Phase behaviour and rheological properties of the lamellar liquid crystals formed in dodecyl polyoxyethylene polyoxypropylene ether/water system

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The temperature-composition phase diagram of the binary nonionic surfactant dodecyl polyoxyethylene polyoxypropylene ether/water system has been determined from 10 °C to 70 °C. Two domains of lamellar liquid crystal phase are found in the binary system as the concentration of the nonionic surfactant increases. The phase boundary of the lamellar phase in the phase diagram has been identified by differential thermal analysis. The steady and dynamic rheological properties of the lamellar liquid crystals have been studied. Steady shear rheology results indicate that the lamellar liquid crystals show shear-thinning behavior, and behave as a plastic system with the \( m \) parameter between 0.6 and 0.7 in the empirical equation. \[ \sigma = \sigma_{\text{HB}} + K\gamma^m. \] Dynamic rheological results show that the lamellar phase exhibits a typical gel-like rheogram. With increase in surfactant content, the dynamic modulus increases, while with increases in temperature, the dynamic modulus decreases.

**Keywords:** Solution chemistry, Liquid crystals, Phase behaviour, Rheological properties, Lamellar liquid crystals, Dodecyl polyoxyethylene polyoxypropylene ether

Surfactants in dilute aqueous dispersions can assemble into a variety of micellar aggregates above both a critical concentration and a critical temperature, exhibiting different geometrical shapes and frequently exhibiting fluid-like rheological properties. When intermicellar interaction reaches a critical level, the so-call lyotropic liquid crystalline or mesomorphic state is achieved\textsuperscript{1}. These self-assembled structures are tunable by changing the ratio of the hydrophilic and hydrophobic parts of surfactants molecule and the concentration of surfactant, for example, on increasing the surfactant concentration, the sequence of the self-assemblies is discontinuous cubic phase, hexagonal phase, discontinuous cubic phase, lamellar phase, hexagonal phase, discontinuous cubic phase, reverse hexagonal phase\textsuperscript{2}. These are considered as an ordered network of giant micelles, formed as a result of the interactions among them, and have found interesting applications in different fields, e.g., the detergent and related industries, pharmacy, biology, lubricants, food industry, etc. In view of their wide application, a detailed rheological characterization is quite important for the design of unit operations (such as pumping, agitation and mixing), quality control, drive parameters that may be related to the system texture and structure, as well as optimization of formulations that establish relationships between the microstructures. This requires the most complex rheological tests\textsuperscript{3}.

Liquid crystals are associated with intermediate states between the almost perfect long-range positional and orientational order of solid crystals and the long-range disorder found in isotropic liquids\textsuperscript{4}. Rheology is a useful tool to assist in the determination of phase diagrams. Likewise, rheological studies of lamellar phases are important for an understanding of the functions of biological membranes and of technical applications of surfactants and lipids in pharmacy. In fact, not only are modifications in the rheological properties to be expected when phase transitions occur between different liquid crystals, but also when either composition or temperatures vary within the realm of
existence of one particular mesophase. The lamellar phase is built up of surfactant bilayers with different topologies. A large number of works are focused on understanding the changes in the lamellar phase microstructure under shear and different solvents. The viscoelastic behavior of a lamellar anionic surfactant, AOT-water system was investigated by Robles-Vasquez et al. They considered the lamellar mesophase as a weak gel, but quantitative descriptions were not used for the explanation of the experimental results. Wang et al. studied lamellar liquid crystals of Brij97 aqueous solutions containing different additives. The lamellar phases show high elasticity as indicated by their mechanical and discrete relaxation spectra. Comparison with Brij97/water/oleic acid system and Brij97/water/bmim-PF system, shows that the lamellar phase formed in the Brij97/water/IPM system has the lowest storage and loss moduli, implying that it has a weak network strength and less stable internal structure.

Dodecyl polyoxyethylene polyoxypropylene ether is a nontoxic nonionic surfactant. In the present work, the phase diagram of C₁₂E₄P₅/water system has been determined with the aid of different thermal analysis (DTA) to identify the phase boundary. Furthermore, the rheological properties of lyotropic liquid crystalline phases formed in the C₁₂E₄P₅/water system have been investigated. The aim of our investigation is to characterize the rheological behaviour of the lamellar phase, relevant to assessment of phase structure.

Materials and Methods

Dodecyl polyoxyethylene polyoxypropylene ether (C₁₂H₂₅O(CH₂CH₂O)₄(CH₂CHCH₂O)₃H, C₁₂E₄P₅) of purity > 99% was purchased from Henkel Chemical Company, Germany. Deionized water was need throughout.

Determination of phase diagrams

C₁₂E₄P₅ and water were homogenized by stirring at a temperature ~60-70 °C. The water phase was added sequentially and the samples were mixed using a vortex mixer and repeated centrifugation. Temperature was increased gradually in the range of 10-70 °C. Sample inside and outside the phase boundary lines were stored in a thermostat for one week to get the complete formation of liquid crystalline structures. Phase equilibria were determined by visual observation of the samples in normal light and the types of liquid crystals were identified by rheological measurements.

Different thermal analysis

DTA measurements were carried out using a SK-1 type differential thermal analyzer. Test lamellar samples were placed in the right bracket of the electric furnace, while the reference samples (α-Al₂O₃) were placed in the left bracket of the electric furnace. Amplification unit range of the differential thermal was between ~15 μV and 15 μV. The scanning rate of temperature was 0.5 °C/min for heating.

Rheological measurements

Rheological measurements were made with an American TA-2000ex rheometer. A cone-plate sensor was used with a diameter of 20 mm and a cone angle of 2°. The sample thickness in the middle of the sensor was 0.105 mm. Samples were kept in saturated water vapor during the measurements. The sample was gently inserted in to the top of the plate of the sensor, and then the plate was slowly elevated to its measuring position with constant velocity. The sample squeezed out from the sensor system was then gently removed. Measurements were carried out after 10 minutes to allow for the stress relaxation. The maximum permitted deviation in temperature was ± 0.1 °C during the measurements.

Initially, controlled stress measurements were performed with all samples at 1.0 Hz, in order to determine the extent of the linear viscoelastic region. Later, frequency sweep measurements were performed at a constant stress of 1.0 Pa, which was found to be in the linear viscoelastic domain in all cases when the amplitude of the deformations was very low. The frequency was varied from 0.1 to 300 rad s⁻¹.

Subsequently, steady shear measurements were performed on all the samples in which the stress was varied. To determine the phase transition temperatures, temperature sweeps were performed for aqueous solutions with a heating rate of 0.2 °C/min.

Results and Discussion

Phase diagrams

A temperature (T)-composition (X) phase diagram of C₁₂E₄P₅/H₂O system is constructed by visual inspection of the samples in Fig. 1. Phase boundary of the lyotropic liquid crystals in the phase diagrams is identified by rheological measurements.
measurements. According to the temperature and composition changes, the phase diagram can be divided into four regions: lamellar phase regions \( L_{\alpha 1} \) and \( L_{\alpha 2} \), an isotropic micellar phase \( L_1 \), and two phase regions \( 2\phi \). The lamellar liquid crystalline phase \( L_{\alpha 1} \) is formed between 49 wt% and 70 wt% of \( C_{12}E_4P_5 \) from 10 °C to 41 °C, while lower amount of the surfactant in water solution gives the other isotropic lamellar liquid crystal \( L_{\alpha 2} \) containing \( C_{12}E_4P_5 \) between 38 wt% and 50 wt% from 30 °C to 43.5 °C. Two domains of lamellar phase are observed, \( L_{\alpha 1} \) and \( L_{\alpha 2} \), where the hydrophobic lipid chains are organized into semicrystalline and amorphous phases, respectively. By increasing the temperatures, both the lamellar phases melt into micelle-type isotropic fluid \( L_1 \), and the boundary of \( L_1 \) phase is undefined.

The DTA thermograms obtained for \( C_{12}E_4P_5/H_2O \) system with different compositions \( (S_1, S_3) \) are shown in Fig. 2. The curve for \( S_1 \) in Fig. 2 is obtained by heating the sample from room temperature to 70 °C, in which a sharp endothermic peak due to melting is observed at 41 °C. Thus, it can be concluded that the heat effect at 41 °C is ascribed to the lamellar phase transition, that is to say, the structure of lyotropic liquid crystalline is damaged at this temperature. The curve of \( S_3 \) shows two phase transition temperatures at 30 °C and 43.5 °C. The heat effects observed in these DTA curves are caused by some phase transformation occurring in the mixture, and hence, the peak temperatures can be regarded to define the boundary between the different phases. Thus, the phase boundary of the lamellar phase can be constructed by plotting the peak temperature as a function of composition, which are consistent with the T-X phase in Fig. 1.

**Steady rheological behavior**

Rheological studies have been carried out on six samples \( (S_1~S_6) \) in phase diagram, belonging to the different lyotropic liquid crystalline phases. The composition and temperature of six samples are listed in Table 1.

**Viscosity change**

The variation of the viscosity \( (\eta) \) with the shear rate \( (\dot{\gamma}) \) for lamellar liquid crystals \( (S_1, S_2, S_3) \) and \( (S_4, S_5) \) at 20 °C and 35 °C are given in Fig. 3. This figure shows that the viscosity values of the liquid crystal phases increases according to the surfactant content. All the samples follow a shear-thinning behavior, because the structure of lamellar liquid crystal is built up from bimolecular leaflets one-by-one. Due to the operating shear force, they can slide between bilayers and into the flowing state. The viscosity decreases with increasing the shear rate according to the power law

\[ \eta = K_1 \dot{\gamma}^{n-1}. \]

| Table 1—Nomenclature and composition of the investigated lamellar samples |
|-------------------------|---------|---------|------|
| Sample | \( C_{12}E_4P_5 \) (wt %) | Water (wt %) | \( T \) (°C) |
| \( S_1 \) | 65.73 | 34.27 | 20 |
| \( S_2 \) | 60.94 | 39.02 | 20 |
| \( S_3 \) | 55.61 | 44.39 | 20 |
| \( S_4 \) | 49.28 | 50.72 | 35 |
| \( S_5 \) | 44.53 | 55.47 | 35 |

Fig. 1—Phase diagram of \( C_{12}E_4P_5/H_2O \).

Fig. 2—Typical DTA curves obtained for the \( C_{12}E_4P_5/H_2O \) systems, \( S_1 \) and \( S_5 \), with varying compositions.
exists for relaxation of the structure and reversion direction tangent to the lamellae, no driving force (point of view, when sliding occurs along any possible direction of the lamellae, and no driving force exists for relaxation of the structure back to the unperturbed state). The shear viscosity of $S_1$, $S_2$, and $S_3$ in 20 °C is more than that of $S_4$, $S_5$ in 35 °C, since a low temperature is a more conducive for aggregation between micelles, and can form dense layered structure, increasing then the shear viscosity increase.

### Shear stress change

The determination of a yield stress as a true material parameter in any system is usually dependent on the measurement technique, and the yield stress used to evaluate rheological data. The viscoelastic behaviour indicates that the lamellar phase behaves as a plastic system with yield stress values ($\sigma_0$), which at low shear rate could be obtained by the same way as $\eta_0$ from the plot of the shear stress versus shear rates (such as $S_2$ in Fig. 4) at 20 °C and 35 °C. The yield stress values ($\sigma_0$) are also listed in Table 2. As shown in Table 2, on increasing the surfactants’ concentration, the values of the yield stress increase. $S_1$ has the largest yield stress amongst the investigated samples, indicating that it has the most stable structure, and therefore, needs a large external force to make $S_1$ to flow. The yield shear of $S_1$, $S_2$ and $S_3$ at 20 °C is more than that of $S_4$, $S_5$ at 35 °C. This is not difficult to understand since the Brownian movement of molecules is accelerated with increasing temperature. Therefore, low temperature is more conducive to formation of a dense layered structure. Since the lamellar phase needs a yield stress to start the flow, dense structures require a large yield shear.
The typical flow curves of the lamellar phase are given in Fig. 4. These curves do not fit any empirical model over the whole range of shear rate. At low stress but higher than the yield stress, a small stress produces a large strain, while at high shear rate the flow curves follow the empirical equation $\sigma = \sigma_{HB} + K\gamma^m$.

Here $\sigma_{HB}$ is the yield stress and $K$ and $m$ are constants, equivalent to the power law parameters commonly used for approximating the behavior of many viscous fluids. The values of the parameters $K$ and $m$ for the different samples are given in Table 2, and one of the fitting curves is shown in Fig. 4. For $m < 1$ the fluid is yield-pseudo plastic; and $m > 1$ corresponds to yield-dilatant behaviour. It can thus be concluded that the lamellar phases exhibits as a plastic behaviour. The parameter $m$ (~0.6) can be considered slightly dependent on the sample composition and is likely to increase with the surfactant content of the sample. Interestingly, a similar behavior was reported by Montalvo and Valiente in the lamellar phase of the CTAB/benzyl/water system.

Dynamic rheological behavior

Concentration effect

More information on the network structure of the liquid crystalline phases can be obtained from oscillatory frequency sweep measurements. The frequency dependence of the storage modulus $G'$, loss modulus $G''$ for lamellar liquid crystals ($S_1$, $S_2$, $S_3$) and the lamellar phase ($S_4$, $S_5$) at various C$_{12}$E$_n$P$_5$ concentrations at 20 °C and 35 °C are shown in Fig. 5. $S_1$, $S_2$, $S_3$, and $S_4$, $S_5$ are characterized by the same type of mechanical spectrum, i.e., a typical gel-like rheogram. In this case, (a) the system is more elastic than viscous in the range of the frequency investigated, and $G'$ is larger by about one order of magnitude than $G''$ throughout the whole frequency range; (b) $G'$ presents a weak dependence on the applied frequency, and, (c) $G''$ shows a shallow minimum ($G''_{min}$) at intermediate frequency. A lamellar microstructure is formed by connected monodomains with random orientation. The occurrence of such a minimum may be ascribed to the formation of an elastic network as a consequence of strong interactions developing within and among the monodomains. A lamellar microstructure is formed by connected monodomains with random orientation. For polymers, the occurrence of such a minimum is

![Fig. 4](image-url)  
Fig. 4—Shear stress ($\sigma$) versus shear rate ($\gamma$) of the different lamellar phases, $S_1$, $S_2$, $S_3$, at 20 °C and $S_4$, $S_5$ at 35 °C. [The solid lines are fixed curves using an empirical equation].

![Fig. 5](image-url)  
Fig. 5—Storage (filled) and loss (hollow) moduli as a function of angular frequency of (a) the $S_1$, $S_2$, $S_3$ phases at 20 °C, and (b) the $S_4$, $S_5$, $S_6$ phases at 35 °C. [The solid lines correspond to calculated $G'$ and $G''$ values using the generalized Maxwell model].
usually associated with the existence of entanglements among macromolecules. In surfactant liquid crystal systems, it may be ascribed to the formation of an elastic network as a consequence of strong interactions developing within and among the monodomains. The entire microstructure is polycrystalline; i.e., it is formed by the combination of clusters of flexible bilayers, each characterized by a director vector which defines the main orientation of the so-called monodomain.

We can see that different mechanical spectra are shown by the investigated lamellar phases in Fig. 5a, and the elastic modulus $G'$ of $S_1$, $S_2$ and $S_3$ is about one order of magnitude larger than $G''$. Moreover, the minimum $G''$ is found in the intermediate frequency region, indicating that $S_1$, $S_2$ and $S_3$ shows plastic behaviour, consistent with the steady rheological results. The $G'$ and $G''$ show increase with increase in surfactant concentration. The observations show that the values of modulus are a function of the lamellar–lamellar interactions. At a given temperature, the distance between the lamellae decreases, indicating increased interaction between lamellae which causes an increase of the modulus $G''$. Figure 5a shows that $S_1$ exhibits relatively higher values of $G'$ and $G''$. The sample $S_1$ with the highest surfactant concentration, shows the strongest network and the most stable internal structure. However, $S_3$ has the special viscoelastic curves, due to existence of liquid crystalline phases and micelles phases. Generally speaking, the lamellar microstructure is formed by connected monodomains with random orientation and consists of flexible bilayers, so that the water molecules can flow between the lamellae. With water content increasing, the distance between the lamellae increases, giving $S_3$ a structure with low stability. Figure 5b shows that $S_4$ and $S_5$ have the same flow curves in the whole frequency range, and conforms to a typical gel-like rheogram.

In Fig. 5 it can be clearly seen that the modulus values of $S_4$ and $S_5$ are slightly higher than the values of $S_1$, $S_2$ and $S_3$. With change in temperature and surfactant content, the packing parameter of the $C_{12}E_4P_5$ changes. With increase in water content, the area of hydrophilic head increases and the volume of hydrophobic end decreases. This causes decrease in packing parameter which promotes formation of close liquid crystalline structures.

**Effect of temperature**

Temperature can largely influence the movement of molecules, and change the viscoelastic properties of the lamellar phase. Therefore, we have examined in detail the changes in the elastic modulus $G'$ and viscosity modulus $G''$, with increase in temperature. We have investigated the frequency sweep at different temperatures for lamellar liquid crystal ($S_1$) in Fig. 6. It is observed that increasing temperature can remarkably change the shapes of the dynamic rheograms of lamellar phases. From the results, it is clearly seen that there are two types of frequency sweep curves. The values of $G'$ and $G''$ gradually decrease with increase in temperature, but the shapes of their curves still follow a typical gel-like rheogram when temperature increases from 20 °C to 35 °C, which shows that the density of connection points of micelles in the lamellar liquid crystal declines when temperature is raised. At 41 °C, with decrease in frequency, $G'$ decreases more quickly than $G''$, and tends to “crossover” $G''$ at lower frequencies. At this stage $S_1$ is fluid-like. The moduli reflect the mechanical properties of the various interactions among the liquid crystalline phases, such as hydrogen bonding, hydration and so on. This is because elevating the temperature accelerates the molecules Brownian movement and enlarges the distance between adjoining micelles, while causes the contact point density of the network to decline, decreasing the...
storage modulus\(^2,3\). Increasingly, the temperature can destroy the hydrogen bonds formed by water and EO chains of C\(_{12}\)E\(_4\)P\(_5\) surfactant molecules and cause an increase in free water molecules, which facilitates viscous flow of the sample and decreases the loss modulus\(^3\). When temperature increases to the phase transition point at 41 °C, an increase in the temperature leads to transition from lamellar liquid crystal phase to isotropic solution and the magnitudes of \(G'\) and \(G''\) decrease sharply. These results indicate that most of the structure of \(S_1\) is destroyed at this temperature, and the ordered structure of the lamellar phase begins to change into the disordered and tangled micelles. Therefore, the system has weak polymer-like viscoelasticity due to the existence of these tangled and disordered micelles\(^2\).

In order to better understand how temperature influences the micelles’ arrangement and movement in the lamellar phase, we have examined in detail the changes in the ratio of viscous and elastic components for lamellar phase when the temperature is raised (Fig. 6 inset). In addition, in the lamellar region the quantitative results of dynamic tests are strongly temperature dependent. The storage and loss moduli gradually decrease with increasing temperature, but the rate of their decrease is different, the decrease of the elastic component being much more pronounced. This can be evaluated from tan δ, which increases with temperature, implying that the distances amongst the micelles in the lamellar phase become large due to faster movements of surfactant molecules.

For the lamellar phase, temperature influences mainly the layer curves. We can see in the inset in Fig. 6 that the change in tan δ with temperature can be divided into three regions\(^2\): In region I, tan δ increases slightly with the increase of temperature and \(G'\), presenting the elastic-component of the sample, remains basically constant. At low temperature, the Brownian movement of the surfactant molecules is very slow, and the surfactant molecules are close together. The layers become large parallel planes and their curve is nearly zero\(^3\). In region II, tan δ becomes smooth and gradually larger. Although \(G'\) and \(G''\) decrease gradually with temperature, \(G'\) declines faster than \(G''\). The elastic component of the flow diminishes as the phase boundary is reached with increasing temperature. This suggests that the lattice structure of \(S_1\) is destroyed to some degree, and this damage is caused by the molecular movement becoming faster and faster with increase in temperature. In this temperature region, \(S_1\) becomes more and more disordered, and its rheological behaviour tends towards that of liquid. In region III, tan δ sharply shoots up, and \(G'\) and \(G''\) drop sharply, eventually reaching an exponential regime which suggests a co-existence of the lamellar phases and the micellar phases. This implies that the structure of \(S_1\) is almost destroyed. The modulus decreases with increasing temperature. In the lamellae formed from non-ionic surfactants the interactions originate from the Van der Walls’ forces, and steric hydration forces. The hydration repulsion is strongly temperature dependent, and decreases with increasing temperature\(^4\). The ordered structures of the liquid crystals are destroyed, and changes into disordered micelles when the temperature rises to 41 °C. This value is very close to the melting point of the water-free surfactant. Assuming that the melting point of the carbon chains is not influenced strongly by the aqueous layers which are separated from these chains with the ethoxylate groups, this breakpoint seems to be a transition temperature between a weak polymer and the liquid crystal state of the lamellar domains. In this case, \(S_1\) shows a weak polymer-like viscoelastic property. \(S_1\) becomes disordered, but the neighboring micelles are randomly tangled in this disordered system. Therefore, within a certain temperature range, \(G'\) and \(G''\) can give valuable information on the major transitions as well as on their viscoelasticity (\(G'\) vs \(G''\)) at a fixed frequency.

**Relaxation spectra of lamellar crystal phase**

The linear viscoelastic behaviour of the liquid crystals can be further interpreted in the time domain by converting the dynamic viscoelastic results in terms of the relaxation spectrum. In early reports\(^17,18\), the frequency dependence of shear rheology for different liquid crystal phases, including the gel-like lamellar phase and Maxwell fluid-like hexagonal phase and cubic phase, have been interpreted using a multiple Maxwell model expressed by Eqs 1 and 2. This model is based on one specific structure with multiple responses at different frequencies, i.e., with several relaxation times. The experimental values of \(G'\) and \(G''\) are given by Eqs 1 and 2 respectively,
\[ G'(\omega) = \sum_{i=1}^{n} G_i \frac{\omega^2 \tau_i^2}{1 + \omega^2 \tau_i^2} \quad \ldots (1) \]

\[ G''(\omega) = \sum_{i=1}^{n} G_i \frac{\omega \tau_i}{1 + \omega^2 \tau_i^2} \quad \ldots (2) \]

where \( \tau_i \) stands for a relaxation time, \( G_i \) stands for the storage modulus corresponding to a particular \( \tau_i \), and \( n \) stands for the number of Maxwell elements.

Following this approach, we have used a nonlinear curve fit procedure in which the logarithmic least squares sum of \( G' \) and \( G'' \) was minimized by fitting with five Maxwell elements with only positive parameter values being allowed. \( G' \) was calculated from the parameters with the five elements model by Eqs 1 and 2 for the investigated lamellar liquid crystals to show the discrete relaxation spectra. The solid lines drawn in Figs 5 and 6 show the theoretical \( G' \) and \( G'' \) values that are fitted by the parameters with the five Maxwell model, and are mostly in agreement with the experimental values, demonstrating the validity of the relaxation parameters obtained. The relaxation spectrum is vital for an insight into the properties of a viscoelastic material. In a multiple Maxwell model, the largest relaxation time, \( \tau_{\text{max}} \), can still be attributed to the relaxation of the water-surfactant interface back to the configuration occupied in the unperturbed state; the second longest relaxation time will correspond to the relaxation of the lipid chains, while the shortest relaxation time, \( \tau_{\text{min}} \), may be attributed to the water confined in the channels. The formation of an elastic network is given by the appearance of a minimum relaxation modulus for the lamellar phases in these systems.

From Fig. 7a, it may be observed that addition of water in \( S_1 \) causes a significant increase of the relaxation modulus \( (G_i) \) corresponding to a particular \( \tau_i \) at 20 °C. It is, therefore, clear that the elastic character of the lamellar phases is strengthened and its viscous behavior weakened as the water concentration increases. Moreover, the relaxation spectra confirm that \( S_1 \) is the most structured lamellar phase in this study. While the storage moduli of \( S_4 \) and \( S_5 \) have a similar tendency at 35 °C, these results are also in agreement with the observed behaviour of \( G' \) and \( G'' \) (Fig. 5). The values of storage modulus of \( S_4 \) and \( S_5 \) are more than that of \( S_1, S_2 \) and \( S_3 \).

Figure 7b shows the discrete relaxation spectra of \( S_1 \) at different temperatures. These results show that the storage modulus clearly decreases with increasing temperature. \( G_i \) is thus a parameter related to the movement of the surfactant molecules. It is not difficult to understand that the accelerating Brownian movement of molecules is the primary reason for the decrease in \( G_i \) with increasing temperature. When the temperature increases from 20 °C to 35 °C, the discrete relaxation curves of \( S_1 \) exhibit the same trends, i.e., the minimum values of \( G_i \) appear on the same intermediate \( \tau_i \) values at different temperatures. This may be attributed to the formation of an elastic network. Moreover, \( S_1 \) has significantly higher moduli and demonstrates higher elasticity at 20 °C. At 41 °C, the storage modulus \( (G') \) increases linearly with increase in frequency, and reaches a constant at higher frequencies. At this temperature, the lamellar phase turns into micellar phase.
Conclusions
The present study demonstrates that the lamellar liquid crystals formed in water solution of C_{12}E_{4}P_{5} exhibit appreciably different rheological properties. The rheological properties of the lamellar mesophase formed from the nonionic surfactant, dodecyl polyoxyethylene polyoxypropylene ether (C_{12}E_{4}P_{5}), were investigated statically (with steady state viscosity measurements) and dynamically (with oscillation tests). Steady rheological results indicate that the studied lamellar liquid crystals exhibit shear-thinning properties and the lamellar phases behave like a plastic material with zero-shear-rate viscosity, $\eta_0$, and yield stress values $\sigma_0$. In the linear viscoelastic region, where the structure of the system does not change significantly during the rheological measurements, the storage modulus of the lamellar mesophase is higher by about one order of magnitude than its loss modulus. Dynamic rheological results indicate that the lamellar liquid crystals have an elastic gel-like rheological response, and the $G'$ and $G''$ values of the lamellar liquid crystals increase with increasing surfactant content. The lamellar phase, $S_1$, has the highest $G'$ and $G''$ values, which decrease when temperature is increased from 20 °C to the phase transition temperature of $S_1$ i.e., 41 °C. The theoretical $G'$ and $G''$ values that were fitted with the parameters of the five Maxwell model are mostly surperimposed on the experimental values, demonstrating the validity of the obtained relaxation parameters. With increasing temperature, the storage modulus ($G_s$) decreases.

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