THE NEED FOR APPLICATION OF DYNAMIC MECHANICAL ANALYSIS IN THE EVALUATION OF INTERLAYER MATERIALS

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ABSTRACT

Interlayer materials like Polyvinyl Butyral (PVB), Silicone and Urethane are viscoelastic in their mechanical behavior. Mechanical properties of a viscoelastic material are not only dependent on temperature, but also highly dependent on frequency or strain rate. Dynamic mechanical analysis provides an effective experimental tool to measure the viscoelastic properties over a wide range of temperatures and in the time range of a few seconds up to 10^{-5} seconds. It is especially suitable for studying the viscoelastic nature of interlayer materials since the temperature and strain rate conditions for windshield design and service are within the measurement and analytical capabilities of DMA.

For illustration of the above facts, the viscoelastic properties of PVB-3GH and PVB-AG2 interlayers have been studied using DMA. Compression modulus and tan δ curves at 4°C increments from 30 to 70°C, in the frequency range of 0.1 Hz to 100 Hz have been measured. Master curves for complex modulus and tan δ with respect to frequency at the reference temperature of 39°C have been obtained by applying the time-temperature superposition principle to the above data. G', G" and tan δ vs. temperature characteristics have been measured for the same materials ranging from -100 to 140°C.

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INTRODUCTION

Interlayers in windshields perform important functions under conditions of large variations in temperature and strain rate. For commercial aircraft windshield application, this temperature range is approximately from -65°F to 130°F and the strain rate range is from a low of 0.01 in./min (.00017 in./in./sec) to a high of 12000 in./in./min (200 in./in.sec)[1]. In the case of low strain-rate loading and high temperature environment, the interlayer must transfer loads without excessive deformation or permanent set, which depend on good elastic properties. Under high strain rate conditions and low temperature environment, good plastic properties interlayers are needed to absorb shock loads like a bird impact.

The mechanical properties of interlayers under these varied but important conditions can be measured more easily and reliably using Dynamic Mechanical Analysis (DMA).

DMA

DMA tests measure the response of a material to a sinusoidal or other periodic stress. Since the stress and strain are generally not in phase, two quantities can be determined - a modulus and a phase angle or a damping term. There are many types of dynamic mechanical test instruments. One type is schematically illustrated in Figure 1. The general types of dynamic mechanical instruments are free vibrations, resonance forced vibrations, non-resonance forced vibrations, and wave and pulse propagation instruments.

Although any one instrument has a limited frequency range, the different types of apparatus are capable of covering the range from a fraction of a cycle per second up to millions of cycles per second or a time range of a few seconds up to 10^{-5} seconds. Whenever the frequency range on any one instrument is not adequate for the application, a master curve covering a wider frequency scale can be generated by conducting the experiments at different temperatures using the available frequency range of the instrument. This is possible to do since most polymers especially interlayers lend themselves for the application of time temperature superposition principle.

The master curves for median batches of PVB-3GH (99081) and PVB/AG2 (57150) are illustrated in Figures 2-5. These plots at the reference temperature shown yield the required data in the strain rate range of interest for the application to windshields.

Schematic of One Type of Dynamic Mechanical Test

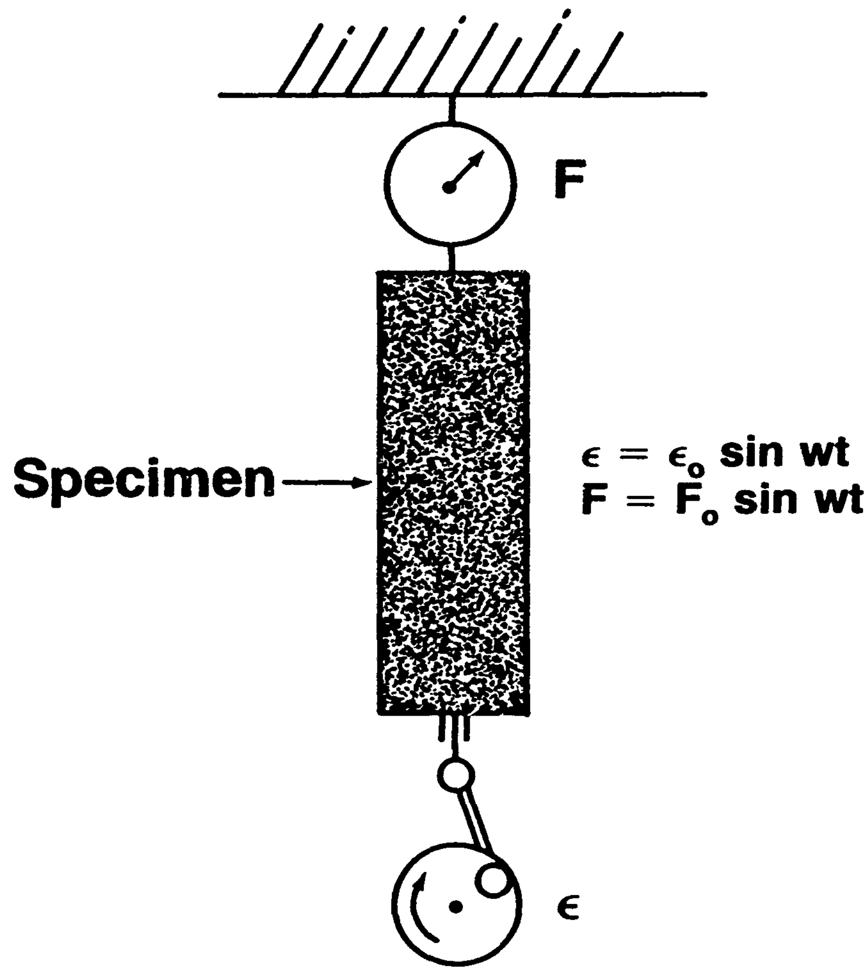

Figure 1

PVB/AG2 Complex Modulus Versus Frequency

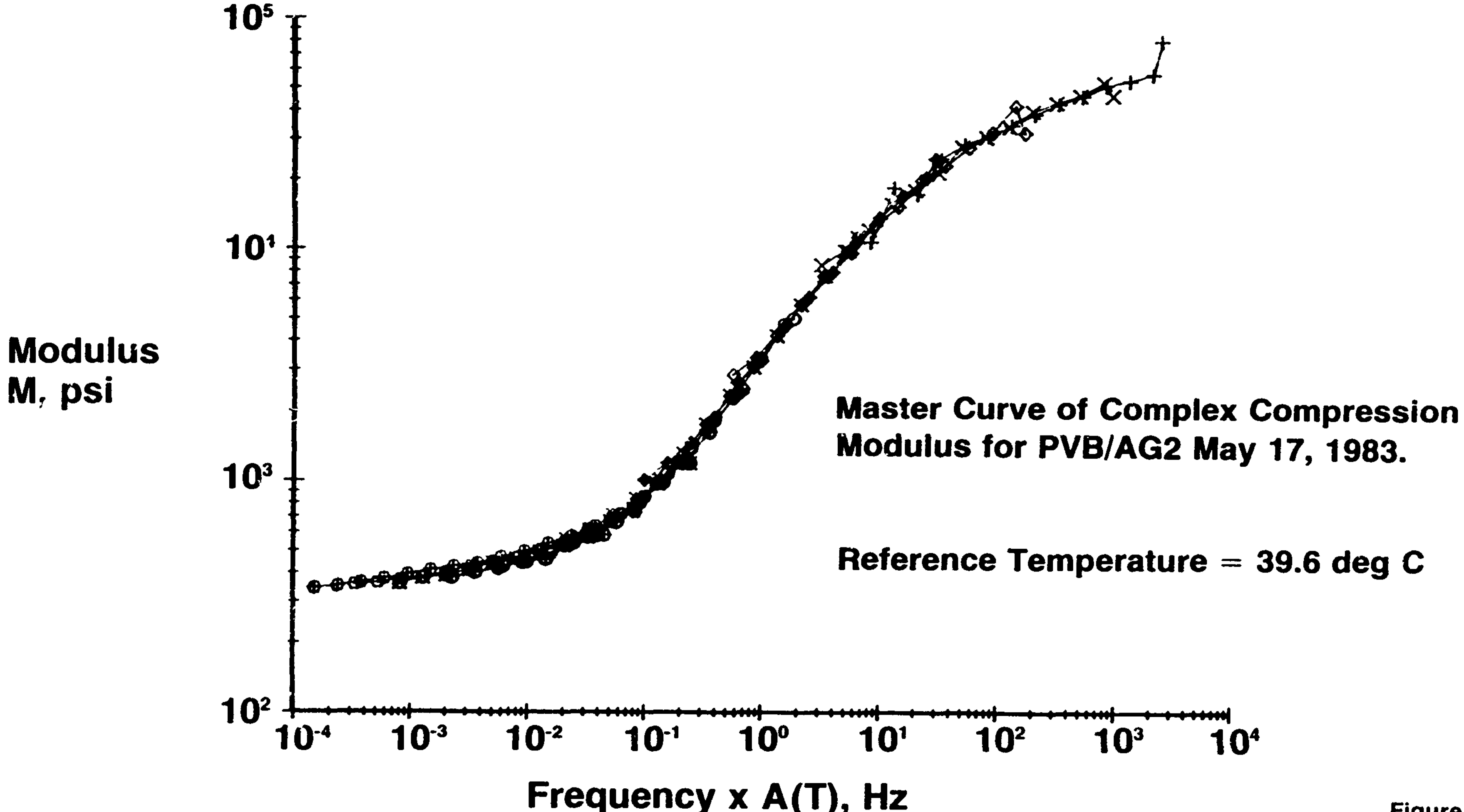

Figure 2

PVB/AG2 Tan δ Versus Frequency

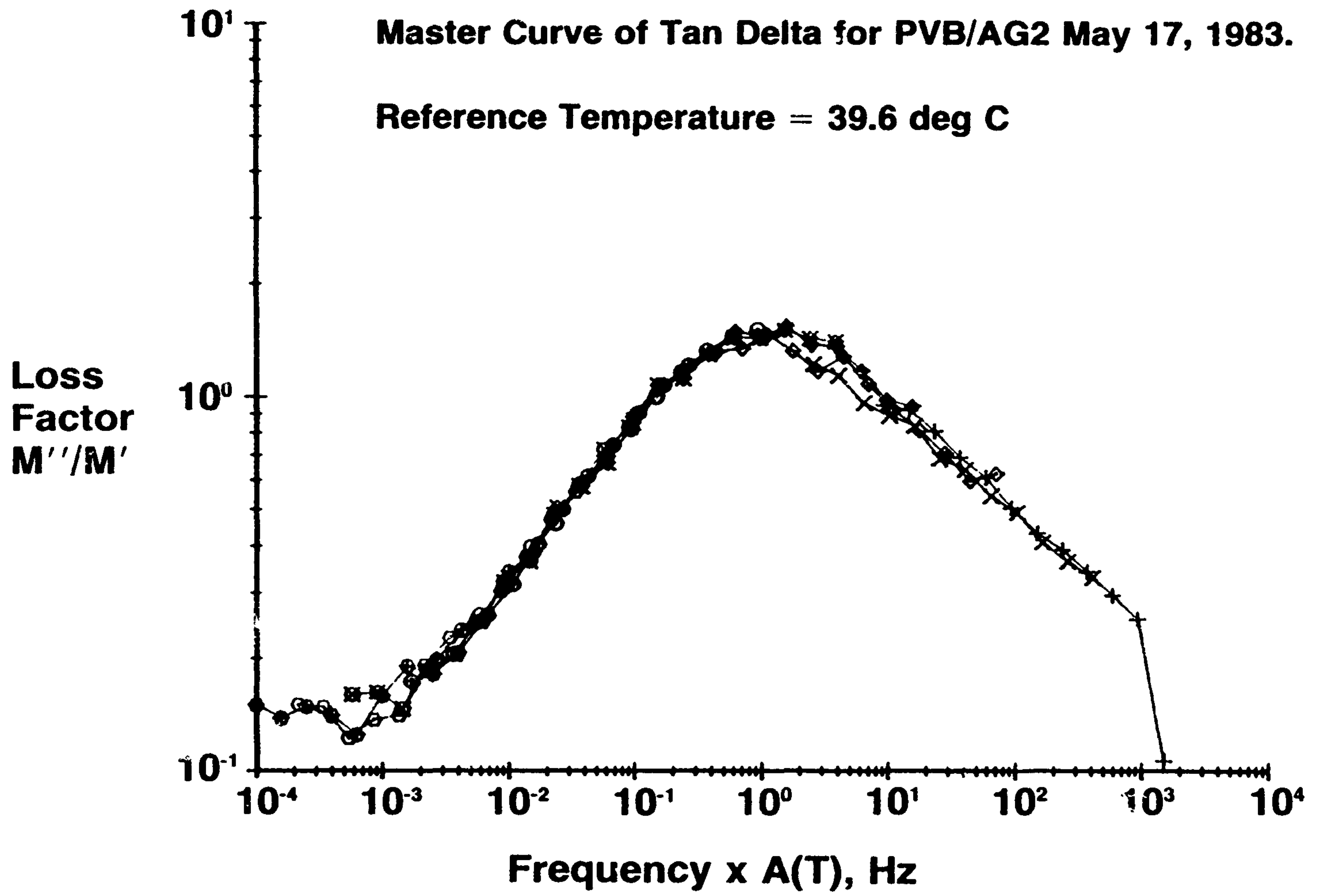

Figure 3

PVB/3GH Complex Modulus Versus Frequency

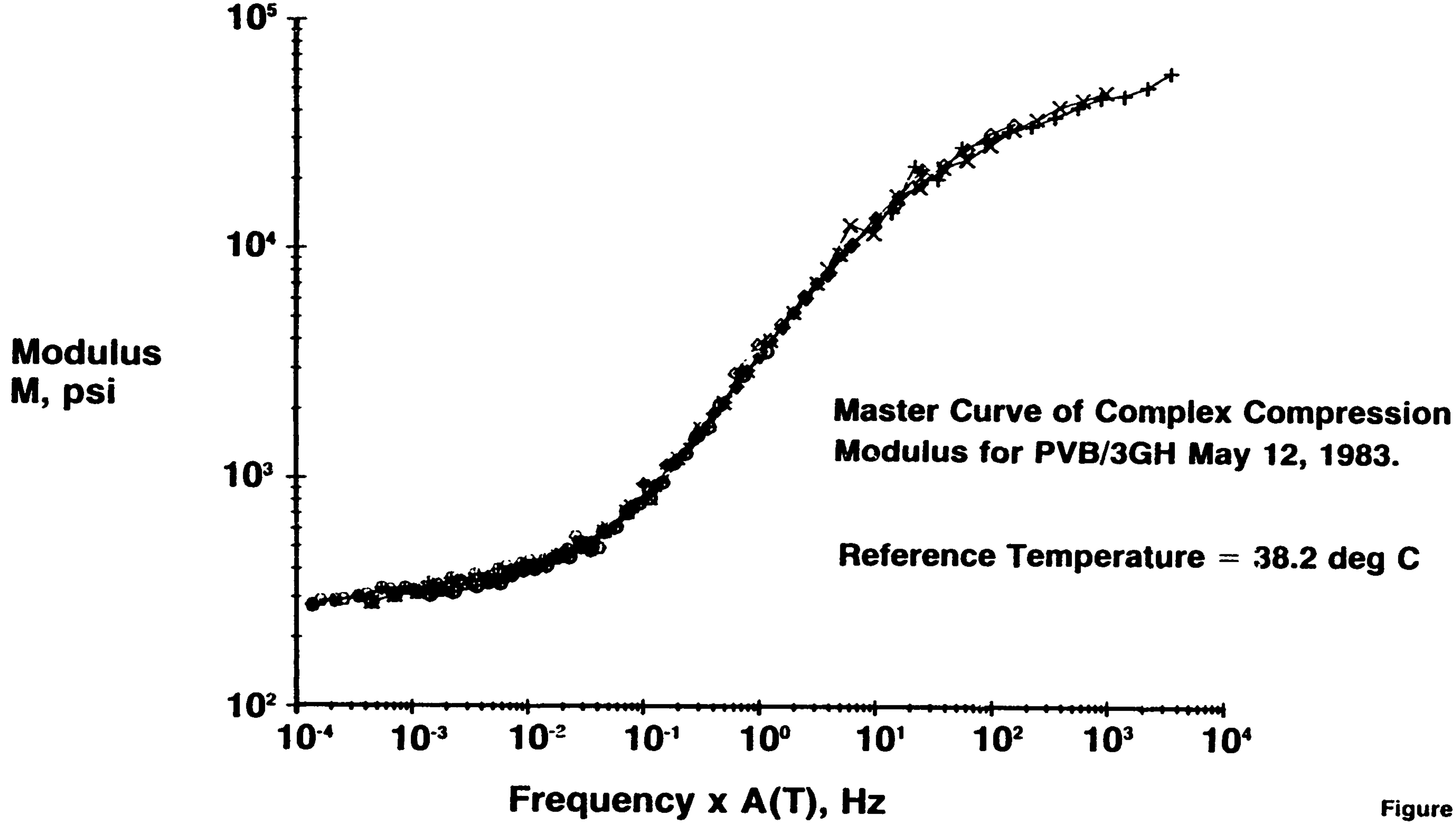

Figure 4

PVB/3GH Tan δ Versus Frequency

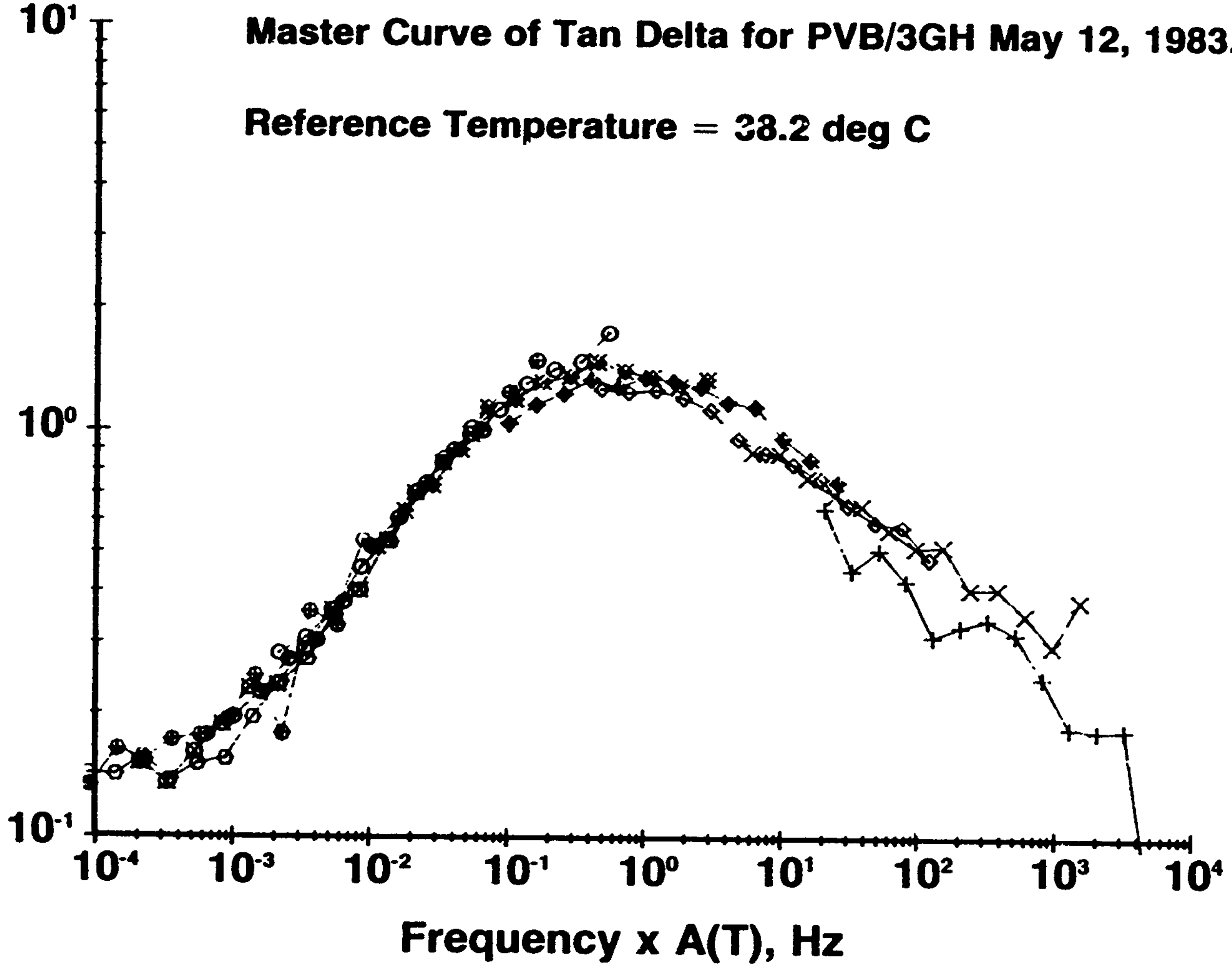

Figure 5

Discussion of DMA Data on PVB Interlayers

[2]Dynamic mechanical results are generally given in terms of complex moduli or compliances. The notation will be illustrated in terms of shear modulus G, but exactly analogous notation holds for Young's modulus E. The complex moduli are defined by:

$$G^* = G' + i\,G'' \qquad (1)$$

where G^* is the complex shear modulus, G' is the real part of the modulus and $i = \sqrt{-1}$. G'' is called the loss modulus and is a damping or energy dissipation term. The angle which reflects the time lag between the applied stress and strain is δ and it is defined by a ratio called the dissipation factor.

$$\tan \delta = G''/G' \qquad (2)$$

The 'tan δ' is a damping term and is a measure of the ratio of energy dissipated as heat to the maximum energy stored in the material during one cycle of oscillation. For small to medium damping, G' is the same as the shear modulus measured by other methods at comparable time scales. The loss factor G'' is directly proportional to the heat H dissipated per cycle as given by,

$$H = \pi\, G''\, \gamma_o \qquad (3)$$

where γ_o is the maximum value of the shear strain during a cycle.

Figures 6, 7, 8 and 9 show G', G" and tan vs. temperature plots for PVB/AG2 interlayer. Figures 10, 11, 12 and 13 show the same plots for PVB/3GH interlayer.

The dynamic modulus or the modulus measured by any other technique is one of the most basic of all mechanical properties and its importance in any structural application is well known. Damping is often the most sensitive indicator of all kinds of molecular motions which are going on in a material even in the solid state. These motions are of great practical importance in determining the mechanical behavior of polymers. The absolute value of the damping and the temperature and frequency at which damping peaks occur will be of considerable interest in the selection and comparison of interlayer materials. Many other mechanical properties are intimately related to damping; these include toughness and impact strength and fatigue life.

PVB/AG2 G′, G″ Versus Temperature Below Tg

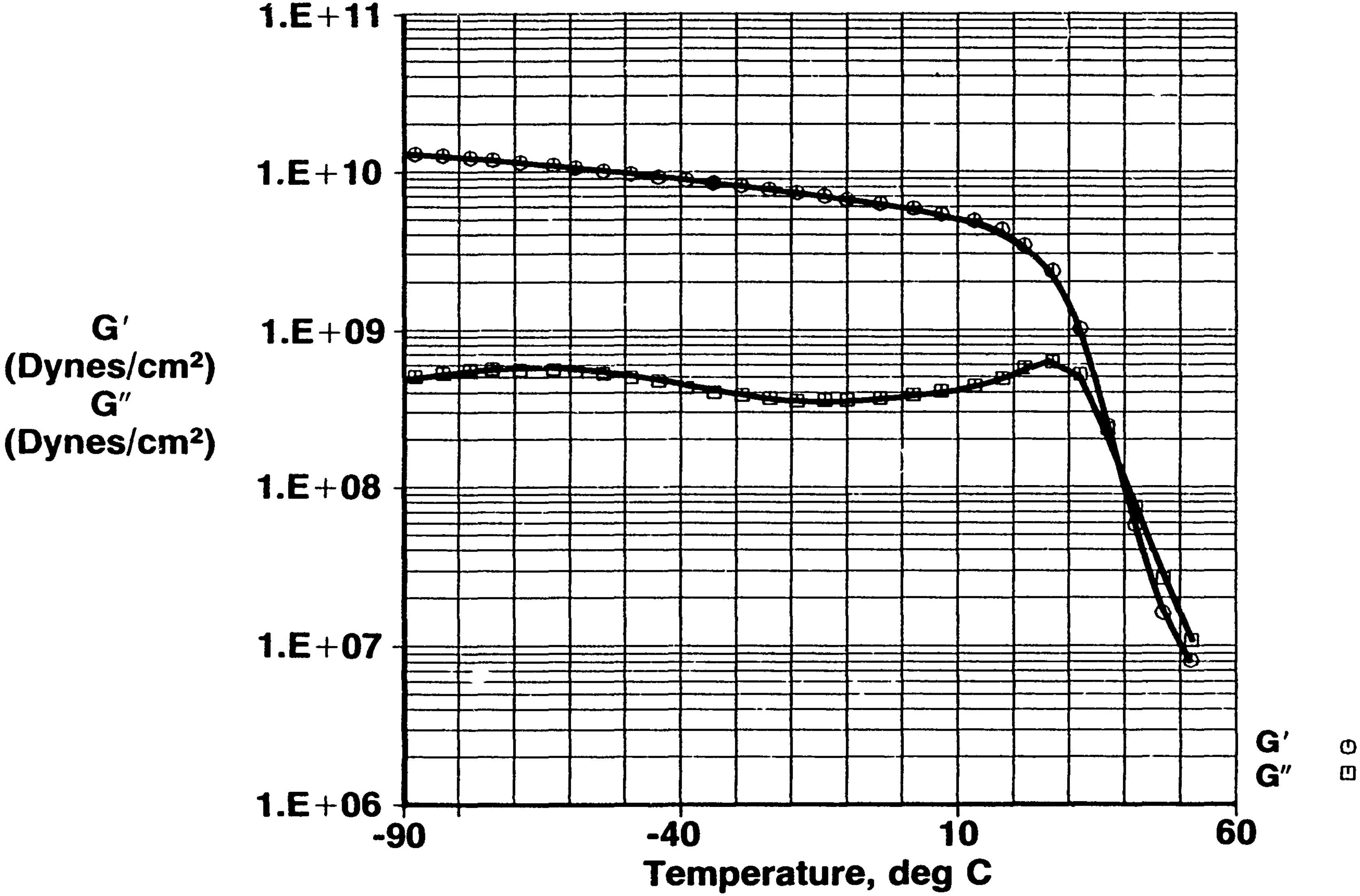

Figure 6

PVB/AG2 Tan δ Versus Temperatures Below Tg

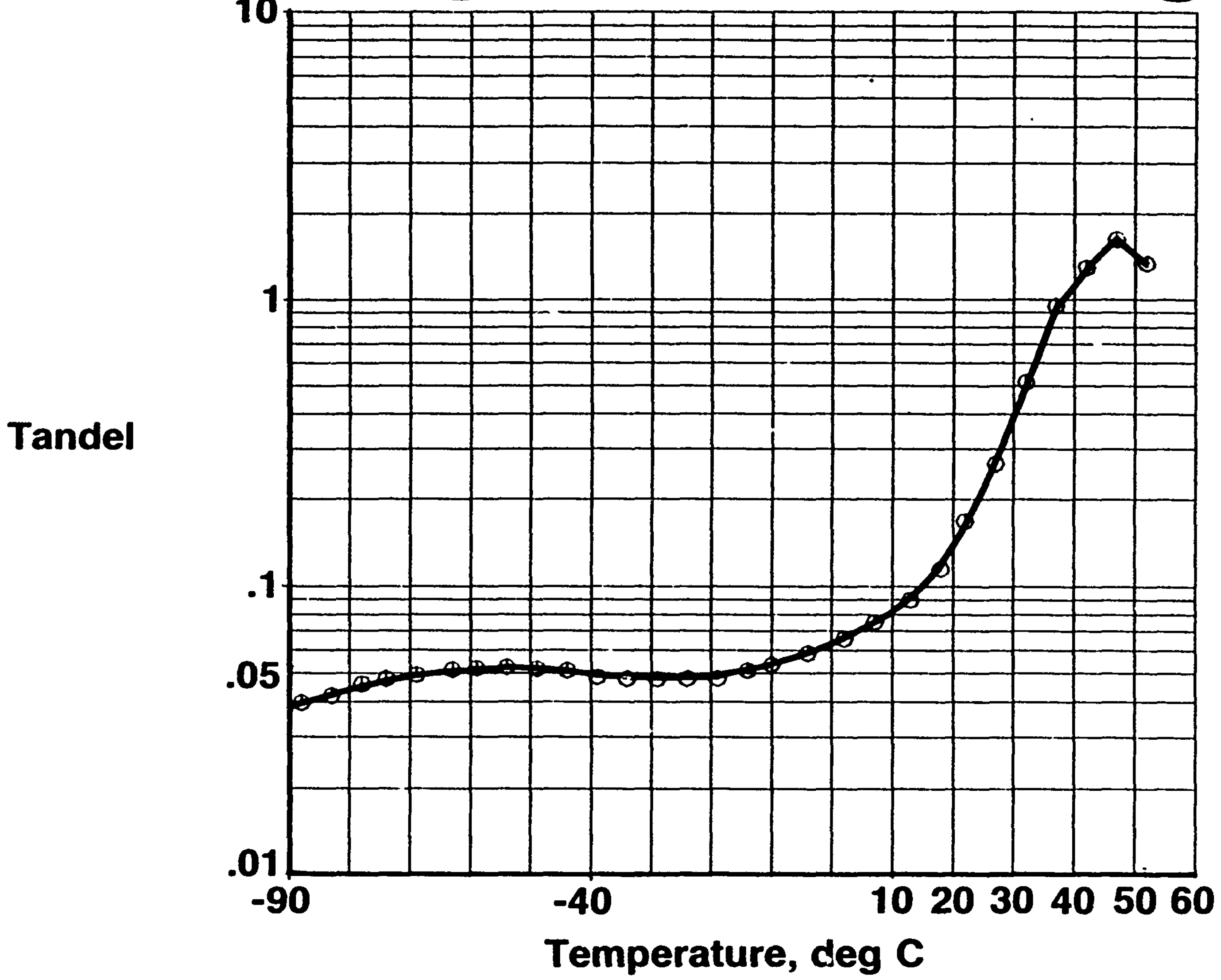

Figure 7

PVB/AG2 G′, G″ Versus Temperatures Above Tg

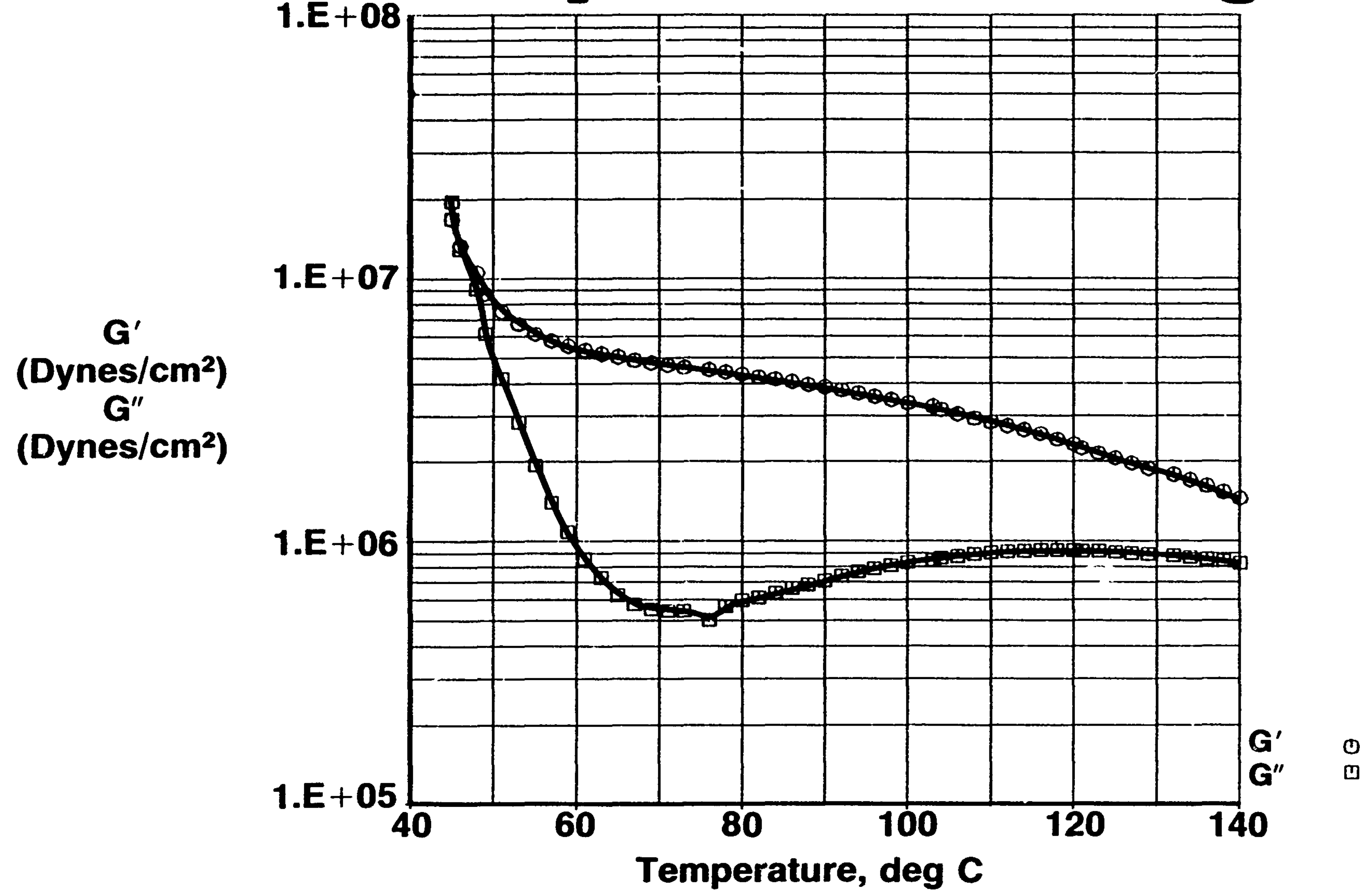

Figure 8

PVB/AG2 Tan δ Versus Temperatures Above Tg

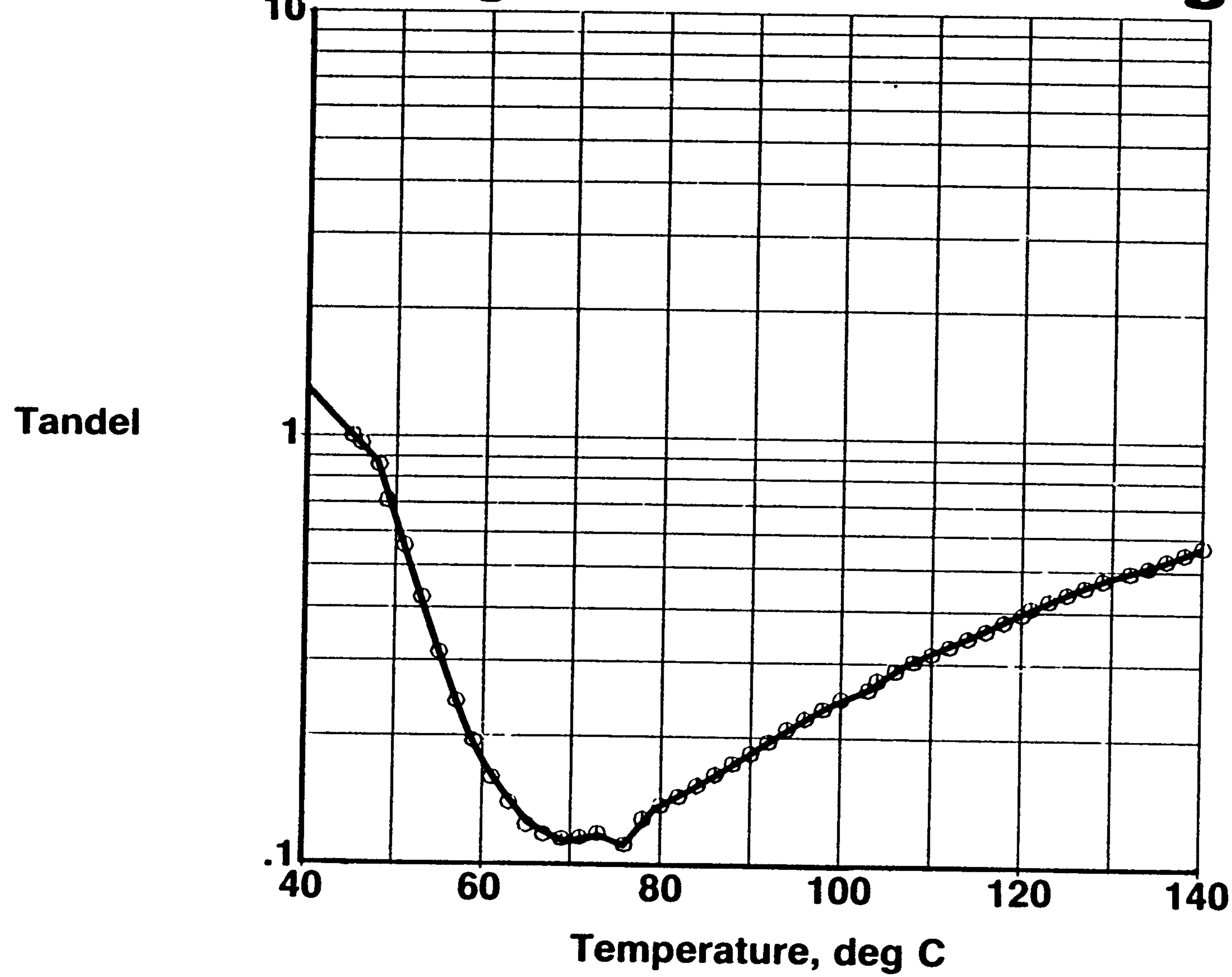

Figure 9

PVB/3GH G′, G″ Versus Temperatures Below Tg

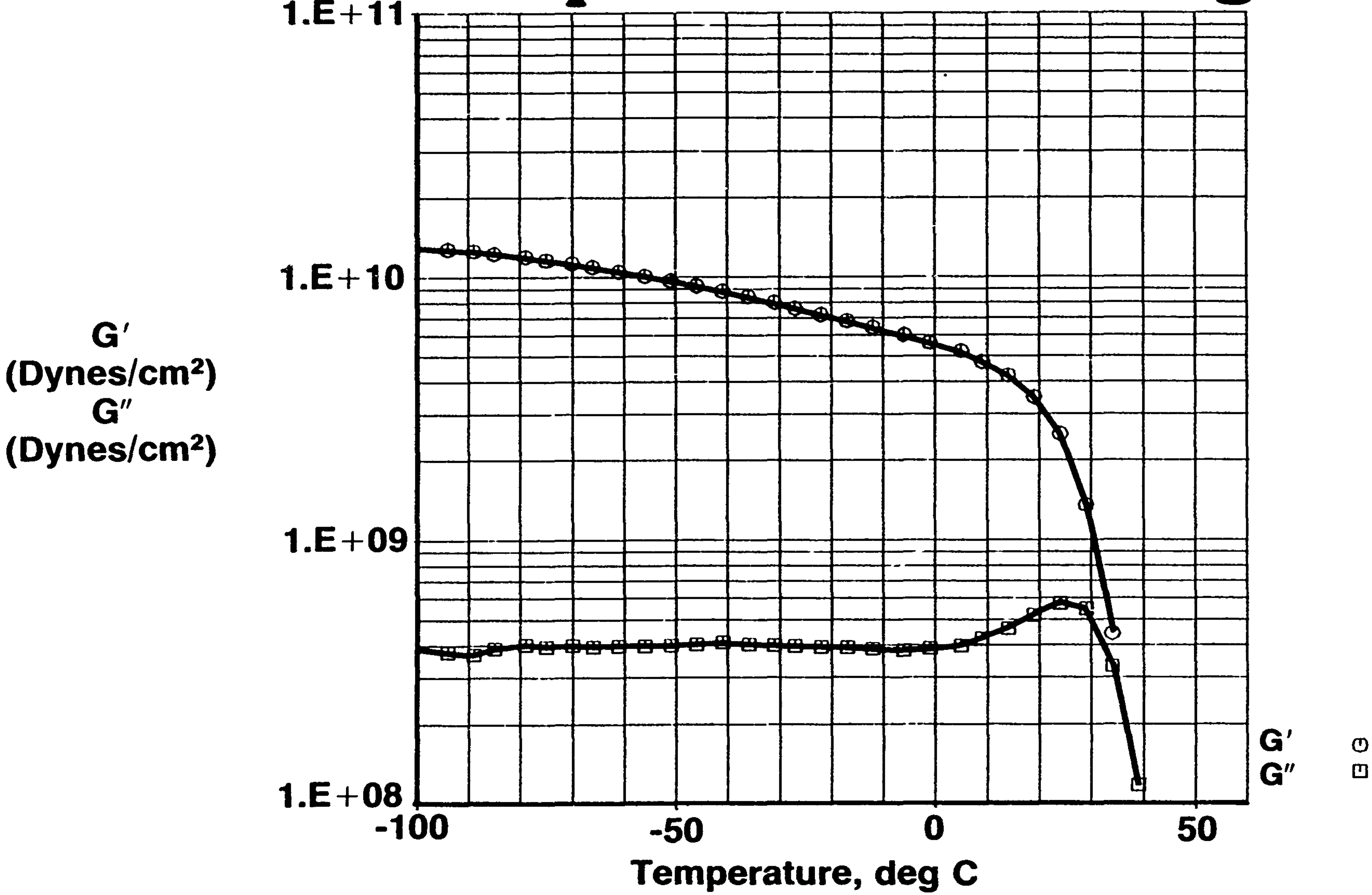

Figure 10

PVB/3GH Tan δ Versus Temperatures Below Tg

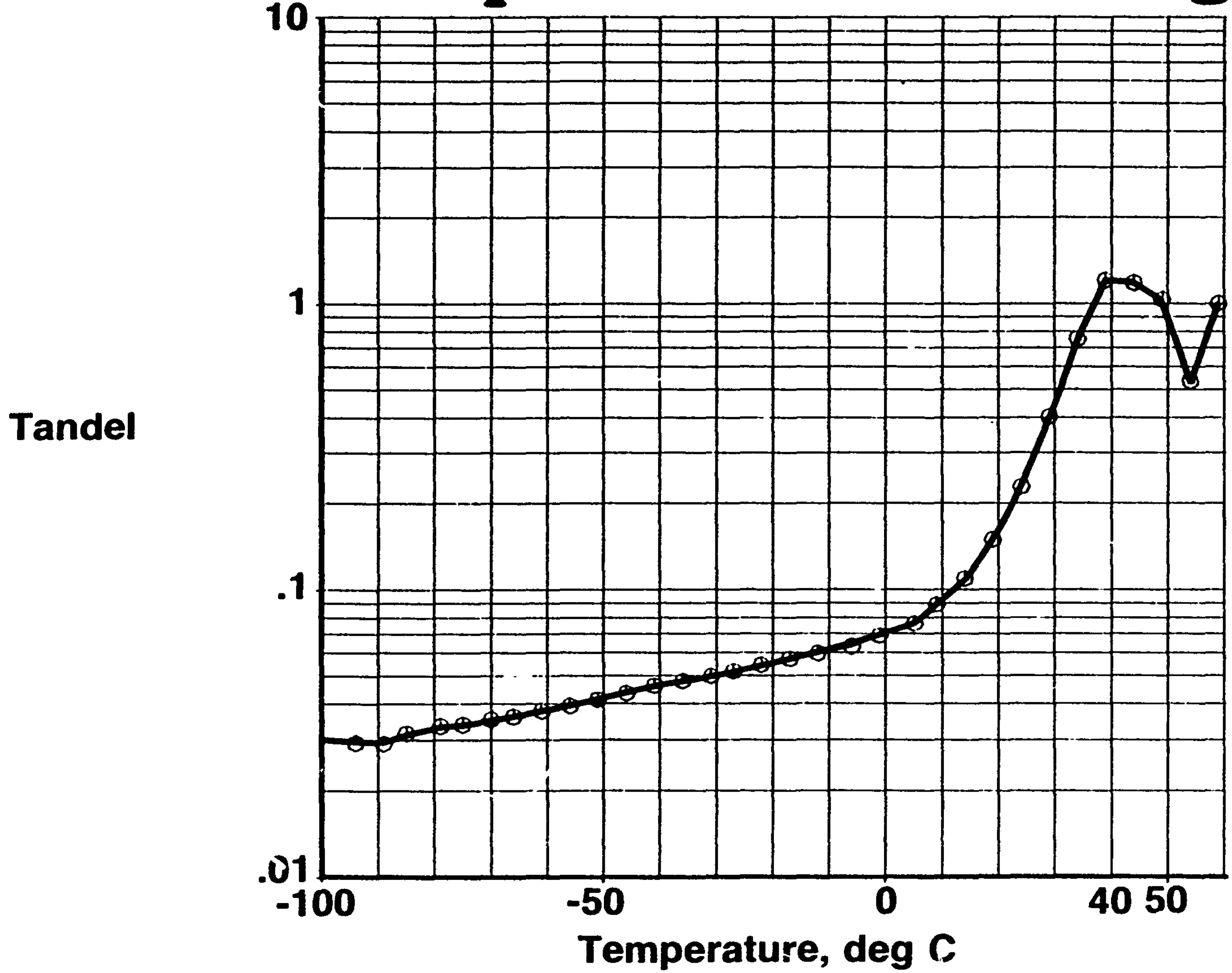

Figure 11

PVB/3GH G′, G″ Versus Temperatures Above Tg

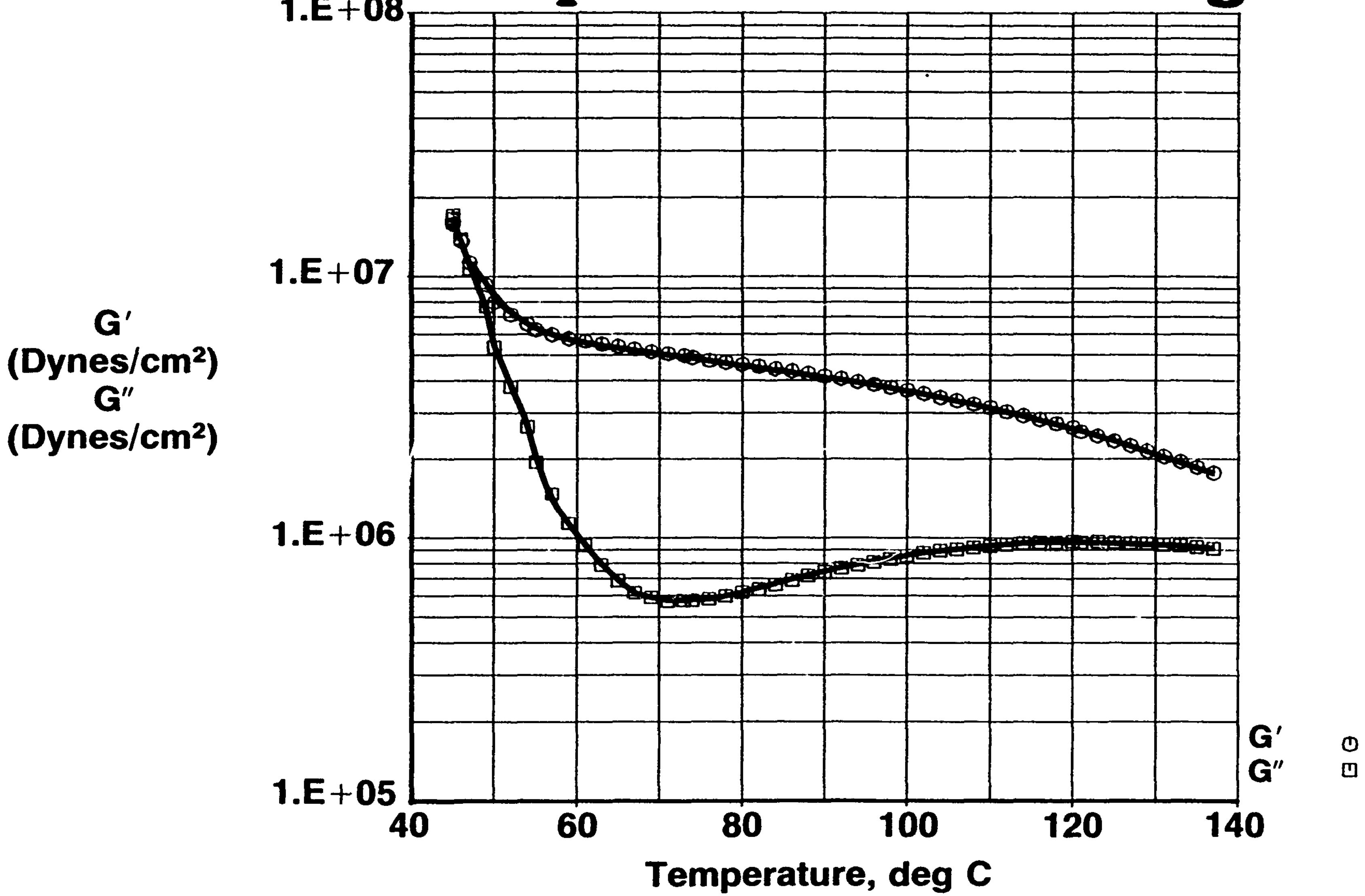

Figure 12

PVB/3GH Tan δ Versus Temperatures Above Tg

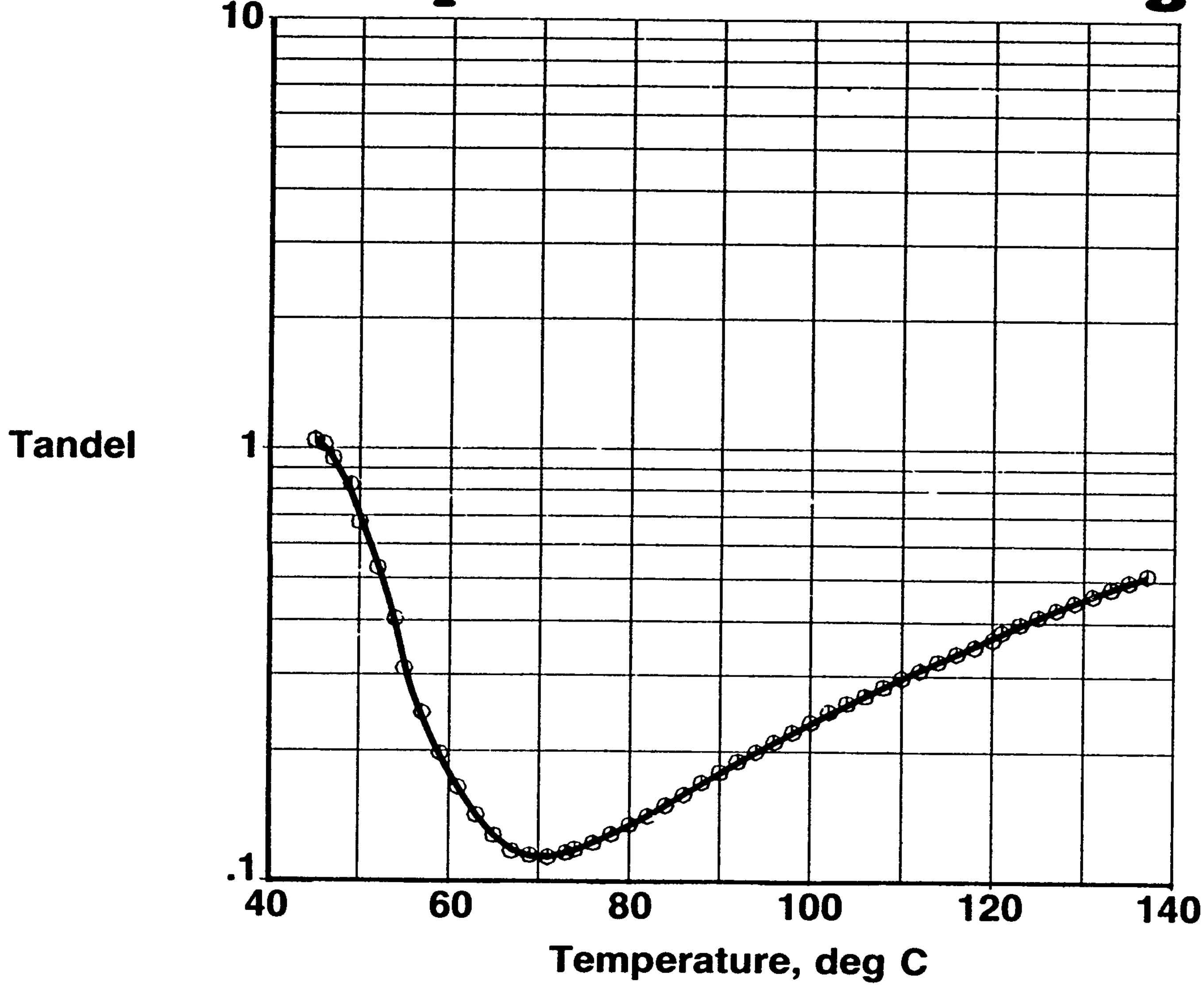

Figure 13

Dynamic Mechanical Analysis Equations

$$G^* = G' + \sqrt{-1}\, G'' \quad \ldots\ldots 1$$

$$\tan \delta = G''/G' \quad \ldots\ldots 2$$

$$H = \pi G'' \gamma_0 \quad \ldots\ldots 3$$

Where

G^* = Complex Modulus

G' = Storage Modulus

G'' = Loss Modulus

δ = Angle Which Reflects the Time Lag Between the Applied Stress and Strain

$\tan \delta$ = Loss or Dissipation Factor

γ_o = Maximum Shear Strain During a Cycle

H = The Heat Dissipated per Cycle

Figure 14

Frequency is expressed using the units of Hertz (1 Hz = 1 cycle/sec.). Time period of a cycle is the inverse of the frequency value.

Table 1 summarizes the damping characteristics for PVB/AG2 and PVB/3GH interlayers. A major damping peak for 3GH plasticized vinyl occurs at a lower temperature and strain rate than AG2 vinyl, but the peak values of tan are slightly smaller.

The secondary damping peak for AG2 vinyl at colder temperatures is an attractive feature of this interlayer. AG2 vinyl has better impact resistance than 3GH vinyl at colder temperatures.

CONCLUSION

DMA offers an important test method to study mechanical behavior of interlayer materials in the temperature and strain rate ranges of interest for windshield applications. This analysis can also aid in material formulation and quality control.

The author is grateful to Mr. Ken Tanino of Boeing Materials Technology for conducting the necessary DMA experiments and producing all the plots included in this paper.

Damping Characteristics of PVB/AG2 and PVB/3GH Interlayers

Material		Tan δ Versus Temperature		Tan δ Versus Frequency	
		Temperature of Damping Peak (ºC)	Absolute Value	Frequency of Peak (Hz)	Absolute Value
57150 PVB/AG2	a)	47	1.63	1.9	1.5
	b)	-54ºC	0.0525	–	–
99081 PVB/3GH	a)	39	1.2	0.4	1.4
	b)	Nil	Nil	–	–

Table 1

REFERENCES

1. Greene, F. E., "Testing for Mechanical Properties of Monolithic and Laminated Polycarbonate Materials," AFFDL-TR-77-96, Part 1, Oct. 1978.

2. Nielsen, L. E., "Mechanical Properties of Polymers and Composites, Vol. 1," Marcel Dikker, Inc., New York, 1974.