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Some Anilines, Phenol and their Binary Mixtures at
Microwave Frequencies**

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Studies on Dielectric Relaxation in Relation to Viscosity of Some Anilines, Phenol and their Binary Mixtures at Microwave Frequencies

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Abstract:

In the present work, the study of variation of relaxation time (τ) with viscosity of the medium (η) is carried out on four polar samples 2-Nitroaniline, 4-Bromoaniline, 4-Chloroaniline, 4-Chlorophenol and also on the binary mixture of (2-Nitroaniline + 4-Bromoaniline) at room temperature by using Microwave bench operating at a frequency of 9.59 GHz. In this regard, the different parameters like dielectric constant (ϵ'), dielectric loss (ϵ''), relaxation time (τ_s), macroscopic steady state viscosity (η_s), dynamic viscosity (η_d) and viscoelastic relaxation time (τ_{ve}) were determined for all the systems. It is observed that, the relaxation time (τ_s) increases with the increase in the viscosity of the medium for all the systems. Plots $\log \tau_s$ vs. $\log \eta_s$ for all the systems shows that, variation of relaxation time is found to be non-linear in the higher viscosity regions. This suggests the failure of Debye's theory at these regions. Further, the non-linear behaviour of relaxation time with the viscosity is explained by using the viscoelastic model suggested by Barlow et al. It is also observed that, macroscopic steady state viscosity (η_s) values are greater than the dynamic viscosity (η_d) and viscoelastic relaxation time (τ_{ve}) values were found to be lower compared to the relaxation time (τ_s). These results suggest that, the effective frictional resistance experienced

by the molecules during reorientation is less and the measured values of macroscopic steady state viscosity (η_s) are frequency dependent.

Keywords: Relaxation time; Dynamic viscosity; Viscoelastic relaxation time; Debye model; Dielectric constant

1. Introduction:

The studies related to the variation of dielectric relaxation with the viscosity of the medium have been the subject of research for a long time. The dielectric relaxation behaviour of polar molecules in dilute solutions of non-polar solvents is very much affected by the viscosity of the medium. The viscosity studies in terms of relaxation time help in drawing certain important conclusions regarding molecular motion, inter and intra molecular forces in liquids, liquid mixtures, dilute solutions and mixtures of polar solutes in dilute solutions, which enable us to get an insight into the molecular dynamics of the system [1-28]. Debye was the first to study the effect of viscosity of the medium on dielectric relaxation time of a polar molecule [1]. Later the study has been extended more systematically by several other investigators like Hill, Magee, Higasi, Barlow, etc. The relationship between the relaxation time (τ) and viscosity of the medium (η) can be broadly classified as theoretical and empirical relations. The theoretical studies include the relationships based on Debye [1], Magee [2], Hill [3], Barlow et al. [4] whereas empirical studies include mainly the relationships proposed by Higasi et al. [5], Fischer [6], etc. The assumption of linear dependence of viscosity with relaxation time irrespective of the size and shape of the surrounding molecules in Debye's theory was found to be valid in case of certain simple molecules which are surrounded by a medium of low viscosity. From the experimental results of different workers it is observed that, the results could be well explained in the case of certain simple molecules by using

Debye's theory. But this theory shows some serious anomalies in some other molecules, which necessitates certain modifications to the Debye's equation. Later Wirtz [7] modified the Debye's equation by expanding the Perrin's concept [8].

From the literature it is observed that, no single expression either based on theoretical or empirical considerations seem to predict the dependence of relaxation time on viscosity more satisfactorily. Because of the absence of a perfect empirical or theoretical relation for the understanding of the variation of dielectric relaxation time with viscosity of the medium, only the experimental investigations on different systems can give a better insight about such studies. It is observed that, some amount of work has been done on the dependence of relaxation time on the viscosity of the medium. But, in order to have a better understanding of the behaviour of viscosity on relaxation time; it seems that still many more experimental investigations are needed.

The present study provides some important experimental results which can be useful for better understanding of the dipolar relaxation behaviour of the polar molecules in the non-polar environment of varying viscosity and it enables one to get an insight into the molecular dynamics of the system. The molecules taken for present investigation are amines and alcohols. 2-Nitroaniline is used in the preparation of agrochemicals, pharmaceuticals, rubber, plastic additives, textile fibers and as an intermediate in the manufacture of diasols, disperse dyes and pigments. 4-Bromoaniline is used in the preparation of azo dyes. 4-Chloroaniline is an important building block used in the chemical industry for the production of dyestuffs, pesticides and drugs. 4-Chlorophenol is used in the preparation of pesticides, herbicides, disinfectants and also as an intermediate in the synthesis of dyes and drugs. In addition to the above, the materials studied here are employed to synthesize a variety of derivatives. However, to the best of author's knowledge there are no reports available in literature

regarding the dielectric relaxation studies in terms of viscosity using Microwave bench for the chosen molecules 2-Nitroaniline, 4-Bromoaniline, 4-Chloroaniline and 4-Chlorophenol.

In view of the above, the dielectric relaxation studies in terms of viscosity have been carried out on pure samples of 2-Nitroaniline, 4-Bromoaniline, 4-Chloroaniline, 4-Chlorophenol and also on the binary mixture of (2-Nitroaniline + 4-Bromoaniline) in dilute solutions in different mixed solvents (benzene + paraffin) at room temperature and it is the continuation of our earlier research work [29].

2. Materials and Methods:

The samples 2-Nitroaniline, 4-Bromoaniline, 4-Chloroaniline, 4-Chlorophenol, benzene and liquid paraffin were procured from Sd-Fine Chem. Co. Ltd. India and are of AR grade with 99% purity. The X-band Microwave bench supplied by Scientific Instrument Co. Ltd (SICO), Ghaziabad India, is used to determine the parameters like dielectric constant (ϵ') and dielectric loss (ϵ'') by employing standing wave techniques [30-32]. The 9.59 GHz frequency microwaves were generated using Klystron (2K25) source, so that the intensity was maximum at the output. The measurement accuracy in the dielectric constant (ϵ') and dielectric loss (ϵ'') is of the order of ± 0.001 and ± 0.0001 respectively. Solutions of different viscosity were prepared by mixing the suitable quantity of liquid paraffin with benzene. The viscosities of different solutions at room temperature were determined by using an Ostwald's viscometer and the measured viscosity values were estimated to be accurate to second decimal.

2.1. Determination of dielectric constant (ϵ') and dielectric loss (ϵ''):

The dielectric constant (ϵ') is a measure of energy storing capability of the dielectric material in the applied electric field. The dielectric loss (ϵ'') is the amount of absorbed electromagnetic

energy by the dielectric material, which gets converted into thermal energy by Joule heating effect. The expressions for dielectric constant (ϵ') and dielectric loss (ϵ'') are given by [30-32]

$$\epsilon' = \left(\frac{\lambda_0}{\lambda_c}\right)^2 + \left(\frac{\lambda_0}{\lambda_d}\right)^2 \quad (1)$$

$$\epsilon'' = (2/\pi) (\lambda_0^2 / \lambda_g \lambda_d) (\text{slope of } \rho_n \rightarrow n) \quad (2)$$

Where, ' λ_0 ' is free space wavelength, ' λ_c ' is cut off wavelength, ' λ_g ' is guide wavelength, ' λ_d ' is dielectric filled guide wavelength and ' ρ_n ' is inverse voltage standing wave ratio (IVSWR) corresponding to n^{th} resonating length with n taking odd values 1,3,5,...etc.

In order to find the value of ' λ_g ', the short-circuited plunger was kept at a fixed position and the probe was moved along the slotted waveguide section and the value corresponding to the minima was recorded from the standing wave pattern. Twice the distance between two successive minima gives the value of ' λ_g '. To find out the value of ' λ_d ', the dielectric cell was filled with the sample under study and the movable probe was fixed at first minima position on the slotted waveguide section. The plunger was moved and the value corresponding to the minima was recorded from the standing wave pattern by using the VSWR meter. Twice the distance between two successive minima gives the value of ' λ_d '. The value of ' λ_c ' is taken to be equal to twice the breadth of the rectangular waveguide. Knowing the values of ' λ_c ' and ' λ_g ', the value of ' λ_0 ' is calculated from the following equation,

$$\frac{1}{\lambda_0^2} = \frac{1}{\lambda_c^2} + \frac{1}{\lambda_g^2} \quad (3)$$

Then by using the values of ' λ_0 ', ' λ_c ', ' λ_d ' and ' λ_g ', the values of dielectric constant (ϵ') and dielectric loss (ϵ'') can be calculated from Eq. (1) and (2).

2.2. Determination of Relaxation time (τ):

Relaxation time (τ) is computed by using the experimentally determined values of dielectric constant (ϵ') and dielectric loss (ϵ'') and from the methods employed by Whiffen and Thompson and others [32-34], in which it is assumed that the polar molecules under investigation conform closely to Debye's theory [1]. The expression for loss tangent ($\tan \delta$) is given by the following equation,

$$\tan \delta = (\epsilon''/\epsilon') \quad (4)$$

$$= [(\epsilon' + 2)^2/\epsilon'] \times [(4\pi n\mu^2)/27kT][\omega\tau/(1 + \omega^2\tau^2)] \quad (5)$$

Where

n indicates number of dipoles per c.c., μ is dipole moment, k is Boltzmann's constant, T is absolute temperature, ω is angular frequency and τ is relaxation time.

$$\tan \delta = P \left[\frac{\omega\tau}{1 + \omega^2\tau^2} \right] \quad (6)$$

$$\text{Where } P = \left[\frac{(\epsilon' + 2)^2}{\epsilon'} \right] \times \left[\frac{4\pi n\mu^2}{27kT} \right] \quad (7)$$

In Eq. (6), ($\tan \delta$) is maximum when $\omega\tau = 1$ and the maximum value is

$$(\tan \delta)_{\max} = P/2 \quad (8)$$

From Eq. (6) and (8), we get

$$[\tan \delta / (\tan \delta)_{\max}] = [2\omega\tau / (1 + \omega^2\tau^2)] \quad (9)$$

Substituting the value of ($\tan \delta$) and ($\tan \delta$)_{max} in Eq. (9) and by solving this quadratic equation, two roots will be obtained and the lower τ value corresponding to $\omega\tau = 1$ is selected.

Thus the relaxation time (τ) for different viscous solutions can be determined by using Eq. (9).

2.3. Estimation of Viscoelastic relaxation time (τ_{ve}), Dynamic viscosity (η_d) and High-frequency rigidity modulus (G_∞):

By treating the dielectric system as viscoelastic i.e. a material system in which stress is dependent on the strain, Barlow et al. [4] have proposed an equation. According to them a highly viscous liquid exhibits viscoelastic relaxation time (τ_{ve}) at microwave frequencies and this is in turn related to the dynamic viscosity (η_d) and the macroscopic steady state viscosity (η_s) and is given by the following equation,

$$\tau_{ve} = \frac{1}{\omega} \left[\frac{\eta_s}{\eta_d} - 1 \right]^{1/2} \quad (10)$$

Further, the viscoelastic relaxation time (τ_{ve}) is related to the high frequency rigidity modulus (G_∞) by the following equation,

$$G_\infty = \frac{\eta_s}{\tau_{ve}} \quad (11)$$

Thus the viscoelastic relaxation time (τ_{ve}) and high frequency rigidity modulus (G_∞) can be estimated from the Eq. (10) and Eq. (11) respectively.

3. Results and Discussions:

In order to study the variation of relaxation time (τ_s) with the viscosity of the medium, different viscous solutions were prepared by mixing liquid paraffin in different proportion, starting from 5% up to 95% to the solvent benzene. For every viscous medium, the steady state viscosity (η_s) values were determined experimentally and the results are given in Table-1.

Then for every viscous medium, the values of dielectric constant (ϵ') and dielectric loss (ϵ'') were determined by using Eq. (1) and (2) for a fixed weight fraction of all the four samples (For 2-Nitroaniline: 5.7×10^{-3} , 4-Bromoaniline: 11.1×10^{-3} , 4-Chloroaniline: 15.5×10^{-3} , 4-Chlorophenol: 11.8×10^{-3}) and the results are presented in Tables-2a-d respectively. For all the four samples, the relaxation time (τ_s) values were determined by using the Eq. (9) and the results are given in Tables-2a-d.

From Tables-2a-d it is observed that, as the viscosity of the medium increases the dielectric constant (ϵ') decreases. It may be due to the reason that, as the viscosity of the medium increases, the distance between the polar solute molecules increases and the value of λ_d also increases. Due to the increase in the distance between the polar solute molecules, the molecular interaction between these molecules decreases. Further, it is observed that, in all the cases as the viscosity of the medium increases, the relaxation time also increases. As the viscosity of the medium increases, the frictional force experienced by the rotating dipoles also increases and this leads to the increase of the steric hindrance experienced by the molecules. As a result, the relaxation time increases with increase in the viscosity of the medium.

In order to find the values of dynamic viscosity (η_d), viscoelastic relaxation time (τ_{ve}) and high frequency rigidity modulus (G_∞), the plots of $\log \tau_s$ vs. $\log \eta_s$ for all the four samples were plotted and are shown in Figs. 1a-d.

According to Debye's theory, relaxation time (τ) is proportional to the viscosity of the medium (η) i.e. $\tau = 4\pi\eta a^3/KT$. From Figs. 1a-d, it is observed that as η_s increases τ_s also increases in the lower viscous ranges. The non-linearity observed in the plots of $\log \tau_s$ vs. $\log \eta_s$ at higher viscosity values may indicate the failure of the Debye's theory. From literature, it is found that other researchers have also reported such behaviour [3-5, 26-27].

The dynamic viscosity (η_d) values were obtained by extrapolating the linear region of the graph of $\log\tau_s$ vs. $\log\eta_s$ as shown in Figs.1a-d and are given in Tables-3a-d for all the four samples. The viscoelastic relaxation time (τ_{ve}) and high frequency rigidity modulus (G_∞) values for all the samples were calculated by using Eq. (10) and Eq. (11) respectively and are given in Tables-3a-d.

The non-linear behaviour of τ_s on η_s may be explained on the basis of viscoelastic behaviour of the solvent medium as proposed by Barlow *et al.* From Tables-3a-d it is observed that, the values of dynamic viscosity (η_d) are found to be much smaller than the corresponding macroscopic steady state viscosity (η_s) for all the four samples i.e. the macroscopic steady state viscosity (η_s) values are of the order of 0.69 to 79.41 mPa.s for all the samples, whereas the dynamic viscosity (η_d) values are of the order of 1.05 to 1.85 mPa.s. The lower values of dynamic viscosity (η_d) indicate that the effective frictional resistance experienced by the dipoles during reorientation is less. Accordingly, the departure of the linear variation of $\log\tau_s$ vs. $\log\eta_s$ at higher viscosities may be attributed to the dynamical nature of the viscosity, which implies that the measured values of macroscopic steady state viscosity (η_s) of the medium are frequency dependent [27]. Further, according to Smyth, if the shape of the molecules undergoing dipole orientation departs little from that of the sphere, then it can rotate without any considerable displacement of the surrounding molecules, so that the relaxation time (τ_s) may become insensitive to the macroscopic steady state viscosity (η_s). On the other hand, if the molecule is unsymmetrical in shape, then its rotation around at least one axis may involve the displacement of neighbouring molecules and the corresponding relaxation time (τ_s) will depend markedly upon the viscosity of the medium [28]. It is to be noted that in the present study, the molecules studied are being fairly spherical [29] and the measurements are being made at fixed temperature, the observed departure of the linear

relation between $\log\tau_s$ vs. $\log\eta_s$ at higher viscosity values may be attributed to the dynamic nature of the viscosity (η_d) rather than the macroscopic steady state viscosity (η_s).

The behaviour of viscosity on relaxation time in case of binary mixture (2-Nitroaniline + 4-Bromoaniline) is also studied and the various determined parameters are presented in Table-4.

In order to find the values of dynamic viscosity (η_d), viscoelastic relaxation time (τ_{ve}) and high frequency rigidity modulus (G_∞), the plot of $\log\tau_s$ vs. $\log\eta_s$ for the binary mixture (2-Nitroaniline + 4-Bromoaniline) is plotted and is shown in Fig.2.

Even in the case of binary mixtures, it is observed from Table-4 that, as the viscosity of the solvent medium increases the relaxation time also increases. The mixture 2-Nitroaniline + 4-Bromoaniline belong to the case of the mixture of two non-associated liquids and it behaves like microscopically homogeneous. Hence, as expected the mixture has exhibited single absorption peak in our investigations. Further, it is observed that the dynamic viscosity (η_d) values are found to be much smaller than the corresponding macroscopic steady state viscosity (η_s) and the plots of $\log\tau_s$ vs. $\log\eta_s$ are found to be non-linear at higher viscosity values. These results suggest that, even the binary mixture 2-Nitroaniline + 4-Bromoaniline also exhibits the dynamic nature of the viscosity (η_d) at higher viscosity values.

4. Conclusions:

The study of variation of relaxation time (τ) with the viscosity of the medium (η) was carried out on four polar samples 2-Nitroaniline, 4-Bromoaniline, 4-Chloroaniline, 4-Chlorophenol and also on the binary mixture of 2-Nitroaniline + 4-Bromoaniline at room temperature by using Microwave bench operating at a frequency of 9.59 GHz. It is observed

that, the relaxation time increases with increase in the viscosity of the medium for all the samples studied.

The plots of $\log \tau_s$ vs. $\log \eta_s$ were found to be linear in the lower viscosity region and deviate from the linearity in the higher viscosity region for all the samples studied. The non-linear behaviour of $\log \tau_s$ vs. $\log \eta_s$ at higher viscosity region may suggest the failure of Debye's theory in these regions. The non-linear dependence of τ_s on η_s was explained by using the Barlow's viscoelastic model.

The dynamic viscosity (η_d) values were found to be lower compared to the macroscopic steady state viscosity (η_s). Further, the viscoelastic relaxation time (τ_{ve}) values were also found to be lower compared to the relaxation time (τ_s). These results suggest that, the effective frictional resistance experienced by the molecules during reorientation is less and the measured values of macroscopic steady state viscosity (η_s) are frequency dependent. Therefore, for the study of the dielectric behaviour of the dependence of τ on η at microwave frequencies, the concept of dynamic viscosity (η_d) and viscoelastic relaxation time (τ_{ve}) are more effective than the macroscopic steady state viscosity (η_s).

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Table-1: Steady state viscosity (η_s) values for different viscous mediums:

Table-2a: Dielectric constant (ϵ'), dielectric loss (ϵ'') and relaxation time (τ_s) values for 2-Nitroaniline at different viscosities:

Table-2b: Dielectric constant (ϵ'), dielectric loss (ϵ'') and relaxation time (τ_s) values for 4-Bromoaniline at different viscosities:

Table-2c: Dielectric constant (ϵ'), dielectric loss (ϵ'') and relaxation time (τ_s) values for 4-Chloroaniline at different viscosities:

Table-2d: Dielectric constant (ϵ'), dielectric loss (ϵ'') and relaxation time (τ_s) values for 4-Chlorophenol at different viscosities:

Table-3a: Steady state viscosity (η_s), relaxation time (τ_s), dynamic viscosity (η_d) and other parameters for 2-Nitroaniline:

Table-3b: Steady state viscosity (η_s), relaxation time (τ_s), dynamic viscosity (η_d) and other parameters for 4-Bromoaniline:

Table-3c: Steady state viscosity (η_s), relaxation time (τ_s), dynamic viscosity (η_d) and other parameters for 4-Chloroaniline:

Table-3d: Steady state viscosity (η_s), relaxation time (τ_s), dynamic viscosity (η_d) and other parameters for 4-Chlorophenol:

Table-4: Dielectric constant (ϵ') and dielectric loss (ϵ'') and other parameters for (2-Nitroaniline + 4-Bromoaniline)

Figure 1a: Plot of $\log\tau_s$ versus $\log\eta_s$ for 2-Nitroaniline

Figure 1b: Plot of $\log\tau_s$ versus $\log\eta_s$ for 4-Bromoaniline

Figure 1c: Plot of $\log\tau_s$ versus $\log\eta_s$ for 4-Chloroaniline

Figure 1d: Plot of $\log\tau_s$ versus $\log\eta_s$ for 4-Chlorophenol

Figure 2: Plot of $\log\tau_s$ versus $\log\eta_s$ for (2-Nitroaniline + 4-Bromoaniline)

Figure 1a: Plot of $\log \tau_s$ versus $\log \eta_s$ for 2-Nitroaniline

Figure 1b: Plot of $\log \tau_s$ versus $\log \eta_s$ for 4-Bromoaniline

Figure 1c: Plot of $\log \tau_s$ versus $\log \eta_s$ for 4-Chloroaniline

Figure 1d: Plot of $\log \tau_s$ versus $\log \eta_s$ for 4-Chlorophenol

Figure 2: Plot of $\log \tau_s$ versus $\log \eta_s$ for (2-Nitroaniline + 4-Bromoaniline)

Table-1: Steady state viscosity (η_s) values for different viscous mediums:

Medium	% of benzene and paraffin	(η_s) mPa.s
Solvent: 1	95% benzene + 5% paraffin	0.69
Solvent: 2	88% benzene + 12% paraffin	0.81
Solvent: 3	80% benzene + 20% paraffin	1.22
Solvent: 4	60% benzene + 40% paraffin	1.48
Solvent: 5	40% benzene + 60% paraffin	3.02
Solvent: 6	20% benzene + 80% paraffin	10.88
Solvent: 7	12% benzene + 88% paraffin	22.70
Solvent: 8	5% benzene + 95% paraffin	79.41

Table-2a: Dielectric constant (ϵ'), dielectric loss (ϵ'') and relaxation time (τ_s) values for 2-Nitroaniline at different viscosities:

η_s (mPa.s)	ϵ'	ϵ''	τ_s (ps)
0.69	2.341	0.0119	7.20
0.81	2.336	0.0126	7.83
1.22	2.303	0.0157	15.94
1.48	2.269	0.0062	76.22
3.02	2.239	0.0025	194.37
10.88	2.196	0.0024	197.98
22.70	2.182	0.0018	264.30
79.41	2.174	0.0012	394.52

Table-2b: Dielectric constant (ϵ'), dielectric loss (ϵ'') and relaxation time (τ_s) values for 4-Bromoaniline at different viscosities:

η_s (mPa.s)	ϵ'	ϵ''	τ_s (ps)
0.69	2.324	0.0040	4.17
0.81	2.310	0.0063	7.37
1.22	2.296	0.0082	15.94
1.48	2.264	0.0068	29.26
3.02	2.216	0.0025	99.09
10.88	2.200	0.0012	209.64
22.70	2.186	0.0004	632.17
79.41	2.174	0.0002	1264.77

Table-2c: Dielectric constant (ϵ'), dielectric loss (ϵ'') and relaxation time (τ_s) values for 4-Chloroaniline at different viscosities:

η_s (mPa.s)	ϵ'	ϵ''	τ_s (ps)
0.69	2.382	0.0268	15.34
0.81	2.346	0.0234	26.33
1.22	2.328	0.0220	29.34
1.48	2.280	0.0112	69.41
3.02	2.237	0.0080	97.91
10.88	2.206	0.0030	264.83
22.70	2.191	0.0018	437.19
79.41	2.174	0.0012	652.00

Table-2d: Dielectric constant (ϵ'), dielectric loss (ϵ'') and relaxation time (τ_s) values for 4-Chlorophenol at different viscosities:

η_s (mPa.s)	ϵ'	ϵ''	τ_s (ps)
0.69	2.311	0.0102	15.94
0.81	2.295	0.0095	22.99
1.22	2.282	0.0069	40.25
1.48	2.253	0.0045	66.13
3.02	2.218	0.0018	172.17
10.88	2.190	0.0012	259.49
22.70	2.185	0.0009	334.13
79.41	2.169	0.0004	638.94

Table-3a: Steady state viscosity (η_s), relaxation time (τ_s), dynamic viscosity (η_d) and other parameters for 2-Nitroaniline:

η_s (mPa.s)	τ_s (ps)	η_d (mPa.s)	τ_{ve} (ps)	$G_\infty = \eta_s/\tau_{ve}$ (GPa)
0.69	7.20			
0.81	7.83			
1.22	15.94			
1.48	76.22	1.05	10.20	0.145
3.02	194.37	1.12	20.77	0.145
10.88	197.98	1.14	46.61	0.233
22.70	264.30	1.16	68.72	0.330
79.41	394.52	1.21	128.20	0.619

Table-3b: Steady state viscosity (η_s), relaxation time (τ_s), dynamic viscosity (η_d) and other parameters for 4-Bromoaniline:

η_s (mPa.s)	τ_s (ps)	η_d (mPa.s)	τ_{ve} (ps)	$G_\infty = \eta_s/\tau_{ve}$ (GPa)
0.69	4.17			
0.81	7.37			
1.22	15.94			
1.48	29.26			
3.02	99.09	1.40	17.15	0.176
10.88	209.64	1.51	39.72	0.274
22.70	632.17	1.72	55.69	0.408
79.41	1264.77	1.85	103.25	0.769

Table-3c: Steady state viscosity (η_s), relaxation time (τ_s), dynamic viscosity (η_d) and other parameters for 4-Chloroaniline:

η_s (mPa.s)	τ_s (ps)	η_d (mPa.s)	τ_{ve} (ps)	$G_\infty = \eta_s/\tau_{ve}$ (GPa)
0.69	15.34			
0.81	26.33			
1.22	29.34			
1.48	69.41	1.09	9.53	0.155
3.02	97.91	1.15	20.33	0.149
10.88	264.83	1.32	42.91	0.254
22.70	437.19	1.41	61.96	0.366
79.41	652.00	1.48	115.72	0.686

Table-3d: Steady state viscosity (η_s), relaxation time (τ_s), dynamic viscosity (η_d) and other parameters for 4-Chlorophenol:

η_s (mPa.s)	τ_s (ps)	η_d (mPa.s)	τ_{ve} (ps)	$G_\infty = \eta_s/\tau_{ve}$ (GPa)
0.69	15.94			
0.81	22.99			
1.22	40.25			
1.48	66.13	1.09	9.53	0.155
3.02	172.17	1.28	18.59	0.162
10.88	259.49	1.35	42.37	0.257
22.70	334.13	1.42	61.73	0.368
79.41	638.94	1.54	113.40	0.700

Table-4: Dielectric constant (ϵ') and dielectric loss (ϵ'') and other parameters for (2-Nitroaniline + 4-Bromoaniline)

η_s (mPa.s)	ϵ'	ϵ''	τ_s (ps)	η_d (mPa.s)	τ_{ve} (ps)	$G_\infty = \eta_s/\tau_{ve}$ (GPa)
0.69	2.37792	0.03160	15.94			
0.81	2.36711	0.03220	30.78			
1.22	2.33120	0.02390	46.31			
1.48	2.27384	0.01920	58.57			
3.02	2.23644	0.00980	119.10	1.32	18.09	0.167
10.88	2.20272	0.00360	325.01	1.56	38.97	0.279
22.70	2.18623	0.00180	647.22	1.74	55.34	0.410
79.41	2.16332	0.00125	931.39	1.82	104.12	0.763