



ARL-TN-0954 • JUNE 2019



# Effect of Abrasion on the Properties of a Glass-Ceramic

by Catherine G Huang, Jeffrey J Swab, and Parimal J Patel

Approved for public release; distribution is unlimited.

## **NOTICES**

### **Disclaimers**

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturer's or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.



# **Effect of Abrasion on the Properties of a Glass-Ceramic**

**by Catherine G Huang**

*Science and Mathematics Academy, Aberdeen High School*

**Jeffrey J Swab and Parimal J Patel**

*Weapons and Materials Research Directorate, CCDC Army Research Laboratory*

**REPORT DOCUMENTATION PAGE**

*Form Approved  
OMB No. 0704-0188*

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

**PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

<b>1. REPORT DATE (DD-MM-YYYY)</b> June 2019			<b>2. REPORT TYPE</b> Technical Note		<b>3. DATES COVERED (From - To)</b> 6 September 2016–1 May 2017	
<b>4. TITLE AND SUBTITLE</b> Effect of Abrasion on the Properties of a Glass-Ceramic					<b>5a. CONTRACT NUMBER</b>	
					<b>5b. GRANT NUMBER</b>	
					<b>5c. PROGRAM ELEMENT NUMBER</b>	
<b>6. AUTHOR(S)</b> Catherine G Huang, Jeffrey J Swab, and Parimal J Patel					<b>5d. PROJECT NUMBER</b>	
					<b>5e. TASK NUMBER</b>	
					<b>5f. WORK UNIT NUMBER</b>	
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> CCDC Army Research Laboratory ATTN: FCDD-RLW-ME Aberdeen Proving Ground, MD 21005					<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>  ARL-TN-0954	
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b>					<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b>	
					<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b>	
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> Approved for public release; distribution is unlimited.						
<b>13. SUPPLEMENTARY NOTES</b> ORCID ID(s): Jeffrey J Swab, 0000-0002-8204-7202						
<b>14. ABSTRACT</b> Glass-ceramic plates were exposed to an increasing number of abrasion cycles to determine if the resulting abrasive damage affected the optical haze and flexure strength. The optical haze continually increased with an increase in the number of abrasion cycles while the flexure strength decreased after the first 150 cycles but did not exhibit any further decrease through 2400 cycles. The change in haze and strength is similar to what was observed previously with borosilicate and soda-lime-silicate float glasses.						
<b>15. SUBJECT TERMS</b> glass-ceramic, borosilicate glass, soda–lime–silicate glass, flexure strength, haze, abrasion						
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b>  UU	<b>18. NUMBER OF PAGES</b>  17	<b>19a. NAME OF RESPONSIBLE PERSON</b> Jeffrey J Swab	
<b>a. REPORT</b> Unclassified	<b>b. ABSTRACT</b> Unclassified	<b>c. THIS PAGE</b> Unclassified			<b>19b. TELEPHONE NUMBER (Include area code)</b> 410-306-0753	

## **Contents**

---

<b>List of Figures</b>	<b>iv</b>
<b>List of Tables</b>	<b>iv</b>
<b>Acknowledgments</b>	<b>v</b>
<b>1. Introduction</b>	<b>1</b>
<b>2. Material</b>	<b>2</b>
<b>3. Experimental Procedure</b>	<b>3</b>
<b>4. Results and Discussion</b>	<b>3</b>
<b>5. Conclusion</b>	<b>5</b>
<b>6. References</b>	<b>6</b>
<b>List of Symbols, Abbreviations, and Acronyms</b>	<b>9</b>
<b>Distribution List</b>	<b>10</b>

## List of Figures

---

---

Fig. 1	Effects of abrasion on the haze and flexure strength of a glass-ceramic (Robax) compared with Boro and SLS glasses. The data for both float glasses between 0 and 1200 cycles comes from Murdock et al.....	4
--------	---	---

## List of Tables

---

---

Table 1	Properties of Robax glass-ceramic.....	2
Table 2	Robax composition .....	2

## **Acknowledgments**

---

---

The lead author would like to acknowledge the assistance and guidance of Mr Luke Gilde, who provided instruction and training on the proper use of all the equipment used in this study.

## 1. Introduction

---

Float glasses are common components in a wide variety of commercial applications including windows and doors for homes and buildings, automobile windows, and display cases. These glasses are also employed as the strike face in some transparent armor systems. In many applications the glass is exposed to environmental conditions that can affect the strength and optical properties; in transparent armor these environmental conditions can also affect the ballistic performance. Extensive research has been conducted showing that the strength of float glass is significantly reduced by the introduction of a single indentation or scratch on the surface.<sup>1-16</sup> Recently, research has revealed that gross contact damage, similar to what might be expected during a sand or hail storm, or after extensive in-service exposure, adversely affects the strength and optical properties of float glass.<sup>17</sup>

A possible alternative to float glass in transparent armor systems could be glass-ceramics. Glass-ceramics have an amorphous phase and contain at least one crystalline phase, which results in better thermomechanical properties than glass. They are formed using a traditional glass-forming process but undergo a subsequent reheat step after forming that nucleates and grows crystallites. The ability to control the nucleation and growth of these crystallites determines both the mechanical and optical properties. The resulting microstructure consists of a glass matrix with a uniformly dispersed crystalline phase where the crystals are less than 100  $\mu\text{m}$  in size. The most common glass-ceramics have a composition based on the  $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$  system.<sup>18-21</sup> Similar to the base glass, these glass-ceramics have high transparency but also have minimal or zero coefficient of thermal expansion values and a maximum use temperature that is higher than the base glass. Many commercial applications, such as telescope mirrors, cooktops, cookware and bakeware, doors in microwave ovens, and fireplaces take advantage of these unique properties.

In this study, gross contact damage was generated on the surface of glass-ceramic plates using abrasive media to ascertain the effect of the resulting damage on the optical properties and flexural strength. These results are compared to the results<sup>17</sup> from similar experiments conducted on borosilicate (Boro) and soda-lime-silicate (SLS) float glasses.



## 2. Material

---

The glass-ceramic examined in this effort is from the  $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$  system. It was produced by SCHOTT\* under the trade name Robax. It is an extremely heat-resistant glass-ceramic with a very low coefficient of thermal expansion that is marketed as a fire-resistant glass for use in fireplace and stove windows. Properties of this glass-ceramic, provided by the manufacturer, are summarized in Table 1 and the chemical composition is provided in Table 2.

**Table 1 Properties of Robax glass-ceramic**

Density ( $\text{g}/\text{cm}^3$ )	2.6
Elastic modulus (GPa)	92.0
Shear modulus (GPa)	38.6
Poisson's ratio	0.25
Fracture toughness <sup>a</sup> ( $\text{MPa}\sqrt{\text{m}}$ )	0.867 <sup>22</sup>
% optical transmission (visible)	90

<sup>a</sup> Measured in dry  $\text{N}_2$  gas using the Single-Edge Pre-cracked Beam Method

**Table 2 Robax composition<sup>23</sup>**

Oxide	Wt%
$\text{SiO}_2$	63.68
$\text{Al}_2\text{O}_3$	21.82
$\text{Li}_2\text{O}$	3.95
$\text{P}_2\text{O}_5$	0.10
$\text{MgO}$	0.42
$\text{ZnO}$	2.08
$\text{TiO}_2$	2.18
$\text{ZrO}_2$	1.25
$\text{Na}_2\text{O}$	1.45
$\text{BaO}$	1.97
$\text{CaO}$	0.08
$\text{MnO}$	0.08
$\text{NiO}$	0.08
$\text{CoO}$	0.01
$\text{Cr}_2\text{O}_3$	0.04
$\text{Fe}_2\text{O}_3$	0.42
$\text{As}_2\text{O}_3$	0.07

The  $\text{TiO}_2$  and  $\text{ZrO}_2$  serve as nucleating agents;  $\text{Na}_2\text{O}$ ,  $\text{BaO}$ , and  $\text{CaO}$  serve as fluxing agents;  $\text{As}_2\text{O}_3$  is a fining agent; and  $\text{MnO}$ ,  $\text{NiO}$ ,  $\text{CoO}$ , and  $\text{Cr}_2\text{O}_3$  are added to control the color.

---

\* SCHOTT North America, Inc., 5530 Shepherdsville Road, Louisville, KY 40228, USA.

### 3. Experimental Procedure

---

Plates, nominally 150-mm square and 5-mm thick, were obtained for evaluation. The dimensions of each plate were determined. The transmission haze\* was measured after each plate was thoroughly cleaned using a commercial glass cleaning solution. Damage was introduced through abrasion by placing 250 grams of #12 grit alumina/zirconia particles on one 150-mm square surface of a plate then laterally oscillating the plate for a designated number of cycles. Five samples, each containing 10 plates, were abraded for 150, 300, 600, 1200, and 2400 cycles, respectively. After the appropriate number of abrasive cycles were completed, the plate was thoroughly cleaned with the glass-cleaning solution and the haze was again measured. Optical transmission was measured as part of the haze determination but the decrease in optical transmission was consistently 1% or less, irrespective of the number of abrasion cycles. As a result, transmission haze was selected as the optical property to compare with the flexure strength.

The equibiaxial flexure strength was determined using a universal load frame following the procedures outlined in ASTM C1499† for a ring-on-ring loading condition. The load and support rings were made of steel, had a diameter ratio of 0.5, and comprised a 42.5-mm diameter load ring and an 85-mm diameter support ring. Specimens were loaded using a crosshead displacement rate of 7.6 mm/min (30–35 MPa/s) until fracture occurred. After fracture, the fracture initiation location was identified, and each datum was classified as a valid fracture (fracture initiated inside the load ring area or at the circumference of the load ring) or an invalid fracture (fracture initiated outside the load ring diameter, typically at the edge of the plate). The average strength was calculated using only data from plates that exhibited valid fractures.

Baseline haze and strength values were determined using 30 plates in their as-received condition. Additional details on the procedures, methodologies, and equipment used in this effort can be found in Murdock et al.<sup>17</sup>

### 4. Results and Discussion

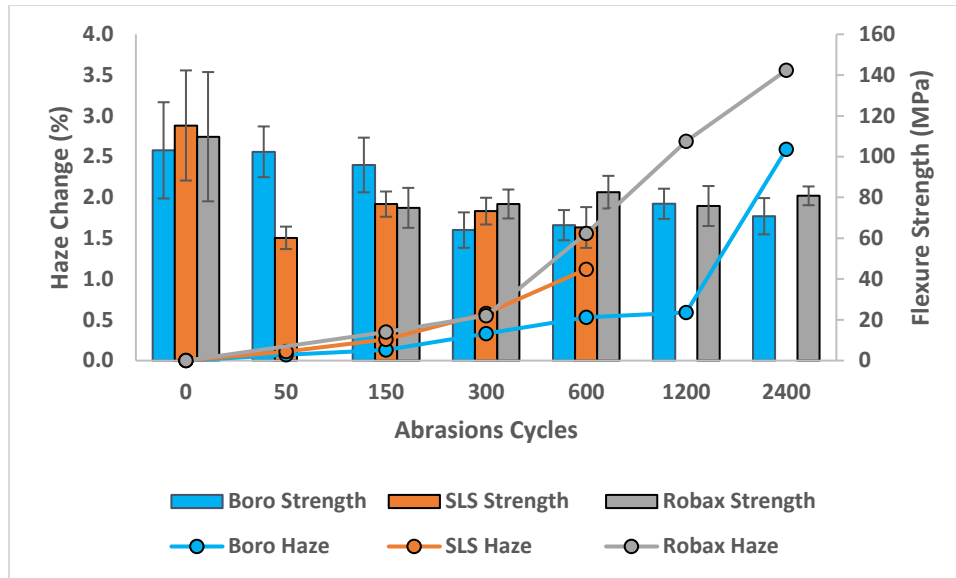
---

Figure 1 summarizes the effect of abrasion cycles on the haze and the equibiaxial flexure strength of the glass-ceramic compared with results for Boro and SLS float glasses.<sup>17</sup>

---

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

† ASTM C1499 “Standard Test Method for Monotonic Equibiaxial Flexural Strength of Advanced Ceramics at Ambient Temperature,” ASTM Annual Book of Standards, Vol. 15.01



**Fig. 1** Effects of abrasion on the haze and flexure strength of a glass-ceramic (Robax) compared with Boro and SLS glasses. The data for both float glasses between 0 and 1200 cycles comes from Murdock et al.<sup>17</sup>

The haze prior to abrasion is essentially the same for both float glasses ( $\approx 0.07$ ) but the haze for the glass-ceramic was appreciably higher at  $\approx 0.20$ . This higher value is most likely the result of the nanosized crystallites that are in the Robax but not the float glasses. The abrasion resistance of the SLS and the Robax are very similar through 300 abrasion cycles but after 600 cycles the haze of Robax is higher, which may indicate a higher amount of damage from the abrasive cycles. The Boro on the other hand appears to be significantly more resistant to this abrasion test, since it is harder<sup>24</sup> and accordingly the haze change is significantly less, at least up to and including 1200 cycles. Previous research<sup>17</sup> on the Boro did not include tests after 2400 abrasion cycles so 10 plates were abraded. There is an almost 80% increase in haze of the Boro between 1200 and 2400 cycles but the haze is still much lower than the Robax after the same number of cycles.

The baseline strength of the Robax is essentially the same as both float glasses and, similar to both float glasses, it has a large standard deviation. The Robax strength after 150 abrasion cycles drops by approximately 30% to a level similar to the SLS while the Boro remains relatively constant, at the baseline strength level, through 150 cycles.<sup>17</sup> After 300 cycles the strength of the Boro decreases to essentially the same level as the Robax and SLS. There is no further strength decrease in either the Robax or the Boro up to and through 2400 abrasion cycles. The standard deviation associated with each Robax strength value decreases to a constant level after abrasion, well below the deviation associated with the baseline strength and, once again, similar to both float glasses. This standard deviation decrease indicates there

is a high density of flaws generated on the surface during the abrasion process and that these flaws have a similar size.

Two additional tests were conducted on the Robax material. The strength was determined after 300 abrasion cycles but the amount of abrasive media placed on the plate was doubled from 250 g to 500 g. Ten plates were exposed to this increased amount of media but the resulting strength and haze was no different than what was obtained when only 250 g of media was used. In the second test the strength was determined after a single, 10-mm long scratch was placed in the center region of one 150-mm square face of 10 plates using a diamond scribe under 10 N applied load. The procedure for scratching the plates is outlined in Swab et al.<sup>16</sup> The resulting strength decreased by about 50% due to the damage created by the scratching process. This is significant but less than the 60–70% decrease noted previously for the float glasses.<sup>16</sup> The Robax is about 15% tougher than the SLS and Boro ( $0.87 \text{ MPa}\sqrt{\text{m}}^{22}$  compared to  $0.75 \text{ MPa}\sqrt{\text{m}}^{25}$ ), which may account for the higher retained strength after the scratch test but this does not translate into improved abrasion resistance as indicated by the strength decrease that is comparable to both float glasses after 300 or more abrasive cycles.

## 5. Conclusion

---

---

The effect of abrasion on the haze and flexure strength of a glass-ceramic (Robax) was examined. The haze increased and strength decreased with an increasing number of abrasion cycles. The change in these properties is comparable to results obtained on Boro and SLS float glasses subjected to similar abrasive conditions. Further studies are needed, but these results coupled with previous results on the float glasses show that there is no distinct advantage of using this glass-ceramic as the strike face in transparent armor systems. It is no more resistant to optical and mechanical degradation than the float glasses that are currently used.

## 6. References

---

1. Dick E, Peter K. Generation of deep cracks in glass. *J Am Ceram Soc.* 1969;52(6):338–339.
2. Mecholsky JJ Jr, Freiman SW, Rice RW. Effect of grinding on flaw geometry and fracture of glass. *J Am Ceram Soc.* 1977;60(3–4):114–117.
3. Rice RW, Mecholsky JJ Jr. The nature of strength controlling machining flaws in ceramics. In: Hockey BJ, Rice RW, editors. *The science of ceramic machining and surface finishing II*. NBS Special Publication 562; 1979. p. 351–378.
4. Rice RW, Mecholsky JJ Jr, Becher PF. The effect of grinding direction on flaw character and strength of single-crystal and polycrystalline ceramics. *J Mater Sci.* 1981;16:853–862.
5. Swain MV. Microfracture about scratches in brittle solids. *Proc R Soc Lond A.* 1979;366:575–597.
6. Glaesemann GS, Jakus K, Ritter JE Jr. Strength variability of indented soda-lime glass. *J Am Ceram Soc.* 1987;70(6):441–444.
7. Howes VR, Szameitat A. Morphology of sub-surface cracks below the scratch produced on soda lime glass by a disc cutter. *J Mater Sci Lett.* 1984;3:872–874.
8. Lu K, Liao TW. Surface/surface damage and the fracture strength of ground ceramics. *J Mater Process Tech.* 1996;57:207–220.
9. Ahn Y, Park SS. The basic study about the effect of single point grinding on the bending strength of brittle materials. *KSME Int J.* 1998;12(4):598–605.
10. Li K, Shapiro Y, Li JCM. Scratch test of soda-lime glass. *Acta Mater.* 1998;46(15):5569–5578.
11. Yoshida S, Tanaka H, Hayashi T, Matsuoka J, Soga N. Scratch resistance of sodium borosilicate glass. *J Ceram Soc Jpn.* 2001;109(6):511–515.
12. Le Houérou V, Sanglebouef JC, Dériano S, Rouxel T, Duisit G. Surface damage of soda-lime-silica glass: indentation scratch behavior. *J Non-Cryst Solids.* 2003;316:54–63.

13. Tóth Z, Nagy A, Stienback G, Juhász A. Investigation of indentation-caused cracking in surface-modified silica glasses. *Mater Sci Eng A*. 2004;387–389:542–545.
14. Glaesemann GS, Gross TM, Payne JF, Price JJ. Fractography in the development of ion-exchanged cover glass. In: *Fractography of advanced ceramics and glasses VI*; 2012. p. 85–93.
15. Gross TM. Scratch damage in ion-exchanged alkali aluminosilicate glass: crack evolution and the dependence of lateral cracking threshold on contact geometry. In: *Fractography of advanced ceramics and glasses VI*; 2012. p. 113–122.
16. Swab JJ, Thies JJ Sr, Wright JC, Schoenstein JA, Patel PJ. Influence of surface scratches on the flexure strength of soda-lime silicate and borosilicate glass. *Exp Mech*. 2013;53:91–96. DOI 10.1007/s11340-012-9674-5.
17. Murdock J, Swab JJ, Patel PJ. Effect of abrasion-induced contact damage on the optical properties and strength of float glass. Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2018 Jun. Report No.: ARL-TR-8381.
18. Beall GH. Glass-ceramics. In: Boyd D, MacDowell J, editors. *Advances in ceramics. volume 18: commercial glasses*. Westerville (OH): The American Ceramic Society; 1986.
19. Scheidler H, Rodek E.  $\text{Li}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$  glass-ceramics. *Ceram Bull*. 1989;68(11).
20. Beall GH, Pinckney LR. Nanophase glass-ceramics. *J Am Ceram Soc*. 1999;82(1):5–16.
21. Höland W, Beall GH. *Glass-ceramic technology*. 2nd ed. The American Ceramic Society. Hoboken (NJ): John Wiley & Sons, Inc; 2012.
22. Quinn GD, Swab JJ, Patel P. Fracture toughness of modern and ancient glasses and glass ceramics as measured by the SEPB method. *Ceram Eng Sci Proc*. 2019;39(2):1–13.
23. Guedes M, Ferro AC, Ferreira JMF. Nucleation and crystal growth in commercial las compositions. *J Eur Ceram Soc*. 2001;21:1187–1194.
24. Wereszczak AA, Johans KE, Kirkland TP, Anderson CE, Behner T, Patel P, Templeton DW. Strength and contact damage responses in a soda-lime-silicate and borosilicate glass. *Proceedings of the 25th Army Science Conference*; 2006 Nov 27–30; Orlando, FL.

25. Quinn GD, Swab JJ. Fracture toughness of glasses as measured by the SCF and SEPB methods. *Ceram Eng Sci Proc.* 2018;38(2):75–88.

## List of Symbols, Abbreviations, and Acronyms

---

Boro	borosilicate
SLS	soda-lime-silicate



1 DEFENSE TECHNICAL  
(PDF) INFORMATION CTR  
DTIC OCA

2 CCDC ARL  
(PDF) IMAL HRA  
RECORDS MGMT  
FCDD RLD CL  
TECH LIB

1 GOVT PRINTG OFC  
(PDF) A MALHOTRA

6 CCDC ARL  
(PDF) FCDD RLW ME  
J SWAB  
V BLAIR  
S KILCZEWSKI  
P PATEL  
S SILTON  
L VARGAS