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Effect of Abrasion-Induced Contact Damage on the Optical Properties and Strength of Float Glass

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14. ABSTRACT

Two commercially available float glasses, a borosilicate and a soda-lime-silicate, were subjected to an increasing number of abrasion cycles to determine the effects of the abrasion-induced contact damage on haze and flexure strength. The borosilicate did not decrease in strength and had a minimal increase in haze through and after 150 abrasion cycles as compared to the soda-lime-silicate glass. After 300 abrasion cycles, the strength of both glasses was essentially the same, but the haze of the soda-lime-silicate was significantly higher than the borosilicate glass. These results show that the borosilicate glass is more abrasion resistant than the soda-lime-silicate glass.

15. SUBJECT TERMS

borosilicate glass; soda-lime-silicate glass; flexure strength, haze; abrasion

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Contents

List of Figures

List of Tables

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1. Introduction

Borosilicate and soda-lime-silicate float glasses are common components in transparent armor systems. Manufactured through the float process, these glasses can be produced as large sheets with a uniform thickness at a much lower price than many other glasses and transparent ceramics, making float glass a practical option in transparent armor applications. Employed as the strike face in the armor system, the glass is subjected to environmental conditions that can affect the strength and the optical properties as well as the ballistic performance.

Extensive research that examined the effect of a single indentation or scratch has on the strength of different glasses has been conducted.[1–16] However, no studies have been found that examined the effect of gross contact damage, such as what might develop on the glass surface during a sand storm, on strength and optical properties. In this study, contact damage was emulated through varying levels of uniform abrasion on the surface of glass plates to identify and document the resulting damage and the impact of this damage on the optical properties and equibiaxial flexural strength of the glass.

2. Experimental Procedure

Borosilicate[*†] and low-iron soda-lime-silicate[‡] plates nominally 150 mm square and, respectively, 6 and 6.5 mm thick were obtained for evaluation. The edge length and thickness were determined for each plate using calipers and micrometers, respectively. To avoid damaging the center portion of each plate when measuring the thickness, the thickness at each corner was measured and the average of these values was used as the plate thickness in all subsequent calculations. Each plate was thoroughly cleaned of all surface debris using a commercial glass cleaning solution, and the haze was measured using haze-gard *plus*[§] (Fig. 1). Haze[**] was measured at four locations around the center of the plate and used to determine the average haze for each plate. The glass plate was then slid into a wooden fixture, (Fig. 2A), which was designed to hold the glass in place and contained the abrasive media (Fig. 2B) during the abrasion cycles. The fixture containing the glass plate was placed on the Bayer Testing Equipment (BTE)[††] (Fig. 3). A piece of wax paper

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[*] BOROFLOAT 33®, Schott North America, Duryea, PA

[†] The views and conclusions contained in this document are those of the US Army Research Laboratory. Citation of manufacturer's or trade names does not constitute as official endorsement or approval of the use thereof.

[‡] Starphire, PPG Industries, Inc., Pittsburgh, PA

[§] BYK-Gardner, Inc., USA

[**] Haze is defined as the ratio of diffuse transmission to total transmission through the plate times 100.

[††] COLTS Laboratories, 702 Stevens Ave, Oldsmar, FL

was laid on the glass surface, and the abrasive media was slowly poured onto the wax paper. The wax paper acted as a cushion to minimize chipping of the glass surface as the abrasive media was added. The wax paper was then slowly removed, transferring the media onto the glass surface. The media used to abrade the glass was 250 g of #12 grit (average particle size of 1.6 mm) alumina/zirconia particles. The abrasion was done only on the tin side of each glass plate as this is typically the strike face in the transparent armor package. (These glasses were made using the float process where the molten glass is floated on a bath of molten tin. As a result, the side in contact with the tin is labeled the "tin" side and the other side is labeled the "air" side. The tin side is typically used as the strike face in transparent armor systems because it is harder than the air side.) The BTE laterally oscillated the fixture, allowing the abrasive media to move freely across the surface of the glass. Six samples, each containing 30 borosilicate plates, were abraded for 0, 50, 150, 300, 600, and 1200 cycles, respectively, while five samples, each containing 30 soda-lime-silica plates, were abraded for 0, 50, 150, 300, and 600 cycles, respectively. After the appropriate number of abrasion cycles were completed, the plate was thoroughly cleaned with the glass cleaning solution and the haze was again measured.

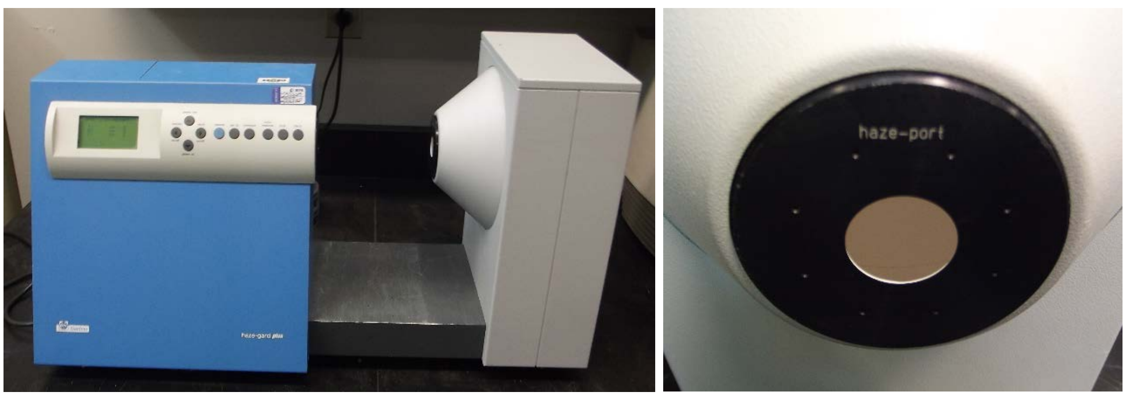

Fig. 1 haze-gard *plus* (left) with the haze port (right) used to determine the haze in the glass plates

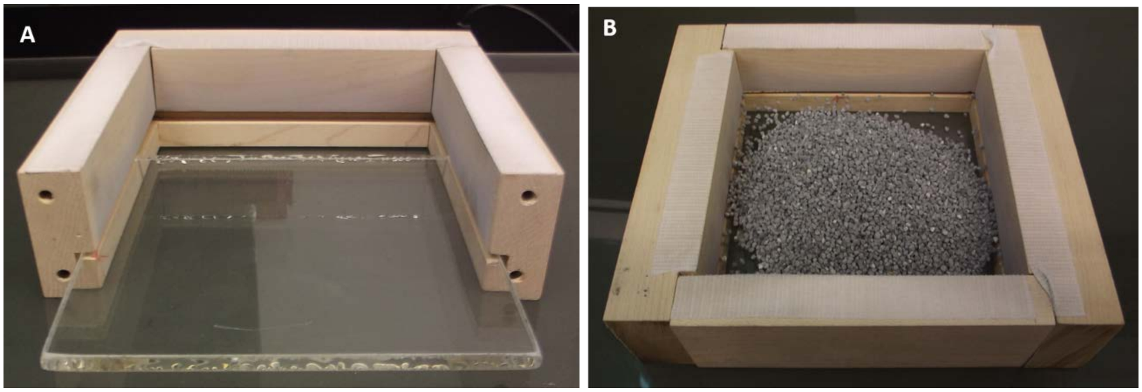

Fig. 2 Wooden fixture used to hold the glass plate, tin side up, in place during vibration testing (A). The plate was slid into the fixture, and the fourth side of the fixture screwed into place to hold the plate steady. The abrasive media was placed inside the box on top of the glass prior to the start of the cycles (B).

Fig. 3 Bayer Testing Equipment (BTE) used to abrade the glass plates

The ring-on-ring equibiaxial flexure strength was determined using a Zwick/Roell Z030[*] load frame following the procedures outlined in ASTM C1499.[17] The load and support rings were made of steel and had a load/support ring ratio of 0.5 with a 42.5-mm-diameter load ring and an 85-mm-diameter support ring. The selection of the ring ratio and ring diameters was based on previous work reported in Swab et al.[18] A thin (0.05 mm) low-tack adhesive plastic, nominally the same size as the glass plate, was then affixed to the air side of each plate to prevent glass fragments from being ejected into the surrounding area upon fracture and to assist with handling and fractography. The side with the low-tack adhesive layer was deemed the compression surface. Plates were subjected to a stressing rate of 30–35 MPa/s (crosshead displacement rate of 7.6 mm/min) until fracture occurred. After fracture,

[*] Zwick USA, Kennesaw, GA

the fracture initiation location was identified, and each datum was classified as valid (fracture initiated inside the load ring area or at the circumference of the load ring) or as invalid (fracture initiated outside the load ring diameter typically at the edge of the plate). A Poisson's ratio of 0.2 was used to calculate the strength according to the equation in ASTM C1499.[17] The average strength was calculated using only data from plates that exhibited valid fractures.

3. Results and Discussion

3.1 Haze

The influence of the abrasion cycles on the haze is provided in Table 1 and Fig. 4. The data in Table 1 show that the haze prior to abrasion is consistent across both glasses. However, the amount of haze increases appreciably more with increasing cycles in the soda-lime-silicate glass than the borosilicate. The borosilicate is harder than the soda-lime-silicate[19] and thus is more abrasion resistant.

Table 1 Haze as a function of abrasion cycles

Cycles	Borosilicate			Soda-Lime-Silicate		
	Pre	Post	Δ	Pre	Post	Δ
0	0.07 ± 0.02	…	0.00	0.07 ± 0.03	…	0.00
50	0.06 ± 0.02	0.13 ± 0.02	0.07	0.06 ± 0.03	0.17 ± 0.03	0.11
150	0.07 ± 0.03	0.20 ± 0.05	0.13	0.07 ± 0.05	0.33 ± 0.05	0.26
300	0.07 ± 0.09	0.40 ± 0.11	0.33	0.05 ± 0.02	0.63 ± 0.12	0.58
600	0.08 ± 0.03	0.61 ± 0.23	0.53	0.07 ± 0.02	1.19 ± 0.3	1.12
1200	0.05 ± 0.03	0.64 ± 0.16	0.59	…	…	…

All values are percentages.

Figure 4 provides a qualitative representation of how the abrasion cycles affect the surface of the borosilicate glass plates. These borosilicate plates were coated with the ink from a black permanent marker and allowed to dry before being subjected to abrasion. Very little of the ink is removed after 300 cycles, but after 1200 cycles all of the ink appears to have been removed from the central area of the plate (Fig. 4, bottom-right). This is consistent with the increase in haze after 1200 cycles compared to the haze after only 300 cycles.

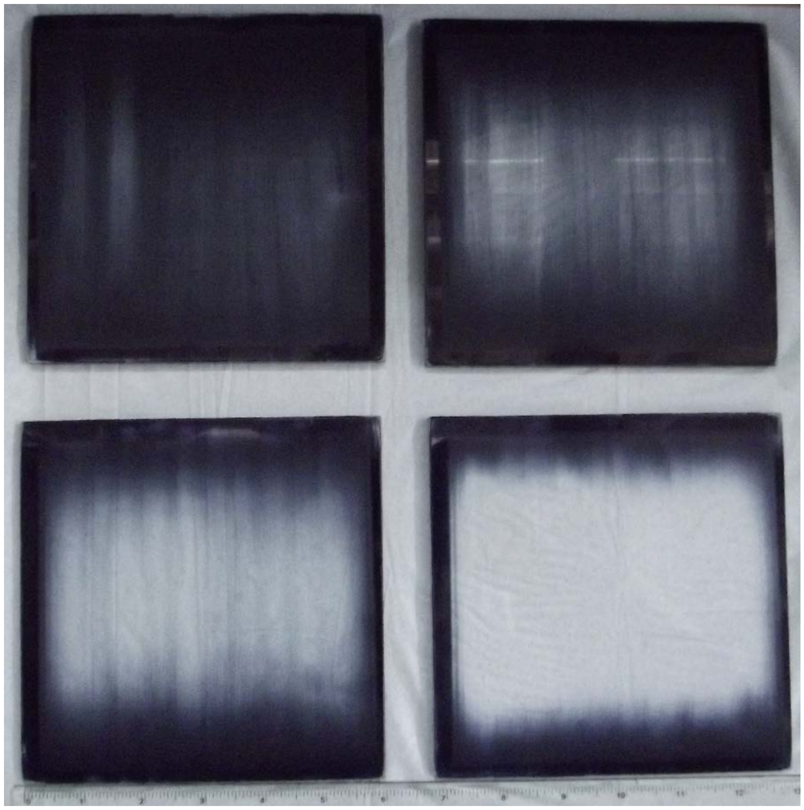

Fig. 4 Borosilicate glass plates coated in black ink from a permanent marker and subjected to abrasion cycles. Top-left: 300 cycles; top-right: 600 cycles; bottom-left: 900 cycles (shown only as an example); and bottom-right: 1200 cycles.

3.2 Strength

The strength of each glass as a function of abrasion cycles is summarized in Table 2. The average baseline strength values are slightly lower than what was previously reported[18] for these same glasses, but the values are not significantly lower considering the high standard deviation associated with each baseline strength. This difference may be due to how the plates were handled from the time they were cut until the strength testing was conducted, which resulted in a slight increase in the flaws on the glass surface.

Table 2 Equibiaxial flexure strength as a function of abrasion cycles

Cycles	Borosilicate strength (MPa)		Soda-Lime-Silicate strength (MPa)	
	Average	**Std Dev**	**Average**	**Std Dev**
0	103.1	23.6	115.3	27.0
50	102.4	12.4	60.2	5.5
150	95.9	13.4	76.7	6.2
300	64.0	8.7	73.3	6.6
600	66.4	7.4	65.3	10.0
1200	76.9	7.4	…	…

The strength of the borosilicate remains essentially constant from 0 through 150 abrasion cycles before there is a significant drop in strength to 64 MPa at 300 cycles. The borosilicate does not exhibit any further strength decrease beyond 300 cycles while the soda-lime-glass drops to the same strength (64 MPa) after only 50 abrasion cycles. This trend indicates that at less than 300 cycles, the strength of the borosilicate glass is still controlled by the inherent surface flaws or that the flaws generated by the abrasion cycles are approximately the same size as the inherent surface flaws. The standard deviation associated with the strength values after 50 and 150 cycles is about half of the standard deviation associated with the baseline strength. This indicates that strength-limiting flaws are the same size but that there is a higher density of these flaws on the glass surface after abrasion. At 300 cycles the abrasion process generates flaws that are larger than the inherent flaws in the borosilicate, but increasing the number of cycles to 600 and 1200 does not result in any further increase in the flaw size. On the other hand, larger flaws are introduced almost immediately on the surface of the soda-lime-silicate glass, after just 50 cycles, but the flaw size does not increase further with an increase in the number of abrasion cycles.

Fracture mechanics can be used to estimate the size of the strength-limiting flaw using Eq. 1:

$$c = \left(\frac{K_{Ic}}{\theta\, Y}\right)^2 , \qquad (1)$$

where c = flaw size (µm); K_{Ic} = fracture toughness = 0.75 MPa$\sqrt{\text{m}}$[20]; σ = strength (MPa); and Y is the crack shape factor which, for simplicity, will equal 1. Using Eq. 1, the flaw size for an assumed strength of 100 MPa is approximately 55 µm, while at an assumed strength of 65 MPa the critical flaw size increases to almost 80 µm.

Figures 5 and 6 show the interrelationship between haze and strength of each glass as a function of the number of abrasion cycles. From this data an approximate haze threshold can be established for both of these glasses. When the haze value of the borosilicate is approximately 0.35, it would imply that the strength of the glass had decreased significantly. The haze threshold value for a similar strength decrease in the soda-lime-silicate glass is appreciably lower at approximately 0.20.

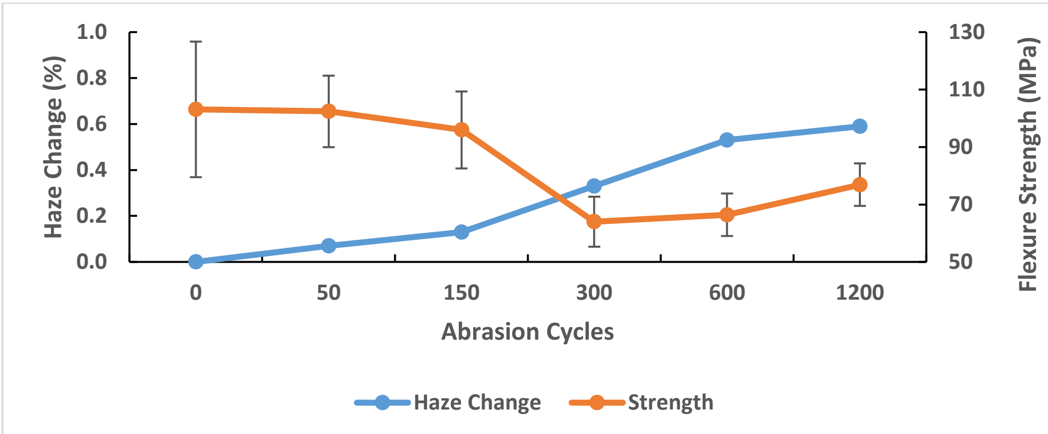

Fig. 5 Plot of haze change and equibiaxial flexure strength of borosilicate glass as a function of the number of abrasion cycles

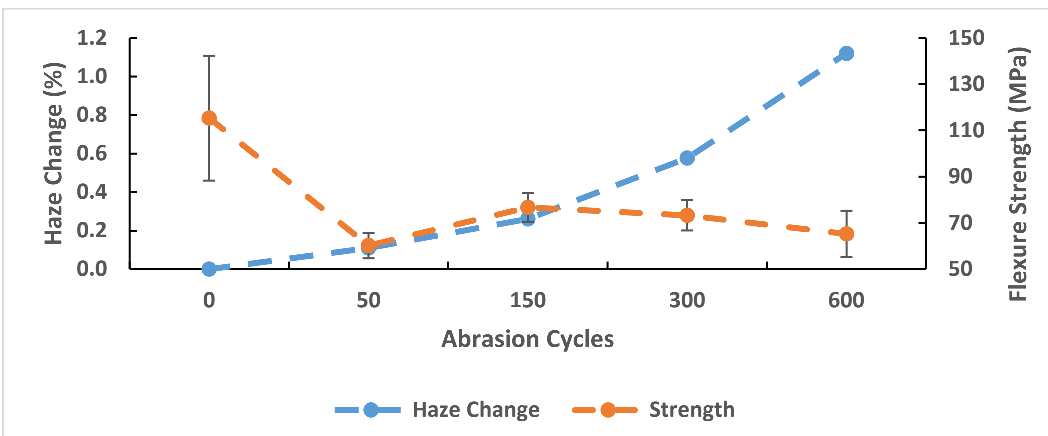

Fig. 6 Plot of haze change and equibiaxial flexure strength of soda-lime-silicate glass as a function of the number of abrasion cycles

4. Conclusion

The effect of abrasion on the haze and flexure strength of borosilicate and soda-lime-silicate glasses was examined. The haze increased and strength decreased in both glasses with an increasing number of abrasion cycles, but the changes occurred more quickly (at a lower number of abrasion cycles) in the soda-lime-silicate glass than the borosilicate. This may be due to the higher hardness of the borosilicate, which makes this glass more resistant to abrasion. Further studies are needed, but this initial study indicates that the borosilicate glass, as the strike face in transparent armor systems, would be more resistant to optical and mechanical degradation in some hostile environments than the soda-lime-silicate glass.

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