T_g and Fragility Determination of Glass-Forming Sugars using a Dynamic Mechanical Analyzer

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Statement of Purpose: Glass-forming sugars are used in a number of fields, including the preservation of biologics. Sugars are widely used as protectants primarily due to their high glass transition temperature (T_g)[1] which, by convention, is the temperature at which the viscosity of the liquid reaches 10^{12} Pa·s (i.e. becomes physically "solid"). The glass transition is a second-order, reversible dynamic phenomenon which exhibits a discontinuity of the second-order properties such as a step change of thermal expansion or heat capacity (c_P).[2] Due to the nature of the glass transition, one of the most widely-used techniques for measuring T_g is differential scanning calorimetry (DSC). Another important property of glass-forming materials used for preservation purposes is fragility, which is generally recognized as a way of classifying the strength of glass-forming liquids.[3] It is defined as the deviation of the temperature dependence of the α-relaxation time (τ) from simple Arrhenius behavior. This deviation determines the steepness of the Arrhenius plot near T_g and thus the "sharpness" of the glass transition.[3] The fragility is usually measured by using dielectric spectroscopy, dynamic mechanical analyzer (DMA) or nuclear magnetic resonance. Because of the importance of these parameters, a comprehensive method to determine both T_g and fragility of the same samples would be highly desirable. In this study, we propose a method based on DMA to estimate both the T_g and fragility index. Results were validated by comparing with literature values of commonly used sugars.

DMA Method: A TA Q800 DMA was used to conduct temperature step/frequency sweep experiments on amorphous samples of trehalose or sucrose enveloped in a steel material pocket. The temperature range was 298-423 K with an increment of 5 K and the oscillation frequency was swept from 20 to 0.01 Hz at each temperature step. For a specific temperature series, the loss modulus (E") data as a function of frequency can be shifted by a_T (x-shift factor) to fit a master curve using a time-temperature superposition (TTS) model. The α-relaxation time can be calculated by $\tau = a_T\tau_r$ where τ_r is the relaxation time at the reference temperature (T_r) and equal to $1/\omega_{max}$.The ω_{max} corresponds to the maximum loss modulus in the TTS master curve (See Figure 1 (b)). The $\tau(T)$ profile of supercooled liquids above T_g follows the Williams-Landel-Ferry (WLF) equation as given by Eq. (1).

$$\log_{10}(\tau/\tau_g) = -\frac{c_1(T-T_g)}{c_2+(T-T_g)} \quad (1)$$

wherein c_1 is a universal constant of 16. The values of c_2 and T_g are obtained by best-fitting $\tau(T)$ with the limitation of $T>T_g$ to Eq. (1). When the relaxation time (τ_g) at T_g is set to 100s,[4] the kinetic fragility index (m) can be obtained by $m=\frac{\mathrm{d}\log_{10}(\tau)}{\mathrm{d}(T_g/T)}\Big|_{T=T_g}$.

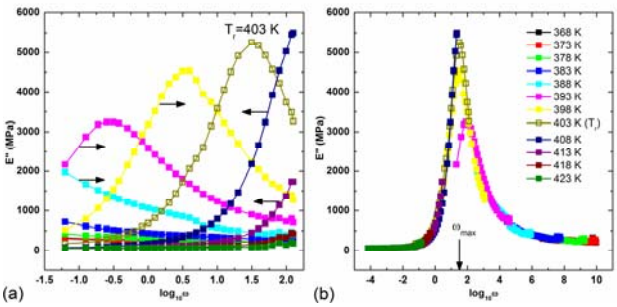

Figure 1. Generation of master curve for loss modulus E".

Results: The T_g and fragility index of trehalose was determined to be 388.8±0.6 K and 115.2±6.3, respectively, both of which are in good agreement with the literature values of 388.15 K[5] (DSC measurement) and 107±3[4] (dielectric measurement). In addition, the T_g of sucrose was determined to be 343.0±0.4 K and the fragility index 98.1±0.9, consistent with the literature values of 350 K[6] (DSC measurement) and 98-100[7] (dielectric measurement).

Conclusions: Given that the glass transition temperature and fragility are both important properties of glass-forming liquids, a comprehensive method is proposed to simultaneously determine these properties by applying the time-temperature superposition principle to relaxation data obtained by DMA. The method was used to determine the T_g and fragility index of trehalose and sucrose, yielding good agreement with literature values. This DMA-based T_g and fragility determination method represents a new approach for identifying optimal compositions for preservation of biologics.

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