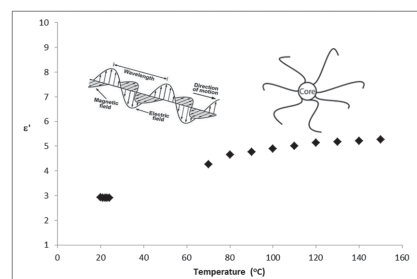


Facile Determination of Molecular Structure Trends in Amphiphilic Core Corona Star Polymer Synthesis via Dielectric Property Measurement

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The use of dielectric property measurements to define specific trends in the molecular structures of poly(caprolactone) containing star polymers and/or the interbatch repeatability of the synthetic procedures used to generate them is demonstrated. The magnitude of the dielectric property value is shown to accurately reflect: (a) the number of functional groups within a series of materials with similar molecular size when no additional intermolecular order is present in the medium, (b) the polymer molecular size for a series of materials containing a fixed core material and so functional group number, and/or (c) the batch to batch repeatability of the synthesis method. The dielectric measurements are validated by comparison to spectroscopic/chromatographic data.



1. Introduction

The last two decades have seen an increasing level of interest in the synthesis of star, branched, and hyperbranched polymers because of the differentiated material properties that they exhibit compared to their linear counterparts. For example, they have shown significant potential to deliver differentiated application performance in areas such as melt flow,^[1–3] drug/gene delivery,^[4–6] and medical imaging.^[7–9] Branched structures are of particular

interest in the case of biosourced polymers because: (a) they are typically more sensitive to processing conditions, e.g., temperature, and/or (b) the physical properties of linear biopolymers are often on the limit of viability for use in many medical, healthcare, and pharma applications.^[9]

In a recent publication, the authors reported that ring-opening polymerization (ROP) of ϵ -caprolactone (CL), using tin octanoate ($\text{Sn}(\text{Oct})_2$) as a precatalyst with a range of multifunctional initiators produced good quality 3 and 4 arm monofunctional hydrophobic and amphiphilic core corona star polymers when using both conventional (CH) and microwave (MWH) heating, i.e., they exhibited polydispersity indexes of less than 1.5.^[10]

However, the analysis of branched polymers is not straightforward and can result in much debate relative to both the: (a) type of structure that has been produced, and (b) batch to batch repeatability of the synthetic procedures used. Therefore, the development of facile analytical methods which can underpin the estimation of process repeatability and polymer chain-end number is critical to understanding, predicting, and commercially delivering the differentiated application performance of star polymers. Additionally, the authors recently reported that the direct, online measurement of polymerization

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media dielectric properties could be used to follow ROP reactions in real time.^[11]

The dielectric properties of a material are related to its complex permittivity, ϵ^* , as a function of frequency and temperature, and the manner in which they relate to the way a material interacts to incident electromagnetic energy has been extensively discussed in the literature.^[12] The ϵ^* of a material can be expressed in the form of a complex number which consists of a real part (ϵ') and an imaginary part (ϵ'') which are related by the relationship $\epsilon^* = \epsilon' - j\epsilon''$. In practical terms, the real part (the dielectric constant) is related to the ability of an electromagnetic wave to propagate within the material and therefore the ability of the material to store energy, while the imaginary part (the dielectric loss), indicates the ability that the material has to transfer this stored energy into heat inside the material via molecular motion and intermolecular friction.^[12,13] The manner in which ϵ^* influences the way that a material will interact with the incident microwave energy has been extensively discussed in the literature.^[12] In the authors' previous study of the dielectric properties of CL polymerizations to form poly(ϵ -capriolactone (PCL)), ϵ' (dielectric constant) was shown to be the most favorable dielectric property to use for such comparisons, because it exhibited the greatest differential, low error levels, and largest operational temperature window.^[11] In practice, ϵ' is related to the ability of an electromagnetic wave to propagate within the material and therefore represents the ability of the material to store energy at a particular frequency. This paper reports an investigation which has successfully extended the use of ϵ' analysis to aid in the structural determination of these branched polymers.

2. Experimental Section

2.1. Materials

The star structures used in this study were either commercially purchased from Aldrich and used without further purification (i.e., trimethylolpropane ethoxylate (TMPE), pentaerythritol ethoxylate (PTOLE), glycerol ethoxylate (GE)) or synthesized by the methods detailed in the authors' previous literature report.^[10]

2.2. Characterization

2.2.1. NMR Analysis

^1H NMR spectra on kinetic/nonprecipitated samples were recorded in deuterated chloroform (CDCl_3) using a Bruker DPX-300 spectrometer (300 MHz). For purified polymers, a Bruker DPX-400 spectrometer (400 MHz) was utilized. Chemical shifts were reported relative to SiMe_4 and were determined by reference to the residual ^1H solvent peak. Number-average molecular weight (M_n) was determined by end-group analysis using ^1H NMR spectroscopy by comparing the integral of the methylene proton resonance adjacent to the carbonyl group ($\delta = 4.1$ ppm), to that of

methylene proton belonging to the initiator ester end group (e.g., $\delta = 5.1$ ppm in linear polymers which was related to the methylene of the benzyl alcohol (BzOH)). The monomer conversion was determined by comparing the integral of the proton resonance of the methylene moiety adjacent to oxygen of the carbonyl group for both the monomer ($-\text{CH}_2\text{OCO}-$, $\delta = 4.24$ ppm) and polymer ($-\text{CH}_2\text{OCO}-$, $\delta = 4.07$ ppm).

2.2.2. Matrix-Assisted Laser Desorption Ionization Time-of-Flight Mass Spectrometry (MALDI-TOF MS) Analysis

These analyses were done on a Bruker Ultraflex III spectrometer. Dithranol (1,8-dihydroxy-9,10-dihydroanthracen-9-one) was used as the matrix and sodium tetrafluoroacetate (NaTFA) as the supported salt for ionization. Various solutions in acetonitrile of dithranol (20 mg mL^{-1}), NaTFA (10 mg mL^{-1}), and the polymer (10 mg mL^{-1}) were prepared. The mixture was formed by mixing individual components at a 20/1/10 v/v/v volume ratio. The mixture was deposited on a stainless steel plate and allowed to dry in air and samples were run in a positive mode.

2.2.3. Differential Scanning Calorimeter (DSC) Analysis

Polymer glass transition (T_g) and melting (T_m) temperatures were determined using a thermal analysis (TA) Q2000 DSC under a nitrogen stream (50 mL min^{-1}). Changes in heat flow were recorded between -80 and 80 $^\circ\text{C}$ over two cycles. Unless otherwise stated, the second scan was used in order to remove the thermal history of the polymer being analyzed. To achieve this, a scan rate of 20 $^\circ\text{C min}^{-1}$ was employed, along with a 10 min isotherm at either end of the temperature range to complete the cycle. In a typical procedure, a polymer sample (3 mg) was loaded into a standard pan and an empty pan was used as a reference. The instrument was calibrated using indium metal standards supplied by TA Instruments Inc. and had a quoted calorimetric precision and reproducibility of $\pm 0.05\%$ and temperature control accuracy of ± 0.1 $^\circ\text{C}$. Analysis of the data was performed using universal analysis by TA and a series of repeat measurements on a single polymer product showed that the standard deviation from the mean T_g was ± 0.35 $^\circ\text{C}$ using this software.

2.2.4. Dielectric Property Analysis

Both ϵ' and ϵ'' were determined using the cavity perturbation technique as described in previous publications.^[12] The cavity perturbation technique was adopted in this case because it could be applied at elevated temperatures and since it was a comparative measurement between an unloaded and loaded cavity, repeated calibration prior to each measurement was not required.^[12] Details of the experimental setup and the frequencies where measurements were carried out could be found in previous publications.^[12] All measurements had been normalized to the same density using the complex refractive index mixture equation.^[13]

2.2.5. Gel Permeation Chromatography

GPC was performed on a Polymer Labs GPC-120 instrument equipped with a PLgel 5 mm guard column and two 30 cm

PolarGel-M columns in series coupled with a refractive index detector. The samples used HPLC grade THF as the mobile phase at a flow of $1.0 \text{ cm}^3 \cdot \text{min}^{-1}$, and were performed at $40 \text{ }^\circ\text{C}$ and typically took 24.5 mins. The GPC was calibrated using poly(styrene) (PS) standards ranging from 580 to 377 400 $\text{g} \cdot \text{mol}^{-1}$. All GPC equipment and standards were supplied by Polymer Laboratories (Varian). GPC data were analyzed using the Cirrus GPC Offline software package. A correction factor of 0.56 was applied to the final Mwt predictions to allow for the differences in the hydrodynamic volumes of the sample and standard polymers.^[10]

3. Results and Discussion

The molecular structure characteristics of the star polymers synthesized by both MWH and CH polymerizations were evaluated, where the ROPs used SnOct₂ with: (a) glycerol (G), trimethylolpropane (TMP) and pentaerythritol (PTOL) to generate monofunctional hydrophobic stars, and (b) GE, TMPE and PTOLE to synthesize the core corona equivalents.

¹H NMR, GPC, and DSC data of the hydrophobic stars defined that the molecular structures of materials synthesized by both heating methods were very similar. However, the presence of the ethoxylate arms in the GE, TMPE, and PTOLE stars resulted in ¹H NMR no longer being a viable method of analysis, because the ethoxylate residues obscured key data. Thus, ϵ' measurement of the star polymers was conducted to determine if this technique could be used to define the molecular structural similarities/differences between these 3 and 4 arm materials. As in previous reports,^[11] the variation in the ϵ' values for the star polymers obtained in this study were shown to be nonlinear with temperature and so the analysis was conducted at a temperature at which all the materials exhibited constant ϵ' values at 2470 MHz, in this case $150 \text{ }^\circ\text{C}$, see Figure 1.

Consequently, Table 1 contains a summary of the ϵ' measurements conducted at $150 \text{ }^\circ\text{C}$, along with the spectroscopic, chromatographic, and physical property data obtained for both the "core" initiators and the CH/MWH ROP chain extended stars which include degree of polymerization (DP) and melting temperature (T_m).

The ϵ' values for all the core initiator materials used to synthesize the star polymers in this study were shown to increase as their T_m decreased. This was attributed to the dipoles within the material exhibiting greater levels of molecular motion with increased liquid physical form. For these low molecular weight materials, comparing Table 1, Nos. 2, 3, 4 with 15, 16, 17 showed that: (a) the addition of the ethoxylate blocks significantly increased the magnitude of the ϵ' values, and (b) the individual values were found to correlate to the number of functional groups present in the structure, e.g., 3 armed species exhibited a value of ≈ 8 where 4 arm PTOLE has a value of ≈ 14 .

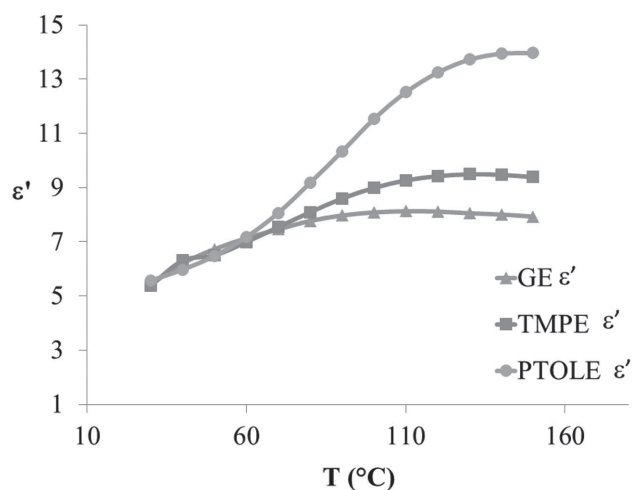


Figure 1. Plot of the variation in average real permittivity (ϵ') values with temperature for GE, TMPE, and PTOLE cores at 2470 MHz.

Meanwhile, comparison of the measured ϵ' values for both the ethoxylated initiators and the chain extended ethoxylated stars showed that these data exhibited variations that could be directly related to the star polymers' molecular structure. The chain extended stars contain a more substantial arm length (typically an increase from 4–7 repeat units in the core initiator to 11–14 in DP 21 and 34–37 in DP 90). This defined that, as the structure builds, there is a reduction in the ratio of functional group to main chain units within the structure. This reduction was reflected in the ϵ' values (comparing Table 1, Nos. 15, 18, and 22, 16, 20, and 23, and 17 and 26) demonstrated that the initiators exhibited higher ϵ' value than the daughter stars. Furthermore, the stars which contained the same core exhibited a reproducible reduction in ϵ' value when

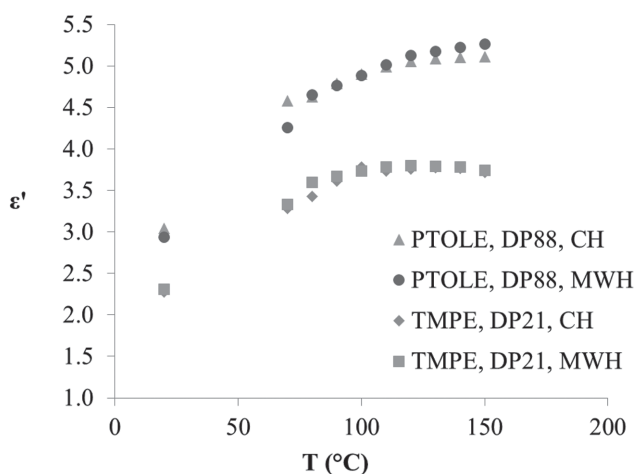


Figure 2. Plot of the variation in average real permittivity (ϵ') values with temperature for star PCL initiated with PTOLE and TMPE of DPs 88 and 21, at 2470 MHz.

■ Table 1. Experimental and dielectric property data for the star branched materials.

No.	Polyol type	Heat type	DP	M_n GPC [g mol ⁻¹]	T_m ^{c)} [°C]	ϵ' at 150 °C
1	BzOH	–	–	–	54	1.40
2	G	–	–	–	18	6.00
3	TMP	–	–	–	58	8.03
4	PTOL	–	–	–	260	2.00
5	BzOH-PCL	CH	86	6100 ^{a)}	62	–
6	G-PCL	CH	90	13 500 ^{b)}	59	–
7	G-PCL	MWH	90	15 300 ^{b)}	58	–
8	TMP-PCL	CH	90	6500 ^{b)}	58	–
9	TMP-PCL	MWH	90	6500 ^{b)}	58	–
10	PTOL-PCL	CH	88	5100 ^{b)}	56	–
11	PTOL-PCL	MWH	88	5100 ^{b)}	56	–
12	BzOH-PCL	CH	19	1700 ^{a)}	54	1.70
13	TMP-PCL	CH	21	1600 ^{b)}	48	–
14	TMP-PCL	MWH	21	1600 ^{b)}	47	–
15	GE	–	–	–	–	8.00
16	TMPE	–	–	–	–	9.25
17	PTOLE	–	–	–	–	14.00
18	GE-PCL	CH	21	–	–	6.50
19	GE-PCL	MWH	21	–	–	6.20
20	TMPE-PCL	CH	21	2300 ^{b)}	–	3.75
21	TMPE-PCL	MWH	21	2400 ^{b)}	–	3.75
22	GE-PCL	CH	90	12 300 ^{b)}	–	4.75
23	TMPE-PCL	CH	90	13 500 ^{b)}	–	1.80
24	TMPE-PCL	MWH	90	13 600 ^{b)}	–	1.80
25	PTOLE-PCL	CH	88	14 400 ^{b)}	–	5.00
26	PTOLE-PCL	MWH	88	14 800 ^{b)}	–	5.00

^{a)}First reported in ref.^[14]; ^{b)}First reported in ref.^[10]; ^{c)}Measured by DSC analysis.

the arm of the star was extended. This demonstrated that relative molecular weight had a direct effect on the magnitude of the ϵ' value for materials containing the same number of functional groups.

However, comparison of the measured values of the amphiphilic star polymers with different cores showed that the level of ϵ' value reduction with arm build was not consistent across all the core structure types. Consequently, a specific experimental ϵ' value cannot be generically applied to indicate a particular molecular weight size across all structural types rather, it indicates a trend in the data only within a “core family” set. It was proposed that this inconstancy was related to macrostructuring in the bulk of the reaction medium that influenced these ϵ' results via the presence of additional molecular interactions within the materials leading to additional restrictions being placed on dipole movement. The actual form of microstructuring exhibited by these materials and

hence the mechanism by which it affected the dielectric property results is currently under further investigation.

Comparison of the 3 and 4 arm stars of the same molar mass showed that ϵ' could also be used to determine structural similarity between batches of materials. The equivalent CH and MWH derived materials exhibited identical ϵ' measurements at 2470 MHz (compare example spot ϵ' values in Table 1, Nos. 19/21, 20/22, 23/24, and 25/26 and temperature variation data in Figure 2). This demonstrated that measurement of ϵ' could be used to define molecular structure consistency and batch to batch repeatability in a connected series of materials.

4. Conclusions

The data presented in this paper have shown that the measurement of a material's real permittivity (or

dielectric constant, ϵ') at microwave frequencies can be used as a facile, nonintrusive, and nondestructive method to determine the relative molecular size and/or the functional group number within a related series of star polymer materials which are in the same phase state, i.e., in this case a fluid polymer melt, and when there is no additional macrostructuring present in the medium. The dielectric property values, and so the differential between the differing structures is noted to be greater when they are in liquid physical form because the dipoles have a greater degree of freedom to align with the phase of the incident electromagnetic energy. The data have also been shown capable of defining molecular structure similarity between two batches of branched materials (i.e., confirming batch to batch repeatability in manufacture). Furthermore, as methodologies to directly measure a reaction medium's ϵ' values, can be applied to reactors without the need to physically sample the reaction medium or design in a sample loop, and so ϵ' values measurement represents a real opportunity to improve the manufacturing efficiency of complex polymer structures.

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