US-China Winter School
New Functionalities in Glass

Why Does Glass Break?

Some considerations of the mechanical properties of glass

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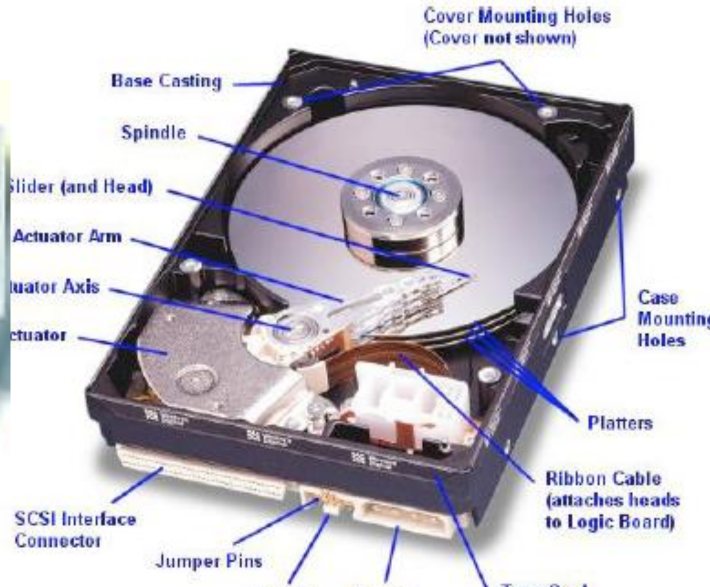
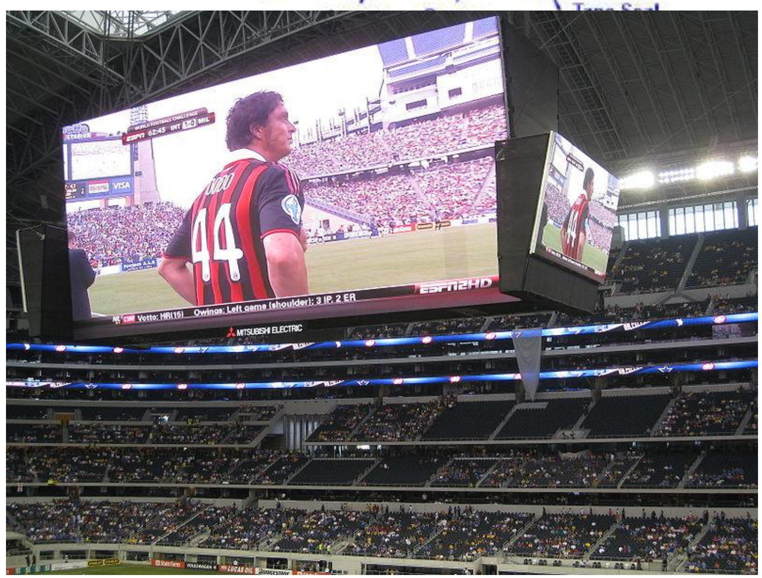
If glass was 100X stronger, what *new* applications would result?

New applications will benefit from stronger glass…..





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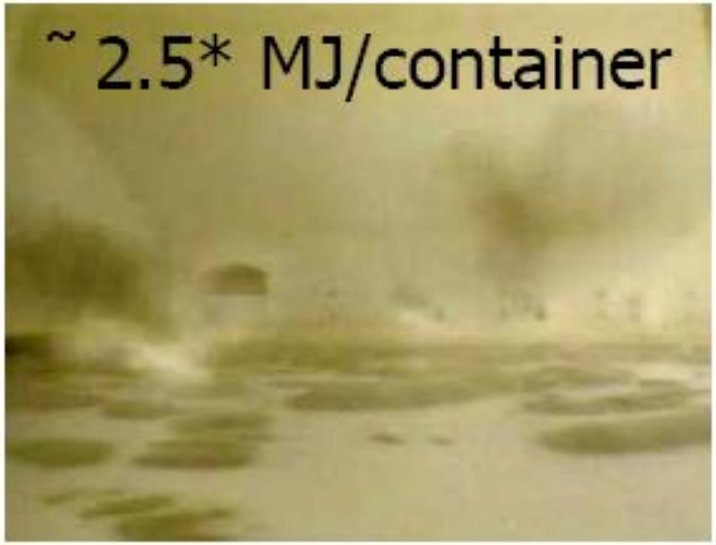
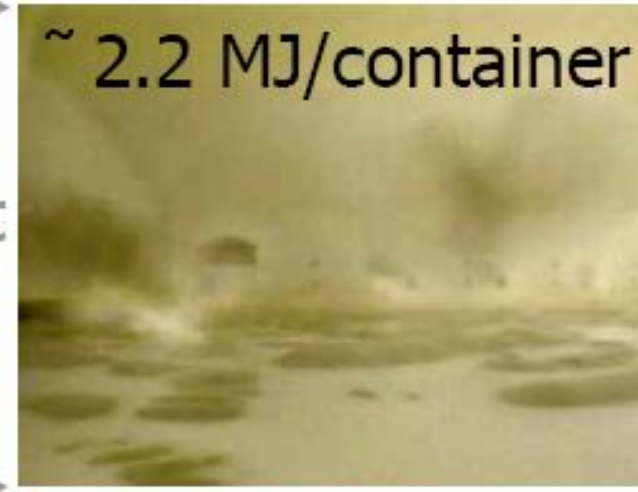
Higher Strength ➡ Less Weight



*US DoE and Bureau of Census Data

-10% Weight



$SO_x + CO_2 + NO_x$

Emilio Spinosa, O-I, Vancouver, June 2009

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Strong glass comes in handy for other applications

Our Outline

1. **Background Information**
   - Elastic modulus
   - Fracture mechanics and strength
   - Fatigue
   - Strengthening
2. **Two-point bend studies of pristine glass**

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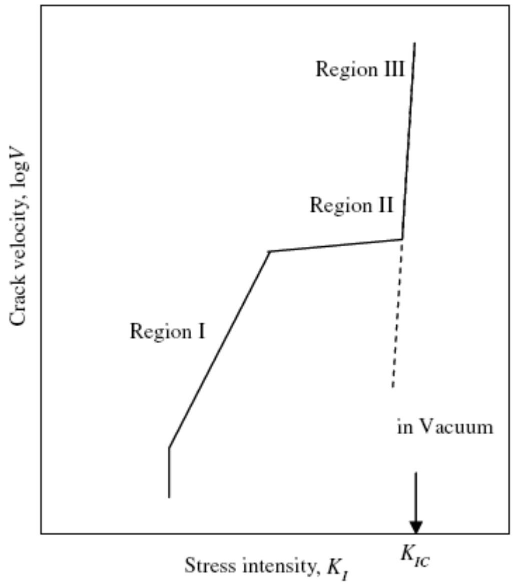
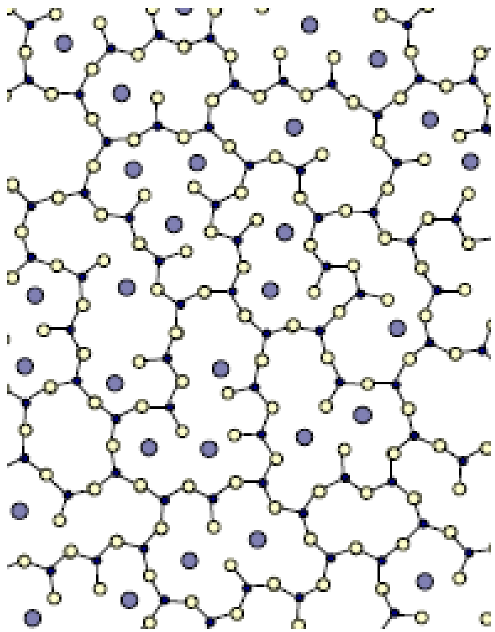
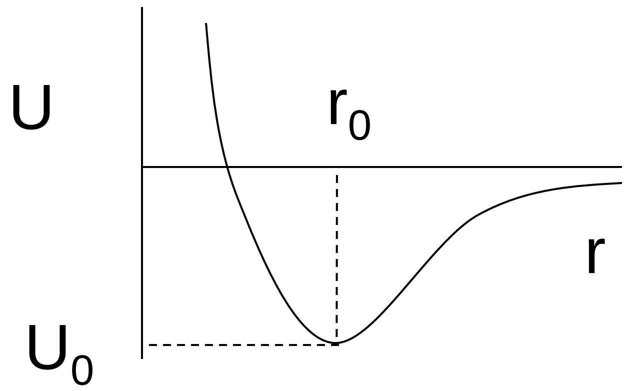
Some useful references:

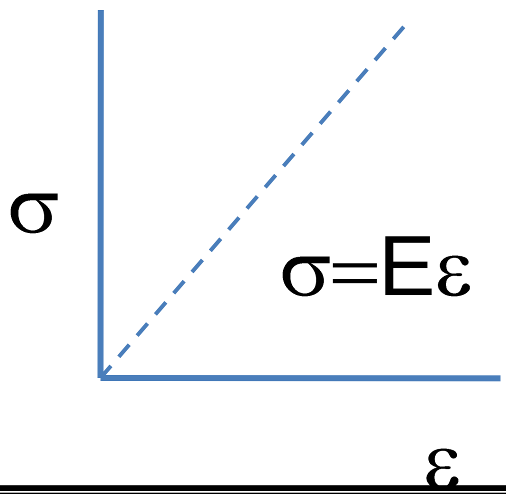
- A. Varshneya, “Fundamentals of Inorganic Glasses”, Society of Glass Technology (2006)- chap. 18
- “Elastic Properties and Short-to Medium-Range Order in Glasses”, Tanguy Rouxel, *J. Am. Ceram. Soc.*, **90** [10] 3019–3039 (2007)
- “Environmentally Enhanced Fracture of Glass: A Historical Perspective,” S. W. Frieman, S.M. Weiderhorn, and J.J. Mecholsky, *J. Am. Ceram. Soc.* **92**[7] 1371-1382 (2009)
- M. Ciccotti, “Stress-corrosion mechanisms in silicate glasses,” *J. Phys. D: Appl. Phys.* **42**, 214006 (2009).
- C. R. Kurkjian, P. K. Gupta, R. K. Brow, and N. Lower,” The intrinsic strength and fatigue of oxide glasses’, J. Noncryst. Solids, 316, 114 (2003).

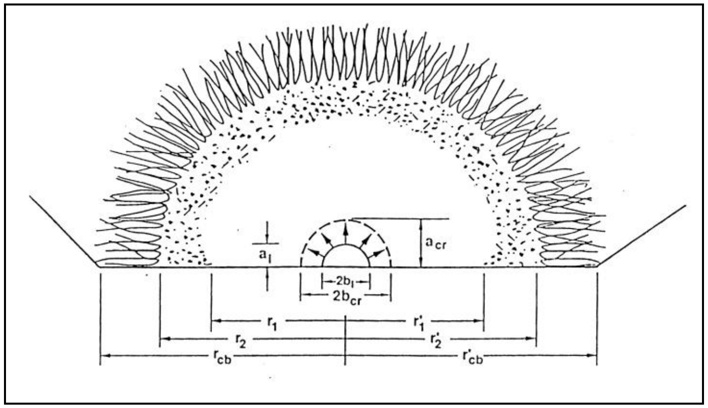
Can we connect mechanical performance to the molecular structure of glass?











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Elastic Modulus

Definitions?

Why should we care about modulus?

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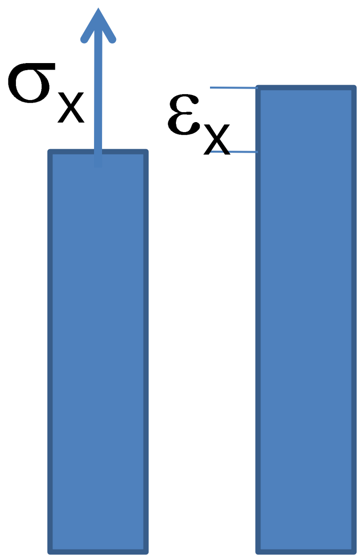
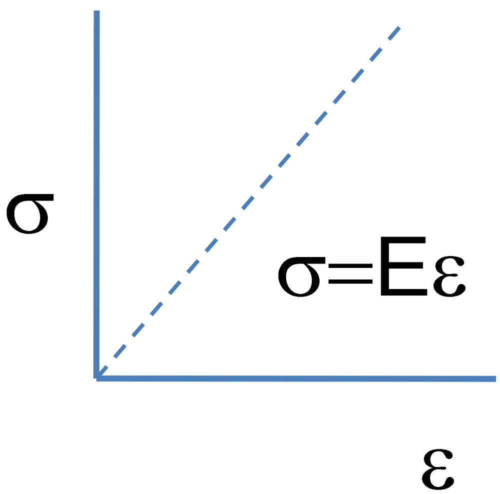
Elastic Modulus- resistance to deflection

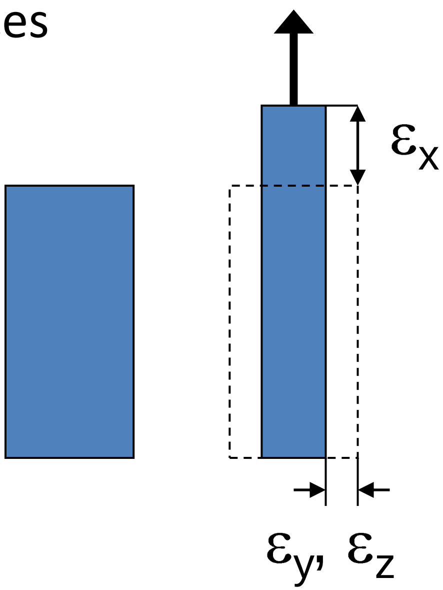


Why is the elastic modulus of a glass important?

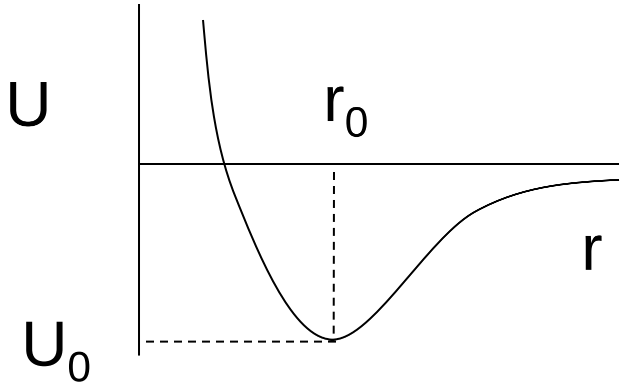
- Stiffer hard-drive disks (minimize deflection at high rpm's)
- Stiffer glass-fiber reinforces composites (larger wind-turbine blades)
- Reduce the thickness (and weight) of architectural glass)
- Increase the stiffness of glass-bearing structures (buildings, bio-glass scaffolds, etc.)
- Design glass or glass-ceramic matrices for aerospace applications

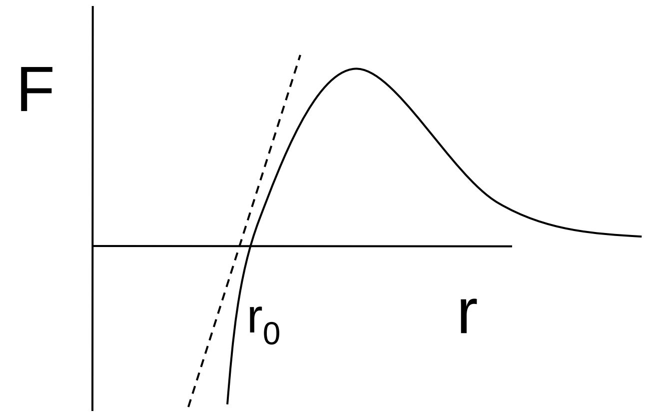


Poisson's Ratio



Elastic Modulus Is Related To The Strength of Nearest Neighbor Bonds





Force = F = - dU/dr

Stiffness = $S_0 = (dU^2/dr^2)_{r = r0}$

Elastic Modulus = E = S / r_0

Elastic Modulus: Pascals = J/m^3 a measure of the volume density of strain energy ($E \approx U_0/V_0$)

Bulk Modulus:

$$K = V_0 \frac{\partial^2 U}{\partial V^2}\bigg|_{V_0} = \frac{mn}{9V_0} U_0$$

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From atomistic to continuum properties:

$$K = V_0 \frac{\partial^2 U}{\partial V^2}\bigg|_{V_0} = \frac{mn}{9V_0} U_0$$

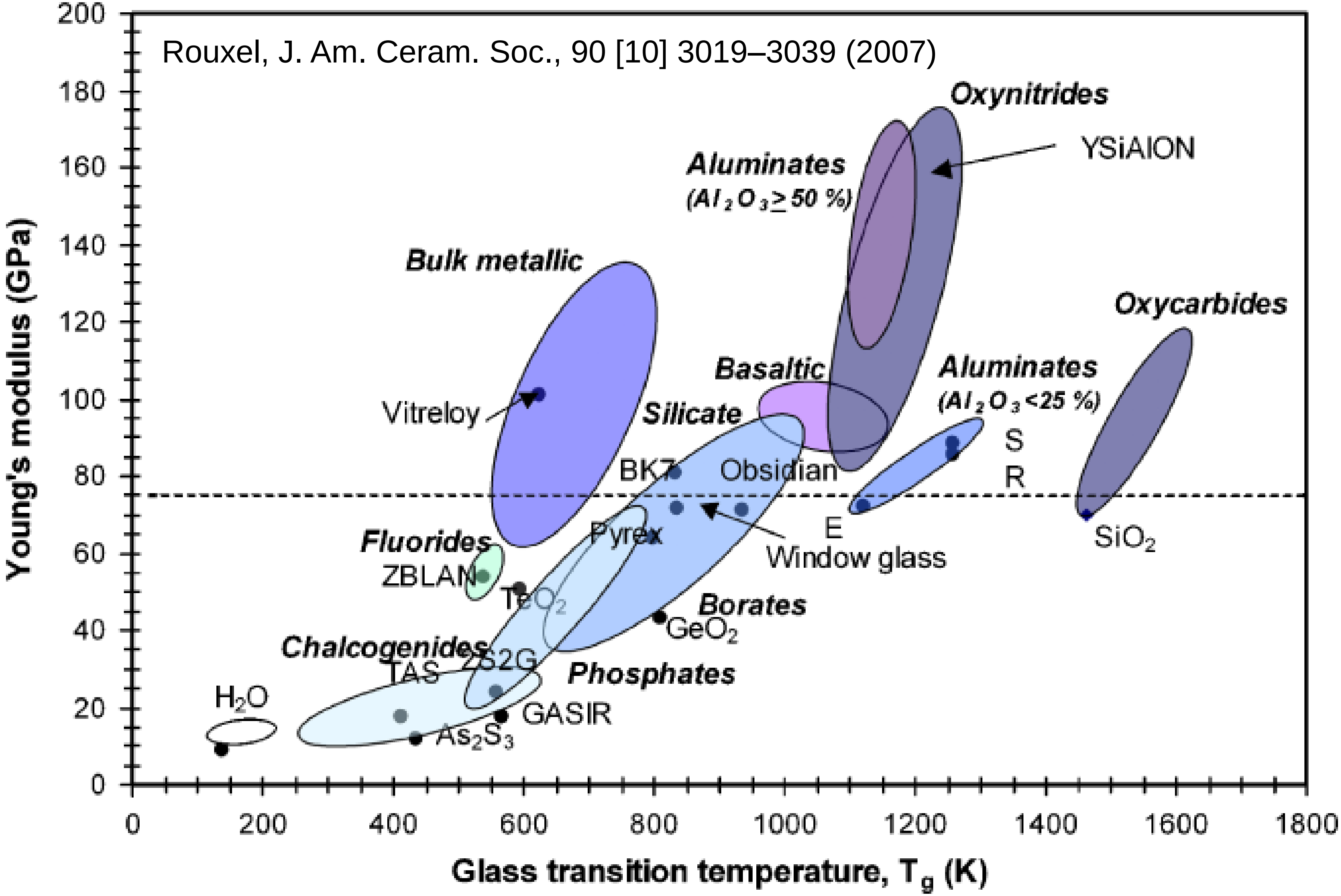
Multi-component glasses:

$$\left\langle \frac{U_0}{V_0} \right\rangle = \sum f_i \Delta H_{ai} / \left(\sum f_i M_i / \rho_i \right)$$

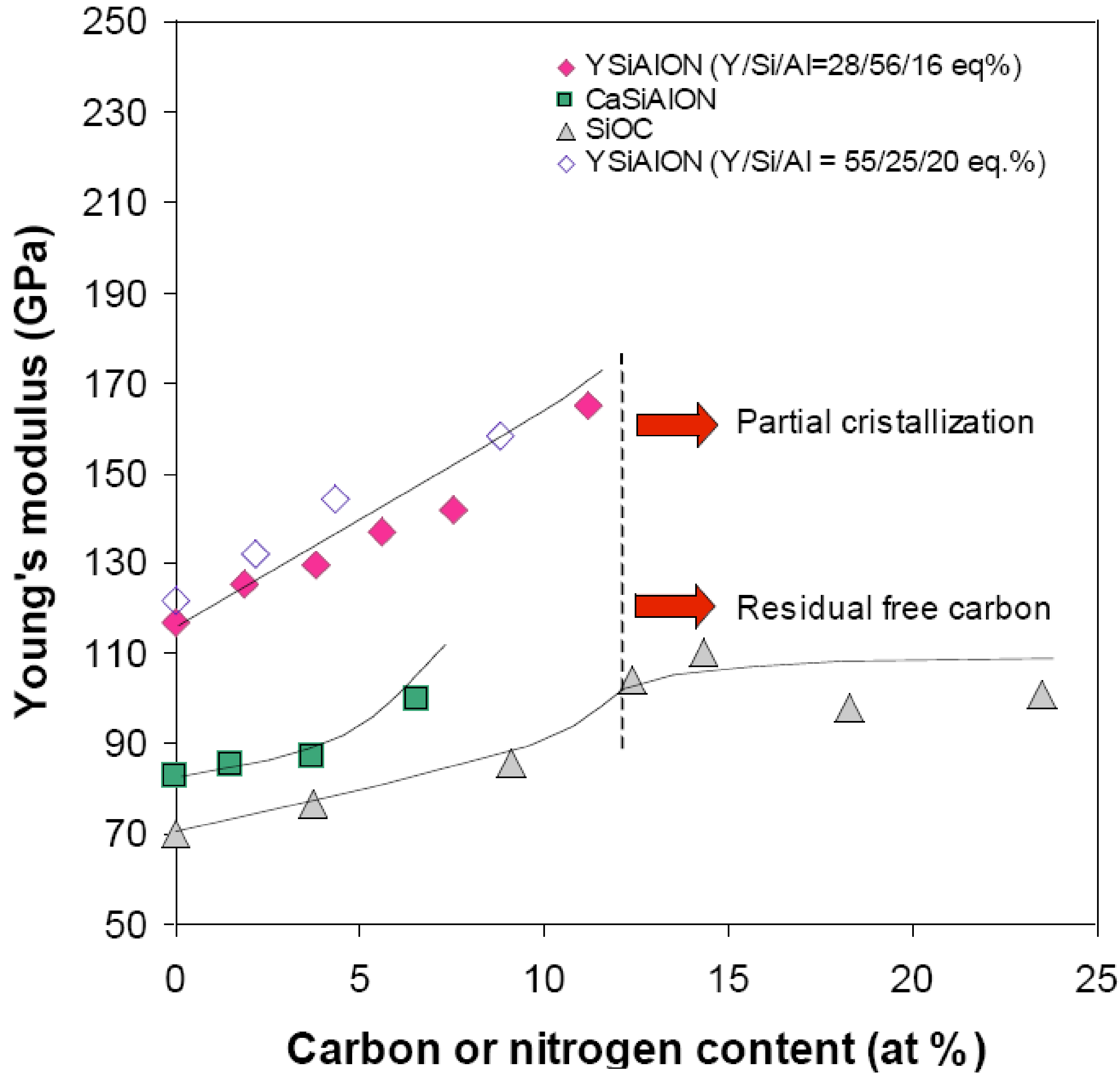
$$\Delta H_{ai} = x \Delta H_f^0(A) + y \Delta H_f^0(B) - \Delta H_f^0(A_x B_y)$$

ρ_i: density
f_i: molar fraction of i^{th} component
M_i: molar mass of i^{th} component
ΔH_{ai}: enthalpy of i^{th} component (Born-Haber cycle)

E and T_g are related within a composition class



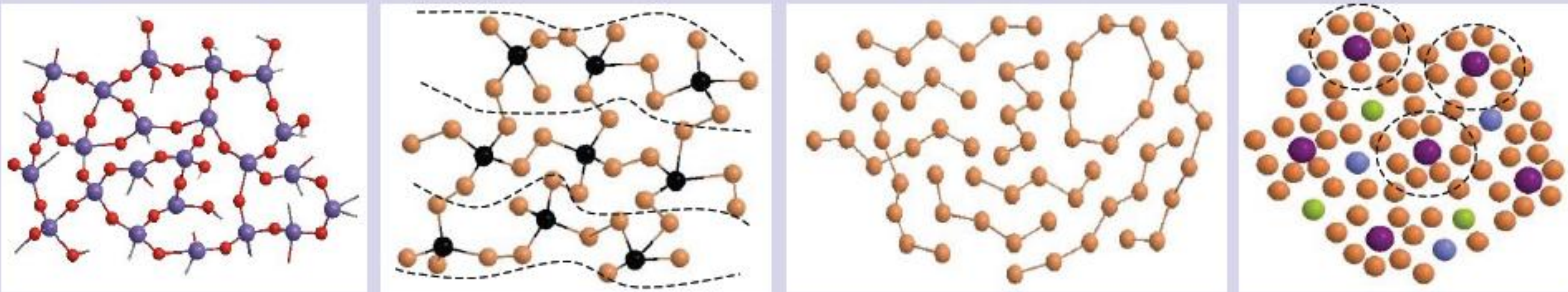
More cross-links: greater E



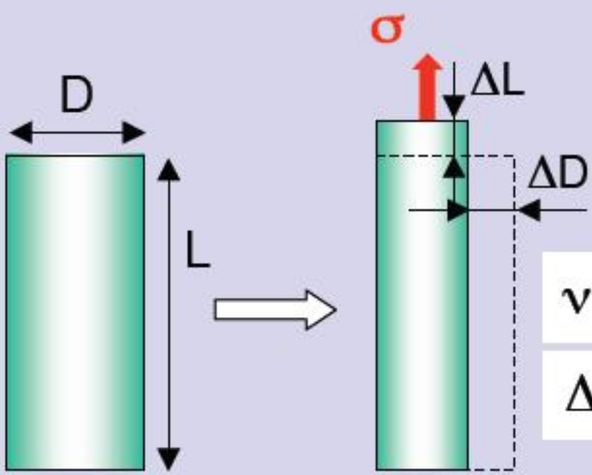
Rouxel, J. Am. Ceram. Soc., 90 [10] 3019–3039 (2007)

Poisson's ratio appears to be sensitive to structure: packing density and 'network dimensionality'

$a\text{-}SiO_2$	$GeSe_4$	a-Se	$Zr_{55}Cu_{30}Al_{10}Ni_5$



$\nu \approx 0.16$	$\nu \approx 0.286$	$\nu \approx 0.323$	$\nu \approx 0.37$
3D	2D	1D	0D?



$$\nu = -\varepsilon_t/\varepsilon_l = -L/D \times \Delta D/\Delta L$$

$$\Delta V/V = \text{Trace } \varepsilon = (1-2\nu)\sigma/E$$

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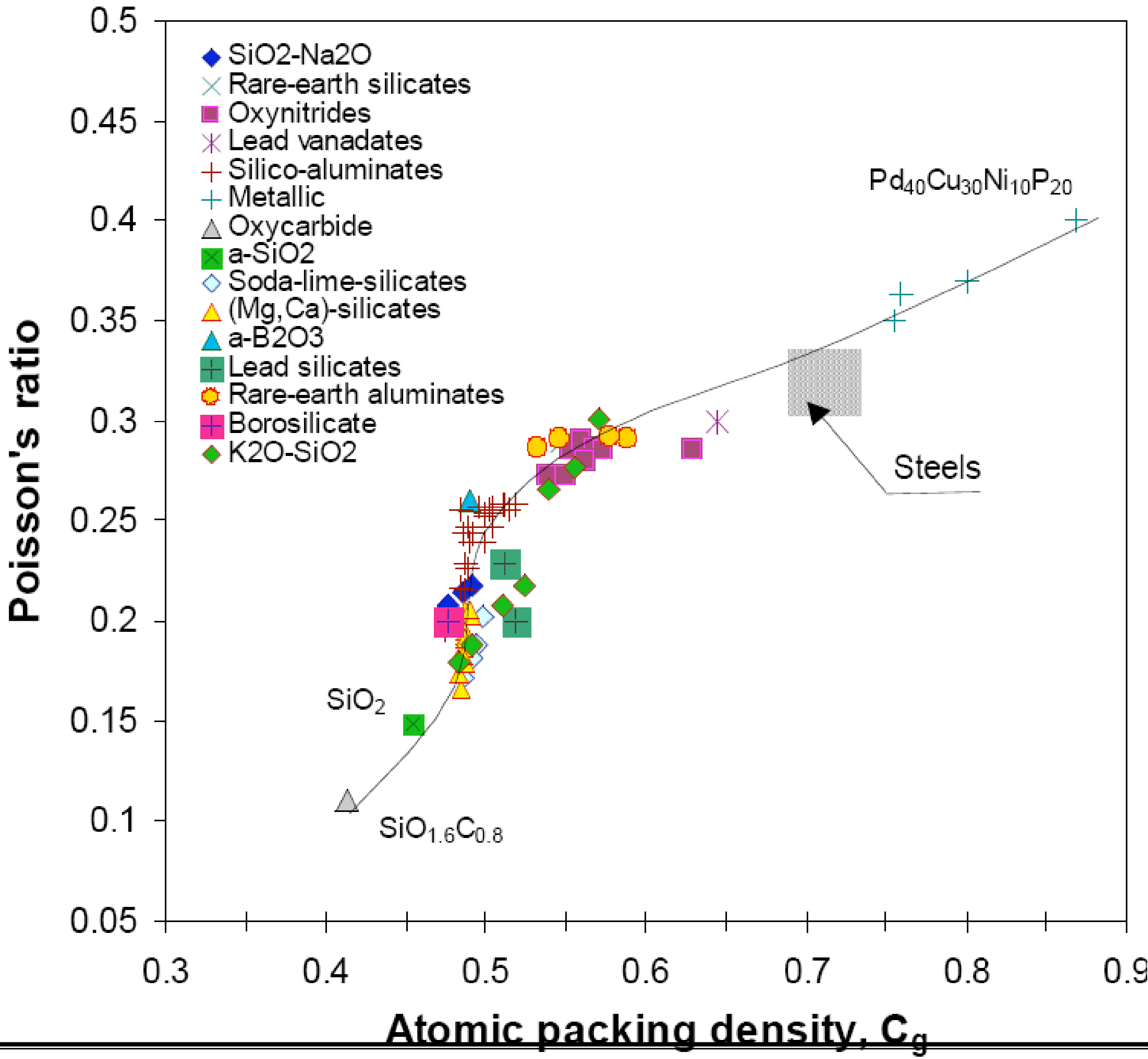
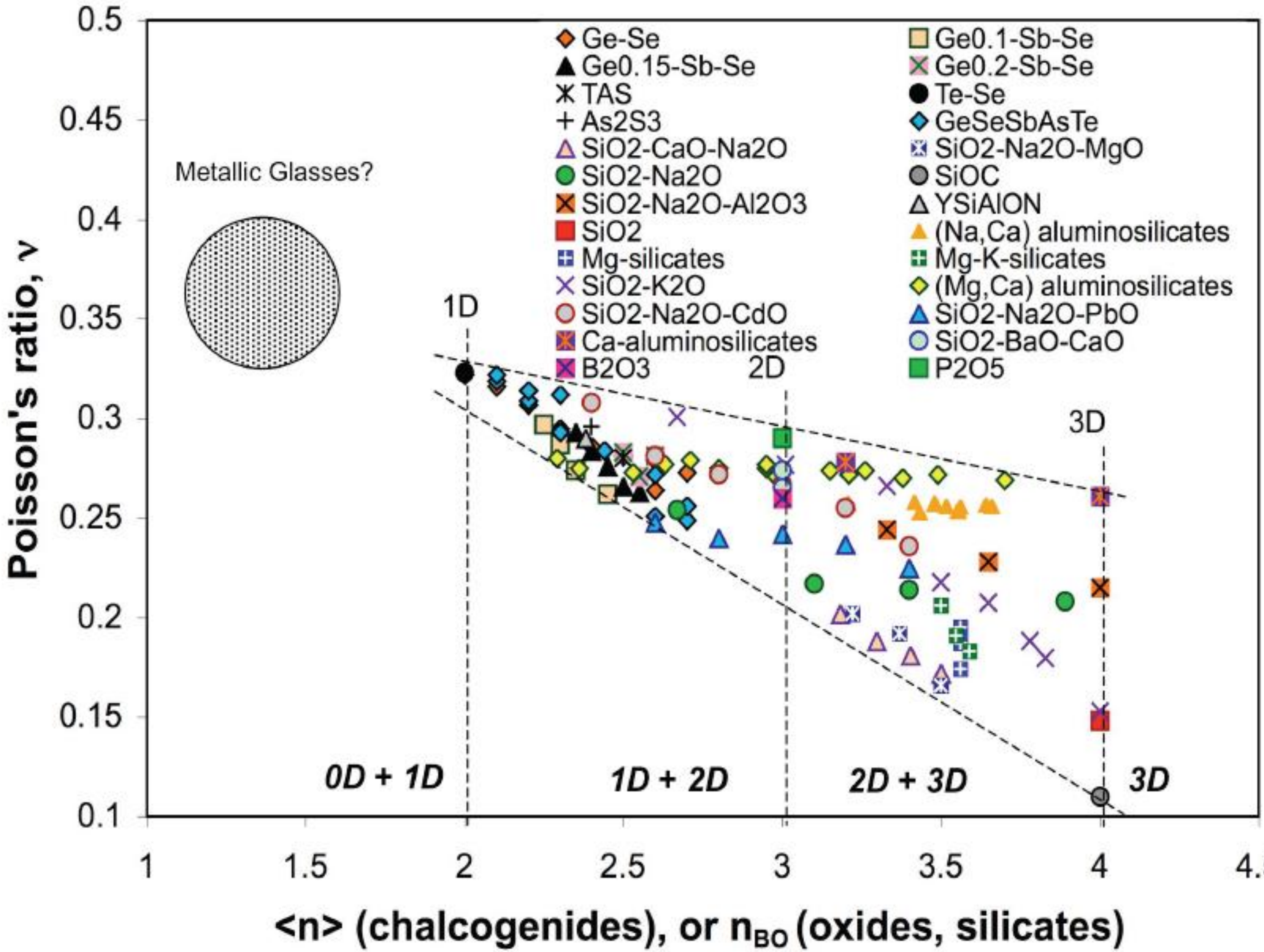
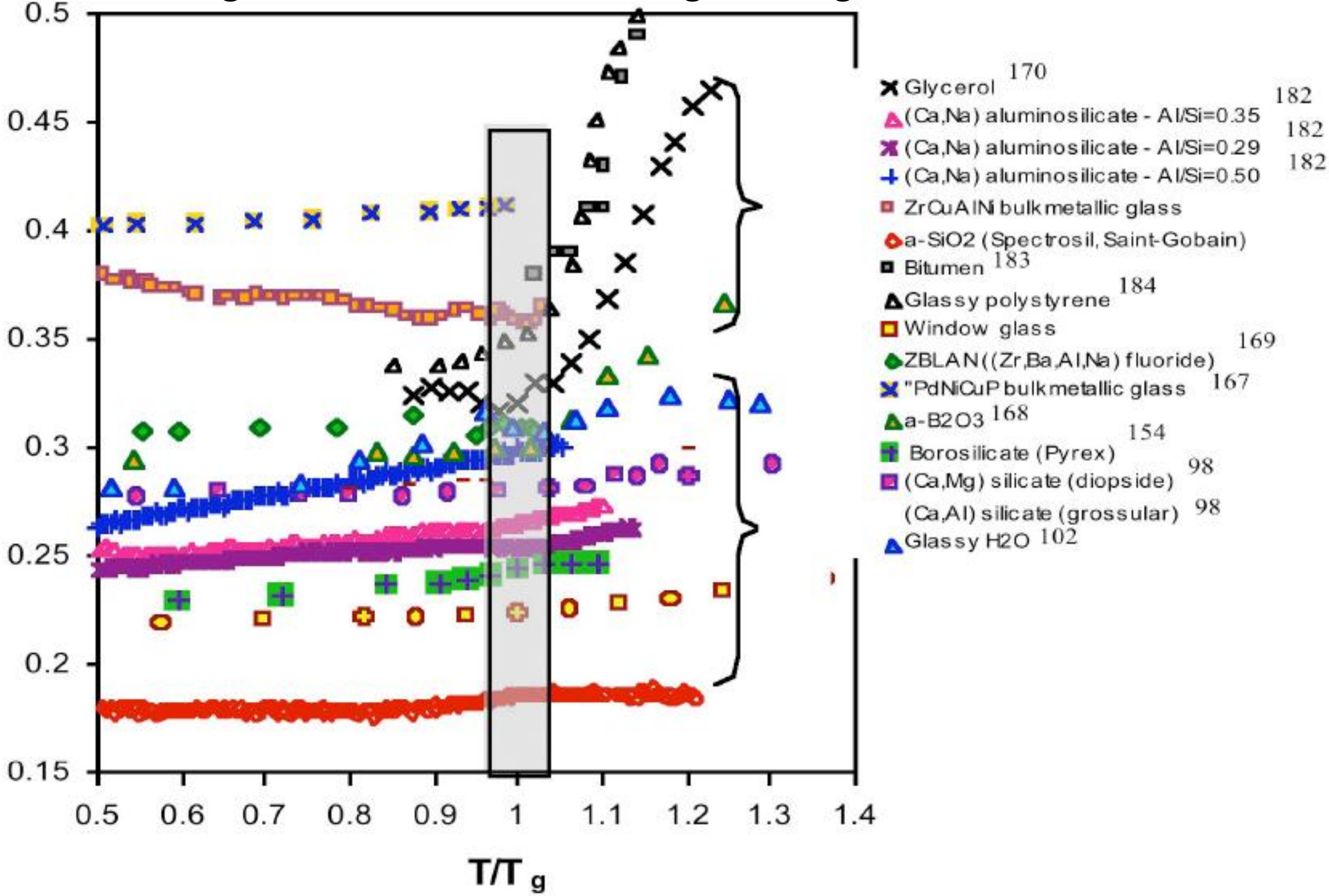


Rouxel, J. Am. Ceram. Soc., 90 [10] 3019–3039 (2007)



Rouxel, J. Am. Ceram. Soc., 90 [10] 3019–3039 (2007)

The temperature-dependence of the Poisson's ratio may indicate changes in structure through the glass transition



Rouxel, J. Am. Ceram. Soc., 90 [10] 3019–3039 (2007)

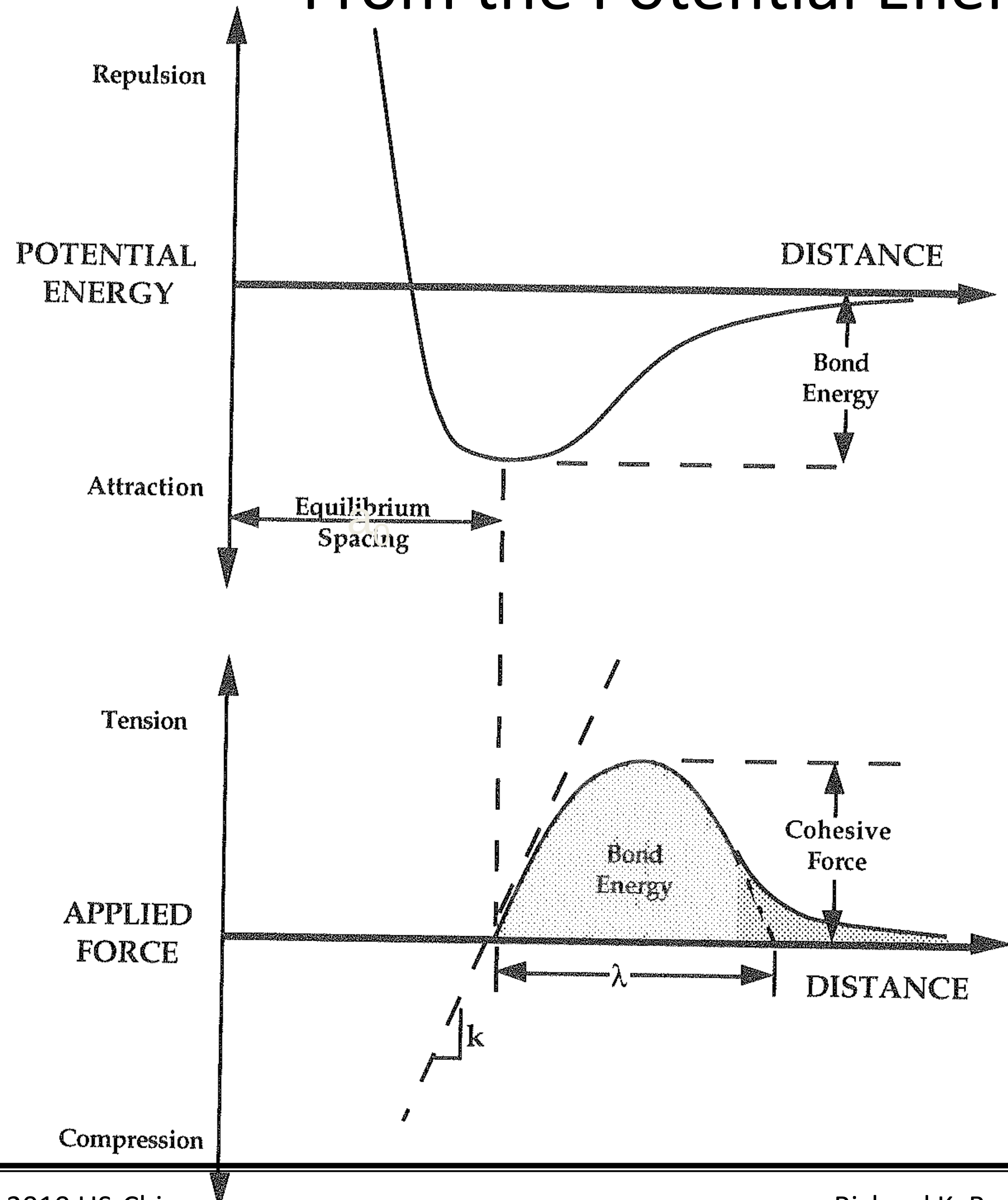
Summary: Elasticity

- There is a limited correlation between E and T_g within compositional series, but not necessarily between compositional types
- High elastic moduli are favored by structural disorder and atomic packing seems to be more important than bond strength
- Poisson’s ratio (ν) correlates with atomic packing density and with network dimensionality (polymerization)
- The temperature dependence of elastic properties above T_g may be related to “fragile” and “strong” viscosity behavior.

Glass Strength

What factors determine the strength of glass?

Theoretical Strength Can Be Estimated From the Potential Energy Curve (Orowan)



$$\sigma_m = \lambda E / \pi a_0$$

$$2\gamma_f = \sigma_m \sin(\pi x/\lambda)\, dx$$
$$= \lambda\sigma_m / (\pi)$$

$$\sigma_m = [\gamma_f E / a_0]^{1/2}$$

If $E = 70$ GPa, $\gamma_f = 3.5$ J/m^2 and $a_0 = 0.2$nm, then

$$\sigma_m = 35 \text{ GPa } !$$

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How does the addition of Na_2O affect the Young's modulus and fracture surface energy of silica glass? Consider what Prof. Pantano discussed the other day….

Practical strengths are significantly less than the theoretical strengths:

Common glass products	~14-70 MPa
Freshly drawn glass rods	~70-140 MPa
Abraded glass rods	~14-35 MPa
Wet, scored glass rods	~3-7 MPa
Armored glass	~350-500 MPa
Handled glass fibers	~350-700 MPa
Freshly drawn glass fibers	~700-2100 MPa
Most metals, including steels	~140-350 MPa

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C. E. Inglis (1913): flaws acted as stress concentrators
A.A Griffith (1921): critical flaws determine strength

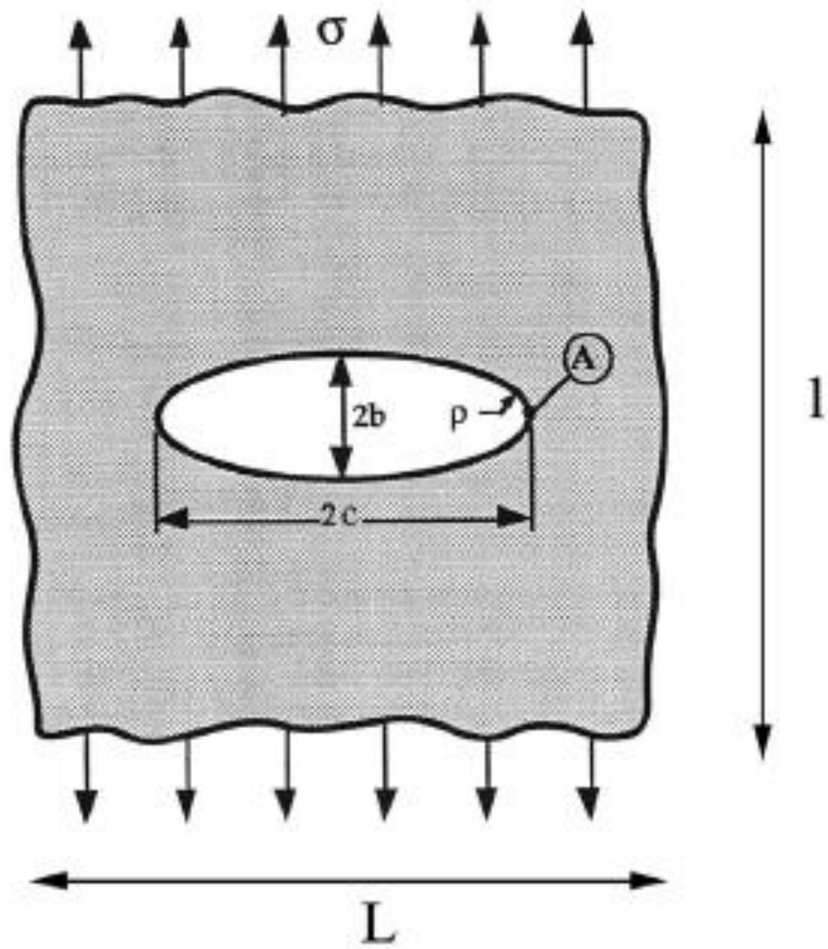
Stress enhancement by flaws with length 2c and radius ρ:

$$\sigma_{yy} \approx 2\,\sigma_a\,(c/\rho)^{1/2}$$

Calculated strength with critical flaw c:*

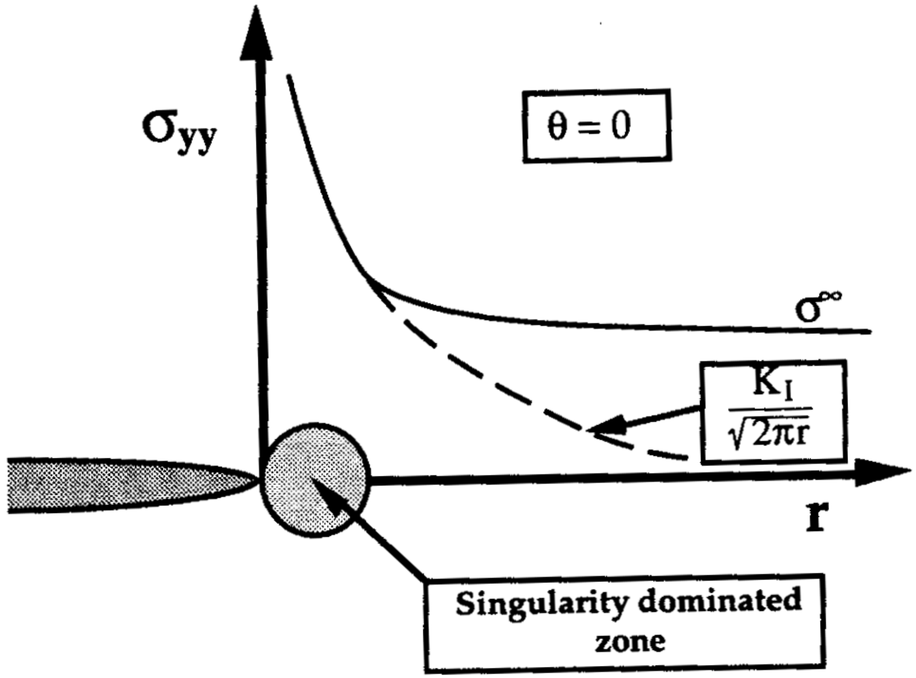
$$\sigma_f = [2\,\gamma_f E/\pi c^*]^{1/2}$$

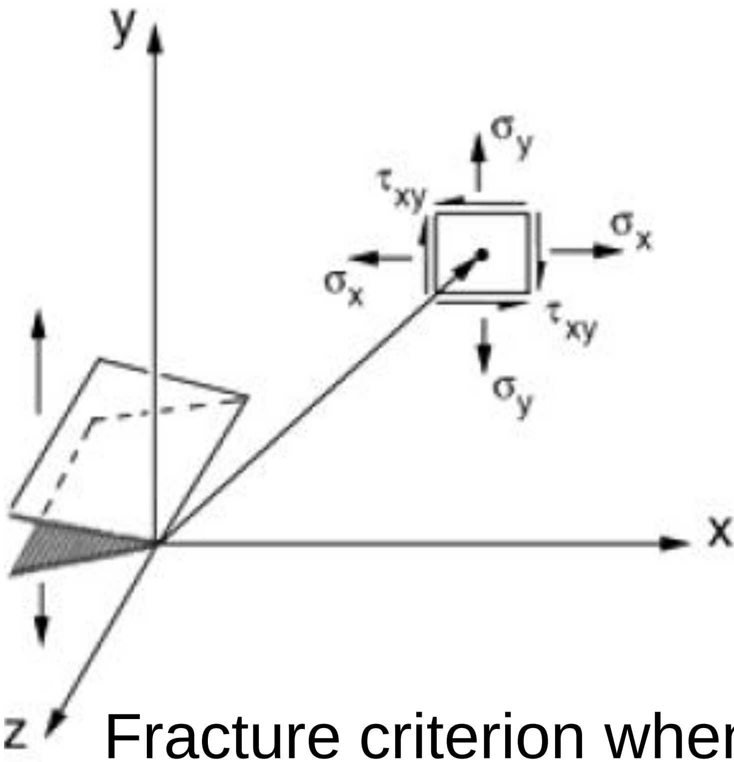
If $E = 70$ GPa, and $\gamma_f = 3.5\ \mathrm{J/m^2}$
Then a crack of 100 microns will result in a failure stress of ≈ 25 MPa



Fracture mechanics allow the evaluation of stresses in the vicinity of a propagating

$$\sigma_{ij} = [K / (2 \pi r)^{1/2}] f_{ij} (\theta)$$





Fracture criterion when stress intensity exceeds the strain energy release rate (depends on E, γ_f)

$$K_{Ic} = \sigma_a (\pi c)^{1/2}$$

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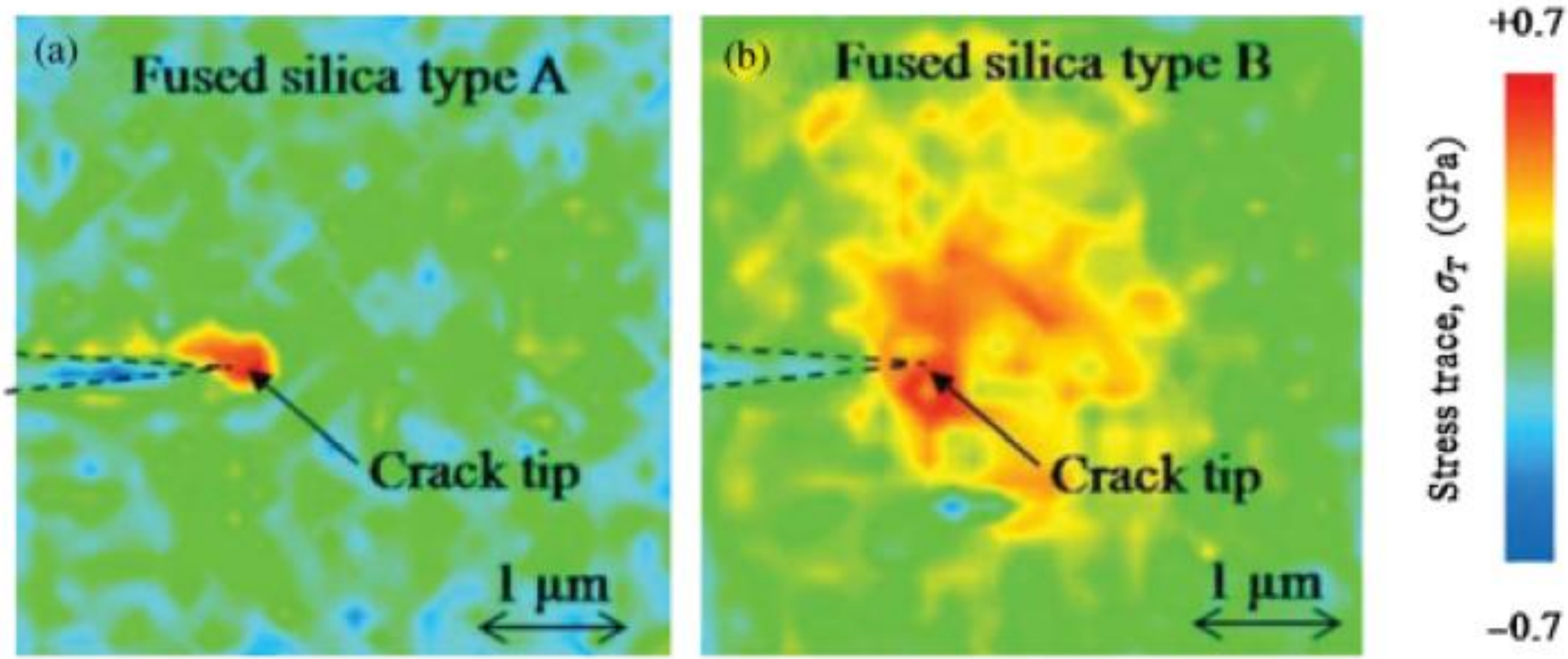
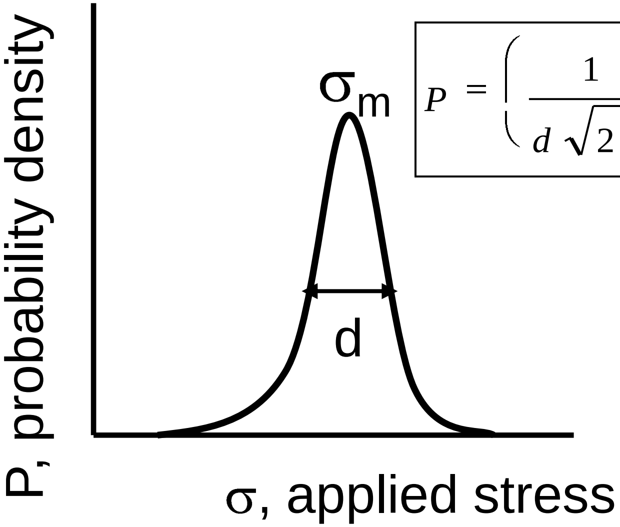
Cathodoluminescence measurements of stress distributions around crack tips (Pezzotti and Leto, 2007)

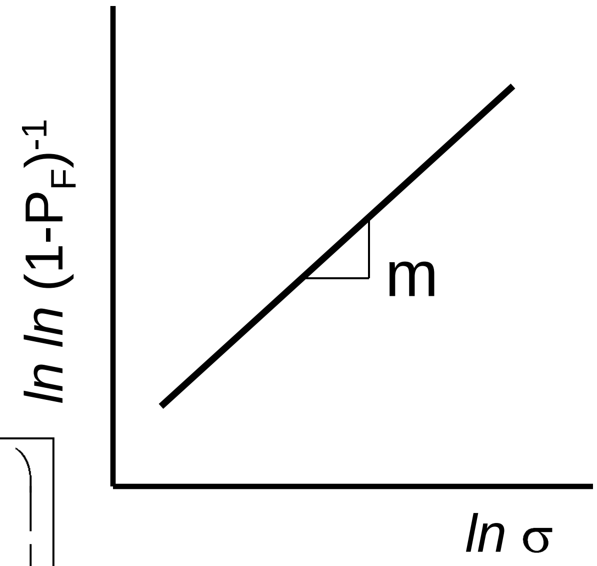


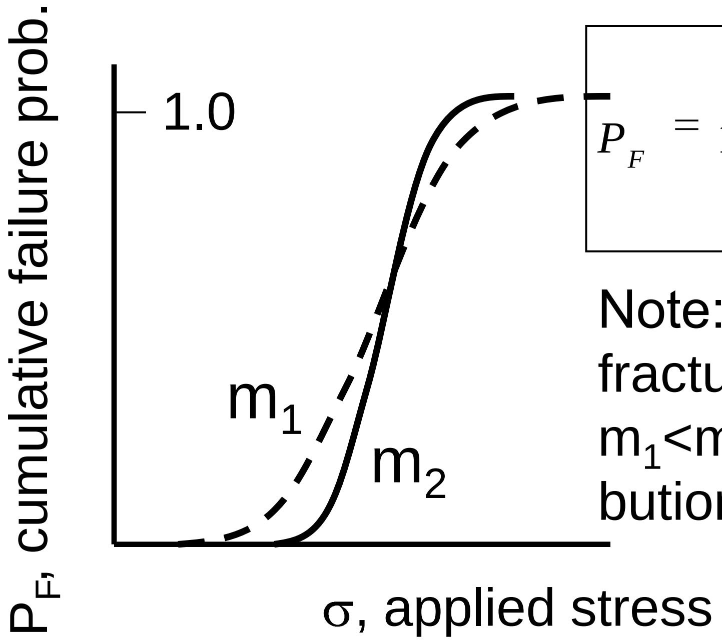
An aside: Weibull Statistics



$$P = \left(\frac{1}{d\sqrt{2\pi}}\right)\exp\left(\frac{-(\sigma-\sigma_m)^2}{2d^2}\right)$$

$$\ln\left[\ln(1-P_F)^{-1}\right] = m\left(\ln\sigma - \ln\sigma_0\right)$$





$$P_F = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_0}\right)^m\right)$$

Note: same ‘average’ fracture strength, but $m_1 < m_2$ (broader distribution of strengths).

Room temperature tensile tests of pristine silica fibers drawn and tested in vacuum- bimodal distribution

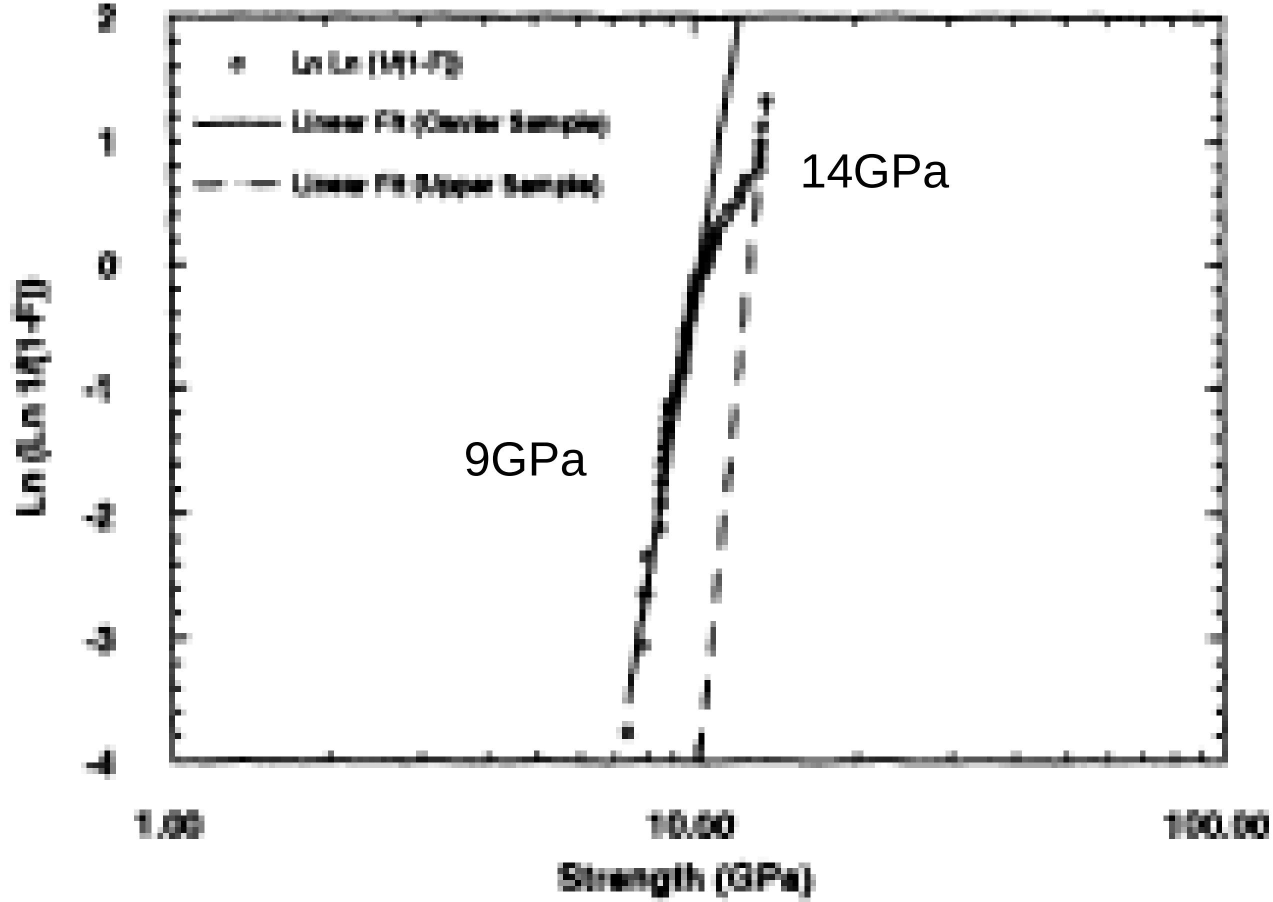
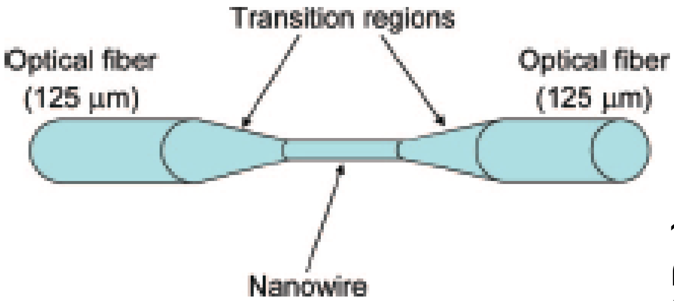


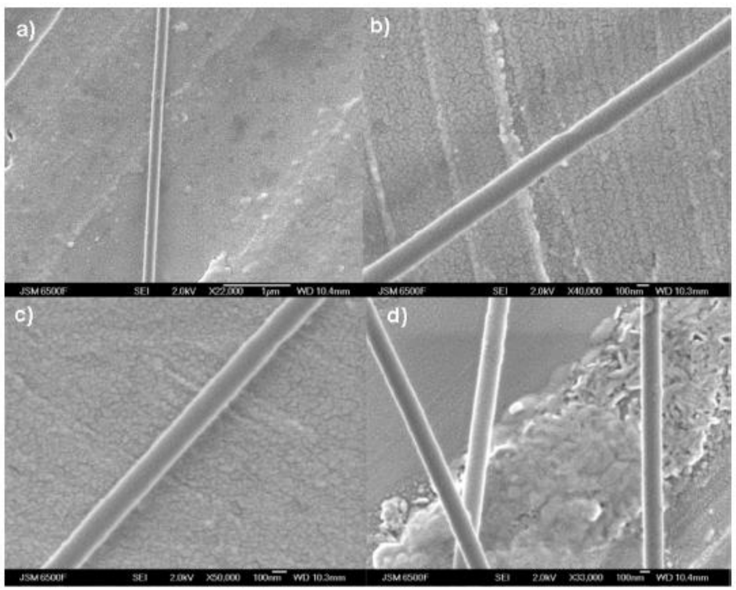
Figure 2 Strength distributions for T-08

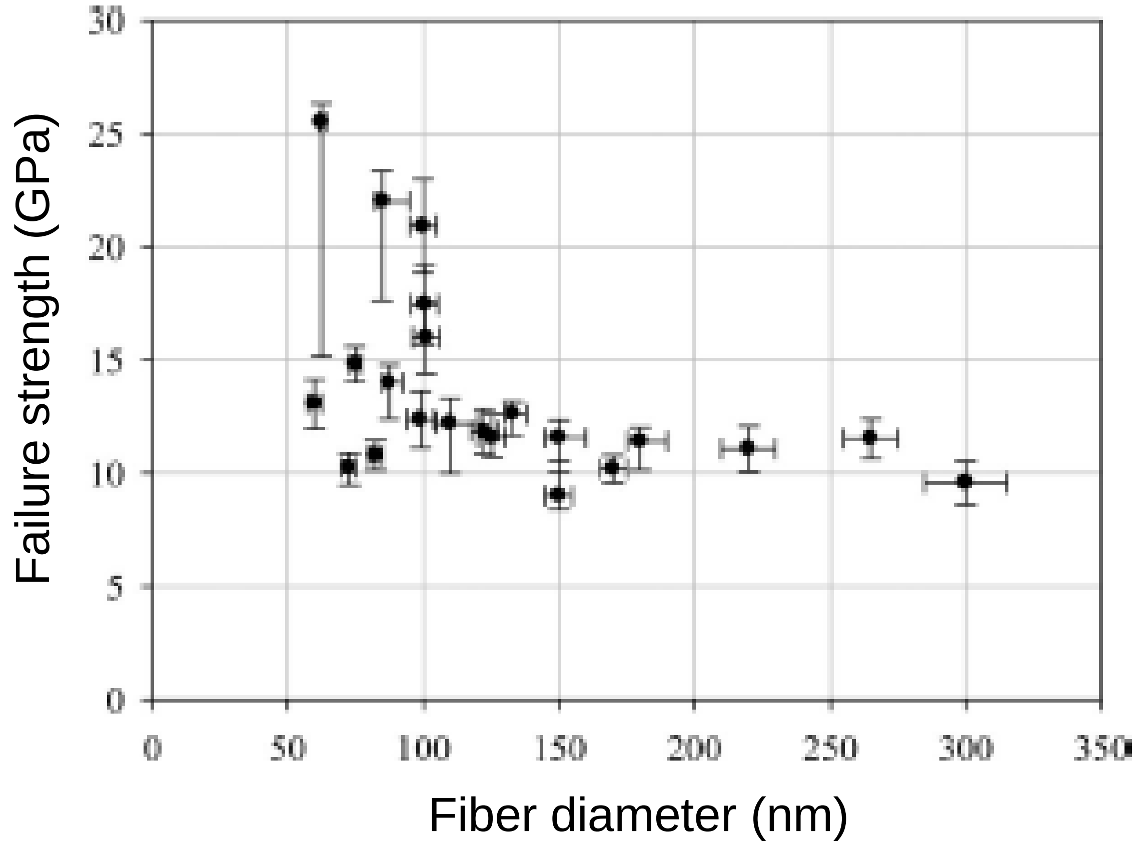
Smith and Michalske, 1992

The Ultimate Strength of Glass Silica Nanowires, G. Brambilla and DN Payne, Nano Letters, 9[2] 831 (2009)



Flame-attenuation of optical fibers





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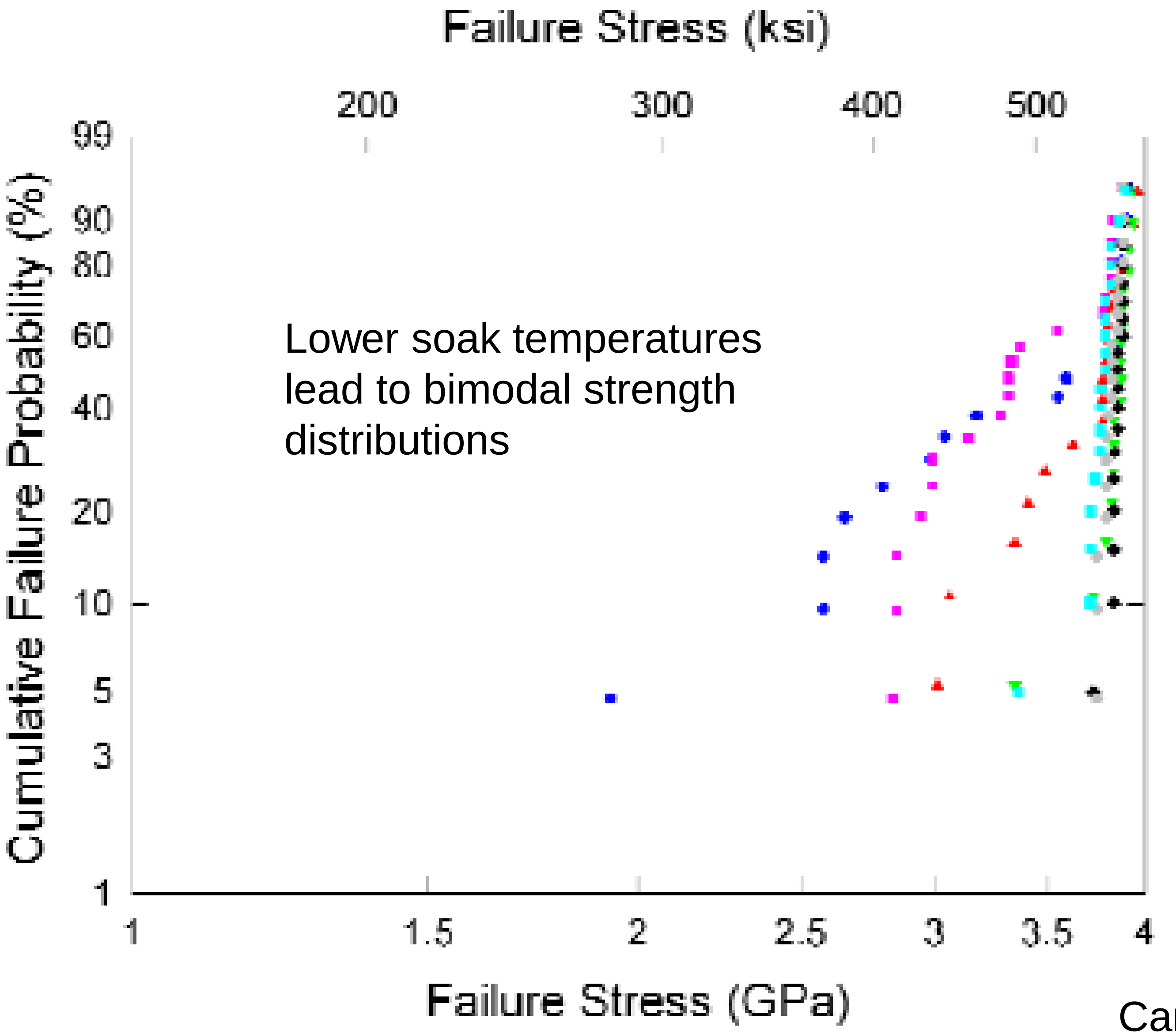
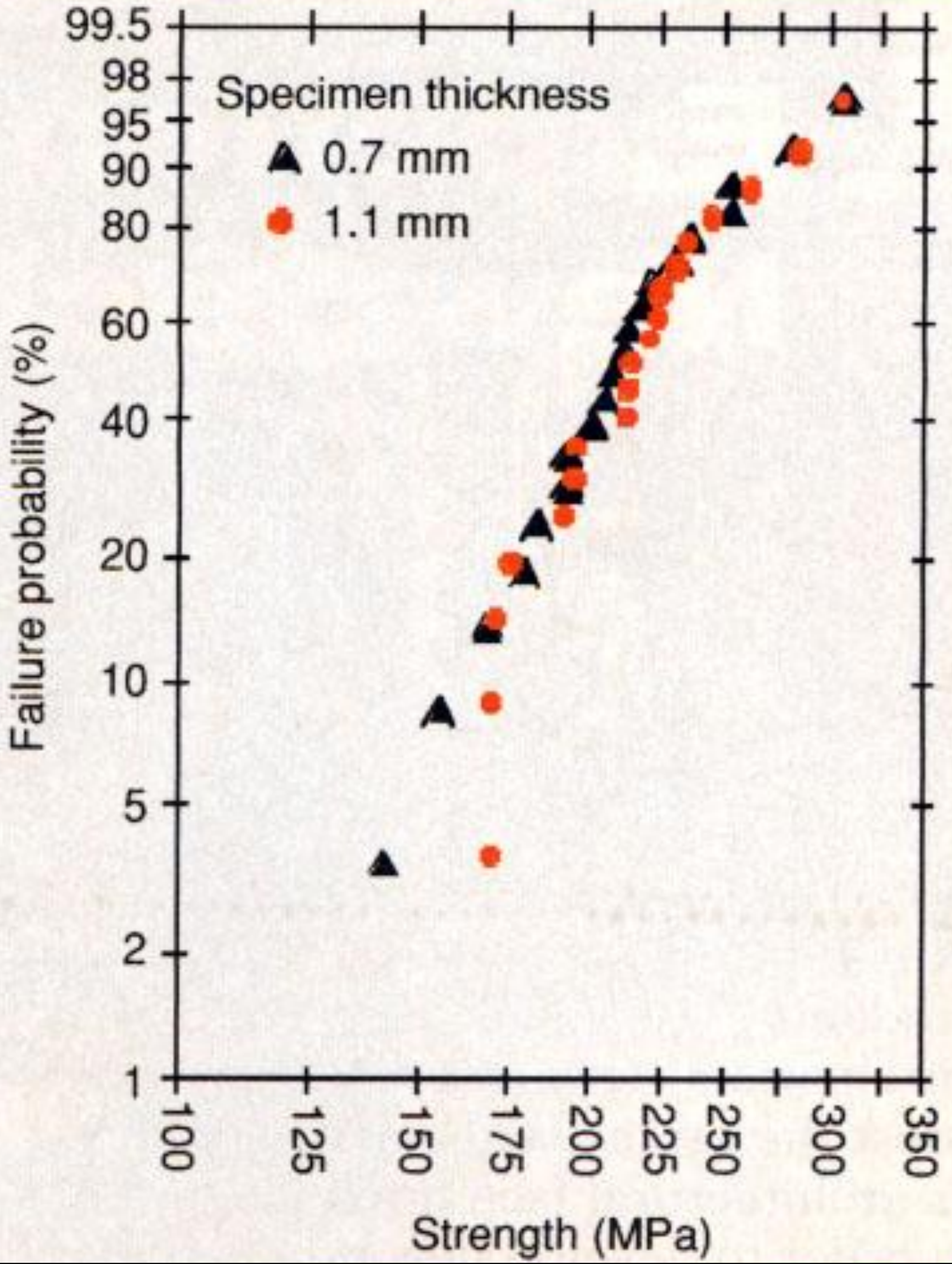
E-glass fibers (tensile tests, in air)



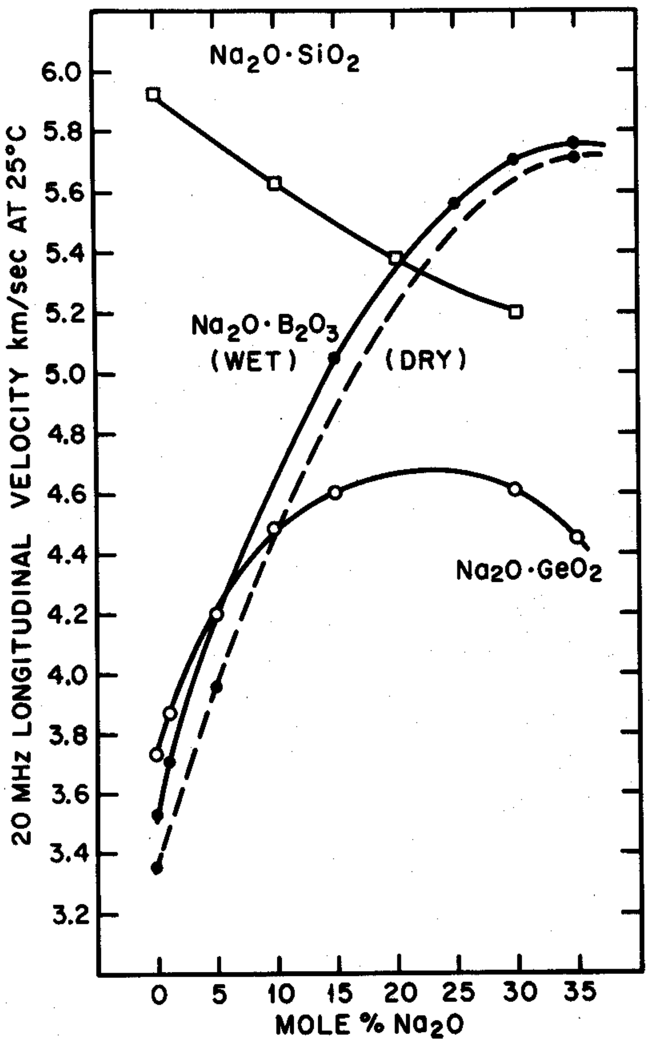
Cameron, 1968



Concentric ring tests, abraded Corning glass 1737, two different thicknesses.

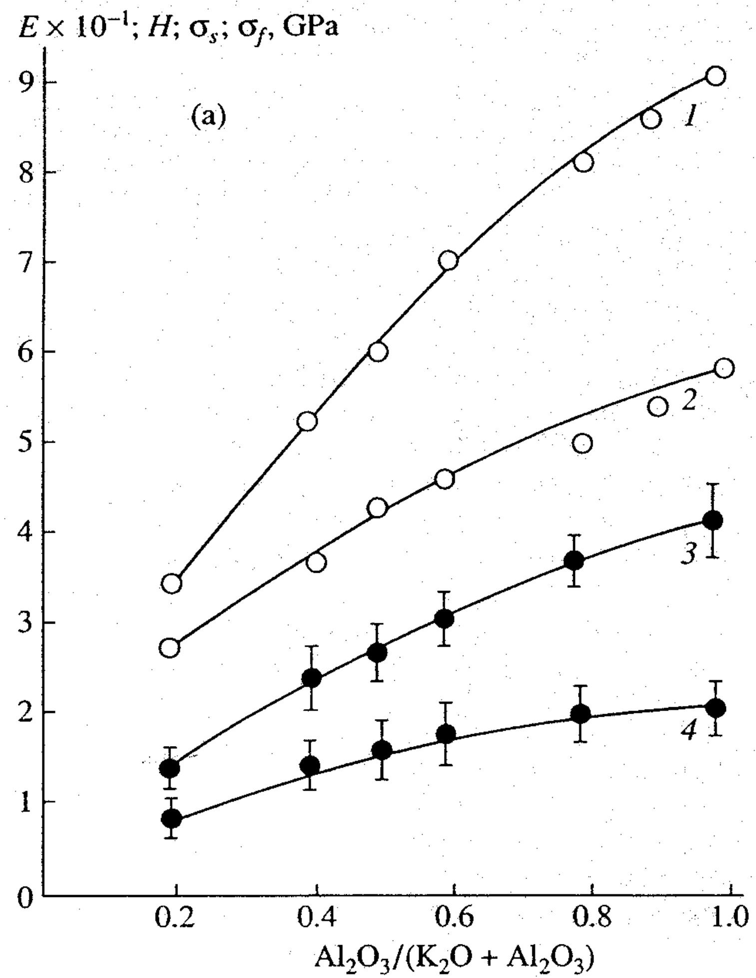
Gulati, et al., *Ceramic Bulletin*, 83[5] 14, 2004

Mechanical properties depend on glass structure



K/Al-metaphosphate glasses

Baikova, et al. *Glass Phys. Chem.*, 21[2] (1995) 115.



E

Hv

σ_{LN}

σ_{RT}

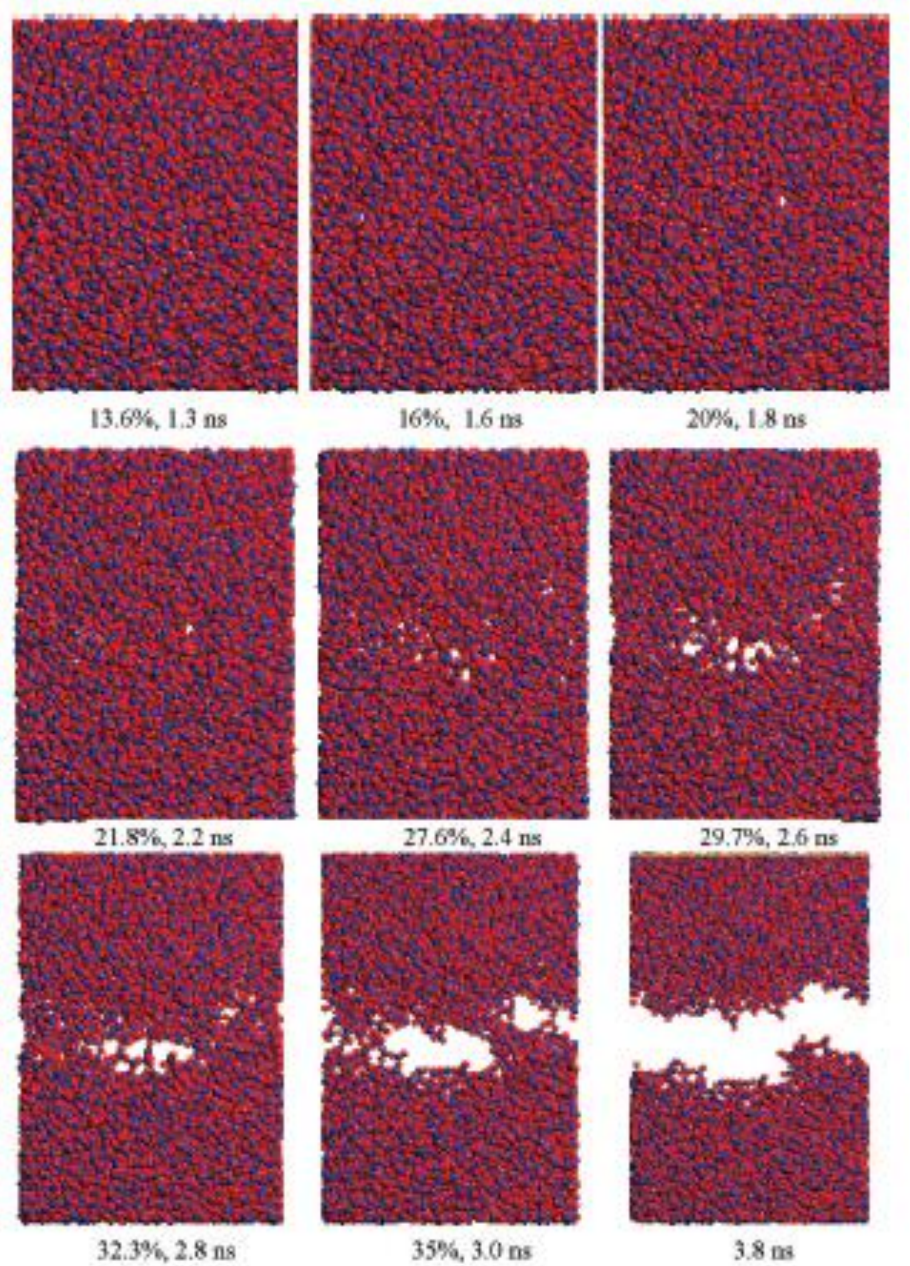
Table 2. Mechanical characteristics of inorganic glasses in three oxide systems

Glass no.	Chemical composition	Strength in liquid nitrogen σ, GPa	Hardness H, GPa	Young's modulus E, GPa	Ultimate elastic strain $\varepsilon = \sigma/E$, %
	Borate glasses				
1	B_2O_3	1.2	1.7	22	5.5
2	$15Na_2O \cdot 85B_2O_3$	2.7	3.9	52	5.2
3	$33Na_2O \cdot 67B_2O_3$	3.0	4.9	73	4.1
	Silicate glasses				
4	SiO_2	12.0	8.5	73(100*)	12.0*
5	$33Na_2O \cdot 67SiO_2$	3.5	3.7	60	5.8
6	$12.5Na_2O \cdot 12.5Al_2O_3 \cdot 75SiO_2$	8.3	5.4	72	11.5
7	$16.5Na_2O \cdot 16.5Al_2O_3 \cdot 67SiO_2$	8.4	5.5	73	11.6
8	$25Na_2O \cdot 25Al_2O_3 \cdot 50SiO_2$	8.5	6.0	74	11.4
9	$14.5MgO \cdot 14.5Al_2O_3 \cdot 71SiO_2$	10.4	6.4	95	10.9
10	$6TiO_2 \cdot 94SiO_2$	7.5	6.5	68	11.0
	Phosphate glasses				
11	$16.5Cs_2O \cdot 16.5Al_2O_3 \cdot 67P_2O_5$	1.6	3.5	50	3.2
12	$16.5Rb_2O \cdot 16.5Al_2O_3 \cdot 67P_2O_5$	2.4	3.8	55	4.4
13	$16.5K_2O \cdot 16.5Al_2O_3 \cdot 67P_2O_5$	2.5	4.1	59	4.2
14	$16.5Na_2O \cdot 16.5Al_2O_3 \cdot 67P_2O_5$	3.0	4.5	68	4.4
15	$16.5Li_2O \cdot 16.5Al_2O_3 \cdot 67P_2O_5$	3.4	4.9	74	4.6
16	$27.5Al_2O_3 \cdot 67.5P_2O_5$	4.0	5.7	89	4.5
17	$17.5Al_2O_3 \cdot 15ZnO \cdot 67.5P_2O_5$	5.7	5.5	81	7.0

* The parameter obtained with due regard for the increase in the Young's modulus with an increase in the strain [17].

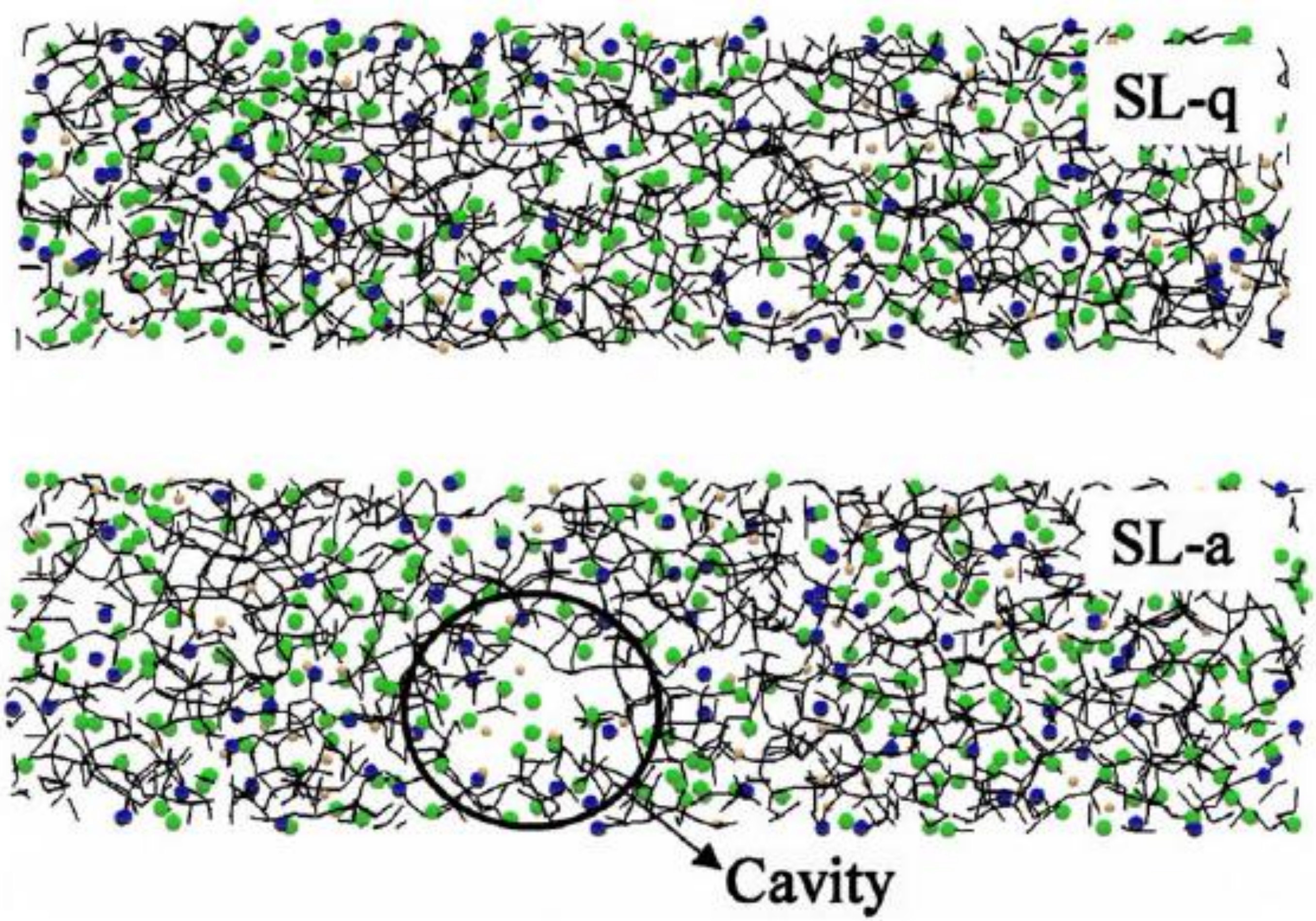
Pukh et al., 2005

MD Simulations of fracture reveal the development of cavities that coalesce to form the failure site



Pedone et al., 2008

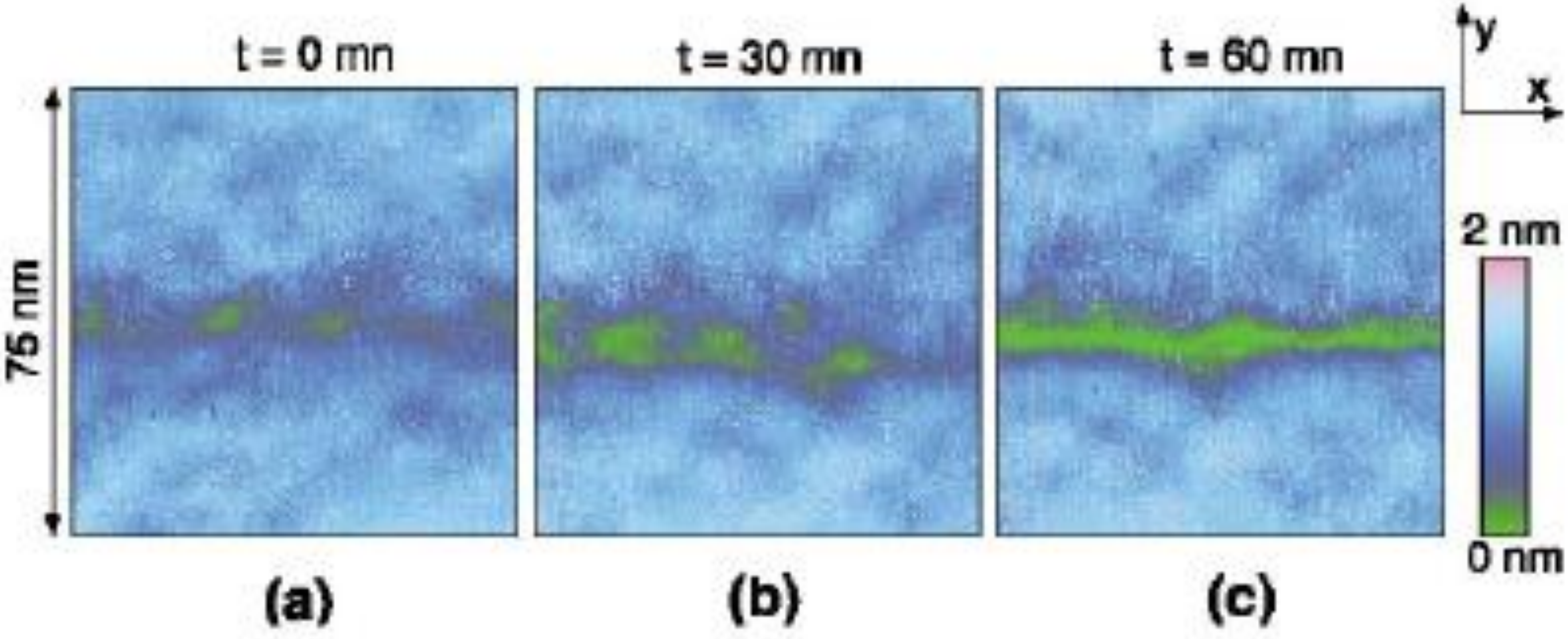
Quenched and annealed soda-lime glasses at 5GPa tension



S. Ito and T. Taniguchi, JNCS (2004)

There may be experimental evidence for cavitation near the tips of slow-moving cracks

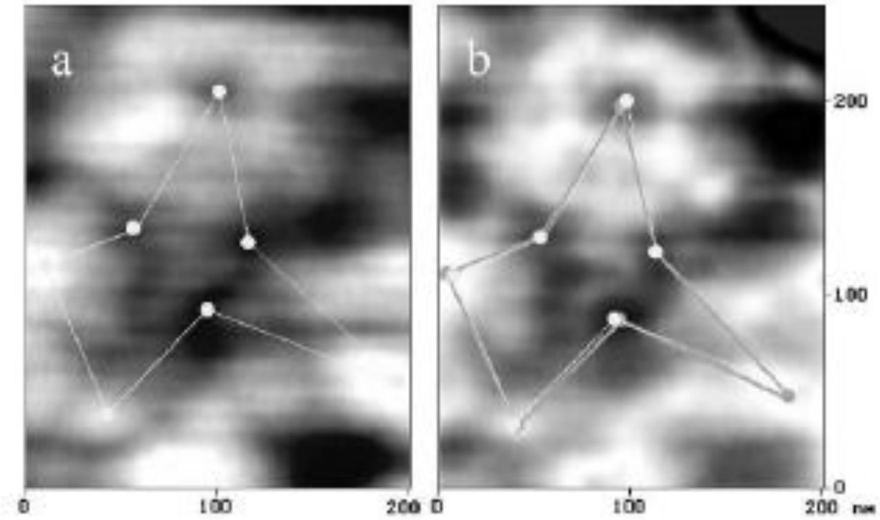
Aluminosilicate glass, 10^{-11} m/s, 45% RH, AFM Images



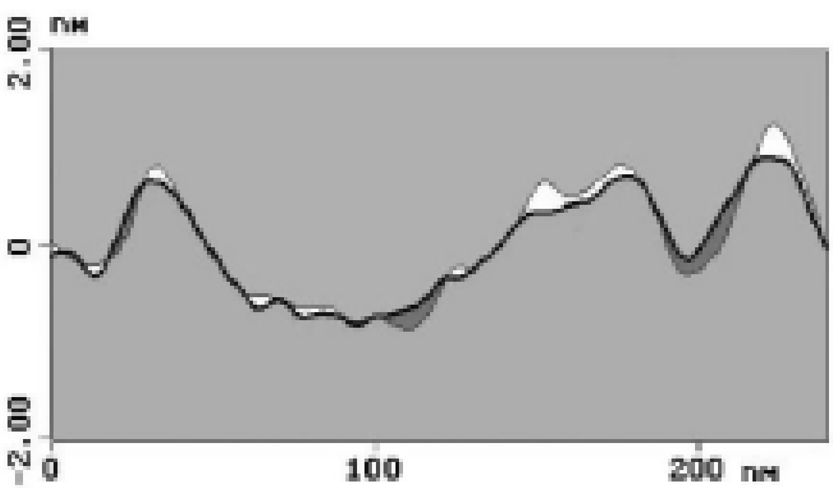
Célarié, et al., PRL (2003)

Formation of 'nano-cavities' interpreted as evidence for 'nano-ductile' fracture of glass!

‘Nano-ductility’ interpretation is not universal



‘Post-mortem’ AFM analyses of the opposing fracture surfaces show no evidence for the formation of nano-cavities



Note the relatively rough surface

Guin and Wiederhorn, PRL (2004)

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Fatigue

An example of fatigue in glass

http://www.youtube.com/watch?v=r8q-R9ZISac

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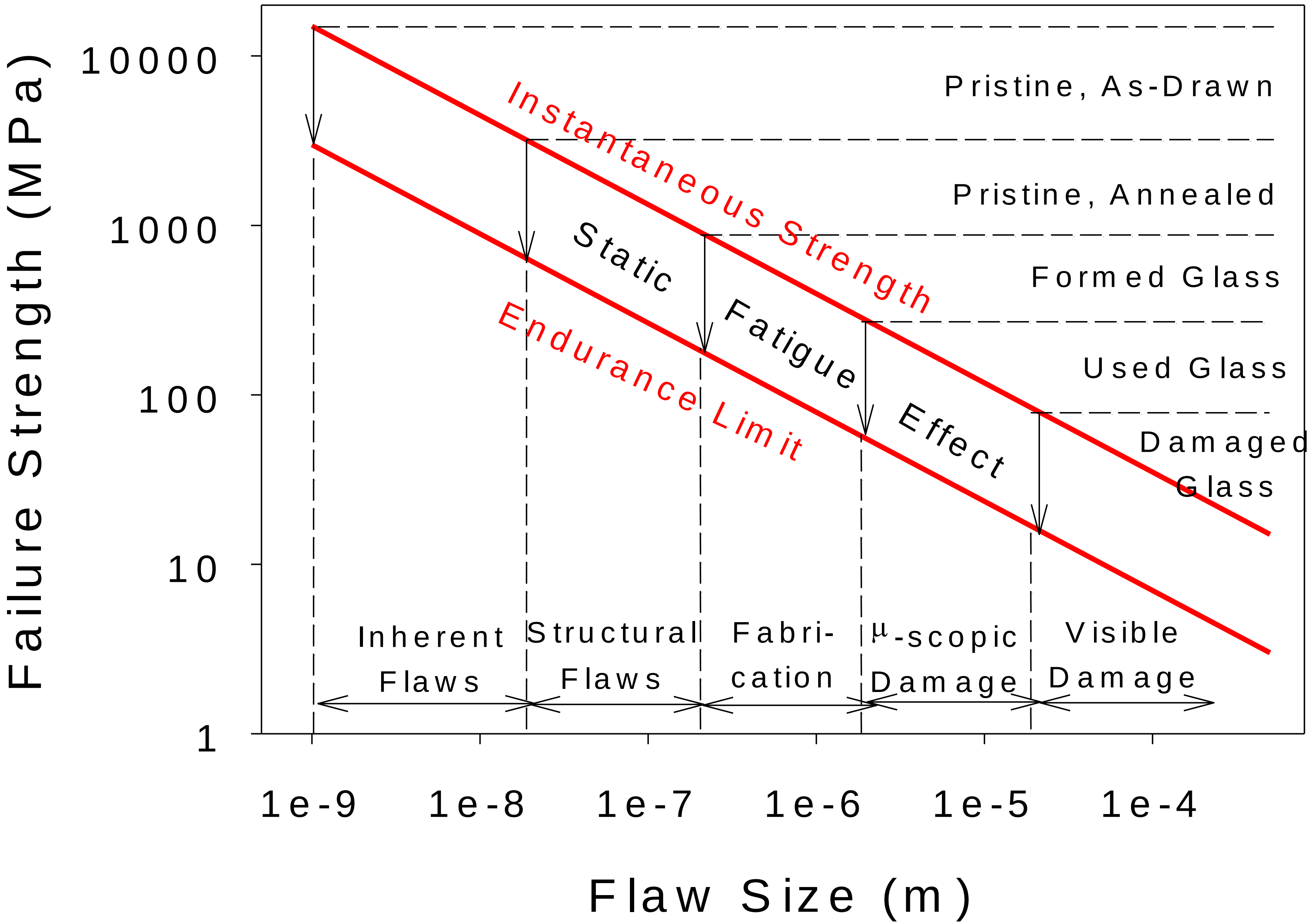


After Mould (1967)

Stress Corrosion: source for static fatigue- the reduction in strength with time

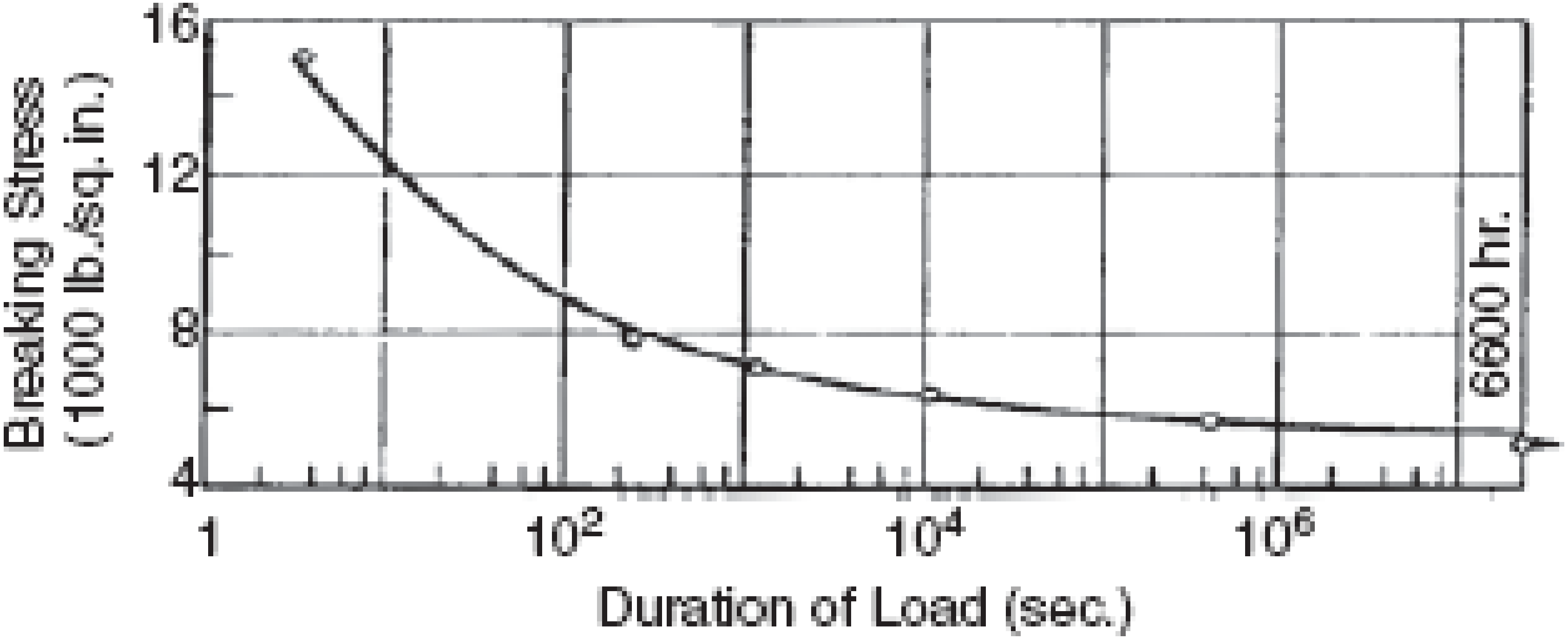
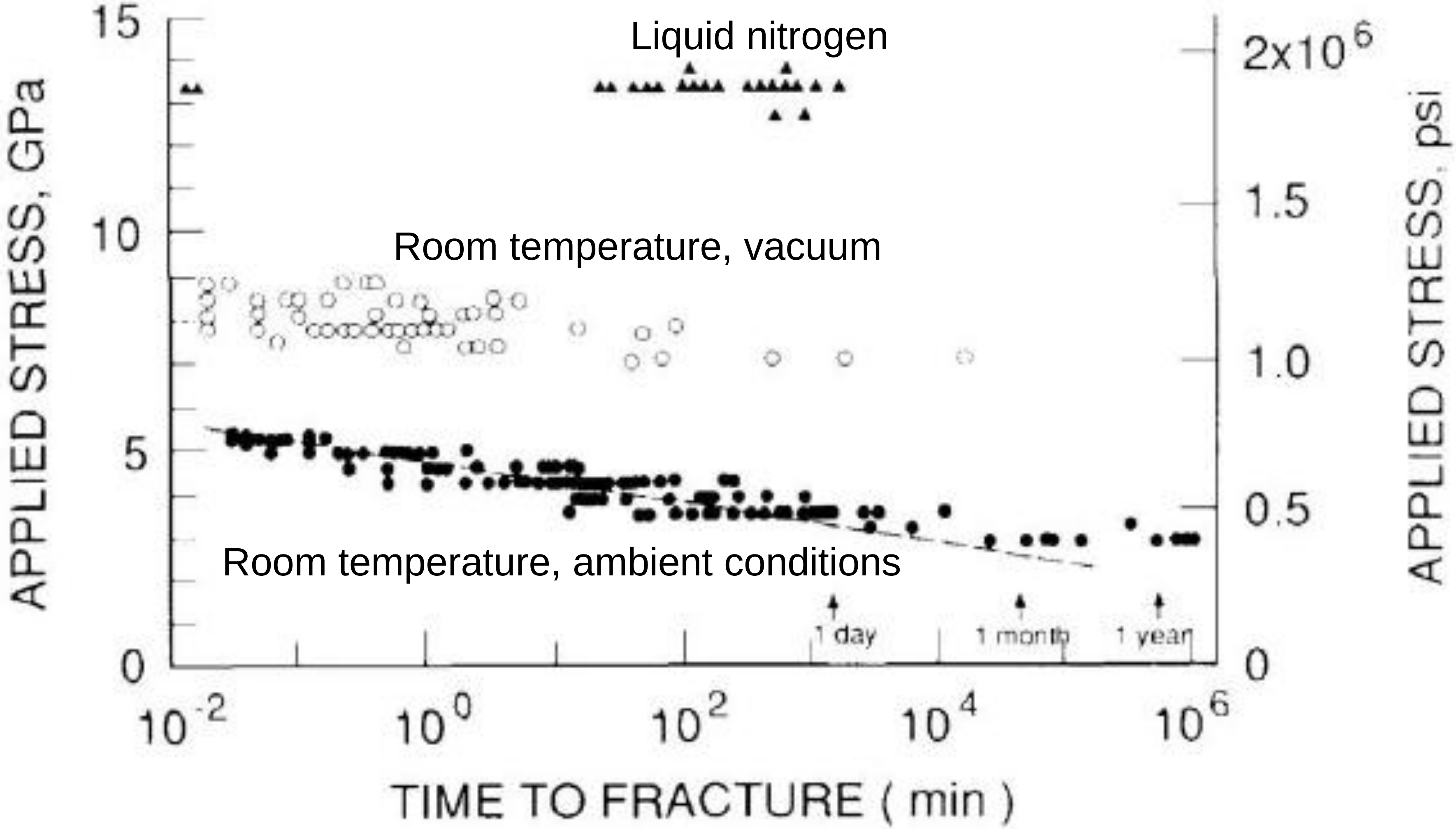


Fig. 1. Stress-time characteristics of glass, from bending tests on 1/4 in. diameter soda-lime-silicate rods. Taken from Shand.[1]

Fatigue data on silica fibers



35. B. A. Proctor, I. Whitney, and J. W. Johnson, Proc Roy Soc **A297,** 534 (1967).

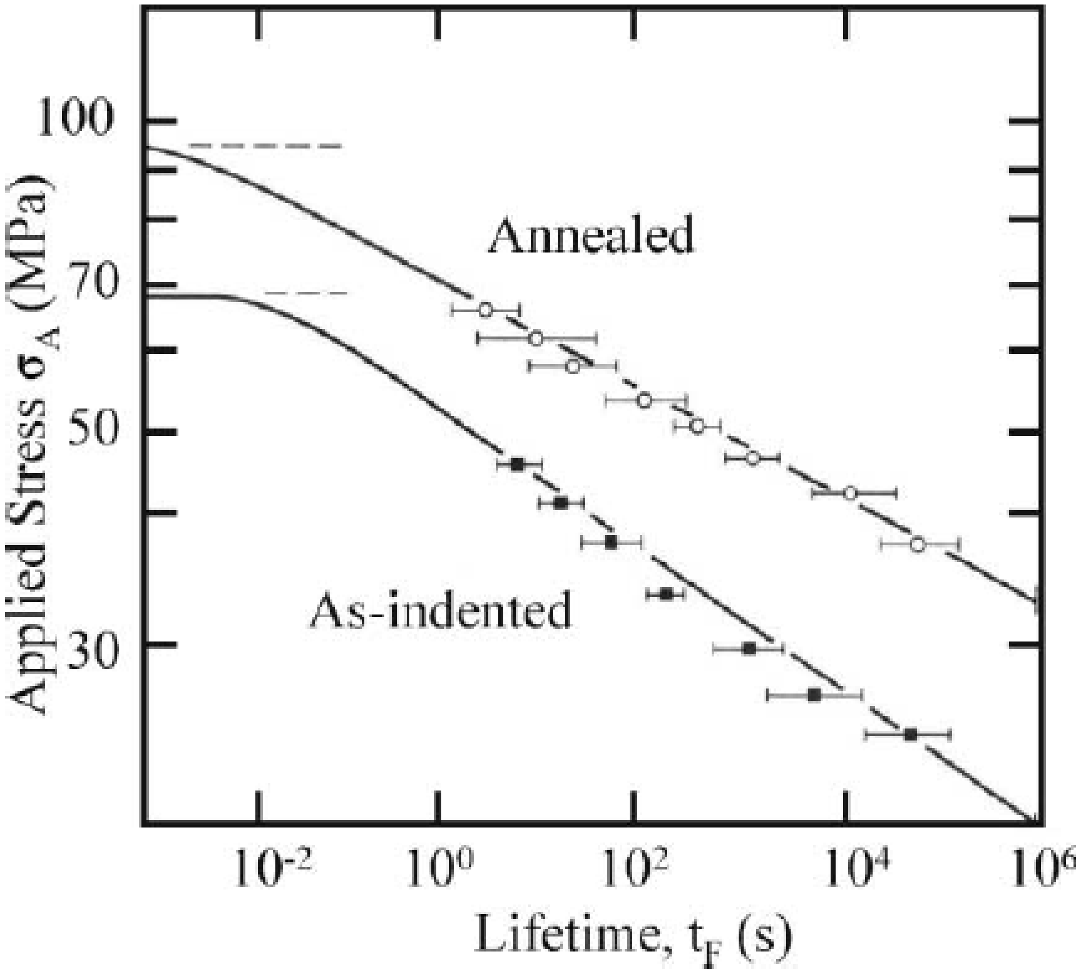


Fig. 10. Increased susceptibility to static fatigue due to indentation residual stresses. Vickers-indented soda-lime glass (load: 5 N), tested in water (from [25]).

Note: residual stresses increase susceptibility to static fatigue

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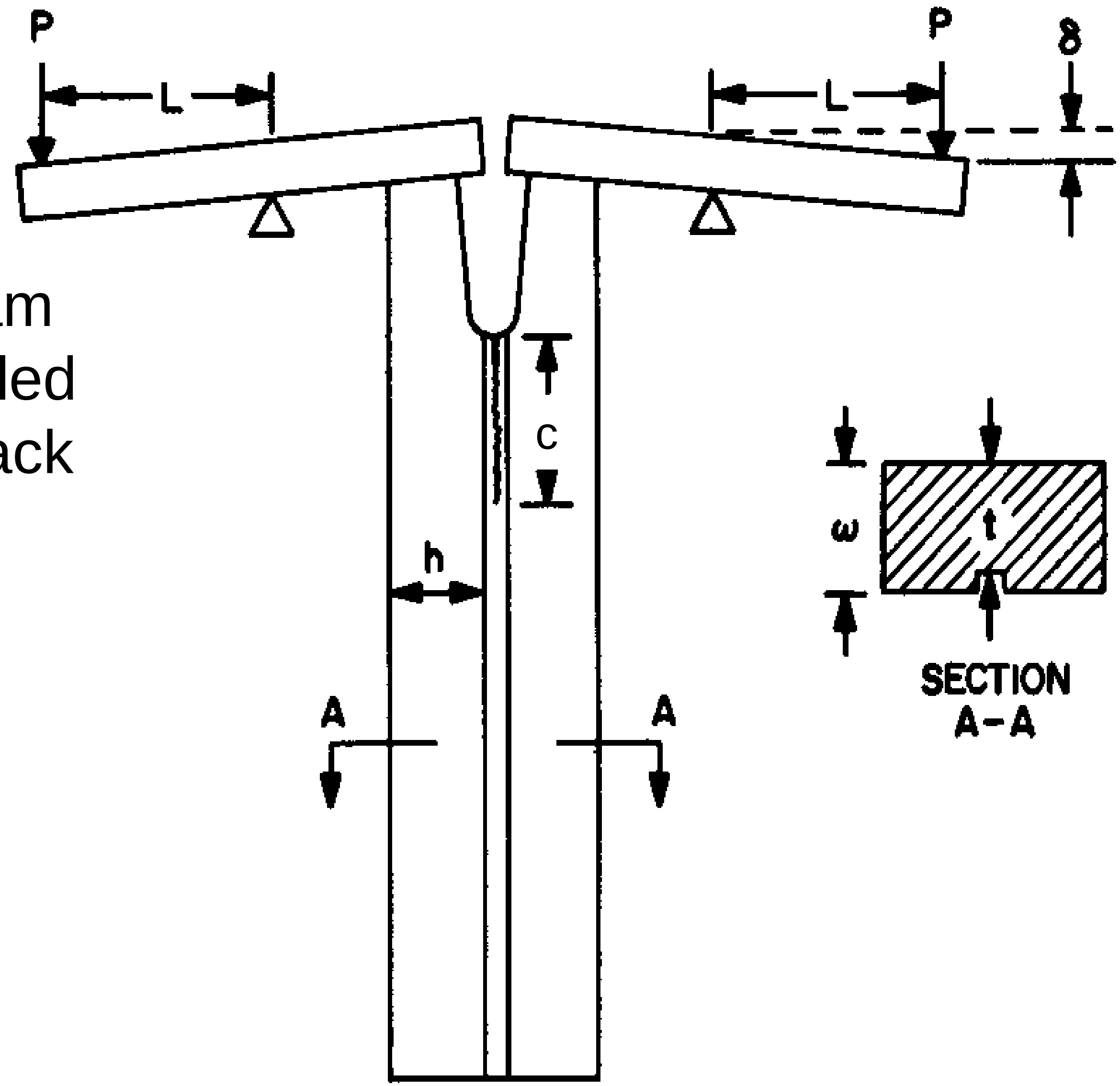
Double-Cantilever Beam (DCB) used for controlled stress intensity and crack velocity experiments

$$V=dc/dt$$

$$K=P^2/f(geometry)$$



S. W. Freiman, D. R. Mulville and P. W. Mast, J. Mater. Sci., 8[11] 1573 (1973).

Crack propagation kinetics depend on the stress intensity

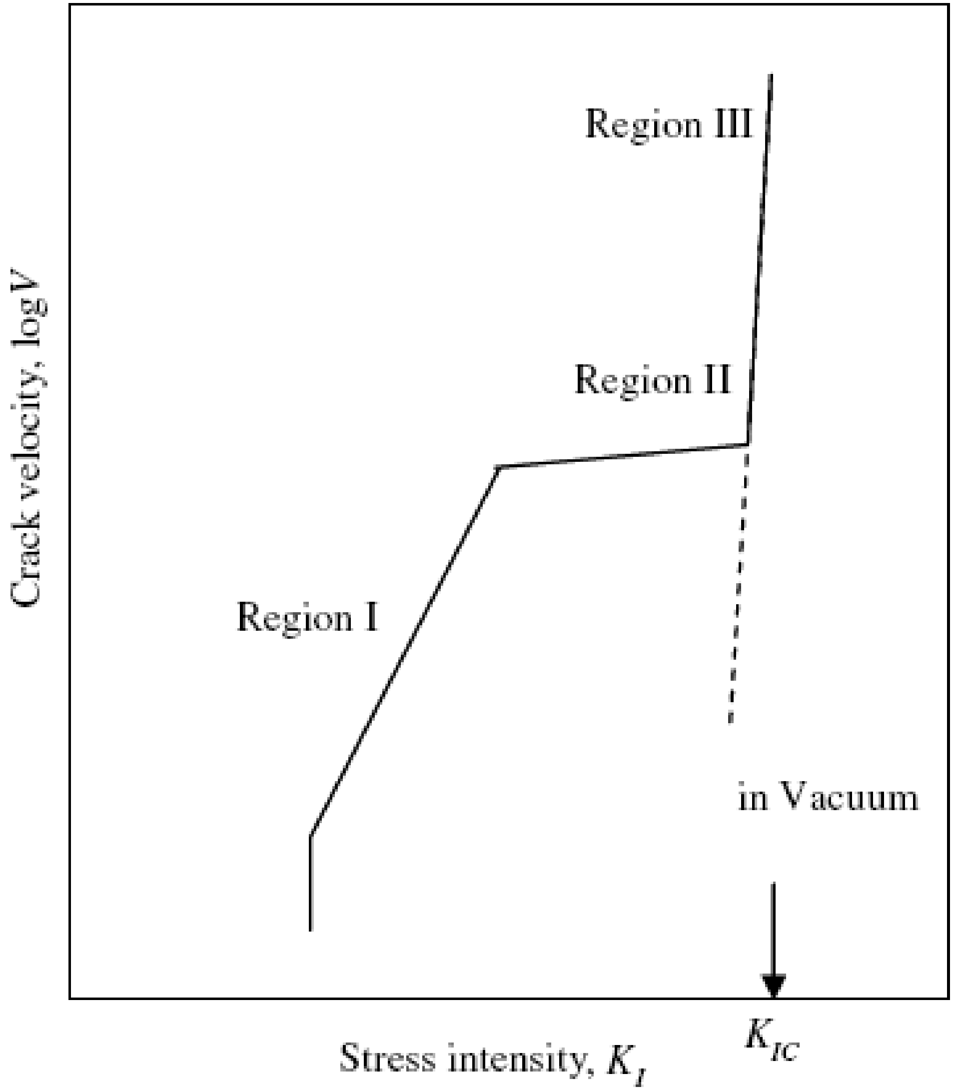


Fig. 1. The schematic of the K_I–V curve for soda-lime-silicate glasses. K_{IC} is the critical stress intensity, i.e., fracture toughness. The dashed line shows the K_I–V curve in a vacuum.

Region I: stress-corrosion

Region II: diffusion-limited

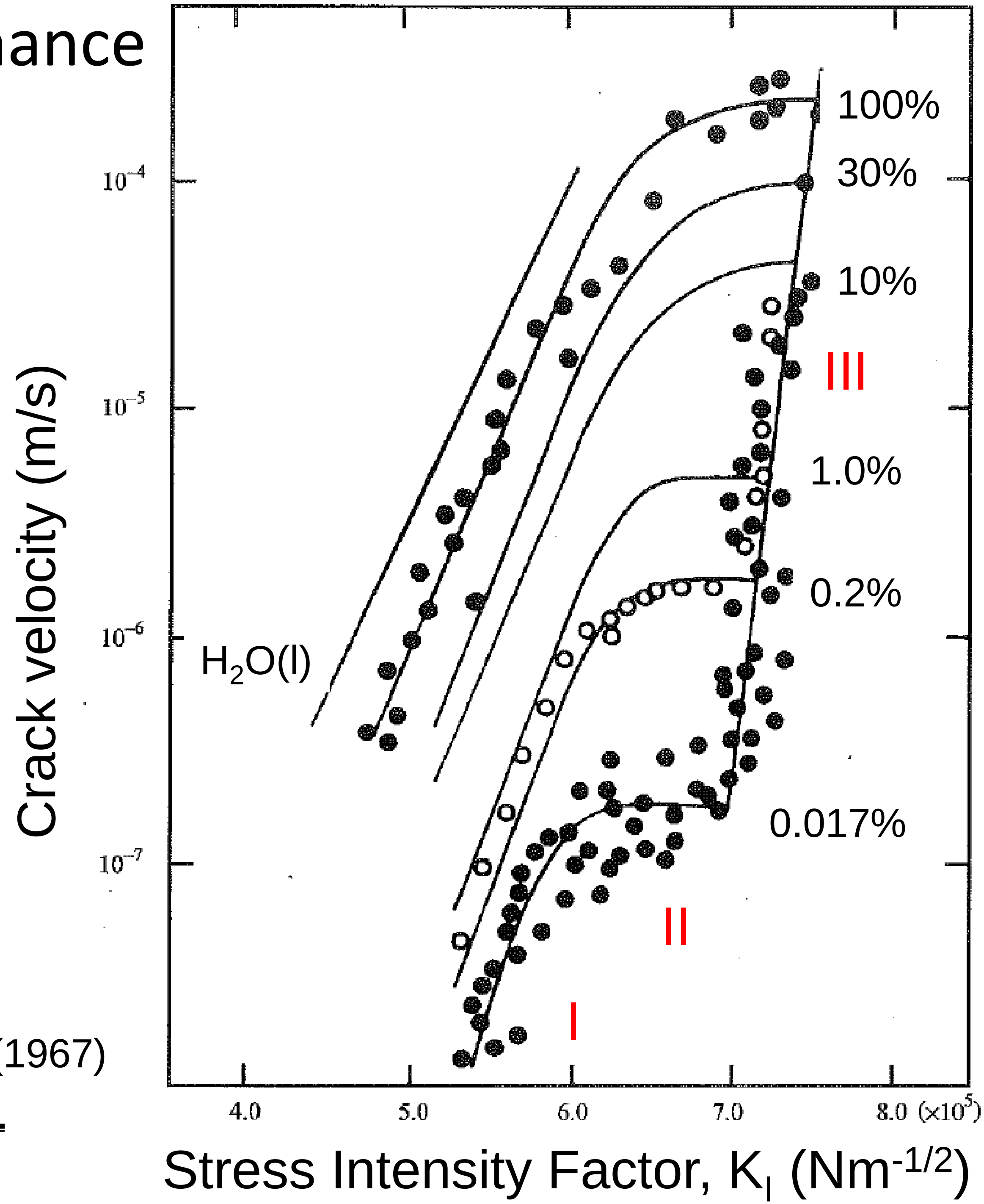
Region III: rapid fracture (K_{IC})

Region 0: propagation threshold

Water and stress enhance crack growth in glass

Region I: stress-corrosion

$v = AK_I^n$, where n is the 'stress corrosion susceptibility factor'

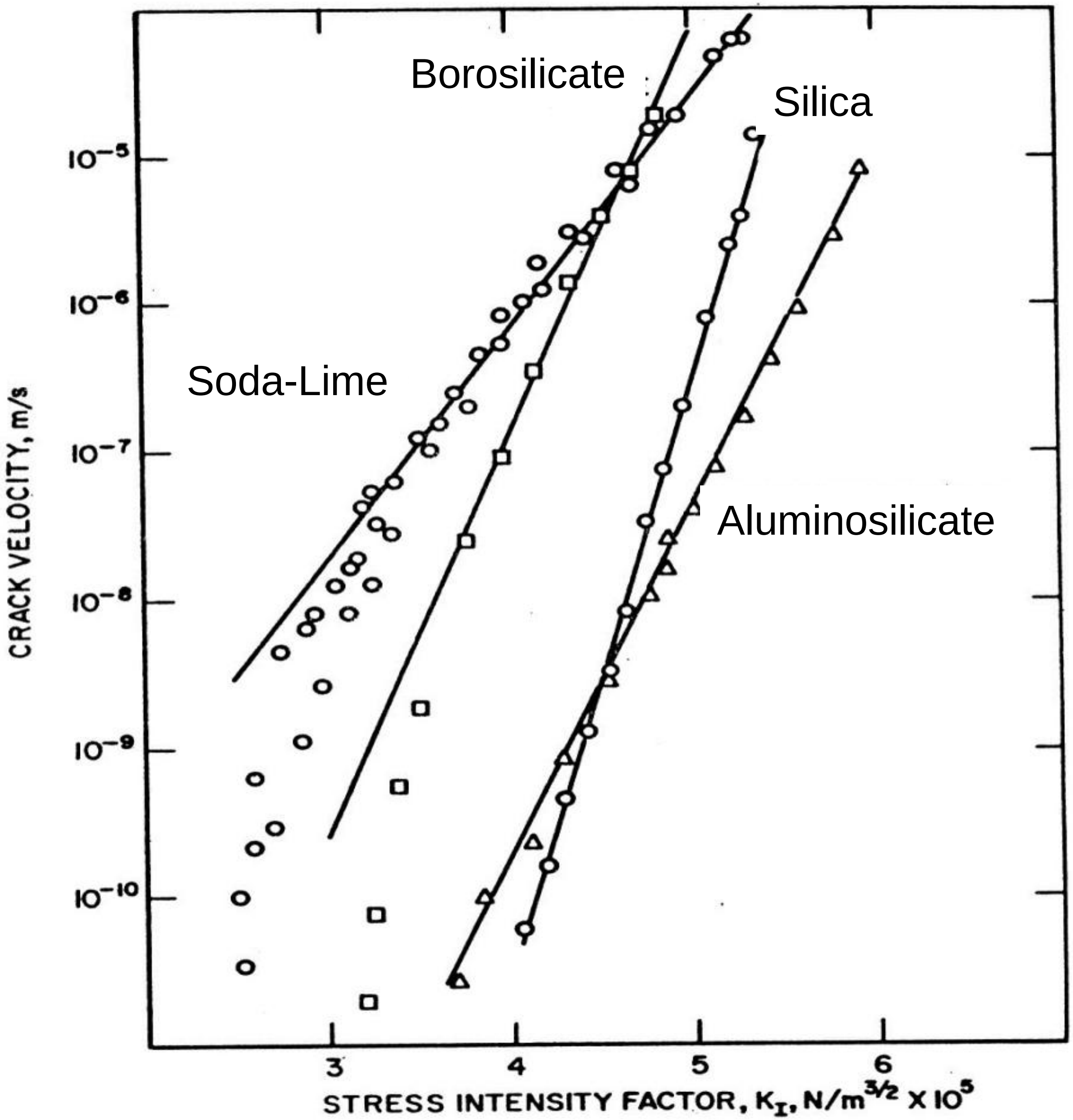


SM Wiederhorn, JACerS, 50 407 (1967)

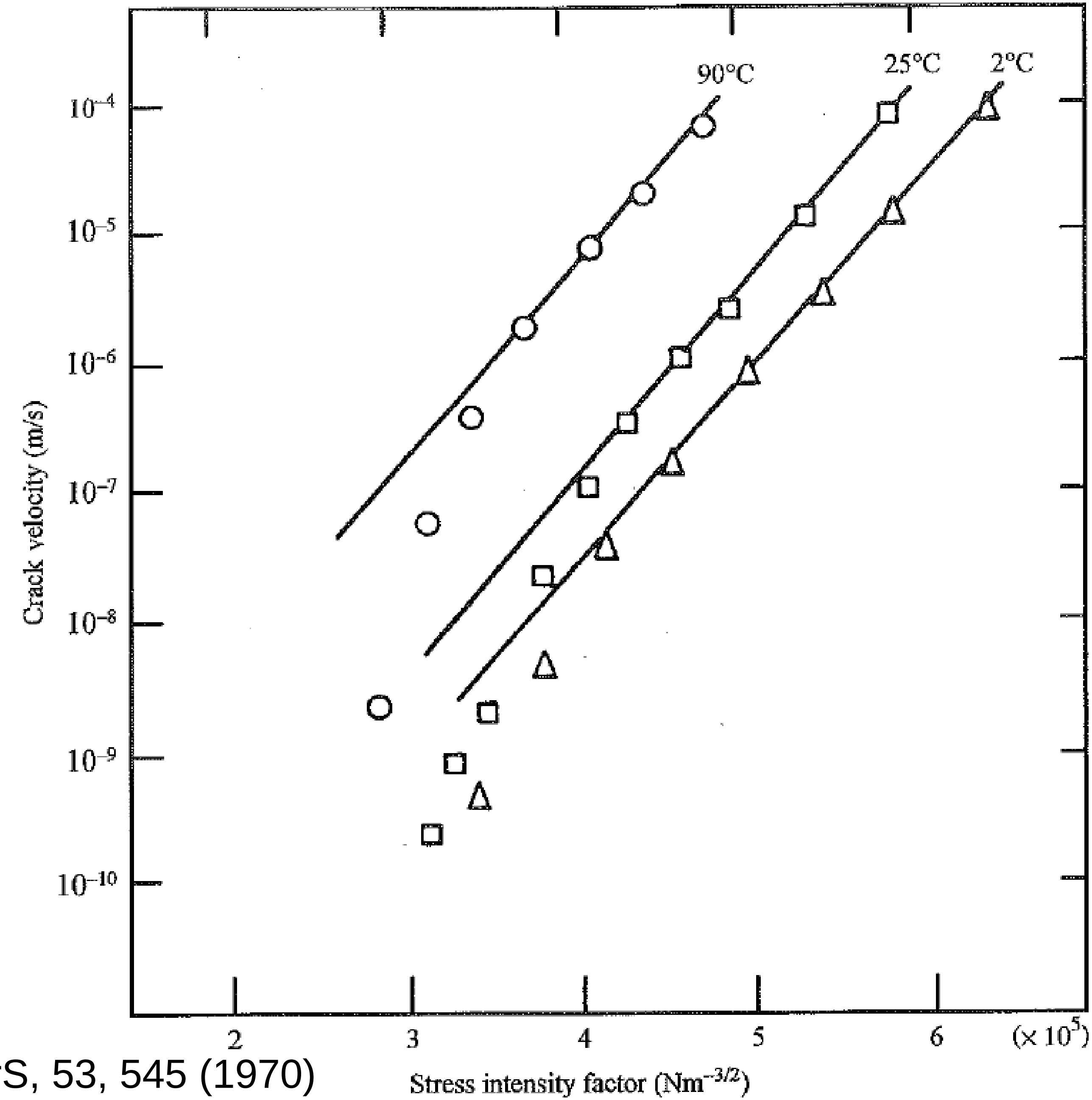
Compositional-dependence of v-K behavior in Region I

Different glasses are more or less susceptible to fatigue effects –

We do not understand this compositional dependence!



Temperature-dependence of v-K behavior in Region I



Wiederhorn and Bolz, JACerS, 53, 545 (1970)

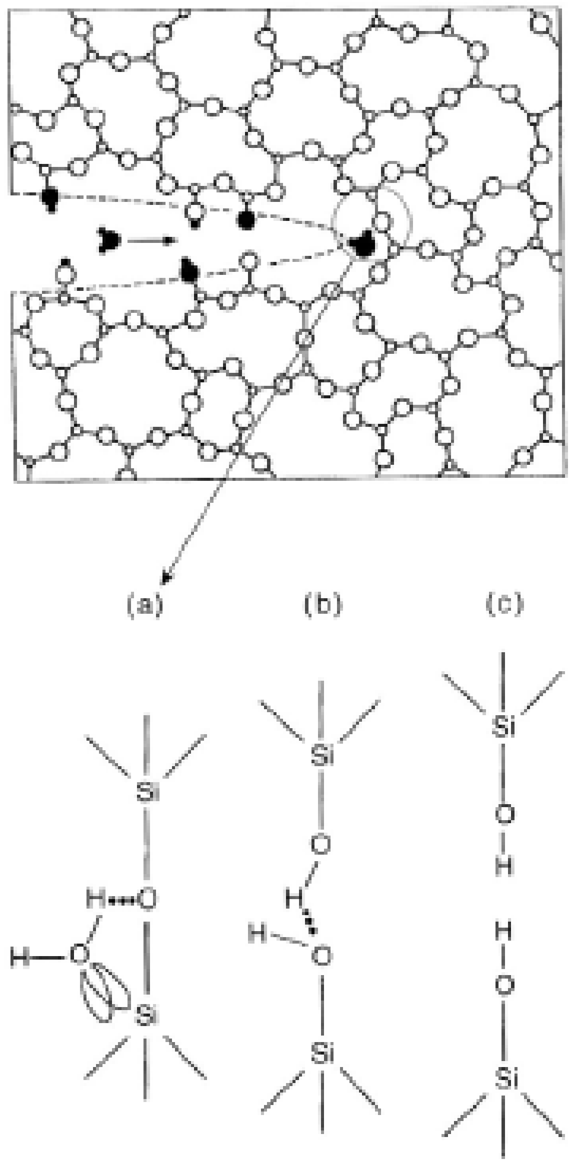
Slow crack growth is a thermally activated process

Chemical rate theory has been used to explain the exponential form of the V –K_I curves:

$$V = V_0 \exp(-E + bK_I / RT)$$

where V_0 is a constant, E is the activation energy for the reaction, R is the gas constant, T is the temperature, and b is proportional to the activation volume for the crack growth process, ΔV*.

Wiederhorn, et al., JACerS, 1974

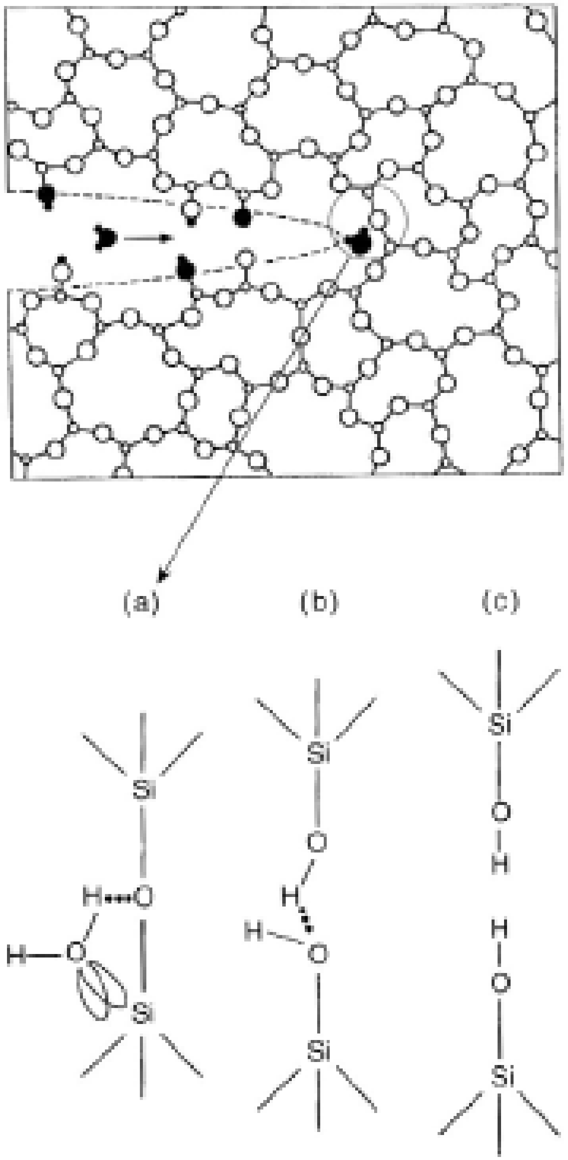


Stress-corrosion in silicate glass:

a. **Adsorption** of a water molecule on a strained siloxane bond at a crack tip;
b. **Reaction** based on proton and electron transfer;
c. **Separation** of silanol groups after rupture of the hydrogen bond.

Net result: extension of the crack length by one tetrahedral unit

Michalske et Bunker, J. Appl. Phys. (1984)



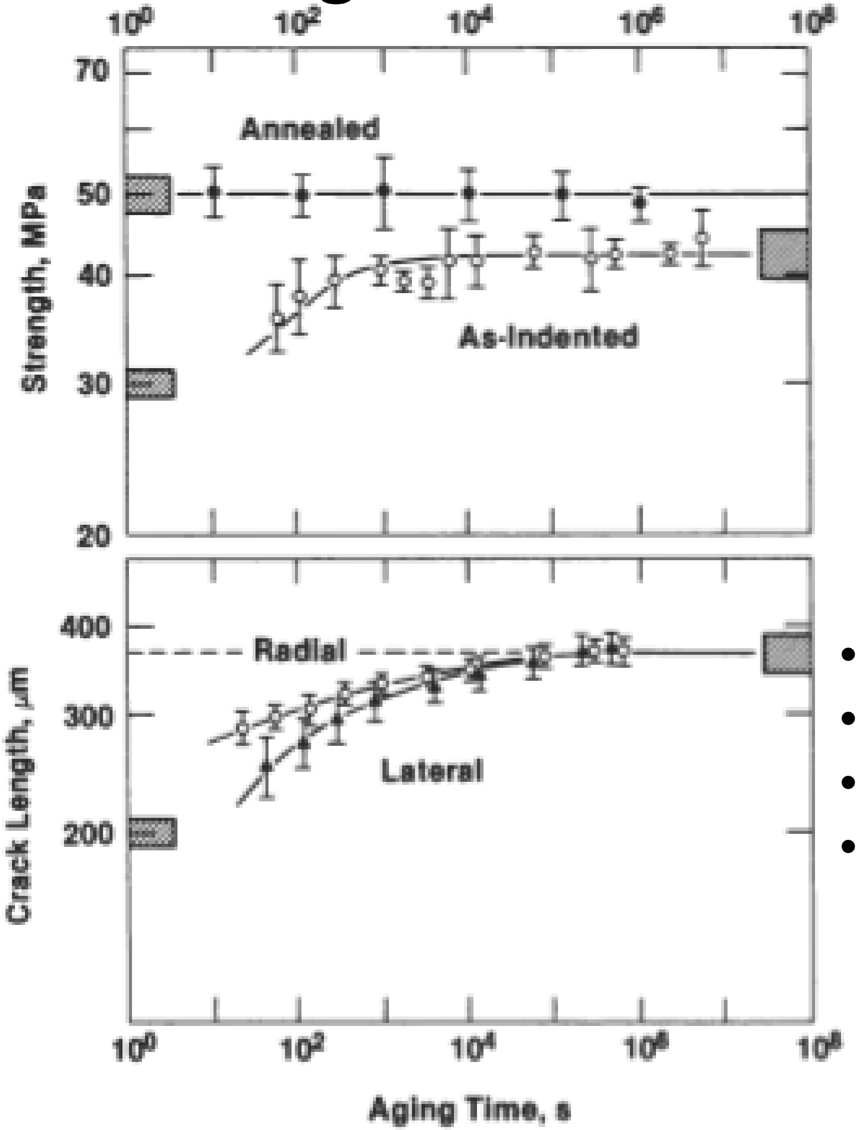
Stress-corrosion in silicate glass:

a. Reactive molecules can donate both protons and electrons to the ruptured siloxane bond;
b. Reactive molecules are small enough to reach the crack tip (<0.5 nm).

Water, ammonia, hydrazine (H_2N-NH_2), formamide (CH_3NO)

Michalske et Bunker, J. Appl. Phys. (1984)

Other 'crack-tip chemistries' lead to strength increasing with time



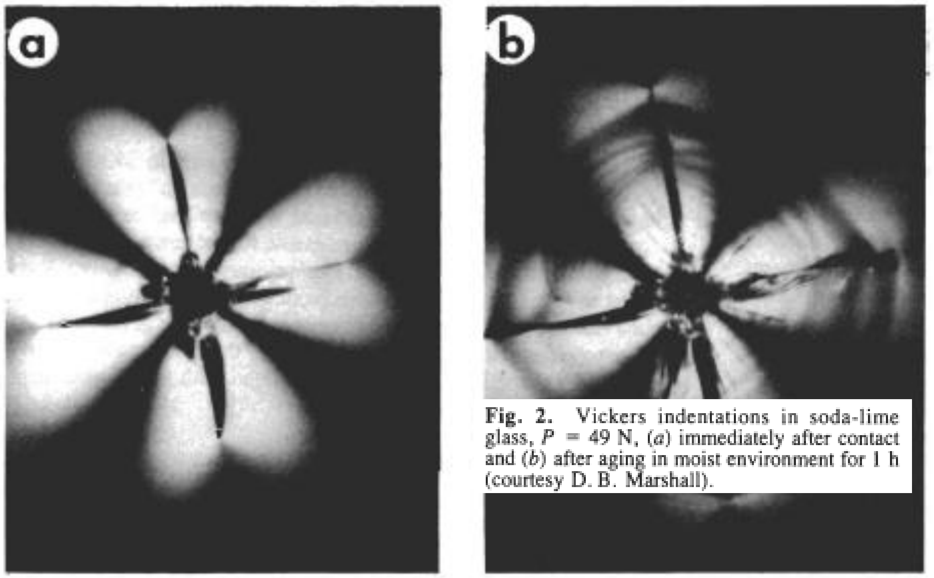
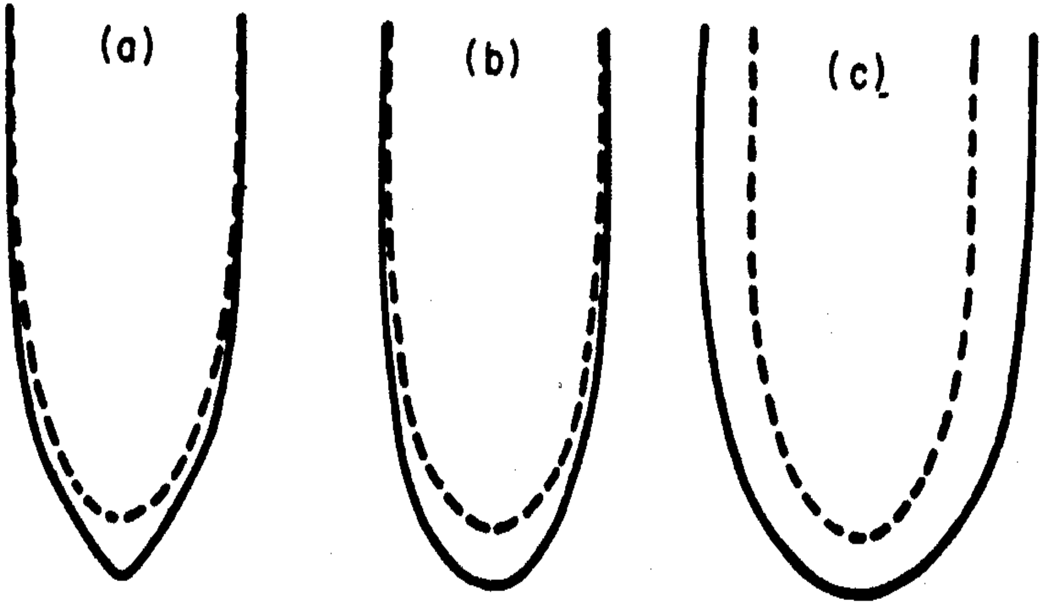


Fig. 2. Vickers indentations in soda-lime glass, $P = 49$ N, (*a*) immediately after contact and (*b*) after aging in moist environment for 1 h (courtesy D. B. Marshall).

- Controlled flaws (Vicker's indents) in S-L-S
- Aging in different environments
- Tensile tests in inert conditions (silicone oil)
- May be due to stress release- not crack geometry?

Lawn et al., JACerS, 68[1] 25 (1985)

Crack-tip sharpness depends on glass structure and corrosion conditions



Change in crack tip geometry due to corrosion: (a) Flaw sharpening for stresses greater than the fatigue limit; (b) Constant flaw sharpness for stresses equal to the fatigue stress; (c) Flaw blunting for stresses below the fatigue limit.

.T.-J. Chuang and E.R. Fuller, Jr. “Extended Charles-Hillig Theory for Stress Corrosion Cracking of Glass,” *J. Am. Ceram. Soc.* 75[3] 540-45 (1992).

W.B. Hillig, “Model of effect of environmental attack on flaw growth kinetics of glass,” *Int. J. Fract.* **143** 219-230 (2007)

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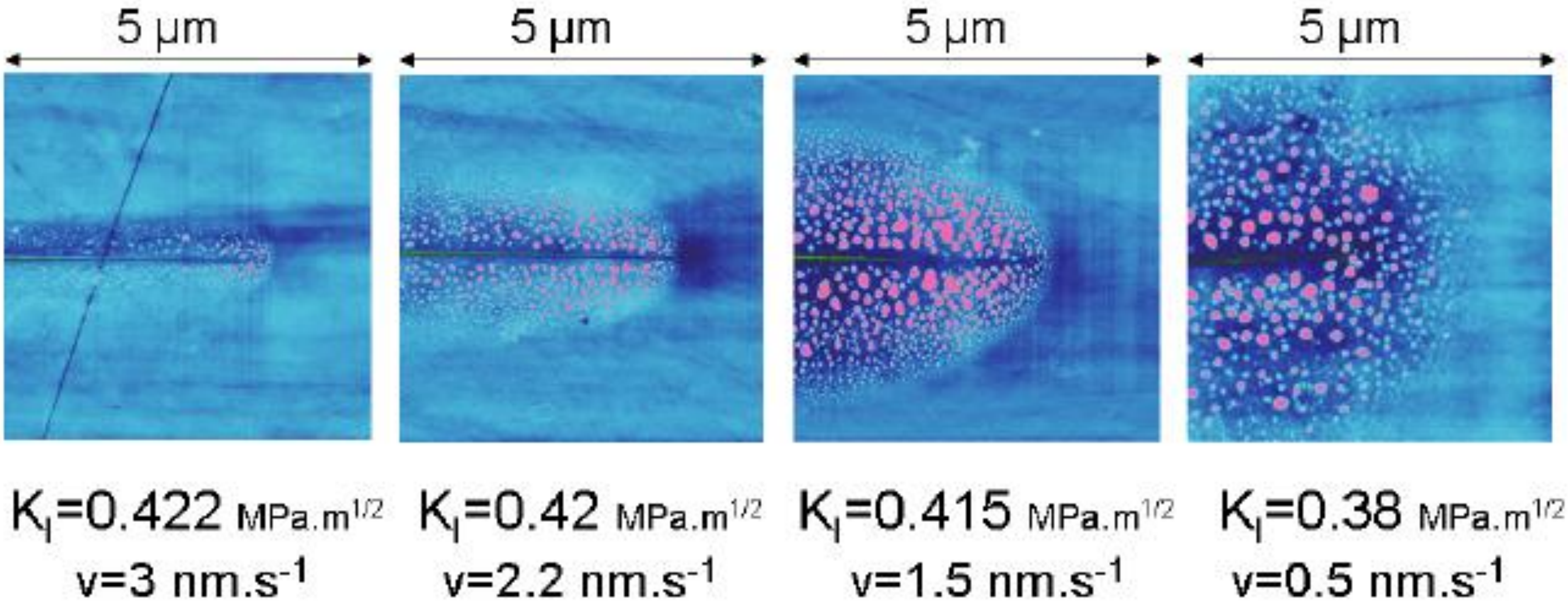
AFM detects significant morphological changes around the crack-tip in aged samples

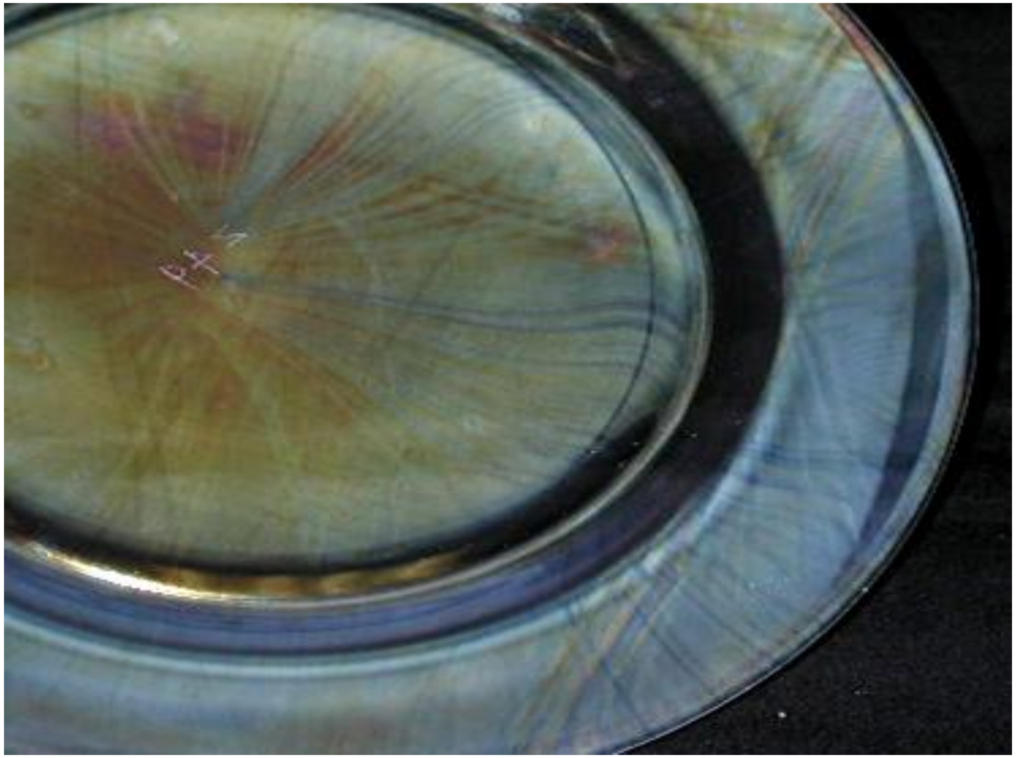


SLS glass, 45% RH

Célarié, et al., JNCS (2007)

- Formation of alkali-rich regions modeled by Na^+-H_3O^+ inter-diffusion
- Alkali depletion from crack-tip region leads to stress-relaxation
    - Crack extension threshold

The ‘corrosion reactions’ at a crack tip are similar to those that occur at glass surfaces



From Prof. Jain:
A clear glass plate is made of soda lime silicate glass by pressing molten gob. It shows the following undesirable pattern upon washing in a dishwasher. Discuss this problem with your roommate. Then develop a collaborative research program to characterize and solve the problem. The proposal should be about 1500 words long.

Water plays many roles at a crack-tip

1. Chemical attack on strained bonds to extend flaws
2. Water films adsorbed on crack surfaces
3. Capillary condensation at the crack tip
4. Water diffusion into the glass network, changing elastic properties
5. Inter-diffusion with alkali ions, changing pH and attacking glass

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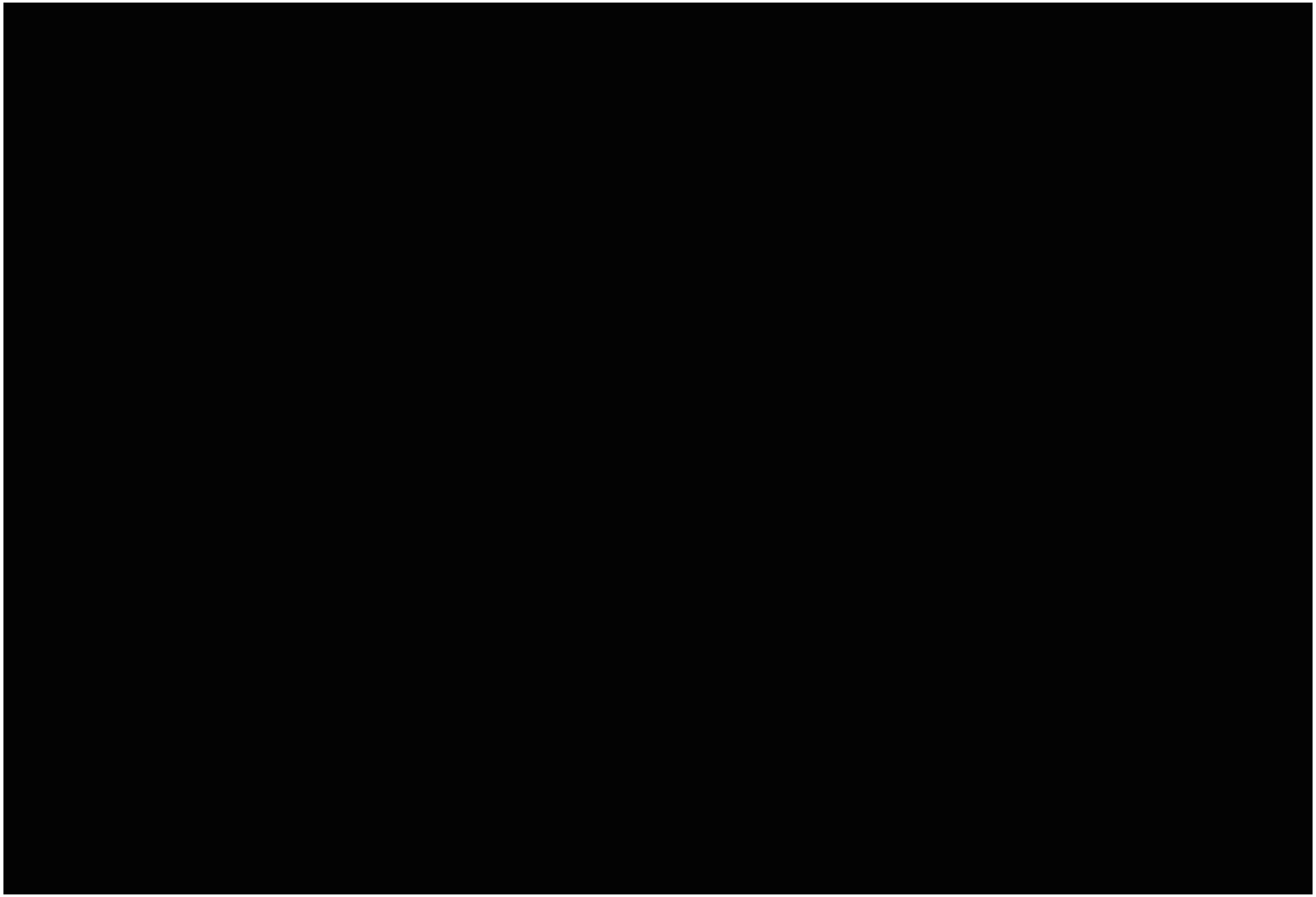
Strengthening- What can we do to make glass stronger (or more reliable)?

- Polished surfaces
- Surface dealkalization
- Protective coatings
- Relaxation of residual stresses (annealing)
- Reduction of expansion coefficients (thermal shock)
- Thermal tempering
- Chemical tempering
- Modified compositions:
  - Increasing elastic modulus and/or surface energy
  - Reducing stress-corrosion
  - Propagation threshold
  - Crack healing

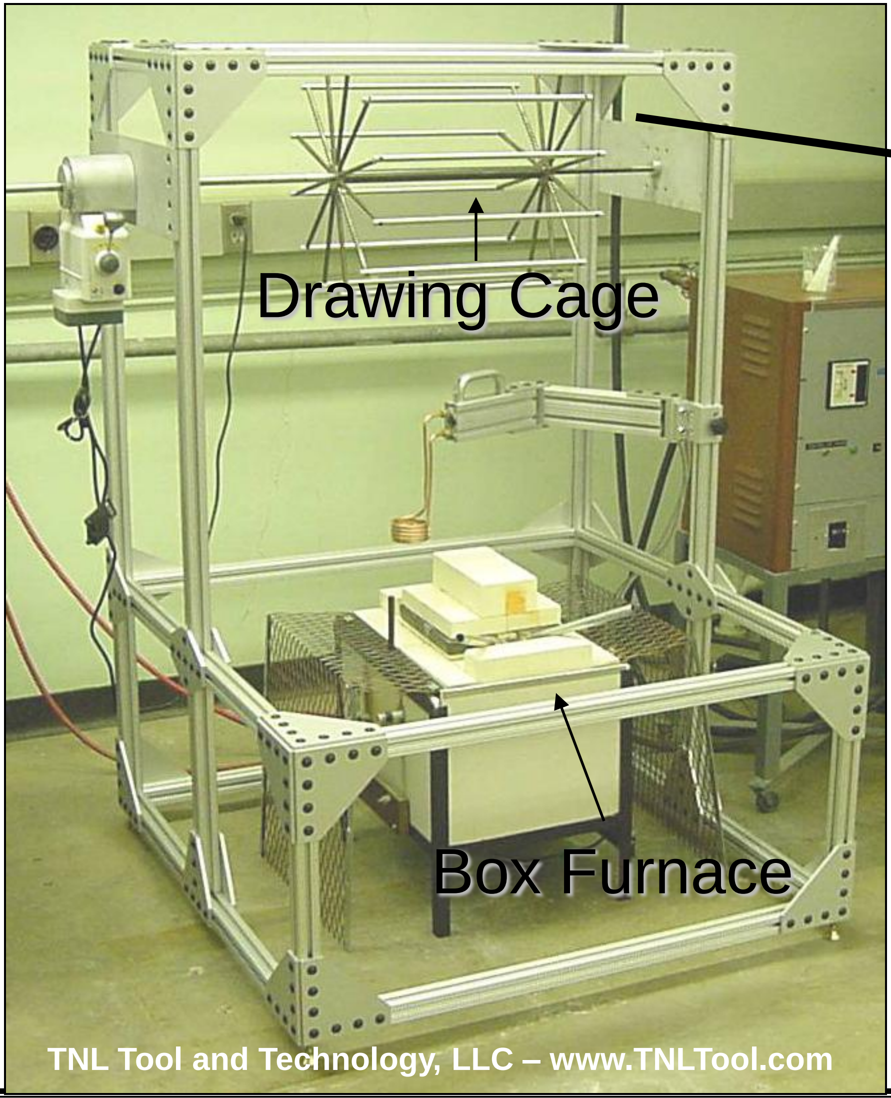
Annealed vs. chemically tempered glass

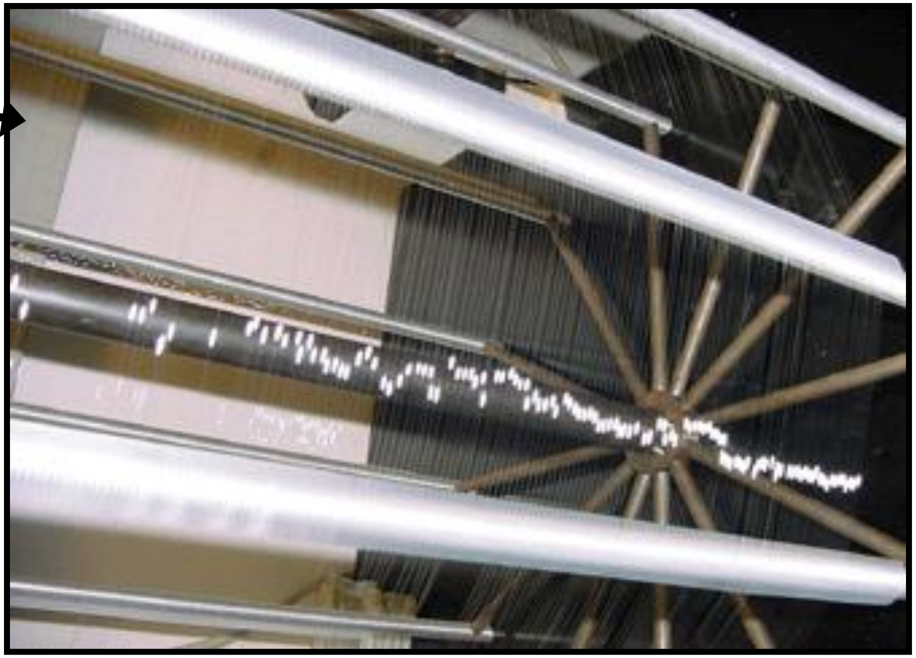


From Jill Glass, Sandia National Labs

Two-point bend studies of the failure characteristics of silicate glasses

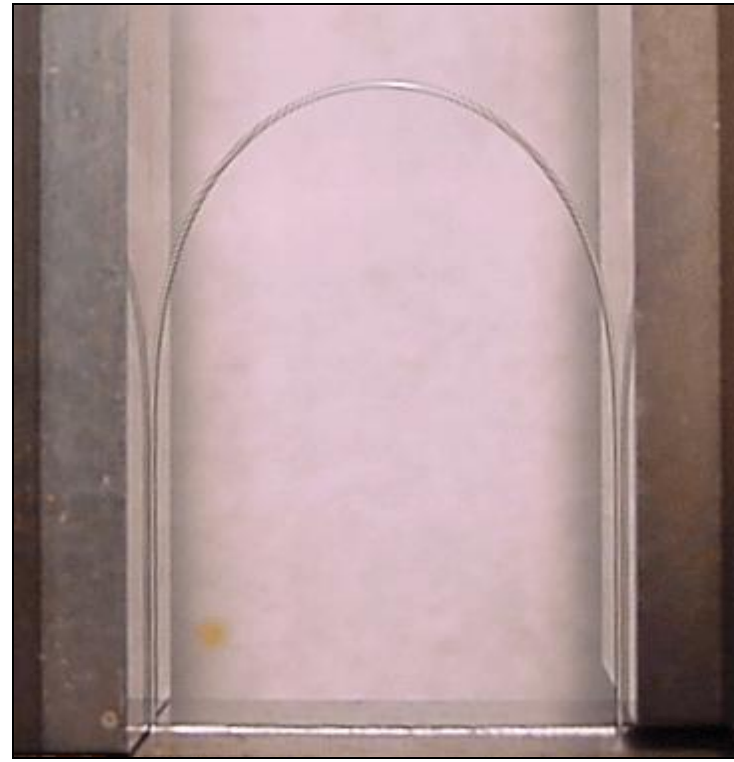
We have produced and tested pristine fibers





- “Pristine” 10 cm length fibers
- Fiber diameters ~125 mm.
- Fibers can be tested immediately.

We have measured failure strains using a Two-Point Bend technique

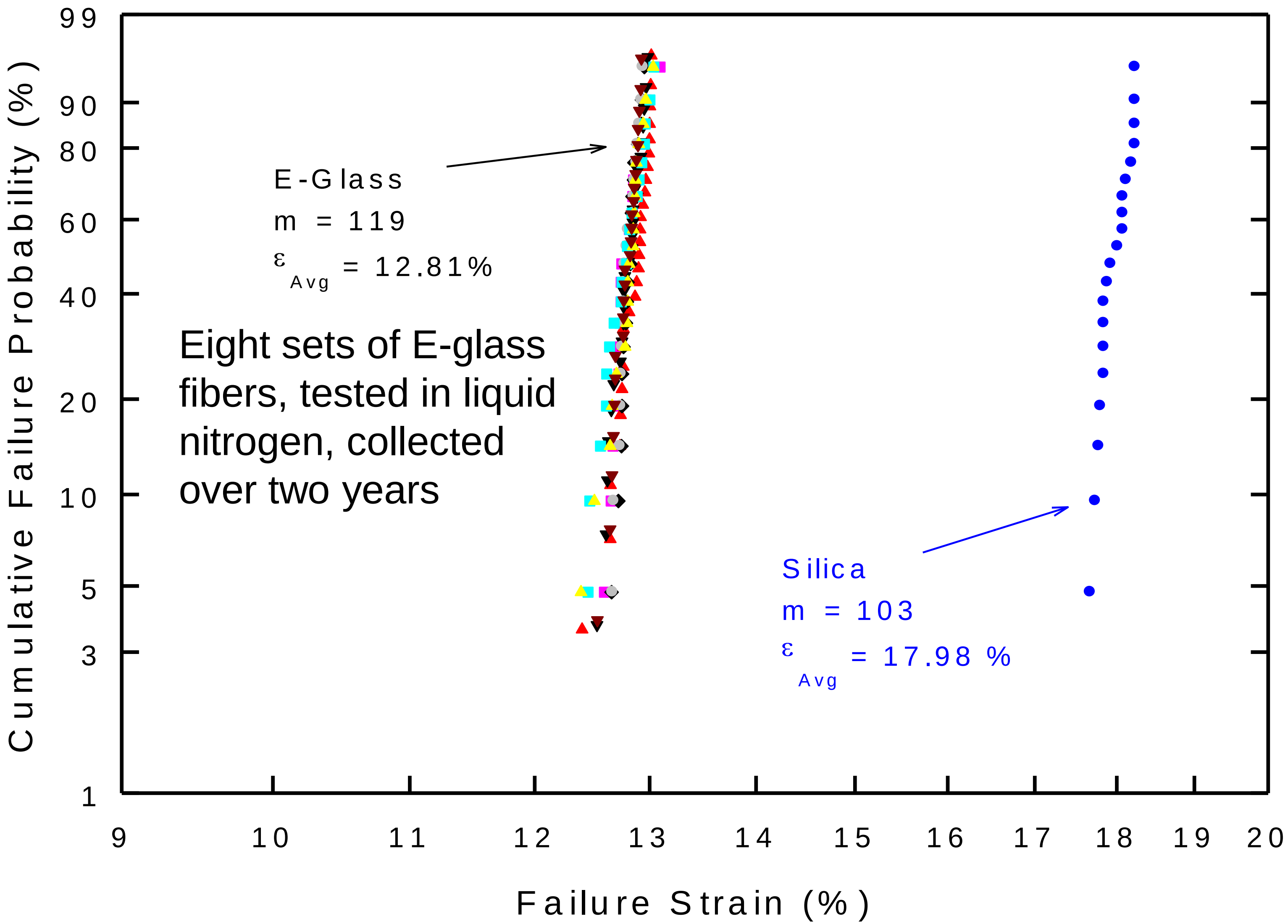


$$\varepsilon_f = \left(\frac{1.198 \cdot d}{D - d} \right)$$

- Face plate velocities: 1 – 10,000 mm/sec
- Liquid nitrogen, room temp/variable humidity.
- Small test volume (25-100mm gauge length).

*M.J. Matthewson, C.R. Kurkjian, S.T. Gulati, *J. Am. Cer. Soc.*, **69**, 815 (1986).

The inert failure strain measurements are reproducible



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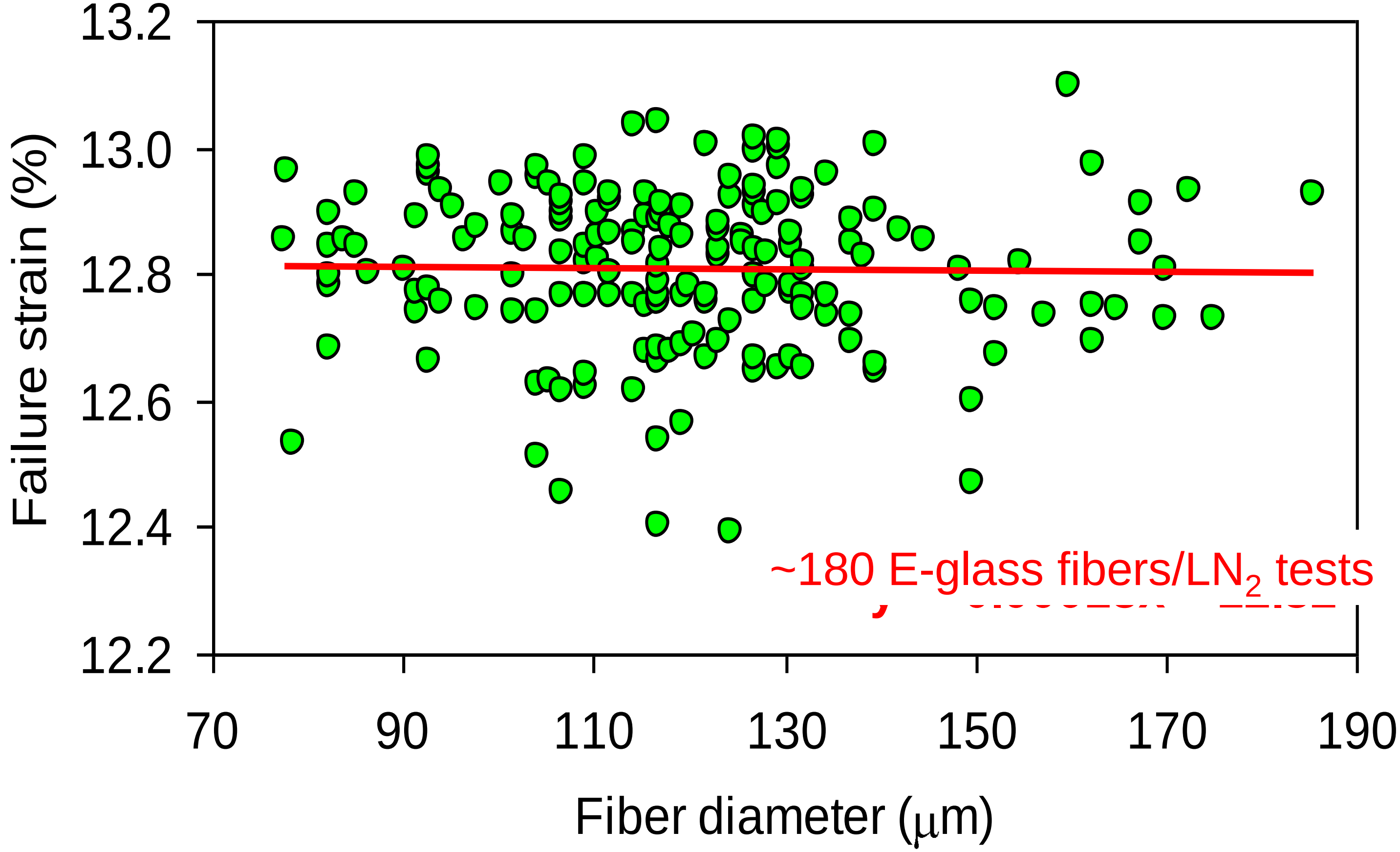
The inert failure strain measurements are intrinsic

Criteria for ‘intrinsic’ failure properties*

- Narrow failure distributions: s(failure) < s(fiber diameter)
- Failure property (strength, strain) independent of diameter

*Gupta and Kurkjian, JNCS 351 (2005) 2343.



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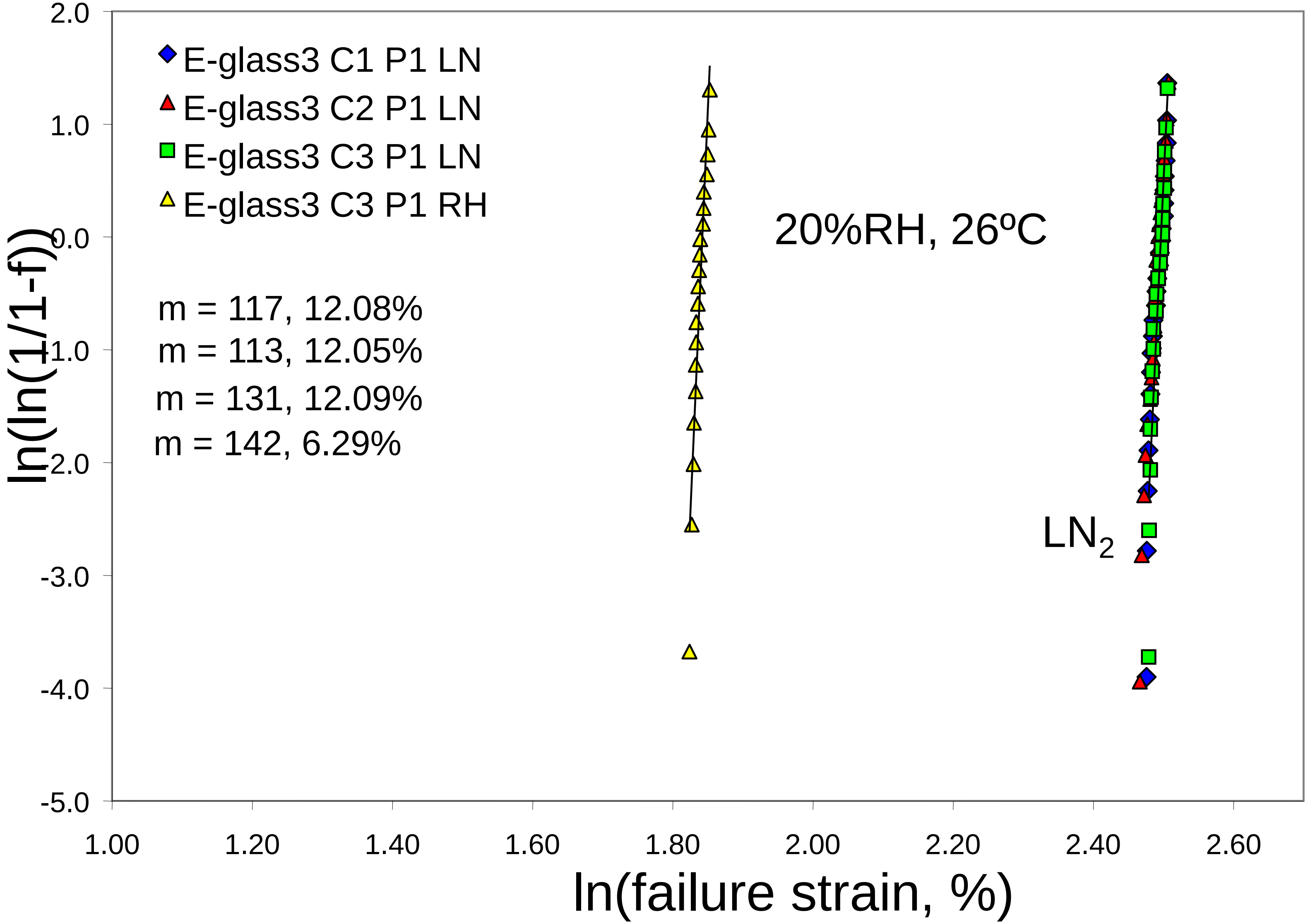
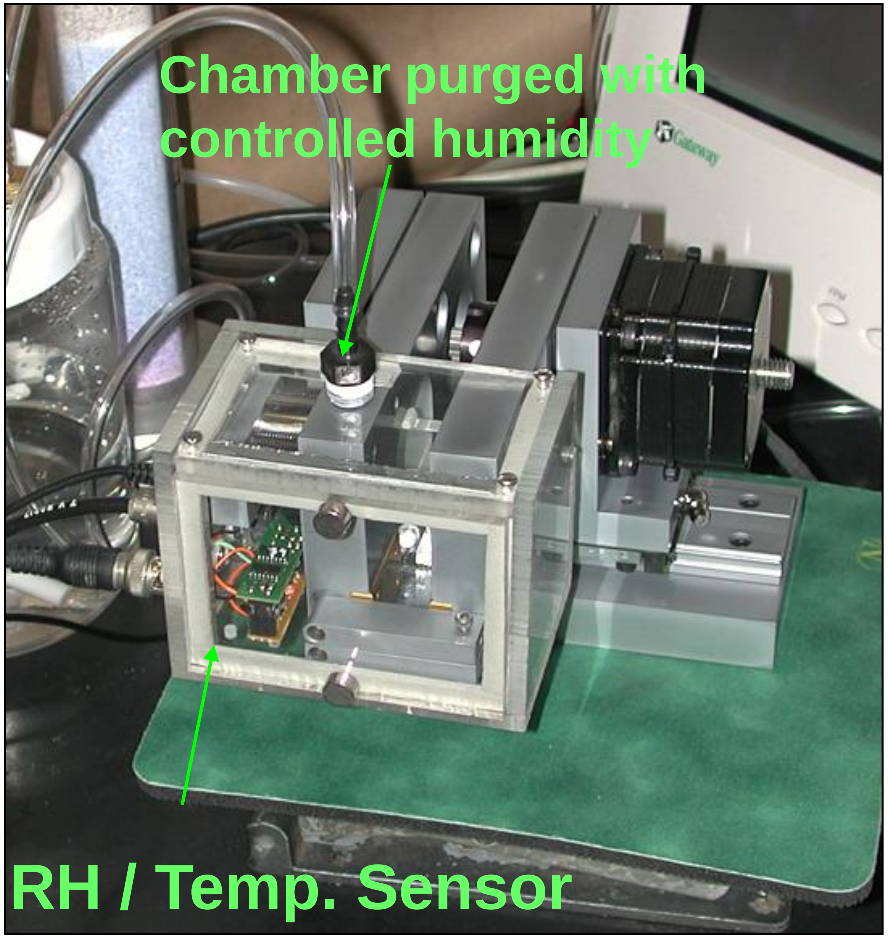
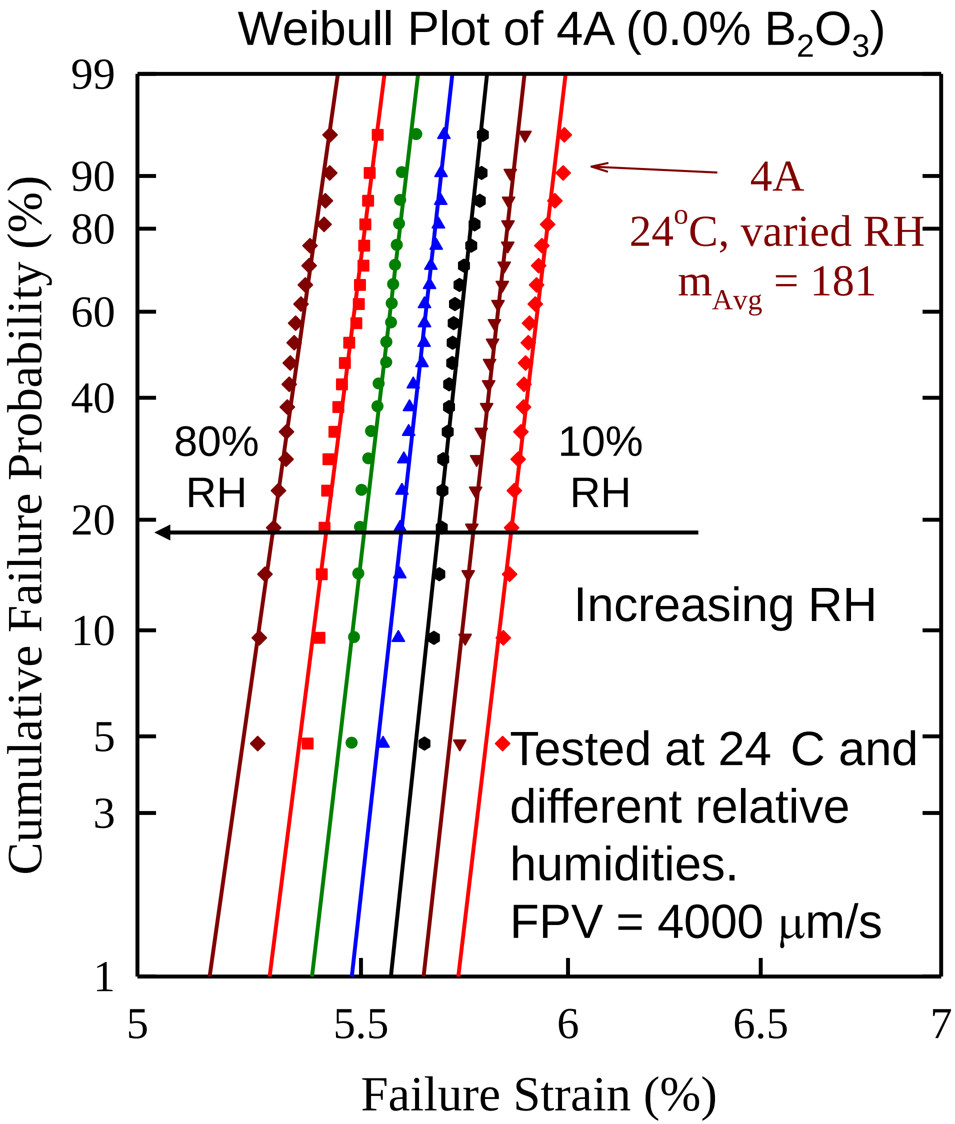
Fibers fail at lower strains in ambient conditions

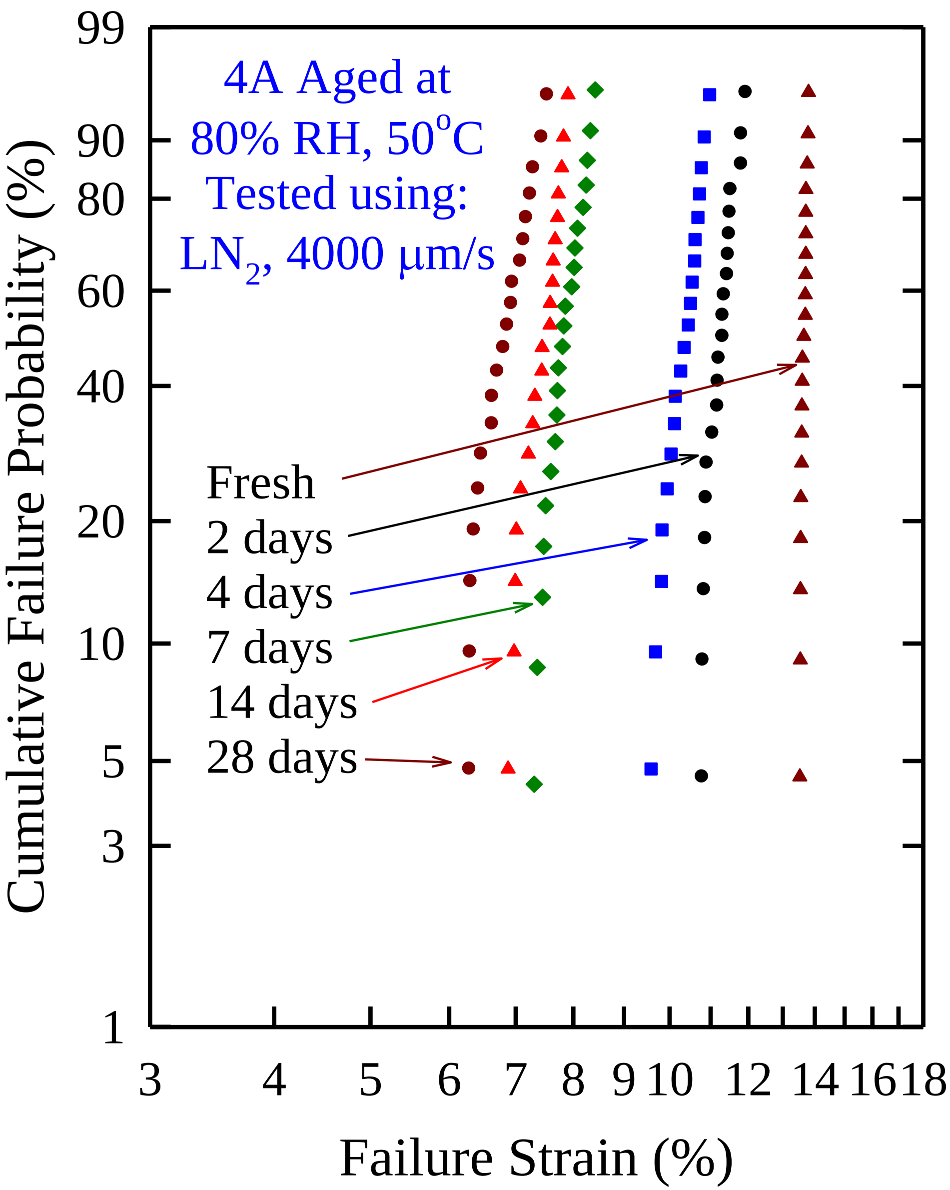


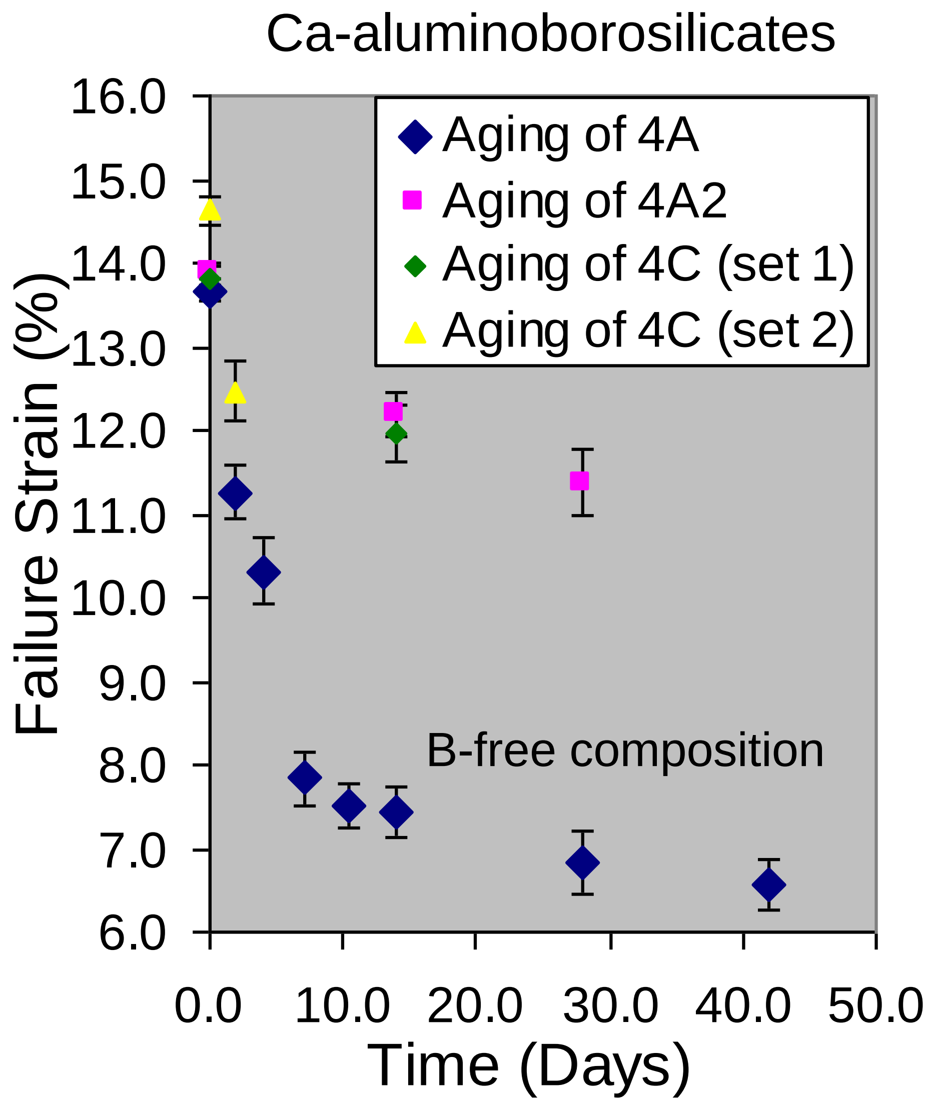
Fatigue effects can be characterized





Aging effects have also been characterized





What might inert 2pb studies tell us about the failure characteristics of silicate glasses?

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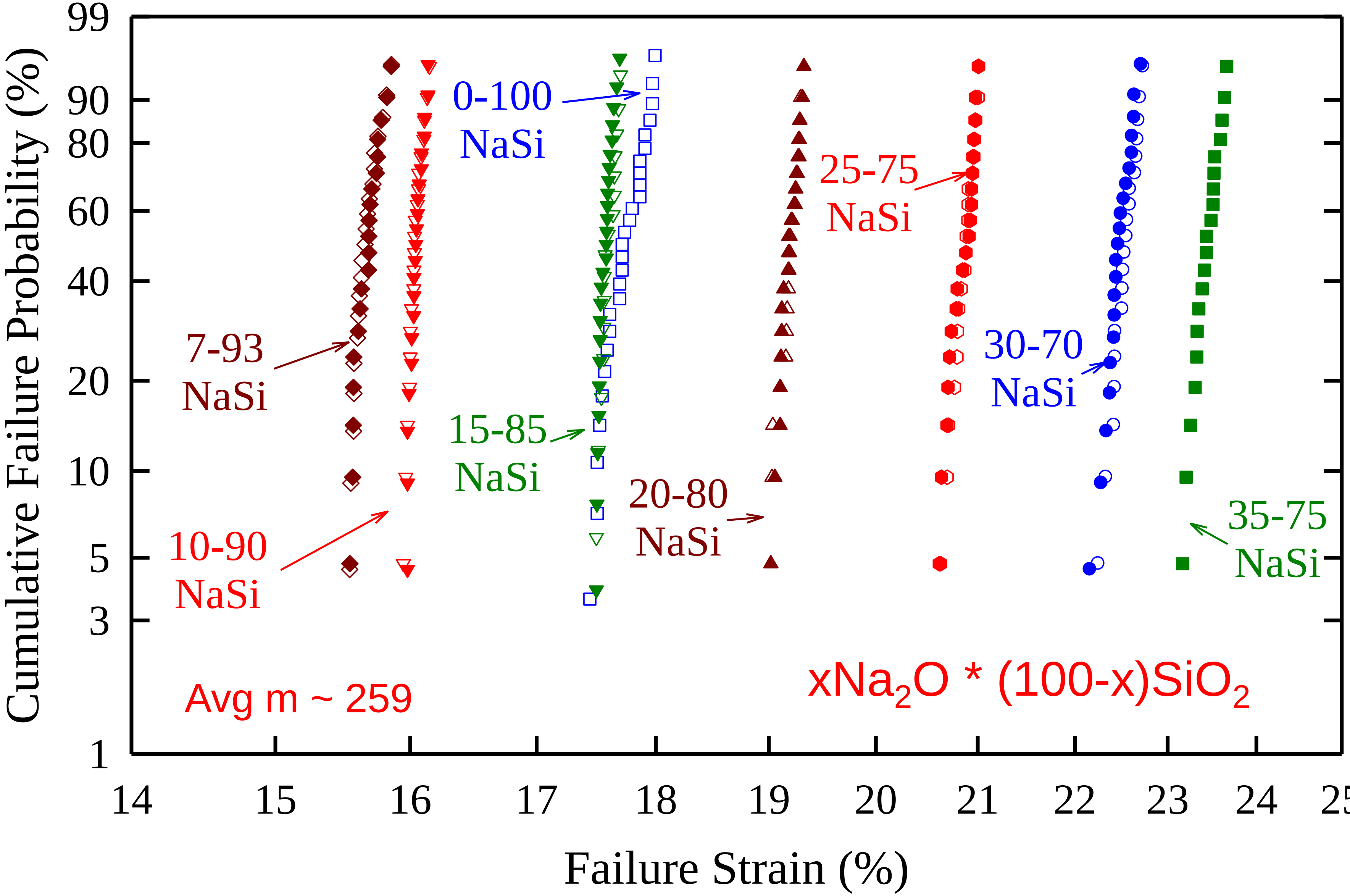
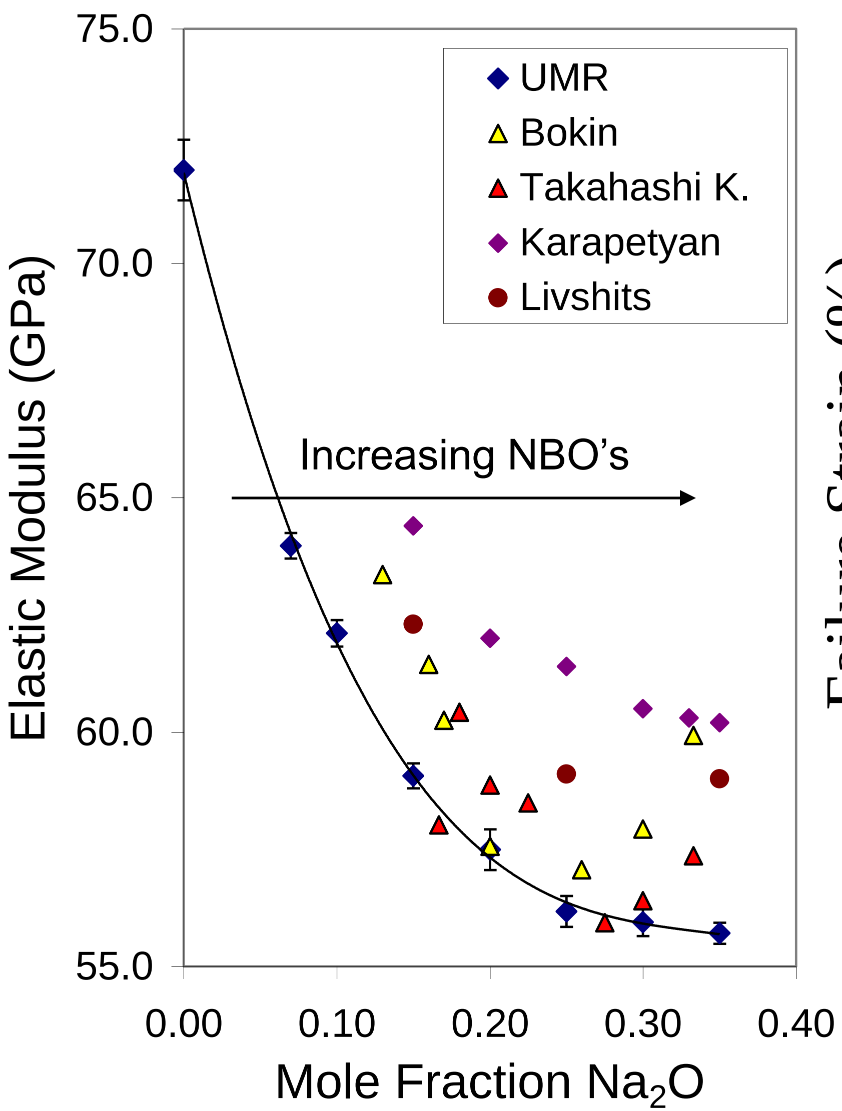
Compositions Studied

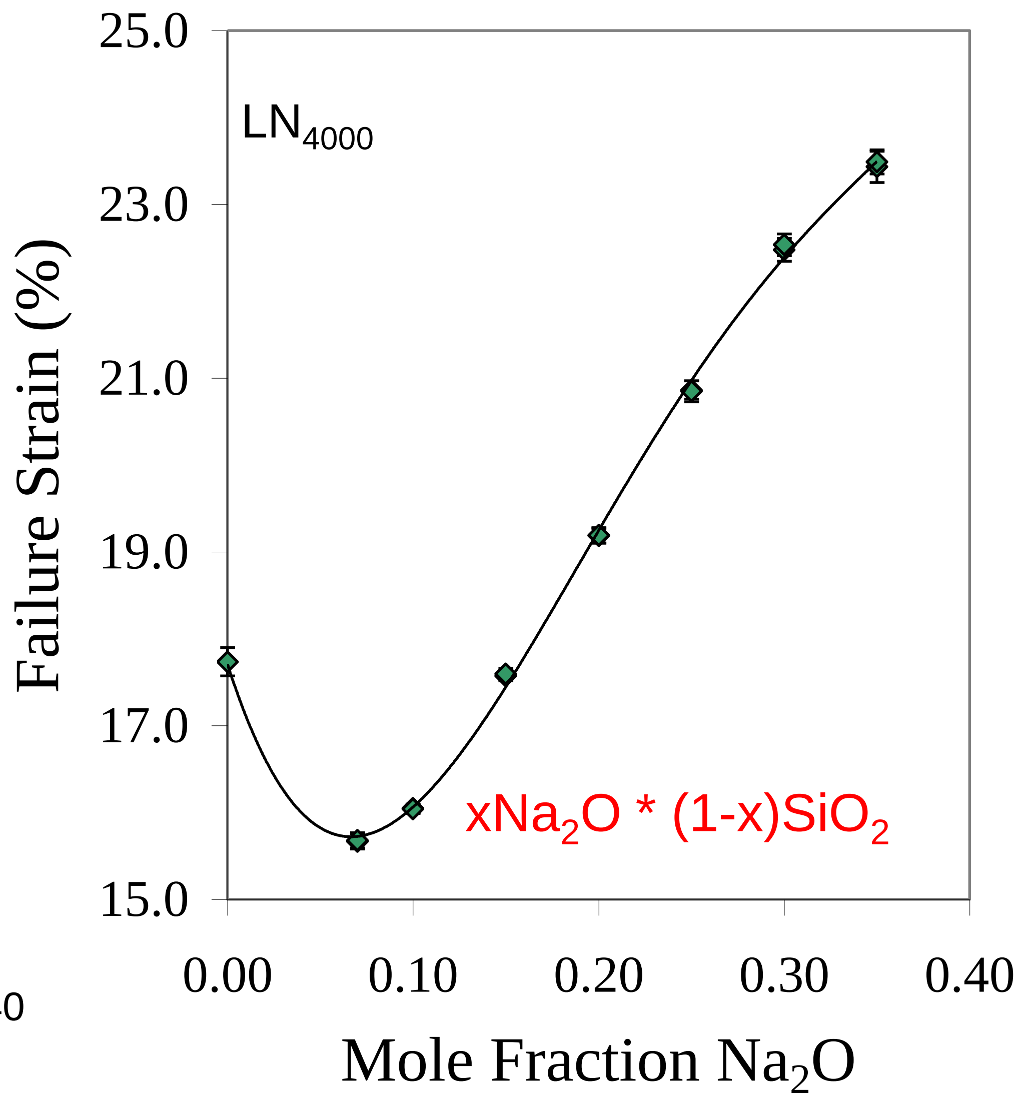
- xNa_2O * $(100-x)SiO_2$
  - x = 0, 7, 10, 15, 20, 25, 30, 35
- xK_2O * $(100-x)SiO_2$
  - x = 0, 4.5, 7, 10, 15, 20, 25
- $25Na_2O$ * xAl_2O_3 * $(75-x)SiO_2$
  - x = 0, 5, 10, 15, 20, 25, 30, 32.5
- xNa_2O * $yCaO$ * $(100-x-y)SiO_2$
  - *Compositions studied by Ito, et al.*

Na-silicate inert failure strains depend on composition



Sodium silicate properties





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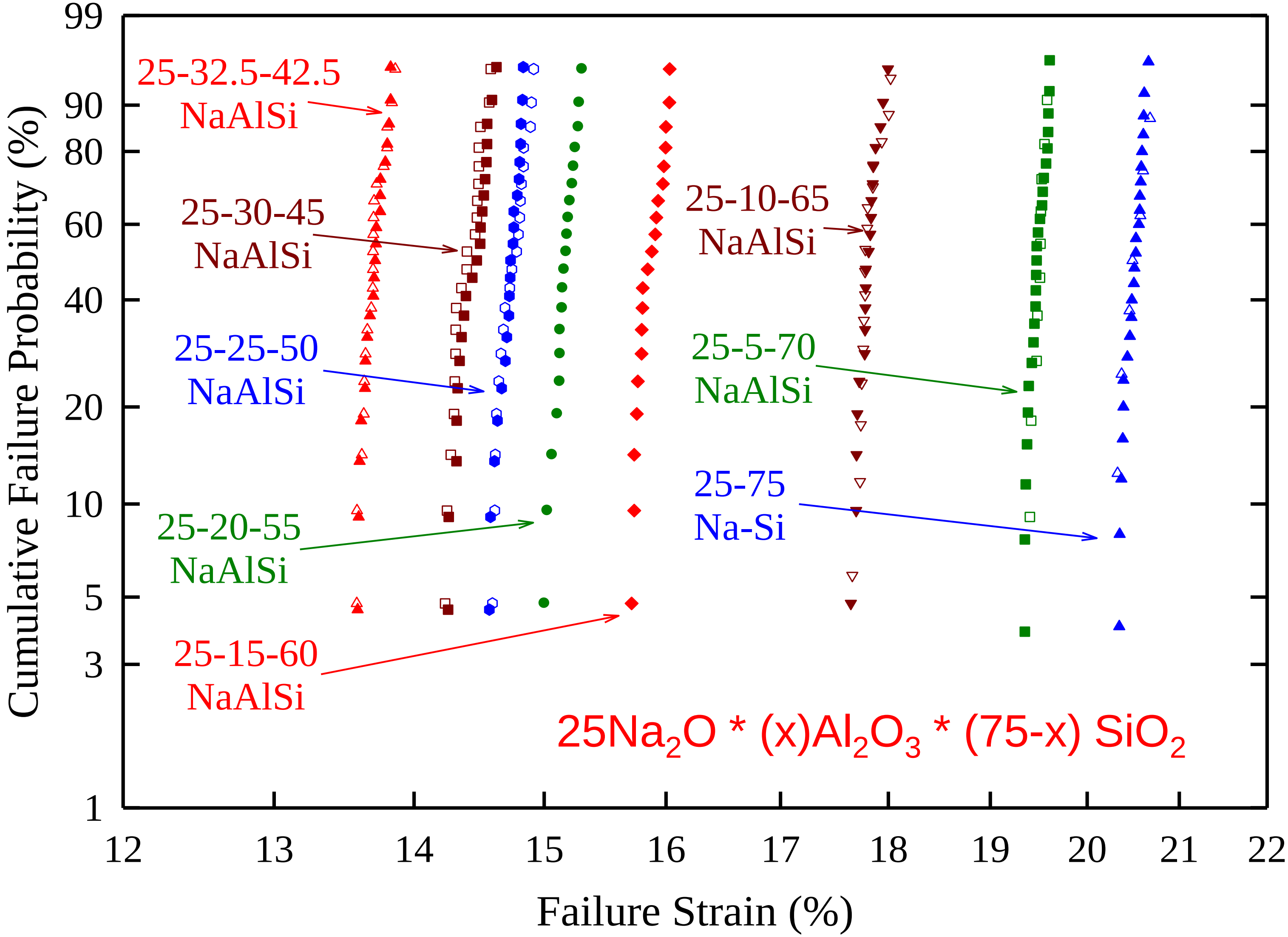
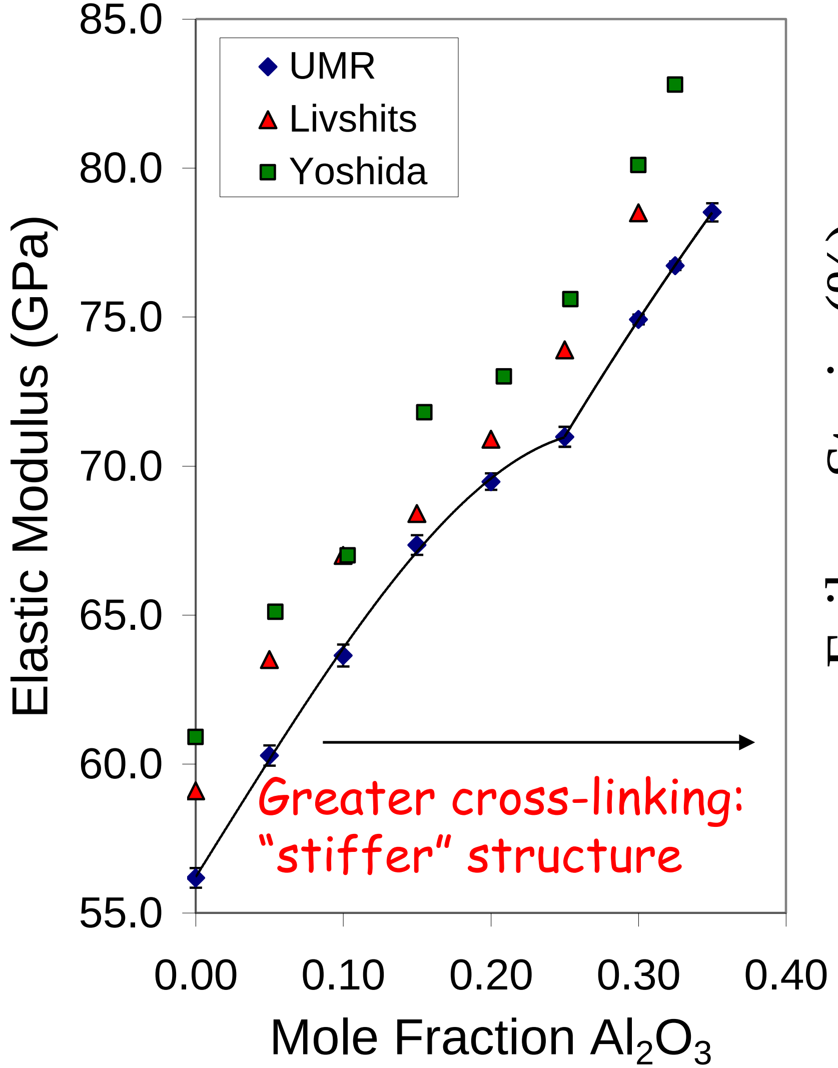
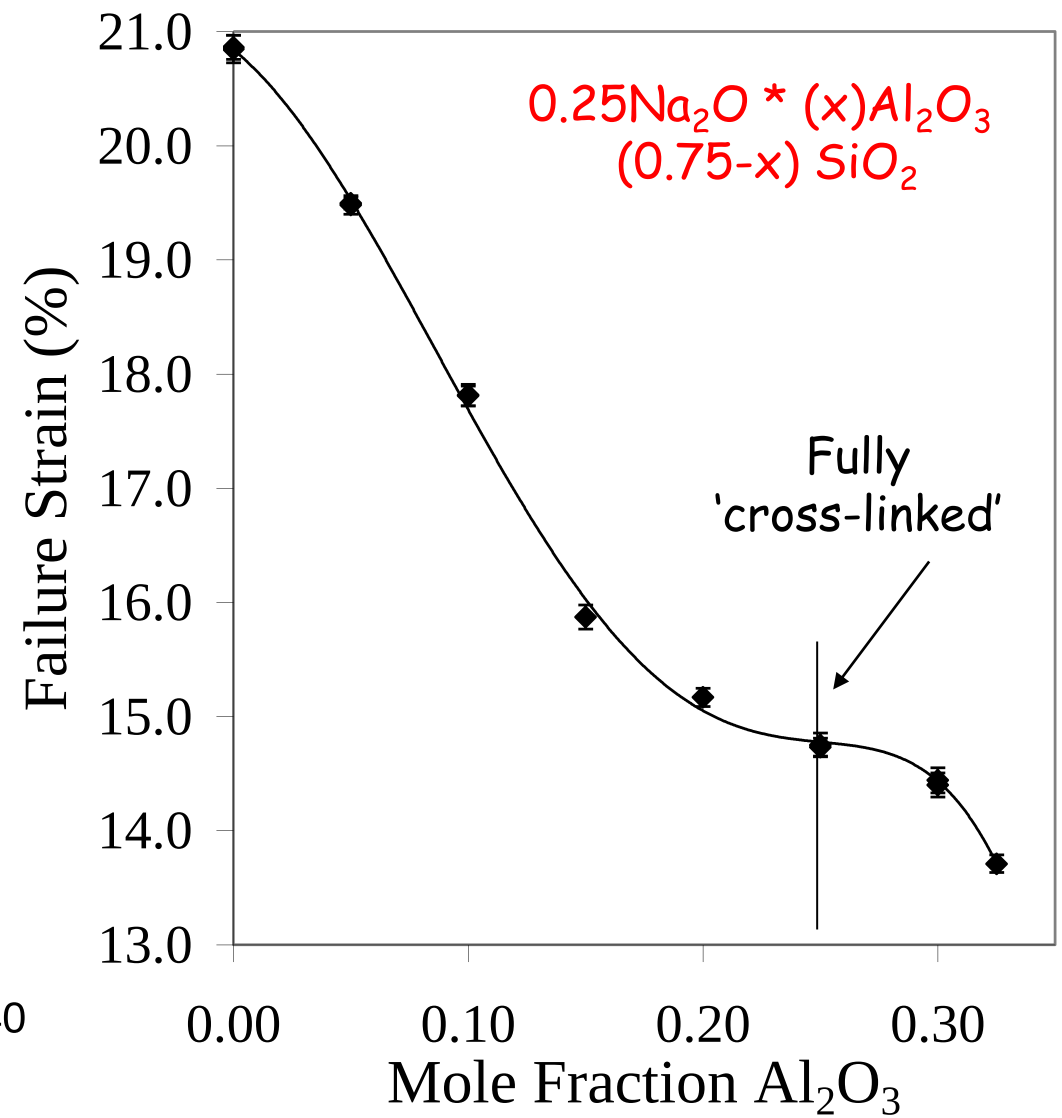
Na-Al-silicate inert failure strains depend on composition



Na-Al-silicate properties depend on structure





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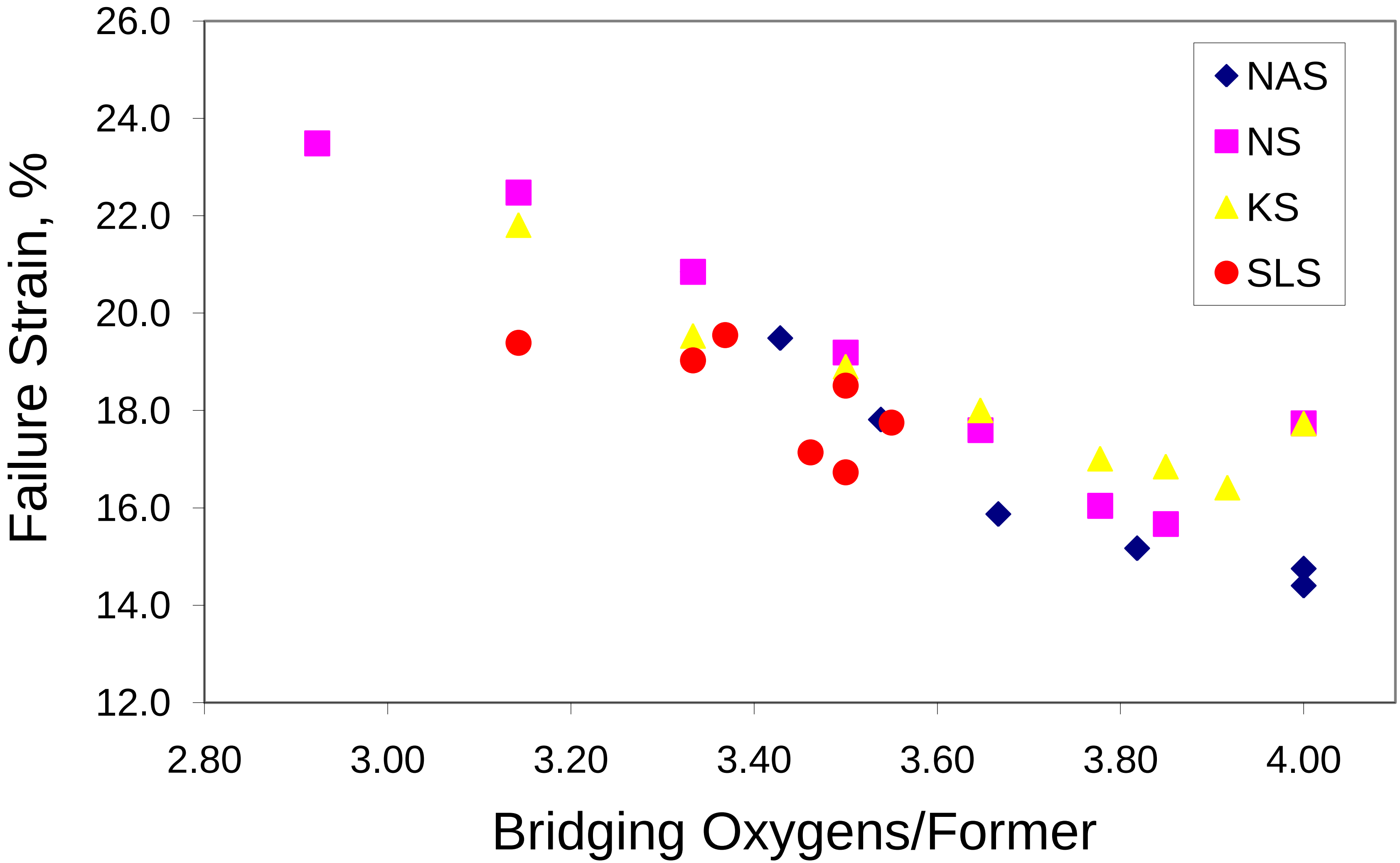
Inert failure strain decreases for 'cross-linked' structures



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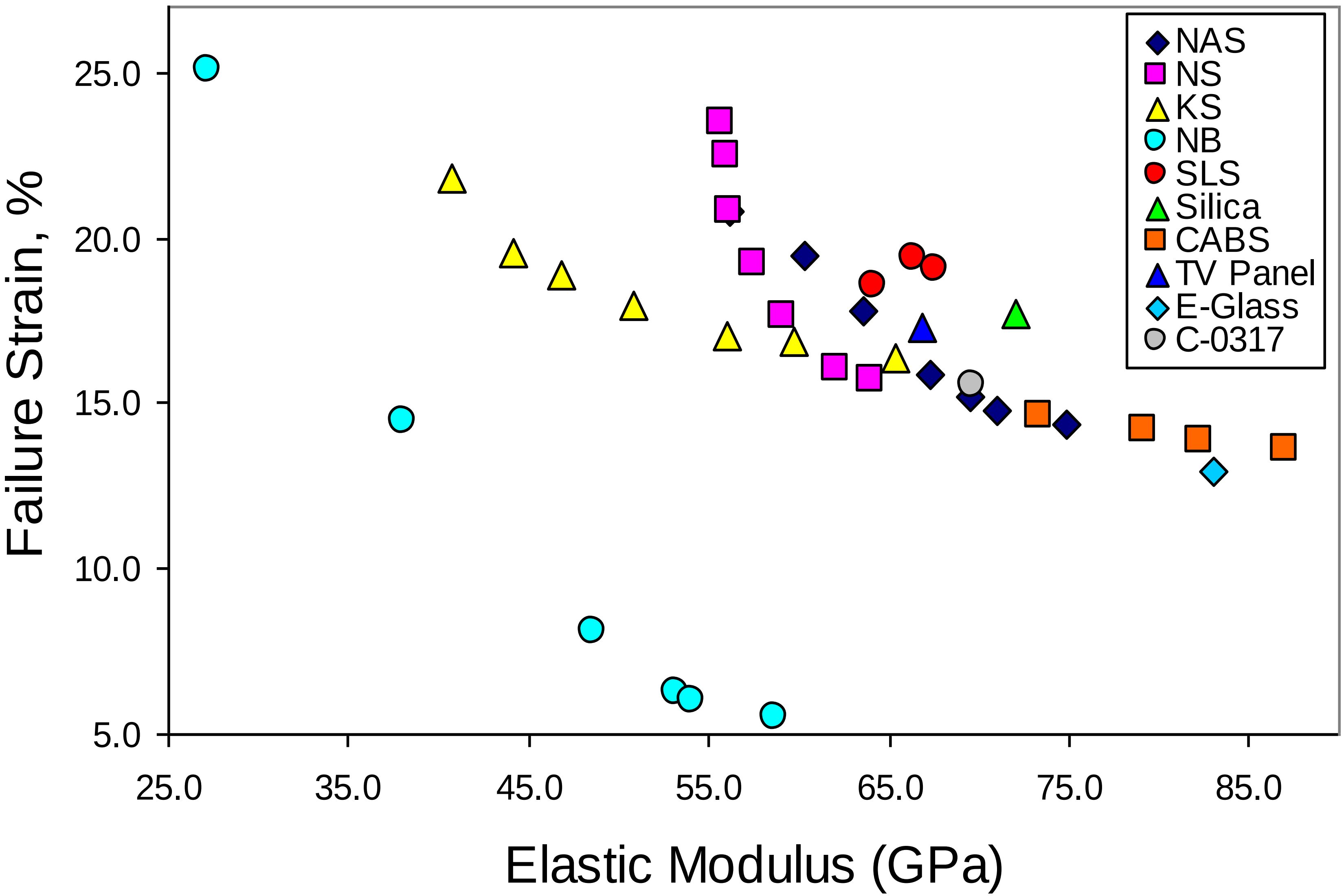
Failure strain depends on elastic modulus



Do these measurements provide information about the strength of glass?

…depends on what we know about the elastic modulus

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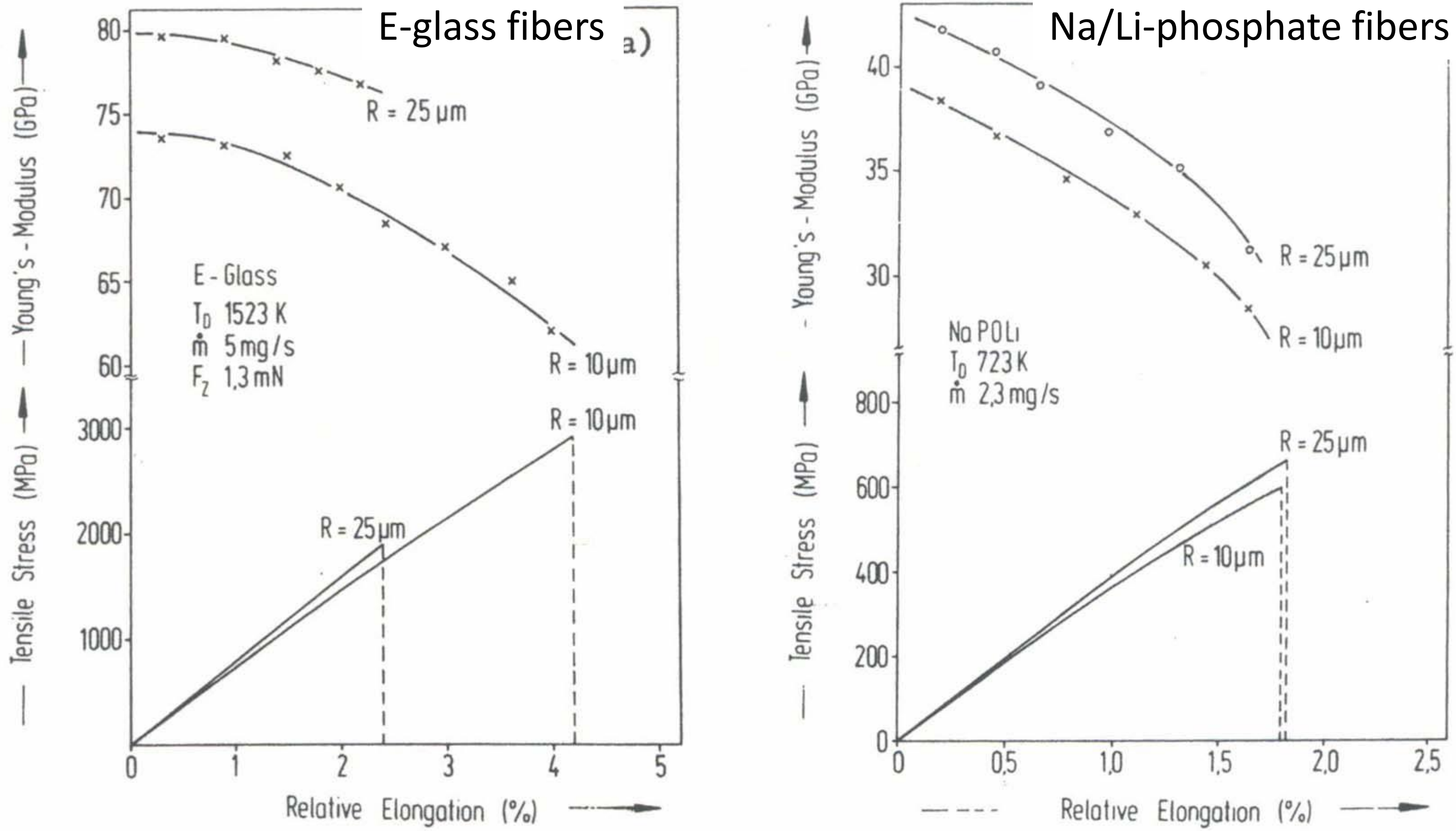
Elastic modulus depends on strain

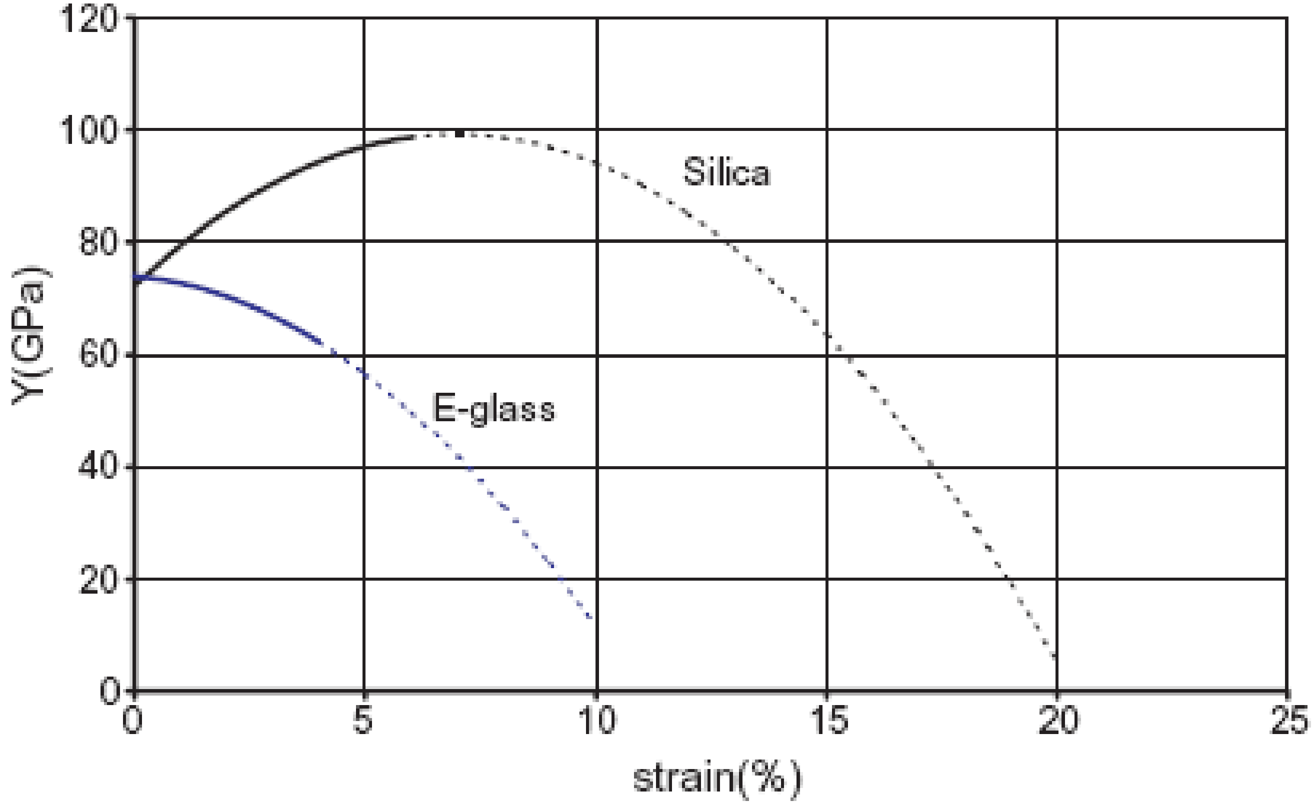


Bruckner, *Strength of Inorg. Glass* 1986

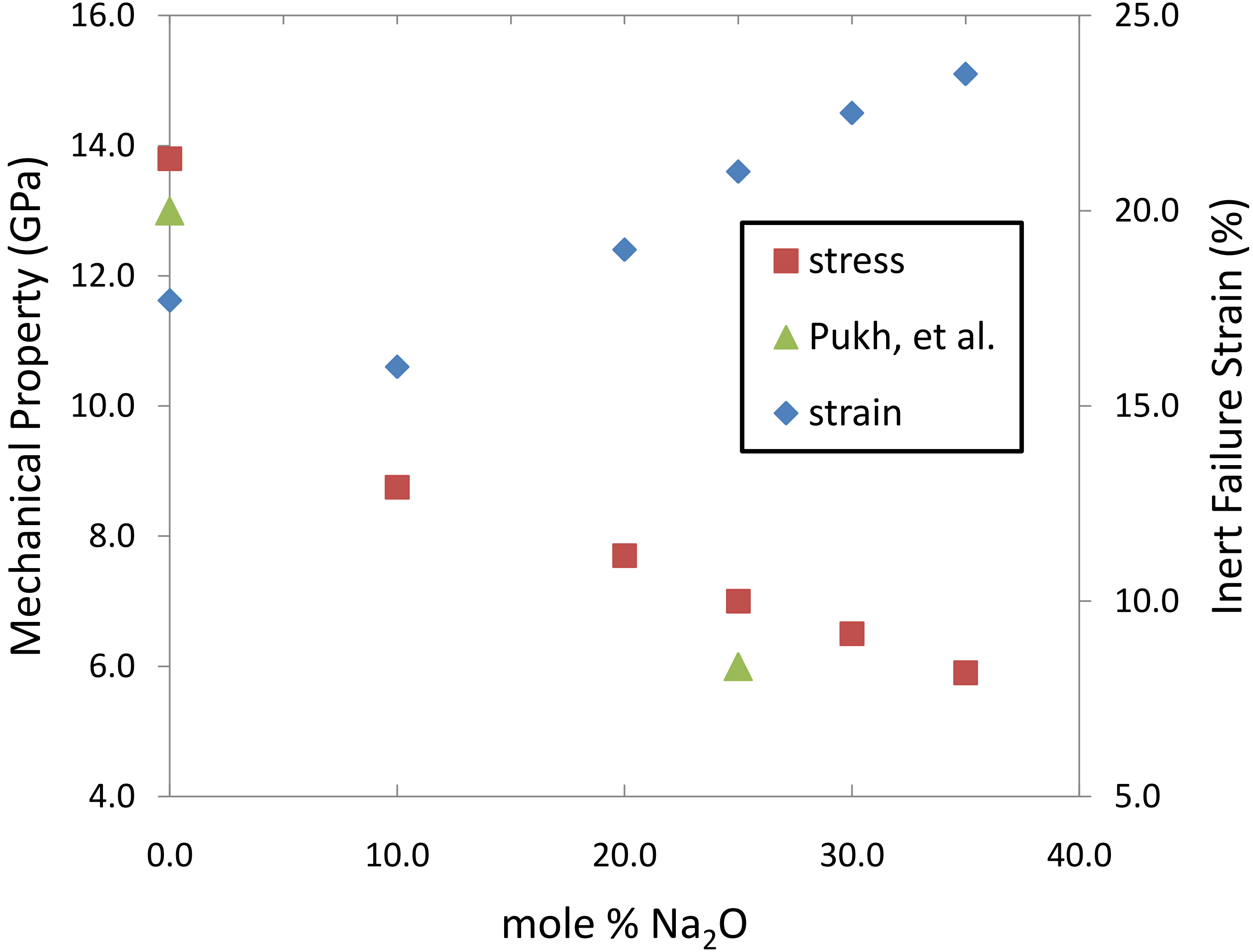
Strain dependence of modulus has been modeled

Converting failure strain to failure stress requires knowledge of $Y(\varepsilon)$: Gupta and Kurkjian, JNCS 351 (2005) 2343

$$Y(\varepsilon) = Y_0+Y_1\varepsilon+(Y_2/2)\varepsilon^2 \; ; \; \sigma_f = \varepsilon_f[(2/3)Y_0+(Y_1/6)\varepsilon_f]$$

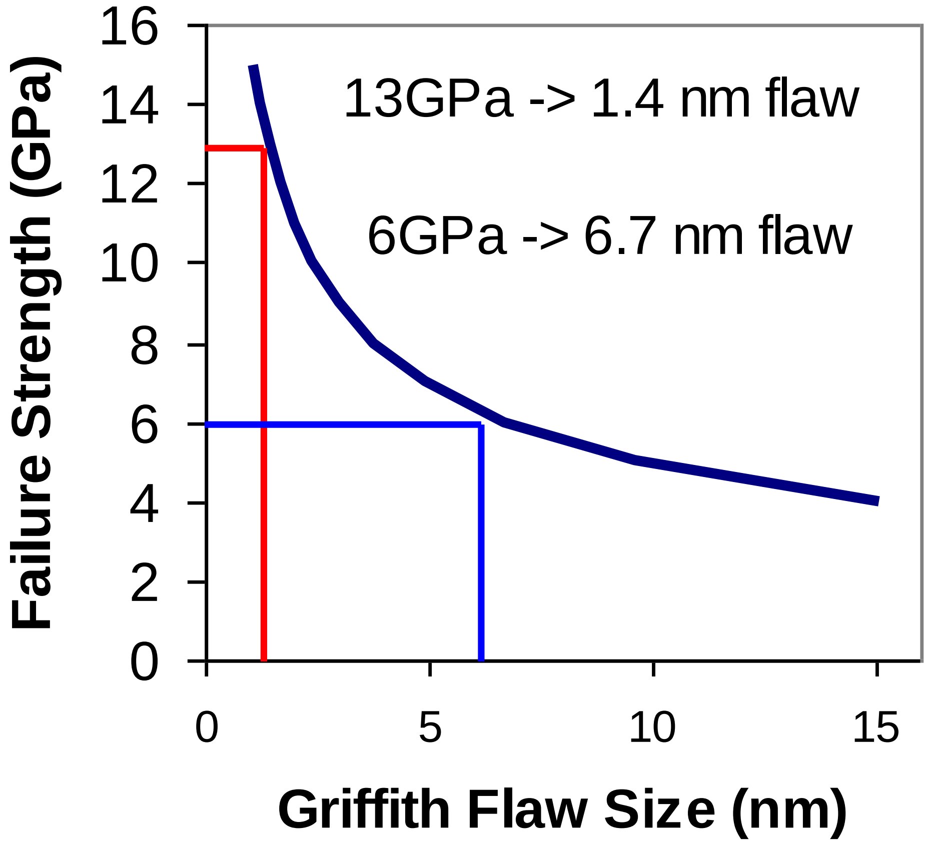


Failure strengths can be calculated if Y(ε) is known



What role is played by ‘critical flaws’?

- There are no apparent surface heterogeneities.
- If Griffith flaws are responsible for low strengths, they will be in the range of 2-7 nm, depending on the flaw (stress concentrator) geometry.



$$\sigma_f = \left(\frac{2E\gamma}{\pi c} \right)^{\frac{1}{2}}$$

Recall processing effects

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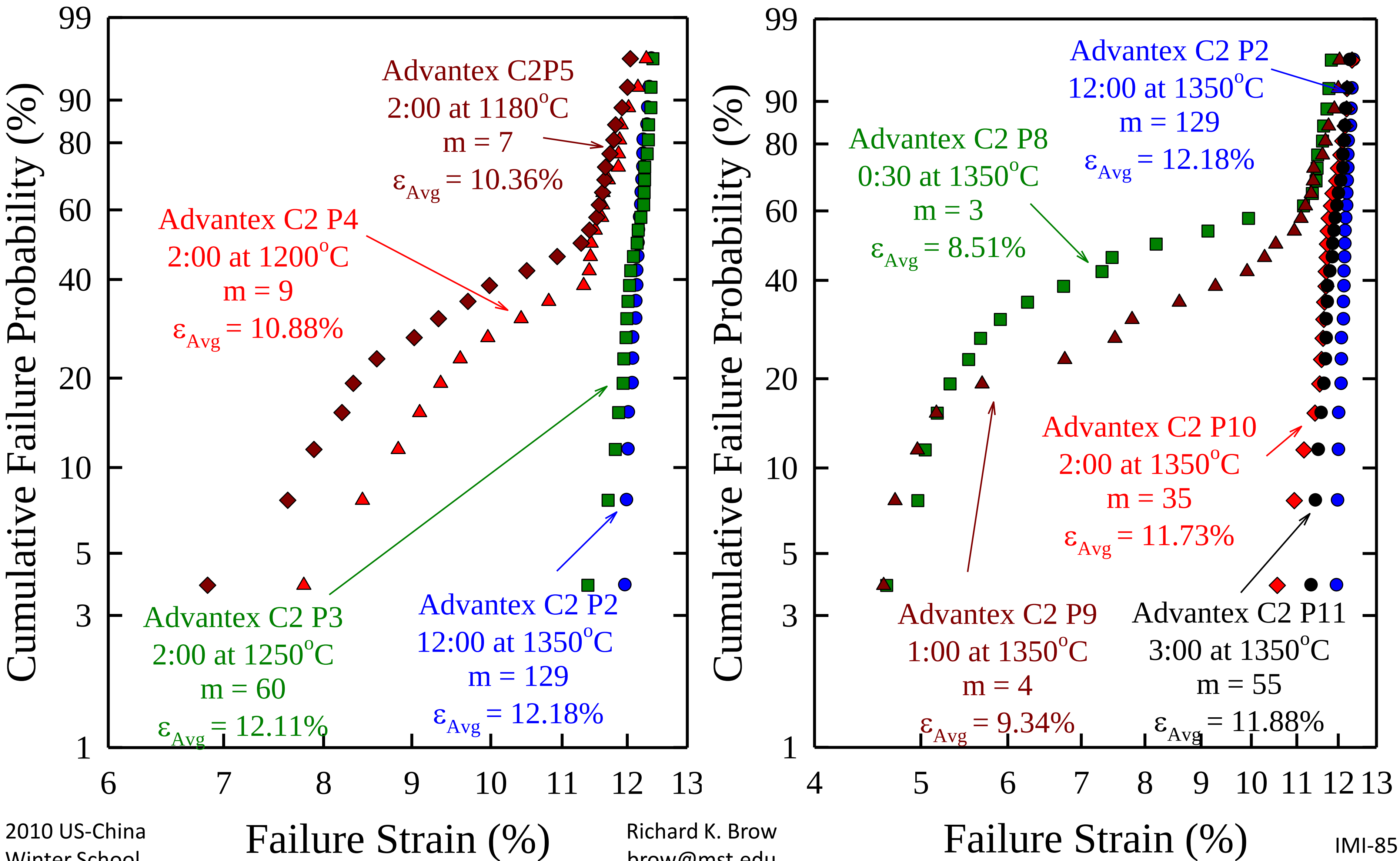
Advantex Failure Strains

Weibull distributions of fibers drawn after different melt histories. Weibull modulus (m), average failure strain (ε_{Avg}), and melt history are reported for each data set.



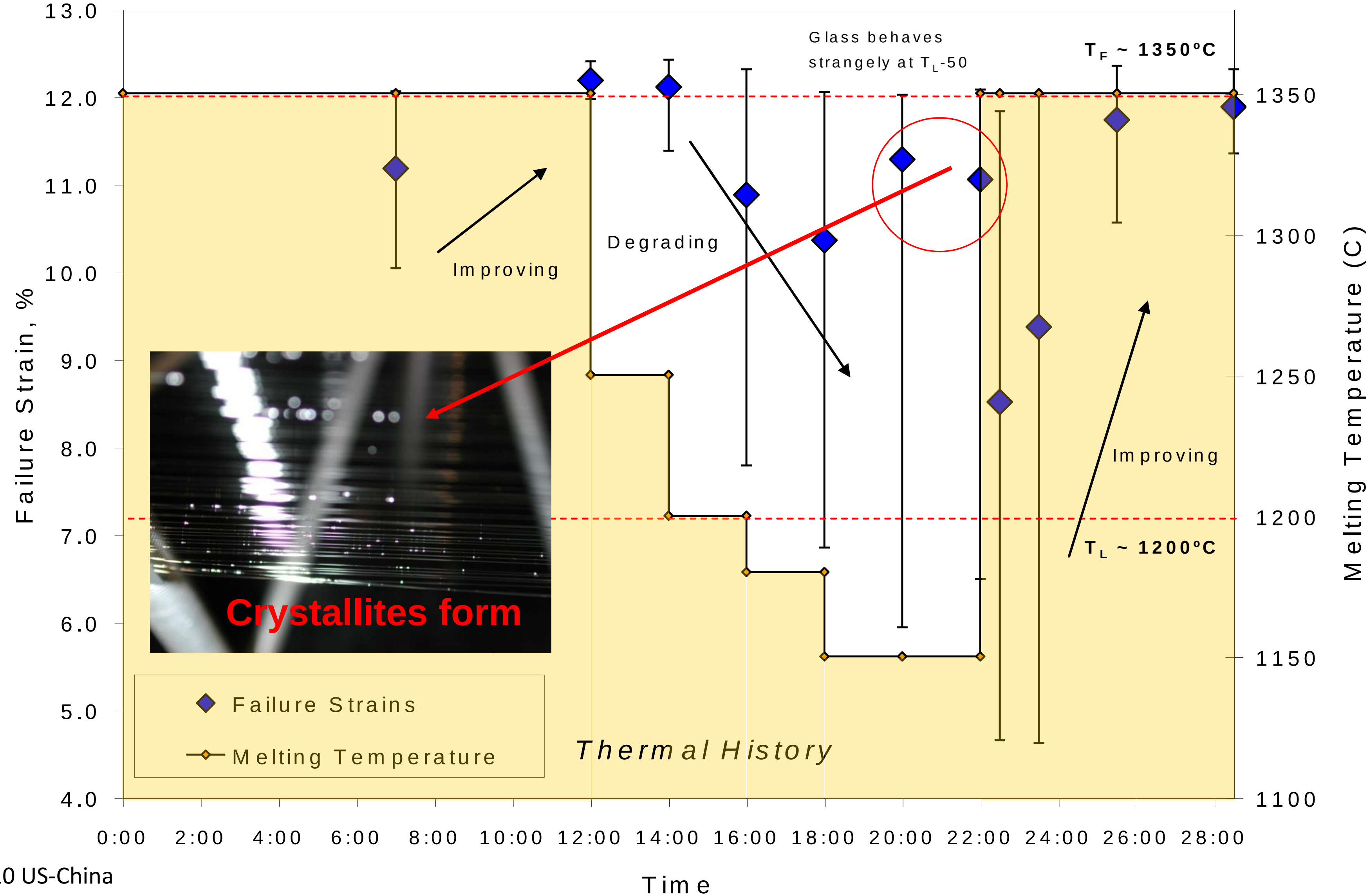
Some questions related to Prof. Sen's lecture:

What type of heterogeneities might account for these distributions in failure strains?

What techniques could you use to characterize these heterogeneities?

Advantex Thermal History Summary

When the glass was melted at 1350ºC, the failure strain distributions narrow with time. Failure strain distributions begin to broaden when melts are cooled to T_L+50ºC.



How does glass break?

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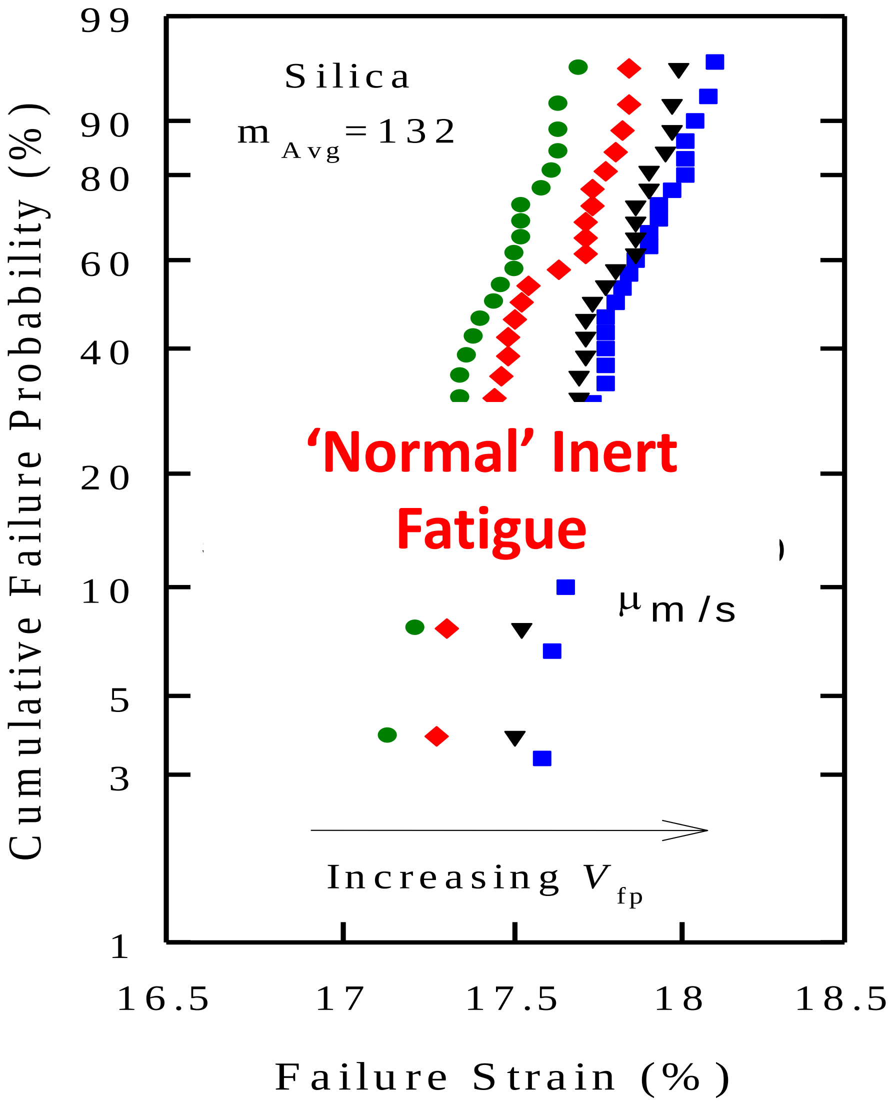
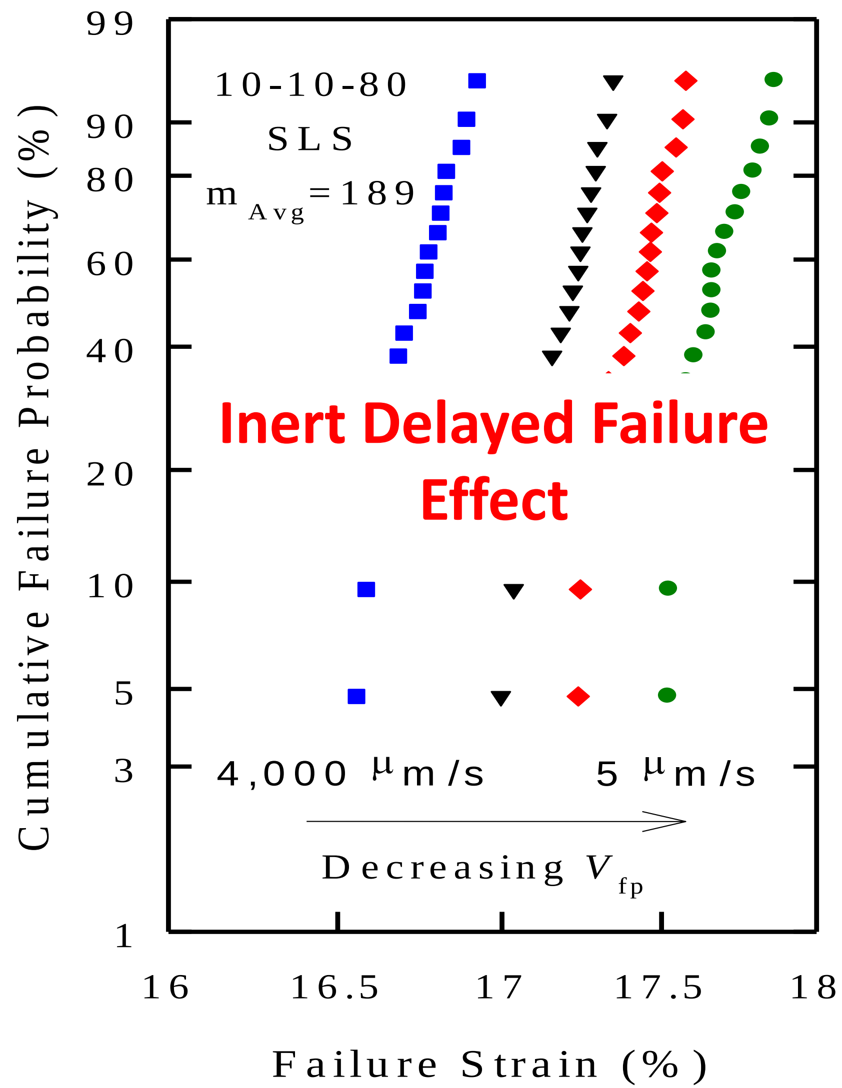
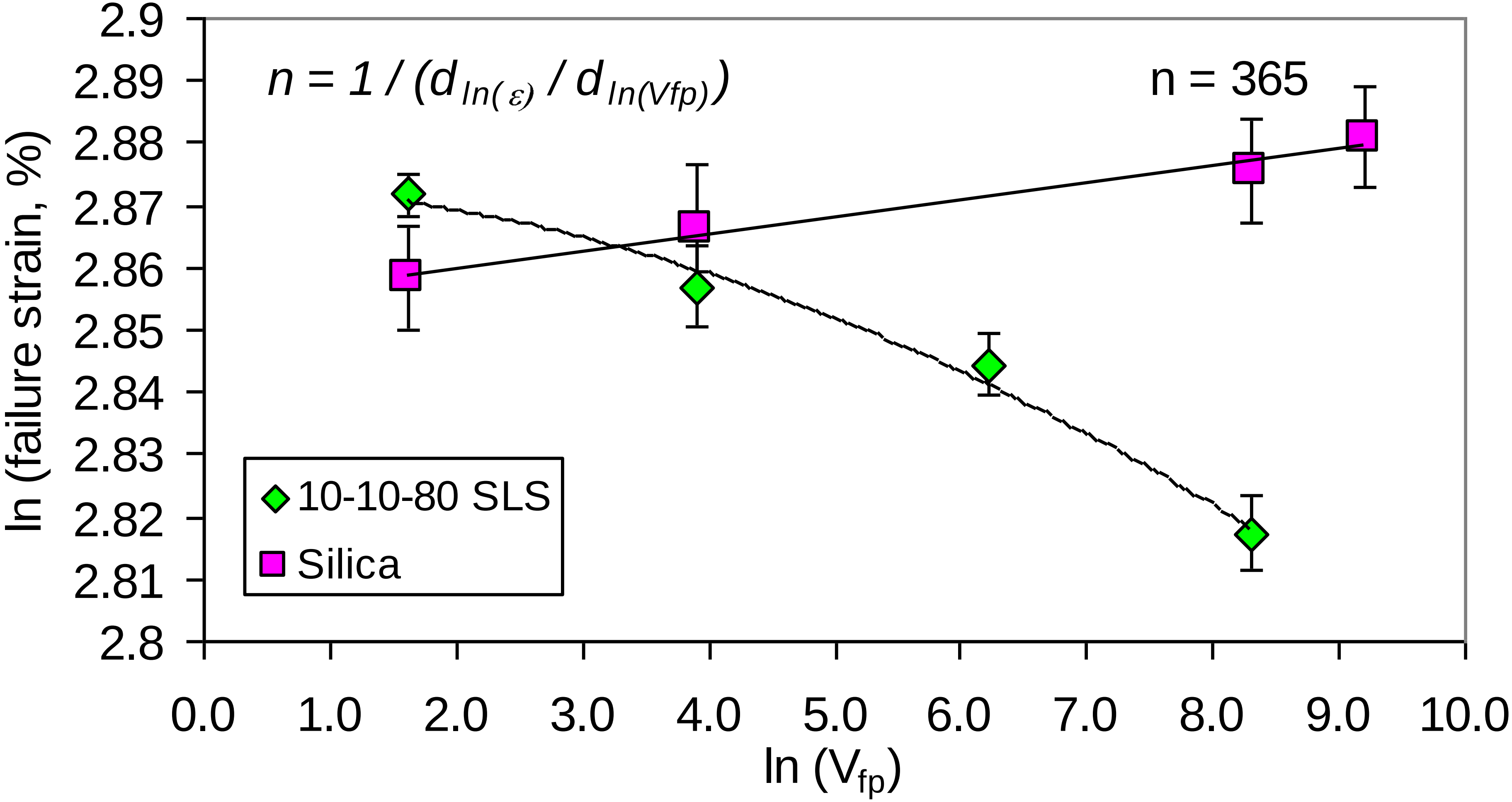
Inert 'failure rate' studies

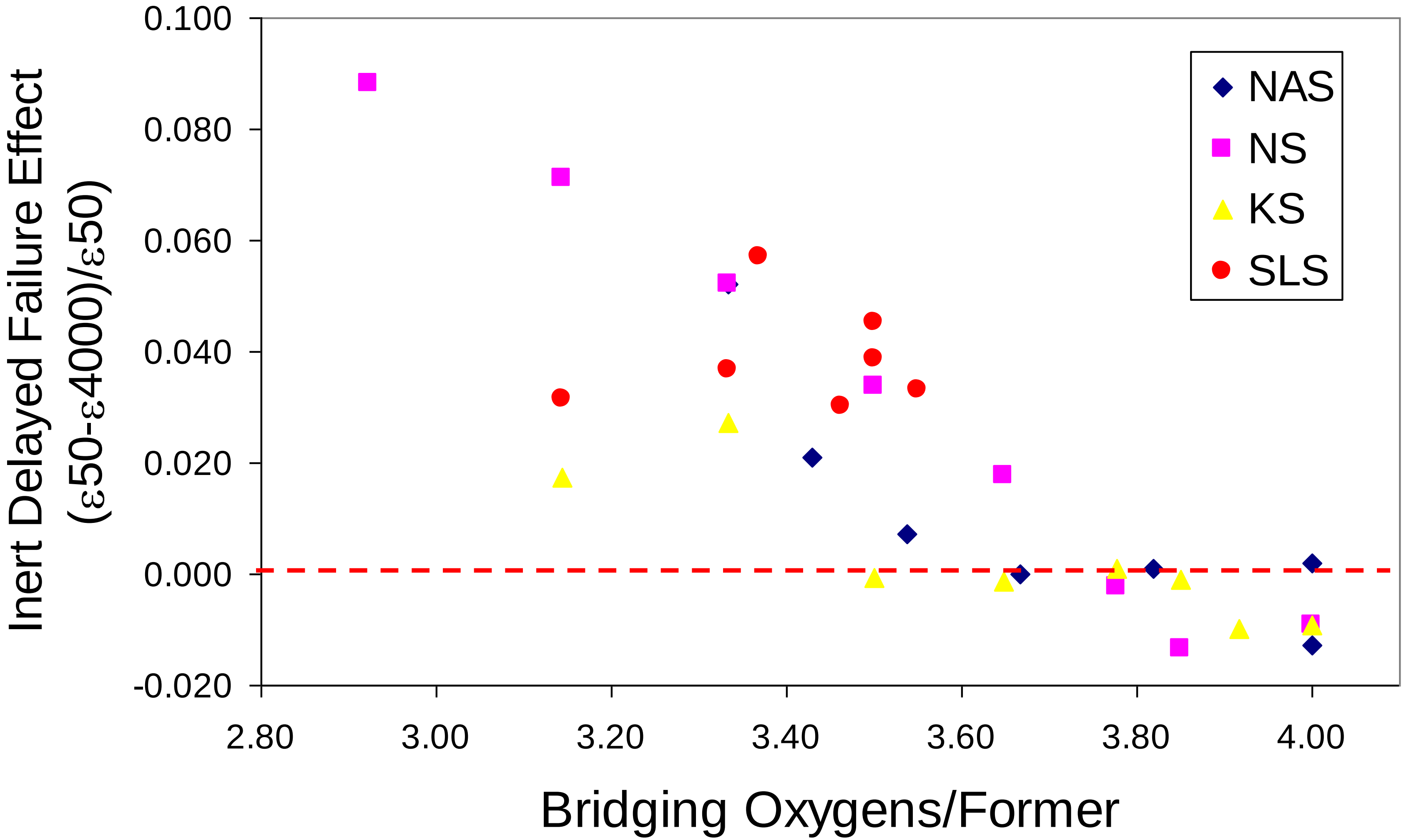




Inert 'failure rate' studies



The inert delayed failure effect depends on structure



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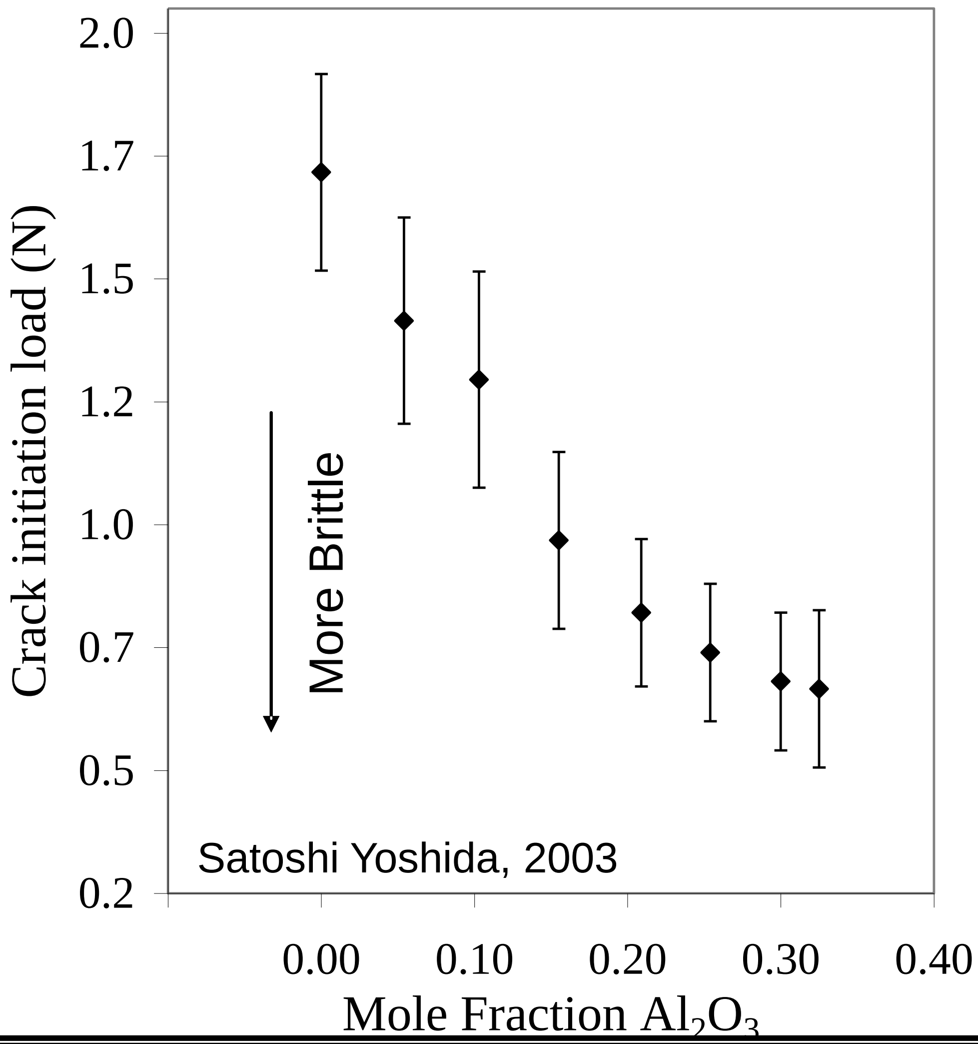
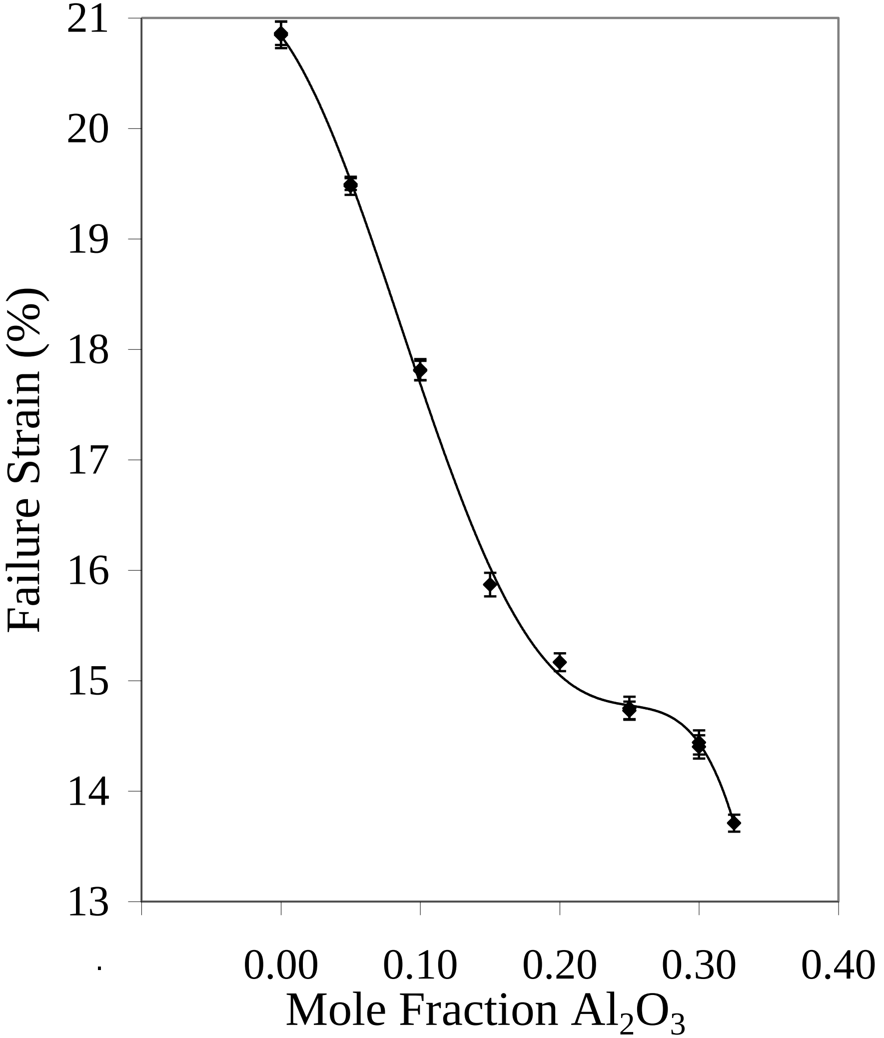
Failure strain measurements also correlate with crack initiation loads

$0.25Na_2O * (x)Al_2O_3 * (0.75\text{-}x) SiO_2$





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Failure strain measurements may provide information about 'less brittle' glasses

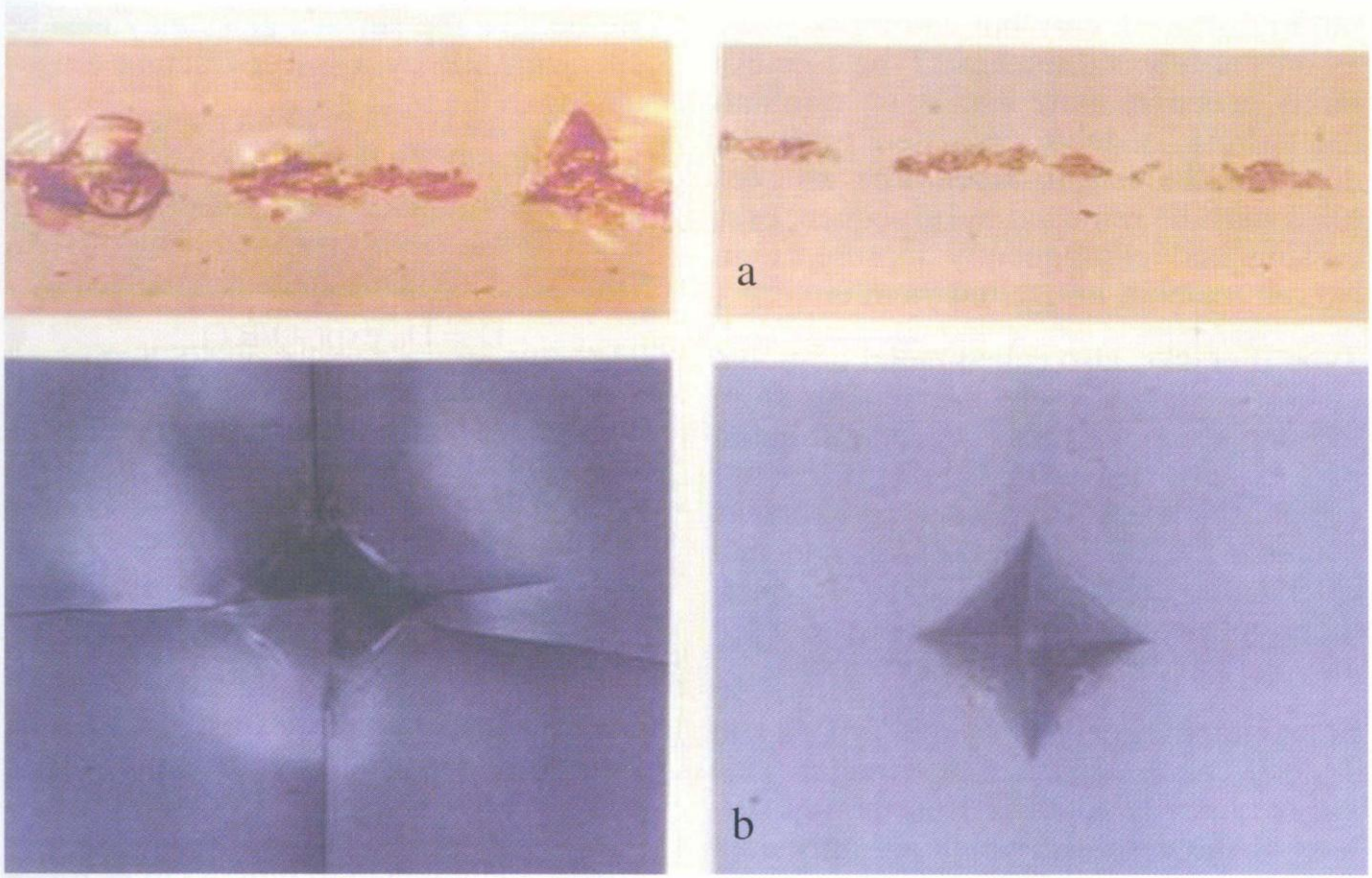


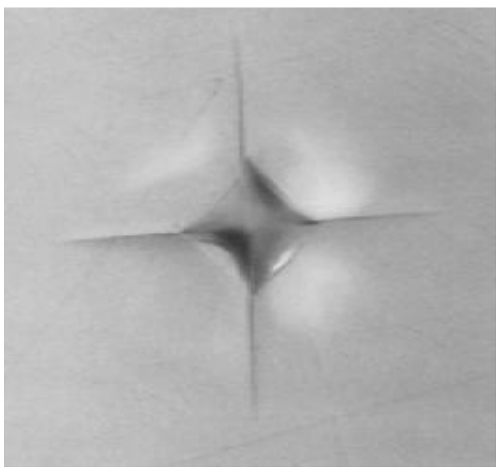
Figure 4 Micrographs of surfaces scratched by steel roller cutter (**a**) and indented by a diamond tool (**b**) at (one)1kg load for a commercial window glass and a new less brittle glass.

Setsuro Ito, 2002

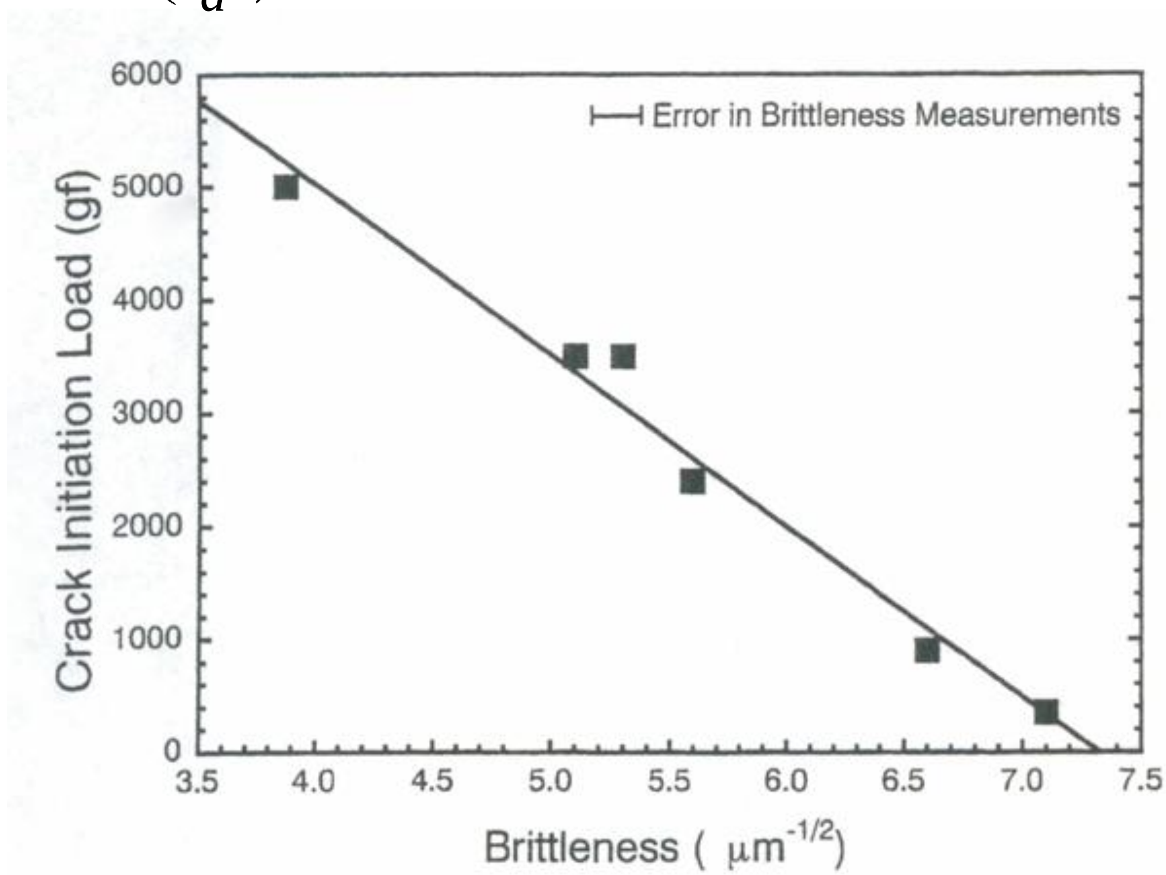
“Brittleness parameter” has been determined from indentation measurements

$$\text{Brittleness} \equiv B = 2.39\ P^{1/4}\left(\frac{C}{a}\right)^{3/2}$$

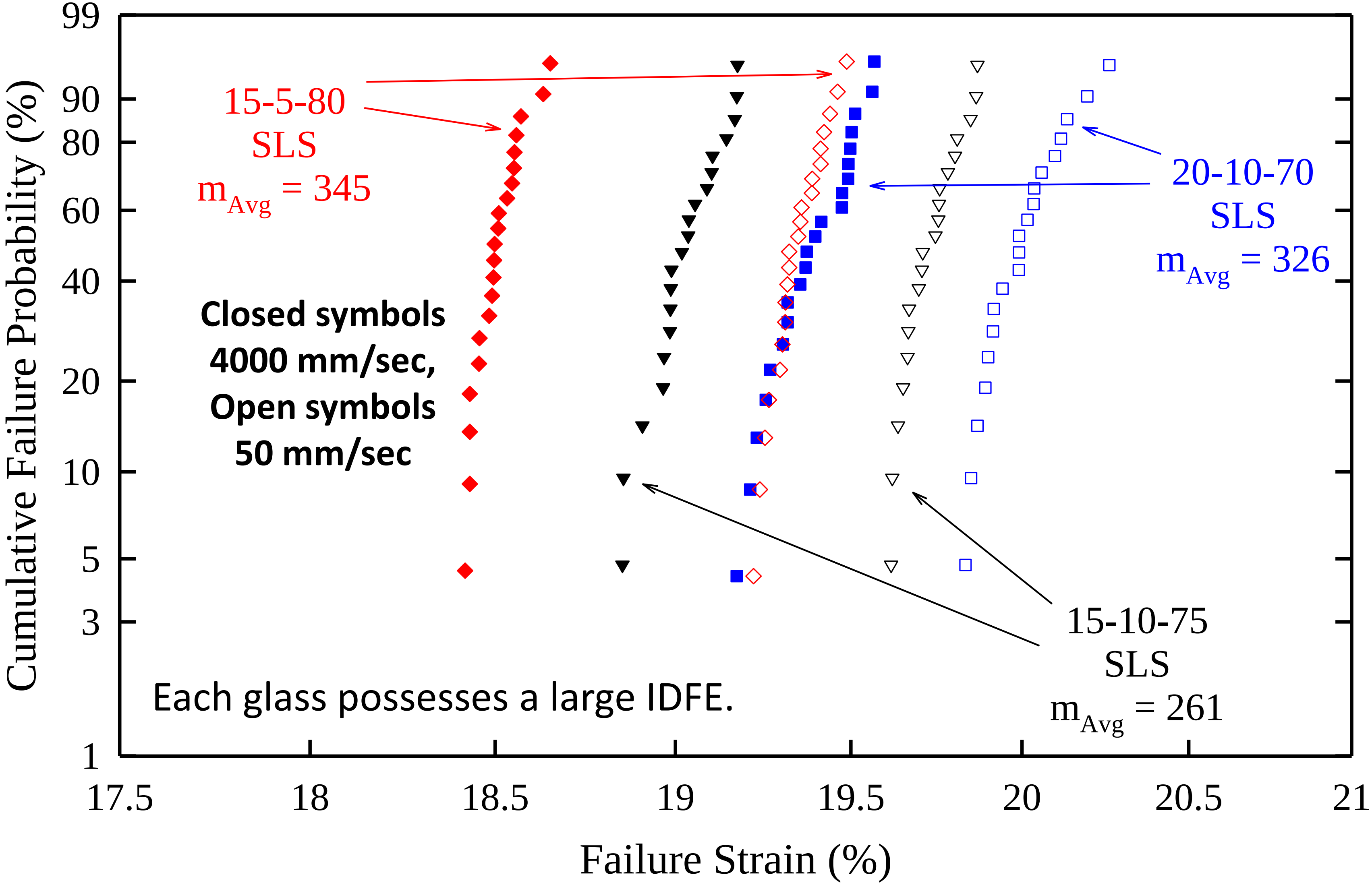
P is applied load, C is crack length, and a is Vickers indentation diagonal length



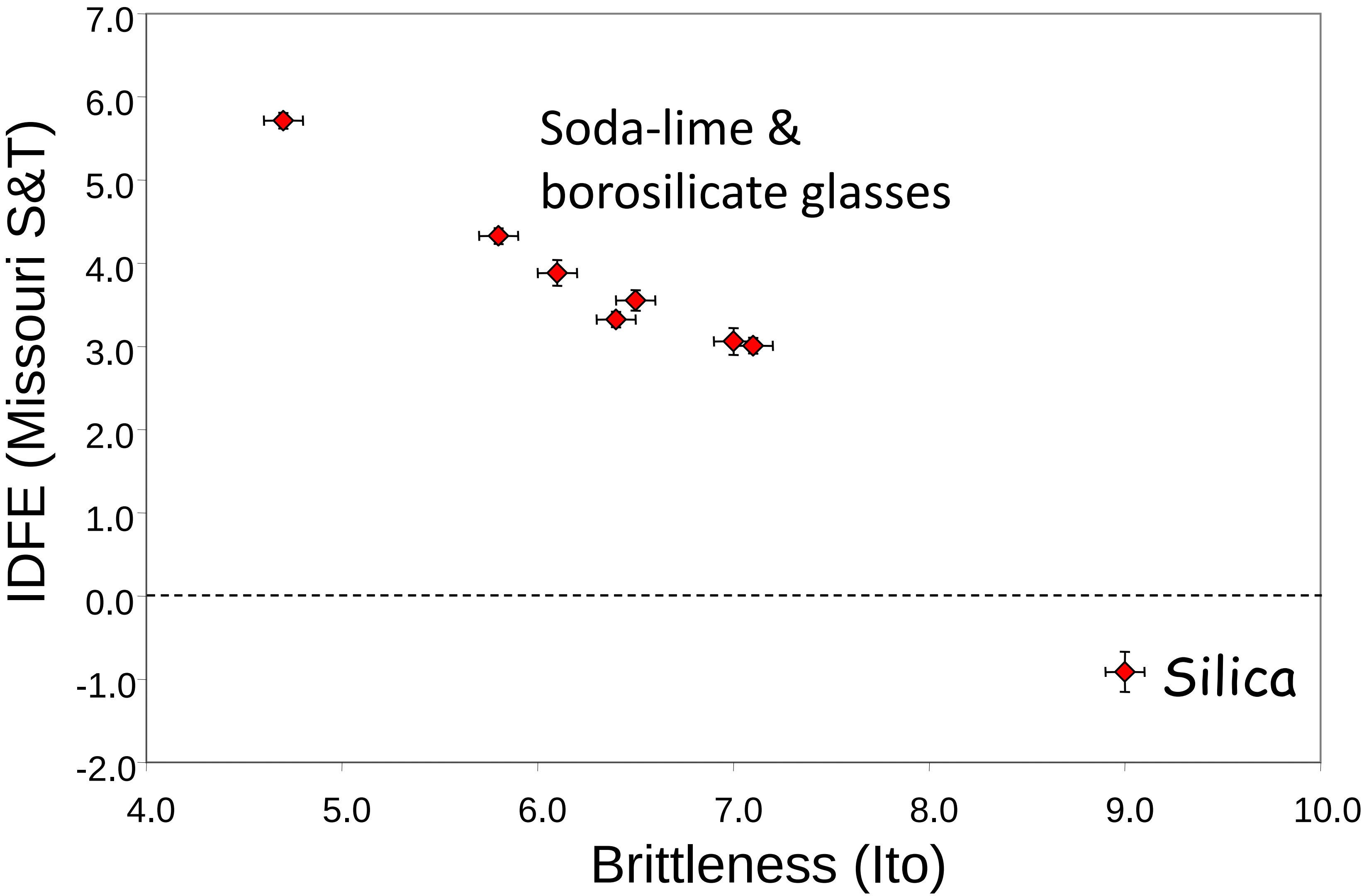
Setsuro Ito, 2002



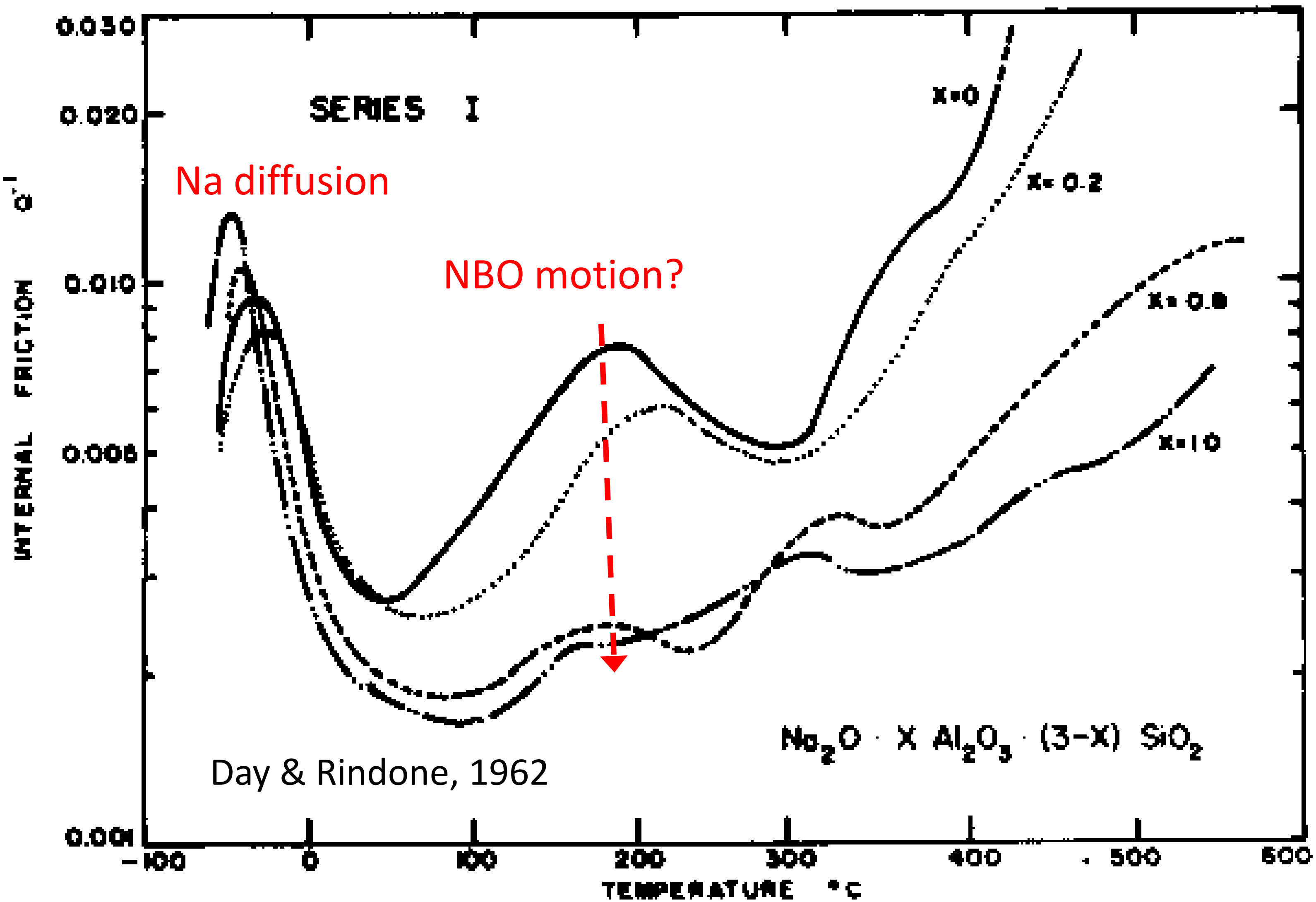
Soda-lime silicate glasses exhibit the 'delayed failure' effect



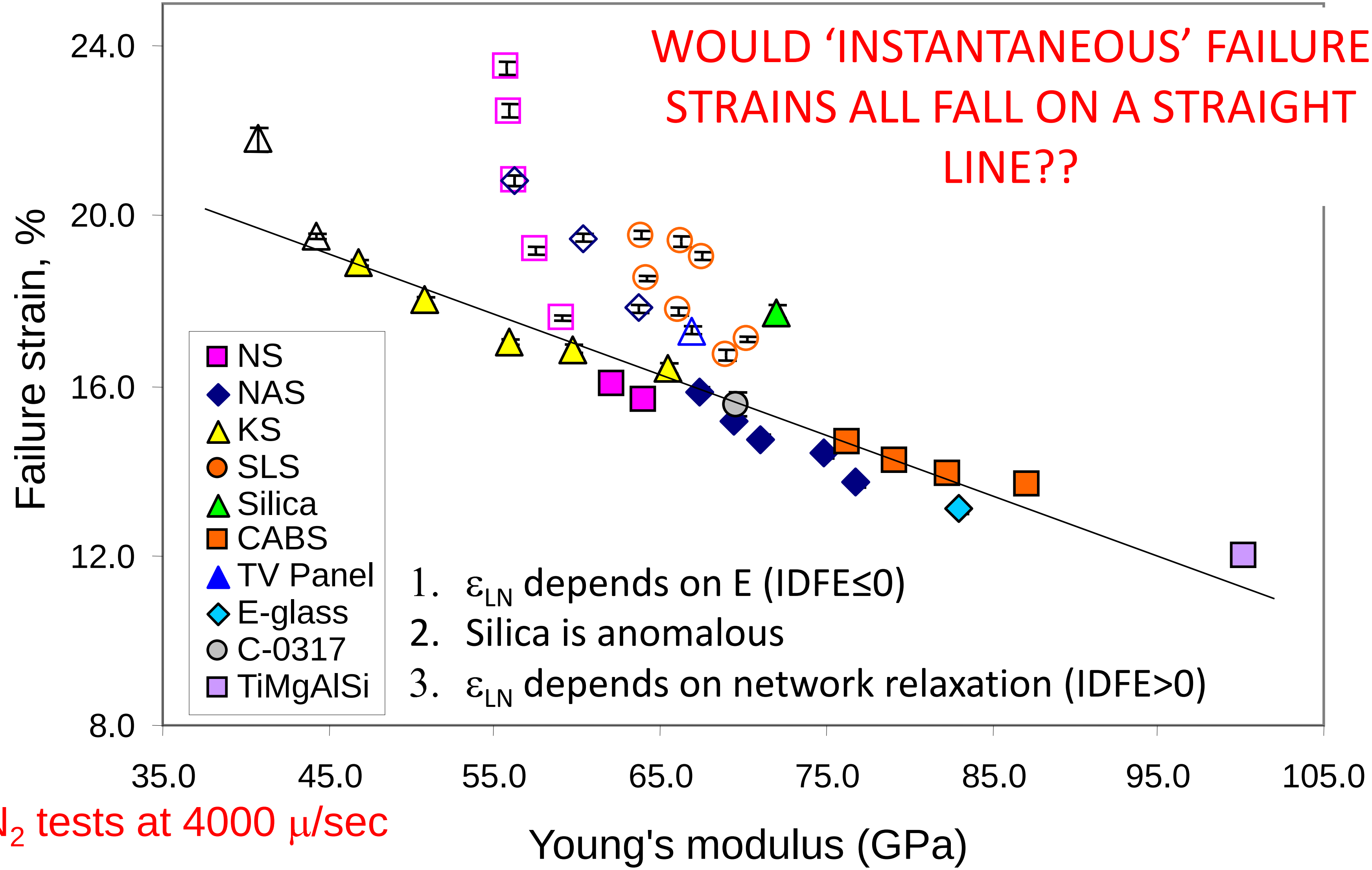
‘Brittleness’ and ‘inert delayed failure’ may be related



Is IDFE related to network relaxation?



Is there a universal dependence of glass failure characteristics on network structure?



LN_2 tests at 4000 μ/sec

Summary

- Inert failure strains are sensitive to the composition/structure of glass fibers.
  - ε_f increases when NBO's replace BO's
  - ε_f increases when Young's modulus decreases
- Inert failure strains are dependent on the applied stressing rates (V_{fp}).
  - Structure with non-bridging oxygens fail at larger strains with slower V_{fp}.
  - 'Framework' structures do not exhibit this 'inert delayed failure effect'.
  - Is IDFE due to relaxation of the network? What role is played by the NBO's?

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The NSF/Industry/University ***Center for Glass Research*** sponsored the two-point bend studies at Missouri S&T

Nate Lower and Zhongzhi Tang collected the data

Chuck Kurkjian (retired, AT&T) inspired the work