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ENGINEERING VISCOELASTIC PROPERTIES IN POLYURETHANE COATINGS TO REDUCE EROSION RISKS IN WIND TURBINE BLADES

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ABSTRACT

The dynamic mechanical response of a commercial prototype Leading Edge Protection (LEP) coating based on polyurethane (PU) chemistry is analysed using Dynamic Mechanical Thermal Analysis (DMTA) as a function of temperature and frequency. The temperature range chosen reflects the operating range used in offshore wind turbines, with the damping characteristics of the coating maximal at 25 °C. The Time Temperature Superposition (TTS) methodology was applied to the DMTA data to predict the viscoelastic behaviour of the PU LEP at frequencies (10^{-2} - 10^{10} Hz) consistent with the predicted strain rates induced by the impact of rain droplets on wind turbine blades (10^6 - 10^9 Hz). A Young's modulus is reported for the PU of 2.78×10^6 GPa at 10^8 s⁻¹, compared with 278 MPa at 1 s⁻¹ *i.e.* the equivalent of quasi-static testing. This method presents a potential for improved understanding of LEP material at high strain rates and a test methodology for generating material properties for coating lifetime prediction.

1. INTRODUCTION

Erosion of materials due to impact has been a topic of research in the wind industry over the last 10 years with *Herring et al.* [1] publishing an recent review detailing the area. It can be caused by rain, hail, sea spray and other particulate debris *e.g.* sand impact; it has become a significant problem as the wind industry (mainly offshore) continues to increase blade lengths (currently at 107 m for GE's Haliade-X 12 MW) and installations move into areas of extreme conditions [1]. Blade erosion via liquid droplet impingement results in reduced aerodynamic efficiency which in turn decreases energy capture. The latter is especially detrimental for the uptake of wind as an energy source as the most significant barrier to the use of renewables is cost. Energy is often compared solely on its cost per unit disregarding other benefits, such as CO₂ reduction [2].

Current offshore wind turbine blades are expected to remain in operation with minimal maintenance for a minimum service life of 25 years. However, it is estimated that up to £1.3 million is spent on each turbine during its lifetime due to Leading Edge Erosion (LEE) from the impact of rain droplets with existing coating systems (see Figure 1) [3], [4].



Figure 1 – Selected photos of leading-edge erosion on wind turbine blades from published literature.[5] Not to scale.

There are a number of protection solutions available that attempt to mitigate LEE and prolong the lifetime of turbines [1]. The most common are protective coatings and are applied either in-mould or post mould. Post-mould coatings, which this work focuses on, generally consist of an elastomeric and durable polyurethane or polyurea material which are designed to absorb the impact energy [5]. This rain droplet impact causes three shockwaves to pass through the coating: the initial longitudinal compressional stress wave, the preceding transverse shear wave and a third Rayleigh wave. The impact pressure generated is referred to as the water hammer pressure and the magnitude is dependent on the difference in acoustic properties between the droplet and the coating material surface. The speed at which these waves travel through a material, known as acoustic impedance, is used as a key parameter in predicting the lifetime of coatings in both accelerated testing and in the field and is related to the density and modulus of the material.

To resist the forces generated by the droplet impact post-mould LEP coatings are typically ductile, possess low acoustic impedance, high flexibility and high strain rates to failure to reduce the stress from the water hammer pressure at the impact surface. This also effectively dampens the oscillating stress waves, ensuring that the energy of the impact is dissipated [1]. The current materials used tend to be viscoelastic, this is where the relationship between stress and strain also depends on time. Viscoelastic materials demonstrate various phenomena such as strain rate dependence, energy dissipation and acoustic wave attenuation. This adds complexity to analysing and predicting the behaviour of the coating materials responses in rain erosion which is associated with high strain rates ($10^6 - 10^9$ Hz) predicted from FEA models of rain droplet impacts [6]. The predicted high strain rates bring into question the validity of using conventional mechanical tests used to analyse for studying a material's erosion properties e.g. modulus as they operate at much lower strain rates.

The Wind Blade Research Hub [7] is developing fundamental understanding to combat the LEE experienced resulting from rain erosion by modifying base coating formulations and connecting the changes to erosion behaviour. The aim of this present work is to develop a greater understanding of the influence of the viscoelastic response of the polymer coating that constitutes the LEP. In doing so, we will be able to improve the lifetime of existing LEPs. Consequently, in this paper we present a study of the viscoelasticity of a polyurethane-based LEP using dynamic mechanical thermal analysis (DMTA) to access the $10^6 - 10^9$ Hz frequency

domain compatible with the impact of rain droplets on a wind turbine blade, through the time temperature superposition principle. The DMTA technique allows for the viscoelastic behaviour of a material to be characterised. A small cyclical deformation is applied to a material and the material's response is measured as a function of stress, strain, temperature and frequency which can be varied to explore the effect of operating and impact conditions on protective coating systems. This allows an expression for the modulus to be formulated containing an in-phase component, *i.e.* the storage modulus (E') representing the elastic behaviour, and an out of phase component, the loss modulus (E''), representing the viscous behaviour. The ratio of E'' to E' is known as $\tan \delta$ and is a measure of damping, this indicates how good a material will be at absorbing/dissipating energy. A higher $\tan \delta$ indicates greater damping behaviour whereas a lower value means that it will absorb more energy. This value usually falls between zero and one and is dependent on the state of the material, its temperature and the applied frequency of oscillation.

2. EXPERIMENTATION

2.1 Materials and Manufacturing

A polyurethane (PU) based LEP which contains pigments, polyol chain extenders, and antioxidants was used without further purification. Mixing of the components was conducted with care to not entrap air and to result in an optimal thickness, where no voids were visible in the specimen. Specimens were cast into silicon moulds forming rectangular samples (60 mm x 10 mm x 2 mm) and cured under atmospheric pressure and temperature following the manufacturer's recommended procedure. The chosen dimensions were determined to be the optimal geometry range for the DMTA dual cantilever clamping setup. Samples with visible voids or surface curvature were discarded. Specimens were left for a further two weeks under constant extraction to allow for any further cure to occur.

2.2 Dynamic Mechanical Thermal Analysis

The cured samples were analysed in dual cantilever mode using a TA Q800 with an ACS chiller. The linear viscoelastic region was determined by strain sweeps defined by a 5 % decrease in E' and all subsequent tests were performed within this range. Temperature sweeps were carried out from -50 °C to +90 °C at 10 °C/min, with an amplitude of 50 μm , and an oscillation frequency of 1 Hz. Frequency sweeps for Time Temperature Superposition (TTS) were performed between -50 °C and +60 °C, with an amplitude of 15 μm . The oscillation frequency was varied between 0 - 100 Hz.

2.3 Application of The Time Temperature Superposition Principle

Having acquired the data using DMTA experiments, the time temperature superposition (TTS) method can be applied, as this allows the viscoelastic behaviour of linear polymers to be studied over a wider range of temperatures and frequencies than could be obtainable directly from experimental results [8]. The TTS methodology states that there is a mutual correspondence between the frequency and temperature effects. Consequently, the observed change in mechanical properties induced by a variation of temperature can be identical to the one produced by a variation in frequency if the material can be defined as thermorheologically simple [9], [10]. This means that all the retardation/relaxation mechanisms of the material have the same temperature dependence and stress magnitudes at all times. Most amorphous polymers fulfill this criteria however crystalline polymers and many composite materials do not as each of the phases can possess different temperature dependencies and relaxation mechanisms. Furthermore, if any phase transitions (e.g. freezing or melting) occur during the

area of interest the material will not be considered thermorheologically simple. Analysis temperatures above the reference temperature shift to lower frequencies, while observed temperatures below shift to higher frequencies. The value of the shift distance is dependent on the reference temperature selected and the material properties of the polymer being tested.

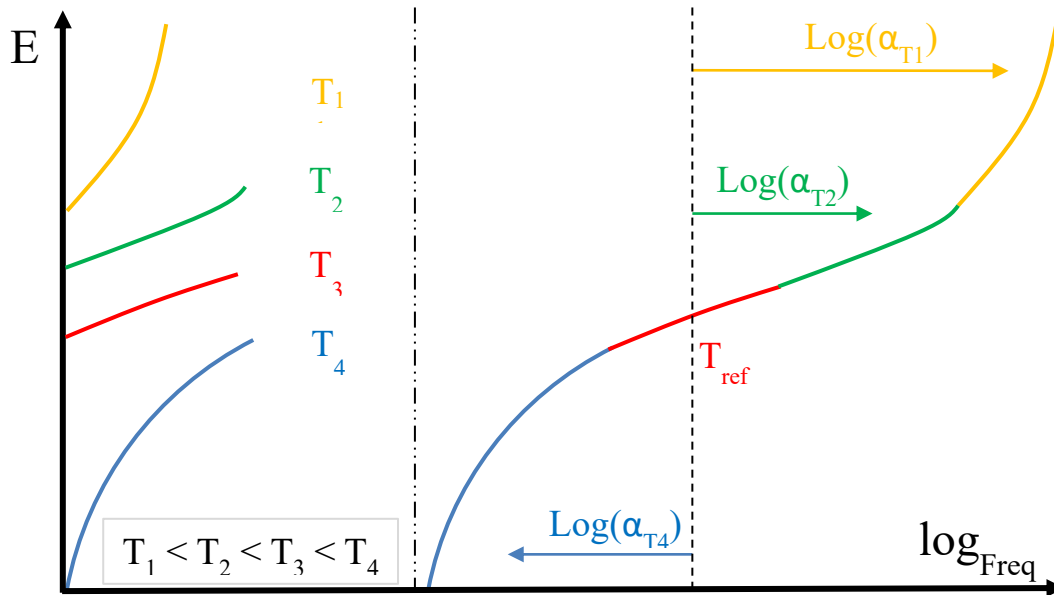


Figure 4. Schematic representation of the time temperature superposition methodology, and construction of the master curve from frequency sweep data at varying temperatures. Shift factors calculated from equation 1. Adapted from [11].

This process of transposing the data across the log frequency axis is called the frequency-temperature shift factor α_T and is defined by Equation 1:

$$\alpha_T = \frac{f_0}{f_T} \quad \text{Equation 1}$$

where f_0 is the frequency at which the material displays the same response as the reference temperature T and f_T is the frequency at which the material reaches a particular response at temperature T . These shift factors are determined from the experimental data by shifting the curves obtained at different temperatures along the frequency axis. This should result in either partial or complete overlap depending on the temperature intervals tested and creates a curve that displays the predicted behavior of the polymer as a ‘master curve’.

3. RESULTS AND DISCUSSION

3.1 The Influence of Temperature on Viscoelastic Behaviour

The initial experiments were performed by subjecting the PU LEP to a dynamic mode analysis with a sweep from -40 °C to +50 °C to determine the influence of temperature on the dynamic moduli. The temperature range was selected to represent a realistic working range for an offshore wind turbine in colder and warmer climates. The storage modulus (Figure 2) is maximal at the lowest measured temperature of -40 °C at approximately 3660 MPa, but begins to fall almost immediately (-40 °C) as the PU undergoes a glass transition, associated with a

significant increase in chain segmental motion (correspondingly the maximum response in the loss modulus is observed at -20 °C). In this temperature regime, the PU changes from a more rigid glassy state to a more compliant rubbery state and is accompanied with a loss a mechanical performance as the storage modulus falls to approximately 37 MPa. The $\tan \delta$ reflects the intrinsic ability of the material to dissipate energy and the response reveals two transitions: a maximum at around 34 °C, where the damping is maximal, and a lower temperature shoulder from -20 °C to 30 °C. The mechanical damping response doubles over a typical working temperature range (*i.e.* -20 °C to +34 °C) from 0.20 to 0.48, which could offer the greatest protection to impacts.

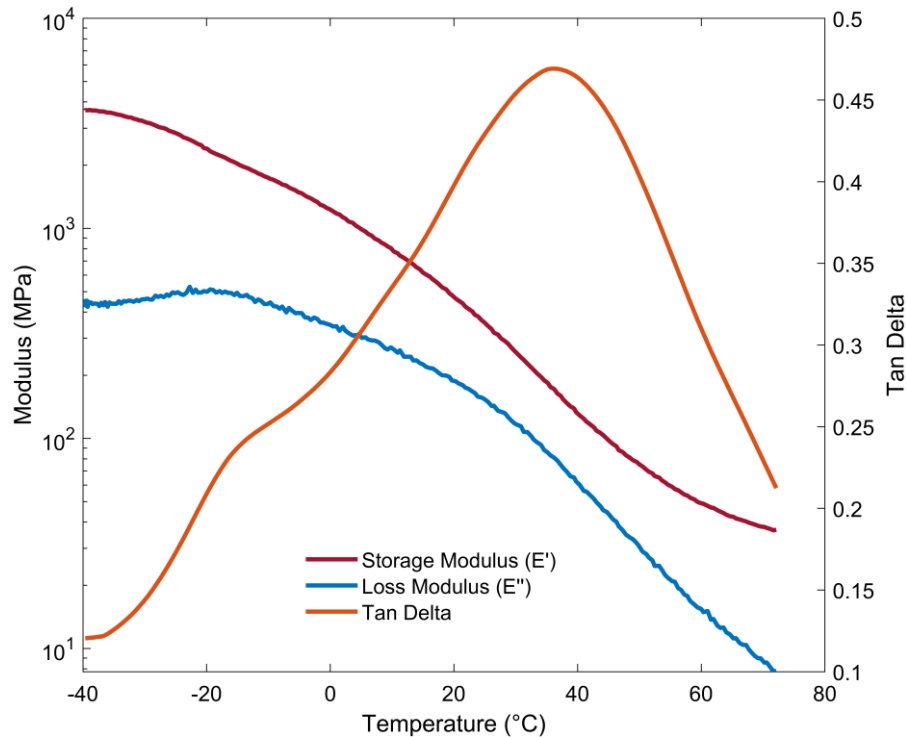


Figure 2. DMTA Temperature sweep data for the PU LEP acquired over -50 °C to +60 °C and amplitude of 50 μm and frequency of 1 Hz: storage modulus (red), loss modulus (blue), and $\tan \delta$ (orange) acquired as a function of temperature.

3.2 The Influence of Frequency On Viscoelastic Behaviour

Frequency sweeps were conducted which involved varying the frequency of the oscillation from 1 to 100 Hz to yield the frequency dependent data (Figure 3). As with other viscoelastic materials, the higher frequencies induce more elastic-like behaviour where the storage modulus is maximised at 1200 MPa. Lower frequencies induce more viscous-like behaviours indicating strain rate sensitivity, as expected for a viscoelastic material. The combination of viscous and elastic behaviour can be visualised using the Kelvin-Voight model involving a combination of a dashpot and spring respectively [12].

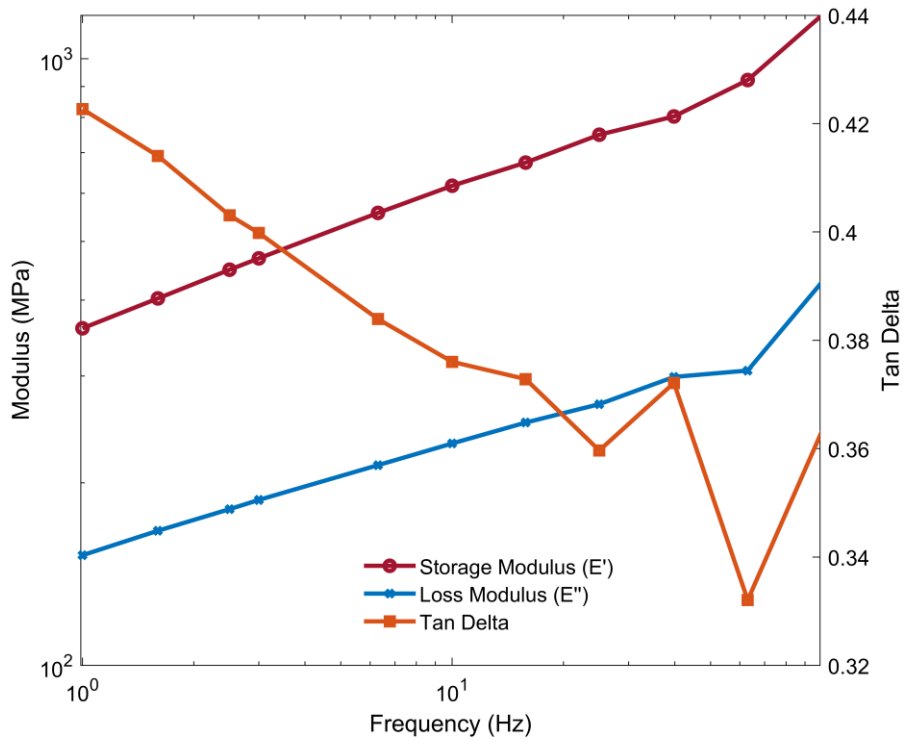


Figure 3 DMTA frequency sweep data for the PU LEP acquired over 1 to 100 Hz, amplitude of 15 μm and at constant 10°C: storage modulus (O), loss modulus (*), and tan δ (\square) acquired as a function of frequency.

3.3 Application of The Time Temperature Superposition Principle

The frequency sweep over the temperature were combined to create the master curve (Figure 5) over the range 10^{-2} - 10^{10} Hz.

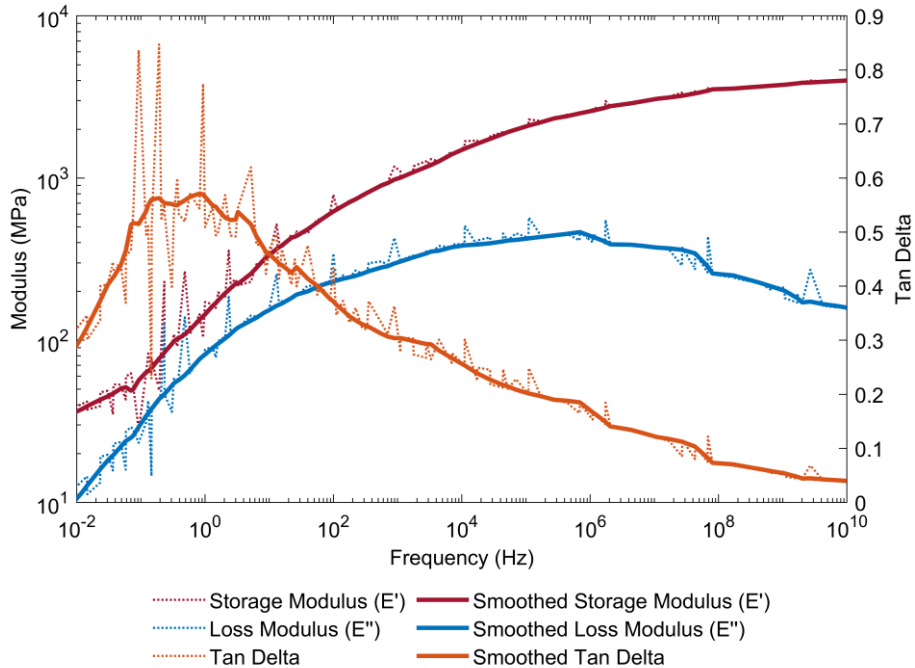


Figure 5. DMTA master curve constructed using the TTS principle for the PU LEP acquired over 1 to 100 Hz, amplitude of 15 μm and a T_{ref} of 10°C: storage modulus (red), loss modulus (blue), and tan δ (orange) acquired as a function of frequency. Data smoothed using ‘Lowess’ robust local regression smoothing.

An increase in the storage modulus was observed over the extended frequency range. However the loss modulus begins to plateau and decrease at approximately 10^6 Hz. This results in a $\tan \delta$ peak at approximately 1 Hz followed by a decrease in the value. This is potentially important for rain erosion performance as this value is related to the damping behaviour of the material. A change in this value will affect a number of key parameters such as the ability of the material to dissipate energy and the speed at which sound passes through a material. These data show that there is a significant difference between the dynamic properties of a material at low frequency testing when compared to higher frequency testing which is predicted to be applicable to rain impacts and highlight that these factors should be considered in lifetime prediction modelling of rain impact erosion.

The data presented displays repeating peaks which could be attributed to resonance of the material. During resonance, the instrument cannot collect sensible data as the strain measured by the instrument will be out of phase with the stress and will not reflect the mechanical properties of the material. The larger variations below 1 Hz could be due to the temperature exceeding the T_g of the material causing the validity of the TTS to breakdown at these frequencies. To mitigate this in the future, replicates of these sweeps could be conducted to identify these points or as in this work smoothing can be used to fit the data, decreasing the weight of outliers in an attempt to reduce their effect on fitting the data.

The rationale for employing DMTA was to access a frequency domain compatible with the impact of rain droplets on a wind turbine blade, which is predicted to be 10^6 - 10^9 Hz. Notably, using this master curve prediction, in this frequency regime the damping is of a significantly lower magnitude compared with the value obtained using the quasi-static condition of conventional testing, *i.e.* 1 Hz, which yields higher damping ($\tan \delta$) and lower modulus. However, it is important to note that these measurements were undertaken at a reference temperature of 10 °C and varying this analysis temperature also shifts the peaks, resulting in a change in material behaviour.

3.3 Comparison of Modulus Against Strain Rate

A transformation of data was performed according to a previously reported method by *Zeltmann et al.* [13], wherein the material response was taken from the master curve (in the frequency domain) and translated into the time domain in order to obtain the relaxation modulus (Figure 6). From E' , the time domain relaxation modulus $E(t)$, an expression representing the gradual decrease of stress when held at constant strain, can be found using:

$$E(t) = \frac{\sigma(t)}{\varepsilon_0} = \frac{2}{\pi} \int_0^{\infty} \frac{E'(\omega)}{\omega} \sin(\omega t) d\omega \quad \text{Equation 2}$$

where σ is a constant stress, ε_0 is the initial strain, ω is the angular frequency and t time.

The relaxation modulus $E(t)$ is a characteristic of material viscoelasticity as used to describe the stress relaxation of materials with time. Stress relaxation describes the material's tendency to decrease its load generation when held under a constant strain or deflection.

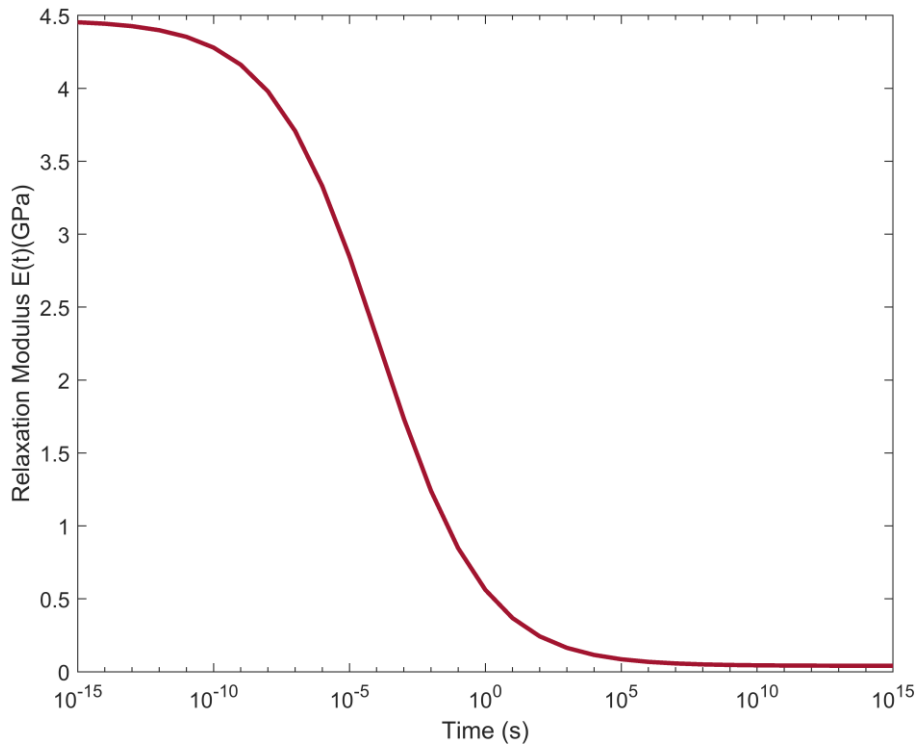


Figure 6. Time domain relaxation function converted from master curve and equation 2 for the LEP.

As viscoelastic materials have significant molecular mobility at the temperatures of interest they have the ability for coordination motion along the chain backbone [14]. Under conditions where the test rate is fast relative to this relaxation time the molecules do not have time to displace during loading. Under conditions where the test rate is very slow the material can relax to the loading resulting in sigmoidal curves. The relaxation modulus is variable and depends on both the strain rate and temperature, which in this case is 10 °C. In terms of rain erosion behaviour this demonstrates the importance of the timescale of the stress applied as it results significantly differing responses. This also raises the question if the coatings themselves undergo any stress relaxation over their lifetimes due to residual stress from cure or flexure of the blades.

Following *Zeltmann's* method the predictions of elastic modulus are evaluated as the secant modulus at 2.5 % strain from the stress-strain values generated from the relaxation function using:

$$\sigma(t) = \dot{\epsilon} \int_0^t E(\tau) d\tau \quad \text{Equation 3}$$

where σ , $\dot{\epsilon}$ and t represent stress, strain rate and a time variable used for integration, respectively.

Using this procedure the elastic modulus at any strain rate can be calculated. The relaxation modulus was finally used to yield a linear relationship predicting the actual Young's modulus of the PU LEP over a range of strain rates (Figure 7). Owing to the manner in which the data are calculated, the relationship breaks down at the extremes as there may be other mechanisms that occur outside of our testing ranges and so are not entirely reliable.

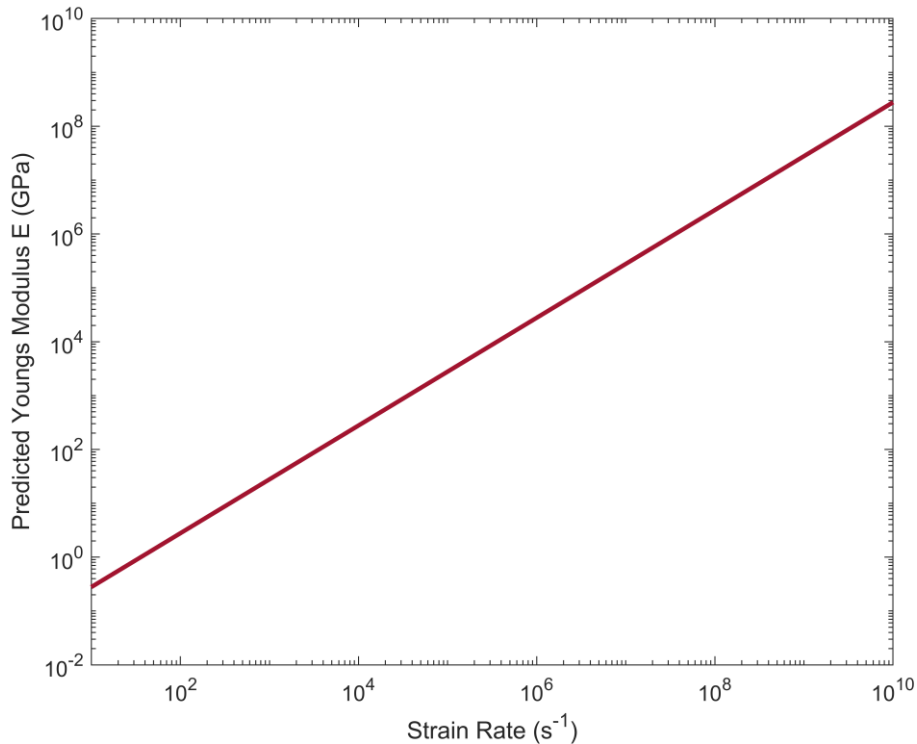


Figure 7. Predicted Young's modulus of the PU LEP as a function of strain rate.

Young's moduli obtained using conventional quasi-static test methods for selected commercial PUs and it is clear that the Young's modulus varies significantly from quasi-static test conditions (0.278 GPa at 1 s⁻¹) to more representative high strain rate impacts (10⁶ GPa at 10⁸ s⁻¹). These differences could have implications on the lifetime prediction of coating systems such as the calculation of the water hammer pressure in the Springer damage model [15]. Increases in modulus result in increased water hammer pressures that may exceed the yield strength of the material. Alternatively this may cause mismatches between layers that alter the ratio of wave reflected and transmitted through the multilayer system.

However, it must be noted that this transformation assumes a linear material and relies upon the master curve data which can also be inaccurate due to the assumption of TTS such as missing certain transition outside the temperature range tested. This work requires validation using high strain rate methods such as Split-Hopkinson pressure bar which can operate at strain rates of up to 10⁵ s⁻¹.

3.4 Risks and Limitation Of Data

While the data obtained may not offer absolute accuracy, they do offer an indication of the trends that might be expected to occur for viscoelastic materials and are thus of potential use when characterising new materials or conducting lifetime predictions of LEP coatings. This method uses conventional equipment that is common in material laboratories to obtain the dynamic responses. Potential limitations are the sensitivity and operating ranges (stresses, strains, temperatures) of the equipment, but most modern equipment should be adequate. Treatment of the raw data can either be conducted using manufacturer supplied software to obtain master curves data or computed using other software. Future work will aim to improve the accuracy of this method and extend the data set. To the knowledge of the author this method

has not been combined with lifetime prediction modelling of the rain erosion for LEP coatings in literature.

4. CONCLUSIONS

This paper presents dynamic mechanical data for a commercial prototype Leading Edge Protection (LEP) material when characterised using the Dynamic Mechanical Thermal Analysis (DMTA) method, to identify key parameters, reflecting the performance of a Polyurethane (PU) LEP under representative frequency conditions. The data have been used to predict higher frequency responses more representative of a PU LEP in-service condition, by using the Time Temperature Superposition methodology. This Time Temperature Superposition (TTS) result was then transformed to yield first relaxation data, and a prediction for the Young's Modulus as a function of strain rate. Simulations predict that rain droplet impacts on wind turbine blades can result in extreme strain rates (10^5 to 10^9 s⁻¹) through the water hammer phenomenon. However, with the use of viscoelastic materials, changes in their mechanical behaviour are observed due to the dependence on time (strain rate/frequency), temperature and amplitude of deformation. These findings offer an additional design tool to predict and modify the damping response, to achieve optimum damping characteristics. However, improvements to the method, accuracy and validation of approach are required.

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