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Stress Optical Coefficient, Test Methodology, and Glass Standard Evaluation

by Clayton M Weiss and Parimal J Patel

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14. ABSTRACT The photoelastic behavior of transparent materials under stress, which is represented by the material property of stress optical coefficient, can be used to evaluate glass samples of known and unknown composition. Using a polariscopic and load frame, we were able to create and observe the conditions of stress-induced birefringence. A modification of an ASTM testing procedure for determining stress optical coefficient is described. Stress optical coefficient data for several types of glasses are computed for comparison and standardization purposes.						
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1. Introduction

Glass is a widely used material in transparent armor systems due to its low cost and availability. Some types of glass that are used include soda lime silica (float glass), borosilicate glass, fused silica, and glass ceramics.[1] These materials demonstrate properties to meet the ballistic requirements and are used, in practice, because of their wide availability and their low cost. The major uses of these glasses are architectural, automotive, and specialty applications such as semiconductor, photovoltaic, mirrors, and optics. These commercial applications drive the need for these materials, and armor designers use the materials to develop transparent armor.

The recent focus to improve and understand the behavior of glasses has been the investigation of glass under high-strain conditions. These investigations are difficult to conduct, so there is a need to assess glasses in the quasi-static regime. There has been extensive research on ceramic and glass materials to correlate materials properties to ballistic performance. Some properties of these materials are shown in Table 1. The hardness of the striking ply material relative to the projectile hardness has been found to be an important property to rank different striking ply materials.[2] However, using hardness to rank materials is not adequate when comparing similar materials such as glasses. Hardness differences for various glass systems are not large enough to observe a change in ballistic performance. Thus, there have been ongoing studies to characterize and understand these commercial glasses.[3–10] One of the critical parameters often overlooked is the surface condition of glass. The numerous surface flaws can affect ballistic performance. Wereszczak et al.[10] scanned the surface of borosilicate and soda lime silica glass and found upward of 730 and160 surface flaws, respectively on a 75- × 75-mm square area. There have been several investigations[11–18] to improve the surface strength of glasses using coating and etching techniques.

Table 1 Material properties of glass

Material	Type	Density	Young's modulus	Knoop hardness	Poisson's ratio
Starphire[a]	Soda lime silica	2.51	73.1	470	0.22
Borofloat[b]	Borosilicate	2.23	64	480 (0.1/20)	0.2
BK-7[c]	Borosilicate	2.53	81	520	0.206
Corning 7740[d]	Borosilicate	2.23	63	418	0.2
Fused quartz	Silica	2.2	72	570	0.17

Notes:
[a]PPG Industries, Inc. Starphire property data sheet. Pittsburgh (PA): PPG Industries, Inc. 2016 [accessed 2016 Mar 17] http://www.jnsglass.com/pdf/Starphire.pdf.
[b]Schott North America, Inc. Schott Borofloat 33 glass data sheet. Louisville (KY): Schott North America, Inc. 2016 [accessed 2016 Mar 17]. http://www.us.schott.com/borofloat/English/attribute/mechanical/index.html.
[c]Esco Optics, Inc. BK-7 glass property data sheet. Oak Ridge (NJ): Esco Optics, Inc. 2016 [accessed 2016 Mar 17]. https://www.escooptics.com/material-data/bk7-optical-glass.html.
[d]MatWeb, LLC. Corning Pyrex 7740 borosilicate glass data sheet. Blacksburg (VA): MatWeb, LLC. 2016 [accessed 2016 Mar 17]. http://www.matweb.com/search/datasheet.aspx?MatGUID=5bb651ca58524e79a503011b2cd8083d.

The properties listed in Table 1 are measured under ambient, quasi-static conditions. Pressure and temperature influence high-strain-rate events and there is limited correlation between high-strain-rate behavior and any of these properties. There is a need to determine critical material parameters that can bring insight into the behavior of different materials. One property that has not been investigated for correlation is the stress optic coefficient as a method to differentiate glasses. Upon review of commercial glasses properties, US Army Research Laboratory (ARL) researchers noted that the stress optic coefficient might correlate to the performance of these glasses. It is unknown if this is happenstance or true dependence. It is not believed the stress optic coefficient is the actual cause of the change in performance. Rather, the stress optic coefficient is an indirect measure of the glass composition and structure. This report discusses the development of an apparatus to measure the stress optic coefficient of different glasses and the results of commercially available glasses.

2. Photoelasticity

Materials that are transparent to visible light can be analyzed through the evaluation techniques of photoelasticity. Materials that are transparent and demonstrate birefringence only when under stress can be looked at with a series of polarizing filters to reveal information about the stress state of the material. A transparent material under a certain given loading and viewed through a polariscope, with crossed polarizing plates so that there is a net extinguishing of the illuminating light, is known as a dark field. In a dark field, configuration regions of constant stress will display a band of a single color and known wavelength. When light is passed through a stressed, optically transparent material the theory of photoelasticity dictates that the light passing through will show constructive and destructive interference within the material itself. This leads to a known wavelength sequence, where each wavelength corresponds to a certain degree of relative retardation of the light.

3. ASTM Testing

ASTM C770, Measurement of Glass Stress–Optical Coefficient,[19] outlines a procedure for identifying the stress optical coefficient (SOC) of bars in 4-point bending, fibers in tension, and bars in compression. In all instances the optical retardation is calculated in response to a number of fixed loads. The measurement apparatus used in the evaluation of these techniques is described. A mechanism for stressing the glass and a polarimeter are used together to evaluate the retardation, which is then used to calculate the SOC.

The polarimeter and loading mechanism described in the ASTM standard, shown in Fig. 1, is as follows: A light source, preferably a single wavelength source A), is followed by an adjustable aperture B), a polarizer C), a loading frame D), a Babinet compensator E), an analyzer (polarizer) F), and telescope with an angular scale G). The polarizer and analyzer are mounted at 45° from the vertical and at right angles from each other creating a full extinction of the transmitted light, or dark field image.

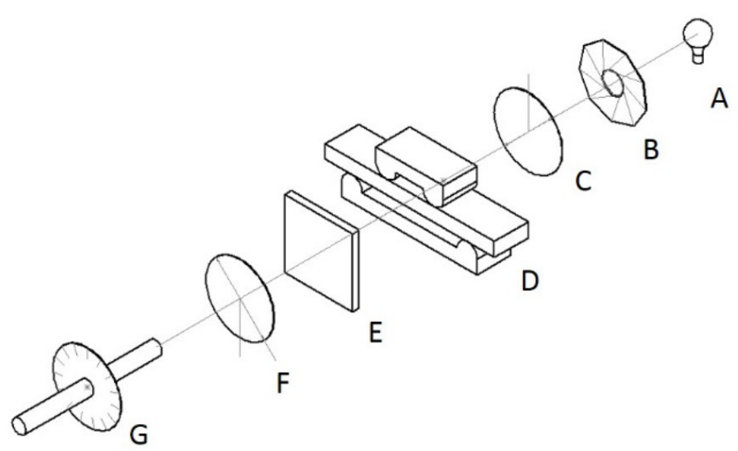

Fig. 1 Beam stressing and polarimeter arrangement

This study is an alternate method of calculating the stress optical condition of stress-birefringent glass material. The beam loading configuration of the ASTM standard is used (Fig. 2).

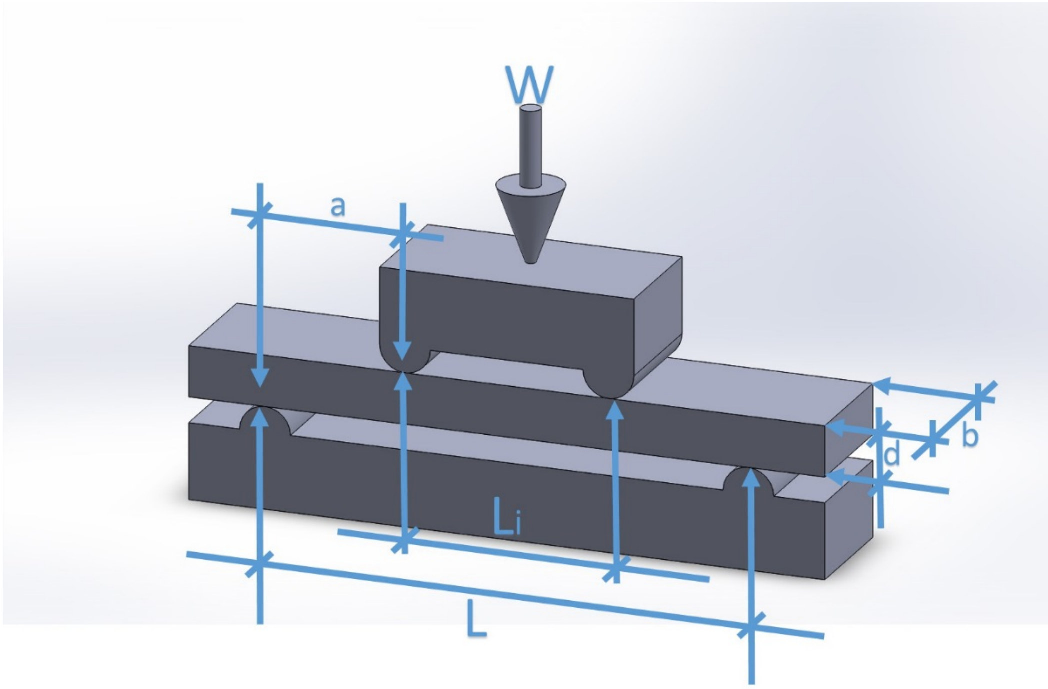

Fig. 2 Loading configuration of glass beams adapted from the ASTM standard. The glass beams used are to have a width b) of 20–30 mm, thickness d) of 6–10 mm, and a length within the range 120–130 mm. The top and bottom surfaces of the specimen are prepared with a fine grind. The faces normal to the light transmission direction (L × d) are polished. The 4 faces, excluding the ends, are flat and parallel to within 0.050 mm. Annealing of the specimens should be performed if the neutral fringe is excessively curved. The 4-point bend loading fixture uses a support span L) of 115 mm and a moment arm a) of 45 mm ($a = (L\text{-}L_i)/2$). The loading points are approximately 5 mm in radius.

The polariscope setup is also in accordance with the ASTM standard. The system is set up as a plane polariscope, which means that the polarizer and the analyzer are at 90° to each other. The system is set up with the broadband light source and polarizer positioned behind the load frame with a glass sample in 4-point bend configuration. The analyzer is situated after the load frame and closest to the observer. Each polarizing plate is set up at 45° from the vertical and so 90° from each other. The system will display a dark field view due to the full extinction of crossed polarizers. Any stress in the test material will create colored fringes that will help to identify the stress state of the material.

4. SOC Experimental Evaluation

The SOC is a material property, independent of sample geometry, that is used in the photoelastic analysis of glass and other transparent materials with stress-induced birefringence. When light passes through a transparent medium, with principle stresses in the plane normal to the propagation direction, it is resolved into slow and fast waves along the principle stress directions. These waves show a relative angular phase difference or retardation (δ). This property is insensitive to wavelength. The SOC (sometimes referred to as C and sometimes K) is a property that relates stress to the retardation in a specific material system. The unit for C is the Brewster (10^{-12} m^2/N) and is used in the relationship

$$\text{Stress} = \text{retardation}/(\text{thickness} * C), \text{ or } \sigma_{(MPa)} = \delta_{(nm)}/(b_{(mm)} * C_{(Brewster)}). \quad (1)$$

This relationship can also be expressed in terms of fringe order (N) and wavelength (λ 565 nm for glass)[20,21]:

$$\sigma = N * \lambda / b * C . \quad (2)$$

In the case of a beam in 4-point bending loading configuration, the value of the maximum tensile or compressive stress is given as

$$\sigma = [3(L - L_i)W]/(2b*d^2). \quad (3)$$

In this study L is 115 mm; L_i is 25 mm, the width in the light-propagating direction; b is 25 mm; and the thickness d is 10 mm. W represents net loading in newtons and the stress σ is in MPa.[22]

5. New Method for Evaluation

The SOC measurement in the ASTM standard is made by applying a series of fixed weights, measuring the retardation, and then calculating the SOC through these measurements. An alternative method for this calculation is the use of a variable load, such as that provided by a computer-controlled load frame, and an identification of the level of retardation. When fixed loads are used, the exact amount of retardation must be evaluated. This is accomplished using a polariscope and a Babinet compensator. The alternative method proposed does not require the use of a Babinet compensator but does need highly controllable loading capabilities. This fine control over loading can be accomplished with a load frame.

The evaluation of the first, second, third, and potentially subsequent order transitions can be used to determine the extent of retardation. A specific color sequence can be observed in photoelastic materials with varying degrees of stress. Crossed polarizers set up to create a dark field image will display a zero stress state as dark (black). Even in material that has some degree of residual stress, the neutral fiber, the transition point from compression to tension, will appear as black. Depending on the state of the polarizing equipment, this black color can appear gray, but it will be equivalent to the fully extinguished dark field background. This central black band is known as the 0-order fringe. The first-order fringe is indigo-violet (transitional purple in some descriptions). The second-order fringe is the transition from red to green, and the third-order fringe is the transition from light red to green. These colors can be difficult to ascertain in isolation but can be identified by their proximity to other colors on the scale. The color scale shown in Fig. 3 is representative of the constructive and destructive interference that is created as incoming light is broken into 2 paths, each parallel to the principle stresses. The light retardation or relative delay is proportional to the principle stress difference.[23]

	Color (lambda=570)	Retardation (nm)	Retardation in N Fringes
	Black	**0**	**0**
	Gray	150	0.26
	White->Yellow	250	0.44
	Bright Yellow	300	0.53
	Orange (Dark Yellow)	450	0.79
	Red	500	0.88
	Indigo->violet	**570**	**1**
	Blue	600	1.05
	Blue->Green	650	1.14
	Green->Yellow	750	1.32
	Yellow	850	1.49
	Orange (Dark Yellow)	950	1.67
	Red	1050	1.84
	Indigo->violet	**1140**	**2**
	Green	1300	2.28
	Green->Yellow	1400	2.46
	Pink	1500	2.64
	Violet	**1710**	**3**
	Green	1750	3.07

Fig. 3 Color scale showing the relationship among retardation, fringe order, and displayed color through crossed polarizers (adapted from Micro-Measurements[24])

In the ASTM test method, fixed weights are used so that the measurable quantity in the analysis is the precise degree of retardation. In the method used for this study, it is possible to shift quantity of interest to the exact loading that produces a known amount of retardation. To achieve this, it is necessary to determine the stress in the sample corresponding to a known retardation value. With a sample bar loaded into a 4-point bend fixture and the polarizer showing the isochromatic fringes, the load is incrementally increased until the fringe color of interest is present at the extreme tensile fiber. It is sometimes hard to determine this exactly but it is possible to observe the transition by surpassing the transition and then decreasing the load until the posttransition color is seen at the extreme fiber. For example, to identify the indigo-to-violet transition that occurs at a retardation value of 575 nm, the load can be increased until blue is distinctly observed and then the load decreased until the blue is extinguished (Fig. 4).

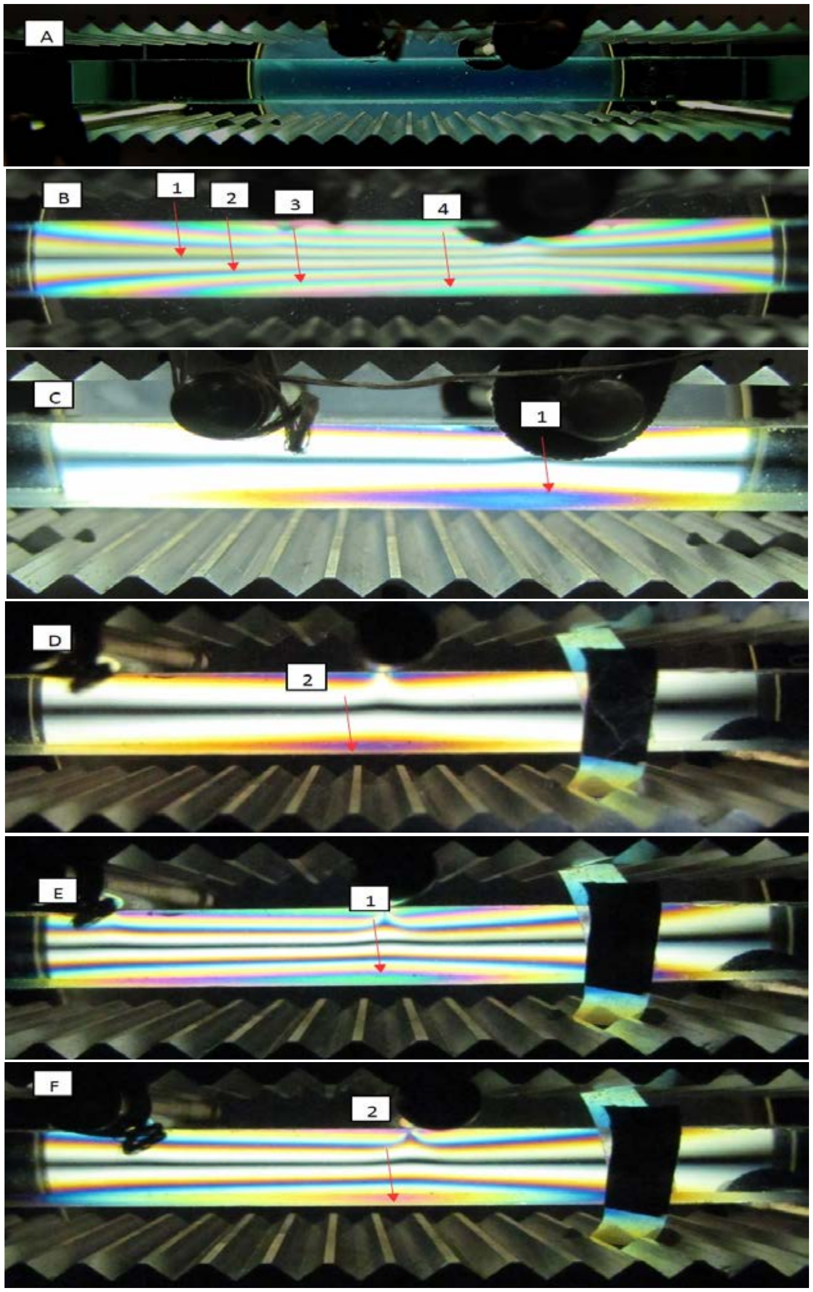

Fig. 4 A) A glass specimen in a 4-point bend with no load applied, a dark field image. B) 0-order (black) fringe at position 1, the first-order fringe (indigo to violet) at position 2, the second-order fringe (red to green) at position 3 and the third-order fringe (red to green) at position 4. C) A beam overloaded so that the blue appears (position 1). D) Relaxation of the applied stress so only the first transitional fringe is shown (position 2). E and F) Repeat of this procedure so that the second-order fringe can be identified with position 1 being overloaded and position 2 showing the transition point at the extreme tensile fiber.

6. Experimental Results

SOC was calculated for various glass samples and 4 samples were prepared for each glass type: fused silica, borosilicate float, Supremax, Starphire, borosilicate, and BK-7. Each sample was tested by 4-point bend. The samples were loaded so that the retardations of 565, 850, 1,130, and 1,695 nm (1-, 1.5-, 2-, 3-order fringes) could be observed by interpreting isochromic fringes. The load at each retardation value was taken 5 times and the corresponding maximum tensile stress calculated from the loading data averages. Plotting the data with the quantity (Stress*thickness in the light propagation direction) with the units of MPa*mm along the X and retardation (nm) on the Y is shown below a linear fit was applied. The slope of the trend line represents the quantity of SOC for each glass type (Fig. 5). Table 2 summarizes the experimental results.

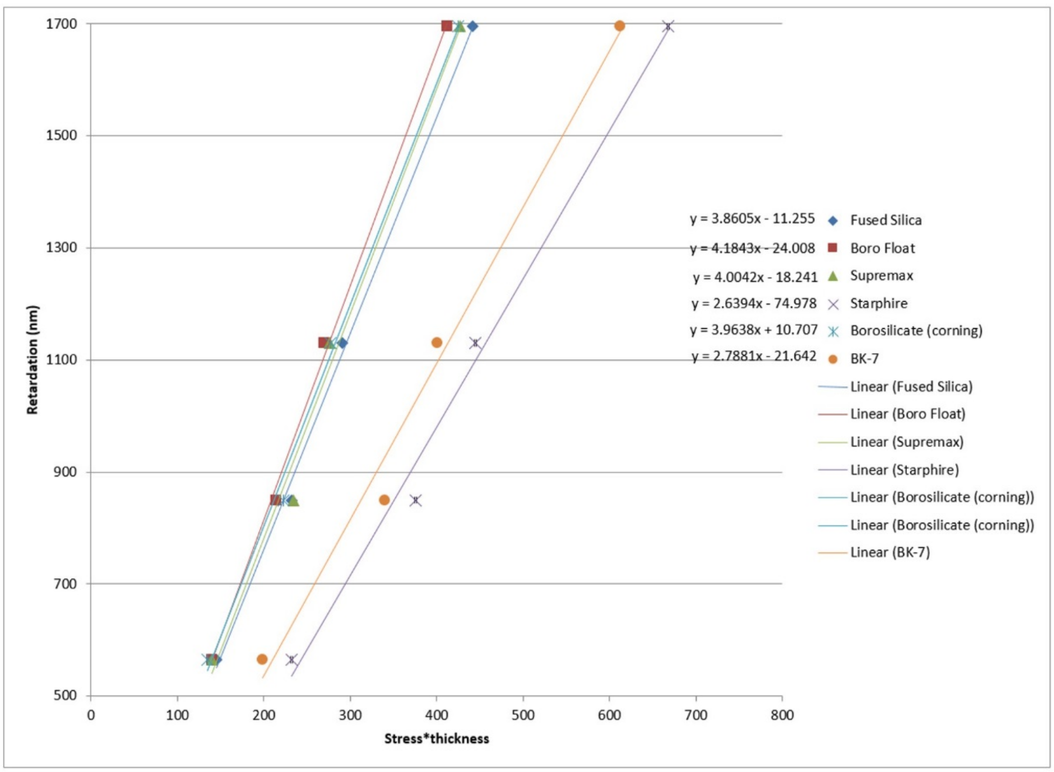

Fig. 5 The slope of each linear fit line represents the SOC for each glass type tested

Table 2 SOC determined experimentally from the retardation and stress values from 4-point bending. Values are shown when the 1.5-order fringe is included and when it is excluded.

Glass type	SOC (1-, 1.5-, 2-, and 3-order fringe)	SOC (1-, 2-, and 3-order fringe)
Fused silica	3.86	3.81
Borofloat	4.18	4.15
Supremax	4	3.92
Starphire	2.63	2.59
Borosilicate	3.96	3.9
BK-7	2.79	2.73

7. Conclusions

SOC can be a tool to help characterize glass samples. The methodology discussed in this report is useful if a load frame is available. The human eye can be used to identify the transitions that occur at known retardation values. If more precise values are needed for the retardation measurement, a Babinet compensator can be used as described in the ASTM specification[19]. Comparing the glass to existing sample values can help to confirm an unknown glasses composition. Because the SOC is a material property, it can be used as an additional glass characterization method. If the SOC of a glass sample is known, the stress state of a glass specimen can be evaluated through photoelastic methods both qualitatively and quantitatively.

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