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NOTE

Mechanical properties of protective spectacles fitted with corrective lenses

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The majority of commercially available corrective spectacles used by workers do not provide effective eye protection against mechanical hazards in the workplace. One of the risks commonly occurring during work is hitting the head on some protruding elements, such as components of machines, buildings or tree branches in a forest. Because of the considerable weight of the human head and the speed of movement during impact, this type of accident may be very serious. This article presents a method of testing the mechanical strength of corrective lenses, simulating the results of an impact of the head on elements of workplaces. The results of tests of commercially available materials used for the construction of corrective and protective spectacles are also presented and discussed.

Keywords: safety spectacles; corrective spectacles; presbyopia; impact resistance

1. Introduction

Defects of eyesight, and in particular presbyopia, significantly affect the ability to perform work by persons aged 45–67 years.[1,2] As many as 30% of Europeans suffer from presbyopia and must use corrective spectacles at work. The majority of commercially available corrective spectacles used by workers do not provide effective eye protection against mechanical hazards in the workplace.[3] Among the 24 models of spectacles tested by the US National Institute for Occupational Safety and Health (NIOSH), only one met the requirements for low energy impact resistance.[4]

Pursuant to a decision of the European Union Commission, safety spectacles with corrective lenses are covered by two directives, 89/686/EEC [5] and 93/42/EEC,[6] as well as relevant harmonized standards. Corrective spectacles are manufactured based on the recommendations of ophthalmologists concerning eye refraction and protection requirements specified by an occupational safety and health specialist. Such spectacles are tailored to the individual user by the optician. The test methods and requirements given in Standard No. EN 166:2001,[7] harmonized with Directive 89/686/EEC, do not take into account the specifics of the construction of corrective spectacles, and especially lens shape and thickness. Corrective lenses can have different profiles. The front and back surfaces of an ophthalmic lens have a positive radius, resulting in a positive (convergent) front surface and a negative (divergent) back surface. The difference in curvature between the front and rear surfaces determines the corrective power of the lens. Differences in lens shape and thickness significantly affect mechanical properties, and in particular impact resistance. In order to evaluate the influence of lens shape on impact resistance, a new test method was developed and applied. The influence of frame construction on the mechanical strength of complete spectacles was also investigated, using the test method described in Standard No. EN 166:2001.[7] Finally, the article presents a discussion of tests of commercially available unmounted lenses made from commonly used ophthalmic materials as well as complete protective spectacles fitted with ophthalmic lenses.

2. Materials

Commercially available materials used for the construction of corrective and protective spectacles were selected for tests. The tests were performed on lenses with optical power in the range from −6.00 to +6.00 diopters made from:

- allyl diglycol carbonate (CR-39);
- bisphenol-A polycarbonate (PC);
- polyurethane and polyurea copolymer (Trivex).

The tested lenses were 70 mm in diameter. For each degree of optical power, three samples were tested. Also two types of complete safety spectacles equipped with corrective lenses made from PC, Trivex and CR-39 were tested against mechanical impacts.

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3. Experimental methods

3.1. Testing the impact resistance of unmounted corrective lenses

One of the hazards commonly occurring at work is hitting the head on some protruding elements of the workplace, such as components of machines, buildings or tree branches in a forest. Because of the considerable weight of the human head (4.32 kg for 50th percentile male adults) [8] and the speed of movement of the head during impact, this type of accident may be very serious. A new testing method for the mechanical strength of lenses was developed, simulating an impact of the head on workplace elements. Drop weights in the form of strikers hitting a lens placed on an anvil were used for the simulation of a head impact.

The apparatus consists of the following (see Figure 1):

- a stable support with a weight of 200 kg (to eliminate returning shock waves);
- guides enabling a free fall of the strikers;
- cylindrical strikers of different ends, in the form of a sphere (Figure 2c), cone (Figure 2b) or cylinder plate (Figure 2a);
- a cylindrical anvil on which the samples were placed, with a diameter larger than that of the flat surface of the tested sample;
- a height-adjustable discharge mechanism, equipped with a magnet supporting and releasing the strikers.

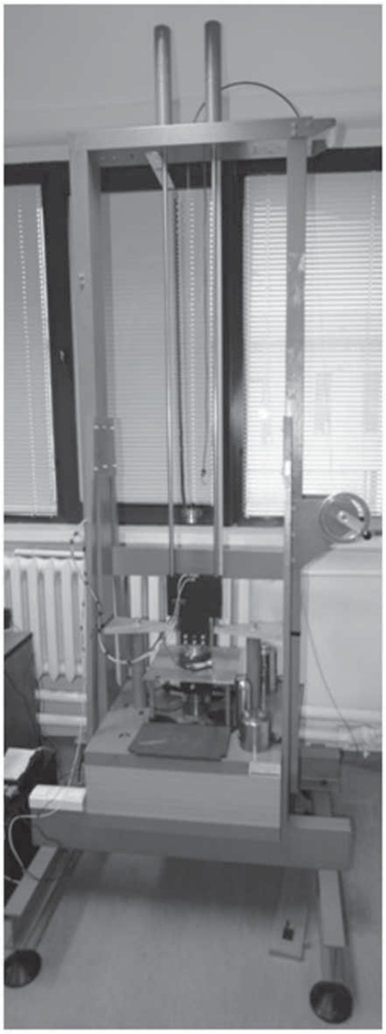

Figure 1. Apparatus for testing impact resistance of unmounted lenses.

The apparatus was designed to minimize friction forces and ensure striker motion approximating free fall as much as possible. Three different strikers with the shape of a sphere, cone and cylinder plate were used for the tests (see Figure 2). The diameter of the base of the strikers was 160 ± 1.0 mm. The radius of the sphere and the cone was

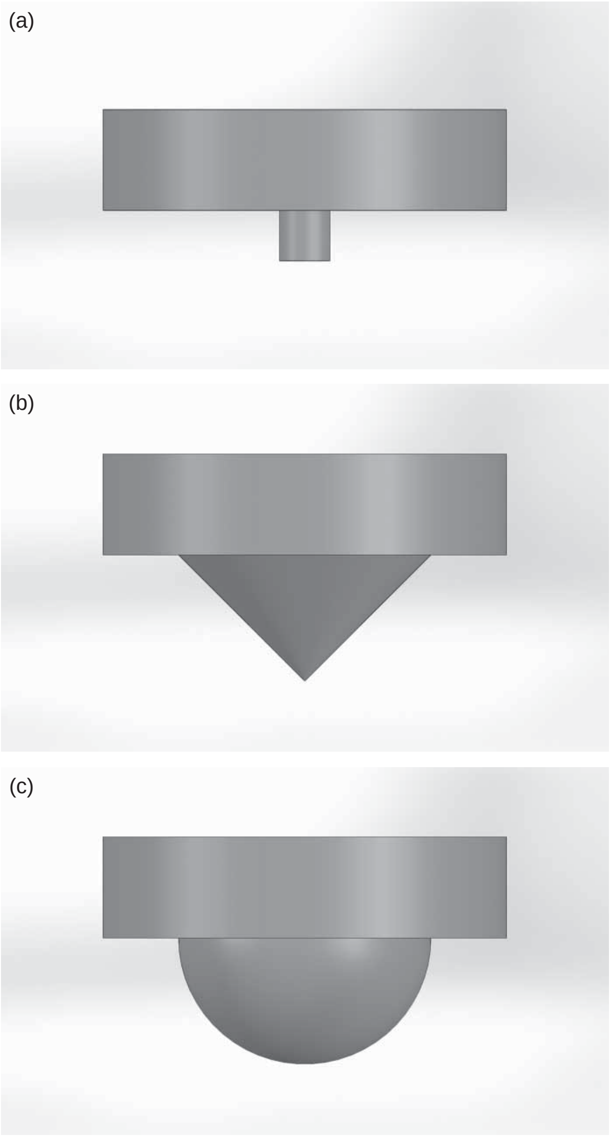

Figure 2. Strikers used in tests: (a) cylinder plate, (b) cone, (c) sphere.

50 ± 0.1 mm and the diameter of the cylinder was 10 ± 0.1 mm. The radius of the tip of the cone was 1 ± 0.001 mm.

A weight with a striker was dropped on the lens from a specified height. The total mass of the weight with the striker was 4.3 ± 0.1 kg. The lenses were placed on a cylinder-shaped anvil of 90-mm diameter. During the test, a striker was dropped without initial velocity from different heights. The maximum height caused a break or deformation of the lenses. Impact energy was calculated using Equation (1):

$$E = m \times g \times h, \tag{1}$$

where g = gravity acceleration; h = height; m = mass of the falling weight.

Energy losses due to friction were omitted because of their small effect on impact energy. Tests were performed on three samples for each level of lens optical power. Analysis of measurement uncertainty was performed in accordance with the following procedure:

1. An arithmetic mean of energy values was determined with Equation (2):

   $$E = \frac{1}{3}\sum_{i=1}^{3} E_i, \tag{2}$$

   where E = mean value of energy causing a break or deformation of the lens; E_i = energy values in subsequent readings.
2. Experimental variance was calculated from Equation (3):

   $$s^2(E) = \frac{1}{2}\sum_{i=1}^{3} (E_i - \bar{E})^2, \tag{3}$$

   where E = arithmetic mean of energy values; E_i = energy values for subsequent readings; $s^2(E)$ = experimental variance.
3. Experimental standard deviation was computed by means of Equation (4):

   $$s(E) = \sqrt{s^2(E)}, \tag{4}$$

   where $s(E)$ = standard deviation of energy
4. The mean value of experimental variance was found using Equation (5):

   $$s^2(\bar{E}) = \frac{s^2(E)}{3}, \tag{5}$$

   where $s^2(\bar{E})$ = the mean value of experimental variance.
5. The standard deviation of the experimental mean value was calculated from Equation (6):

   $$s(\bar{E}) = \frac{s(E)}{\sqrt{3}}, \tag{6}$$

   where $s(\bar{E})$ = standard deviation of the experimental mean value.
6. Standard uncertainty was given in the form of Equation (7):

   $$u(E) = s(\bar{E}), \tag{7}$$

   where $u(E)$ = standard uncertainty.
7. The percentage of standard uncertainty of the measured values was calculated from Equation (8):

   $$u_1 = u(E) \times 100\%, \tag{8}$$

   where u_1 = percentage of standard uncertainty.
8. Total measurement uncertainty was obtained from Equation (9):

   $$u_c(\overline{E}) = \sqrt{u_1^2 + u_2^2 + u_3^2}, \tag{9}$$

   where $u_c(\overline{E})$ = total measurement uncertainty; u_1 = uncertainty derived from the measurement of samples; $u_2 = \pm 0.1\%$ = uncertainty from height adjustment error; and $u_3 = \pm 2.3\%$ = uncertainty of the weight of the striker.
9. Expanded uncertainty was computed using Equation (10):

   $$U = k \times u_c(E), \tag{10}$$

   where k = coverage factor ($k = 2$ for the assumed confidence level of 95%); U = expanded uncertainty.

3.2. *Testing resistance to high-speed particles for spectacles fitted with corrective lenses*

Spectacles fitted with corrective lenses were also tested using the method described in Standard No. EN 168:2001.[9] Tests were performed for two models of spectacles (see Figure 3), equipped with corrective lenses made from CR-39, PC and Trivex, with optical power of −6.0, −3.0, +3.0 and +6.0 diopters.

Because commercially available protective spectacles can withstand a medium or even high energy impact, in order to compare different types of lenses the impact applied was higher than that recommended in Standard No. EN 166:2001.[7] The spectacles were tested using a steel ball with a mass of 0.86 g traveling at a speed of 45, 120 and 190 m/s. Energy values resulting in a lens puncture or deformation potentially damaging the eye were recorded.

Total measurement uncertainty for the test method was calculated from Equation (11):

$$u_c(\overline{E_p}) = \sqrt{u_1^2 + u_2^2}, \tag{11}$$

where $u_c(\overline{E_p})$ = total measurement uncertainty; $u_1 = \pm 1.4\%$ = uncertainty derived from the measurement of

Figure 3. Models of spectacles fitted with corrective lenses tested for resistance to high-speed particles: (a) spectacles with a frame equipped with shock-absorbing elements, (b) standard spectacles with a plastic frame.

the mass of the ball; $u_2 = \pm 2.1\% =$ uncertainty from the measurement of ball velocity.

Expanded uncertainty was calculated from Equation (12):

$$U = k \times u_c(\overline{E_p}), \qquad (12)$$

where $k =$ coverage factor ($k = 2$ for the assumed confidence level of 95%); $U =$ expanded uncertainty.

4. Results and discussion

4.1. Mechanical strength of unmounted lenses

The results of testing the mechanical strength of lenses made from selected ophthalmic materials, with different optical powers, are presented in the following. The tests were conducted under the following climatic conditions: temperature from 20 to 22 °C and relative humidity from 50 to 65%. The maximum expanded uncertainty for all of the tested samples was less than 4.32% (see Equation (9)).

4.1.1. CR-39

The obtained impact energy values causing a break or penetration of lenses made from CR-39 are shown in Figure 4. As can be seen, CR-39 exhibits very low mechanical resistance to impact. The mechanical strength of CR-39 lenses depends significantly on their optical power and the shape of the striker applied. The lowest impact resistance was recorded for the cone-shaped striker. Lenses with optical powers of −6.0 and −4.0 diopters were resistant to impact energy of less than 0.35 J, which corresponds to the striker dropped from a height of 0.005 m. A slight increase in impact resistance was observed for lenses with positive optical powers (>2.0 diopters). The energy values causing a break of CR-39 lenses with the cone-shaped striker were also very low (<1.0 J) for the optical power of +4.0 diopters. In addition, it should be noted that, upon impact, all lenses made from CR-39 were completely shattered, posing an additional hazard to the user's eyes.

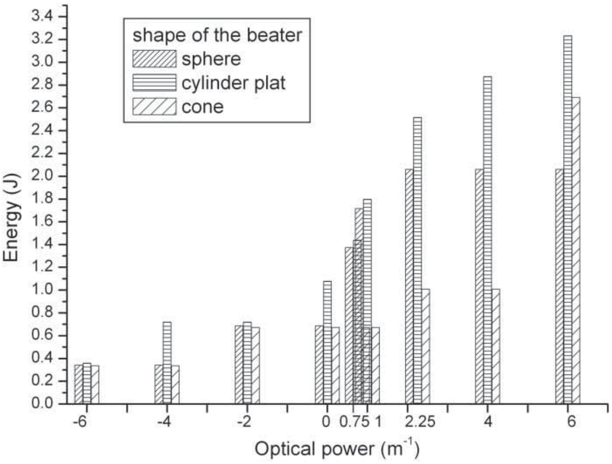

Figure 4. Impact energy causing a break or penetration of allyl diglycol carbonate (CR-39) lenses of different optical powers (shape and thickness).

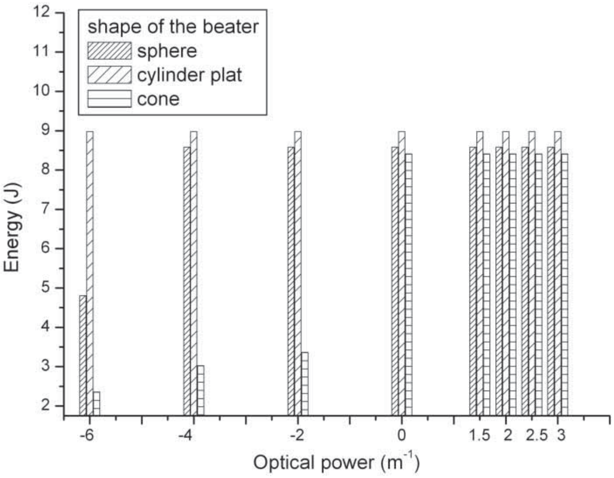

Figure 5. Impact energy causing a break or penetration of polyurethane and polyurea copolymer (Trivex) lenses of different optical powers (shape and thickness).

4.1.2. Trivex

The impact resistance results for Trivex lenses of different optical powers are shown in Figure 5. These lenses exhibit superior mechanical strength throughout the entire range of optical powers as compared with those made from CR-39. The impact resistance of lenses made from Trivex also depends on the shape of the striker, especially in the case of negative optical powers (see Figure 5). The cone-shaped striker punctured lenses of −6.0, −4.0 and −2.0 diopters upon impact with an energy of 2.35, 3.03 and

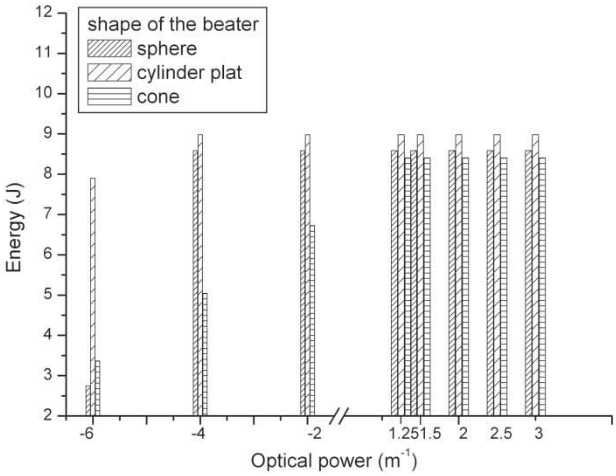

Figure 6. Impact energy causing break or penetration of polycarbonate lenses of different optical powers (shape and thickness).

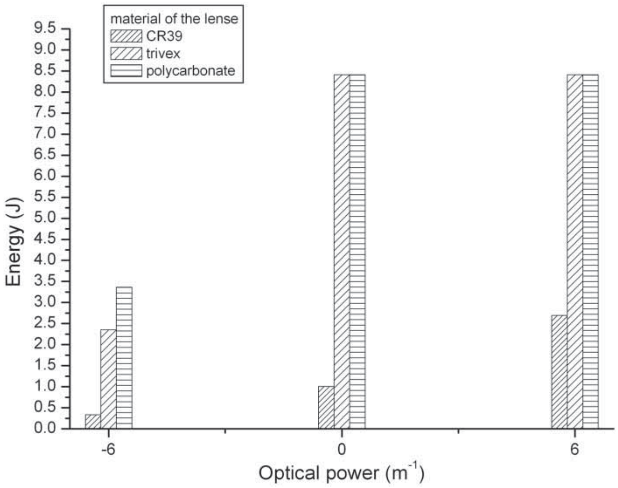

Figure 7. Impact energy of the cone-shaped striker causing a break or penetration of lenses made from different ophthalmic materials, depending on their optical power.
Note: CR-39 = allyl diglycol carbonate; Trivex = polyurethane and polyurea copolymer.

3.36 J. In the case of lenses with positive optical powers, punctures, cracks or deformations were not recorded even at the maximum energy used in the test (9.0 J).

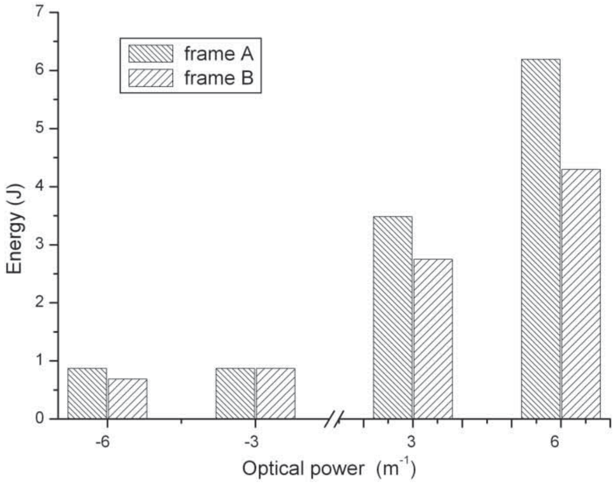

Figure 8. Impact energy damaging the lenses of two models of safety spectacles equipped with allyl diglycol carbonate (CR-39) corrective lenses of different optical powers.

4.1.3. Polycarbonate

Figure 6 shows the results for impact resistance testing for PC lenses with different optical powers. No cracking or fragmentation of lenses was observed upon impact. PC lenses exhibit the highest mechanical strength among the tested samples (see Figure 6). Because PC is characterized by high flexibility, the center of the lens was deflected upon impact, causing a mark on the flat surface on which the samples were placed. Therefore, it is recommended that such lenses should be fitted in spectacle frames allowing a greater distance between the lens and the pupil.

Mechanical strength test results indicate that the lowest impact energy causing a break or puncture of the tested lenses was obtained for the cone-shaped striker. The values of the impact energy of that striker causing a break or penetration of lenses made from different ophthalmic materials, depending on their optical power, are shown in Figure 7.

It can be concluded that the impact resistance of corrective lenses with negative optical powers made from all of the tested ophthalmic materials is less than half of the corresponding value for lenses with positive optical powers.

Table 1. Results for testing the resistance of safety spectacles fitted with allyl diglycol carbonate (CR-39) corrective lenses to high-speed particles.[9]

	Model of spectacles			
	Frame A		Frame B	
Optical power of lens (diopters)	Test ball speed (m/s)	Impact energy (J)	Test ball speed (m/s)	Impact energy (J)
−6.0	45	0.871	40	0.688
−3.0	45	0.871	45	0.871
+3.0	90	3.483	80	2.752
+6.0	120	6.192	100	4.300

Table 2. Results for testing the resistance of spectacles fitted with lenses made from polycarbonate, Trivex, andCR-39 to the impact of high-speed particles.[9]

	Ophthalmic material					
	CR-39		Polycarbonate		Trivex	
Optical power of lens (diopters)	Impact velocity (m/s)	Impact energy (J)	Impact velocity (m/s)	Impact energy (J)	Impact velocity (m/s)	Impact energy (J)
−6.0	40	0.688	>190	>15.52	120	6.19
−3.0	45	0.871	>190	>15.52	190	>15.52
+3.0	80	2.752	>190	>15.52	120	6.19
+6.0	100	4.300	>190	>15.52	190	>15.52

Note: CR-39 = allyl diglycol carbonate; Trivex = polyurethane and polyurea copolymer.

4.2. Mechanical strength of safety spectacles with corrective lenses

The results of mechanical strength testing of two models of spectacles (see Figure 3) fitted with corrective lenses made from CR-39 are presented in Table 1 and Figure 8. The calculated expanded uncertainty for the test method was ±2.52% (see Equation (11)).

It can be concluded that CR-39 lenses with negative optical powers do not meet the low energy impact requirements specified in Standard No. EN 166:2001.[7] The shock-absorbing elements fitted in spectacles with a type A frame significantly increased their impact resistance. It can be expected that the protective elements are capable of absorbing and spreading the impact energy over a larger area of the user's face, limiting the severity of injury to the face and nose of the spectacle wearer.

Test results for the resistance of spectacles fitted with PC, Trivex and CR-39 lenses to high-speed particles are presented in Table 2. The tests were performed for lenses mounted on a type B frame (without energy-absorbing elements). As can be seen, spectacles fitted with corrective lenses made from PC and Trivex exhibit much better impact resistance than CR-39 lenses.

Spectacles fitted with PC lenses of negative optical powers withstand high energy impacts (as defined in Standard No. EN 166:2001 [7]) corresponding to the impact of a steel ball traveling at 190 m/s. Spectacles with lenses fitted with Trivex lenses of negative optical powers (−6.0 and −3.0 diopters) fractured upon the impact of a steel ball traveling at 120 m/s.

5. Summary

The test results revealed a significant relationship between the ophthalmic material type, the optical power of the lens and mechanical strength. From the point of view of impact resistance, the best ophthalmic material for safety spectacles is PC. However, due to its poor optical properties, this has limited applicability. A suitable alternative is offered by lenses made from Trivex. Because of the very low mechanical strength of CR-39 lenses, this material is not recommended for safety spectacles (particularly for myopic users). Moreover, upon impact CR-39 lenses were observed to break into small, sharp pieces which could cause serious eye injury.

Furthermore, the obtained test results for mechanical resistance of spectacles to high-speed particles showed that shock-absorbing elements fitted to the frame and nose bridge significantly increased the impact resistance of spectacle lenses. Thus, these elements can also be expected to reduce the severity of potential injury to the face and nose of the spectacle wearer.

Disclosure statement

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