

Article



Nematogenic Laterally Substituted Supramolecular H-Bonded Complexes Based on Flexible Core

H.A. Ahmed ^{1,2,*} and Muna S. Khushaim ^{3,4}

- ¹ Faculty of Science, Department of Chemistry, Cairo University, Cairo 12613, Egypt
- ² Chemistry Department, College of Sciences, Yanbu, Taibah University, Yanbu 30799, Saudi Arabia
- ³ Department of Physics, Faculty of Science, Taibah University, P. Box: 30002, Al-Madina 41447, Saudi Arabia; mkhushaim@taibahu.edu.sa
- ⁴ Nanotechonolgy Center, Taibah University, P. Box: 30002, Al-Madina 41447, Saudi Arabia
- * Correspondence: ahoda@sci.cu.edu.eg

Received: 6 September 2020; Accepted: 27 September 2020; Published: 28 September 2020



Abstract: New laterally CH₃-substituted series of 1:2 hydrogen-bonded supramolecular complexes (HBSMCs) based on flexible acid core were prepared and mesomorphically investigated. Mixtures were formed through H-bonded interactions between adipic acid (A) and 4-(2-(pyridin-4-yl)diazenyl-(3-methylphenyl) 4-alkoxybenzoate (Bn). Mesomorphic and optical properties were investigated by differential scanning calorimetry (DSC), polarized optical microscopy (POM), X-ray diffraction (XRD), and UV-spectroscopy. HBSMCs formed from 1:2 mol mixture of A:2Bn, where the base component (B) bearing different alkoxy chain lengths from n = 8 to 14. The new HBSMCs (A/2B) interactions were confirmed by Fermi-bands formation via FT-IR spectroscopy measurements. Results revealed that all prepared HBSMCs are enantiotropic, exhibiting induced nematic (N) phase. The XRD pattern confirmed the POM texture results. Moreover, a comparison was made between the new laterally HBSMC series based on flexible core and the previously analyzed laterally neat complexes.

Keywords: lateral-group; supramolecular H-bonding complexes; X-ray diffraction; induced phase; adipic acid; flexible core

1. Introduction

An interesting study was undertaken to prepare and design enormous new mesogenic liquid crystal (LC) structures for display applications and technologies [1–6]. Kato et al. [7] reported in 1989 the first hydrogen-bonded supramolecular liquid crystal complex (HBSMCs) induced via intermolecular hydrogen-bonding (H-bonding) interactions between pyridine derivative and a carboxylic acid. H-bonding interactions are power tools for forming and inducing new mesophases [7–13]. Thus, HBSMCs have been attracting considerable attention based on the preparation of new geometrical molecules, as well as the mesomorphic characterizations and the structure–property relationships of them [1–6,14–18].

The introduction of azo-pyridine derivatives in the synthesized complexes enhances the powerful polar induction [19] and influences the conjugation power of the mesogenic cores, which offer photonic application [20]. In addition, the *trans-cis*-isomerization ability of azo-linkage makes it a suitable candidate for photo-responsive property [21,22].

LC substituent in the lateral position decreases the melting temperature of solid states and the thermal stability of the mesophase due to the steric effects and the intramolecular hindering of the lateral substituent [23–30]. Moreover, the lateral substituent makes molecules broad, having an effective

role in the mesomorphic characters of the resulting derivatives. Furthermore, the lateral moiety in the rigid core can destroy the molecular closed packing of liquid crystalline materials.

Geometry and terminal chain length of the LC molecule play an important role in the formation, type, thermal stability, and range of the mesophase. The molecules tend to be oriented in a parallel arrangement as the length of the terminal chain increases [31]. Moreover, the lengths of terminals can influence the twist-bend and heliconical N mesophases [32,33].

For further established structure–property relationships of HBSMCs, and due to the H-bonding interactions effects on the molecular association leading to increase the mesogenic core moiety length, we increased molecular biaxiality of the HBSMCs by introducing a lateral methyl group on the complex skeleton. From this point of view, the goal of our work is to synthesize new structural symmetrical 1:2 lateral HBSMCs based on the H-bonding interactions between the flexible core adipic acid (A) and the lateral CH₃ azo-pyridine base derivatives (Bn) [30], with changeable terminal alkoxy chain length (n). The aim of the study is also to investigate their mesomorphic, optical properties, and photo-physical behavior of prepared HBSMCs (A/2Bn, Scheme 1), and to estimate the effect of the terminal length of alkoxy chain (n) on the mesomorphic and optical behaviors of complexes. Further, a comparison is constructed between the present lateral HBSMCs and the previously reported laterally neat complexes [34] to investigate the effect of the position and orientation of lateral CH₃-group on mesomorphic characters.



A/2Bn

Scheme 1. 1:2 hydrogen-bonded supramolecular complex (HBSMC), A/2Bn.

2. Experimental

4-(2-(pyridin-4-yl)diazenyl-(3-methylphenyl) 4-alkoxybenzoate (Bn) were prepared according to the previous method [30] that is attached in Supplementary Materials (Table S1, Figures S1 and S2).

Preparation of 1:2 HBSMCs Complexes

HBSMCs (A/2Bn) were formed from one mole of adipic acid (A) and two moles of 4-(2-(pyridin-4-yl)diazenyl-(3-methylphenyl) 4-alkoxybenzoate (Bn), with n values between n = 8 and 16 for carbons. The solid mixture was melted with stirring to form an intimate blend and then allowed to cool to room temperature (Scheme 2). The formations of the HBSMCs (A/2Bn) were confirmed via differential scanning calorimetry (DSC) and FT-IR spectroscopy.



Scheme 2. Preparation of 1:2 hydrogen-bonded supramolecular complexes (A/2Bn).

3. Results and Discussion

3.1. FT-IR Characterizations of 1:2 HBSMCs Complexes

FT-IR spectroscopy was used to confirm the formation of H-bonded intermolecular interactions of present HBSMCs (A/2Bn) between the adipic acid component (A) and laterally azopyridine-based components (Bn). Measurements were performed for the individual components and their 1:2 HBSMCs. The alkoxy chain length (n) was not significantly affected by the mesomeric absorbtion value of the C=O group of azopyridine compounds B8, B10, B12, and B16 before complexation. FT-IR spectrum of adipic acid (A), lateral azopyridine homologue (B12), and their HBSMC A/2B12 are shown in Figure 1 as examples and Figure S3 in Supplementary Materials.

As shown in Figure 1, the spectrum of B12 has an ester carbonyl band at 1727.0 cm⁻¹, which changes in the FT-IR spectrum due to the complexation to 1735.0 cm⁻¹, and at the same time the carboxylic carbonyl peak of acid A changes from 1631.0 to 1651.0 cm⁻¹. These results confirm the intermolecular H-interactions between them. Moreover, the observation of three Fermi-resonance vibration bands of the H-bonded OH groups A-, B-, and C-types is also confirmation of the HBSMCs formation [35–42]. The A-type Fermi-band of complex A/2B12 is overlapped with that of the C-H vibrational peaks at 2920.0 to 2853.0 cm⁻¹. The observed peak at 2348.0 cm⁻¹ for (A/2B12) could be assigned to B-type of the in-plane bending vibration of the O–H group. On the other hand, the band at 1914.0 cm⁻¹ corresponds to C-type Fermi-band due to the interaction between the fundamental stretching vibration of the OH group and the overtone of the torsional effect.



Figure 1. FT-IR spectra of (a) acid, A, (b) base, B12, and (c) complex, A/2B12.

3.2. Mesomorphic Studies of 1:2 HBSMCs, A/2Bn

All prepared supramolecular mixtures (A/2Bn) were investigated by DSC and polarized optical microscopy (POM) to evaluate their thermal and mesomorphic properties. DSC results, given as transition temperatures as well as enthalpy and normalized entropy, are collected in Table 1. All thermal measurements were recorded from the second heating scan. DSC thermogram taken from the second heating/cooling scans for A/2B12 complex is represented in Figure 2 as an example (Figures S4 and S5, Supplementary Materials). In order to ensure the stability of the formed 1:2 mixtures, measurements were performed for two heating/cooling scans and found to be the same. Only one mesomorphic peak was observed in the DSC thermogram upon both the heating and cooling cycles. Examples of observed textures of nematic mesophases under POM are depicted in Figure 3. Nematic phase was only observed upon heating and cooling rounds, indicating that the textures are confirming the DSC measurements. Dependency relation of transition temperatures on the length of alkoxy terminal chain (n), for the characterized HBSMCs A/2Bn, was represented graphically in Figure 4. That relation was constructed in order to evaluate the impact of the terminal chain lengths of the base moieties on the mesomorphic property.

It should be noted that the flexible core adipic acid (A) is non-mesomorphic with melting temperature ≈ 152 °C, whereas the lateral CH₃ azo-pyridines (Bn) are monomorphic exhibiting smectic C (SmC) phase, except the homologue B10 which has very narrow enantiotropic SmC phase [30,43]. Therefore, it was interesting to study the mesophase property by incorporating a polar lateral group, with spatial orientation angle, of present HBSMCs and compare their mesomorphic results with the previous laterally neat synthesized complexes [34].

Generally, for H-bonded complexes, the lateral group, mesogenic linkage, and terminal chain length have a shared impact on the thermal stability of the formed mesophase. Moreover, the polarity changes between H-donors and H-acceptors affect the H-bonding strength and enhancement of the molecular anisotropy, resulting in the promotion of the broadening of the mesomorphic range [44]. However, the terminal length of the alkoxy chain of the complex does not affect the polarity of either individual. The attachment of heterocyclic moiety in the mesomorphic compounds strongly affects

polarity and/or polarizability, as well as the geometric arrangement. In addition, the molecular size and shape of the lateral group affects the mesophase stability and the polarizability [45,46].

Table 1. Phase transition temperatures (T, $^{\circ}$ C), enthalpy of transitions (Δ H, kJ/mol), and normalized transition entropy (Δ S/R) of HBSMCs, A/2Bn.

| System | T _{Cr-N} | $\Delta H_{\rm Cr-N}$ | T _N -I | $\Delta H_{\rm N}$ -I | $\Delta S_{\text{N-I}}/R$ |
|--------|-------------------|-----------------------|-------------------|-----------------------|---------------------------|
| A/2B8 | 83.5 | 71.40 | 100.4 | 1.11 | 0.36 |
| A/2B10 | 81.0 | 76.11 | 99.2 | 1.99 | 0.64 |
| A/2B12 | 81.4 | 80.81 | 95.9 | 2.34 | 0.76 |
| A/2B16 | 77.2 | 73.65 | 66.0 | 2.45 | 0.87 |

Abbreviations: Cr-N = solid to nematic phase transition; N-I = nematic to isotropic liquid transition.



Figure 2. Differential scanning calorimetry (DSC) curve at rate 10 °C/min for 1:2 HBSMC, A/2B12 upon the second heating/cooling cycles.



Figure 3. Nematic phase textures during heating under polarized optical microscopy (POM) of 1:2 HBSMC, A/2B12 (**a**) at 83.0 °C, (**b**) at 91.0 °C, and (**c**) at 95.0 °C.

It could be seen from Table 1 and Figure 4 that the nematic mesophase is exhibited by all 1:2 supramolecular complexes, independent of the length of terminal alkoxy chain (n). In addition, the N phase stability is affected by the increase of n; it decreases as n increases. The melting point transitions of the investigated 1:2 HBSMCs (A/2Bn) are related randomly with n. Therefore, despite the fact that the lateral methyl-azopyridines possess only less stable SmC phases and the adipic acid is non-mesomorphic, all synthesized 1:2 complexes (A/2Bn) exhibit unique induced N mesophase with

enantiotropic ranges, except the mixture A/2B16, which is monomorphic. The higher N stability value is observed for the complex A/2B8 (\approx 100.4 °C) and the lower value for A/2B16 (\approx 66.0 °C); the higher N range value is observed for the mixture A/2B10 (\approx 18.2 °C) and the lower range for A/2B16 (\approx 11.2 °C). Additionally, the nematic stability enhancement decreases with the increment of the chain length (n), thus the stability of the N phase is affected by the length of alkoxy chain. It was reported that as the molecular anisotropy increases in the HBSMCs, the broadening of N phases will be promoted [34], which revealed that the increment of the length of mesogenic core will increase the stability of N phase.



Figure 4. DSC transitions of 1:2 HBSMCs series, A/2Bn.

The monotropic N phase at terminal chain length n = 16 can be attributed to the dilution of the rigid mesogenic core [33]. Moreover, the higher value of Van der Waals attraction forces between the longer terminal chains enhances the terminal interactions and aggregation of alkyl groups, that attraction forces an effect on the formation of N phase. The mesomorphic properties of HBSMCs depend mainly on various factors: (1) Lateral adhesion interaction of molecules that increases with the increment of the terminal-chain length or aspect ratio. (2) Molecular geometry, which is affected by the steric hindrance of the terminal and lateral groups. (3) End-to-end interaction, which depends on the polarity and/or polarizability of terminal and lateral substituents. Furthermore, the linking groups highly impact the conjugation within the mesogenic core of the molecule.

3.3. Entropy Changes, $\Delta S/R$

Terminal alkoxy-chains are very labile and can make multi-conformational changes. Therefore, they play a dominant role in entropy changes (Δ S/R). An influence of entropy change is observed in all investigated HBSMCs A/2Bn, suggesting the increment in the conformational and orientational changes of the complex compared with its pure individuals. The normalized transition entropies (Δ S/R) were estimated for the present symmetric 1:2 HBSMCs (A/2Bn), as driven from DSC results and tabulated in Table 1, as well as represented graphically as function of n, in Figure 5. It can be concluded that the increment of the entropy changes, with increasing the terminal alkoxy-chain length (n), is due to the increase in the biaxiality of the mesogenic part due to the incorporation of the lateral CH₃ group. In addition, this may be further attributed to the change in geometrical interactions between individuals of the mixtures, which is accordingly affected by the polarizability and the molecular shape of the terminal and lateral substituents.



Figure 5. Entropy changes as a function of chain length (n) of present HBSMCs A/2Bn.

3.4. Effect of Incorporation of Lateral Group in HBSMCs

In order to study the effect of addition of a lateral methyl group in the mesogenic core of the HBSMCs on the mesomorphic behavior, a comparison was established between the mesomeric behavior of present HBSMCs, A/2Bn, and our previously investigated laterally neat complexes, A/2Cn [34]. Figure 6 represents the graphical comparison, which indicates that the mesophase stabilities of laterally neat mixtures (A/2Cn) are relatively higher than those of the present HBSMCs (A/2Bn), i.e., attachment of lateral CH₃ group, in meta-position with respect to the ester moiety of the base component, in the molecular structure, has destabilized the N stability. Thus, it seems that the incorporation of lateral CH₃ moiety into azopyridine derivatives decreases the polarizability of the whole molecule and consequently disrupts the intermolecular interactions between individual molecules.



Figure 6. 1:2 HBSMCs A/2Cn [34].

3.5. Photo-Physical Investigation

Azopyridine compounds undergo *trans-cis* isomerization when irradiated with light of an appropriate wavelength. Those phenomena make it an essential component of various molecular devices as well as functional materials [47,48]. The photo-physical measurements of the present lateral CH₃-HBSMCs, A/2Bn, were carried out by measuring UV-vis spectra. To evaluate the spectrophotometric absorption spectra, a solution of concentration C = 1.8×10^{-6} mol/L in chloroform was prepared. Figure 7 represents the resulting absorption bands graphically. It could be found from Figure 7, the light radiation in the wavelength range 380–800 nm for present 1:2 lateral CH₃-HBSMCs is found to be strongly absorbed with the maximum at \approx 456–457 nm, according to the terminal alkoxy chain (n), which can be attributed to the π - π * transition of the chromophore in the molecule. The absorbance values at the maximum wavelength increased in an irregular manner independent of the alkoxy chain (n). In addition, the intensity and absorption of the peak in the absorption spectrum are dependent on the molecular geometry of the material that absorbs the light at the given wavelength. Furthermore, the absorption spectra of the present HBSMC, A/2Bn, showed the maximum bands at 457 nm, which also attributed to the π - π electronic transitions from the HOMO (highest occupied molecular orbitals) to LUMO (lowest unoccupied molecular orbitals) [49–51].



Figure 7. UV-absorption spectrum of present HBSMCs, A/2Bn, in chloroform.

3.6. X-ray Diffraction Investigation

The mesomorphic properties of the present prepared HBSMCs (A/2Bn) were confirmed by X-ray diffraction (XRD) measurements. XRD is another tool to confirm the mesophase assignments [34,52]. XRD experiments were performed at different temperatures upon cooling of the sample from the isotropic liquid mesophase. Figure 8 shows the homologue A/2B8 as a representative example for the present 1:2 laterally substituted HBSMCs series (A/2Bn). It can be seen from Figure 8, XRD analysis pattern at all recorded temperatures showed only one peak at angle 2θ = 25°, assigned to the presence of nematic transition phase upon cooling for all recorded temperatures, which related to the lateral interactions between mesogenic groups. Thus, the temperature dependent XRD investigations of the present lateral CH₃-HBSMCs confirmed the presence of a monomorphic broad peak of N mesophase. After comparing the XRD and POM results, the existence of only N mesophases in all formed HBSMCs A/2Bn were assigned.



Figure 8. X-ray diffraction (XRD) patterns of A/2B8 at different temperatures upon cooling from the isotropic liquid mesophase.

4. Conclusions

New 1:2 symmetrical homologues of lateral methyl HBSMCs, bearing different lengths of terminal alkoxy groups, were synthesized and evaluated by different tools. Appearance of Fermi-bands in FT-IR spectroscopic analysis confirmed the presence of H-bonding interactions. Mesomorphic properties of present 1:2 HBSMCs were investigated by DSC, POM, and XRD measurements. UV-spectroscopy was performed to evaluate the photo-physical characters of the complexes. Results revealed that all prepared complexes that are nematogenic exhibit induced enantiotropic N phase except for the complex of longer terminal alkoxy chain at n = 16, which possess monotropic nematogenic phase. In addition, the temperature-dependent XRD pattern was consistent with the intrinsic character of N mesophase and that is in agreement with both the DSC and POM results. A comparative study was established between the present HBSMCs and their corresponding laterally neat complexes, resulting that the attaching of the lateral CH₃ group decreases the mesophase stability with only an N phase obtained. Finally, the increment in the biaxiality of the mesogenic part due to the addition of a lateral CH₃ group leads to increases in the entropy changes of present complexes with terminal chain length.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4352/10/10/878/s1, Figure S1: The mass spectrum of B16, Figure S2: The 1H-NMR spectrum of B10, Figure S3: FT-IR spectra of (a) B8; (b) B10; (c) A/2B8 and (d) A/2B10, Figure S4: DSC curve at rate 10 °C/min for 1:2 HBSMC, A/2B8 upon the second heating/cooling cycles, Figure S5: DSC curve at rate 10 °C/min for 1:2 HBSMC, A/2B16 upon the second heating/cooling cycles, Table S1: Mass spectra (m/z) of the Azopyridine derivatives (Bn).

Author Contributions: Data curation, H.A.A. and M.S.K.; Formal analysis, H.A.A. and M.S.K.; Funding acquisition, M.S.K.; Investigation, H.A.A. and M.S.K.; Methodology, H.A.A. and M.S.K.; Project administration, H.A.A. and M.S.K.; Resources, H.A.A.; Writing—original draft, H.A.A. and M.S.K.; Writing—review and editing, H.A.A. and M.S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

- 1. Alhaddad, O.; Ahmed, H.; Hagar, M. Experimental and theoretical approaches of new nematogenic chair architectures of supramolecular H-bonded liquid crystals. *Molecules* **2020**, *25*, 365. [CrossRef]
- Alaasar, M.; Poppe, S.; Tschierske, C. Photoresponsive halogen bonded polycatenar liquid crystals. *J. Mol. Liq.* 2019, 277, 233–240. [CrossRef]
- 3. Sunil, B.N.; Srinatha, M.K.; Shanker, G.; Hegde, G.; Alaasar, M.; Tschierske, C. Effective tuning of optical storage devices using photosensitive bent-core liquid crystals. *J. Mol. Liq.* **2020**, *304*, 112719. [CrossRef]
- 4. Alnoman, R.B.; Ahmed, H.A.; Hagar, M.; Abu Al-Ola, K.A.; Alrefay, B.S.; Haddad, B.A.; Albalawi, R.F.; Aljuhani, R.H.; Aloqebi, L.D.; Alsenani, S.F. Induced phases of new H-bonded supramolecular liquid crystal complexes; mesomorphic and geometrical estimation. *Molecules* **2020**, *25*, 1549. [CrossRef] [PubMed]
- Alnoman, R.B.; Hagar, M.; Ahmed, H.A.; Abu Al-Ola, K.A.; Naoum, M.M.; Al-Elati, F.; Abdullah Zaid, Y.; Alsharif, A.; Al-Juhani, Y.; Abulrhelh, A. Characterization of New H-Bonded Liquid Crystalline Complexes Based on Iminophenyl Nicotinate. *Crystals* 2020, *10*, 499. [CrossRef]
- Alhaddad, O.A.; Abu Al-Ola, K.A.; Hagar, M.; Ahmed, H.A. Chair-and V-Shaped of H-bonded Supramolecular Complexes of Azophenyl Nicotinate Derivatives; Mesomorphic and DFT Molecular Geometry Aspects. *Molecules* 2020, 25, 1510. [CrossRef] [PubMed]
- 7. Kato, T.; Frechet, M.J. A new approach to mesophase stabilization through hydrogen bonding molecular interactions in binary mixtures. *J. Am. Chem. Soc.* **1989**, *111*, 8533. [CrossRef]
- 8. Kato, T.; Frechet, J.M.J. Stabilization of a liquid-crystalline phase through noncovalent interaction with a polymer side chain. *Macromolecules* **1990**, *23*, 360. [CrossRef]
- 9. Kato, T.; Kichara, H.; Uryu, T.; Fujishima, A.; Frechet, J.M.J. Molecular self-assembly of liquid crystalline side-chain polymers through intermolecular hydrogen bonding. Polymeric complexes built from a polyacrylate and stilbazoles. *Macromolecules* **1992**, *25*, 6836. [CrossRef]
- Yu, L.J.; Wu, J.M. Mesophases Induced by Hydrogen Bonds between Nonmesogens. *Mol. Cryst. Liq. Cryst.* 1991, 198, 407. [CrossRef]

- 11. Kumar, U.; Kato, T.; Frechet, J.M.J. Use of intermolecular hydrogen bonding for the induction of liquid crystallinity in the side chain of polysiloxanes. *J. Am. Chem. Soc.* **1992**, *114*, 6630. [CrossRef]
- 12. Kato, T.; Fukumasa, M.; Frechet, J.M.J. Supramolecular Liquid-Crystalline Complexes Exhibiting Room-Temperature Mesophases and Electrooptic Effects. Hydrogen-Bonded Mesogens Derived from Alkylpyridines and Benzoic Acids. *Chem. Mater.* **1995**, *7*, 368. [CrossRef]
- 13. Paterson, D.A.; Abberley, J.P.; Harrison, W.T.A.; Storey, J.; Imrie, C.T. Cyanobiphenyl-based liquid crystal dimers and the twist-bend nematic phase. *Liq. Cryst.* **2017**, *44*, 127. [CrossRef]
- Walker, R.; Pociecha, D.; Strachan, G.J.; Storey, J.; Gorecka, E.; Imrie, C.T. Molecular curvature, specific intermolecular interactions and the twist-bend nematic phase: The synthesis and characterization of the 1-(4-cyanobiphenyl-4'-yl)-6-(4-alkylanilinebenzylidene-4'-oxy) hexanes (CB6O.m). *Soft Matter* 2019, *15*, 3188. [CrossRef] [PubMed]
- Zang, X.Y.; Gao, L.; Zhang, R.; Dong, L.; Chen, X.S.; Li, Y.N.; Yao, D.S.; Hue, J.S.; Jia, Y.G.; Li, F.H.; et al. Fluorinated chiral nematic liquid crystal dimers based on (S)-1-phenylethane-1,2-diol. *Liquid Crystal* 2020, 47, 689. [CrossRef]
- 16. Ahmed, H.A.; Hagar, M.; Alhaddad, O.A.; Zaki, A.A. Optical and Geometrical Characterizations of Non-Linear Supramolecular Liquid Crystal Complexes. *Crystals* **2020**, *10*, 701. [CrossRef]
- Sultan, A.A.; Fahmi, A.A.; Saad, G.R.; Naoum, M.M. Effect of orientation of lateral fluorine atom on the mesophase behavior of azo/ester molecules with terminal naphthyl group. *Liq. Cryst.* 2019, *46*, 2322. [CrossRef]
- 18. Walker, R.; Pociecha, D.; Storey, J.M.D.; Gorecka, E.; Imrie, C.T. The Chiral Twist-Bend Nematic Phase (N*TB). *Chem. A Eur. J.* **2019**, 25, 13329. [CrossRef]
- 19. Ghosh, T.; Lehmann, M. Recent advances in heterocycle-based metal-free calamitics. *J. Mater. Chem. C* 2017, 5, 12308–12337. [CrossRef]
- 20. Zhang, X.-B.; Tang, B.-C.; Zhang, P.; Li, M.; Tian, W.-J. Synthesis and characterization of 1, 3, 4-oxadiazole derivatives containing alkoxy chains with different lengths. *J. Mol. Struct.* **2007**, *846*, 55–64. [CrossRef]
- 21. Chen, Y.; Yu, H.; Quan, M.; Zhang, L.; Yang, H.; Lu, Y. Photothermal effect of azopyridine compounds and their applications. *RSC Adv.* **2015**, *5*, 4675–4680. [CrossRef]
- 22. Garcia-Amorós, J.; Reig, M.; Cuadrado, A.; Ortega, M.; Nonell, S.; Velasco, D. A photoswitchable bis-azo derivative with a high temporal resolution. *Chem. Commun.* **2014**, *50*, 11462–11464. [CrossRef] [PubMed]
- 23. Vorländer, D. Über durchsichtig klare, krystallinische Flüssigkeiten. *Ber. Der Dtsch. Chem. Ges.* **1908**, *41*, 2033–2052. [CrossRef]
- Demus, D.; Diele, S.; Hauser, A.; Latif, I.; Selbmann, C.; Weissflog, W. Thermotropic liquid crystalline compounds with lateral long-chain substituents (IV). Physical properties of 1, 4-bis-[4-n-octyloxybenzoyloxy]-2-n-alkylbenzenes. *Cryst. Res. Technol.* 1985, 20, 1547–1558. [CrossRef]
- 25. Weissflog, W.; Demus, D. Compounds with lateral long-chain substituents—A new molecule structure concept for thermotropic liquid crystals. *Cryst. Res. Technol.* **1983**, *18*, K21–K24. [CrossRef]
- 26. Demus, D.; Hauser, A. Selected Topics in Liquid Crystal Research; Akademie: Berlin, Germany, 1990.
- 27. Hey, M.; Gray, G.W. Molecular structure and the properties of liquid crystals. London and New York (Academic Press) 1962. vii+ 314 pp. Price 63s. *Mineral. Mag. J. Mineral. Soc.* **1963**, *33*, 440. [CrossRef]
- Osmiałowski, B.; Kolehmainen, E.; Dobosz, R.; Gawinecki, R.; Kauppinen, R.; Valkonen, A.; Koivukorpi, J.; Rissanen, K. Self-organization of 2-acylaminopyridines in the solid state and in solution. *J. Phys. Chem. A* 2010, 114, 10421–10426. [CrossRef]
- 29. O'smiałowski, B. Noncovalent interactions between classical supramolecular synthons in solution: Hydrogen bonding in hindered 2-acylaminopyridine/2-pyridone associates. J. Mol. Struct. 2012, 1018, 84–87. [CrossRef]
- 30. Ahmed, H.A.; Hagar, M.; Alhaddad, O.A. Phase behavior and DFT calculations of laterally methyl supramolecular hydrogen-bonding complexes. *Crystals* **2019**, *9*, 133. [CrossRef]
- 31. Dave, J.S.; Menon, M. Azomesogens with a heterocyclic moiety. Bull. Mater. Sci. 2000, 23, 237–238. [CrossRef]
- Abberley, J.P.; Killah, R.; Walker, R.; Storey, J.M.; Imrie, C.T.; Salamończyk, M.; Zhu, C.; Gorecka, E.; Pociecha, D. Heliconical smectic phases formed by achiral molecules. *Nat. Commun.* 2018, *9*, 228. [CrossRef] [PubMed]

- Paterson, D.A.; Crawford, C.A.; Pociecha, D.; Walker, R.; Storey, J.M.; Gorecka, E.; Imrie, C.T. The role of a terminal chain in promoting the twist-bend nematic phase: The synthesis and characterisation of the 1-(4-cyanobiphenyl-4'-yl)-6-(4-alkyloxyanilinebenzylidene-4'-oxy) hexanes. *Liq. Cryst.* 2018, 45, 2341–2351. [CrossRef]
- 34. Ahmed, H.A.; Khushaim, M.S. Nematic phase induced from symmetrical supramolecular H-bonded systems based on flexible acid core. *Crystals* **2020**, in press. [CrossRef]
- 35. Martinez-Felipe, A.; Cook, A.G.; Abberley, J.P.; Walker, R.; Storey, J.M.; Imrie, C.T. An FT-IR spectroscopic study of the role of hydrogen bonding in the formation of liquid crystallinity for mixtures containing bipyridines and 4-pentoxybenzoic acid. *RSC Adv.* **2016**, *6*, 108164–108179. [CrossRef]
- Cleland, W.; Kreevoy, M.M. Low-barrier hydrogen bonds and enzymic catalysis. *Science* 1994, 264, 1887–1890. [CrossRef] [PubMed]
- 37. Lizu, M.; Lutfor, M.; Surugau, N.; How, S.; Arshad, S.E. Synthesis and characterization of ethyl cellulose–based liquid crystals containing azobenzene chromophores. *Mol. Cryst. Liq. Cryst.* **2010**, *528*, 64–73. [CrossRef]
- 38. Martínez-Felipe, A.; Imrie, C.T. The role of hydrogen bonding in the phase behaviour of supramolecular liquid crystal dimers. *J. Mol. Struct.* **2015**, *1100*, 429–437. [CrossRef]
- 39. Ghanem, A.; Noel, C. FTIR investigation of two alkyl-p-terphenyl-4, 4"-dicarboxylates in their crystalline, smectic and isotropic phases. *Mol. Cryst. Liq. Cryst.* **1987**, 150, 447–472. [CrossRef]
- 40. Paterson, D.A.; Martínez-Felipe, A.; Jansze, S.M.; Marcelis, A.; Storey, J.; Imrie, C.T. New insights into the liquid crystal behaviour of hydrogen-bonded mixtures provided by temperature-dependent FTIR spectroscopy. *Liq. Cryst.* **2015**, *42*, 928–939. [CrossRef]
- Walker, R.; Pociecha, D.; Abberley, J.; Martinez-Felipe, A.; Paterson, D.; Forsyth, E.; Lawrence, G.; Henderson, P.; Storey, J.; Gorecka, E. Spontaneous chirality through mixing achiral components: A twist-bend nematic phase driven by hydrogen-bonding between unlike components. *Chem. Commun.* 2018, 54, 3383–3386. [CrossRef]
- 42. Gopunatha, A.J.; Chitravela, T.; Kavithab, C.; Pongali Sathya Prabub, N.; Madhu Mohanb, M.L.N. Thermal, Optical, and Dielectric Analysis of Hydrogen-Bonded Liquid Crystals Formed by Adipic and Alkyloxy Benzoic Acids. *Mol. Cryst. Liq. Cryst.* **2014**, *592*, 63. [CrossRef]
- Naoum, M.M.; Fahmi, A.A.; Mohammady, S.Z.; Abaza, A.H. Effect of lateral substitution on supramolecular liquid crystal associates induced by hydrogen-bonding interactions between 4-(40-pyridylazo-3-methylphenyl)-4"-alkoxy benzoates and 4-substituted benzoic acids. *Liq. Cryst.* 2010, 37, 475–486. [CrossRef]
- 44. Ahmed, H.; Naoum, M.; Saad, G. Mesophase behaviour of 1: 1 mixtures of 4-n-alkoxyphenylazo benzoic acids bearing terminal alkoxy groups of different chain lengths. *Liq. Cryst.* **2016**, *43*, 1259–1267. [CrossRef]
- 45. Naoum, M.M.; Metwally, N.H.; Abd Eltawab, M.M.; Ahmed, H. Polarity and steric effect of the lateral substituent on the mesophase behaviour of some newly prepared liquid crystals. *Liq. Cryst.* **2015**, *42*, 135. [CrossRef]
- Ahmed, H.; Saad, G. Mesophase behavior of laterally di-fluoro-substituted four-ring compounds. *Liq. Cryst.* 2015, 42, 1765. [CrossRef]
- 47. Saccone, M.; Spengler, M.; Pfletscher, M.; Kuntze, K.; Virkki, M.; Wölper, C.; Gehrke, R.; Jansen, G.; Metrangolo, P.; Priimagi, A.; et al. Photoresponsive Halogen-Bonded Liquid Crystals: The Role of Aromatic Fluorine Substitution. *Chem. Mater.* **2019**, *31*, 462–470. [CrossRef]
- 48. Dhammika Bandara, H.; Burdette, S.C. Photoisomerization in different classes of azobenzene. *Chem. Soc. Rev.* **2012**, *41*, 1809–1825. [CrossRef]
- 49. Zhang, X.; Feng, H.; Yan, M.; Guo, H.; Yang, F. The novel rufigallol-based liquid crystals with cholesterol units: Synthesis, mesomorphic and photophysical properties. *Liq. Cryst.* **2019**, *46*, 787–796. [CrossRef]
- 50. Lin, L.; Qin, W.; Cheng, B.; Guo, H.; Yang, F. The influence of multiple alkyl chains on mesomorphic and photophysical properties of diphenylacrylonitrile liquid crystals. *Liq. Cryst.* **2019**, *47*, 1–10. [CrossRef]

- 51. Yang, M.; Liu, Z.; Li, X.; Yuan, Y.; Zhang, H. Influence of flexible spacer length on self-organization behaviors and photophysical properties of hemiphasmidic liquid crystalline polymers containing cyanostilbene. *Eur. Polym. J.* **2020**, *123*, 109459. [CrossRef]
- 52. Zhang, B.Y.; Jia, Y.G.; Yao, D.S.; Dong, X.W. Preparation and properties of siloxane liquid crystalline elastomers with a mesogenic crosslinking agent. *Liq. Cryst.* **2004**, *31*, 339. [CrossRef]



© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).