ORIGINAL ARTICLE

Investigation of the hydrogen bonded host⋯guest and guest⋯guest interactions present in complexes of a polyaromatic wheel-and-axle host compound with dioxane, morpholine, piperidine and pyridine

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Abstract

1,4-Bis(diphenylhydroxymethyl)benzene (**H**), a host compound possessing wheel-and-axle geometry, was found to possess host ability for dioxane (DIO), morpholine (MOR) and piperidine (PIP), forming inclusion compounds with each one with 1:2 host:guest ratios. This observation prompted an investigation of the host behaviour in mixtures of these guest compounds but where pyridine (PYR) was also considered (PYR was reported earlier to also form a 1:2 complex with **H**). In mixtures, **H** demonstrated significant affinities for, more especially, MOR and PIP, while DIO and PYR were usually disfavoured guest species. Single crystal X-ray diffraction experiments revealed that MOR (a favoured guest species) interacted by means of three hydrogen bonds with both adjacent guest and host molecules, plausibly explaining the host preference for this guest species; each of DIO, PYR and PIP were involved in only one interaction of this type with **H**. Total energy calculations revealed that the host-guest molecular pairs involving preferred MOR and PIP possessed significantly lower energies than those with disfavoured DIO and PYR. Thermal analyses demonstrated that the complex containing the least favoured guest compound, **H**·2(DIO), possessed the lowest thermal stability of the four complexes, but these experiments did not clearly explain the affinity of **H** for MOR.

Keywords Host−guest · Supramolecular chemistry · Complexes · Hydrogen bonding · Selectivity

Introduction

Many crystalline wheel-and-axle shaped compounds have demonstrated host ability. As early as 1968, Toda and Agaki reported on the inclusion properties of two such shaped compounds, namely 1,1,6,6-tetraphenylhexa-2,4-diyne-1,6-diol (1) and 1,1,4,4-tetraphenylbut-2-yne-1,4-diol (2) (Scheme 1) [1], which were capable of forming a number of inclusion compounds with a wide variety of organic molecules. The axles of these molecules are, more usually, long and linear,

while the wheels are bulky and rigid and often comprise one or more aromatic moieties.

Numerous subsequent reports have been published with respect to host compounds with the wheel-and-axle design. As examples, Weber *et al* [2] reported on six novel host compounds based on two di(benzo[*b*]thien-2-yl)hydroxymethyl units that successfully enclathrated a number of different organic solvents, while Desiraju and co-workers [3] predicted accurately that 4-(triphenylmethyl)benzoic acid would form a wheel-and-axle host compound supramolecularly as a result of two molecules interacting, through their carboxylic acids, by means of hydrogen bonding. This supramolecule possessed the ability to form complexes, more especially with aromatic guest compounds such as xylene. Additionally, Nassimbeni and co-workers revealed the selectivity behaviour of 4,4'-bis(diphenylhydroxymethyl)diphenyl in mixed picolines [4].

In the present investigation, we observed that the wheel-and-axle compound 1,4-bis(diphenylhydroxymethyl)benzene (**H**, Scheme 1) has host ability for dioxane (DIO), morpholine (MOR) and piperidine (PIP), which prompted

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Scheme 1 Structures of the two earliest reported wheel-and-axle host compounds **1** and **2** (top), and bis(diphenylhydroxymethyl) benzene (**H**, bottom), the host compound relevant to the present investigation
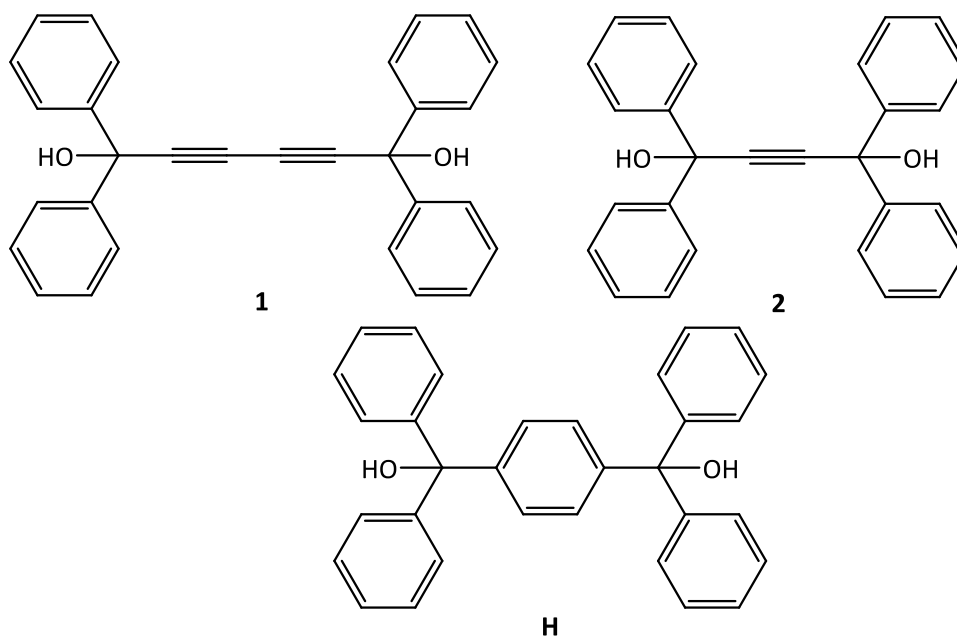
an investigation of the selectivity behaviour of **H** in mixtures of these guest compounds. Pyridine was also considered in these guest/guest competition experiments since it was previously reported to, similarly, form an inclusion compound with **H** [5]. From single crystal X-ray diffraction (SCXRD) experiments were identified influential intermolecular noncovalent interactions between host and guest, and/or guest and guest molecules, the cornerstone of self-assembly itself and supramolecular chemistry [6, 7], that explained the selectivity behaviour of this host compound in such mixtures. Toda and co-workers [8] were the first group to report on the inclusion behaviour of **H** with a great variety of organic compounds that possessed wide-ranging functional groups, while other research groups [9, 10] have focussed their attentions on amide and nicotine complexes with **H**. The behaviour of **H** in mixtures of these heterocyclic compounds (DIO, MOR, PYR, PIP) was never established in those works, and neither were provided any of the crystal structures of the complexes formed with them. In addition to SCXRD analyses on all successfully formed complexes in this work, thermal experiments were also carried out in order to determine and compare the relative thermal stabilities of each complex. We report on all of these findings here.

Experimental

Materials

All chemicals/solvents were purchased from Merck and were used without further manipulation.

Methods

¹H-NMR spectroscopy

¹H-NMR experiments were carried out in CDCl₃ by means of a Bruker Ultrashield Plus 400 MHz spectrometer and the data were analysed by means of Topspin 3.2 software.

Single crystal diffraction (SCXRD) analyses

The crystal structure data of the three novel complexes produced in this work, namely **H**·2(DIO), **H**·2(MOR) and **H**·2(PIP), were analysed at 296, 200 and 200 K, correspondingly, by employing a Bruker Kappa Apex II diffractometer with graphite-monochromated MoKα radiation ($\lambda = 0.71073$ Å). (**H**·2(PYR) has been described on a previous occasion in an entirely different context [5].) APEXII was used for data collection while SAINT was employed for cell refinement and data reduction; SADABS was used for absorption corrections [11]. SHELXT-2018/2 [12] was used to solve the structures and refinements were carried out by means of least-squares procedures using SHELXL-2018/3 [13] together with SHELXLE [14] as a graphical interface. All non-hydrogen atoms were refined anisotropically. Carbon- and oxygen-bound hydrogen atoms were added in idealized geometrical positions in a riding model. The nitrogen-bound hydrogens were located on the difference Fourier maps and included in the refinement using riding models. Data were corrected for absorption effects using the numerical method implemented in SADABS [11]. The crystal structures of **H**·2(DIO), **H**·2(MOR) and **H**·2(PIP) were deposited at

the CCDC (Cambridge Crystallographic Data Centre), and their CCDC numbers are 2,271,343, 2,271,344 and 2,271,345, respectively (**H**·2(PYR), CCDC 2,259,171).

Thermal analyses

Thermal experiments were conducted by employing a TA SDT Q600 module system. The complexes were first isolated from their solutions using vacuum filtration and, still under suction, these solids were washed with low boiling petroleum ether and then padded dry in folded filter paper. All data were analysed using either Pyris or TA Universal data analysis software. Samples were heated in ceramic pans with an empty pan serving as the reference; the heating rate was 10 °C·min^{-1} from 40 to 400 °C. The purge gas was high purity nitrogen.

Synthesis of 1,4-bis(diphenylhydroxymethyl) benzene (H)

This host compound was facilely prepared by considering a previous report [15].

Assessment of the host potential of H for DIO, MOR and PIP

In order to investigate whether **H** has host ability for DIO, MOR and PIP, this compound (0.1 g; 0.2 mmol) was dissolved, in glass vials, in each potential guest solvent (10 mmol) using mild heat to ensure complete dissolution where required. (Note that the host potential of **H** for PYR had been established previously [5], and a 1:2 host:guest (H:G) complex was isolated in that work.) The vials were kept open to the ambient conditions, and crystals formed in the solutions in this way. These were recovered by suction filtration (0.10 g of host compound produced 0.13 g of complex) and washed with low boiling petroleum ether, and then analysed by ^{1}H-NMR spectroscopy. If complexation was successful, both host and guest resonance signals were observed on the spectrum, and the H:G ratio was obtained through a comparison of the integrals of relevant host and guest signals. These ^{1}H-NMR spectra are provided in the Supplementary Information, Figures S1a–c.

Assessment of the selectivity behaviour of H in mixtures of DIO, MOR, PYR and PIP

The selectivity behaviour of host compound **H** was investigated in two separate sets of experiments, in equimolar mixtures involving all possible combinations of these guest solvents, and in binary mixtures where the molar amounts of two guest solvents present (Guest A and Guest B, G_A and G_B) were varied in sequence.

In the first of these, **H** (0.5−0.7 g; 1−2 mmol) was dissolved in equimolar binary, ternary and quaternary mixtures of these guests (10 mmol combined amount). The vials were closed and stored in a cold room (4 °C). After some time had passed, crystallization occurred, and these crystals were recovered as per the procedure in the single guest solvent experiments. Analysis was by means of ^{1}H-NMR spectroscopy which allowed for the quantification of the guests present in the so-formed complexes as well as a calculation to obtain the overall H:G ratios.

In the second set of experiments, **H** (0.5−0.7 g; 1−2 mmol) was dissolved in solutions prepared by mixing two guest solvents (G_A and G_B) in ratios ranging from 20:80, 40:60 and 60:40 to 80:20. The vials were closed once more and stored in the cold room. The crystals that formed in this fashion were isolated as before and analysed by means of ^{1}H-NMR spectroscopy in order to quantify the amounts of G_A and G_B in the so formed complexes. Selectivity profiles were then constructed by plotting the amount of G_A (or G_B) in the complex (Z_A or Z_B) against this amount in the original solution (X_A or X_B), as described by Pivovar et al. [16], according to the host selectivity equation $K_{A:B} = Z_A/Z_B \times X_B/X_A$ ($X_A + X_B = 1$) (where K serves as a measure of the extent of the host selectivity). Also inserted into these profiles are straight lines that represent a host compound that is unselective (and $K = 1$) so that this scenario may readily be compared with the experimental data points.

Software

SCXRD data were analysed by means of program Mercury [17]. In so doing, the unit cells, space groups, bond lengths and angles, and noncovalent intra- and intermolecular interactions could all be identified. Furthermore, by deleting the guest molecules from the packing diagrams, the type of guest accommodation could be ascertained (whether in continuous channels or in discrete cages): the spaces that remained after these deletions that could accommodate a probe with a 1.2 Å radius could thus be visualized and are the voids in which the guests were housed. Program Crystal Explorer 17.5 was employed for the energy calculations reported herein [18].

Results and discussion

Assessment of the host potential of H for DIO, MOR and PIP

When **H** was independently crystallized from DIO, MOR and PIP, complexation occurred in each instance, and the results are summarised in Table 1.

Table 1 H:G ratios of complexes formed in the single solvent crystallisation experiments

Guest	H:G ratio
DIO	1:2
MOR	1:2
PYR[a]	1:2[a]
PIP	1:2

[a]This had been ascertained on a prior and independent occasion and is included in this table for completeness [5]

The H:G ratios of all complexes formed in this way were consistently 1:2 (Table 1).

Assessment of the selectivity behaviour of H in mixtures of DIO, MOR, PYR and PIP

Table 2 contains the selectivity data that were obtained when **H** was crystallised from equimolar mixtures of DIO, MOR, PYR and PIP. The G:G and overall H:G ratios were obtained from ^{1}H-NMR spectroscopy experiments. The favoured guests are in red bold font face, and all experiments were carried out in duplicate, and hence the percentage standard deviations (% e.s.d.s) are also provided in this table.

From the equimolar binary experiments, MOR was a particularly preferred guest species, more especially when PIP was absent: DIO/MOR and MOR/PYR solutions furnished complexes with 92.7 and 95.3% MOR, respectively. In the absence of MOR, however, significant **H** selectivities were still observed: DIO/PYR, DIO/PIP and PYR/PIP solutions afforded inclusion compounds with 88.8, 91.7 and 95.5% PYR, PIP and PIP, correspondingly. Only in the case where both MOR and PIP were present was there noted some competition: MOR remained favoured, however, but the crystals now only contained 72.7% MOR. Interestingly, the ternary experiments containing DIO/MOR/PYR and MOR/PYR/PIP produced complexes with enhanced quantities of

MOR and PIP (90.0 and 88.1%). The latter result was not an expected one since MOR was always selected for in every other experiment where it was present, but here, where PIP was now significantly favoured (88.1%) despite the presence of MOR. (This experiment was conducted in duplicate, and comparable results were obtained in each instance, as indicated by the low %e.s.d. values, Table 2.) The reason for this observation is not currently clear. In the remaining experiments, both ternary and quaternary in nature, the selectivity of **H** decreased significantly (54.1−68.9%), but MOR was consistently favoured in experiments involving it. Note that in all of these experiments, DIO remained disfavoured in every instance. However, the DIO/PYR/PIP experiment resulted in a mixed complex with as much as 43.4% DIO (though PIP was preferred, as expected, 54.1%). This was, once more, not an expected result and the reason for this observation is also unclear.

The selectivity profiles that were constructed from the binary G_A:G_B mixtures where the molar ratios of the two guests were sequentially varied are provided in Fig. 1a−f.

As expected, given the equimolar solution data in Table 2, experiments in MOR/DIO solutions (Fig. 1a) revealed that MOR was consistently preferred across the concentration range. Even at low concentrations of MOR in the solution, significant quantities of this guest were extracted by **H**: as an example, when only 40% MOR was present in the mixture, the complex already contained 96% MOR. Similar significant selectivities were noted in PIP/DIO (Fig. 1c) and MOR/PYR (Fig. 1d) solutions: in the former, 40% PIP in the solution furnished crystals with as much as 92% PIP, while the crystals isolated in the latter from a solution comprising 20% MOR were enriched in MOR (95%). In the case of experiments in DIO/PYR (Fig. 1b) and PYR/PIP (Fig. 1e), the selectivity of **H** was usually for the guest that was present in the greater concentration. Finally, and unsurprisingly, experiments in MOR/PIP solutions demonstrated that, despite MOR being favoured across the concentration range, this

Table 2 The G:G and H:G ratios of mixed complexes isolated from equimolar mixed guests

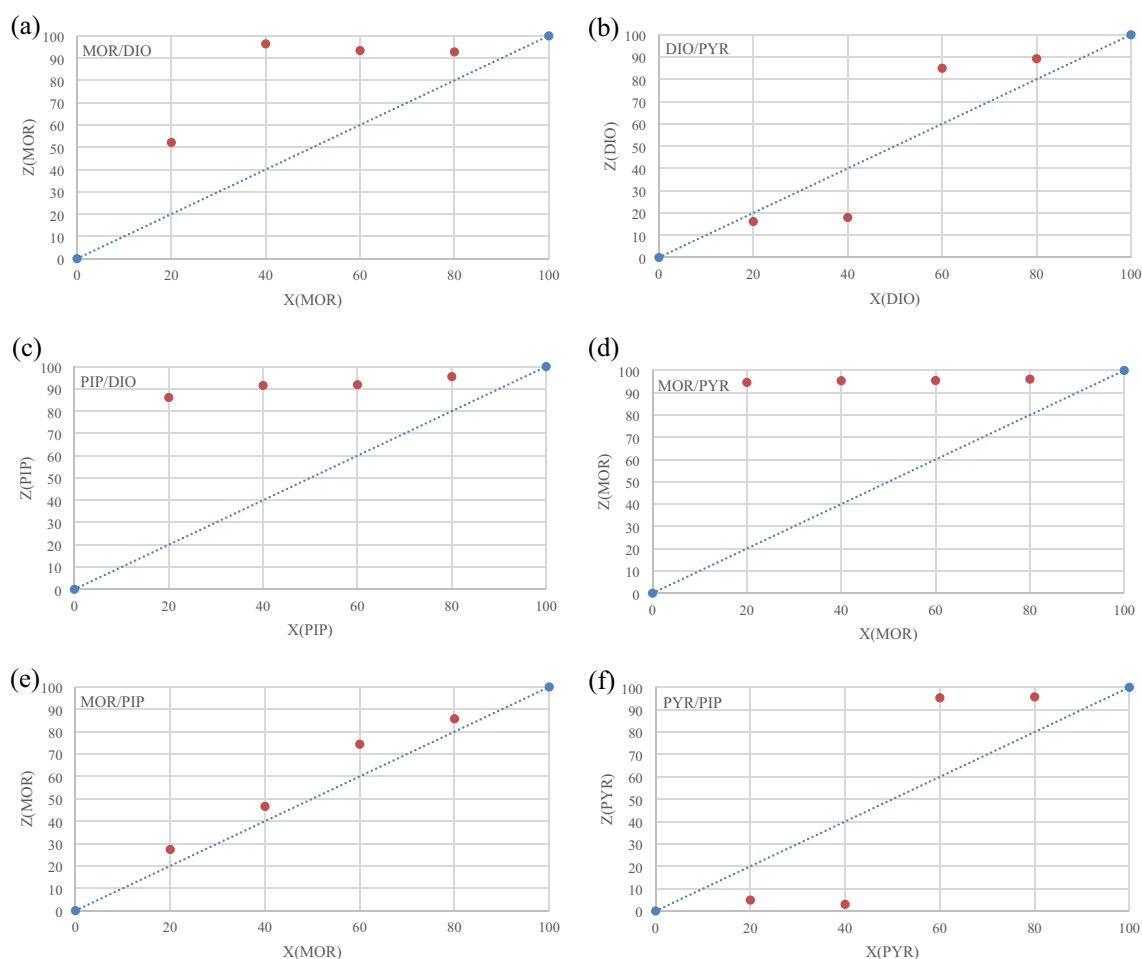| DIO	MOR	PYR	PIP	G:G	Overall H:G	%e.s.d.s
X	**X**			7.3:**92.7**	1:2	1.0
X		**X**		11.2:**88.8**	1:2	0.3
X			**X**	8.3:**91.7**	1:2	0.5
	X	X		**95.3**:4.7	1:2	0.3
	X		X	**72.7**:27.3	1:2	0.4
		X	**X**	4.5:**95.5**	1:2	0.3
X	**X**	X		5.9:**90.0**:4.1	1:2	0.8;0.5;0.2
X	**X**		X	2.2:**68.9**:28.9	1:2	0.4;3.9;3.5
	X	X	**X**	8.3:3.6:**88.1**	1:2	1.1;0.7;1.8
X		X	**X**	43.4:2.5:**54.1**	1:2	2.0;0.1;1.9
X	**X**	X	X	3.4:**64.6**:3.2:28.8	1:2	1.6;2.9;0.0;1.3

Fig. 1 Selectivity profiles for H obtained in **a** MOR/DIO, **b** DIO/PYR, **c** DIO/PIP, **d** MOR/PYR, **e** MOR/PIP and **f** PYR/PIP mixtures

selectivity was not extreme, and all data points are close to the line represented by K = 1 for an unselective host compound.

These data clearly confirm that MOR is a guest solvent that is extremely preferred by **H**, and also PIP to some extent, while both DIO and PYR are guest solvents less favoured by this host compound. Our research group was intrigued to identify the reasons pertaining to these selectivity observations, and so SCXRD experiments were carried out on each single solvent complex formed in this work.

Single crystal diffraction (SCXRD) analysis

The relevant crystallographic data for the **H**·2(DIO), **H**·2(MOR) and **H**·2(PIP) complexes are summarized in Table 3. All of these inclusion compounds crystallized in the monoclinic crystal system and space group $P2_1/c$ (**H**·2(PYR), however, crystallized in the triclinic crystal system and space group $P\bar{1}$ [5]) (Table 3). Two disorder components of each of DIO, MOR and PIP were noted in their complexes (while PYR did not experience disorder in its inclusion compound with **H** [5]). Figure 2a–d are illustrations of the unit cells and host-guest packing (left) and the voids remaining after guest deletion from the packing calculations (yellow, right). (Guests are in spacefill and hosts in stick representation.)

From the void diagrams, all guest molecules were accommodated in infinite unidirectional channels, along the a-axis in the case of **H**·2(PYR) (Fig. 2d) [5] and the c-axis in the remaining three complexes (Fig. 2a–c).

The geometry of the host molecule in each complex was always centrosymmetric around an inversion point positioned in the centre of the central aromatic ring.

In **H**·2(DIO), no significant (host)π···π(host) interactions could be identified. However, the DIO guest species was retained in the crystal of the complex by means of (host) O−H···O (guest) classical hydrogen bonding

Table 3 Selected crystallographic data for the complexes of **H** with DIO, MOR, PYR and PIP

	H·2(DIO)	H·2(MOR)	H·2(PYR)^a	H·2(PIP)
Chemical formula	$C_{32}H_{26}O_2 \cdot 2(C_4H_8O_2)$	$C_{32}H_{26}O_2 \cdot 2(C_4H_9NO)$	$C_{32}H_{26}O_2 \cdot 2(C_5H_5N)$	$C_{32}H_{26}O_2 \cdot 2(C_5H_{11}N)$
Formula weight	618.73		600.73	612.82
Crystal system	Monoclinic	Monoclinic	Triclinic	Monoclinic
Space group	$P2_1/c$	$P2_1/c$	$P\bar{1}$	$P2_1/c$
μ (Mo-Kα)/mm^{-1}	0.084	0.081	0.074	0.072
a/Å	8.7616(5)	9.1145(8)	8.3285(3)	8.4209(2)
b/Å	16.6455(10)	16.1341(16)	8.9276(4)	17.2887(4)
c/Å	11.2965(7)	11.3570(11)	12.0622(5)	12.4134(3)
alpha/°	90	90	83.246(2)	90
beta/°	98.540(2)	102.596(4)	83.033(2)	107.687(1)
gamma/°	90	90	68.742(2)	90
V/Å^3	1629.23(17)	1629.9(3)	827.04(6)	1721.80(7)
Z	2	2	1	2
F(000)	660	660	318	660
Temp./K	296	200	296	200
Restraints	132	84	0	159
Nref	4060	4082	4103	4279
Npar	264	265	210	271
R	0.0448	0.0400	0.0415	0.0438
wR2	0.1235	0.1085	0.1162	0.1140
S	1.03	1.05	1.04	1.03
θ min − max/°	2.2, 28.3	2.2, 28.4	1.7, 28.4	2.1, 28.3
Tot. data	32,172	31,158	20,068	28,247
Unique data	4060	4082	4103	4279
Observed data [I > 2.0 sigma(I)]	3085	3516	3304	3411
R$_{int}$	0.022	0.019	0.017	0.018
Completeness	1.000	1.000	1.000	1.000
Min. resd. dens. (e/ Å^3)	−0.19	−0.19	−0.17	−0.21
Max. resd. dens. (e/ Å^3)	0.23	0.36	0.26	0.31

^{a}These data have been published on a prior occasion [5]

interactions involving both components of guest disorder (interestingly, only one of the two oxygen atoms of each guest molecule experienced this interaction type). These measured 2.769 (3) and 2.82 (2) Å (D···A) (1.99 and 2.03 Å (H···A)) and the respective angles (O−H···O) were 158 and 160°. Figure 3 is a stereodiagram depicting these interactions (here, one disorder component was deleted for clarity).

Additionally, both disorder components of DIO experienced (guest) C−H···π(host) interactions with **H** (H···π 2.66−2.98 Å, C−H···π 125−147°), two contacts of this type being identified for one of the disorder components (Fig. 4) and one for the other.

Once more, there were no significant (host)π···π(host) interactions present in **H**·2(MOR). However, both disorder components of MOR experienced (host) O−H···N(guest) H-bonding interactions, and these measured 2.825(3) and 2.822(10) Å (O···N) with angles 169 and 164°

(H···N distances were both 2.00 Å); additionally, (guest) N−H···O(guest) interactions were also identified, resulting in endless ribbons of H-bonded guest molecules in this complex. Here, N···O distances were 3.191(3) and 3.268(9) Å (H···O 2.35 and 2.40 Å) (155, 163°). These are illustrated in Fig. 5 (a stereoview, top, and the endless ribbons of guest molecules, bottom) for the one disorder guest component only.

Furthermore, and as was the case in the DIO-containing inclusion compound, MOR also experienced (guest) C−H···π(host) stabilizing contacts with the aromatic moieties of the host compound, and both components of the disordered guest were involved in two such interactions; H···π distances ranged between 2.68 and 2.92 Å (144−147°). Figure 6 is an illustration and was prepared by considering, once more, only one of the guest disorder components for clarity.

In a similar fashion, no significant (host)π···π(host) contacts were observed in the complex containing PIP but, once
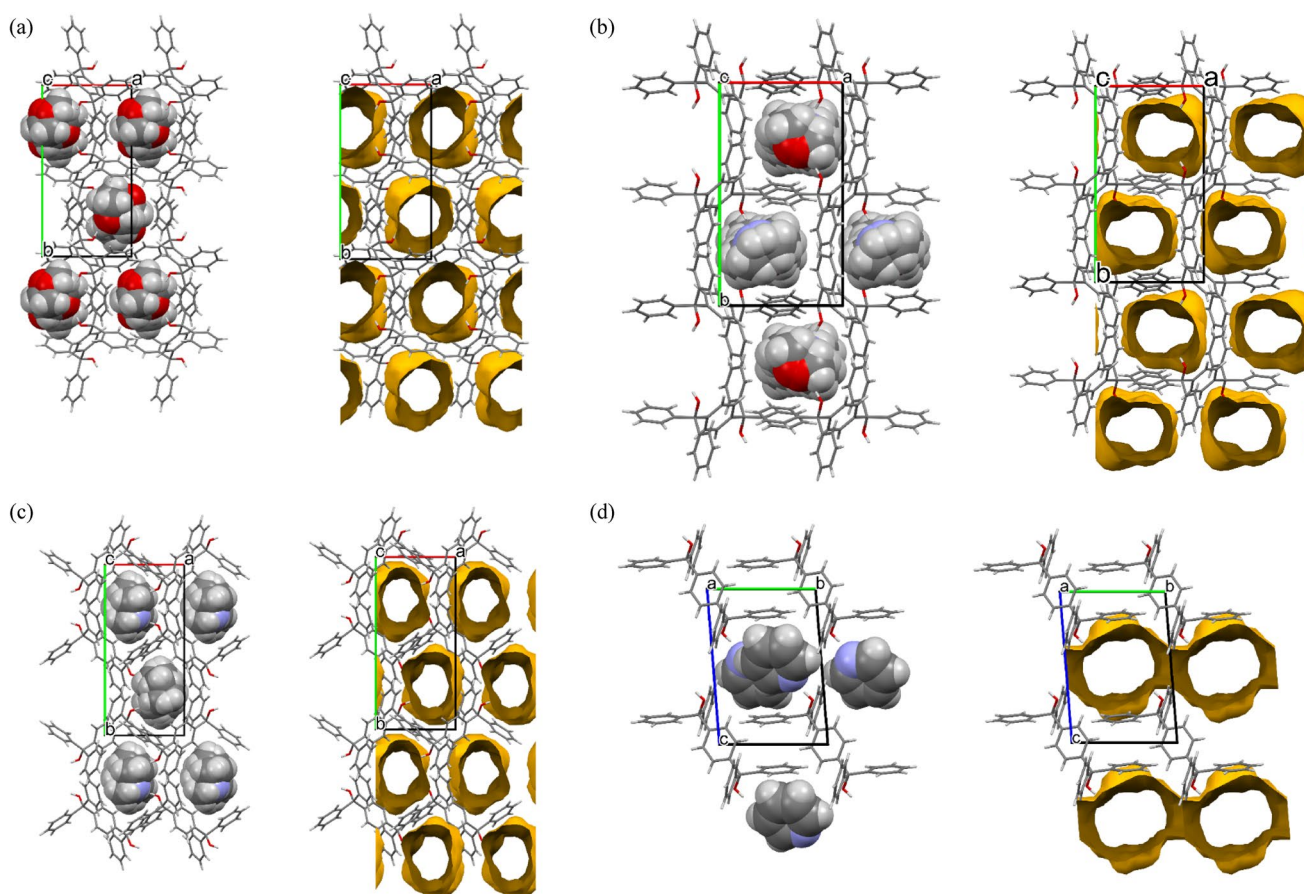
Fig. 2 Unit cell and host-guest packing (left) and void (right) diagrams in (a) **H**·2(DIO) ([001]), (b) **H**·2(MOR) ([001]), (c) **H**·2(PIP) ([001]) and (d) **H**·2(PYR) ([100])
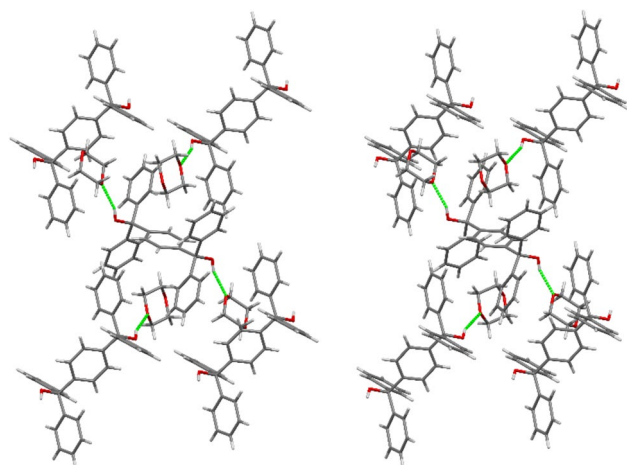
Fig. 3 A stereoview of the (host) O−H···O(guest) hydrogen bonds (green) in **H**·2(DIO). (Color figure online)

more, PIP was involved in (host)O−H···N(guest) interactions with the host molecule; these were also experienced by both disorder components, and O···N distances were 2.810(3) and

2.626(16) Å (H···N 1.97 and 1.81 Å) (174, 163°). Figure 7 is a stereoview to illustrate these interactions but where one of the two guest disorder components has been deleted.

Additionally, each **H** molecule interacted with two PIP molecules by means of (guest) C−H···π(host) interactions, and only one of the two components of disorder was involved in this fashion. Measurements (H···π) were 2.74 Å and 149° (Fig. 8).

It has been reported that PYR, in its complex with **H**, is also H-bonded to the host molecule (O−H···N 2.8195(16) Å; H···N 2.01 Å, 168°) [5]. This guest species, furthermore, interacted with a neighbouring guest molecule through π···π contacts (3.779 (1) Å), while C−H···π interactions were also identified in the complex.

Subsequently, Crystal Explorer 17.5 software[18] was employed to calculate the energies experienced by each host-guest molecular pair. Each disorder guest component in the case of DIO, MOR and PIP was considered in turn. Using this program, the host and guest molecules were selected after having completed all the molecular fragments, and then the total energy calculated for the pair at the HF/3-21G level (the total energy is
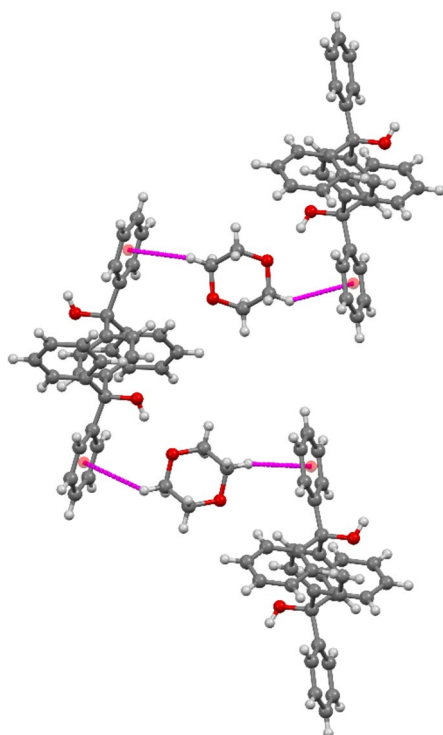
Fig. 4 The (guest)C−H···π(host) interactions (magenta) present in **H**·2(DIO), showing only one of the two components of the disordered guest species

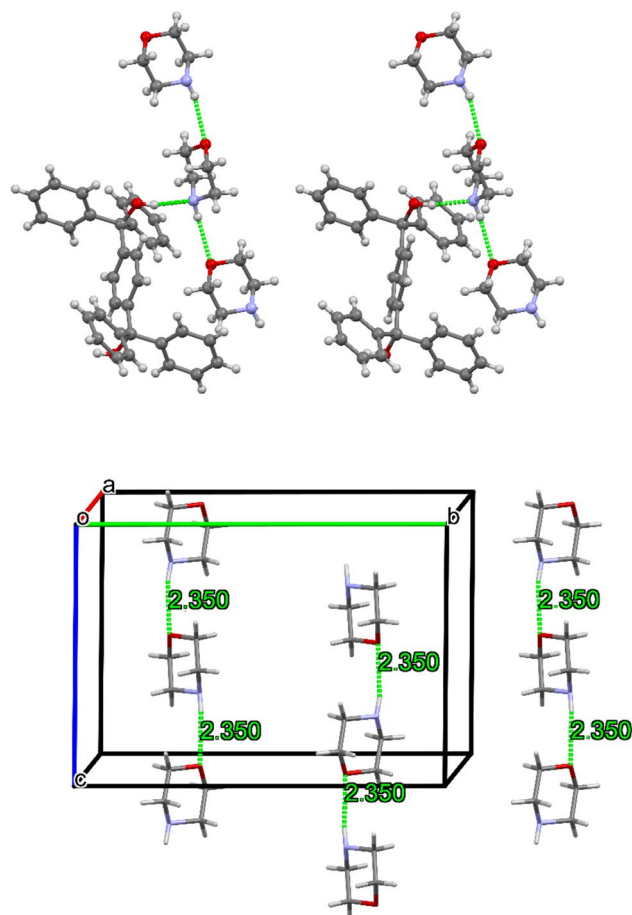**Fig. 5** A stereoview demonstrating the host···guest and guest···guest H-bonding interactions (green) in **H**·2(MOR) (top) and a depiction of the endless ribbons of H-bonded guest···guest molecules (bottom) that resulted (the H-bonded arrangement shown in the top stereoview is repeated by inversion at the bottom left of that figure but is not shown here for simplicity). (Color figure online)
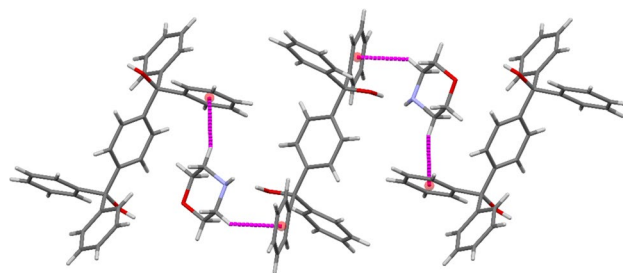
comprised of electrostatic, polarisation, dispersion, and exchange–repulsion contributions). Table 4 summarises the energy data that was so obtained.

These energy data (Table 4) clearly suggest that the lowest energy host-guest molecular pairs (and hence the more stable) are those having the preferred MOR and PIP guest species; total energies were much lower (ranging between −59.4 and −66.6 kJ·mol^{-1}) than in the complexes with disfavoured guests, DIO and PYR. These latter two molecular pairs were significantly less stable since their energies were higher, ranging between −40.3 and −48.0 kJ·mol^{-1}.

In summary, the affinity of **H** for MOR is attributed to the fact that this guest molecule experiences three stabilizing hydrogen bonds, two N−H···O H-bonds with neighbouring guest molecules and one O−H···N H-bond with the host molecule; all other guest molecules in this work are involved in only one contact of this type with **H**. Furthermore, host-guest molecular pairs involving the preferred guests MOR and PIP experienced increased stabilities compared with those having DIO and PYR, as indicated by the energy calculations.

Thermal analyses

The relative thermal stabilities of each of the four complexes was ascertained through thermoanalytical

Fig. 6 The (guest)C−H···π(host) interactions (magenta) present in **H**·2(MOR)

experiments, and the resultant thermal traces (overlaid DSC, TG and DTG) are provided in Figure S2a–c of the Supplementary Information, while Table 5 summarises the relevant data that were obtained from these.

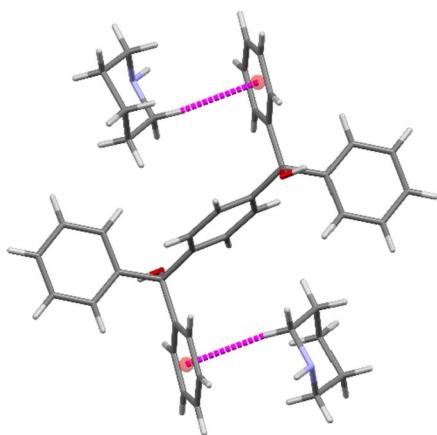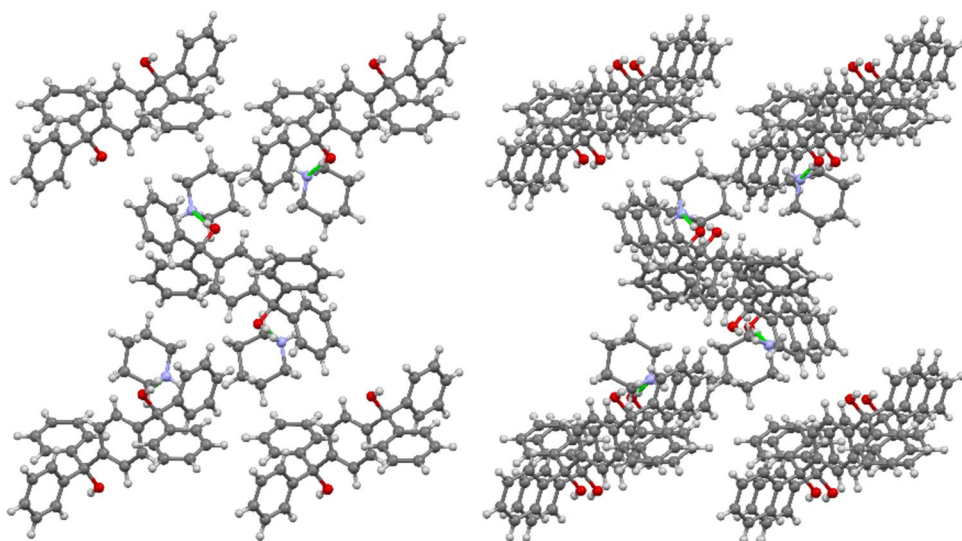**Fig. 7** A stereoview of the H-bonding interactions (green) present in **H**·2(PIP). (Color figure online)

Fig. 8 The (guest)C−H···π(host) interactions (magenta) in **H**·2(PIP)

Table 5 Relevant data obtained from the thermal traces

Complex	$T_{on}{}^a$/°C	$T_p{}^a$/°C	Measured mass loss/%	Expected mass loss/%
H·2(DIO)	47.2	179.4	27.3	28.5
H·2(MOR)	51.8	172.8	29.9	28.3
H·2(PYR)[b]	59.7	179.3	25.9	26.3
H·2(PIP)	53.4	178.9	28.5	27.8

[a]T_{on} is the temperature at which the guest release process commenced and represents the relative thermal stability of the complex; T_p is the peak endotherm temperature of the host melting process

[b]These data for **H**·2(PYR) were published on a prior occasion [5]

Table 4 Total energies of host-guest molecular pairs

Complex	E_{tot}/kJ·mol^{-1}
H·2(DIO)[a]	− 40.7, − 40.3
H·2(MOR)[a]	− 64.5, − 59.4
H·2(PYR)	− 48.0
H·2(PIP)[a]	− 66.6, − 62.2

[a]Each disorder guest component was considered in turn, and hence two energy values are provided in these instances

The measured mass losses were in close agreement with those expected for each of the 1:2 complexes produced in this work (Table 5). From the guest/guest competition experiments (Table 2), it was observed that the host selectivity behaviour was in the order MOR > PIP > PYR > DIO (Table 2). The T_{on} values provided in Table 5, the temperature at which the guest release process commenced, and which serves as a measure of the relative thermal stabilities of these complexes, demonstrates that, indeed, the DIO-containing complex with the least favoured guest solvent possessed the lowest thermal stability of the four, and T_{on} was only 47.2 °C. However, **H**·2(PYR) (containing the second least preferred guest), surprisingly, displayed a significantly enhanced stability (T_{on} 59.7 °C) compared with the complexes of each of the remaining guests, even those with the more preferred MOR (T_{on} 51.8 °C) and PIP (T_{on} 53.4 °C). These stability data, therefore, do not concur wholly with the host selectivity observations made in the competition experiments (Table 2).

Conclusions

1,4-Bis(diphenylhydroxymethyl)benzene (**H**) was a successful host compound when presented with each of DIO, MOR and PIP, forming 1:2 H:G inclusion complexes with each one (PYR was also included with the same ratio, as previously reported). In various equimolar and non-equimolar

guest/guest mixtures, **H** demonstrated a significant affinity for MOR, while DIO was never preferred in any of these crystallization experiments. The host selectivity was determined to thus be in the order MOR > PIP > PYR > DIO. SCXRD experiments showed that the preferred guest species, MOR, formed three hydrogen bonds, two with adjacent guest molecules and one with the host compound, while DIO, PIP and PYR experienced only one interaction of this type with **H**, thus explaining the preference of **H** for MOR. Present in all four complexes were (guest) C−H···π(host) interactions. Also, the host-guest molecular pairs in the MOR- and PIP-containing complexes with preferred guests were more stable than those with disfavoured DIO and PYR, as indicated by total energy considerations. Thermal analysis revealed that the complex with the least preferred guest compound (DIO) possessed the lowest thermal stability of the four, but could not explain the affinity of **H** for MOR.

Declarations

Competing interests The authors declare no competing interests.

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