens was in one piece. There was no loss of lens material
3,10,12,18,23	50-80%	 LENS 20	Most lenses in this group had a part of the lens material missing
8,21	90-100%	 LENS 8	Lens 8 had a single dent in the middle while lens 21 had a crack. There was no loss of material in both lenses.

Table 4-1 Examples of lenses classified as passed by the experienced researchers and the percentage of naive subjects that agreed with this classification.

Figure 4-2 shows percentage agreement of the graduate students and public with the experienced researchers as to whether the lenses failed the impact resistance criterion. There were five lenses for which 100% of the graduate students agreed with the researchers' classification. There were only 2 of these lenses for which 100% subjects of the public agreed with researchers. The figure shows that there was a tendency for the public to classify the failed lens as a pass compared to the graduate students. However, the tendency was not statistically significant (Mann-Whitney U Statistic= 59.000 P = 0.190).

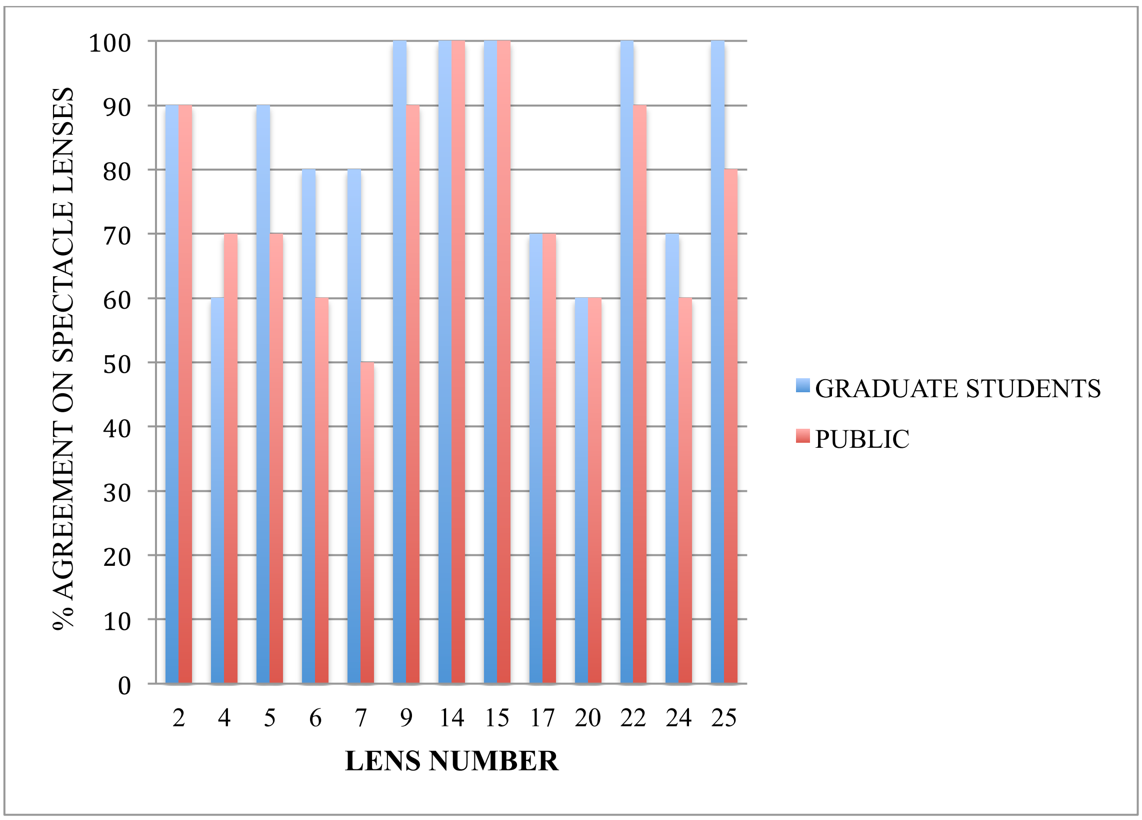


Figure 4-2 Percentage agreement of the graduate students and public with the researchers results on lenses that failed to meet the requirement.

Similar to the lenses that passed the impact resistance definition, we divided the lenses into two categories of moderate (50-80%) and high agreement (90-100%) to help determine why the subjects disagreed with the classification. There were no lenses that would fall into the low agreement category (10-40% agreement). This indicates that participants were more likely to agree with the researchers on failed lenses. Table 4-2 shows characteristics of lenses. Nearly all the subjects agreed that the lens failed when it was broken into multiple pieces. The result that is somewhat surprising was that it was not always the case. Looking at the characteristics of the lenses in the high agreement group, participants were not able to identify failure when a missing piece existed. Lenses in the moderate group had loss of lens material but participants might have called it a pass because the affected area was in the middle and did not radiate to the edges or they simply didn't notice the missing piece. It is possible this confused the participants.

LENS NUMBER	AGREEMENT CATEGORY	SAMPLE LENS OF THE GROUP	COMMENT
4,6,7,17,20,24	50-80%	 LENS 20	Most lenses in this group had a part of the lens material missing
2,5,9,14,15,22,25	90-100%	 LENS 15	All lenses in this category were actually broken into pieces of 2 or more.

Table 4-2 Examples of lenses classified as failed by the researchers and the percentage of naive subjects that agreed with this classification.

4.6 Discussion

Of the twenty-five lenses given to observers, there were only two lenses in which all participants agreed with the outcome of the experienced researchers. These were failed lenses that were broken into two or more pieces. If there was any visible damage to the lens as a result of the impact, at least one person would classify the lens as a failure regardless of whether the damage met the CSA definition of a failure. It was easier for participants to identify most failed lenses. This might be because of the visible separation of the lens pieces.

This sort of disagreement between expected finding and individual ranking/agreement has been seen by Honson *et al (*1986). They discovered a lack of agreement between lens characteristics classified by their observers and the objective photometric results. This study shows that individual perception of lens quality or damage may not necessarily reflect the real physical extent of lens damage. Perhaps individuals have their own criteria or understanding of what a damaged lens is since no pictorial exemplar exists to show lens defects. This might mean that the observer's ability to classifying lenses is difficult and that simply reading the definition of a lens failure is insufficient and visual exemplars are necessary in order to understand CSA criteria, or any classification criterion. Note that not all lenses were correctly identified as failed. For these lenses, it was obvious that either the loss of lens material and the fact that the cracks did not completely radiate to the edges of the lens might have confused the participants, This might mean visual examples would help in identifying failed lenses in these situations.

Winder *et al* (1998) results indicate that there is often inadequate attention paid to written policies on eye safety in the workplace. This inadequate attention could be regular review of the polices and ensuring the workers understand the policy. Our results suggest that this problem is also present in the public. Whether we are testing an assumed to be higher educated group, such as graduate students, or a public sample visiting their eye care practitioner, the public did not appear to understand the CSA criteria as it is written. The majority of the participants complained about the wording of the CSA Standard and wanted more explanation for terms like “laminar”. It is possible this affected their interpretation of the Standard’s criteria. This might explain why the participants could not classify the lenses according the CSA written criteria they had read because they could not remember it or they didn’t understand it. There were no questions allowed concerning the criterion and its meaning. Our results suggest that workplace safety committees may have difficulty in interpreting the CSA standard which makes their task of evaluating protective eye wear more challenging.

The findings from this study could help workplace health and safety committee members have a better idea regarding how their workers might perceive damaged lenses in eye protectors. The study shows that since there were disagreements over the status of some lenses, it is possible lay members of the health and safety committee may feel that a lens in an eye protector that shows damage or breaks during an accident is unsatisfactory even if the user is unharmed. This might persuade some workers to work without using their eye protectors. Workers need to understand that a damaged or destroyed protector that prevented or reduced the level of injury is satisfactory, and once it has done its job, it has to be replaced. This applies to lenses as well as to complete protectors.

Chapter 5

Conclusions

5.1 Conclusions from the impact resistance study

The Hi-Vex lens material can be used for industrial safety lenses at 3mm since it passed the minimum requirement of the CSA for industrial lenses. The results also showed that the Hi-Vex material with a mean breakage speed of 50.88±3.39m/s at 24°C and 52.57±2.99m/s at -29°C was still durable at room temperature and subzero temperatures. It was also superior to CR39 at more extreme temperatures with a mean breakage speed of 57.01±3.51m/s at 50°C and 66.38±4.00m/s at -49°C.

5.2 Conclusions from the perception of lens failure study

Our data confirms that simply reading the definition of a lens failure is insufficient. Some type of training with actual lenses or revision of the standard is necessary so that the general public and likely workplace safety committees can understand it. Our results also indicate that individuals who perform the impact testing need to be trained on the evaluation of lenses. Whether revising the text of the Standard, changing the wording to make it more understandable, or easier to remember would reduce this problem is uncertain. If there was any visible damage to the lens as a result of the impact, at least one person would classify the lens as a failure regardless of whether the damage met the CSA definition. Our results suggest that the vision care community and CSA may need to educate the public on the meaning of impact resistance of eye protectors. Perhaps having repetitive training on this would also help.

Appendix A

Sample Lens parameters for Hi-Vex

Mean and Standard deviation of Centre thickness and Prescription for Hi-vex lenses tested at 24°C

Lens number	Centre thickness mm	Prescription
1	3.15	-0.12
2	3.25	0
3	3.2	0.12
4	3.25	0
5	3.2	0
6	3.2	0
7	3.1	0
8	3.15	0.12
9	3.2	0
10	3.2	0.12
11	3.2	0
12	3.3	0
13	3.25	-0.12
14	3.2	0
15	3.2	0
16	3.2	0
17	3.3	0.12
18	3.3	0
19	3.25	0
20	3.3	0
Mean+/-Std	3.22+/-0.05	0.012+/-0.066

Mean and Standard deviation of Centre thickness and Prescription for Hi-vex lenses tested at 50°C.

Lens number	Centre thickness mm	Prescription
21	3.25	0
22	3.2	0
23	3.3	0
24	3.2	0
25	3.2	0
26	3.3	0
27	3.2	0
28	3.2	0
29	3.2	0
30	3.2	0
31	3.2	0
32	3.3	0
33	3.3	0
34	3.25	0.12
35	3.2	0
36	3.2	-0.12
37	3.25	0.12
38	3.2	0
39	3.3	0
40	3.3	0
Mean+/-Std	3.23+/-0.044	0.006+/-0.047

Mean and Standard deviation of Centre thickness and Prescription for Hi-vex lenses tested at -49°C

Lens number	Centre thickness mm	Prescription
41	3.3	-0.12
42	3.1	0
43	3.3	0.12
44	3.3	0
45	3.1	0
46	3.3	0
47	3.3	0
48	3.3	0.12
49	3.1	0
50	3.3	0.12
51	3.3	0
52	3.25	0
53	3.3	-0.12
54	3.1	0
55	3.2	0
56	3.3	0
57	3.3	0.12
58	3.3	0
59	3.3	0
60	3.2	0
Mean+/-Std	3.25+/-0.08	0.018+/-0.058

Mean and Standard deviation of Centre thickness and Prescription for Hi-vex lenses tested at -29°C.

Lens number	Centre thickness mm	Prescription
61	3.1	0.12
62	3	0
63	3	0.12
64	3	-0.12
65	3	-0.12
66	3	0
67	3.1	0.12
68	3	-0.12
69	3	-0.12
70	3	0
71	3	0
72	3	0
73	3	-0.12
74	3.05	0.12
75	3	0
76	3	-0.12
77	3	0.12
78	3.1	0
79	3	0
80	3	0
Mean+/-Std	3.02+/-0.037	-0.03+/-0.094

Appendix B

Sample Lens parameters for CR39

Mean and Standard deviation of Centre thickness and Prescription for CR39 lenses tested at 24°C.

Lens number	Centre thickness mm	Prescription
1	3.15	0
2	3.2	0.12
3	3.05	0
4	3.2	0
5	3.25	0.12
6	3.2	-0.12
7	3.1	0
8	3.1	0.12
9	3.1	0
10	3.1	0.12
11	3.1	0
12	3.2	0
13	3.1	0
14	3.1	0
15	3.2	0
16	3.2	0.12
17	3.1	0
18	3.1	0
19	3.2	-0.12
20	3.2	0
Mean+/-Std	3.15+/-0.06	0.012+/-0.066

Mean and Standard deviation of Centre thickness and Prescription for CR39 lenses tested at 50°C.

Lens number	Centre thickness mm	Prescription
21	3.1	0
22	3.2	0
23	3.2	0
24	3.1	0
25	3.1	0.12
26	3.2	0.12
27	3.2	0.12
28	3	0
29	3.2	0.12
30	3.1	0
31	3.2	0
32	3.1	0
33	3.2	0
34	3.1	0
35	3.25	0
36	3.2	0
37	3.2	0
38	3.1	0
39	3.2	0.12
40	3.05	0
Mean+/-Std	3.05+/-0.067	0.03+/-0.053

Mean and Standard deviation of Centre thickness and Prescription for CR39 lenses tested at -49°C

Lens number	Centre thickness mm	Prescription
41	3.2	-0.12
42	3.2	0.12
43	3.2	0.12
44	3.15	0
45	3.1	0
46	3.1	0
47	3.05	-0.12
48	3.1	0
49	3.1	0
50	3.15	0
51	3.2	0
52	3.2	0
53	3.2	0
54	3.2	0
55	3.1	0
56	3.05	-0.12
57	3.05	-0.12
58	3.05	0
59	3.05	-0.12
60	3.1	0
Mean+/-Std	3.13+/-0.06	-0.018+/-0.070

Mean and Standard deviation of Centre thickness and Prescription for CR39 lenses tested at -29°C.

Lens number	Centre thickness mm	Prescription
61	3.1	0
62	3.1	0
63	3.1	0
64	3.1	0
65	3.1	0
66	3.1	0
67	3.15	0.12
68	3.1	0
69	3.1	0
70	3.1	0
71	3.1	0
72	3.1	0
73	3.1	0.12
74	3.1	-0.12
75	3.1	-0.12
76	3.1	0
77	3.1	0
78	3.1	-0.12
79	3.1	-0.12
80	3.1	0
Mean+/-Std	3.10+/-0.011	-0.012+/-0.066

Appendix C

Parameters used in the Zippy Estimation by Sequential Testing (ZEST) program.

```
Method - ZEST Parameters:

Range:            5.00 log units

Step Size:        0.025 log units

Initial P.D.F.    Hyperbolic Secant

Parameters:

Initial Velocity: 2.30 log units

Decay constant:   2.00 log units

Psychometric Function - Logistic

Parameters:

Slope Beta:      20

False positives Gamma: 0.010

False negatives Delta: 0.010
```

ZEST output for Hi-vex lenses tested at 24°C

Actual trial velocity	S.D. %	S.D	Suggested velocity	Result
88.14	169.73	338.66	199.53	Pass
73.83	111.13	34.44	30.99	Break
59.81	99.88	23.77	23.80	Break
71.36	97.46	19.23	19.74	Break
48.25	96.94	18.57	19.16	Pass
62.20	38.54	18.55	48.12	Break
57.05	41.34	18.82	45.52	Break
39.95	45.72	19.42	42.48	Pass
49.00	14.22	6.97	48.98	Pass
53.02	11.08	5.75	51.91	Break
46.52	10.50	5.24	49.88	Pass
49.51	9.44	4.85	51.39	Pass
53.04	8.76	4.63	52.88	Pass
60.46	8.24	4.49	54.44	Break
50.85	7.86	4.21	53.57	Break
53.11	7.54	3.93	52.06	Break
51.31	7.25	3.70	51.02	Pass
42.02	6.89	3.59	52.10	Break
42.84	6.86	3.46	50.47	Pass

```
Mean Log Velocity (mean ± s.d.): 1.7066 ± 0.0289
Threshold Velocity (mean ± s.d.): 50.88 ± 3.39  |  (S.D.%:
6.66)
Probability: 160.625

MAXIMUM VALUES FOR P.D.F.:

   NM              Q-                Q              Q+
NMX          QMX
   76         29.9809         54.4723          45.6125
76.2344       55.3881

MAXIMUM LIKELIHOOD VALUES:
Log Velocity: 1.7059
Threshold Velocity: 50.7994
Probability: 55.388
```

ZEST output for Hi-vex lenses tested at 50°C

Actual trial velocity	S.D. %	S.D	Suggested velocity	Result
66.03	169.73	338.66	199.53	Break
54.46	135.79	412.80	304.01	Pass
60.30	130.08	445.16	342.22	Break
50.76	108.07	92.39	85.49	Pass
44.54	25.38	12.11	47.71	Pass
50.66	25.70	12.81	49.83	Break
49.44	35.10	19.29	54.95	Pass
52.12	12.62	6.20	49.08	Pass
57.83	12.57	6.31	50.24	Break
56.11	9.43	4.58	48.56	Break
46.43	8.77	4.14	47.23	Break
49.85	8.21	3.99	48.58	Pass
51.92	7.85	3.93	50.04	Pass
56.31	7.53	3.85	51.18	Pass
55.41	7.10	3.55	50.04	Break
50.96	6.84	3.39	49.50	Pass
57.07	6.61	3.23	48.86	Pass
59.02	6.36	3.15	49.52	Pass
68.89	6.16	3.10	50.37	Break

```
Mean Log Velocity (mean ± s.d.): 1.7559 ± 0.0268
Threshold Velocity (mean ± s.d.): 57.01 ± 3.51  |  (S.D.%: 6.16)
Probability: 12.536

MAXIMUM VALUES FOR P.D.F.:

   NM              Q-                Q              Q+
NMX          QMX
   78          2.4323           4.6628          3.5279
78.1628        4.7074

MAXIMUM LIKELIHOOD VALUES:
Log Velocity: 1.7541
Threshold Velocity: 56.7635
Probability: 4.707
```

ZEST output for Hi-vex lenses tested at -49°C

Actual trial velocity	S.D. %	S.D	Suggested velocity	Result
62.43	169.73	338.66	199.53	Break
56.25	112.78	26.75	23.72	Break
44.56	96.70	17.71	18.31	Pass
46.83	39.28	18.07	46.01	Pass
49.41	22.08	11.75	53.21	Pass
54.99	23.65	13.38	56.58	Pass
62.10	29.07	17.60	60.54	Pass
63.07	41.10	27.43	66.74	Pass
66.87	54.55	40.48	74.20	Break
61.80	12.85	8.14	63.34	Break
63.81	9.05	5.50	60.75	Pass
66.49	8.82	5.55	62.97	Pass
67.94	8.93	5.82	65.17	Break
64.98	7.80	4.97	63.68	Pass
70.10	7.57	4.94	65.30	Break
66.78	7.12	4.57	64.25	Pass
68.76	6.93	4.55	65.73	Break
66.84	6.59	4.27	64.71	Pass
69.94	6.42	4.23	65.98	Pass
69.24	6.30	4.24	67.32	Break

```
Mean Log Velocity (mean ± s.d.): 1.8221 ± 0.0262
Threshold Velocity (mean ± s.d.): 66.38 ± 4.00  |  (S.D.%: 6.03)
Probability: 10.862

MAXIMUM VALUES FOR P.D.F.:

   NM              Q-                Q              Q+
NMX          QMX
   81          2.9476           4.1603          2.2646
80.8901        4.1791

MAXIMUM LIKELIHOOD VALUES:
Log Velocity: 1.8223
Threshold Velocity: 66.4131
Probability: 4.179
```

ZEST output for Hi-vex lenses tested at -29°C

Actual trial velocity	S.D. %	S.D	Suggested velocity	Result
47.89	169.73	338.66	199.53	Pass
47.09	130.90	444.05	339.21	Pass
49.36	128.58	455.84	354.51	Break
54.10	124.13	146.27	117.84	Break
43.20	31.58	16.24	51.43	Pass
47.44	33.62	18.11	53.86	Pass
47.89	39.47	22.45	56.89	Pass
56.05	45.47	27.19	59.80	Break
54.52	11.72	6.23	53.19	Break
47.00	8.84	4.55	51.46	Break
51.43	8.20	4.06	49.53	Pass
51.59	7.84	4.00	51.00	Pass
55.25	7.54	3.94	52.26	Break
52.24	7.13	3.66	51.36	Pass
51.59	6.91	3.63	52.46	Pass
49.05	6.73	3.59	53.38	Break
51.12	6.39	3.33	52.15	Pass
58.72	6.23	3.30	52.93	Break
49.78	6.01	3.15	52.43	Pass
58.54	5.88	3.12	53.03	Break

```
Mean Log Velocity (mean ± s.d.): 1.7208 ± 0.0247
Threshold Velocity (mean ± s.d.): 52.57 ± 2.99  |  (S.D.%: 5.69)
Probability: 19.315

MAXIMUM VALUES FOR P.D.F.:

   NM             Q-               Q              Q+
NMX          QMX
   77          5.5524          7.7384          3.7527
76.8542        7.8040

MAXIMUM LIKELIHOOD VALUES:
Log Velocity: 1.7214
Threshold Velocity: 52.6447
Probability: 7.804
```

ZEST output for CR39 lenses tested at 24°C

Actual trial velocity	S.D. %	S.D	Suggested velocity	Result
33.82	169.73	338.66	199.53	Pass
47.52	135.79	412.80	304.01	Pass
51.62	130.08	445.16	342.22	Pass
52.75	108.07	92.39	85.49	Break
39.43	25.38	12.11	47.71	Pass
51.90	25.70	12.81	49.83	Pass
46.89	35.10	19.29	54.95	Break
42.49	12.62	6.20	49.08	Pass
52.59	12.57	6.31	50.24	Break
50.51	9.43	4.58	48.56	Break
46.95	8.77	4.14	47.23	Pass
50.59	8.21	3.99	48.58	Pass
49.48	7.85	3.93	50.04	Pass
50.88	7.53	3.85	51.18	Break
56.60	7.10	3.55	50.04	Break
53.40	6.84	3.39	49.50	Break
46.16	6.61	3.23	48.86	Pass
50.39	6.36	3.15	49.52	Pass
56.69	6.16	3.10	50.37	Break
49.50	5.99	2.99	49.95	pass

```
Mean Log Velocity (mean ± s.d.): 1.7045 ± 0.0252
Threshold Velocity (mean ± s.d.): 50.64 ± 2.94  |  (S.D.%:
5.81)
Probability: 50.357

MAXIMUM VALUES FOR P.D.F.:

   NM             Q-                Q              Q+
NMX         QMX
   76         9.9792         19.8661         14.1652
76.1343       20.0066

MAXIMUM LIKELIHOOD VALUES:
Log Velocity: 1.7034
Threshold Velocity: 50.5076
Probability: 20.007
```

ZEST output for CR39 lenses tested at 50°C

Actual trial velocity	S.D. %	S.D	Suggested velocity	Result
50.21	169.73	338.66	199.53	Break
44.18	115.09	23.13	20.10	Pass
50.39	108.99	77.17	70.81	Break
50.95	48.50	19.49	40.18	Break
47.43	49.80	18.31	36.78	Pass
46.04	16.15	7.42	45.95	Pass
50.48	11.97	5.82	48.59	Break
49.41	10.10	4.73	46.86	Break
47.31	9.72	4.42	45.53	Pass
47.80	8.52	4.02	47.25	Break
43.09	8.17	3.76	46.03	Pass
53.43	7.63	3.58	46.92	Pass
53.02	7.31	3.55	48.49	Pass
56.78	7.07	3.52	49.86	Break
50.81	6.81	3.36	49.34	Pass
53.38	6.57	3.31	50.35	Pass
53.51	6.41	3.29	51.42	Pass
55.19	6.27	3.29	52.40	Break
52.28	6.02	3.11	51.75	Pass
57.81	5.88	3.09	52.53	Pass

```
Mean Log Velocity (mean ± s.d.): 1.7287 ± 0.0253
Threshold Velocity (mean ± s.d.): 53.54 ± 3.12  |  (S.D.%: 5.83)
Probability: 2.379

MAXIMUM VALUES FOR P.D.F.:

   NM             Q-                Q               Q+
NMX          QMX
   77          0.5013          0.9485          0.6347
77.0876        0.9515

MAXIMUM LIKELIHOOD VALUES:
Log Velocity: 1.7272
Threshold Velocity: 53.3569
Probability: 0.951
```

ZEST output for CR39 lenses tested at -49°C

Actual trial velocity	S.D. %	S.D	Suggested velocity	Result
37.08	169.73	338.66	199.53	Pass
51.43	134.50	420.03	312.29	Pass
58.25	128.89	454.21	352.39	Break
49.78	98.15	84.00	85.59	Break
45.88	27.86	14.05	50.45	Pass
52.17	30.41	16.44	54.04	Break
43.88	12.46	6.16	49.46	Pass
51.45	11.78	6.00	50.94	Pass
47.49	12.21	6.50	53.22	Break
49.17	9.24	4.67	50.48	Break
46.74	8.52	4.15	48.79	Break
46.93	8.10	3.83	47.26	Pass
45.43	7.62	3.69	48.42	Pass
44.23	7.30	3.59	49.25	Pass
51.14	7.06	3.52	49.87	Break
54.27	6.72	3.29	49.00	Pass
59.39	6.56	3.29	50.23	Pass
59.20	6.53	3.37	51.61	Break
51.80	6.32	3.23	51.17	Break
50.19	6.08	3.06	50.41	Break

```
Mean Log Velocity (mean ± s.d.): 1.6960 ± 0.0255
Threshold Velocity (mean ± s.d.): 49.66 ± 2.92  |  (S.D.%: 5.88)
Probability: 5.212

MAXIMUM VALUES FOR P.D.F.:

   NM              Q-                Q                Q+
NMX          QMX
   76           1.4464          2.0366          1.0549
75.8755         2.0488

MAXIMUM LIKELIHOOD VALUES:
Log Velocity: 1.6969
Threshold Velocity: 49.7607
Probability: 2.049
```

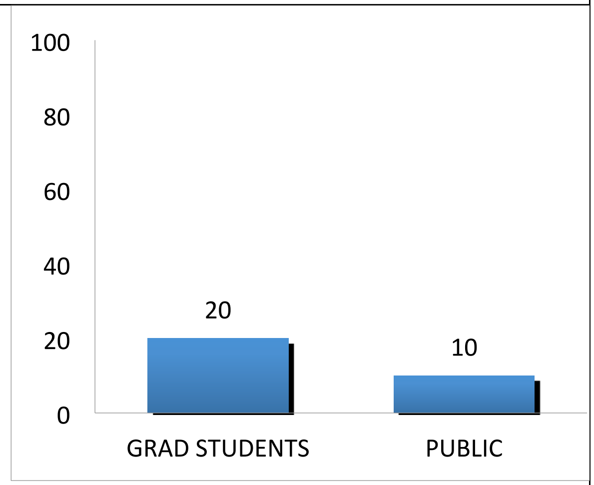
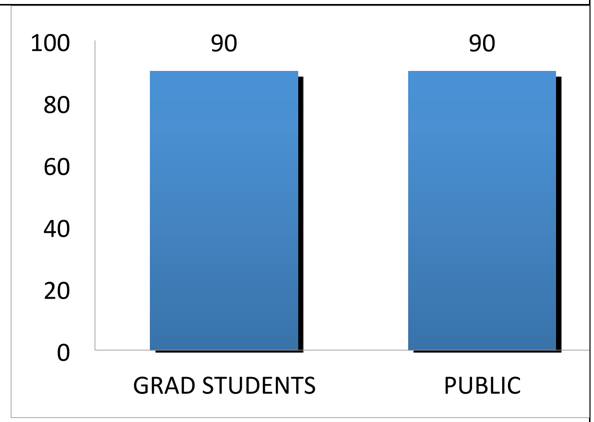
ZEST output for CR39 lenses tested at -29°C

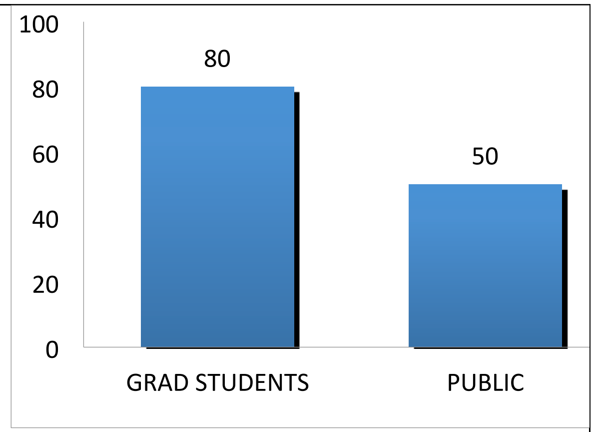
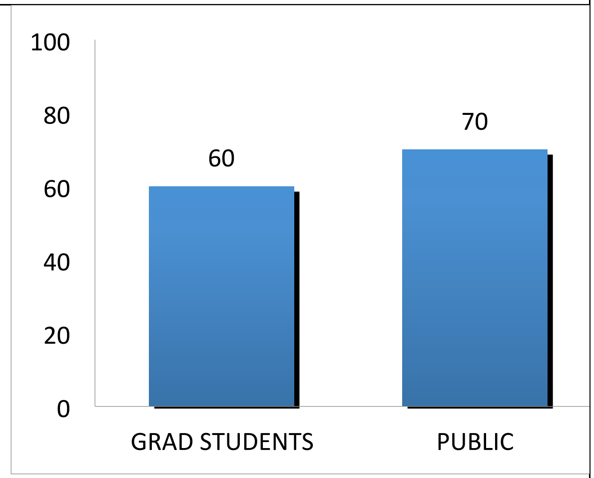
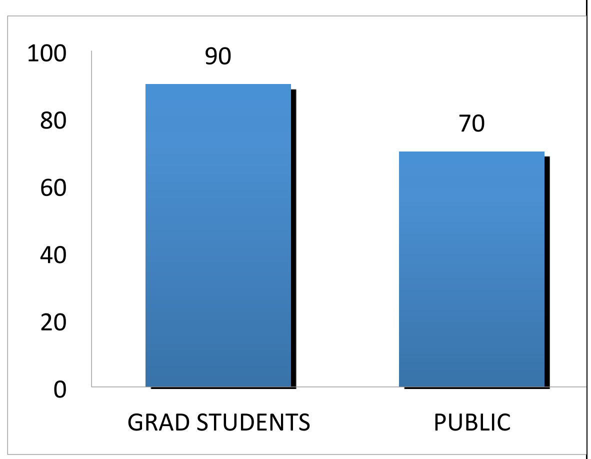
Actual trial velocity	S.D. %	S.D	Suggested velocity	Result
60.30	169.73	338.66	199.53	Break
49.44	113.07	26.11	23.09	Pass
44.71	94.14	68.73	73.01	Break
48.36	62.13	24.52	39.46	Pass
48.53	37.75	20.08	53.18	Pass
51.92	43.85	25.48	58.11	Break
48.76	13.37	6.80	50.85	Pass
52.31	13.75	7.28	52.92	Break
48.16	9.51	4.82	50.66	Pass
43.35	9.05	4.71	52.02	Pass
54.66	8.82	4.64	52.64	Pass
45.83	8.89	4.84	54.38	Pass
55.37	7.80	4.07	52.16	Break
53.23	7.30	3.74	51.22	Pass
56.15	7.09	3.72	52.46	Pass
56.00	6.96	3.75	53.78	Break
49.49	6.60	3.49	52.93	Break
44.63	6.31	3.27	51.80	Pass
51.76	6.17	3.22	52.18	Pass
60.66	6.03	3.19	52.95	Break

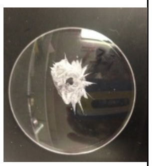
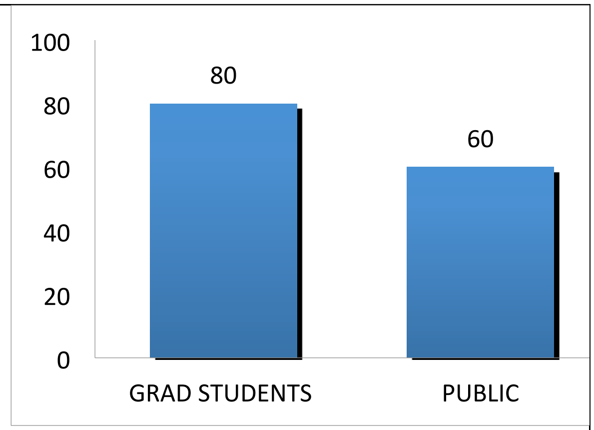
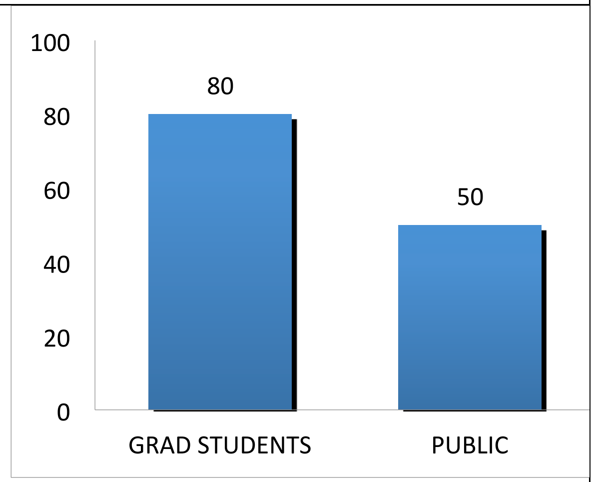
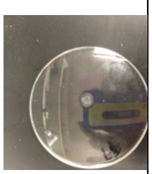
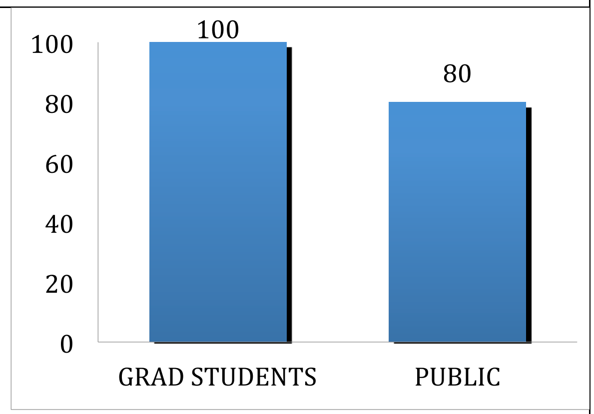
```
Mean Log Velocity (mean ± s.d.): 1.7207 ± 0.0254
Threshold Velocity (mean ± s.d.): 52.56 ± 3.08  |  (S.D.%:
5.85)
Probability: 4.524

MAXIMUM VALUES FOR P.D.F.:

   NM              Q-               Q              Q+
NMX          QMX
   77          1.2951          1.7623          0.8837
76.8471        1.7780

MAXIMUM LIKELIHOOD VALUES:
Log Velocity: 1.7212
Threshold Velocity: 52.6233
Probability: 1.778
```

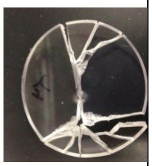
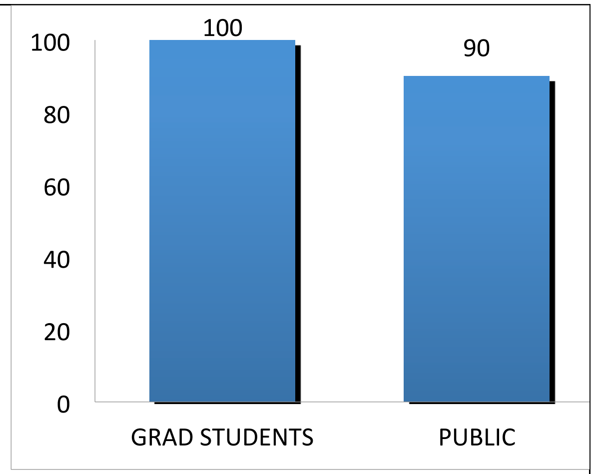
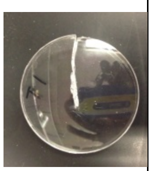
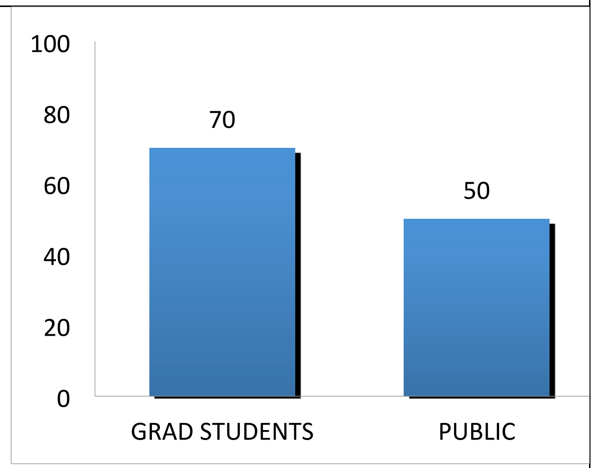
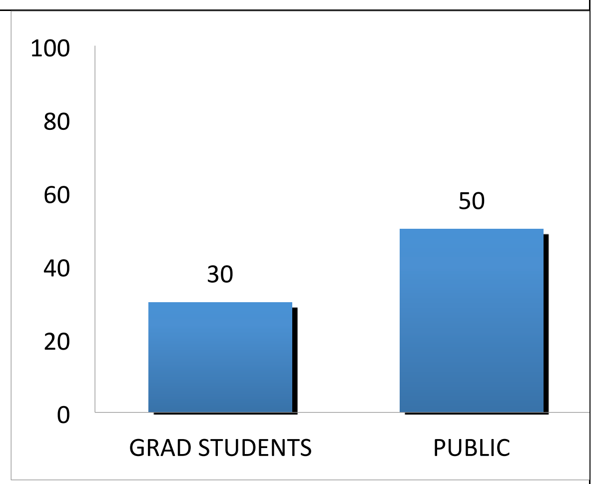
Appendix D

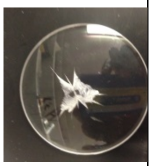
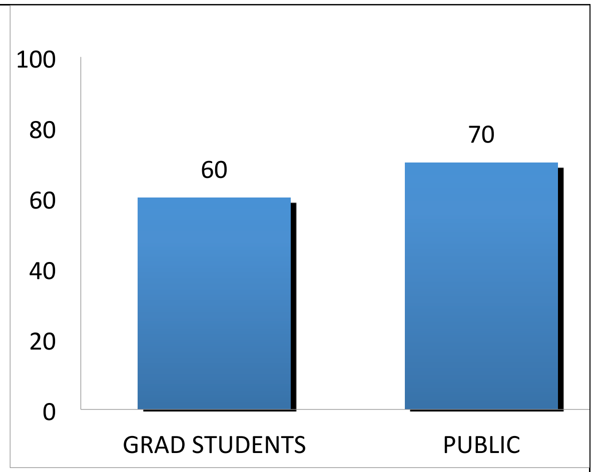
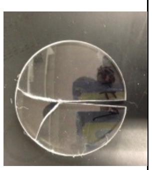
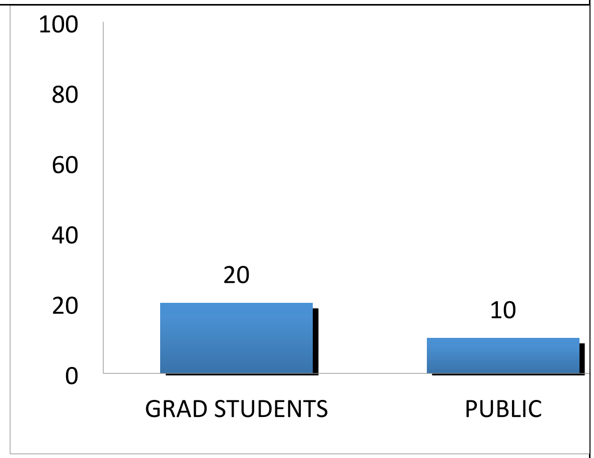
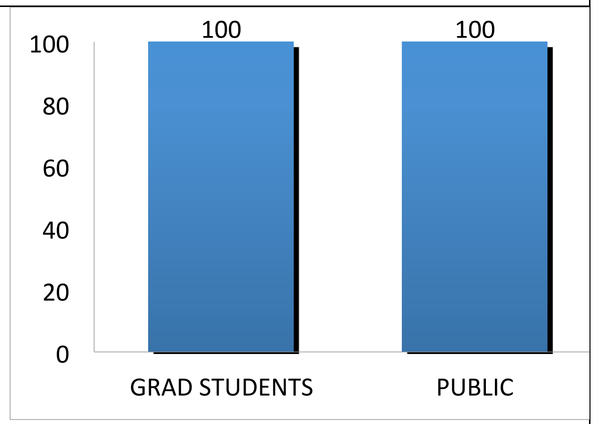
Spectacle lenses observed during the procedure and the researcher's opinion based on the CSA.

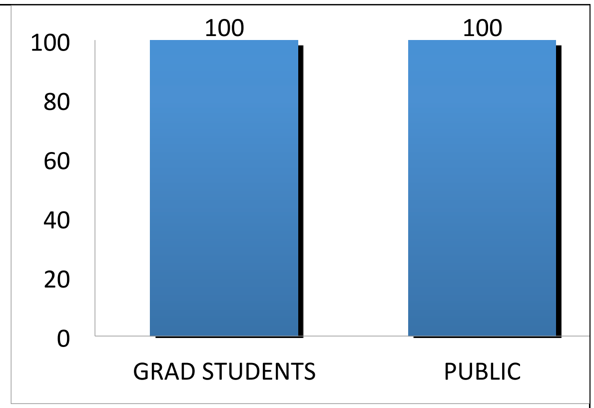
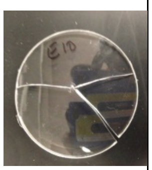
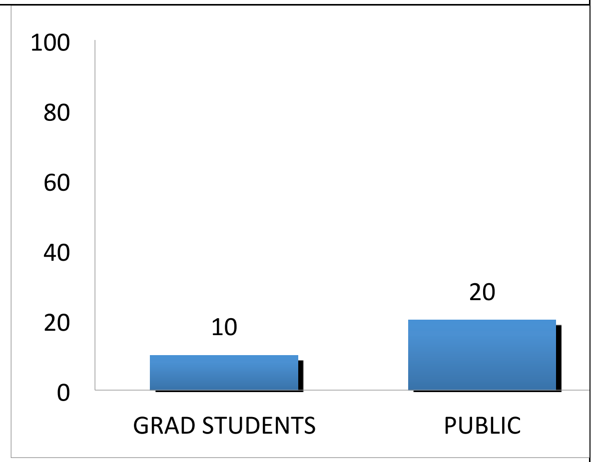
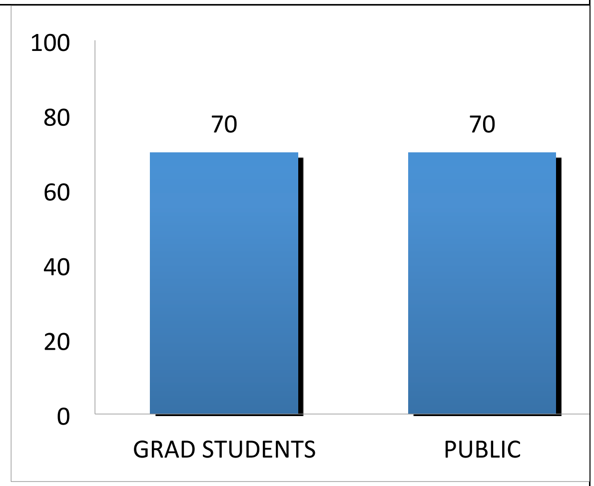
LENS NUMBER	NATURE OF DAMAGE: RESEARCHER'S POINT OF VIEW	PASS/FAIL BASED ON THE CSA	BAR GRAPH SHOWING PERCENTAGE AGREEMENT (VERTICAL AXIS) BETWEEN THE GENERAL PUBLIC AND GRADUATE STUDENTS
1 	4 crack lines all radiating from the centre of the lens. The lens is intact	PASS	
2 	6 cracks /lines in the lens radiating from the centre. Lens is broken into two	FAIL	

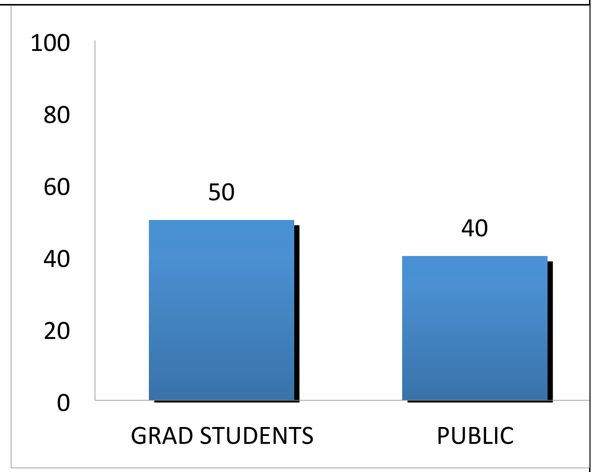
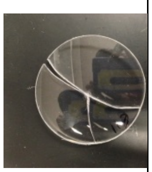
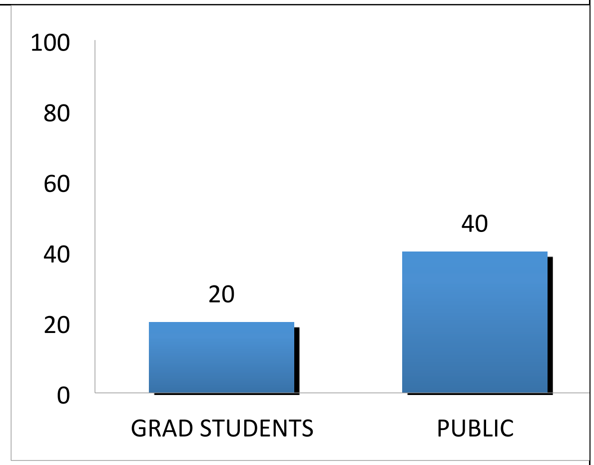
<table>
<tr><td>3
</td><td>7 cracks radiating from the centre but not extending to the edge of the lens. All lens in one piece</td><td>PASS</td><td>
</td></tr>
<tr><td>4
</td><td>8 radial cracks extending from the centre and to the edge with a piece of the lens close to the centre missing</td><td>FAIL</td><td>
</td></tr>
<tr><td>5
</td><td>Portion of lens protruding outwards with a piece missing and some cracks</td><td>FAIL</td><td>
</td></tr>
</table>

6 	Missing piece in the centre and few cracks. Lens in one piece	FAIL	
7 	Missing piece in the centre. Lens in one piece	FAIL	
8 	Dent in the centre	PASS	

9 	Large line radiating from one edge to the other. 7 cracks close to the edge and a missing piece in between the cracks	FAIL	
10 	1 single crack radiating from the centre. Crack leads to an opening but the missile cant pass through	PASS	
11 	Radial smudge and crack and an illusion that a part of the lens is missing	PASS	

12 	Radial smudge and crack with no loss of lens material	PASS	
13 	Though a crack clearly divides the lens in two with a smaller crack radiating to the edge, the lens is in one piece.	PASS	
14 	Lens broken into two separate halves	FAIL	

15 	Lens broken in to three separate pieces	FAIL	
16 	Though a crack clearly divides the lens in two with a smaller crack radiating to the edge, the lens is in one piece	PASS	
17 	A crack radiating across the lens to the edge with a piece of the lens dislodged inward enabling access of missile. No part of lens	FAIL	

	missing but a hole is made with the protrusion		
18 	Though a crack clearly divides the lens in two with a smaller crack radiating to the edge, the lens is in one piece	PASS	
19 	Though a crack clearly divides the lens in two with a smaller crack radiating to the edge, the lens is in one piece	PASS	

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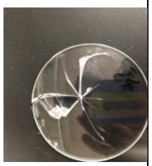
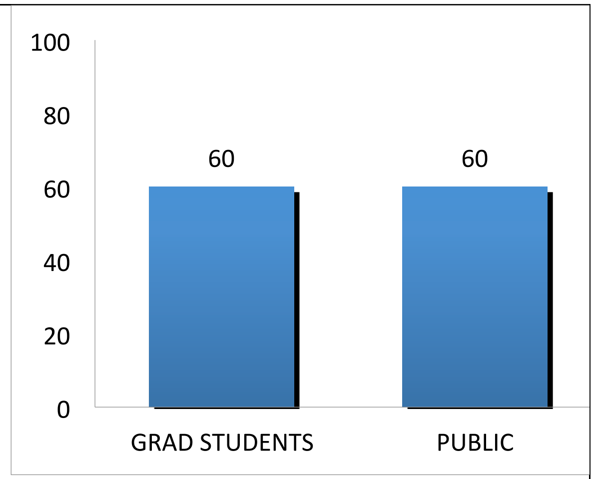
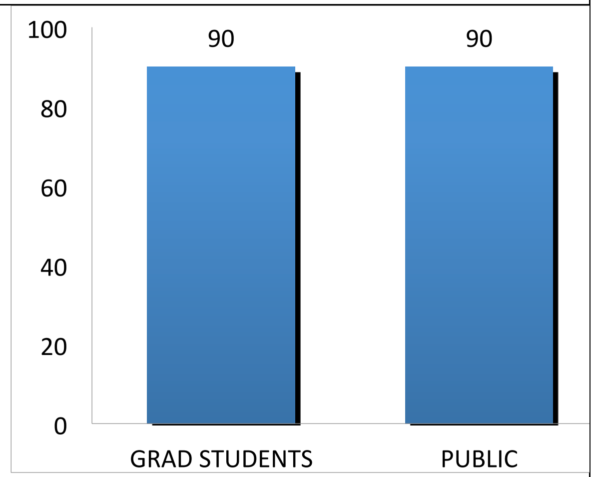
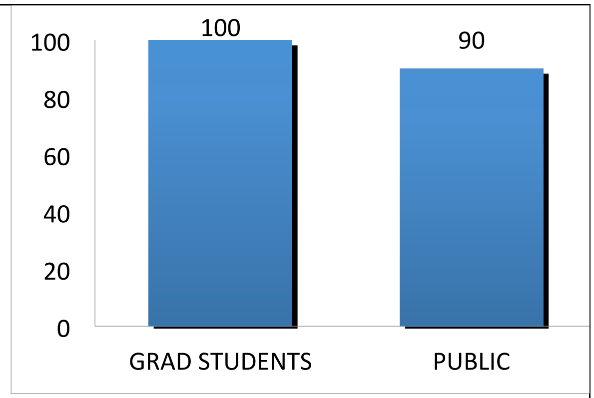
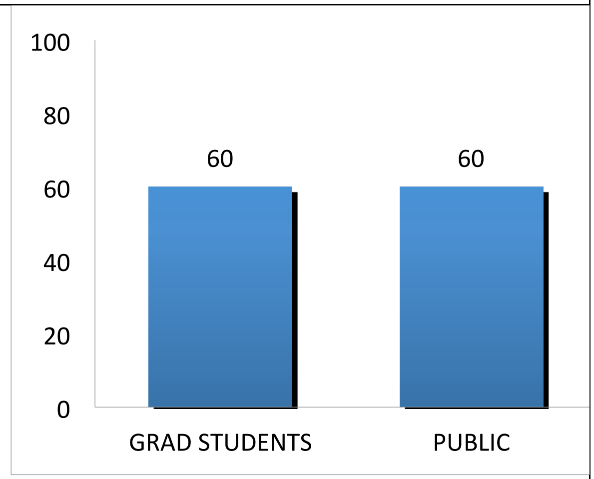
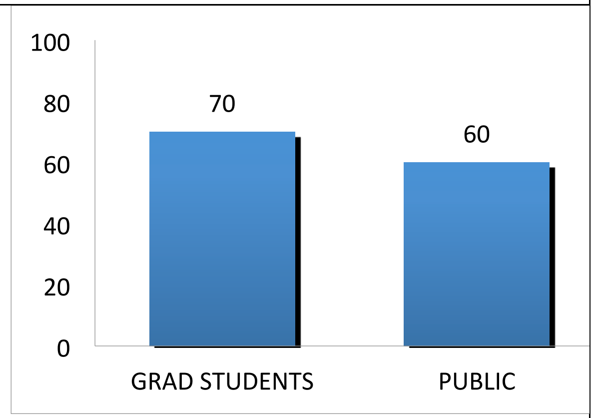
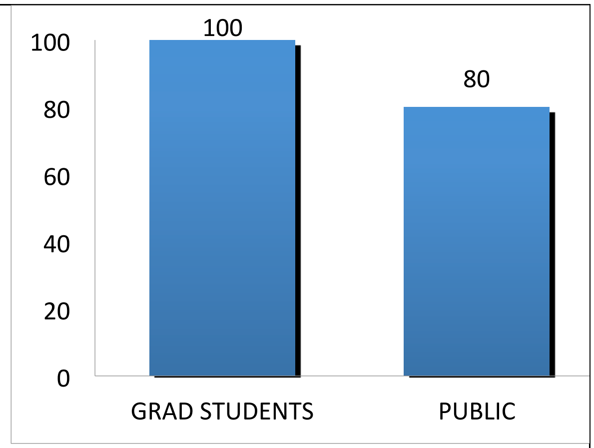
</td><td>Cracks radiating from the centre but not separating lens into bits. However there is loss of lens material from grazing on the lens surface</td><td>FAIL</td><td>
</td></tr>
<tr><td>21
</td><td>Spoke like crack in the centre of the lens not radiating to the edge and lens is in one piece.</td><td>PASS</td><td>
</td></tr>
</table>

22 	Lens broken in to 4 separate pieces	FAIL	
23 	Radial smudge and crack and an illusion that a part of the lens is missing, though lens is intact	PASS	
24 	Radial smudge and crack in the centre of the lens and a part of the lens is missing in the centre	FAIL	

25 	A dent in the centre and cracks towards the edge with space within the lens though lens is in one piece	FAIL	

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