# Engineering Hydrogen-Bonded Hexagonal Networks Built from Flexible 1,3,5-Trisubstituted Derivatives of Benzene

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S Supporting Information

ABSTRACT: 2,4-Diamino-1,3,5-triazinyl (DAT) groups are known to form N–H···N hydrogen bonds according to reliable patterns of self-association. In compounds **3a–c**, three DAT groups are attached to trigonally substituted phenyl cores via identical flexible arms. Crystallization of compounds **3a–c** produces robust networks in which each molecule is linked to its immediate neighbors by a total of 10–12 hydrogen bonds. In compound **3a**, the DAT groups are designed to lie close to the plane of the phenyl core, thereby giving hydrogen-bonded sheets built from hexameric rosettes. In contrast, the more highly substituted phenyl cores of analogues **3b** and **3c** favor conformations in which the DAT groups are no longer coplanar, leading predictably to the formation of three-dimensional networks. In general, the nominally trigonal topologies of compounds **3a–c** favor structures in which hexagonal networks are prominent, so they behave like trimesic acid despite their greater complexity and flexibility. The structures of all crystals incorporate open networks with significant fractions of volume accessible to guests (32–60%). Despite their flexibility, compounds **3a–c** appear to be unable to assume conformations that pack efficiently and simultaneously allow the DAT groups to engage in normal hydrogen bonding.
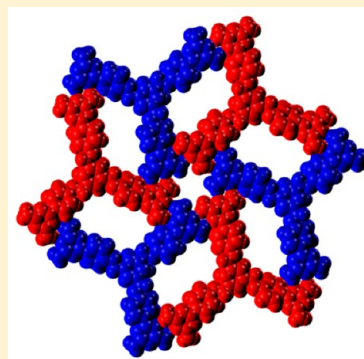
INTRODUCTION

The properties of molecular materials are determined in part by how the individual components are arranged, which depends in turn on their shape and intermolecular interactions. Rising interest in advanced materials makes it increasingly important to understand collective molecular behavior and to develop better tools for predicting and controlling organization. An effective emerging strategy for rational construction focuses on using molecules designed so that their topology and interactions work in harmony to place neighbors in predetermined relative positions.[1,2] For example, planar trigonal molecules with three peripheral sites that engage in strong interactions aligned with the core are expected to produce hexagonal frameworks (Figure 1). Such behavior is shown by trimesic acid (**1**) and analogues, which can form related frameworks held together by either hydrogen bonds or coordination to metals.[3–6]

The strategy of using molecular topology and interactions in tandem to produce predictably ordered materials is simple but powerful. It is particularly effective when (1) the components have well-defined structures with little flexibility, (2) the intermolecular interactions are strong and directional, and (3) topology and interactions operate synergistically. Nevertheless, the approach remains broadly valuable even when these conditions are not met, such as when conflicting topology and interactions favor different patterns of molecular packing. Indeed, the strategy can even be used to specifically design molecules so that they do not readily crystallize or form other ordered arrays.[7–14]

It is instructive to test the strategy by altering molecular structures systematically and observing how the overall organization changes in response. Previously, we studied the association of
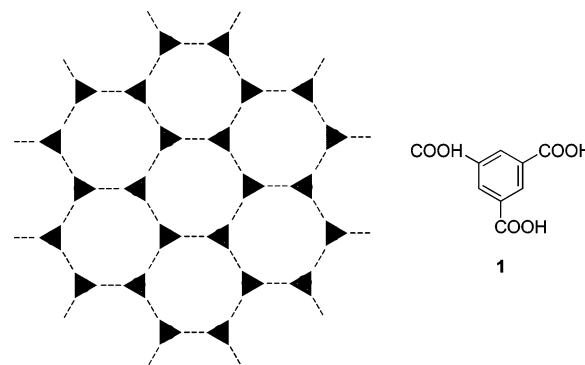

Figure 1. Representation of a hexagonal framework built from trigonal planar molecules such as trimesic acid (**1**). The molecules are represented by triangles, and intermolecular interactions aligned with the trigonal core are shown as broken lines.

compounds **2a** and **2b**[15] in which the trigonal planar 1,3,5-trisubstituted phenyl core of trimesic acid (**1**) is retained but the COOH groups are replaced with 2,4-diamino-1,3,5-triazinyl (DAT) groups. DAT groups can form multiple hydrogen bonds according to three established motifs (**I–III**), which differ only in the relative orientation of the molecular cores (represented by gray spheres). Molecules **2a** and **2b** are larger than trimesic acid (**1**), the sites of hydrogen bonding are placed farther from the central core, and 2,4,6-trialkyl substitution forces the DAT groups to lie nearly perpendicular to the plane of the core.

2a (R = CH₃)
2b (R = CH₂CH₃)

3a (R = H)
3b (R = CH₃)
3c (R = CH₂CH₃)
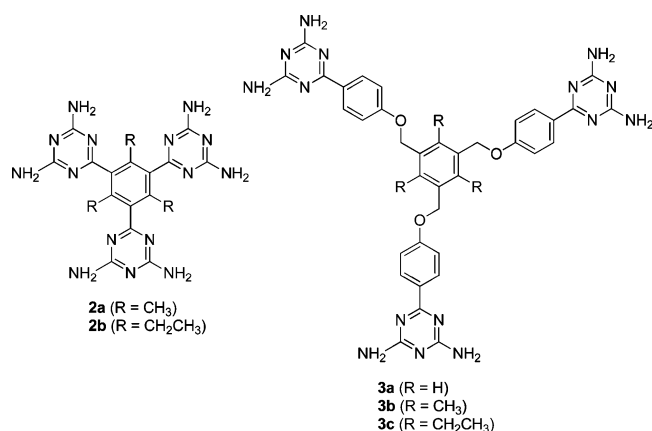
Analysis of crystals by X-ray diffraction confirmed that compounds **2a** and **2b** adopt complex nonplanar topologies, making efficient packing difficult and leading to the formation of open three-dimensional hydrogen-bonded frameworks with significant volume available for including guests. In these structures, the DAT groups fail to form all of the potential hydrogen bonds permitted by motifs I–III, possibly because the central 1,3,5-trisubstituted phenyl cores of compounds **2a** and **2b** are too compact to accommodate many neighbors.

I   II   III
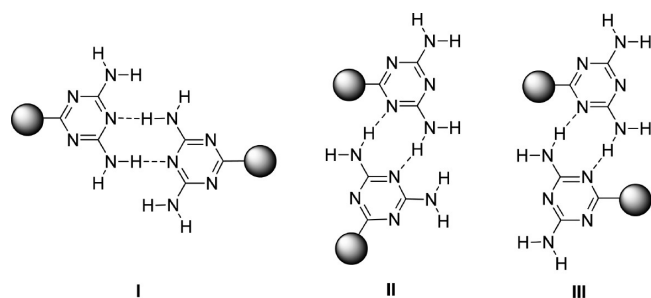
To gain deeper understanding of how topology and interactions direct molecular organization, we have now examined the association of trigonal analogues **3a–c**. They resemble compounds **2a** and **2b** but introduce significant new features, including increased flexibility and greater separation between the congested trigonal core and the principal sites of intermolecular interaction.[16−18] Despite these changes, we have found that the nominally trigonal topologies of compounds **3a–c** continue to favor the formation of open hydrogen-bonded hexagonal networks with significant fractions of volume accessible to guests.

■ RESULTS AND DISCUSSION

Synthesis of Compounds 3a–c. Compounds **3a–c** were synthesized in 88, 86, and 85% yields, respectively, by treating the corresponding trinitriles **4a**, **4b**,[19] and **4c** with dicyandiamide and KOH under standard conditions.[20] Trinitrile **4b** was prepared from 1,3,5-tris(bromomethyl)-2,4,6-trimethylbenzene[21] by a modification of the published method,[19] and trinitriles **4a** and **4c** were made in a similar way.

Structure of Crystals of Compound 3a Grown from DMF/Toluene. Exposing a solution of compound **3a** in DMF to vapors of toluene induced the formation of crystals of composition **3a**·2 DMF·0.5 toluene·0.5 H₂O.[22] The crystals proved to belong to the triclinic space group $P\bar{1}$. Crystallographic details are provided in Table 1, and views of the structure appear in Figures 2 and 3. Equal numbers of two slightly different conformations of compound **3a** are present (**3a_A** and **3a_B**), and each adopts a flattened structure of approximate C_3 symmetry in which the 1,3,5-trisubstituted phenyl core and the three DAT rings lie close to the same plane. As is normally observed,[23] the dihedral angles between the DAT groups and the aryl substituent at C6 are small (13−22°). The extended flattened conformation of compound **3a** fully exposes each DAT group and allows it to engage in a total of

Table 1. Crystallographic Data for Compounds 3a–c

compound	3a·2 DMF·0.5 PhMe·0.5 H₂O	3b[a]	3c[a]	3c[a]
crystallization medium	DMF/PhMe	DMF/PhCl	DMF/PhCl	DMSO/PhMe
formula	$C_{91}H_{104}N_{34}O_{11}$	$C_{39}H_{39}N_{15}O_3$	$C_{42}H_{45}N_{15}O_3$	$C_{42}H_{45}N_{15}O_3$
crystal system	triclinic	orthorhombic	triclinic	monoclinic
space group	$P\bar{1}$	$Pca2_1$	$P\bar{1}$	$P2_1/n$
a (Å)	12.6738(3)	28.7618(17)	12.4986(9)	29.665(6)
b (Å)	19.3375(5)	11.6367(7)	14.7043(10)	9.049(2)
c (Å)	20.0114(7)	35.138(2)	20.3073(13)	31.666(6)
α (deg)	88.963(2)	90	70.131(4)	90
β (deg)	72.912(1)	90	74.396(4)	99.090(6)
γ (deg)	75.267(1)	90	72.114(4)	90
V (Å³)	4525.2(2)	11760.4(13)	3283.4(4)	8394(3)
Z	2	8	2	4
T (K)	150	100	100	100
ρ_{calc} (g cm⁻³)	0.772	0.865	0.817	0.639
λ (Å)	1.54178	1.54178	1.54178	1.54178
μ (mm⁻¹)	2.577	0.479	0.445	0.348
R_1, I > 2σ(I)	0.0478	0.0645	0.0778	0.0604
R_1, all data	0.0516	0.0910	0.1307	0.1538
wR_2, I > 2σ(I)	0.1365	0.1888	0.2234	0.0947
wR_2, all data	0.1409	0.2146	0.2629	0.1048
measured reflections	74264	186187	49760	157058
independent reflections	14340	22105	12253	15916

[a]Guests not identified unambiguously by crystallography are omitted from the composition, as described in more detail in the Supporting Information.
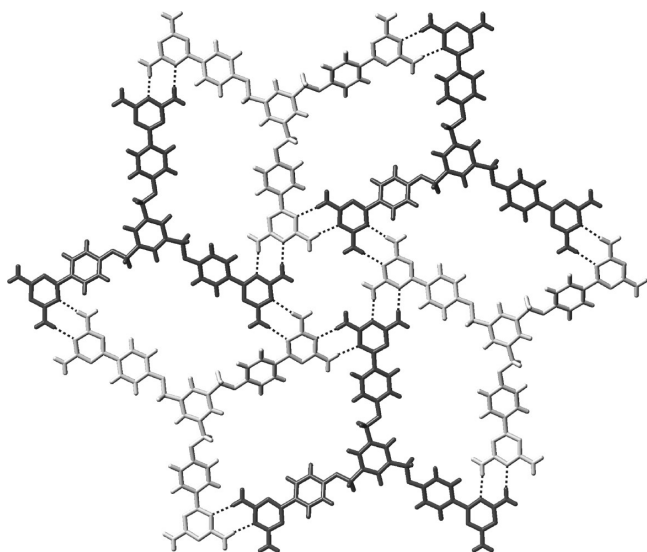
Figure 2. Partial view of a sheet in the structure of crystals of compound **3a** grown from DMF/toluene, showing a hexameric rosette formed by the association of three molecules **3a$_A$** (light gray) and three molecules **3a$_B$** (dark gray) that engage in hydrogen bonding according to motif **II**. Hydrogen bonds are represented by broken lines, and guests are omitted for clarity.

four N−H···N hydrogen bonds according to standard motif **II**. In this way, each molecule **3a$_A$** (or **3a$_B$**) is linked to three adjacent molecules **3a$_B$** (or **3a$_A$**) by a total of 12 N−H···N hydrogen bonds to define sheets (Figure 2), which stack to form various π···π contacts and to produce the observed structure (Figure 3). All N···N distances lie in the normal range (2.985−3.122 Å).[23] The sheets are of special interest because they can be considered to be built from molecules **3a$_A$** and **3a$_B$** that associate by hydrogen bonding of DAT groups to form hexameric rosettes. Rosettes of this type have often been postulated to explain the association of aminotriazines in solution, in liquid crystals, and on surfaces,[24−27] but they have rarely been characterized crystallographically.[28]

Hydrogen-bonded molecules of compound **3a** thereby define an open network, and approximately 32% of the volume of the crystals can be considered to be accessible to guests.[29−31] Space within the network is occupied by ordered molecules of DMF, toluene, and H$_2$O. DMF and H$_2$O engage in hydrogen bonding with DAT groups of compound **3a** using sites not involved in the formation of hexameric rosettes.[32] Hydrogen-bonded

molecules of H$_2$O bridge adjacent sheets and help control their relative positions.[32]

Structure of Crystals of Compound 3b Grown from DMF/Chlorobenzene. Exposing a solution of analogue **3b** in DMF to vapors of chlorobenzene produced crystals that were found to belong to the orthorhombic space group *Pca*2$_1$. The crystals contained disordered guests, and the exact composition could not be determined crystallographically. Table 1 summarizes crystallographic details, and Figures 4−8 provide views of the structure. Compound **3b** is present in equal numbers of two symmetry-independent conformations (**3b$_A$** and **3b$_B$**). As expected, methyl groups at the 2,4,6-positions of the trigonal aryl core help orient the flexible CH$_2$O arms connecting the DAT groups to the core. The oxygen atoms are forced out of the plane of the central aromatic ring, thereby producing extended nonplanar conformations in which the DAT groups are nearly perpendicular to the core. In both conformers, two of the arms are directed above the plane of the core and one below. Again, the dihedral angles between the DAT rings and their aryl substituent at C6 are small (4−23°). In these ways, conformers **3b$_A$** and **3b$_B$** adopt closely related molecular structures in which the DAT groups form hydrogen bonds above and below the plane of the trigonal core.

In the observed structure, symmetry-independent molecules **3b$_A$** and **3b$_B$** have the same connectivity, and each forms a total of 12 N−H···N hydrogen bonds with six neighbors, two of the same conformation and four of the alternative conformation (Figure 4). The three DAT groups of each molecule are linked to those of three neighbors by pairs of N−H···N hydrogen bonds according to standard motif **I**. In addition, one of the three DAT groups forms hydrogen bonds of type **III** with two other neighbors, and each molecule is also paired with a symmetry-independent neighbor by two single N−H···N hydrogen bonds as well as by C−H···aromatic and C−H···O interactions. Hydrogen bonds of type **I** are observed to be stronger than those of type **III**, as shown by the average N···N distances (2.996 and 3.070 Å, respectively). The difference arises in part because the DAT groups that participate in motif **III** are constrained to lie in distinctly different planes.

The resulting network is complex, but the primacy of motif **I** (as measured both by the number of hydrogen bonds and their strength) reveals that the structure is analogous to that of trimesic acid with open hexagonal sheets constructed from hydrogen-bonded trigonal subunits (Figure 5). At each **3b$_A$**/**3b$_B$** contact, one of the DAT groups engaged in motif **I** simultaneously forms supplementary hydrogen bonds of type
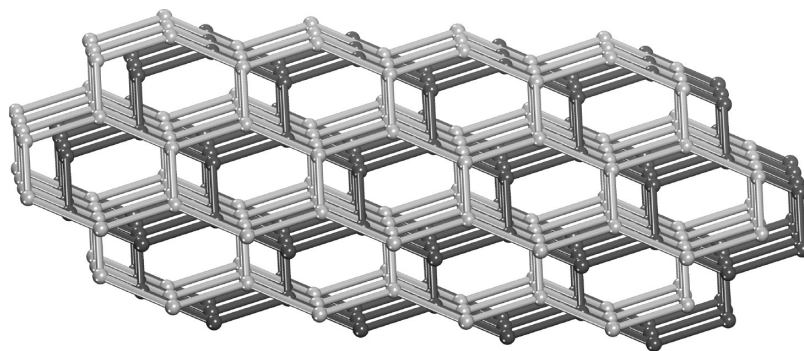

Figure 3. Representation of the hydrogen-bonded framework obtained by crystallizing compound **3a** from DMF/toluene, showing how the structure is composed of slightly offset parallel sheets. The centroid of each molecule **3a** is shown as a sphere, and each line connecting a sphere to its three neighbors corresponds to the formation of four intermolecular hydrogen bonds of type **II**, as shown in Figure 2.
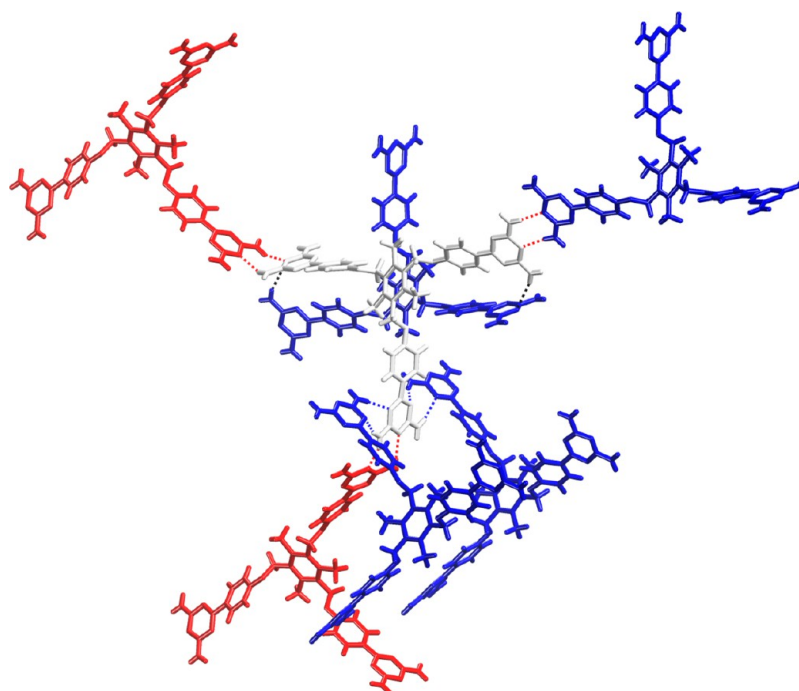
Figure 4. Representation of the structure of crystals of compound **3b** grown from DMF/chlorobenzene. A central molecule of conformation **3b$_A$** is shown in white with six hydrogen-bonded neighbors, two of the same conformation (in red) and four of symmetry-independent conformation **3b$_B$** (in blue). Hydrogen bonds are represented by broken lines with those of type **I** shown in red, those of type **III** in blue, and others in black.
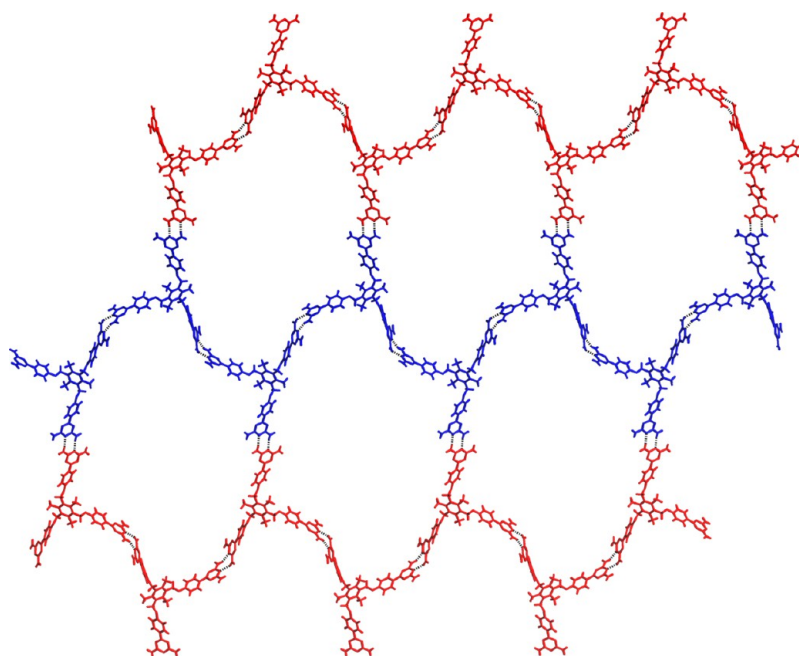

Figure 5. View along the *b*-axis of the structure of crystals of compound **3b** grown from DMF/chlorobenzene, showing part of a single hexagonal network constructed by hydrogen bonding of type **I**. Symmetry-independent molecules **3b$_A$** and **3b$_B$** appear in red and blue, respectively.

III with neighbors in the two adjacent sheets, thereby forming hydrogen-bonded zippers aligned with the *b*-axis (Figure 6). This yields a three-dimensional network in which adjacent sheets are offset (Figure 7). The full structure consists of three equivalent interpenetrated networks of this type (Figure 8) linked by single N—H···N bonds as shown in Figure 4.[33,34] Despite interpenetration, approximately 44% of the volume of the resulting crystals of compound **3b** remains accessible to

guests, which occupy channels parallel to the *b*-axis with cross sections of approximately 6 Å × 5 Å.[35]

Structure of Crystals of Compound 3c Grown from DMF/Chlorobenzene. Exposing solutions of compound **3c** in DMF to vapors of either toluene or chlorobenzene yielded crystals with the same structure. The crystals proved to belong to the triclinic space group $P\overline{1}$ and to contain disordered guests so the exact composition could not be determined
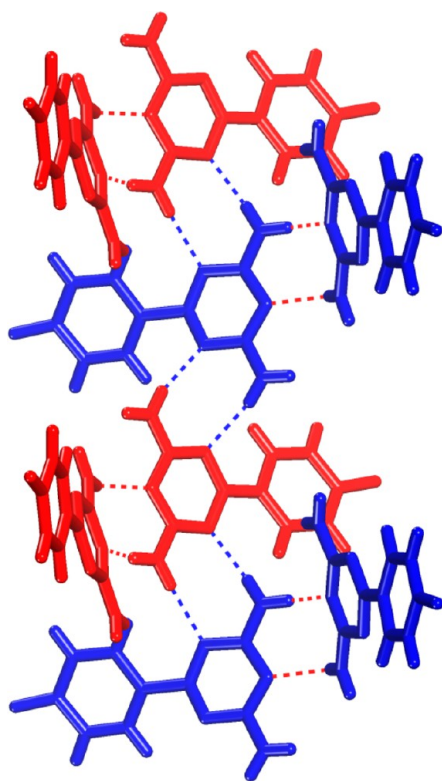
so-called *ababab* conformations **IV** in which the substituents X are oriented alternately above and below the plane of the central ring.[36−38] In the observed structure, however, compound **3c** does not obey this pattern; instead, two of the DAT groups lie above the plane and one below (Figure 9). Estimates based on use of the MM2 force field suggest that the observed conformation is approximately 2.0 kcal/mol less stable than the normal *ababab* alternative. As expected, the dihedral angles between the DAT rings and the aryl substituent are small (15−27°). Molecules of compound **3c** thereby adopt a well-defined extended conformation with three readily accessible DAT groups available to form hydrogen bonds above and below the plane of the trigonal core.

IV
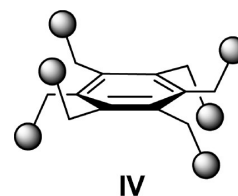
In the observed structure, the DAT groups of compound **3c** interact normally to give a total of ten N−H···N hydrogen bonds involving five neighbors (Figure 9), three linked by bonding of type **I** and two others by motif **III**. DAT groups that interact according to motif **I** are nearly coplanar, and the average N···N distances are short (2.957 Å), whereas groups bonded according to motif **III** lie in widely different planes, and the average distances are relatively long (3.138 Å). The primary network can therefore be considered to be maintained by motif **I** based both on the number of hydrogen bonds of this type and their strength. Again, the resulting structure resembles that of trimesic acid with corrugated hexagonal sheets constructed from hydrogen-bonded trigonal subunits (Figure 10). Adjacent sheets are joined by hydrogen bonds of type **III** (Figure 9) to form an open three-dimensional network (Figure 11), which accommodates 3-fold interpenetration (Figure 12).[33,34] Despite


Figure 6. View of the structure of crystals of compound **3b** grown from DMF/chlorobenzene, showing how adjacent sheets joined by hydrogen bonds of type **I** (broken lines in red) are further interconnected along the *b*-axis by hydrogen bonds of type **III** (broken lines in blue), thereby defining a zipper. Symmetry-independent molecules **3b**$_A$ and **3b**$_B$ appear in red and blue, respectively.

crystallographically. Details are summarized in Table 1, and views of the structure are shown in Figures 9−11. Hexasubstituted derivatives Ph(CH$_2$X)$_6$ of hexamethylbenzene normally adopt
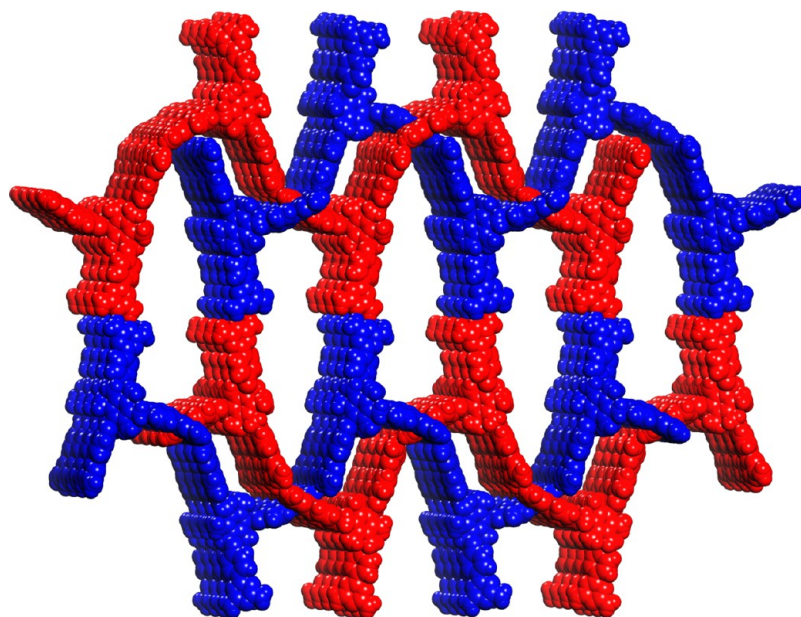

Figure 7. Partial representation of the structure of crystals of compound **3b** grown from DMF/chlorobenzene, as viewed approximately along the *b*-axis. This representation shows offset hexagonal sheets linked by hydrogen-bonded zippers to form a three-dimensional network. Symmetry-independent molecules **3b**$_A$ and **3b**$_B$ appear in red and blue, respectively.
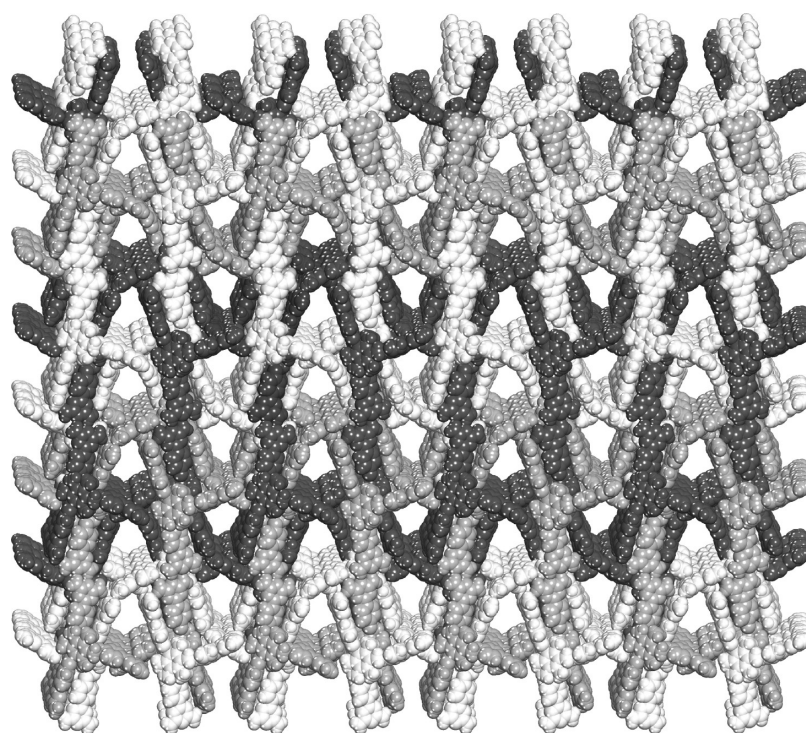
Figure 8. Representation of the complete structure of crystals of compound **3b** grown from DMF/chlorobenzene, as viewed approximately along the *b*-axis. The view shows how three equivalent networks (in white, light gray, and dark gray) of the type shown in Figure 7 are further linked through single hydrogen bonds (Figure 4) to produce the final three-dimensional structure.
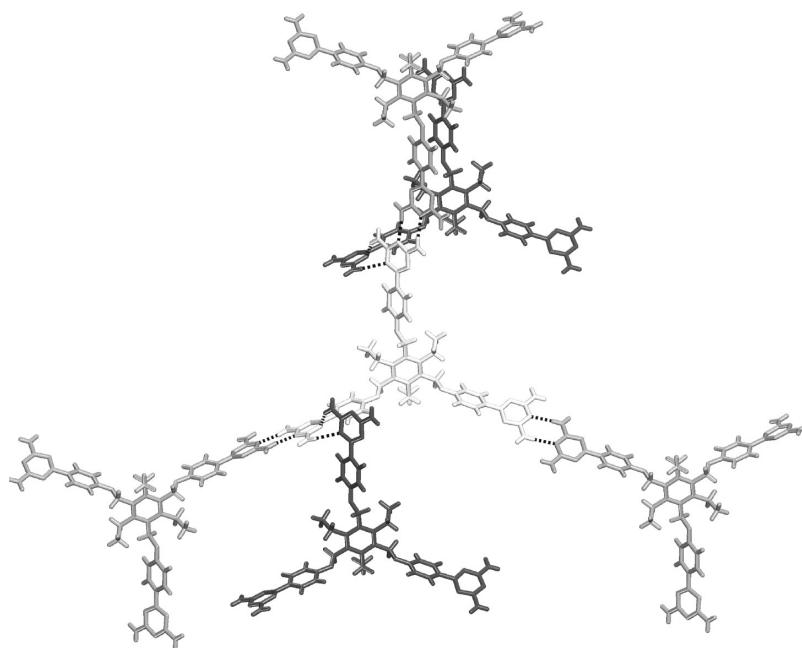

Figure 9. Representation of the structure of crystals of compound **3c** grown from DMF/chlorobenzene, showing a central molecule (in white), three neighbors that form N–H···N hydrogen bonds of type **I** (light gray), and two other neighbors that interact according to motif **III** (dark gray). Hydrogen bonds are represented by broken lines, and guest molecules are omitted for clarity.

interpenetration, approximately 44% of the volume of crystals of compound **3c** is accessible to guests.[29]

Structure of Crystals of Compound 3c Grown from DMSO/Toluene. Crystals belonging to the monoclinic space group $P2_1/n$ were obtained when vapors of toluene were allowed to diffuse into solutions of compound **3c** in DMSO. The crystals were found to contain disordered guests, and the

exact composition could not be determined crystallographically. Table 1 summarizes additional crystallographic details, and Figures 13–16 provide views of the structure. Like typical hexasubstituted derivatives Ph(CH$_2$X)$_6$ of hexamethylbenzene, compound **3c** adopts a characteristic *ababab* conformation (**IV**) in crystals grown from DMSO/toluene, unlike those grown from DMF/chlorobenzene. As a result, all three DAT groups lie on
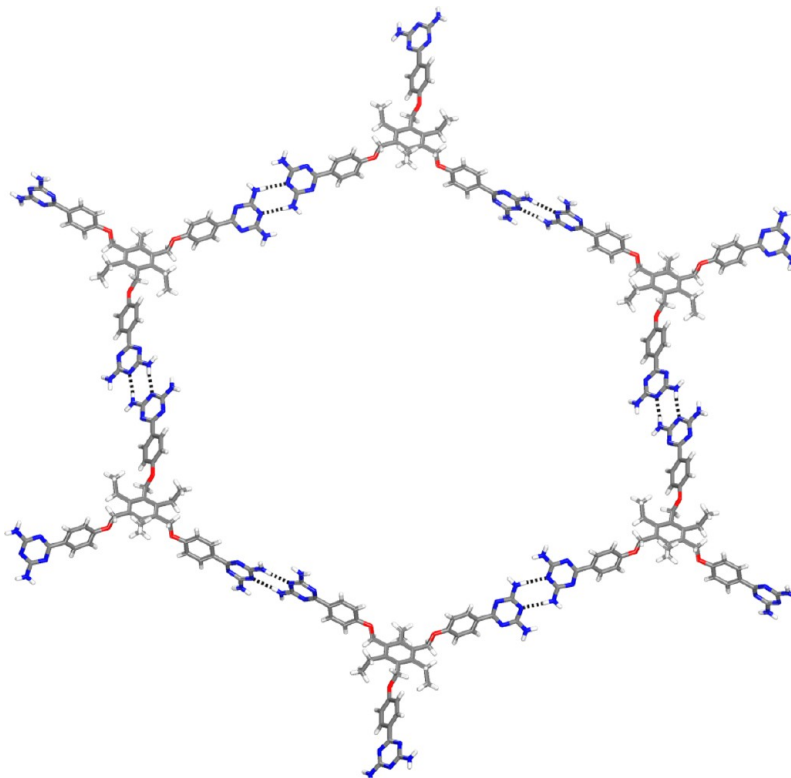
Figure 10. View along the *b*-axis of the structure of crystals of compound **3c** grown from DMF/chlorobenzene, showing part of a single hexagonal network constructed by hydrogen bonding of type **I**. Carbon atoms appear in gray, hydrogen atoms in white, nitrogen atoms in blue, and oxygen atoms in red.
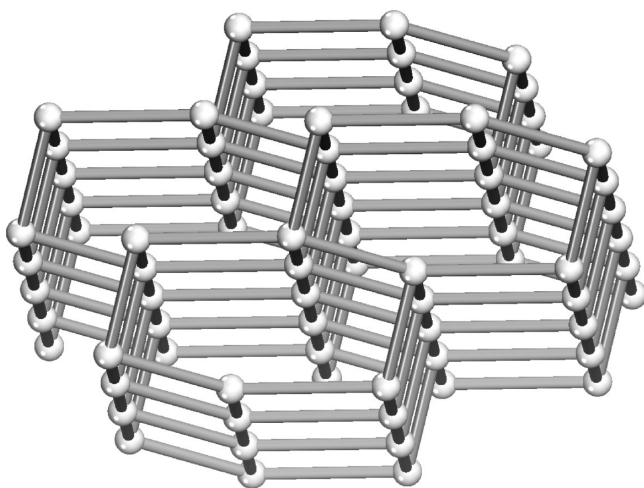

Figure 11. Partial representation of the three-dimensional hydrogen-bonded network observed in crystals of compound **3c** grown from DMF/chlorobenzene. White spheres correspond to molecular centroids, light gray lines represent hydrogen bonds of type **I** that link molecules into hexagonal sheets, and dark gray lines indicate hydrogen types of type **III** that join adjacent sheets.

one side of the plane of the central aromatic ring (Figure 13). Dihedral angles between the DAT rings and the aryl substituents are small (2–19°), as usual, so molecules of compound **3c** favor a well-defined conformation with DAT groups extended trigonally on the same face of the aromatic core.

Each molecule of compound **3c** forms a total of ten N−H···N hydrogen bonds with four neighbors (Figure 13). The DAT groups are attached to divergent trigonally extended arms, but

each molecule is nevertheless paired with one neighbor in a special two-armed embrace that forms four hydrogen bonds of type **II**. A second neighbor is linked by two additional hydrogen bonds of type **I**, and the other two neighbors both form two single N−H···N hydrogen bonds. Molecules of compound **3c** are thereby joined in zigzag chains by primary hydrogen bonds of types **I** and **II** (Figure 14). The secondary single hydrogen bonds connect the chains in a helical manner (Figure 15), thereby producing a three-dimensional hydrogen-bonded structure with the unusual *dmp* topology.[39−42]

The resulting network is open and defines two types of channels parallel to the *b*-axis, one 10 Å × 10 Å in cross section and the other 10 Å × 4 Å (Figure 16).[35] The channels are occupied by disordered molecules of solvent, and approximately 60% of the volume of crystals is accessible to guests.[29] In crystals of compound **3c** grown from DMSO/toluene, the degree of openness is high (60%), six hydrogen bonds of standard types **I**−**III** are formed per molecule, and molecules adopt standard *ababab* conformation **IV**. In contrast, in crystals grown from DMF/chlorobenzene, the openness is lower (46%), ten hydrogen bonds of types **I**−**III** are formed per molecule, and the molecules have a conformation destabilized by approximately 2.0 kcal/mol. These differences reveal how topology and interactions vie to control molecular organization. In one structure, the molecules adopt a preferred conformation but packing is ineffective, as measured by the greater openness of the network and the smaller number of standard hydrogen bonds of types **I**−**III**; in the alternative structure, the molecular conformation is unfavorable, but packing is improved. These conclusions, although primarily qualitative in nature, provide valuable guidelines based solidly on measured experimental values. In particular, assessing the efficiency of packing by
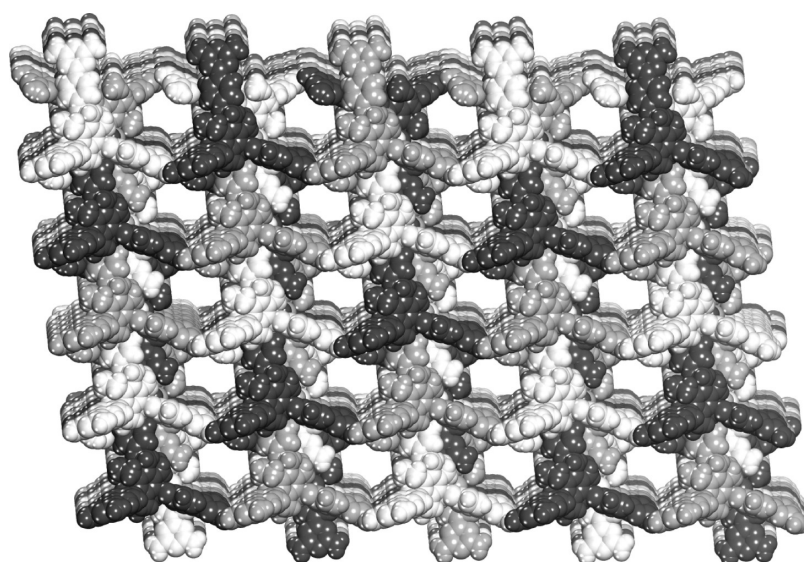
Figure 12. Representation of the complete structure of crystals of compound **3c** grown from DMF/chlorobenzene, as viewed approximately along the *b*-axis. The view shows how three independent networks (in white, light gray, and dark gray) of the type shown in Figure 11 interpenetrate to produce the final three-dimensional structure.
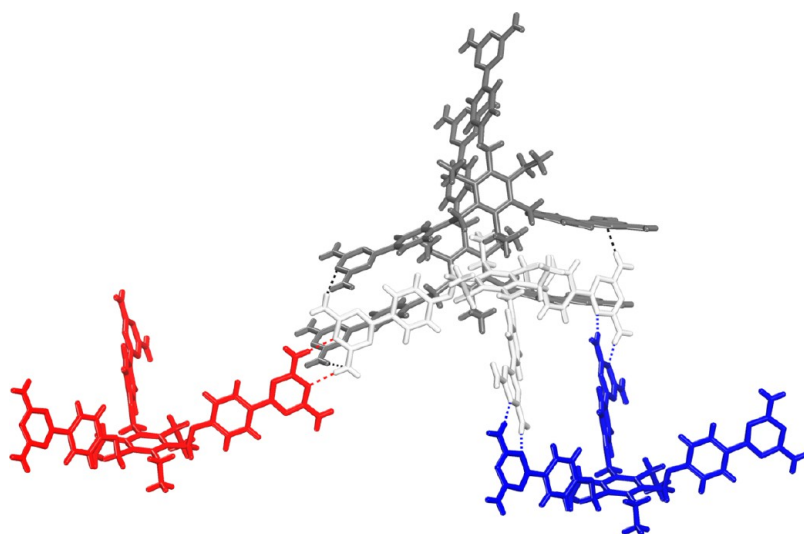

Figure 13. View of the structure of crystals of compound **3c** grown from DMSO/toluene, showing a central molecule (in white) and its four hydrogen-bonded neighbors, including one (in blue) that engages in a two-armed embrace involving motifs of type **II**, another (in red) that associates according to motif **I**, and two others (in gray) that both form two single N−H···N hydrogen bonds to the central molecule. Hydrogen bonds are represented by broken lines, and molecules of guests are omitted for clarity.
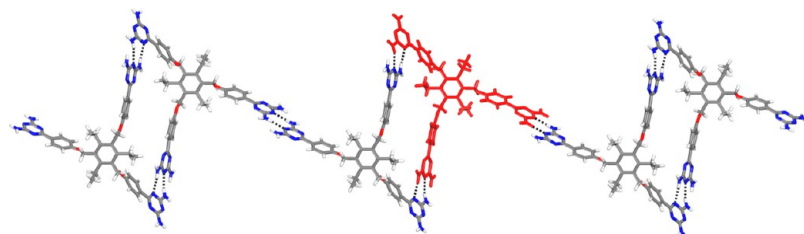

Figure 14. View of the structure of crystals of compound **3c** grown from DMSO/toluene, showing a zigzag chain held together by N−H···N hydrogen bonds of types **I** and **II**. One molecule is highlighted in red. In the other molecules, carbon atoms appear in gray, hydrogen atoms in white, nitrogen atoms in blue, and oxygen atoms in red.

comparing volumes accessible to guests is appropriate because the guests are closely similar in both cases. Improved packing in crystals grown from DMF/chlorobenzene, together with the larger number of standard hydrogen bonds, appears to compensate adequately for the need to adopt a slightly unfavorable conformation.
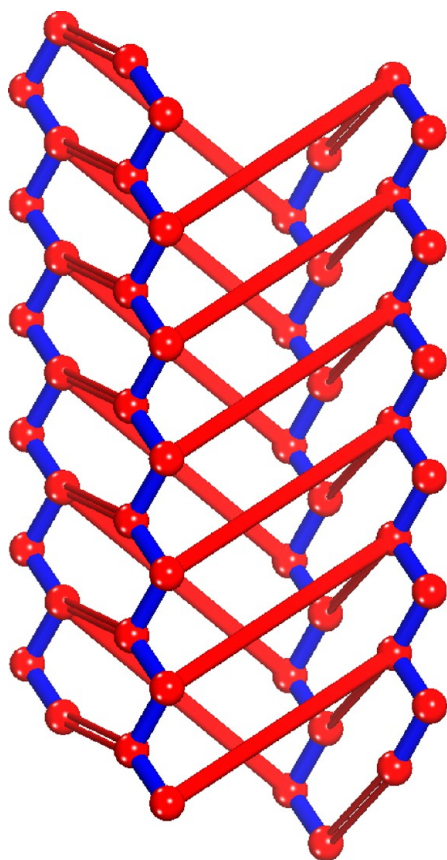
Figure 15. View along the *ac* diagonal of the helical connection between adjacent zigzag chains in crystals of compound **3c** grown from DMSO/toluene. Red spheres correspond to molecular centroids. Intrachain N−H···N hydrogen bonds between centroids are represented by single and double red lines, which correspond to motifs of type **I** and **II**, respectively. Blue lines represent single hydrogen bonds that link adjacent chains.

CONCLUSIONS

Compounds **3a−c** form a structurally related series of molecules in which trigonally substituted phenyl cores are attached via identical flexible arms to three DAT groups, which form hydrogen bonds according to reliable patterns. As a result, compounds **3a−c** can be expected to crystallize as hydrogen-bonded networks with architectures that jointly reflect the nominally trigonal molecular topology and the associative preferences of DAT groups. Unlike trimesic acid and other analogues with relatively rigid geometries and obvious patterns of association, compounds **3a−c** are complex molecules with significant flexibility, and their precise organization in the crystalline state cannot be predicted with confidence. Nevertheless, certain expected patterns of association are observed, and the structures provide valuable new understanding of how topology and interactions work in tandem to control molecular organization.

In all structures studied, association is directed primarily by N−H···N hydrogen bonds formed by DAT groups according to standard motifs **I−III**. The resulting structures are robust, with each molecule of compounds **3a−c** linked to its neighbors by 10−12 hydrogen bonds. By design, compound **3a** orients its three DAT groups close to the plane of the phenyl core, thereby favoring the formation of hydrogen-bonded sheets built from hexameric rosettes. In contrast, the hexasubstituted cores

of analogues **3b** and **3c** ensure the adoption of conformations in which the DAT groups are no longer coplanar, leading predictably to the formation of three-dimensional hydrogen-bonded networks. In general, the nominally trigonal molecular topologies favor structures in which hexagonal networks are a prominent feature. Compounds **3a−c** thereby can be considered to behave like trimesic acid despite their greater complexity and flexibility.

It is noteworthy that all structures incorporate open networks with significant fractions of volume accessible to guests (32−60%). Despite their flexibility, compounds **3a−c** appear to be unable to assume low-energy conformations that can pack efficiently and simultaneously allow the DAT groups to engage in normal hydrogen bonding. This observation underscores how options for molecular organization are severely constrained by the introduction of substituents that form strong directional interactions.

Materials with predetermined structures and properties can be built from molecular components by ensuring that their individual topologies and interactions work in concert to control local organization. This strategy is now widely used in many areas of science and technology. Our study of flexible trigonal compounds **3a−c** confirms that the strategy is broadly useful and can lead to new ordered materials with expected features, even when fine structural details cannot be predicted with confidence.

EXPERIMENTAL SECTION

1,3,5-Tris[(4-cyanophenoxy)methyl]benzene (4a). K_2CO_3 (1.38 g, 10.0 mmol) was added to a solution of 1,3,5-tris-(bromomethyl)benzene (0.893 g, 2.50 mmol) and 4-cyanophenol (1.19 g, 10.0 mmol) in acetone (40 mL). The mixture was then heated at reflux for 6 h, cooled to 25 °C, and filtered. Volatiles were removed from the filtrate by evaporation under reduced pressure, and the residual solid was purified by flash column chromatography on silica gel (CH_2Cl_2) to give a pure sample of 1,3,5-tris[(4-cyanophenoxy)-methyl]benzene (**4a**; 1.10 g, 2.33 mmol, 93%) as a colorless solid: mp 173 °C; FTIR (ATR) 3926, 3803, 3576, 3303, 3174, 2969, 2321, 2217, 1972, 1601, 1563, 1532, 1506, 1435, 1394, 1299, 1235, 1161, 1114, 1046, 982, 904, 852, 813, 771, 708, 671, 645 cm^{-1}; ^{1}H NMR (400 MHz, CDCl$_3$, 293 K) δ 7.51 (d, 6H, ^3J = 8.9 Hz), 7.40 (s, 3H); 6.95 (d, 6H, ^3J = 8.9 Hz), 5.07 (s, 6H); ^{13}C NMR (100 MHz, CDCl$_3$, 293 K) δ 161.7, 137.1, 134.1, 126.3, 119.0, 115.6, 104.6, 69.7; HRMS (+ESI, TOF) calcd for $C_{30}H_{21}N_3O_3$ + H m/e 472.1656, found 472.1655.

1,3,5-Tris[(4-cyanophenoxy)methyl]-2,4,6-trimethylbenzene (4b).[19] An analogous reaction transformed 1,3,5-tris(bromomethyl)-2,4,6-trimethylbenzene (1.19 g, 2.98 mmol)[21] into 1,3,5-tris[(4-cyanophenoxy)methyl]-2,4,6-trimethylbenzene (**4b**; 1.36 g, 2.65 mmol, 89%) as a colorless solid: mp 210 °C; FTIR (ATR) 3303, 3211, 2914, 2330, 2219, 1601, 1506, 1436, 1392, 1300, 1222, 1166, 1111, 1047, 980, 903, 852, 813, 772 cm^{-1}; ^{1}H NMR (400 MHz, CDCl$_3$, 293 K) δ 7.64 (d, 6H, ^3J = 8.8 Hz), 7.08 (d, 6H, ^3J = 8.8 Hz), 5.17 (s, 6H), 2.43 (s, 9H); ^{13}C NMR (100 MHz, CDCl$_3$, 293 K) δ 162.6, 140.2, 134.5, 131.5, 120.1, 115.7, 104.9, 65.6, 16.4; HRMS (+APPI, TOF) calcd for $C_{33}H_{27}N_3O_3$ + H m/e 514.21252, found 514.21293.

1,3,5-Tris[(4-cyanophenoxy)methyl]-2,4,6-triethylbenzene (4c). An analogous reaction transformed 1,3,5-tris(bromomethyl)-2,4,6-triethylbenzene (1.12 g, 2.55 mmol)[43] into 1,3,5-tris[(4-cyanophenoxy)methyl]-2,4,6-triethylbenzene (**4c**; 1.19 g, 2.14 mmol, 84%), which was isolated as a colorless solid: mp 224 °C; FTIR (ATR) 3789, 3655, 3483, 3319, 3188, 2969, 2218, 1956, 1600, 1505, 1435, 1393, 1299, 1234, 1165, 1113, 1047, 980, 904, 851, 812, 772, 707, 613 cm^{-1}; ^{1}H NMR (400 MHz, CDCl$_3$, 293 K) δ 7.68 (d, 6H, ^3J = 8.6 Hz), 7.11 (d, 6H, ^3J = 8.6 Hz), 5.16 (s, 6H), 2.80 (q, 6H, ^3J = 7.4 Hz), 1.25 (t, 9H, ^3J = 7.4 Hz); ^{13}C NMR (100 MHz, CDCl$_3$, 293 K) δ 162.3, 147.1, 134.6, 130.7, 119.5, 115.7, 104.9, 64.8, 23.5, 16.8;
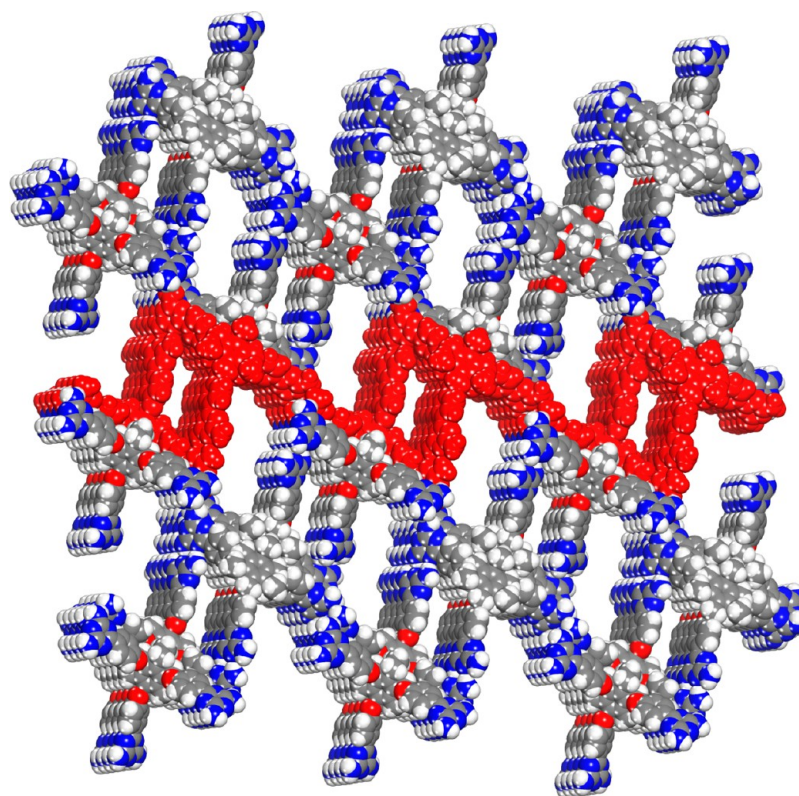
Figure 16. View along the *b*-axis of the structure of crystals of compound **3c** grown from DMSO/toluene, showing how parallel chains (one highlighted in red) are connected to build an open three-dimensional network with channels of two types parallel to the *b*-axis. Unless otherwise noted, carbon atoms are shown in gray, hydrogen atoms in white, nitrogen atoms in blue, and oxygen atoms in red. Molecules of guests are omitted for clarity.

HRMS (+APPI, TOF) calcd for $C_{36}H_{33}N_3O_3$ + H *m/e* 556.2597, found 556.2594.

1,3,5-Tris[[4-(4,6-diamino-1,3,5-triazin-2-yl)phenoxy]-methyl]benzene (3a). A mixture of 1,3,5-tris[[4-(4-cyanophenoxy)-methyl]benzene (**4a**; 1.41 g, 3.00 mmol), dicyandiamide (1.68 g, 20.0 mmol), and powdered KOH (0.396 g, 7.06 mmol) in 2-methoxyethanol (40 mL) was heated at reflux for 12 h. The resulting mixture was cooled, and the precipitated solid was separated by filtration. The solid was washed thoroughly with hot H_2O, rinsed with MeOH, and dried in vacuo to give a pure sample of 1,3,5-tris[[4-(4,6-diamino-1,3,5-triazin-2-yl)phenoxy]methyl]benzene (**3a**; 1.91 g, 2.64 mmol, 88%) as a colorless solid: mp >200 °C (dec); FTIR (ATR) 3790, 3306, 3189, 2889, 2291, 1602, 1520, 1435, 1395, 1301, 1227, 1159, 908, 905, 846, 811, 611 cm^{-1}; ^{1}H NMR (400 MHz, DMSO-d_6, 293 K) δ 8.23 (d, 6H, ^3J = 8.7 Hz), 7.57 (s, 3H), 7.12 (d, 6H, ^3J = 8.7 Hz), 6.70 (br s, 12H), 5.22 (s, 6H); ^{13}C NMR (100 MHz, DMSO-d_6, 293 K) δ 169.7, 167.3, 160.8, 137.4, 129.7, 129.4, 126.7, 114.3, 69.1; HRMS (+ESI, TOF) calcd for $C_{36}H_{33}N_{15}O_3$ + H *m/e* 724.29636, found 724.29654.

1,3,5-Tris[[4-(4,6-diamino-1,3,5-triazin-2-yl)phenoxy]-methyl]-2,4,6-trimethylbenzene (3b). An analogous reaction transformed 1,3,5-tris[[4-(4-cyanophenoxy)methyl]-2,4,6-trimethylbenzene (**4b**; 1.92 g, 3.74 mmol) into 1,3,5-tris[[4-(4,6-diamino-1,3,5-triazin-2-yl)phenoxy]methyl]-2,4,6-trimethylbenzene (**3b**; 2.46 g, 3.21 mmol, 86%), which was isolated as a colorless solid: mp >200 °C (dec); FTIR (ATR) 3780, 3696, 3573, 3304, 3194, 2325, 1602, 1525, 1435, 1393, 1304, 1230, 1159, 1108, 1047, 980, 904, 846, 812, 696 cm^{-1}; ^{1}H NMR (300 MHz, DMSO-d_6, 293 K) δ 8.24 (d, 6H, ^3J = 8.3 Hz), 7.13 (d, 6H, ^3J = 8.3 Hz), 6.70 (br s, 12H), 5.17 (s, 6H), 2.37 (s, 9H); ^{13}C NMR (75 MHz, DMSO-d_6, 293 K) δ 170.6, 168.2, 162.1, 139. 9, 132.2, 130.5, 130.3, 114.9, 65.8, 16.5; HRMS (+ESI, TOF) calcd for $C_{39}H_{39}N_{15}O_3$ + H *m/e* 766.34331, found 766.34298.

1,3,5-Tris[[4-(4,6-diamino-1,3,5-triazin-2-yl)phenoxy]-methyl]-2,4,6-triethylbenzene (3c). An analogous reaction transformed 1,3,5-tris[(4-cyanophenoxy)methyl]-2,4,6-triethylbenzene (**4c**; 1.55 g, 2.79 mmol) into 1,3,5-tris[[4-(4,6-diamino-1,3,5-triazin-2-yl)phenoxy]methyl]-2,4,6-triethylbenzene (**3c**; 1.92 g, 2.37 mmol, 85%), which was isolated as a colorless solid: mp >200 °C (dec); FTIR (ATR) 3784, 3574, 3308, 3174, 2905, 2180, 2162, 2047, 2018, 1601, 1532, 1435, 1394, 1301, 1233, 1159, 1115, 1046, 984, 904, 847, 814, 771, 638, 612 cm^{-1}; ^{1}H NMR (300 MHz, DMSO-d_6, 293 K) δ 8.26 (d, 6H, ^3J = 8.5 Hz), 7.17 (d, 6H, ^3J = 8.5 Hz), 6.69 (br s, 12H), 5.17 (s, 6H), 2.73 (q, 6H, ^3J = 7.2 Hz), 1.19 (t, 12 H, ^3J = 7.2 Hz); ^{13}C NMR (75 MHz, DMSO-d_6, 293 K) δ 170.7, 168.2, 162.0, 146.7, 131.6, 130.7, 130.4, 114.9, 65.2, 23.4, 17.2; HRMS (+ESI, TOF) calcd for $C_{42}H_{45}N_{15}O_3$ + H *m/e* 808.39026, found 808.39059.

X-ray Crystallographic Studies. The structure for compound **3a**·2 DMF·0.5 PhMe·0.5 H_2O was solved using SIR2004.[44] Other structures were solved by direct methods using SHELXS-97, and all the refinements were performed using SHELXL-97 and SHELXL-2014.[45,46] All non-hydrogen atoms were refined anisotropically, whereas hydrogen atoms were placed in ideal positions and defined as riding atoms. For some structures, guest molecules were highly disordered, and the PLATON/SQUEEZE procedure was applied.[47]

ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.5b02552.

> ^{1}H and ^{13}C NMR spectra of compounds **3a−c** and **4a−c** as well as additional crystallographic details, including ORTEP drawings. (PDF)
>
> Structural data for compounds **3a−c** (CIF)

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Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) Wuest, J. D. *Chem. Commun.* **2005**, 5830−5837.

(2) Hosseini, M. W. *Acc. Chem. Res.* **2005**, *38*, 313−323.

(3) Kolotuchin, S. V.; Thiessen, P. A.; Fenlon, E. E.; Wilson, S. R.; Loweth, C. J.; Zimmerman, S. C. *Chem. - Eur. J.* **1999**, *5*, 2537−2547.

(4) Herbstein, F. H. In *Comprehensive Supramolecular Chemistry*; MacNicol, D. D., Toda, F., Bishop, R., Eds.; Pergamon: Oxford, 1996; Vol. 6, pp 61−83.

(5) Eddaoudi, M.; Moler, D. B.; Li, H.; Chen, B.; Reineke, T. M.; O'Keeffe, M.; Yaghi, O. M. *Acc. Chem. Res.* **2001**, *34*, 319−330.

(6) Chui, S. S.-Y.; Lo, S. M.-F.; Charmant, J. P. H.; Orpen, A. G.; Williams, I. D. *Science* **1999**, *283*, 1148−1150.

(7) Tahara, K.; Ghijsens, E.; Matsushita, M.; Szabelski, P.; De Feyter, S.; Tobe, Y. *Chem. Commun.* **2011**, *47*, 11459−11461.

(8) Maly, K. E.; Gagnon, E.; Wuest, J. D. *Chem. Commun.* **2011**, *47*, 5163−5165.

(9) Gagnon, E.; Maris, T.; Wuest, J. D. *Org. Lett.* **2010**, *12*, 404−407.

(10) Gagnon, E.; Halperin, S. D.; Métivaud, V.; Maly, K. E.; Wuest, J. D. *J. Org. Chem.* **2010**, *75*, 399−406.

(11) Wuest, J. D.; Lebel, O. *Tetrahedron* **2009**, *65*, 7393−7402.

(12) Blunt, M. O.; Russell, J. C.; Giménez-López, M. d. C.; Garrahan, J. P.; Lin, X.; Schröder, M.; Champness, N. R.; Beton, P. H. *Science* **2008**, *322*, 1077−1081.

(13) Zhou, H.; Dang, H.; Yi, J.-H.; Nanci, A.; Rochefort, A.; Wuest, J. D. *J. Am. Chem. Soc.* **2007**, *129*, 13774−13775.

(14) Lebel, O.; Maris, T.; Perron, M.-È.; Demers, E.; Wuest, J. D. *J. Am. Chem. Soc.* **2006**, *128*, 10372−10373.

(15) Helzy, F.; Maris, T.; Wuest, J. D. *Cryst. Growth Des.* **2008**, *8*, 1547−1553.

(16) The structures of simple derivatives of 1,3,5-tris(phenoxymethyl)-2,4,6-trialkylbenzene have been reported.[17,18]

(17) Bhattacharya, S.; Saha, B. K. *Cryst. Growth Des.* **2012**, *12*, 169−178.

(18) Ma, M.; Kong, L.; Li, X.; Jin, H.; Zhao, X.; Wen, K. *Chin. J. Chem.* **2011**, *29*, 1503−1510.

(19) Banfi, S.; Carlucci, L.; Caruso, E.; Ciani, G.; Proserpio, D. M. *Cryst. Growth Des.* **2004**, *4*, 29−32.

(20) Simons, J. K.; Saxton, M. R. *Organic Syntheses*; Wiley: New York, 1963; Collect. Vol. *IV*, p 78.

(21) van der Made, A. W.; van der Made, R. H. *J. Org. Chem.* **1993**, *58*, 1262−1263.

(22) When guests were ordered, compositions of crystals were determined by X-ray diffraction and confirmed by ^{1}H NMR spectroscopy of dissolved samples. The composition of crystals containing disordered guests was not determined precisely.

(23) Maly, K. E.; Gagnon, E.; Maris, T.; Wuest, J. D. *J. Am. Chem. Soc.* **2007**, *129*, 4306−4322.

(24) Maly, K. E.; Dauphin, C.; Wuest, J. D. *J. Mater. Chem.* **2006**, *16*, 4695−4700.

(25) Miura, A.; Jonkheijm, P.; De Feyter, S.; Schenning, A. P. H. J.; Meijer, E. W.; De Schryver, F. C. *Small* **2005**, *1*, 131−137.

(26) Jonkheijm, P.; Miura, A.; Zdanowska, M.; Hoeben, F. J. M.; De Feyter, S.; Schenning, A. P. H. J.; De Schryver, F. C.; Meijer, E. W. *Angew. Chem., Int. Ed.* **2004**, *43*, 74−78.

(27) Thalacker, C.; Würthner, F. *Adv. Funct. Mater.* **2002**, *12*, 209−218.

(28) Telfer, S. G.; Wuest, J. D. *Chem. Commun.* **2007**, 3166−3168.

(29) The percentage of volume accessible to guests was estimated by the PLATON program.[30,31] PLATON calculates the accessible volume by allowing a spherical probe of variable radius to roll over the van der Waals surface of the network. PLATON uses a default value of 1.20 Å for the radius of the probe, which is an appropriate model for small guests such as water. The van der Waals radii used to define surfaces for these calculations are C, 1.70 Å; H, 1.20 Å; N, 1.55 Å; and O, 1.52 Å. The percentage of accessible volume is given by $100V_g/V$, where V is the volume of the unit cell and V_g is the guest-accessible volume as calculated by PLATON.

(30) Spek, A. L. *PLATON, A Multipurpose Crystallographic Tool*; Utrecht University: Utrecht, The Netherlands, 2001.

(31) van der Sluis, P.; Spek, A. L. *Acta Crystallogr., Sect. A: Found. Crystallogr.* **1990**, *46*, 194−201.

(32) See the Supporting Information for details.

(33) Batten, S. R. *CrystEngComm* **2001**, *3*, 76−82.

(34) Batten, S. R.; Robson, R. *Angew. Chem., Int. Ed.* **1998**, *37*, 1460−1494.

(35) The dimensions of a channel in a particular direction correspond to those of an imaginary cylinder that could be passed through the hypothetical open network in the given direction in contact with the van der Waals surface. The stated values measure the cross section at the most narrow constriction, so they underestimate the size of channels that are not uniform and linear.

(36) MacNicol, D. D.; Downing, G. A. In *Comprehensive Supramolecular Chemistry*; MacNicol, D. D., Toda, F., Bishop, R., Eds.; Pergamon: Oxford, 1996; Vol. 6, pp 421−464.

(37) Jessiman, A. S.; MacNicol, D. D.; Mallinson, P. R.; Vallance, I. *J. Chem. Soc., Chem. Commun.* **1990**, 1619−1621.

(38) MacNicol, D. D.; Mallinson, P. R.; Robertson, C. D. *J. Chem. Soc., Chem. Commun.* **1985**, 1649−1651.

(39) Li, Z.-X.; Ye, G.; Han, J.; Yang, Y.; Zou, K.-Y.; Wang, X.; Wang, X.-L.; Gou, X.-F. *Dalton Trans.* **2015**, *44*, 9209−9220.

(40) The topology was analyzed by the TOPOS program.[41,42]

(41) Blatov, V. A.; Proserpio, D. M. In *Modern Methods of Crystal Structure Prediction*; Oganov, A. R., Ed.; Wiley: Weinheim, 2011.

(42) Blatov, V. A.; Carlucci, L.; Ciani, G.; Proserpio, D. M. *CrystEngComm* **2004**, *6*, 378−395.

(43) Wallace, K. J.; Hanes, R.; Anslyn, E.; Morey, J.; Kilway, K. V.; Siegel, J. *Synthesis* **2005**, *2005*, 2080−2083.

(44) Burla, M. C.; Caliandro, R.; Camalli, M.; Carrozzini, B.; Cascarano, G. L.; Giacovazzo, C.; Mallamo, M.; Mazzone, A.; Polidori, G.; Spagna, R. *J. Appl. Crystallogr.* **2012**, *45*, 357−361.

(45) Sheldrick, G. M. *Acta Crystallogr., Sect. A: Found. Crystallogr.* **2008**, *64*, 112−122.

(46) Sheldrick, G. M. *Acta Crystallogr., Sect. A: Found. Adv.* **2015**, *71*, 3−8.

(47) Spek, A. L. *Acta Crystallogr.* **2015**, *C71*, 9−18.