A ballistic assessment of eye protector lens materials

E. C. Wigglesworth

The impact resistance of commonly used eye protector lens materials is measured with a ballistic system, using 1/4 inch (6.3 mm.) and 1/8 inch (3.2 mm.) steel balls. The results, taken in conjunction with the findings of earlier drop-tower work, permit a comprehensive evaluation of the impact resistance of 3 mm. and 2 mm. thicknesses of allyl resin and thermally toughened glass against a series of steel balls ranging in size from 1 3/4 inches (28.6 mm.) to 1/8 inch (3.2 mm.). While 3 mm. toughened glass is stronger than 3 mm. allyl resin when impacted by the larger missiles, the position is reversed when the smaller missiles are used. This is held to postulate the need for both drop-tower and ballistic tests in acceptance requirements. Additionally, the relative inferiority of 2 mm. toughened glass at all points of the scale is shown.

Key words: Eye injuries, safety lenses, impact resistance, ballistic testing

Haddon has defined a hazard as a source of potentially damaging energy. Occupational eye hazards threaten delivery of mechanical, thermal, chemical, or radiant energy, the major hazard being that of mechanical energy delivery, i.e., impact. The mechanical energy of a missile depends upon its mass, m, and its velocity, v, and is calculated by Formula 1.

\[ E = \frac{1}{2}mv^2 \]  

In the field of eye protection, clinically observed injuries depend on the amount of energy delivered, the rate at which the energy is delivered, and the surface area of contact. Mechanical injuries can be classified in two categories: (1) contusion injuries from low-velocity, nonpenetrating missiles, and (2) penetrating injuries from high velocity missiles.

In general, the latter injuries are caused by small missiles under 3 mm. maximum dimension, while contusion injuries are produced by larger missiles of mass three or four orders of magnitude greater than that of the small penetrating missiles.

Since both types of injury arise occupationally, eye protection is required over a large range of missile sizes. Therefore, evaluation of impact resistance should include measurements at both ends of the range and, if practicable, large-missile low-velocity tests to simulate the types of hazard that give rise to contusion injuries and small-missile high-velocity tests to simulate the types of hazard that give rise to perforating injuries. Large-missile tests have pre-
Fig. 1. The ballistic range. The components are: a, nitrogen cylinder; b, pressure reservoir; c, firing button; d, breech-loading cannon; e, velocity-measuring device; f, counter-chronometer; g, head-form. Note that the guards have been removed to permit greater photographic clarity.

Previously been carried out by Keeney, and small missile tests by Rose and Stewart.

The results of a drop-tower experimental investigation by the present author into the impact resistance of toughened glass and allyl resin have been reported. This paper presents the results of complementary ballistic work on the same materials.

Methods and materials

Equipment. The experimental ballistic range is shown in Fig. 1. This equipment projects steel balls of 6.3 mm. or 3.2 mm. diameter at measured velocities. It is pressurized by dry nitrogen and consists essentially of a pressure reservoir (b), a breech-loading cannon (d), a velocity-measuring device (e), and an anthropometric head form (g) on which the eye protector materials under test are mounted. The velocity-measuring device (e), originally designed for explosives testing, consisted of a pair of vertical light beams, 250 mm. apart, impinging on photoelectric cells. Interruption of the light beams, respectively, started and stopped a counter-chronometer (f) with capacity to measure values from one second to ten microseconds. The measured time interval was then used to calculate velocity.

The maximum velocity of the equipment was approximately 220 M. per second for the ¼ inch (6.3 mm.) steel ball and 310 M. per second for the ½ inch (3.2 mm.) steel ball. These velocities are potentially lethal and, to protect the operator, the entire system was enclosed by ¼ inch thick sheets of perspex.

The trajectory of the missile underwent significant deflection from the horizontal at velocities below 10 M. per second. This was taken as the lower limit of the apparatus. When experimental requirements dictated lower velocities, the work was carried out by the author in the research laboratories of the College of Optometry, University of Melbourne. As this equipment was built with a shorter spacing (150 mm.) between the sensing elements, missiles with velocities as low as 6 M. per second could be accurately delivered and measured.

Materials. Allyl resin and thermally toughened glass lenses were obtained in 2, 3, and 4 mm. thicknesses (tolerance ± 0.1 mm.). Twenty specimens of each lens type were tested in the form of 50 mm. round, bevel-edged, 6.00 diopter base curve, finished stock piano lenses. All the lenses were new and conformed with clause 2.4.2. Quality, of Australian Standard Z.7., i.e., they were free from such surface defects as pits, scratches, cracks, waves, and dull spots observable.
by the naked eye. All the glass lenses were examined in a polariscope for regularity of birefringence pattern.

Support system. In their pioneering work with a ballistic system, Rose and Stewart used lenses that were "mounted in rubber." Their photograph showed the lenses mounted in what was essentially a vertical vice with rubber jaws. Recently, Newton tested some spectacle lenses in the frame and tested others that were "freely supported," but gave no indication as to how the latter method was achieved.

The Woods committee suggested that not only should testing be carried out on the material per se, but also that the test should measure the strength of the protective system as a whole by testing the assembly mounted in the "as worn" position. This view has been accepted in both the British and the Australian Standards, in which eye protectors are required to be mounted in the "as worn" position for ballistic testing.

To conform with this requirement, while simultaneously maintaining compatibility of lens size and symmetry with the earlier work, it seemed appropriate and convenient to mount all 50 mm. round lenses in welding cup goggles. The goggles selected, molded from rigid polyvinyl chloride, are shown in Fig. 2.

However, before the decision to use this support system was finally confirmed, some preliminary experiments were carried out to determine whether the values of fracture velocities obtained were higher than those achieved by mounting in spectacle frames. Had this been the case, the results obtained in the body of the work would have been overestimates of the actual impact strength. The results of these experiments are given in Table I.

In each case, the mean fracture velocity obtained by using specimens mounted in a cup goggle system was less than the corresponding figure for specimens of similar thicknesses, mounted in spectacle frames.

Therefore, the mean fracture velocities for toughened glass and allyl resin reported here can be considered as conservative estimates of the attainable strength of these materials in new condition when mounted in spectacle frames.

Test method. The two test methods available are those of single and repeated impact. In the first method, known as the "up-and-down" or "step" method, each specimen is subjected to one impact only. If it fractures, the next specimen is impacted at a lower velocity. If it does not fracture, the next specimen is impacted at a higher velocity. This is repeated until fracture occurs; the fracture velocity is then recorded.

In the drop-tower system, the step method produced values of fracture height that were about 50 per cent higher than the values obtained from the repeated impact method.† The expected

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Table I. Mean fracture velocity: Effect of lens mounting

<table>
<thead>
<tr>
<th>Missile diameter (mm.)</th>
<th>Lens thickness (mm.)</th>
<th>Mean fracture velocity (M./sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>46 mm.</td>
<td>27 shape spectacle lens held in frame*</td>
<td></td>
</tr>
<tr>
<td>50 mm. round lens held in welding goggles f</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/8 (6.4)</td>
<td>4</td>
<td>24</td>
</tr>
<tr>
<td>1/8 (3.2)</td>
<td>3</td>
<td>32</td>
</tr>
</tbody>
</table>

6.00 Diopter base curve toughened glass lenses, 4 mm. and 3 mm.
†Mean of 10 specimens.
‡Mean of 20 specimens.

†The expected
increase in velocity in a ballistic system is therefore about 20 to 25 per cent. The actual increase found was about 35 per cent (Table II), in reasonably good agreement with the expected ratio.

In the earlier work,\textsuperscript{1} the repeated impact method was preferred, principally on the ground that it is a better simulation of the real-life aging process. For consistency and compatibility, it was also adopted in this study.

Commencing velocity. The earlier work\textsuperscript{4} on drop-tower testing showed that mean fracture height varied with commencing height and recommended that the latter be selected from Formula 2,
\[ h_n = \bar{x} - 2s \]  
where \( \bar{x} \) and \( s \) are estimates, respectively, of the mean and standard deviation of the values of the fracture height of the twenty specimens.

One set of experiments was carried out on flat toughened glass lenses to ascertain whether a corresponding relationship existed in ballistic testing. The results are given in Table III and seem to show that a similar relationship exists.

Consequently, except in cases in which comparative testing requirements took precedence, the commencing velocity was selected by using Formula 3.
\[ v_c = \bar{v} - 2s \]  

Fracture velocity determination. At the lower velocities required for toughened glass, it proved difficult to shoot exactly at the required velocity if this was changed after each shot. Consequently, the procedure adopted was to stabilize the equipment at the commencing velocity and then subject each sample in turn to impact at this velocity, the number of fractures being noted. The velocity, which was measured for every shot, was then raised, and each of the remaining samples was subjected to a further impact. This process was repeated until all samples were fractured. It was found to be a reliable and accurate procedure.

Results

Temperature, relative humidity, batch size, commencing and incremental velocities, and minimum and maximum fracture velocities obtained, together with the calculated mean and standard deviation, for each type of lens and for both sizes of steel ball are presented in Table IV.

The information presented in Table IV is designed for compatibility with the results of the drop-tower work. Those results\textsuperscript{4} were presented in terms of fracture height (\( h \)), but, by using Formula 4, they can be converted to velocity. The validity of the conversion was experimentally verified at the 1 M. and 2 M. points. Using this conversion, fracture velocity values for the larger missiles can be calculated, and this information is included in Table V.

The information is given to two significant figures to enable it to be plotted on a logarithmic scale graph, given in Fig. 3. The experimental values appear to fall on a continuous mass-velocity curve for each lens type, arising at the ends of the scale.

Discussion

When strength measurements are made on a batch of apparently identical glass specimens, there is usually a considerable spread in the results. The coefficient of variation of the results has been reported as being 25 to 30 per cent,\textsuperscript{3} 38 to 53 per cent,\textsuperscript{10} or of the order of 15 per cent.\textsuperscript{11} In the work reported here, there were similar variations in the range of values obtained for both glass and allyl resin lenses. Typically, the maximum value obtained was about twice the minimum, and values of the standard deviation were corresponding.

Table II. Mean fracture velocity: Effect of test method

<table>
<thead>
<tr>
<th>Test method</th>
<th>Mean fracture velocity (M./sec.)</th>
<th>Standard deviation (M./sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single impact, &quot;step&quot; method (ten lenses)</td>
<td>85</td>
<td>10</td>
</tr>
<tr>
<td>Repeated impact with increasing velocities (twenty lenses)</td>
<td>63</td>
<td>12</td>
</tr>
</tbody>
</table>

6.00 Diopter base curve allyl resin lenses, 50 mm. round, 2 mm. thick; versus % inch (3.2 mm.) ball. Temperature 18° C, relative humidity 55 to 60 per cent.

Table III. Mean fracture velocity: Effect of commencing velocity

<table>
<thead>
<tr>
<th>Commencing velocity (M./sec.)</th>
<th>Increment size (M./sec.)</th>
<th>Mean fracture velocity (M./sec.)</th>
<th>Standard deviation (M./sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>4</td>
<td>19</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>4</td>
<td>22</td>
<td>4</td>
</tr>
</tbody>
</table>

Twenty lenses in each group. Flat toughened glass lenses, 50 mm. round, 3 mm. thick; versus 1/4 inch (6.3 mm.) ball. Temperature 17° C, relative humidity 54 per cent.
Table V. Mean fracture velocity of eye protector lens materials

<table>
<thead>
<tr>
<th>Missile diameter in inches (mm.)</th>
<th>3 mm. thick</th>
<th>2 mm. thick</th>
<th>3 mm. thick</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mm. round 6.00 diopter plano lenses</td>
<td>7.3</td>
<td>3.5</td>
<td>5.9*</td>
</tr>
<tr>
<td>Thermally toughened glass</td>
<td>7.8</td>
<td>3.7</td>
<td>6.8</td>
</tr>
<tr>
<td>Allyl resin</td>
<td>9.0</td>
<td>5.3</td>
<td>8.9</td>
</tr>
</tbody>
</table>

*Data from drop-tower tests. †Mean of 2.8 and 3.2 mm. values.

The coefficients of variation of the results of Table IV lie between 17 and 22 per cent for the glass lenses and between 14 and 21 per cent for the allyl resin lenses.

Fig. 3 demonstrates the change in rank order with missile size. For larger missiles, glass lenses of thicker thicknesses have higher impact resistance than allyl resin of thinner thicknesses. For small missiles, the position is reversed, glass having a lower impact resistance than both thicknesses of allyl resin. This explains the reason for the apparently conflicting conclusions of Rose and Stewart and Newton, using ballistic tests, from those of Keeney and Wigglesworth, using drop-tower tests.

The trend of decreasing strength with decreasing lens thickness also occurs as expected. In particular, the 2 mm. glass lenses have the lowest fracture velocity at all points of the scale.

The effect of base curvature on fracture velocity was also examined for 2 mm. thick allyl resin lenses. The results are reported in Table IV. The effect is not clear, since increasing base curvature causes a reduction in fracture velocity for the 6.3 mm. ball but an increase for the 3.2 mm. ball. Significance tests at the one per cent level show no significant differences for the former group, but they do show that the differences between the 10.00 diopter lenses on the one hand and the 6.00 and 8.00
diopter lenses on the other are both significant at this level, the 10.00 diopter lenses having the highest impact resistance. In these circumstances, evidence for the existence of a base curvature-impact strength dependency should be considered indicative but not conclusive.

From the information of Table V, the fracture energy can be calculated for each value of fracture velocity obtained. The results of these calculations are plotted in Fig. 4.

The trend of decreasing energy tolerance with decreasing lens thickness is still present, but two other features of interest also appear. These features are that (1) for all four materials, fracture energy tolerance decreases with increasing velocity, an effect previously noted by Haward, and (2) the energy curves for ruptured glass and allyl resin lenses are dissimilar. For glass, the points arise at the ends of the scale in a manner that suggests the presence of a smooth curve. By contrast, both the allyl resin curves show a discontinuity in the intermediate velocity values, not here measured. This discontinuity probably indicates some form of strain-rate dependency, associated with the properties of the material. Although this is a difficult area experimentally, equipment to investigate this effect is currently under development.

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