Aggregation of asphaltene model compounds using a porphyrin tethered to a carboxylic acid†

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A Ni(i) porphyrin functionalized with an alkyl carboxylic acid (3) has been synthesized to model the chemical behavior of the heaviest portion of petroleum, the asphaltenes. Specifically, porphyrin 3 is used in spectroscopic studies to probe aggregation with a second asphaltene model compound containing basic nitrogen (4), designed to mimic asphaltene behavior. NMR spectroscopy documents self-association of the porphyrin and aggregation with the second model compound in solution, and a Job’s plot suggests a 1 : 2 stoichiometry for compounds 3 and 4.

Introduction

The foreseeable exhaustion of conventional fossil fuels has resulted in an increasing focus on efficient use of alternative petroleum sources, such as heavy crude oil.1 In order to convert heavy oil to valuable fuels, however, significant upgrading is required,2 and these processes are hampered by the heaviest and most problematic component of heavy oil, the asphaltenes.3 Asphaltenes are commonly known to cause problems for a variety of practical processes, such as transportation, storage, and refining.2,3 To solve these issues, significant efforts have been expended to understand the bulk behavior of asphaltenes,2,4,5 and these efforts have even suggested that the carbon-rich and heteroatom doped composition of asphaltenes might yield materials for electronic devices.6,7 In spite of these studies, however, the general molecular structure of the asphaltenes remains to be resolved,8 and a major barrier to this goal is the formation of very stable aggregates between individual molecules that complicates many analysis techniques.9

For almost a century, it has been suggested and, for the most part, accepted that asphaltenes are composed of large aromatic cores that also contain heteroaromatics and metalloporphyrins, with a molecular weight (MW) of ca. 750 g mol−1 (Fig. 1a). These large aromatic islands are then surrounded by functional groups, including alkyl groups and alkyl carboxylic acids.10−12 This paradigm gives rise to the “continental” or “island” model (more specifically the Yen−Mullins model), and it is believed that aggregation in these types of molecules is driven primarily by π−π stacking interactions.13

Alternatively, an archipelago model for the asphaltenes has been introduced, in which smaller aromatic islands are tethered together by alkyl chains (Fig. 1b).8 In the case of archipelago asphaltenes, it has been hypothesized that aggregation results from the cumulative effect of numerous intermolecular stabilizing forces, which might include, among others, π−π-stacking, axial coordination of metalloporphyrins, hydrogen bonding, hydrophobic interactions, and acid−base interactions.8

Fig. 1 Schematic example of an (a) island asphaltene compound (MW = 756 g mol−1) from ref. 13 and (b) archipelago asphaltene compound (MW = 754 g mol−1) from ref. 8. Examples of model compounds used to study aggregation of asphaltenes, representing (c) island (MW = 1280 g mol−1)14 and (d) archipelago (MW = 613 g mol−1)15 structures.

†Electronic supplementary information (ESI) available: NMR spectra of compounds 3–10, 2D NMR spectra of compound 4, as well as experimental details and NMR data of the aggregation studies. See DOI: 10.1039/c5ob00836k
Much of the support for the island model comes from a “top-down” approach, i.e., the study of natural asphaltene samples by various physical and analytical methods. Evidence for the archipelago model using the “top-down” approach has also been reported, including ruthenium-ion-catalyzed oxidation (RICO) experiments, small-angle neutron scattering, small-angle calculations, and thermal cracking experiments. We hypothesize that a “bottom-up” approach, is paramount to understanding asphaltene aggregation on a molecular level. While the “top-down” approach looks at properties of the bulk material, a “bottom-up” study targets specific molecules with functionalities found in asphaltenes (Fig. 1c), while Anisimov examined the aggregation behavior of a tert-butyl substituted HBC, however, have an aromatic core built from 13 fused rings, and the majority of asphaltene molecules are expected to have only 4 to 10 fused rings. Akbarzadeh et al. have used smaller ring systems (alkyl bridged pyrene model compounds) either with or without heteroatoms, and only structures with heteroatoms form dimers in organic solvents. In line with these results, Tan et al. have described that the 2,2′-bipyridine derivative 2 forms dimers both in solution and in the solid state (Fig. 1d), and it is suggested that water enhances dimer formation, presumably by the formation of hydrogen bonding, bridging the heteroatoms between two individual molecules. Experimental results were also supported by density functional theory and 3D-RISM-KH calculations.

Studies to date with model asphaltene compounds, as briefly summarized in the preceding paragraphs, are not fully consistent with the view that asphaltene aggregation is dominated by π-stacking. Given the acknowledged structural diversity of the asphaltenes, it seems likely that intermolecular associations might be better described by multiple cooperative interactions facilitated by heteroatoms and functional groups. An obvious target under this premise is the interaction of an acid and a base, as expected in natural asphaltenes, for example, between pyridyl and carboxylic acid groups. To explore this concept, in the current study two model compounds have been chosen, an acid and a base (Fig. 2). A porphyrin group has been chosen as a platform for the acid moiety, namely compound 3. Porphyrins are known to exist in petroleum since the pioneering work by Treibs in 1934, and these so-called petroporphyrins are mainly observed as V(IV)O and Ni(II) species. To the best of our knowledge, however, only simple, unfunctionalized, and commercially available porphyrins have been employed to model asphaltene aggregation. Archipelago-type porphyrins have been used for the investigation of thermal cracking behavior, but there are no studies that report a synthetic strategy specifically designed for porphyrins that enable the study of asphaltene aggregation. It is worth noting the extensive synthetic porphyrins independently reported by Clezy and Lash to serve as model compounds for petroporphyrins, albeit without a focus on aggregation.

To explore the aggregation behavior of porphyrin 3, it is combined with a compound that features a basic nitrogen group. Namely, we have chosen archipelago model compound 4 (Fig. 2), in which the pyridyl-ring is combined with large aromatic groups appended via flexible alkyl tethers. Binding studies by NMR spectroscopy show self-association of porphyrin 3 and the formation of an aggregate between 3 and 4 in solution, demonstrating the potential of this aggregation motif for native asphaltenes.

**Results and discussion**

**Synthesis**

Aldehyde 5 (Scheme 1) was synthesized from 1-bromo-2-(methoxymethyl)benzene as described by Ullenius and coworkers. Subsequently, aldehyde 5, commercial 4-n-butylbenzaldehyde (6), and pyrrole were used in a mixed porphyrin condensation with BF₃·OEt₂ as a Lewis-acid and EtOH as a co-catalyst, followed by oxidation with DDQ, according to procedures reported by Lindsey and Jux. From this reaction, the unsymmetrical methoxymethyl substituted porphyrin 7a and the symmetrical derivative 8 were isolated in significant yields. The desired target, porphyrin 7a, was then reacted with HBr in AcOH, according to a procedure by Jux, to give...
Aggregation in solution

Before exploring aggregation of porphyrin 3 with archipelago model compound 4, a series of control experiments were done. First, phenylacetic acid was used as a simple carboxylic acid in a NMR titration experiment with pyridine in benzene-d$_6$ at 24 ± 2 °C (while toluene is more commonly used for aggregation studies, the symmetrical structure of benzene allows more facile analysis of $^1$H NMR spectra due to the reduced number of signals from the solvent). Specifically, addition of pyridine (1 to 8 equivalents) to a 2.5 mM solution of phenylacetic acid gave changes in the $^1$H NMR chemical shift for the signal of the methylene protons of phenylacetic acid (see ESI†). Nonlinear curve fitting for the chemical shift data with a 1 : 1 binding model gave an association constant $K_{\text{assoc}} = 123 ± 12$ M$^{-1}$.

In a second experiment, phenylacetic acid was titrated with model compound 4, rather than pyridine. At first, a 2.5 mM solution of phenylacetic acid was used for the titration with 4. Limited by the solubility of 4, only up to 4 equivalents could be added. As only weak binding was observed, a second titration with a 1.25 mM solution of phenylacetic acid was performed allowing addition up to 8 equivalents of 4. Both titrations gave concentration dependent changes for the chemical shift for the signal of the methylene protons of phenylacetic acid, but the binding was quite lower compared to pyridine, with an averaged $K_{\text{assoc}} = 24 ± 8$ M$^{-1}$ (see ESI†), obtained from the two titrations detailed above. In general, it is known that substitution in the 2,6-positions of the pyridyl-ring has an impact on basicity, e.g., for pyridine, 2,6-lutidine, and 2,6-diisopropylpyridine, $pK_a = 4.38$, 5.77, and 5.34, respectively. Likewise, substitution also causes steric repulsion inhibiting hydrogen bonding. Thus, the observed decrease in $K_{\text{assoc}}$ going from pyridine to model compound 4 is likely explained by a combination of steric and electronic effects, as described in detail by Kitao and Jarboe for simple pyridine derivatives.

Turning attention to the porphyrin carboxylic acid 3, dilution titrations were first investigated by $^1$H NMR spectroscopy to determine self-association. It was clear from these titrations that porphyrin 3 forms a dimeric species in benzene-d$_6$, and chemical shift analysis and fitting from multiple signals gave a dimerization constant of $K_{\text{dim}} = 390 ± 27$ M$^{-1}$ (see ESI†).

Finally, a $^1$H NMR titration experiment was done with porphyrin 3 by addition of pyridine (1 to 8 equivalents). Fitting of the chemical shifts from multiple signals and considering $K_{\text{dim}} = 390 ± 27$ M$^{-1}$ for 3, $K_{\text{assoc}} = 178 ± 18$ M$^{-1}$ was determined (see ESI†), which was comparable to the binding experiment between phenylacetic acid and pyridine (vide supra).
The interactions between model compounds 3 and 4 were then explored, using an analogous set of conditions for both the titration and $^1$H NMR chemical shift analysis. Namely, the concentration of porphyrin 3 was kept constant at 2.5 mM, and the concentration of model compound 4 was varied from a minimum of 1.25 mM to a maximum of 10 mM (this was the solubility limit of 4). The signals of the two methylene groups of 4 (H$_g$ and H$_b$, see Fig. 2) shifted upfield from 3.86/3.34 (H$_g$/H$_b$) to 3.78/3.29 (H$_g$/H$_b$) ppm upon addition of 0.5 equivalents 4 to the porphyrin solution (Fig. 3), whereas further addition of 4 resulted in less significant downfield shifts. The signal of the methylene group protons of 3 (H$_a$, see Fig. 2) shifted downfield upon addition of 4, from 3.20 ppm to a maximum of 3.43 ppm, after addition of four equivalents of 4.

The observed relationship between chemical shift and concentration is consistent with expected acid–base interactions between the carboxylic acid functionality of 3 and the basic nitrogen of 4. The chemical shifts for multiple signals upon titration of 3 with 4 were fit to a 1:1 binding model, suggesting a $K_{assoc} = 316 \pm 32$ M$^{-1}$ (Fig. 4). The 1:1 binding model is also supported by the presence of a weak signal for a 1:1 complex between 3 and 4 in the high resolution APPI mass spectrum (see ESIF).

To further investigate the nature of the complex formed between 3 and 4 in solution, Job’s method of continuous variation was used.$^{38,59}$ Interestingly, the maximum is observed in the Job’s plot at a mole fraction of 0.3 for 3, suggesting a 1:2 complex between the porphyrin acid 3 and model compound 4, respectively. Nonlinear curve fitting, considering both binding events, namely self-association of 3 ($K_{assoc} = 390 \pm 27$ M$^{-1}$) and a 1:2 binding model, results in an overall association constant of $1.23 \pm 0.1 \times 10^6$ M$^{-2}$.60

![Fig. 3 $^1$H NMR titration of 3 (2.5 mM constant) with increasing amounts of 4 in benzene-d$_6$: (a) 3 (2.5 mM); (b) 4 (1.25 mM); (c) 3:4 = 2:1; (d) 3:4 = 1:1; (e) 3:4 = 1:1.5; (f) 3:4 = 1:2: (g) 3:4 = 1:2.5; (h) 3:4 = 1:3; (i) 3:4 = 1:3.5; (j) 3:4 = 1:4; * = signal of the methylene group protons H$_g$ of 3; see Fig. 2 for proton assignment.](image)

![Fig. 4 Concentration dependent chemical shifts for the signal of the methylene group protons of porphyrin 3 upon titration with 4 and fitting to a 1:1 binding model.](image)

The formation of a 1:2 complex between model compounds 3 and 4 would be in line with the results of Tan et al., who report formation of a dimer for the ethano-linked pyrene substituted 2,2′-bipyridine derivative 2 (in CDCl$_3$),$^{15}$ which shares a structure similar to that of 4. It has also been shown that dimerization of 2 is enhanced by the addition of water, which had the effect of forming an intermolecular bridge between bipyridyl groups.$^{10}$ It is, thus, reasonable that the carboxylic acid functionality of porphyrin 3 might mediate similar interactions between 4, by bridging between two pyridyl-units, as in the role of water for the dimerization of 2.

The suggested stoichiometry from the Job’s plot must be interpreted with caution, however, due to the self-association of porphyrin 3. Thus, it is not possible at this point to unambiguously declare the nature of the interaction between 3 and 4.

**Conclusions**

We have synthesized a new metalloporphyrin bearing an alkyl carboxylic acid (3), and specific aspects of asphaltene aggregation have been studied using this porphyrin. NMR spectroscopic analyses document the self-dimerization of the porphyrin carboxylic acid 3 in benzene-d$_6$, as well as aggregation of 3 with an asphaltene model compound that bears a basic pyridine group (i.e., archipelago 4). A Job’s plot analysis between 3 and 4 suggests a 1:2 complex, but the exact nature of the association cannot be categorically established, due mainly to the self-association (self-dimerization) of porphyrin acid 3.

While the stoichiometry of the 3:4 complex remains unresolved, this study does clearly show that the interactions between 3 and 4 are stronger than those of the individual model compound with either a simple base or acid, respectively. That is to say that the $K_{assoc}$ determined for 3 with pyridine (178 ± 18 M$^{-1}$) and 4 with phenylacetic acid (24 ± 8 M$^{-1}$) are weaker than for 3 and 4 together, regardless of whether a 1:1 or 1:2 complex is formed. Based on our results, we hypothesize that the enhanced aggregation observed for 3 and...
4 originates from the presence of additional intermolecular forces beyond the expected acid–base interactions (e.g., π-stacking, hydrogen bonding), as suggested in the archipelago model. Further analysis by both experiment and theoretical calculations are underway.

**Experimental section**

**General**

All chemicals and solvents were used as received from commercial suppliers. 1-Ethynylpyrene was prepared according to literature. For the aldehyde synthesis, dry THF was distilled from sodium/benzophenone and DMF “with molecular sieve” (water <50 ppm) from Acros Organics was used. Solvent ratios were given as volume:volume. NMR spectra were recorded on a Bruker Avance 300 operating at 300 MHz (1H NMR) and 75 MHz (13C NMR), or a Bruker Avance 400 operating at 400 MHz (1H NMR) and 100 MHz (13C NMR), or a Jeol GX 400 operating at 1H NMR (300 MHz, CDCl3) and 13C NMR (CDCl3, 77.0 ppm; C6D6, 128.0 ppm). Coupling constants are given in parts per million (ppm) 1H: CDCl3, 7.26 ppm; C6D6, 7.16 ppm; 13C: CDCl3, 77.0 ppm; C6D6, 128.0 ppm. NMR spectra were recorded on a Varian 660-IR spectrometer. UV-vis spectra were recorded on a Varian Cary 5000 UV-vis spectrophotometer (λ in nm; ε in M⁻¹ cm⁻¹). TLC analysis was carried out with TLC plates from Macherey-Nagel (ALUGRAM® SIL G/UV 254) and visualized by UV-light of 254 nm or 366 nm. Silica Gel 60 M (0.04–0.063 mm) for column chromatography was purchased from Macherey-Nagel.

**Compound 4.** 1-Ethynylpyrene (0.491 g, 2.17 mmol) was added to a deoxygenated solution of 2,6-dibromopyridine (0.222 g, 0.937 mmol) in THF (70 mL) and diisopropylamine (0.27 mmol) were sequentially added and the solution stirred at reflux for 16 h under a N2-atmosphere. The solvents were removed in vacuo, and the resulting solid was washed with MeOH (5 × 20 mL), H2O (5 × 20 mL), MeOH (2 × 20 mL), hexanes (50 mL) and dried in vacuo. The crude product, toluene (300 mL), and Pd/C (10%, 0.050 g) were added to a flask. The flask was fitted with a balloon filled with H2 (ca. 15 psi), purged with H2 (3 times), and stirred at rt for 3 d. The heterogeneous mixture was filtered over Celite and the solvent removed. Purification by column chromatography (silica gel, CHCl3/hexanes 4:1) afforded compound 4 as a yellow solid (0.366 g, 73%). Mp 186–187 °C. IR (ATR) 3037 (w), 2924 (w), 1708 (w), 1579 (m), 1453 (m) cm⁻¹; 1H NMR (300 MHz, CDCl3) δ 8.35 (d, J = 9.3 Hz, 2H), 8.14 (d, J = 7.6 Hz, 2H), 8.11–7.94 (m, 10H), 7.83 (d, J = 7.8 Hz, 2H), 7.32 (t, J = 7.7 Hz, 1H), 6.80 (d, J = 7.7 Hz, 2H), 3.88–3.83 (m, 4H), 3.48–3.43 (m, 4H); 13C NMR (400 MHz, CDCl3) δ 3.83 (d, J = 9.2 Hz, 2H), 7.97–7.90 (m, 8H), 7.85–7.73 (m, 8H), 6.89 (t, J = 7.6 Hz, 1H), 6.51 (d, J = 7.6 Hz, 2H), 3.87–3.83 (m, 4H), 3.36–3.32 (m, 4H); 13C NMR (75 MHz, CDCl3) δ 160.4, 135.7, 131.4, 130.9, 129.9, 128.7, 127.5, 127.34, 127.31, 126.6, 125.8, 125.01, 124.97, 124.9, 124.8, 124.7, 123.4, 120.8, 39.8, 33.6 (one signal coincident or not observed); 13C NMR (100 MHz, CDCl3) δ 161.1, 136.6, 136.3, 132.0, 130.5, 129.3, 128.6, 127.0, 126.0, 125.8, 125.7, 125.2, 125.1, 123.9, 120.5, 40.7, 33.9 (three signals coincident or not observed); Thermospray ionization (ESI) and Tandem Mass Spectrometer (APPI) (-) experiments were carried out with LC/MS (Waters, Xevo G2-S QTof, Micromass Autospec Ultima). ESI-HRMS values were calculated for [M + H]+; ESI-HRMS values were calculated for [M + H]+. Technical calculations are underway.

2-Methoxymethyl benzaldehyde (5). 1-Bromo-2-(methoxymethyl)benzene (1.50 g, 7.46 mmol) was dissolved in dry THF (75 mL) under a N2-atmosphere. After cooling to −78 °C, n-BuLi (2.5 M in hexane, 3.6 mL, 9.0 mmol) was slowly added. After stirring for 1 h, DMF was added (0.82 g, 0.86 mL, 11 mmol), and the mixture was allowed to warm to rt while stirring over night for 16 h. The solution was poured into a mixture of brine and HCl (150 mL, 1:1) and extracted with EtO (2 × 75 mL). The combined organic layers were washed with H2O (3 × 150 mL) and dried over MgSO4. After filtration and removal of the solvent, the residue was dissolved in CH2Cl2 and filtered through a plug of silica gel. Evaporation of the solvent and drying in vacuo afforded the product 5 (0.695 g, 62%) as a yellow oil. IR (ATR) 3067 (vw), 2983 (w), 2927 (w), 2874 (w), 2822 (w), 2736 (w), 1691 (s) 1599 (m), 1574 (m), 1451 (m) cm⁻¹; 1H NMR (300 MHz, CDCl3, δ 10.12 (1H, s, 1H), 7.78–7.76 (m, 1H, 1H), 7.56–7.48 (m, 2H), 7.39 (td, J = 7.3 Hz, 1.4 Hz, 1H), 4.78 (2H, 3H, 3H) (75 MHz, CDCl3) δ 192.4, 140.5, 133.5, 133.0, 132.0, 127.7, 127.4, 71.5, 58.2. ESI HRMS m/z caled for C24H30N ([M + H]+) 353.2374, found 353.2374.

Porphyrin 7a. In degassed CH2Cl2 (1.5 L), 4-n-butylbenzaldehyde (90% pure, 2.1 mL, 11 mmol), pyrrole (1.0 g, 1.0 mL, 15 mmol), and aldehyde 5 (0.563 g, 3.75 mmol) were dissolved under a N2-atmosphere. After addition of EtOH (1.5 mL) and BF3·OEt2 (0.24 g, 0.21 mL, 1.7 mmol), the solution was stirred for 1 h at rt. DDQ (3.41 g, 15.0 mmol) was added and the mixture stirred for 2 h at rt. The solution was concentrated by rotary evaporation and the residue filtered through a plug of silica gel (CH2Cl2). The black/purple solid obtained after removal of the solvent was purified by column chromatography (silica gel, hexanes/CH2Cl2 1:1) to afford the porphyrin 8 (0.430 g, 18%) as the first fraction and the porphyrin 7a (0.445 g, 14%) as the second fraction as purple solids. Mp 226–228 °C. IR (ATR) 3314 (w), 2951 (m), 2923 (m), 2858 (m), 1465 (m), 1346 (m) cm⁻¹; 1H NMR (300 MHz, CDCl3) δ 8.92–8.89 (m, 6H), 8.73 (d, J = 4.8 Hz, 2H), 8.20–8.09 (m, 7H), 7.97 (d, J = 7.2 Hz, 1H), 7.85 (td, J = 7.6 Hz, J = 1.2 Hz, 1H), 7.66 (td, J = 7.5 Hz, J = 1.2 Hz, 1H), 7.60–7.57 (m, 6H), 4.15 (s, 2H), 2.99 (t, J = 7.7 Hz, 6H), 2.89 (s, 3H), 1.94 (pent, J = 7.6 Hz, 6H), 1.62 (sext, J = 7.4 Hz, 6H), 1.13 (t, J = 7.3 Hz, 9H), −2.66
(br s, 2H); 13C NMR (75 MHz, CDCl3) δ 142.3, 140.19, 140.17, 139.5, 139.3, 134.6, 134.0, 131.1 (br), 130.7 (br), 128.6, 126.73, 126.69, 126.3, 125.5, 120.6, 120.3, 116.9, 72.7, 58.1, 35.7, 33.8, 22.6, 14.2 (12 signals coincident or not observed). APPI HRMS m/z calcd for C58H59N4O ([M + H]+) 839.5047, found 839.5053.

Porphin 8. M.p. >300 °C. Rf = 0.85 (hexanes/CH2Cl2, 1 : 1). IR (ATR) 3314 (w), 3020 (vw), 2951 (w), 2923 (m), 2854 (m), 1466 (w), 1347 (w) cm⁻¹; 1H NMR (300 MHz, CDCl3) δ 8.89 (s, 8H), 8.14 (d, J = 8.0 Hz, 8H), 7.57 (d, J = 8.0 Hz, 8H), 2.97 (t, J = 7.7 Hz, 8H), 1.98–1.88 (m, 8H), 1.61 (s, t = 7.4 Hz, 8H), 1.12 (t, J = 7.3 Hz, 12H), −2.71 (s, 2H); 13C NMR (100 MHz, CDCl3) δ 142.3, 143.9, 134.6, 134.0, 130.9 (br), 126.7, 120.1, 35.7, 33.8, 22.6, 14.1 (1 signal coincident or not observed). ESI HRMS m/z calcd for C60H63N4 ([M + H]+) 839.5047, found 839.5053.

Porphin 9. To a solution of 7a (58 mg, 0.070 mmol) in CH2Cl2 (15 mL), was added HBr in glacial HOAc (33%, 4.0 g, 0.020 mL, 12 mmol) in PEG 400 (12 mL), the crude mixture stirred at rt for 2 h. H2O (50 mL) and CH2Cl2 (15 mL), was added HBr in glacial HOAc (33%, 4.0 g, 0.070 mmol) in PEG 400 (12 mL), the crude mixture stirred at rt for 2 h. H2O (50 mL) and CH2Cl2 (15 mL), was added HBr in glacial HOAc (33%, 0.94 g, 2.0 mL, 12 mmol) was added and the mixture stirred at rt for 2 h. H2O (50 mL) and CH2Cl2 (50 mL) were added. The organic layer was separated, washed with H2O (2 : 1, 150 mL), and H2O (50 mL). The solution was filtered. The solvent was removed and the crude product Rf = 0.67 (hexanes/CH2Cl2 1 : 1) dried in vacuo to yield the product 7b. ESI HRMS m/z calcd for C58H57N4O2 ([M + H]+) 919.3493, found 919.3486; UV-vis (CH2Cl2) λmax (ε) 415 (312 000), 528 (22 100) nm; IR (ATR) 3023 (w), 2953 (s), 2926 (s), 2859 (m), 1709 (m), 1460 (m), 1352 (m) cm⁻¹; 1H NMR (300 MHz, CDCl3) δ 8.66 (d, J = 5.0 Hz, 2H), 8.73 (h, J = 5.0 Hz, 2H), 8.68 (d, J = 5.0 Hz, 2H), 8.51 (d, J = 4.9 Hz, 2H), 7.96–7.82 (m, 7H), 7.69–7.63 (m, 1H), 7.55 (t, J = 6.9 Hz, 2H), 7.48 (d, J = 8.2 Hz, 2H), 7.38 (d, J = 8.2 Hz, 4H), 3.24 (s, 2H), 2.90 (t, J = 7.7 Hz, 2H), 2.82 (t, J = 7.7 Hz, 4H), 1.91–1.74 (m, 6H), 1.62–1.44 (m, 6H), 1.09–1.01 (m, 9H); 13C NMR (100 MHz, CDCl3) δ 175.2, 142.8, 142.4, 142.3, 142.2, 142.1, 141.9, 139.5, 139.2, 135.4, 134.6, 134.5, 134.4, 134.3, 132.0, 131.2, 128.6, 126.7, 126.6, 125.5, 120.6, 120.3, 116.7, 38.9, 35.7, 35.6, 33.8, 33.7, 22.6, 14.1 (6 signals coincident or not observed).

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Notes and references

49. The assignment of H8 and Hb was possible by 2D NMR spectroscopic measurements, primarily using long range
correlations of H_b and H_c to the carbons of the pyridyl ring (see ESI†).
56 No evidence for self-association was found (see ESI†).