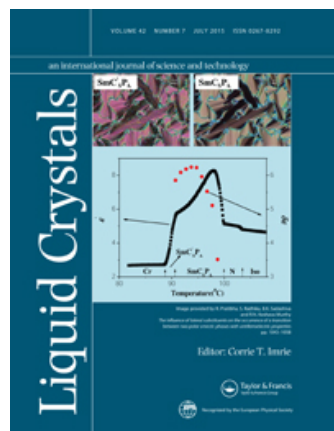


This article was downloaded by: [University of Hyderabad]

On: 22 August 2015, At: 07:11

Publisher: Taylor & Francis

Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: 5 Howick Place, London, SW1P 1WG



Liquid Crystals

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/tlct20>

Phase transitions, optical, dielectric and viscoelastic properties of colloidal suspensions of BaTiO₃ nanoparticles and cyanobiphenyl liquid crystals

M.V. Rasna^a, L. Cmok^b, D.R. Evans^c, A. Mertelj^d & Surajit Dhara^a

^a School of Physics, University of Hyderabad, Hyderabad, India

^b Department of Physics, University of Ljubljana, Ljubljana, Slovenia

^c Air Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, OH, USA

^d J. Stefan Institute, Ljubljana, Slovenia

Published online: 08 Apr 2015.



[Click for updates](#)

To cite this article: M.V. Rasna, L. Cmok, D.R. Evans, A. Mertelj & Surajit Dhara (2015) Phase transitions, optical, dielectric and viscoelastic properties of colloidal suspensions of BaTiO₃ nanoparticles and cyanobiphenyl liquid crystals, *Liquid Crystals*, 42:7, 1059-1067, DOI: [10.1080/02678292.2015.1021719](https://doi.org/10.1080/02678292.2015.1021719)

To link to this article: <http://dx.doi.org/10.1080/02678292.2015.1021719>

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at <http://www.tandfonline.com/page/terms-and-conditions>

Phase transitions, optical, dielectric and viscoelastic properties of colloidal suspensions of BaTiO₃ nanoparticles and cyanobiphenyl liquid crystals

M.V. Rasna^a, L. Cmok^b, D.R. Evans^c, A. Mertelj^d and Surajit Dhara^{a*}

^aSchool of Physics, University of Hyderabad, Hyderabad, India; ^bDepartment of Physics, University of Ljubljana, Ljubljana, Slovenia; ^cAir Force Research Laboratory, Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, OH, USA; ^dJ. Stefan Institute, Ljubljana, Slovenia

(Received 6 January 2015; accepted 18 February 2015)

We report experimental studies on the phase transitions and physical properties of colloidal suspensions of BaTiO₃ nanoparticles and two cyanobiphenyl liquid crystals (4-pentyl-4'-cyanobiphenyl and 4-octyl-4'-cyanobiphenyl). From the differential scanning calorimetric measurements, we show that the nanoparticles have antagonistic effect on the isotropic to nematic and nematic to smectic-A phase transitions. The birefringence, dielectric anisotropy and splay elastic constant remain almost unchanged, whereas the bend elastic constant and rotational viscosity decrease considerably. The experimental results are discussed based on the possible contribution of BaTiO₃ nanoparticles and free surfactant molecules in the suspensions.

Keywords: nanoparticles; liquid crystals; phase transitions; viscoelastic properties

1. Introduction

The study on the colloidal suspension of nanoparticles in liquid crystals is interesting from both the fundamental and technological points of view. The effect of dispersion of nanoparticles on various physical properties depend on an important length scale, called the extrapolation length (ξ), defined as the ratio between the typical elastic constant K and the surface anchoring energy W . When the size of the nanoparticle, R , is much smaller than ξ , the molecules are not strongly pinned at the nanoparticles and there is no long-range elastic distortion. If the initial liquid crystal orientation is monodomain, it is likely to remain as such with no apparent evidence of dissolved nanoparticles. Although the molecular orientation does not change much, the small particles affect significantly the anisotropic physical properties that depends on the size, shape, concentration and properties of the nanoparticles.[1–6] There are several reports on the various physical measurements on liquid crystal nanocomposites based on ferromagnetic, ferroelectric, metal and inorganic nanoparticles.[7–15] The colloidal dispersion of these nanoparticles in liquid crystals combines the physical properties of nanoparticles and orientational order of liquid crystals. It has been reported that the several liquid crystal nanocomposites are useful for display applications.[16–21]

In this article, we present experimental results on the phase transitions and physical properties of colloidal suspension of two liquid crystals, namely, 4-pentyl-4'-cyanobiphenyl (5CB)- and 4-octyl-4'-

cyanobiphenyl (8CB)-doped BaTiO₃ nanoparticles. We show from the thermal measurements that the nematic (N) temperature range of both the compounds have decreased while the smectic-A (SmA) temperature range is increased in 8CB. We measured birefringence, dielectric, curvature elastic constants and rotational viscosity at various temperatures by using an electrooptic technique. We show that birefringence, dielectric anisotropy and splay elastic constant are unchanged, whereas the bend elastic constant and rotational viscosity decrease.

2. Experimental

Indium-tin-oxide-coated (ITO) glass plates with circularly patterned electrode were used to make experimental cells. The ITO plates were spin-coated with polyimide AL-1254 and cured at 180°C for 1 h and rubbed antiparallel way for homogeneous alignment of the director (the average alignment direction of the molecules). For homeotropic alignment, plates were coated with JALS-204 and cured at 200°C for 1 h. Empty cells of different gaps in the range 5–13 μm were fabricated using appropriate spacers. Using an impedance analyser (Novocontrol, Alpha-A), the perpendicular and parallel components of the dielectric constant were measured in a planar and homeotropic cells, respectively. All the measurements were performed at a frequency 1 KHz by applying a very small voltage (much less than the Fredericksz's threshold voltage) across the cell.

*Corresponding author. Email: sdsp@uohyd.ernet.in

Birefringence and elastic constants were measured using an electrooptic technique. The sample retardation was measured by using a helium–neon laser ($\lambda = 632.8$ nm), photoelastic modulator (PEM) and a lock-in amplifier.[22, 23] Using an LCR meter (Inductance-Capacitance-Resistance), sinusoidal voltage of frequency 1 KHz and amplitude up to 20 V was applied. The phase retardation and sample capacitance were measured simultaneously as a function of temperature and voltage. A photodetector collected the light transmitted through the liquid crystal, and lock-in amplifier measured the first and second harmonics of the ac signal. The first and second harmonics signals (1f and 2f signals) measured by the lock-in amplifier are given by $I_{1f} = I_0 J_1(A_0) \sin(\Delta\phi)$ and $I_{2f} = I_0 J_2(A_0) \cos(\Delta\phi)$ where $J_1(A_0)$ and $J_2(A_0)$ are first- and second-order Bessel coefficients, I_0 is the transmitted intensity and $\Delta\phi$ is the optical phase shift and $A_0 = 2.405$ is the retardation amplitude of the PEM. The birefringence of the sample is given by [24]

$$\Delta n = \frac{\lambda}{2\pi d} \Delta\phi = \frac{\lambda}{2\pi d} \arctan\left(\frac{I_{1f} \times J_2(A_0)}{I_{2f} \times J_1(A_0)}\right) \quad (1)$$

The splay elastic constant is obtained directly from the Freedericksz threshold voltage (V_{th}) and is given by $K_{11} = \epsilon_o \Delta\epsilon (V_{th}/\pi)^2$. At strong surface anchoring condition, the voltages above the threshold voltage (V_{th}) and the retardation ($\Delta\phi$) are given by the parametric equations: [25, 26]

$$\Delta\phi = 2\pi \frac{n_e d}{\lambda} \times \left[\int_0^{\frac{\pi}{2}} \sqrt{\frac{(1+\gamma \sin^2 \phi_m \sin^2 \psi)(1+\kappa \sin^2 \phi_m \sin^2 \psi)}{(1-\sin^2 \phi_m \sin^2 \psi)(1+\nu \sin^2 \phi_m \sin^2 \psi)}} d\psi - \frac{n_o}{n_e} \right], \quad (2)$$

and

$$\frac{V}{V_{th}} = \frac{2}{\pi} \sqrt{1 + \gamma \sin^2 \phi_m} \times \int_0^{\frac{\pi}{2}} \sqrt{\frac{1 + \kappa \sin^2 \phi_m}{(1 + \gamma \sin^2 \phi_m \sin^2 \psi)(1 - \sin^2 \phi_m \sin^2 \psi)}} d\psi \quad (3)$$

where d is the cell thickness, ϕ_m is the tilt angle at the middle of the cell and the other terms of the reduced quantities are $\gamma = (\epsilon_{||}/\epsilon_{\perp}) - 1$, $\kappa = (K_{33}/K_{11}) - 1$,

$\nu = (n_e^2/n_o^2) - 1$, $\sin^2 \phi = \sin \phi_m \sin \psi$. The sample retardation at higher voltage is fitted to the above equations by an iterative procedure to get the bend elastic constant K_{33} . [27, 28] It may be mentioned that it is ideal to measure the elastic constants by using magnetic field instead of electric field for such nanocomposite, especially where the ionic conductivity is large. However, comparatively, the enhancement of conductivity in our sample was not so high and in addition we did not observe any agglomeration of the nanoparticle under applied electric field. Hence, it was reasonable to use the electric field technique.

3. Results

3.1. Sample observation and thermal measurements

The liquid crystals used for the experiments are 8CB and 5CB. These compounds were obtained from Sigma-Aldrich and used without further purification. 8CB and 5CB exhibit the following phase transitions: Cr. 22°C SmA 32.5°C N 40 °C I and Cr. 22.5 °C N 35 °C I, respectively. The BaTiO₃ nanoparticles were obtained by milling micron sized particles together with heptane and oleic acid (surfactant).[29] The details of the particle harvesting is discussed in [30]. The average size of the nanoparticles measured by transmission electron microscope is approximately 12 nm. It has been reported that the ferroelectricity is retained in these nanoparticles due to the compressive and tensile surface strain. The ferroelectric nanoparticles were suspended in liquid crystals and the solvent was evaporated. Two different concentrations of BaTiO₃ nanoparticles, namely, 0.2 and 0.4 wt% of both the samples, were prepared. Physical observations indicate that the dispersions are stable and homogeneous. Figure 1(a) shows that the suspension with 0.4 wt% of nanoparticle also appears like pure liquid crystal with no evidence of dispersion. We show the textures obtained under polarising optical microscope for 5CB + 0.4 wt% BaTiO₃ nanocomposite in Figures 1(b) and (c), respectively. It is noticed that the director is uniformly oriented with no evidence of agglomeration of nanoparticles. The measurements were restricted to 0.4 wt% of nanoparticles as the agglomeration-free stable suspension (over a few months) was achieved approximately up to this concentration.

Figure 2 shows the differential scanning calorimetry (DSC) measurements of all the samples. It is observed that the nematic to isotropic transition temperature (T_{NI}) of 5CB liquid crystal decreases with increasing concentration of nanoparticles (Figure 2(a)). In particular, it decreases by about 2.5°C compared to the pristine sample although the enthalpy remains almost

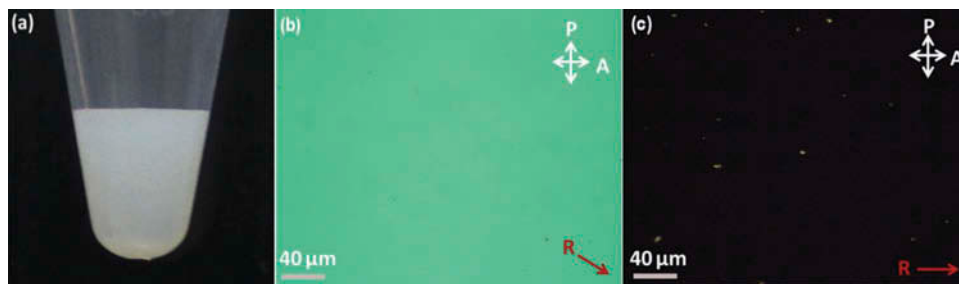


Figure 1. (a) (colour online) Physical appearance of a colloidal suspension of 5CB (with 0.4 wt% BaTiO₃). Photomicrograph of textures under crossed polarisers with rubbing direction (b) 45° with respect to the polariser and (c) parallel to the polariser.

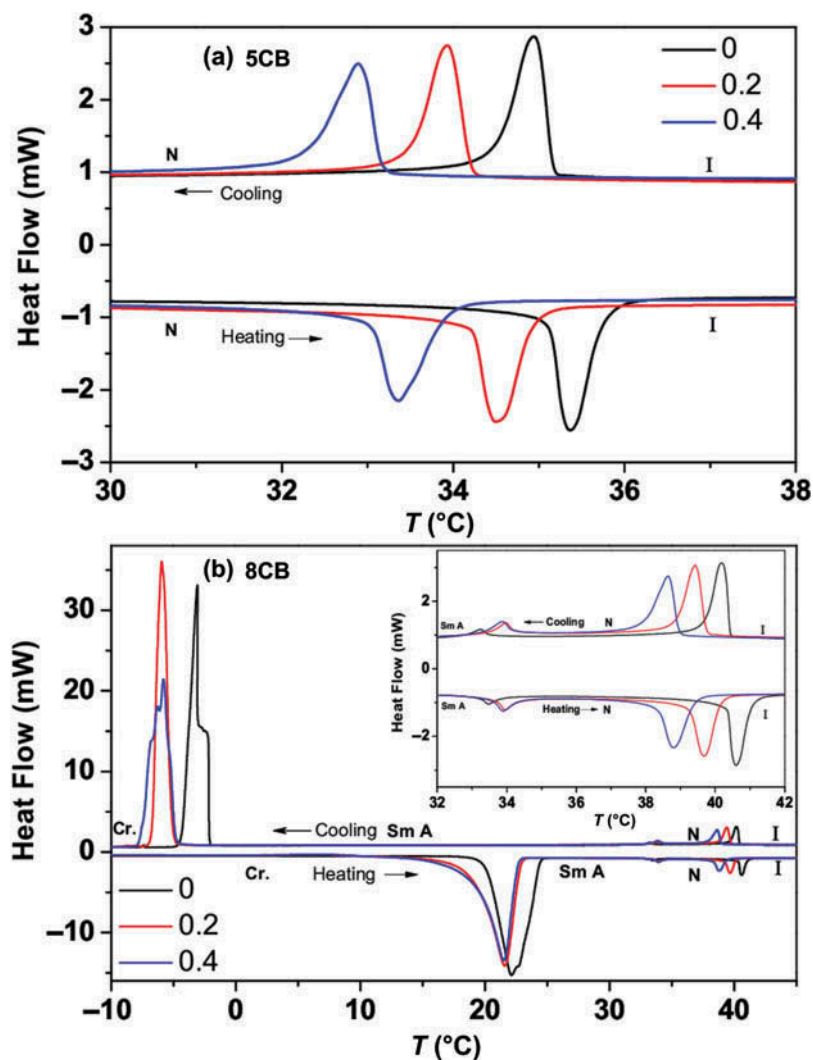


Figure 2. (colour online) Heat flow versus temperature on heating and cooling of (a) 5CB and (b) 8CB and various colloidal suspensions. The inset shows an enlarged part of SmA to N and N to I phase transitions.

unchanged ($\Delta H_{NI} \approx 3$ J/gm). The DSC data of 8CB samples are presented in Figure 2(b). It is observed that T_{NI} decreases and the N to SmA transition temperature (T_{NA}) increases with increasing concentration of

nanoparticles. The SmA to crystallisation temperature is also decreased compared to the pristine sample. For example, in suspension with 0.4 wt% of BaTiO₃ in 8CB, T_{NI} is decreased by 2°C whereas T_{NA} is increased by

Table 1. Nematic and SmA temperature range and enthalpy of N–I and N–SmA transitions of 8CB and the colloidal suspensions.

	Cooling			Heating		
	0	0.2	0.4	0	0.2	0.4
BaTiO ₃ (wt%)	0	0.2	0.4	0	0.2	0.4
ΔH_{NI} (J/gm)	3.3	3.1	3.0	3.4	3.0	2.9
ΔH_{NA} (J/gm)	0.41	0.48	0.66	0.47	0.56	0.75
N range (°C)	6.9	5.5	4.8	7.1	5.7	4.9
SmA range (°C)	36.3	39.2	39.3	11.4	12.3	12.4

1.5°C. Thus, the nematic temperature range is shortened and SmA temperature range is widened with increasing concentration of BaTiO₃ nanoparticles. We also measured the enthalpy of the respective phase transitions of 8CB and they are listed in Table 1. It is observed that the enthalpy (ΔH_{NI}) of the NI transition decreases in both heating and cooling experiments compared to the pristine sample. On the other hand, the enthalpy (ΔH_{NA}) of the N–SmA transition increases with the concentration of BaTiO₃ nanoparticles. For example, ΔH_{NA} of pristine sample is 0.41 J/gm whereas in suspension with 0.4 wt%, it is 0.66 J/gm and this is about 60% larger than the pristine sample.

3.2. Birefringence and dielectric measurements

We measured birefringence ($\Delta n = n_e - n_o$) and dielectric anisotropy ($\Delta\epsilon = \epsilon_{\parallel} - \epsilon_{\perp}$) of all the samples as a function of temperature. The variations of Δn and $\Delta\epsilon$ of 5CB as a function of relative temperature ($T - T_{NI}$) are shown in Figure 3. Both Δn and $\Delta\epsilon$ of 5CB remain almost unchanged compared to the pristine sample. The temperature variations of Δn and $\Delta\epsilon$ of 8CB are shown in Figure 4. It is observed that Δn remains almost unaffected, and in addition, the enhancement of T_{NA} is reflected in both the measurements in accordance with DSC measurements (Figure 2(b)). The small jump of Δn at the N–SmA transition is about 0.007 and comparable to the value obtained by direct intensity measurement technique.[31] The perpendicular component of the dielectric constant ϵ_{\perp} in the nematic phase of 8CB liquid crystal remains almost unchanged, whereas the parallel component (ϵ_{\parallel}) shows a small decreasing tendency with increased concentration of nanoparticles. For example, at $T - T_{NI} = -4^\circ\text{C}$, in the suspension with 0.4 wt% nanoparticles, $\Delta\epsilon$ is decreased by 10%.

3.3. Elastic constant measurements

Figures 5 and 6 show the temperature variation of splay (K_{11}) and bend (K_{33}) elastic constants of both

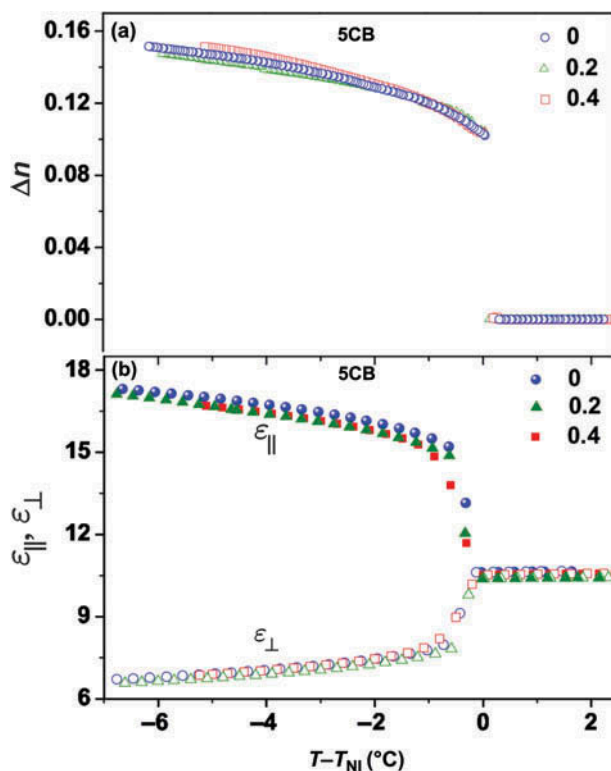


Figure 3. (colour online) Relative temperature dependence of (a) birefringence (Δn) and (b) parallel (ϵ_{\parallel}) and perpendicular (ϵ_{\perp}) components of dielectric constant of pure 5CB and the colloidal suspensions.

the samples and various suspensions. In the pristine sample, both K_{11} and K_{33} are comparable to the previously reported values.[32, 33] When they are compared with relative temperature, it is observed that there is no significant change in K_{11} (Figures 5 (a) and 6(a)), whereas K_{33} decreases considerably (Figures 5(b) and 6(b)). For example, in both samples, at 0.4 wt% of nanoparticles, it decreases almost 20% compared to the respective pristine samples.

3.4. Rotational viscosity measurements

Rotational viscosity was measured by using a phase-decay-time measurement technique.[34] First ac voltage-dependent (frequency 1 KHz) transmitted intensity in a planar aligned cell was measured. A small voltage (V_b) corresponding to first minima or maxima of the transmitted intensity was applied, and at time $t = 0$, the voltage V_b was removed and the relaxation transmission intensity change was measured. The time-dependent transmitted intensity at a particular temperature is given by $I = I_0 \sin^2[\Delta_{\text{tot}} - \delta(t)]/2$, where I_0 is the maximum intensity and Δ_{tot} is the

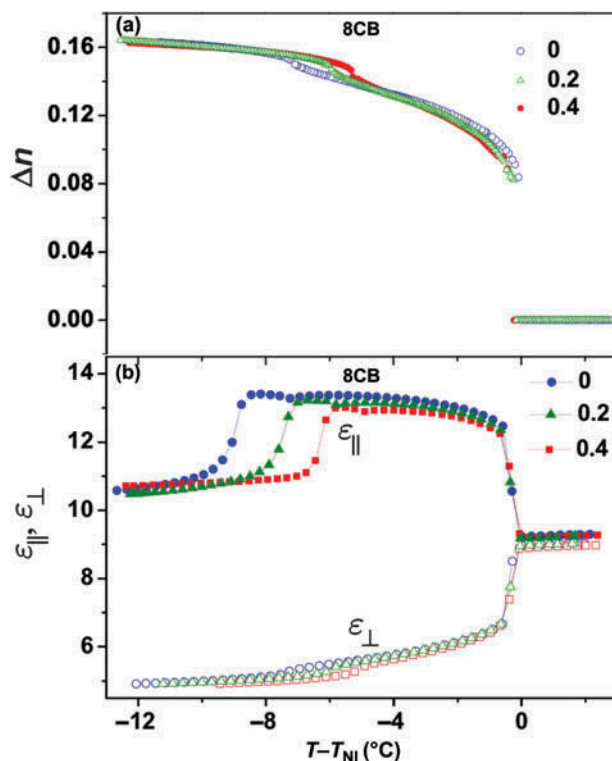


Figure 4. (colour online) Relative temperature dependence of (a) birefringence (Δn) and (b) parallel (ϵ_{\parallel}) and perpendicular (ϵ_{\perp}) components of dielectric constant of pure 8CB and the colloidal suspensions.

total phase difference. The optical phase difference $\delta(t) = \delta_0 \exp(-2t/\tau_0)$, where δ_0 is the total phase difference under bias voltage V_b . The slope of the plot $\ln(\delta_0/\delta(t))$ with time (t) gives the relaxation time (τ_0). Rotational viscosity is given by $\gamma_1 = \pi^2 K_{11} \tau_0 / d^2$, where d is the cell thickness. The variation of γ_1 of both 5CB and 8CB liquid crystals at various concentrations of nanoparticles is shown in Figure 7. Rotational viscosity increases in all the samples with decreasing temperature as expected. More importantly, at a relative temperature, it decreases with increasing concentration of nanoparticles. For example, in 8CB at $T - T_{NI} = -2^\circ\text{C}$, γ_1 decreases from 0.04 to 0.03 Pa s. This is about 25% reduction compared to the pristine sample. It may be mentioned that γ_1 is a derived quantity and depends on K_{11} . The reduction in γ_1 is entirely due to the decrease of the relaxation time as K_{11} remains almost unchanged.

4. Discussion

There are several studies on the N-I and N-SmA phase transitions in nanoparticle-dispersed liquid crystals.[35–37] It has been found that in aerosil-dispersed liquid crystals, both T_{NI} and T_{NA} decrease.

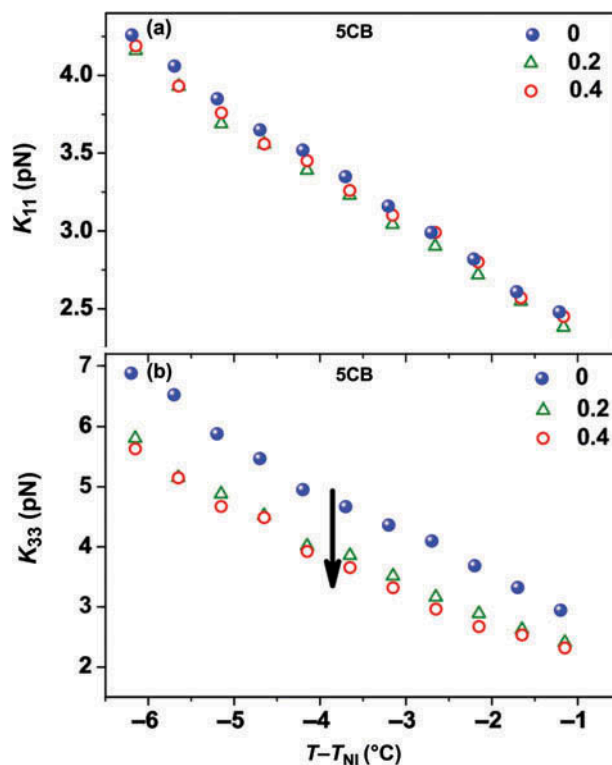


Figure 5. (colour online) Relative temperature variation of (a) splay (K_{11}) and (b) bend (K_{33}) elastic constants for pure 5CB and various colloidal suspensions. The vertically downward arrow indicates the decreasing behaviour of K_{33} .

[37, 38] In case of ferroelectric nanoparticles, such as $\text{Sn}_2\text{P}_2\text{S}_6$, it is reported that T_{NI} can increase or decrease.[39] Gupta et al. showed that T_{NI} decreases in 4-n-octyloxy-4'-cyanobiphenyl liquid crystal doped with BaTiO_3 nanoparticles.[40] In colloidal systems with BaTiO_3 nanoparticles, in a negative dielectric anisotropy nematic liquid crystal mixture, T_{NI} is reported to get enhanced.[41] From the temperature-dependent birefringence measurements, Mertelj et al. reported that T_{NI} decreases whereas T_{NA} increases with concentration of BaTiO_3 in 8CB liquid crystal.[31] The decrease of T_{NI} was attributed to the contribution of the free oleic acid molecules. The increase of T_{NA} was argued due to the increase of de Gennes coupling coefficient C in the relation $\delta S = \chi(T)C|\psi|^2$, where δS is the increase in the nematic order parameter, ψ is the SmA order parameter and $\chi(T)$ is the response function.[31] This could be a pointer to the fact that the oleic acid molecules act like a mesogenic dopant in 8CB liquid crystal. The typical length of a fully stretched oleic acid molecule is about 19.7 \AA , which is almost comparable to the typical length of a 8CB molecule (22.1 \AA). However, in the low melting form of oleic acid, a cis-double bond introduces a pronounced bend in the alkyl chain.[42] Thus, the

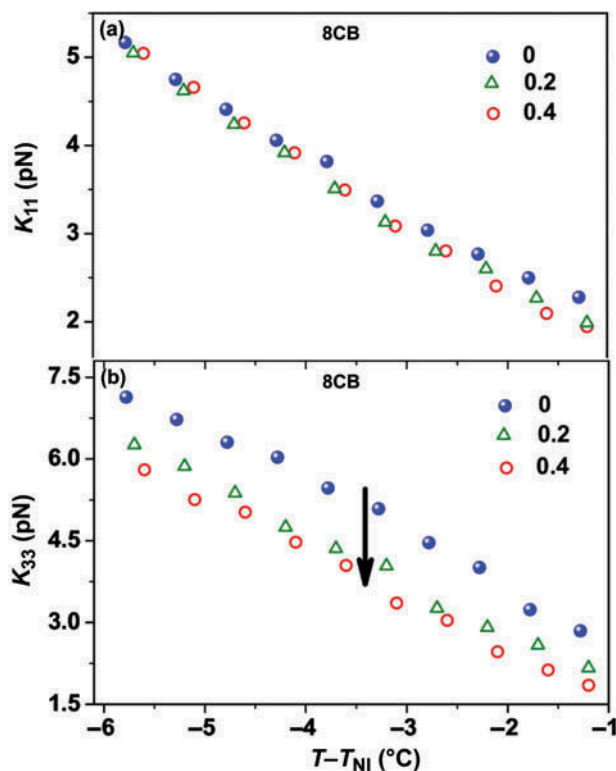


Figure 6. (colour online) Relative temperature variation of (a) splay (K_{11}) and (b) bend (K_{33}) elastic constants for pure 8CB and various colloidal suspensions. The vertically downward arrow indicates the decreasing behaviour of K_{33} .

oleic acid molecules may act as a dopant similar to that of a bent-shaped molecule. Another interesting aspect is the significant change in the enthalpy values of the respective transitions. The decrease of enthalpy corresponding to the N–I transition (see Table 1) suggests that the first-order N–I transition is weakened due to inclusions. On the other hand, the enthalpy of the N–SmA transition is increased suggesting that this weakly first-order transition is becoming relatively stronger with the inclusions. Thus, the increase of T_{NA} is consistent with enhanced enthalpy of the N–SmA transition.

There are several reports on the phase transitions and physical properties of the binary mixture of rod-like and bent-core liquid crystals. Here, we cite a particular example that reports on the effect of doping of bent-core molecules in rod-like nematic system. Pratibha et al. reported that in binary mixtures of rod-like and bent-core liquid crystals, T_{NI} decreases whereas T_{NA} increases with the concentration of bent-core molecules.[43] In the same system, we reported that K_{11} remains almost constant whereas K_{33} decreases with increasing concentration of bent-core molecules.[23] The shift of N–I and N–SmA phase

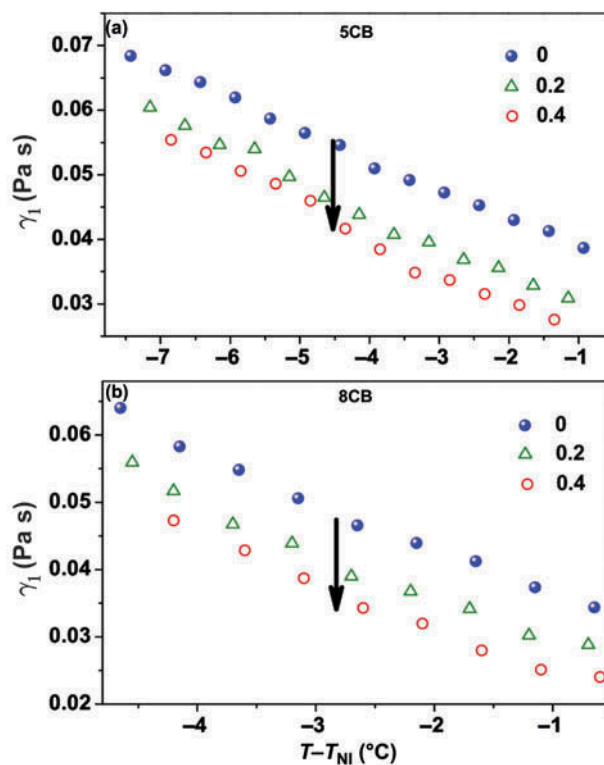


Figure 7. (colour online) Relative temperature variation of rotational viscosity (γ_1) of (a) 5CB and (b) 8CB and various colloidal suspensions. The vertically downward arrow indicates the decreasing behaviour of γ_1 .

transition temperatures and the variation of the physical properties in our present system as discussed are somewhat similar to that reported in [23, 43]. In the mean field theory, $K_{ii} \propto S^2 \propto \Delta n^2$, Δn and S being the birefringence and orientational order parameter, respectively. In the present systems, no significant change in $\Delta n(\propto S)$ is observed (Figures 3(a) and 4(a)) except the order parameter increases more steeply with decreasing temperature in 8CB. Hence, elastic constants are expected to remain unaffected and it is seen only in case of K_{11} (Figures 5(a) and 6(a)). However, it is known that K_{33} may decrease in the binary system of rod and bent-core molecules due to the shape of the bent-core molecules keeping the orientational order the same.[23] This is due to the strong coupling of bent shape with the bend distortion.

The small concentration of BaTiO₃ nanoparticles does not significantly alter the dielectric constants and hence the anisotropy, except a tendency to decrease the parallel component of the dielectric constant (ϵ_{\parallel}). This suggests that either the ferroelectricity of the particles is lost or the effective polarisation of the nanoparticles is screened by the ionic impurities. The ion screening effect in similar systems has been

reported by several authors.[16, 44, 45] We have not performed any additional measurements such as the polarisation current to test their ferroelectric properties in the suspension. Moreover, the concentration of nanoparticles is too low to be isolated from the contribution of ionic polarisation current. The decreasing tendency of ϵ_{\parallel} suggests the lowering of effective dipole moment in the corresponding direction and this could be due to the transverse dipole moments of the oleic acid molecules. This is expected when the bow axes of the oleic acid molecules are parallel to the long axes of the 8CB molecules. We conjecture that the reduction in K_{33} is due to the effective shape (bent shape) of the oleic acid molecules. However, it has to be verified by independent experiments by adding oleic acid in 8CB liquid crystal. Several experiments are planned for the future to study the impact of oleic acid alone on various physical properties of liquid crystals. The decrease of γ_1 in various nematic liquid crystal nanocomposites has been reported previously.[5, 17] This could be due to the trapping of some mobile ions, reducing the free ions concentrations and hence the internal friction of the nematic medium as recently reported by Basu et al. [44].

5. Conclusion

To summarise, we have performed DSC, birefringence, dielectric and viscoelastic measurements of colloidal systems of BaTiO₃ nanoparticles and two liquid crystals (5CB and 8CB). We found that apart from the nanoparticles, the free oleic acid molecules also significantly affect the phase transition and physical properties. The DSC data suggest that the temperature range of nematic is decreased whereas the temperature range of SmA is increased with increasing concentration of nanoparticles. In addition, the N–I transitions become relatively weaker and the N–SmA transitions become relatively stronger with concentration of BaTiO₃ nanoparticles. The birefringence, dielectric anisotropy and splay elastic constant remains almost unchanged. We provided a possible explanation on the reduction of bend elastic constant based on the effective shape of the free oleic acid molecules.

Acknowledgement

We acknowledge experimental support of Dr. S. Maqbool Ahmed, Principal Scientific Officer, CIL, UoH.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

We gratefully acknowledge the support from the UPE-II, DST(SR/NM/NS-134/2010), CSIR(03(1207)/12/EMR-II) and DST-PURSE. MVR acknowledges UGC-BSR for fellowship.

References

- [1] Lynch MD, Patrick DL. Organizing carbon nanotubes with liquid crystals. *Nano Lett.* 2002;2:1197–1201. doi:10.1021/nl025694j.
- [2] Rahman M, Lee W. Scientific duo of carbon nanotubes and nematic liquid crystals. *J Phys D: Appl Phys.* 2009;42:063001–12. doi:10.1088/0022-3727/42/6/063001.
- [3] Basu R, Iannacchione GS. Orientational coupling enhancement in a carbon nanotube dispersed liquid crystal. *Phys Rev E.* 2010;81:051705-1–5. doi:10.1103/PhysRevE.81.051705.
- [4] Basu R, Iannacchione GS. Evidence for directed self-assembly of quantum dots in a nematic liquid crystal. *Phys Rev E.* 2009;80:010701R-1–4. doi:10.1103/PhysRevE.80.010701.
- [5] Manda R, Dasari V, Sathyanarayana P, Rasna MV, Paik P, Dhara S. Possible enhancement of physical properties of nematic liquid crystals by doping of conducting polymer nanofibres. *Appl Phys Lett.* 2013;103:141910–141914. doi:10.1063/1.4824030.
- [6] Rasna MV, Zuhail KP, Manda R, Paik P, Haase W, Dhara S. Discontinuous anchoring transition and photothermal switching in composites of liquid crystals and conducting polymer nanofibers. *Phys Rev E.* 2014;89:052503-1–5. doi:10.1103/PhysRevE.89.052503.
- [7] Blach J-F, Saitzek S, Legrand C, Dupont L, Henninot J-F, Warengem MJ. BaTiO₃ ferroelectric nanoparticles dispersed in 5CB nematic liquid crystal: synthesis and electro-optical characterization. *Appl Phys.* 2010;107:074102–7. doi:10.1063/1.3369544.
- [8] Kaczmarek M, Buchnev O, Nandhakumar I. Ferroelectric nanoparticles in low refractive index liquid crystals for strong electro-optic response. *Appl Phys Lett.* 2008;92:103307–3. doi:10.1063/1.2884186.
- [9] Reznikov Y, Buchnev O, Tereshchenko O, Reshetnyak V, Glushchenko A, West J. Ferroelectric nematic suspension. *J Appl Phys Lett.* 2003;82:1917–3. doi:10.1063/1.1560871.
- [10] Atkuri H, Zhang K, West J. Fabrication of paraelectric nanocolloidal liquid crystals. *Mol Cryst Liq Cryst.* 2009;508:183/[545]–190. doi:10.1080/15421400903060581.
- [11] Glushchenko A, Cheon C, West J, Li F, Büyüktanir E, Reznikov Y, Buchnev A. Ferroelectric particles in liquid crystals: recent frontiers. *Mol Cryst Liq Cryst.* 2006;453:227–237. doi:10.1080/15421400600653852.

- [12] Mertelja A, Lisjak D, Drogenik M, Čopič M. Ferromagnetism in suspensions of magnetic platelets in liquid crystal. *Nature*. 2013;504:237–241. doi:10.1038/nature12863.
- [13] Mertelja A, Osterman N, Lisjak D, Čopič M. Magneto-optic and converse magnetoelectric effects in a ferromagnetic liquid crystal. *Soft Matter*. 2014;10:9065–9072. doi:10.1039/C4SM01625D.
- [14] Yadav N, Dabrowski R, Dhar R. Effect of alumina nanoparticles on dielectric permittivity, electrical conductivity, director relaxation frequency, threshold and switching voltages of a nematic liquid crystalline material. *Liq Cryst*. 2014;41(12):1803–1810. doi:10.1080/02678292.2014.950619.
- [15] Lebovka NI, Lisetski LN, Nesterenko MI, Panikarskaya VD, Kasian NA, Minenko SS, Soskin MS. Anomalous selective reflection in cholesteryl oleyl carbonate - nematic 5CB mixtures and effects of their doping by single-walled carbon nanotubes. *Liq Cryst*. 2013;40(7):968–975. doi:10.1080/02678292.2013.786796.
- [16] Cook G, Reshetnyak VY, Ziolo RF, Basun SA, Banerjee PP, Evans DR. Asymmetric Freedericksz transitions from symmetric liquid crystal cells doped with harvested ferroelectric nanoparticles. *Opt Express*. 2010;18:17339–17345. doi:10.1364/OE.18.017339.
- [17] Chen HY, Lee W, Clark N. Faster electro-optical response characteristics of a carbon-nanotube-nematic suspension. *Appl Phys Lett*. 2007;90:033510–3. doi:10.1063/1.2432294.
- [18] Chen H, Lee W. Suppression of field screening in nematic liquid crystals by carbon nanotubes. *Appl Phys Lett*. 2006;88:222105–3. doi:10.1063/1.2208373.
- [19] Lu SY, Chien LC. Carbon nanotube doped liquid crystal OCB cells: physical and electro-optical properties. *Opt Express*. 2008;16:12777–12785. doi:10.1364/OE.16.012777.
- [20] Shiraishi Y, Toshima N, Maeda K, Yoshikawa H, Xu J, Kobayashi S. Frequency modulation response of a liquid-crystal electro-optic device doped with nanoparticles. *Appl Phys Lett*. 2002;81:2845–2847. doi:10.1063/1.1511282.
- [21] Li F, West J, Glushchenko A, Cheon CI, Reznikov Y. Ferroelectric nanoparticle/liquid-crystal colloids for display applications. *J SID*. 2006;14:523.
- [22] Sathyanarayana P, Jampani VSR, Skarabot M, Musevic I, Le KV, Takezoe H, Dhara S. Viscoelasticity of ambient-temperature nematic binary mixtures of bent-core and rodlike molecules. *Phys Rev E*. 2012;85:011702-1–9. doi:10.1103/PhysRevE.85.011702.
- [23] Sathyanarayana P, Sadashiva BK, Dhara S. Splay-bend elasticity and rotational viscosity of liquid crystal mixtures of rod-like and bent-core molecules. *Soft Matter*. 2011;7:8556–8560. doi:10.1039/c1sm05751k.
- [24] Oakberg TC, Goldstein DH, Chipman RA. Measurement of waveplate retardation using a photoelastic modulator. *Proc SPIE*. 1997;3121:19–22. doi:10.1117/12.278971.
- [25] Kundu B, Pratibha R, Madhusudana NV. Anomalous temperature dependence of elastic constants in the nematic phase of binary mixtures made of rodlike and bent-core molecules. *Phys Rev Lett*. 2007;99:247802-1–4. doi:10.1103/PhysRevLett.99.247802.
- [26] Barbero G, Evangelista LR. An elementary course on the continuum theory for nematic liquid crystals. Singapore: World Scientific; 2000.
- [27] Sathyanarayana P, Mathews M, Li Q, Sastry VSS, Kundu B, Le KV, Takezoe H, Dhara S. Splay bend elasticity of a bent-core nematic liquid crystal. *Phys Rev E*. 2010;81:010702R-1–4. doi:10.1103/PhysRevE.81.010702.
- [28] Sathyanarayana P, Varia MC, Prajapati AK, Kundu B, Sastry VSS, Dhara S. Splay-bend elasticity of a nematic liquid crystal with T-shaped molecules. *Phys Rev E*. 2010;82:050701R-1–4. doi:10.1103/PhysRevE.82.050701.
- [29] Atkuri H, Cook G, Evans DR, Cheon CI, Glushchenko A, Reshetnyak V, Reznikov Y, West J, Zhang K. Preparation of ferroelectric nanoparticles for their use in liquid crystalline colloids. *J Opt A: Pure Appl Opt*. 2009;11:024006–5. doi:10.1088/1464-4258/11/2/024006.
- [30] Cook G, Barnes JL, Basun SA, Evans DR, Ziolo RF, Ponce A, Reshetnyak VY, Glushchenko A, Banerjee PP. Harvesting single ferroelectric domain stressed nanoparticles for optical and ferroic applications. *J Appl Phys*. 2010;108:064309–5. doi:10.1063/1.3477163.
- [31] Mertelj A, Cmok L, Čopič M, Cook G, Evans DR. Critical behavior of director fluctuations in suspensions of ferroelectric nanoparticles in liquid crystals at the nematic to smectic-A phase transition. *Phys Rev E*. 2010;85:021705-1–7. doi:10.1103/PhysRevE.85.021705.
- [32] Bogi A, Faetti S. Elastic, dielectric and optical constants of 4'-pentyl-4-cyanobiphenyl. *Liq Cryst*. 2001;28:729–739. doi:10.1080/02678290010021589.
- [33] Karat PP, Madhusudana NV. Elastic and optical properties of some 4'-n-Alkyl-4-cyanobiphenyls. *Mol Cryst Liq Cryst*. 1976;36:51–64. doi:10.1080/00268947608084830.
- [34] Wu ST, Wu CS. Experimental confirmation of the Osipov–Terentjev theory on the viscosity of nematic liquid crystals. *Phys Rev A*. 1990;42:2219–2227. doi:10.1103/PhysRevA.42.2219.
- [35] Denolf K, Roie BV, Glorieux C, Thoen J. Effect of nonmesogenic impurities on the order of the nematic to smectic-A phase transition in liquid crystals. *Phys Rev Lett*. 2006;97:107801-1–4. doi:10.1103/PhysRevLett.97.107801.
- [36] Denolf K, Cordoyiannis G, Glorieux C, Thoen J. Effect of nonmesogenic impurities on the liquid crystalline phase transitions of octylcyanobiphenyl. *Phys Rev E*. 2007;76:051702-1–9. doi:10.1103/PhysRevE.76.051702.
- [37] Sigdel KP, Iannacchione GS. Calorimetric study of the nematic to smectic-A phase transition in octylcyanobiphenyl-hexane binary mixtures. *Phys Rev E*. 2010;82:051702-1–8. doi:10.1103/PhysRevE.82.051702.
- [38] Cruceanu F, Liang D, Leheny RL, Garland CW, Iannacchione GS. High resolution calorimetric study of the nematic to smectic-A transition in aligned liquid crystal aerosol gels. *Phys Rev E*. 2009;79:0117101–8. doi:10.1103/PhysRevE.79.011710.
- [39] Kurochkin O, Atkuri H, Buchnev O, Glushchenko A, Grabar O, Karapinar R, Reshetnyak V, West J, Reznikov Y. Nano-colloids of $Sn_2P_2S_6$ in nematic liquid crystal pentyl-cyanobiphenyl. *Condens Matter Phys*. 2010;13:33701. doi:10.5488/CMP.13.33701.

- [40] Gupta M, Satpathy I, Roy A, Pratibha R. Nanoparticle induced director distortion and disorder in liquid crystal-nanoparticle dispersions. *J Colloid Inter Sci.* 2010;352:292–298. doi:10.1016/j.jcis.2010.08.027.
- [41] Li F, Buchnev O, Cheon CI, Glushchenko A, Reshetnyak V, Reznikov Y, Sluckin TJ, West JL. Orientational coupling amplification in ferroelectric nematic colloids. *Phys Rev Lett.* 2006;97:147801-1–4. doi:10.1103/PhysRevLett.97.147801.
- [42] Gunstone ED, Harwood JL, Dijkstra AJ. *The lipid handbook*. 3rd ed. Boca Raton (FL): CRC Press, Taylor and Francis Group; 2007.
- [43] Pratibha R, Madhusudana NV, Sadashiva BK. An orientational transition of bent-core molecules in an anisotropic matrix. *Science.* 2000;288:2184–2187. doi:10.1126/science.288.5474.2184.
- [44] Basu R, Garvey A. Effects of ferroelectric nanoparticles on ion transport in a liquid crystal. *Appl Phys Lett.* 2014;105:151905–5. doi:10.1063/1.4898581.
- [45] Shukla RK, Liebig CM, Evans DR, Haase W. Electro-optical behaviour and dielectric dynamics of harvested ferroelectric LiNbO₃ nanoparticle-doped ferroelectric liquid crystal nanocolloids. *RSC Adv.* 2014;4:18529–18536. doi:10.1039/c4ra00183d.