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Dynamic mechanical analysis of polymeric systems of pharmaceutical and biomedical significance

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Abstract

Dynamic mechanical analysis (DMA) is an analytical technique in which an oscillating stress is applied to a sample and the resultant strain measured as functions of both oscillatory frequency and temperature. From this, a comprehensive knowledge of the relationships between the various viscoelastic parameters, e.g. storage and loss moduli, mechanical damping parameter (tan δ), dynamic viscosity, and temperature may be obtained. An introduction to the theory of DMA and pharmaceutical and biomedical examples of the use of this technique are presented in this concise review. In particular, examples are described in which DMA has been employed to quantify the storage and loss moduli of polymers, polymer damping properties, glass transition temperature(s), rate and extent of curing of polymer systems, polymer–polymer compatibility and identification of sol–gel transitions. Furthermore, future applications of the technique for the optimisation of the formulation of pharmaceutical and biomedical systems are discussed.

Keywords: Dynamic mechanical analysis; Viscoelastic; Sol–gel; Polymer; Glass transition; Gel

1. Introduction

Modern polymeric biomaterials have found widespread applications in medical and veterinary sciences, particularly as components of drug delivery systems and medical devices. It is accepted that the rheological (mechanical) properties of biomaterials directly affect their clinical performance (Jones et al., 1997a,b). Therefore, in the development of both pharmaceutical and biomedical systems, it is important to accurately and usefully characterise their rheological properties to ensure optimisation of their design, and hence performance.

There are several techniques that may be employed to rheologically/mechanically characterise polymeric systems (Craig and Johnson 1995).

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These include:

1. Thermomechanical analysis, in which a non-oscillatory stress is applied to the sample and the resultant deformation (strain) measured as a function of temperature. One example of this technique is creep analysis.
2. Thermodilatometry, in which the sample is exposed to a range of temperatures and changes in the dimensions of the sample recorded.
3. Dynamic mechanical analysis, a non-sample destructive technique in which an oscillatory stress is applied to the sample and the resultant strain determined as a function of both frequency and temperature. Examples of this technique include thermal-ramped oscillatory rheometry and conventional dynamic thermal mechanical analysis. Dynamic mechanical methods enable accurate and rapid quantification of the viscoelastic properties of pharmaceutical and biomedical systems

1.1. Common terms used in dynamic mechanical analysis

At this point, it may be useful to provide definitions of the commonly employed terms in dynamic mechanical analysis (Ferry, 1980; Barnes et al., 1996). These are:

Stress, the force per unit area (Pa) required to deform the sample.

Strain, the amount by which the sample is deformed. In dynamic mechanical analysis the strain is termed amplitude (distance), due to the vertical nature of the deformation, whereas, in oscillatory rheometry, the strain is horizontal (torsional) and is measured in radians.

Damping, the ability of a material to dissipate applied mechanical energy into heat (dimensionless quantity).

Modulus, the resistance of a materials to deformation (Pa).

Dynamic mechanical techniques have been widely employed in the polymer, and related industries, however, the applications of such techniques for the characterisation of pharmaceutical and certain biomedical systems have not received similar attention. In light of this, the aims of this review are, firstly, to describe the theoretical and practical basis of dynamic mechanical techniques and, secondly, to provide an overview of reported, and future, applications of the techniques for the characterisation of pharmaceutical and biomedical systems.

2. Theory of dynamic mechanical analysis

Dynamic mechanical methods characterise the viscoelastic properties of materials as functions of both frequency of applied oscillatory stress (or strain) and temperature. The term *viscoelastic* has been defined as the 'simultaneous existence of viscous (liquid) and elastic (solid) properties in all materials' (Barnes et al., 1996). The rheological behaviour of ideal solids is mathematically described by Hooke's Law, which states that the strain of a sample is directly proportional to the applied stress, the proportionality constant being referred to as Young's modulus. Importantly, ideal solids may be observed to recover completely following removal of an applied stress. This phenomenon is depicted in Fig. 1. Deviations from ideality occur whenever the elastic limit of the solid material is exceeded, i.e. irreversible sample deformation has occurred (Craig and Johnson, 1995; Barnes et al., 1996). Conversely, for ideal liquids, Newton proposed that the applied stress is proportional to the rate of strain (the velocity gradient), the proportionality constant in this case being referred to as the viscosity. Therefore, the response of ideal liquids to an applied stress is time dependent, i.e. dependent on the rate of strain and not the strain itself (Barnes et al., 1996). Deviations of liquids from ideality also

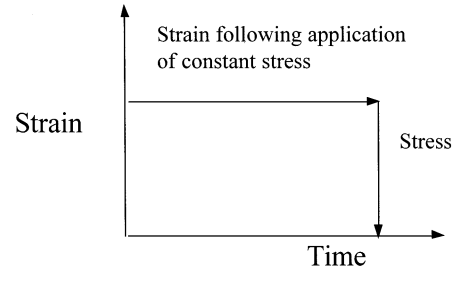

Fig. 1. The elastic response of an ideal solid.

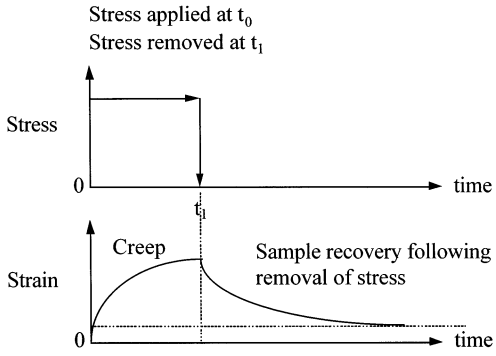

Fig. 2. Characteristic deformation (creep) of viscoelastic solids as a function of time.

occur in which the relationship between stress and the rate of strain is non-linear, e.g. pseudoplastic (shear thining) systems and dilatant (shear thickening) systems. Thus, solid bodies store applied energy and use this to recover from the deformation induced by the applied stress, whereas, liquids dissipate applied energy as heat and hence are unable to recover their structure (Ferry, 1980; Barnes et al., 1996). Interestingly, many polymeric systems exhibit behaviour that combines both elastic (solid) and viscous (liquid) properties, in which the applied stress is proportional to both the resultant strain and rate of strain. Such systems are termed viscoelastic. Common characteristics of viscoelastic systems include (Ferry, 1980; Ward and Hadley, 1993; Craig and Johnson, 1995):

1. Following application of a constant stress, viscoelastic solids do not maintain constant deformation, but continue to deform as a function of time. This phenomenon is referred to as creep and is depicted in Fig. 2.
2. During the process of flow, a viscoelastic liquid may store some of the applied energy and use this energy to partially recover from the stress-induced deformation.

The majority of measurements of viscoelastic properties of polymeric systems are performed within a region referred to as the linear viscoelastic region. In this region, as the stress applied to a sample is increased, the relationship between the stress and strain is constant, despite the variance of strain with time. Measurement of viscoelasticity within this region ensures a relatively simple interpretation of results.

Comprehensive mathematical treatments of the theory of dynamic mechanical analysis have been previously described elsewhere (e.g. Ferry, 1980; Ward, 1983; Ward and Hadley, 1993) and consequently, only an overview of the theory is described below. In dynamic mechanical analysis, a sinusoidal stress (or strain) is applied to the sample and the mechanical response measured as functions of both oscillatory frequency and temperature. For a Hookean solid, the maximum strain is observed at the same instance as the maximum applied stress (Fig. 3), i.e. the applied energy is employed to allow instantaneous recovery from deformation. Conversely, a Newtonian liquid will exhibit a 90° phase lag to an applied stress, i.e. the strain lags behind the stress by 90° (Fig. 4). Viscoelastic materials will exhibit phase angles between these two extremes (0–90°) (Fig. 5).

The stress and strain in dynamic mechanical analysis is mathematically described by the following equations, respectively (Barry, 1974; Wetton et al., 1991; Craig and Johnson, 1995; Anseth et al., 1996):

$$\sigma^* = \sigma_0 \exp[i(\omega t + \delta)] \quad (1)$$

$$\gamma^* = \gamma_0 \exp(i\omega t) \quad (2)$$

where $i^2 = -1$ and δ is the phase angle between the stress and strain.

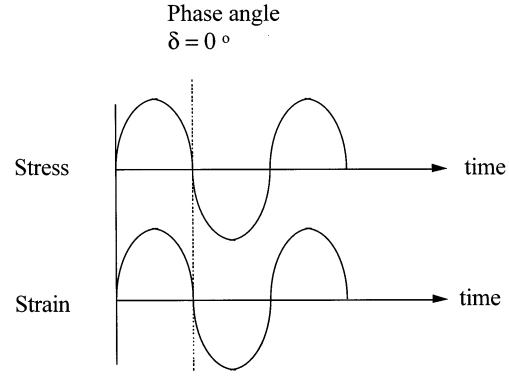

Fig. 3. Instantaneous response (strain) of an ideal solid following application of an oscillatory stress. Note: the phase angle between the applied stress and resultant strain is 0°.

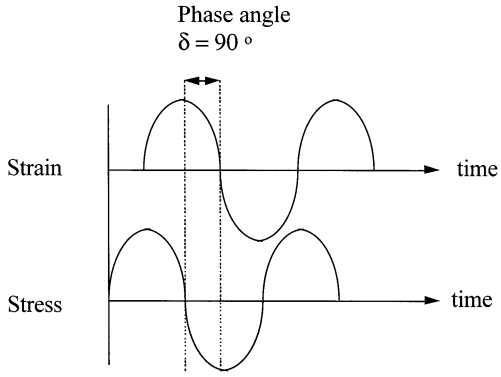

Fig. 4. Time-dependent response (strain) of an ideal (Newtonian) liquids following application of an oscillatory stress. Note: the phase angle between the applied stress and resultant strain is 90°.

A complex modulus may therefore be defined as follows:

$$G^* = G' + iG'' = \frac{\sigma^*}{\gamma^*} \tag{3}$$

G' is referred to as the storage (real or elastic) modulus and represents the energy stored per cycle within the sample (i.e. the 'solid' response). G'' is refered to as the loss (imaginary or viscous) modulus and represents the energy dissipated per cycle within the sample (i.e. the 'liquid' response).

Combining Eqs. (1)–(3), one obtains the following Eq. (4) (Barry, 1974; Anseth et al., 1996)

$$G^* = \frac{\sigma_0 \exp[i(\omega t + \delta)]}{\gamma_0 \exp(i\omega t)} \tag{4}$$

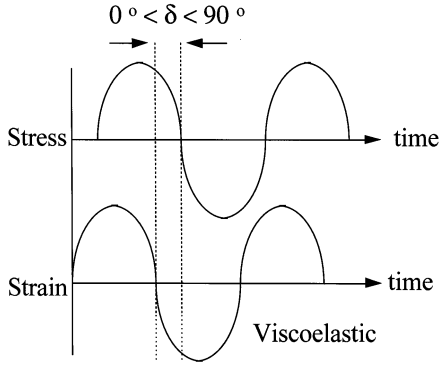

Fig. 5. Stress–strain relationships for viscoelastic materials.

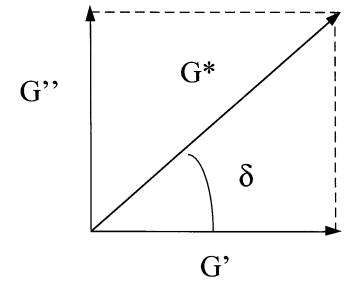

Fig. 6. Vectorial diagram for the complex modulus ($G^* = G' + iG''$).

$$G^* = \frac{\sigma_0}{\gamma_0} \exp[i(\omega t + \delta)] \exp(-i\omega t)$$

$$G^* = \frac{\sigma_0}{\gamma_0} \exp(i\delta) \tag{5}$$

The expression '$\exp(i\delta)$' may be defined as follows:

$$\exp(i\delta) = \cos\delta + i \sin\delta \tag{6}$$

Substituting Eq. (6) into Eq. (5), one obtains the following:

$$G^* = \left(\frac{\sigma_0}{\gamma_0}\right) \cos\delta + i\left(\frac{\sigma_0}{\gamma_0}\right) \sin\delta \tag{7}$$

Allowing:

$$G' = \left(\frac{\sigma_0}{\gamma_0}\right) \cos\delta$$

$$G'' = \left(\frac{\sigma_0}{\gamma_0}\right) \sin\delta$$

Thus:

$$G^* = G' + G''$$

The relationship between the complex modulus (G^*), storage modulus (G') and loss modulus (G'') may be represented using a vectorial diagram (Fig. 6).

3. Pharmaceutical and biomedical applications of dynamic mechanical analysis

Dynamic mechanical analysis is a versatile technique that may be used to simultaneously characterise both the rheological and thermal properties

of a wide range of sample types. In particular, the development of modern sample clamping systems (geometries) allows for the rapid thermorheological characterisation of many pharmaceutical and biomedical systems, ranging from viscoelastic liquids to rigid viscoelastic polymeric films. Typically, the following information concerning polymeric systems may be obtained using dynamic mechanical analysis:

1. Quantitative modulus, i.e. storage and loss moduli
2. Glass transitions (primary, secondary etc.)
3. Rate and extent of polymeric curing
4. Quantification of gelation, e.g. sol–gel transitions
5. Damping properties, i.e. characterisation of the ratio of loss to storage moduli at defined temperatures
6. Polymer morphology/compatibility
7. Interactions between polymeric components or between drug molecules and polymeric constituents of pharmaceutical/biomedical systems.

It is important to note that this is not an exhaustive list of applications of dynamic mechanical analysis, however, relevant pharmaceutical and biomedical examples of many of these applications will be considered in this review.

4. Dynamic thermal analysis of polymeric gel systems

A gel may be defined as a cross-linked polymer network that is swollen in a liquid solvent (Ross-Murphy, 1995). Pharmaceutical and biomedical applications of gel systems include, topical drug delivery systems (Jones et al., 1997a), electrically-conductive interfaces (Jones et al., 1997c), implantable drug delivery systems (Rao et al., 1994) and as artificial body fluids, e.g. aqueous and vitreous humour. Dynamic mechanical methods have been suucessfully employed to characterise the thermorheological properties of gel systems, examples of which are described below.

4.1. Characterisation of temperature dependent sol–gel transitions in gel systems

Poloxamers are commercially available block co-polymers of polyoxyethylene and polyoxypropylene that have been employed for the topical administration of drugs to, e.g. the skin (Suh and Jun, 1996), eye (Miller and Donovan, 1982) and to the periodontal pocket (Esposito et al., 1996). These materials undergo a temperature-dependent sol–gel transition that dramatically affects their rheological properties, and hence, their clinical efficacy (Brown et al., 1997, 1998). In our laboratories, dynamic thermal methods have been employed to characterise the effects of formulation components, e.g. addition of pharmaceuticaly-acceptable co-solvents, molecular weight of the Poloxamer system and the presence of therapeutic drug substances, on their thermorheological properties. The characteristic sol–gel transition of poloxamer in a mixed solvent system (90:10 water:propylene glycol) is graphically displayed in Fig. 7. Increasing the average molecular weight of poloxamer increased the sol–gel temperature whereas increasing co-solvent concentration (ethanol, propylene glycol or glycerol)

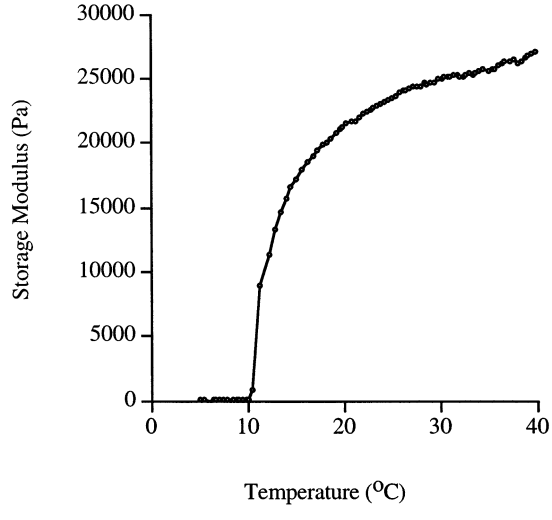

Fig. 7. Plot of elastic modulus against temperature for poloxamer 407 (25% w/w) in a mixed solvent system (90:10 water:propylene glycol), illustrating the temperature-dependent transition in elastic modulus (sol–gel transition).

decreased this parameter. These observations may be attributed to the effects of the aforementioned formulation variables on the ability of adjacent poloxamer chains to desolvate and form cross-linked aggregates. Subsequently, these formulations would be expected to exhibit different clinical efficacies and, indeed, patient acceptabilities. Similarly, the sol–gel transitions of other pharmaceutical and related systems have been reported using dynamic mechanical methods, e.g. cellulose in an ammonia/ammonia thiocyanate solvent system (Frey et al., 1996), hydroxyethylated starch aqueous systems (Jauregui et al., 1995), agarose in a dimethyl sulphoxide/water solvent system (Watase and Nishinari, 1988).

4.2. Characterisation of rheological properties of gel systems

Dynamic thermal methods may also be effectively employed to gain an understanding of the structure of gel systems, the determinant of gel rheology. In a series of publiations, Watase and Nishinari (1988, 1989, 1993) examined the relationships between structure and gelling characteristics of agarose, polyvinyl alcohol, and high methoxyl pectin–water gels in mixed solvent systems composed of dimethyl sulphoxide (DMSO) and water. The authors described the significant effects of DMSO, a co-solvent that interacts with, and alters the structure of water, on the gel structure and hence on the sol–gel transition. The rheological properties and compatibility of mixed gels composed of the polysaccharide κ-carrageenan and various galactomannans (locust bean gum, tara gum and guar gum) has been described by Muruyama et al. (1995). The elastic properties of κ-carrageenan were improved by the addition of locust bean gum (primarily) or tara gum and were accredited to the binding of the 'smooth zone' of the galactose portion of these gums to the double helix of κ-carrageenan. Conversely, the presence of guar gum did not enhance the elastic properties of gels of κ-carageenan.

Dynamic mechanical analysis was also employed by Jauregui et al. (1995) to examine the effects of concentration of hydroxyethylated starch in an aqueous solvent on their thermorheological properties. It was reported that, depending on the concentration of polymer, three viscoelastic regions were identified. Firstly, at low concentrations, a fluid-like zone, corresponding to a homogeneous solution in which there were no interactions between polymeric chains, was observed. Secondly, at intermediate concentrations, the fluid-gel transition zone was apparent in which specific intermolecular interactions between adjacent polymer chains were operative. Finally, at high concentrations, rheological measurements suggested the presence of a structured network, the gel-like zone. This study highlights the gradual attainment of organisation of gel systems, and the impact of such structural properties on thermomechanical properties. It is important to note that similar, concentration-dependent, rheological properties are operative in numerous other pharmaceutical and biomedical gel systems.

5. Dynamic thermal analysis of solid polymeric systems of pharmaceutical and biomedical significance

Solid polymeric systems are extensively employed in the design of pharmaceutical and biomedical systems. For example, polymeric films are used as components of packaging systems, as coatings of solid dosage forms and as integral layers of transdermal drug delivery systems and wound dresings, whereas, many medical devices (e.g. dental prostheses, catheters, ureteral stents) are exclusively solid (viscoelastic) polymeric systems. In many of these examples, the mechanical properties of the solid polymeric components are essential for their performance, e.g. to ensure efficient mastication, conductance of body fluids (urine, peritoneal dialysate, cerebrospinal fluid), to offer effective protection to compromised sites (wound dresings) and to prevent the rapid release (burst) of therapeutically active agents. Dynamic mechanical analysis may be usefully employed to provide information concerning the mechanical properties of solid polymeric systems, e.g. glass transition (T_g) temperature(s) and formulation effects on this parameter, compatibility of polymer blends, quantification of moduli, damping proper-

ties and rate of curing of polymeric systems. Examples in which dynamic mechanical methods have been employed to provide such information are described below.

5.1. Characterisation of glass transition temperatures of solid polymeric systems using dynamic mechanical methods

Polymeric systems (amorphic, semi-crystalline and crystalline) exhibit distinctive temperature-dependent effects on their viscoelastic properties. In amorphous polymers (primarily), a primary relaxation transition, referred to as the glass transition (T_g), may be observed at a characteristic temperature, at which there is conversion of the polymer from a glass-like state, in which there is restricted motion of the polymeric chains, to a rubber-like state in which there is a loss in rigidity (i.e. increased relaxation) associated with enhanced polymeric chain mobility (Ferry, 1980; Ward and Hadley, 1993). In addition, there may be several other temperature-dependent relaxations associated with primarily amorphous polymer systems that may be associated with structural features, e.g. temperature-dependent mobility of side groups. The ability of dynamic mechanical methods to accurately detect changes in the moduli of polymeric systems forms the basis of the experimental determination of glass transition temperatures (Ferry, 1980). Typically, the glass transition is defined as the temperature(s) at which either a maximum in the mechanical damping parameter (tan δ) or loss modulus (G'') occurs. Fig. 8 shows the characteristic generic temperature dependency of modulus in an amorphous polymer system. A further example of this is presented in Fig. 9 in which the relationship between the loss modulus of a congeneric series of polymethacrylate esters and temperature is presented (Heijober, 1965). From this, three of the four relaxations (T_g) in these polymers may be observed and are denoted as α, β and γ, designated in alphabetical order as a function of decreasing temperature. The primary transition (α) may be attributed to increased mobility of main polymeric chains, whereas, the β and γ transitions may be accredited to either side group mobility and/or end group motions of the main polymeric chains.

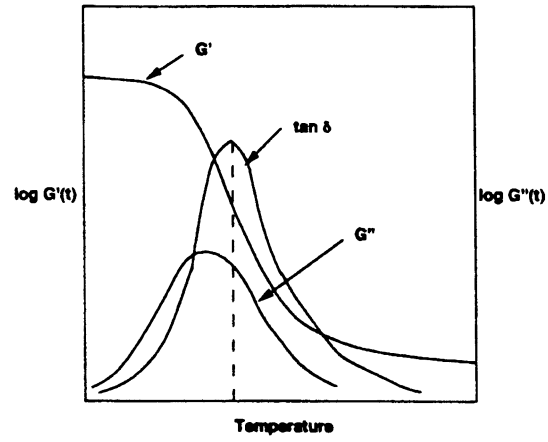

Fig. 8. Graphical representation of the relationship between modulus and temperature for a viscoelastic polymer system (reproduced with permission from Anseth et al., 1996)

Several studies have employed dynamic mechanical methods to elucidate relaxation processes in cellulose polymers and other polysaccharides. For example, Rials and Glasser (1988), using differential scanning calorimetry and dynamic mechanical analysis, described three distinct relaxation transitions for hydroxypropylcellulose films (cast from dioxane and acetone) that were attributed to three phases, namely amorphous, crystalline and intermediate. Cross-linking of this polymer using toluene diisocyanate increased the glass transition temperatures. Similarly, dynamic mechanical analysis has been successfully employed to determine glass transitions within other cellulose polymers, e.g. hydroxyethylcellulose, hydroxypropylmehylcellulose and hydroxypropylcellulose (Kararli et al., 1990). In many cases, the greater sensitivity of dynamic mechanical analysis for the determination of discrete glass transitions has been reported. Kim et al. (1994) described the thermal characteristics of chitin and hydroxypropyl chitin, materials that have received recent attention for their potential applications for drug delivery and as medical devices. The α transitions for chitin and hydroxypropylchitin were 236 and 252°C, respectively. In addition, β transitions, associated with the presence of acetamide groups, were observed at 143°C in both polysaccharides and, furthermore, a further β transition was ob-

served at 105°C for hydroxypropylchitin that was accredited to the relaxation of the hydroxypropyl moiety. This latter transition was only observed using dynamic mechanical analysis.

Dynamic mechanical methods have also been employed to evaluate chemical and formulation effects on the glass transitions of polymeric systems. For example, these techniques may be used to quantify the ability of plasticisers to lower the glass transition temperature of polymers and, additionally, to assess the compatibilty of plasticisers with polymeric systems. Consequently, the resolution of the loss tangent peak (associated with the T_g) is high whenever there is good compatibility between polymer and plasticiser, whereas, peak broading is observed whenever the plasticiser has a limited solubility in the polymer system (Ferry, 1980; Ward and Hadley, 1993).

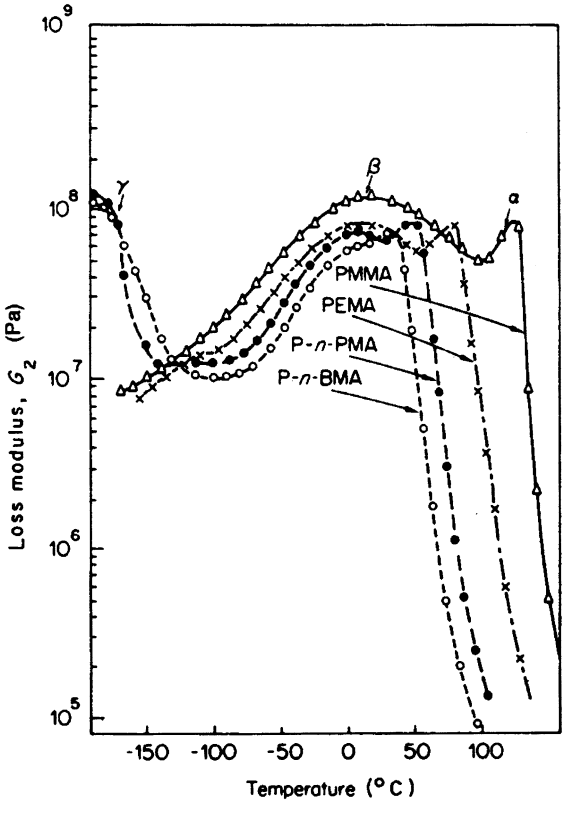

Fig. 9. Relationship between the loss modulus of a series of polymethacrylate esters and temperature is presented (reproduced with permission from Heijober, 1965).

Furthermore, dynamic mechanical methods are frequently employed to evaluate the effects of cross-linking agents and also various formulation additives on polymer T_g. As a result of reduced main chain mobility and also reduced distance between these chains (i.e. reduced free volume), the T_g of cross-linked systems is generally greater than their non-crosslinked counterparts. For example, Oysaed (1990) examined the effects of a range of chemically-related dimethacrylate cross-linking agents on the dynamic mechanical properties of multiphase acrylate systems formed by autopolymerisation of a mixture of liquid methacrylate monomers and polymethylmethacrylate (PMMA). The author reported increased T_g values as the concentrations of cross-linking agents increased. Similarly, Cascone (1997) reported elevated T_g values for cross-linked gelatin films compared with their uncross-liked counterparts.

5.2. Characterisation of thermorheological properties of pharmaceutical and biomedical polymers designed for use in the oral cavity

The viscoelastic properties of polymeric formulations designed for implantation into the oral cavity are important determinants of product performance as, within this environment, such products are exposed to oscillatory stresses often within the linear viscoelastic range (Jones et al., 1997a). Consequently, there have been several reports that have examined the dynamic mechanical properties of polymers employed as dental prostheses, e.g. dentures, temporary crown materials, bridge materials, denture soft lining materials. In a series of publications, Clarke (1989a,b,c) described the dynamic mechanical properties of heat cured poly(methyl methacrylate)-based materials, bis-phenol A-related resins and heterocyclic methacrylates, respectively. In particular, the author described their thermal viscoelastic spectra, the effects of formulation additives on these properties and the various T_g values for these materials. In addition, by plotting the logarithm of the oscillatory frequency against the reciprocal of ei-

ther the primary (α) or secondary (β) glass transition temperatures, the author calculated activation energies, i.e. the energy required to induce relaxation phenomena, within the designated samples, and additionally, examined the effects of formulation aditives, e.g. fillers, crosslinking agents, on the energy requirements for such transitions.

More recently, Vaidyanathan and Vaidyanathan (1995) reported the dynamic mechanical properties of commercially available denture base resins (Triad, Lucitone 199, Acron MC) that had been cured using a range of different energy sources (heat. microwave and visible light). This study showed that the viscoelastic properties of visible light cured denture bases were significantly different from those cured using either microwave or heat (which exhibited statistically similar properties). The observed differences were attributed to the effects of filler loading and crosslinking agents in the visible light cure resin, and indeed, it was concluded that the viscoelastic properties of this biomaterial were potentially inappropriate for the desired clinical applications. Dynamic mechanical analysis has also been employed to characterise the viscoelastic properties of commercially available denture lining materials to, firstly, derive a greater understanding of structure–property relationships of these systems and, secondly, to examine the mechanical properties under experimental conditions that simulate the rate and type of deformation that these materials would encounter in vivo. Recently Kalachandra et al. (1995) and Waters et al. (1996) examined the viscoelastic properties of commercially available soft liners. In the former study the authors described the effects of water sorption on the viscoelastic properties of four commercial materials, and significantly, highlighted the similar numerical values of G', G'' and $\tan\delta$ at 37°C, despite the obvious differences in chemical composition of each material. On the other hand, Waters et al. described differences in some of the viscoelastic properties of alternative materials and importantly, highlighted their potential clinical relevance.

5.3. Dynamic mechanical analysis of mixed polymeric systems

Frequently, polymers are physically blended to, e.g. improve mechanical properties, enhance biocompatibility or modify drug release properties. There are a number of methods by which this may be performed, including the physical blending of two or more polymers and the formation of interpenetrating networks (IPN), i.e. the combination of two or more different polymer networks that consist of purely physical entanglement of the polymer chains (Jones et al., 1997d). Following formation of these systems, dynamic mechanical methods may be readily employed to characterise their physicochemical properties in terms of, compatibility between constituent polymers, their T_g values and rheological properties. In a recent study, Jones et al. (1997d) described the dynamic mechanical properties of IPNs composed of polymethylmethacrylate (PMMA) and polyurethane (PU) that had been designed as ureteral stent biomaterials to offer greater resistance to extrinsic compression following implanation. This study exhibited the range of moduli that can be obtained by altering the ratio of these polymers, and, identified specific ratios of PMMA to PU that possessed optimal properties to resist compression yet offer comfort to the patient following implantation. Additionally, the T_g of the IPN increased (linearily) as the percentage of PMMA was increased, indicative of good compatibility between the two polymers (Fig. 10). Conversely, Tsuji and Ikada (1996) described the dynamic mechanical properties of blends of two aliphatic polyesters, poly(DL-lactide) and poly(ε-caprolactone), that have received interest as components of drug delivery systems and biomedical devices due to their biodegradability. Using dynamic mechanical analysis, the authors described the moduli of the various blends and pure components alone over a wide temperature range ($-$100–circa 60°C), from which it was concluded that phase-separation of the two polymeric components ocurred following evaporation of the casting solvent (dichloromethane). In a similar

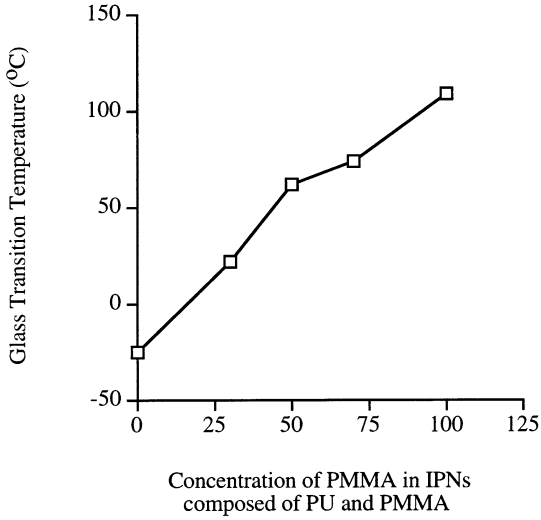

Fig. 10. Graphical representation of the relationship between primary glass transition temperature and polymeric ratio of sequential interpenetrating polymer networks composed of (poly(methylmethacrylate) and polyurethane (data transcribed from Jones et al., 1997d).

fashion, Vasquez-Torres and Cruz-Ramos (1994) employed dynamic mechanical analysis to describe the moduli and T_g properties of blends of cellulosic esters (cellulose triacetate, cellulose acetate butyrate and cellulose diacetate) and poly(ε-caprolactone) that had been prepared following solvent evaporation. The relationships between both the viscoelastic moduli and T_g and polymeric composition of the various blends allowed the authors to conclude that blends of poly(ε-caprolactone) and cellulose acetate butyrate were partially immiscible whereas blends of poly(ε-caprolactone) and either cellulose triactetae or cellulose diacetate were immiscible.

5.4. Assessment of cure of polymeric materials using dynamic mechanical analysis

Dynamic mechanical methods may be also used to characterise both the rate and extent of polymer curing/cross-linking, as such processess are associated with time-dependent changes in the elastic modulus. In a recent study, Skrovanek (1990) described the successful use of dynamic mechanical thermal analysis to evaluate both the curing rate and optimal curing temperature of candidate polymeric coatings and, additionally, the effects of catalysts on these processes. It is expected that this technique will be more frequently used for the evaluation of curing (and related processes) of pharmaceutical and biomedical polymeric systems.

6. Conclusions

This review has concisely described both the theory of dynamic mechanical analysis and, additionally, the applications of this technique for the characterisation of the thermorheological properties of pharmaceutical and biomedical systems. In particular, information may be derived concerning, polymer viscoelastic properties as functions of temperature, glass transition temperature(s), sol–gel transitions, rate and extent of polymer curing, polymer morphology and polymer-polymer compatibility. Whilst dynamic mechanical techniques have been widely employed in the polymer, and related industries, their applications for the characterisation of pharmaceutical and certain biomedical systems have not received similar attention, due, in part, to practical difficulties in sample analysis. The availability of newer sample clamps that allow for convenient dynamic analysis should overcome this problem and thus improve the acceptability of this technique to these industries. Furthermore, it is suggested that dynamic mechanical analysis may be usefully employed for the improved characterisation of pharmaceutical dosage forms and biomedical devices, with a view to optimisation of their formulation. Finally, as many implanted dosage forms/devices are subjected to oscillatory, non-destructive, stresses, dynamic mechanical analysis is a useful technique for the prediction of the effect of these stresses on their in vivo performance. The diversity of information that may be obtained from dynamic mechanical methods should ensure their establishment within the pharmaceutical and biomedical industries.

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