Supramolecular architectures of cyclohexane-1, 3*cis*, 5*cis*-tricarboxylic acid in acid:base complexes

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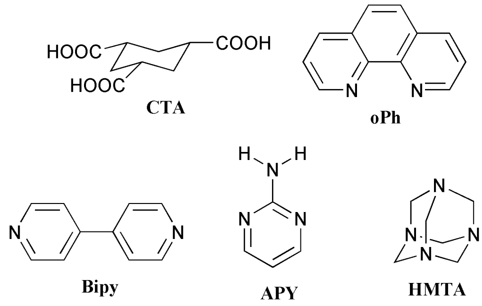
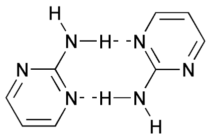
Cyclohexane-1, 3*cis*, 5*cis*-tricarboxylic acid (CTA) has been co-crystallised with a range of organic bases containing one, two or more hydrogen bond acceptors. Various supramolecular acid motifs have been identified, including tapes, sheets and interpenetrating networks. Supramolecular zigzag tapes are observed in the 1:1 co-crystal structure of CTA with acetonitrile (An) and in the 1:1:2 co-crystal with 1,10-phenanthroline (oPh) and methanol. In the 1:1 co-crystal structures of CTA with 4,4′-bipyridyl (Bipy) and with 2-aminopyrimidine (APY), two types of linear supramolecular acid tapes are observed. Co-crystallisation with hexamethyltetramine (HMTA) in the molar ratio of 1:1 results in supramolecular acid networks with pseudo-hexagonal grids, with HMTA located within the network cavities. Strong O–H···O and weak C–H···O hydrogen bonds are observed between CTA molecules in these structures.

Considerable effort has recently been devoted to understanding the relationship between molecular and crystal structures, especially from the viewpoint of crystal engineering.[1–3] In general, the approach adopted in crystal engineering is a combination of synthesis and analysis, whereby systematic patterns are identified from known crystal structures and subsequently exploited in order to create specific 'engineered' molecular materials possessing desired crystallographic architectures as well as specific physical and chemical properties.[4] As a result, considerable effort has been made to identify reliable and robust intermolecular interactions. A particular emphasis is placed on the use of hydrogen bonds.[1–4] Strong O–H···N H-bonds, for example, have been used in the creation of co-crystal structures of carboxylic acids and organic bases.[5,6] Additionally, by appropriate choice and location of functional groups, specific types of supramolecular motifs (*e.g.*, tapes, sheets and 3-dimensional networks) can be formed.[1–3]

In the context of designing specific arrays, highly symmetric molecules are of particular interest. One example, trimesic acid ($C_6H_3(COOH)_3$, benzene-1,3,5-tricarboxylic acid), with three carboxylic acid groups symmetrically arranged around a benzene ring, has been extensively studied.[7,8] In contrast, however, the related molecule cyclohexane-1, 3*cis*, 5*cis*-tricarboxylic acid ($C_6H_9(COOH)_3$, CTA), has received little attention, with only one co-crystal structure[9] reported to date in the Cambridge Structural Database.[10] The crystal structure of CTA itself has only recently been solved by structure solution of its X-ray powder diffraction pattern.[11] As part of a study to examine the types of supramolecular architectures that are adopted by CTA, we have prepared various co-crystals of CTA with a variety of organic bases. Acetonitrile (An) and 1,10-phenanthroline (oPh) have been selected as organic bases containing a single hydrogen bond acceptor (Scheme 1) (in the case of oPh, the close proximity of the two N atoms allows only one carboxylic acid molecule to H-bond[12,13]). 4,4′-Bipyridyl (Bipy), an organic base with two H-bond acceptors, is also used since it is frequently employed as a building block in crystal engineering studies. With trimesic acid, for instance, the cavity size that is formed can be expanded beyond that in pure trimesic acid by the incorporation of Bipy molecules.[7] 2-Aminopyrimidine (APY) may occur in crystal structures as single molecules[14] or as dimers (Scheme 2),[6] with both forms capable of H-bonding to carboxylic acid groups. APY, therefore, may be used in supramolecular assembly with CTA in a manner similar to that of Bipy, with two hydrogen bond acceptors. Hexamethyltetramine (HMTA), additionally, is used as an organic base with multi-H-bond acceptors.



Scheme 1



Scheme 2

Experimental

Starting materials with purity of *ca.* 98% were obtained from Aldrich and used without further purification. Mixtures of CTA and the organic base were prepared from methanol except for CTA·An, which was obtained directly by slow evaporation from a solution of CTA in An. For the co-crystals obtained from methanol, the input ratio of acid and base was 1:1. The solutions were left to evaporate slowly at room

Table 1 Crystallographic data for CTA co-crystals

Co-crystal	CTA·An	CTA·oPh·2CH_3OH	CTA·APY	CTA·HMTA
Solvent	Acetonitrile	Methanol	Methanol	Methanol
Input ratio	1:1	1:1	1:1	1:1
Empirical formula	$C_{11}H_{15}NO_6$	$C_{23}H_{28}N_2O_8$	$C_{13}H_{17}N_3O_6$	$C_{15}H_{24}N_4O_6$
Crystal system	Orthorhombic	Triclinic	Monoclinic	Monoclinic
Space group	*Pbca*	*P*-1	$P2_1/c$	$P2_1/c$
a/Å	6.8309 (5)	8.8501 (5)	5.6250 (2)	10.9547 (4)
b/Å	16.0470 (13)	11.0316 (8)	23.8851 (18)	14.4867 (6)
c/Å	22.8001 (11)	11.8635 (7)	11.2217 (9)	10.4289 (4)
α/°	90	90.185 (3)	90	90
β/°	90	95.174 (4)	100.109 (5)	93.987 (2)
γ/°	90	92.475 (4)	90	90
U/Å^3	2499.2 (3)	1152.4 (1)	1484.3 (2)	1651.0 (1)
Z	8	2	4	4
μ/mm^{-1}	0.112	0.101	0.112	0.112
Reflections collected	11 028	9137	7803	9159
Independent reflections	2185	4035	1447	3723
R_{int}	0.0827	0.0254	0.1362	0.0400
$R1$ [$I > 2\sigma(I)$]	0.0535	0.0447	0.0445	0.0449
$wR2$ [$I > 2\sigma(I)$]	0.1164	0.1110	0.1021	0.1240

temperature in air. X-Ray diffraction data were collected using a Nonius Kappa CCD diffractometer equipped with an Oxford Cryosystems cryostream. Data were collected at 180(2) K. Data reduction and cell refinement were performed with the programs DENZO[15] and COLLECT,[16] and multi-scan absorption corrections were applied with the program SORTAV.[17] Structures were solved by direct methods using SHELXS-97[18] and refined on F^2 against all data using SHELXL-97.[18] The crystallographic data are summarised in Table 1. All non-hydrogen atoms were refined with anisotropic displacement parameters. Hydrogen atoms bonded to carbon were placed geometrically and allowed to ride during subsequent refinement with an isotropic displacement parameter fixed at 1.2 times U_{eq} for the atoms to which they are attached. Hydrogen atoms bonded to O or N were located in difference Fourier maps and refined isotropically with the O–H and N–H distances restrained to 0.84(2) and 0.88(2) Å, respectively. These bond distances are intended to provide the best fit to the X-ray data, but do not reflect the true position of the hydrogen nucleus. For discussion of intermolecular distances and angles involving hydrogen atoms, the positions of the hydrogen atoms were normalised to standard neutron-derived distances[19] along the bond vector derived from the X-ray results. Cerius[2] was used to visualise the structures.[20]

CCDC reference numbers 189057–189060. See http://www.rsc.org/suppdata/nj/b2/b208686g/ for crystallographic files in CIF or other electronic format.

Results and discussion

Co-crystals of CTA and organic bases possessing one H-bond acceptor

Co-crystals of CTA and An (CTA·An) form in space group *Pbca*, with the asymmetric unit comprising one CTA and one An molecule [Fig. 1(a)]. Extended zigzag supramolecular acid tapes are formed [Fig. 1(b)] by hydrogen bonds within a $R_2^2(8)$ carboxylic acid group dimer [O2···O3, H2···O3, O2–H2···O3 ($-x$, $y-0.5$, $-z+0.5$): 2.694(3), 1.68 Å, 177.4°; O4···O1, H4···O1, O4–H4···O1 ($-x$, $y+0.5$, $-z+0.5$): 2.665(3), 1.65 Å, 177.1°]. These tapes are linked by An molecules *via* O–H···N and C–H···O interactions (Table 2) to create a two-dimensional supramolecular network, similar to that found in trimesic acid (Scheme 3). Cavities are created that are approximately 14 × 10 Å in size [Fig. 1(c)], with the puckered honeycomb grid filled by interpenetration of four independent networks [Fig. 1(d)]. This interpenetration, running approximately perpendicular to the plane of the cavity, is facilitated by puckering of the pseudo-hexagons that form the networks. The hexagons resemble the 'chair' conformation of cyclohexane.[21]

The CTA·oPh·2CH_3OH co-crystal contains two methanol molecules in space group $P-1$ [Fig. 2(a)]. Zigzag supramolecular acid tapes, similar to those seen in CTA·An, are formed, linked by $R_2^2(8)$ hydrogen bonds between carboxylic acid groups [O2···O1, H2o···O1, O2–H2o···O1 ($-x+1$, $-y+1$, $-z+1$): 2.610(2), 1.60 Å, 172.1°; O4···O3, H4o···O3, O4–H4o···O3 ($-x+1$, $-y$, $-z+2$): 2.595(2), 1.58 Å, 174.8°] [Fig. 2(b)]. The linkage of CTA to the organic base is different from that in CTA·An [Fig. 2(c)], in that the CTA tapes are linked to the bases *via* two methanol molecules (Table 2). Identical 1-D assemblies are arranged parallel to each other to form supramolecular sheets, stabilised by C–H···O hydrogen bonds [Fig. 2(c)]. The supramolecular sheets stack to give a close-packed layered arrangement.

Co-crystals of CTA and organic bases with two H-bond acceptors

The co-crystal structure of CTA and Bipy (CTA·Bipy) has been reported previously.[22] Supramolecular acid tapes are formed *via* the linkage of $R_2^2(9)$ hydrogen bonds involving O–H···O and C–H···O interactions [O2···N1, H100···N1, O2–H100···N1: 2.608(2), 1.61 Å, 163.6°; C10···O1, H10···O1, C10–H10···O1: 3.889(2), 3.31 Å, 114.8°] [Fig. 3(a)]. In contrast to CTA·An and CTA·oPh·2CH_3OH, and also trimesic acid, linear supramolecular acid tapes and crinkled 2-D sheets are formed. The supramolecular sheets are formed by Bipy molecules linking adjacent carboxylic acid tapes [(Table 2; Fig. 3(b)]. As a result of the orientation of the carboxylic acid groups on the cyclohexyl ring, the supramolecular sheets are crinkled perpendicular to the direction of the acid tapes [Fig. 3(c)].

The co-crystal of CTA and APY (CTA·APY) forms in space group $P2_1/c$ with the asymmetric unit comprising one CTA molecule and one APY molecule [Fig. 4(a)]. It is noted that proton transfer has occured from the carboxyl oxygen to the aromatic nitrogen. Supramolecular acid tapes are again formed, but with yet a different type of arrangement [Fig. 4(b)]. Two orientationally distinct CTA molecules are linked together, following an ABAB arrangement, and involving

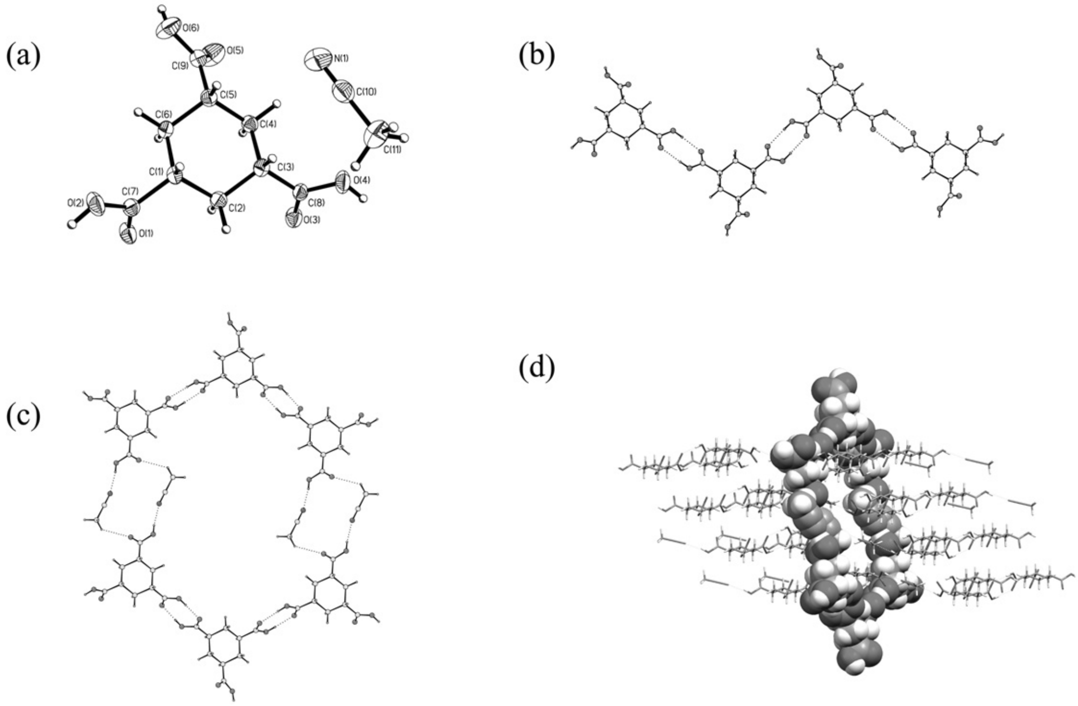


Fig. 1 (a) Atomic numbering scheme of CTA·An with displacement ellipsoids at the 50% probability level. (b) Supramolecular tape formed by hydrogen bonds involving $R_2^2(8)$ carboxylic acid group dimers. (c) Pseudo-hexagon formed by acid tapes and An involving O–H···N and C–H···O hydrogen bonds. (d) Cavity filled by interpenetration of four honeycomb networks.

two types of O–H···O hydrogen bonds [O4···O2, H101···O2, O4–H101···O2 ($x+1$, $-y+1.5$, $z+0.5$): 2.682(3), 1.69 Å, 163.6°; O6···O1, H102···O1, O6–H102···O1 ($x-1$, $-y+1.5$, $z-0.5$): 2.712(3), 1.69 Å, 177.6°]. APY dimers, analogous to Bipy, link adjacent acid tapes to form supramolecular sheets [Fig. 4(c)] *via* $R_2^2(8)$ hydrogen bond motifs (Table 2). As in CTA·Bipy, the supramolecular sheets of CTA·APY adopt a crinkled geometry and stack upon one another [Fig. 4(d)].

Complex of CTA and HMTA

The salt formed by CTA and HMTA (CTA·HMTA) crystallises in space group $P2_1/c$ with proton transfer observed from the carboxyl oxygen to the HMTA nitrogen [Fig. 5(a)]. CTA molecules, rather than forming 1-D supramolecular acid tapes, adopt a 2-D network arrangement [Fig. 5(b)] involving two types of hydrogen bonds [O2···O5, H2o···O5, O2–H2o···O5 ($-x$, $-y-1$, $-z$): 2.627(2), 1.69 Å, 174.0°; O4···O6, H4o···O6, O4–H4o···O6 ($-x+1$, $y-0.5$, $-z-0.5$): 2.587(2), 1.57 Å, 171.9°]. These 2-D acid networks are planar and create large (*ca.* 14 × 10 Å) cavities, with each pseudo-hexagon filled by two HMTA molecules. Within the cavity, each HMTA molecule is fixed by one N–H···O hydrogen bond between the acid and base [Fig. 5(c)]. Although four N atoms are available for H-bonding from each HMTA in CTA·HMTA, only one N atom is H-bonded to one carboxylic acid group.

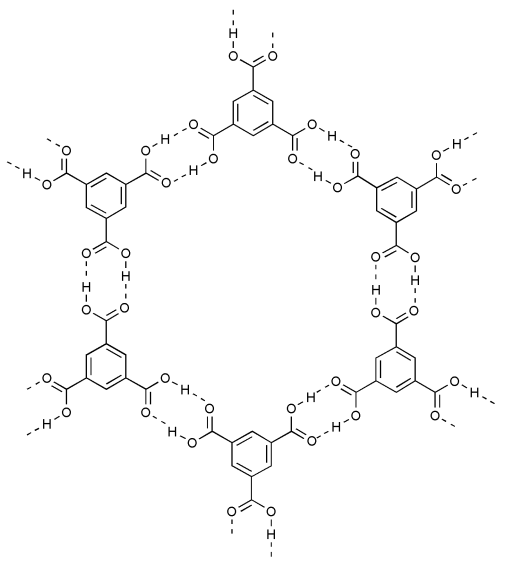
Description of supramolecular CTA motifs

The supramolecular acid motifs observed in the crystal structures described here can be divided into two classes, according to the geometry of the CTA motifs. Supramolecular acid tapes form in the structures of CTA·An, CTA·oPh·2CH$_3$OH, CTA·Bipy and CTA·APY, with the organic bases acting as

Table 2 Selected hydrogen bond parameters for CTA co-crystals[19]

Co-crystal	D–H···A	D···A/Å	H···A/Å	D–H···A/°	Symmetry operator[a]
CTA·An	O6–H6···N1	2.795(4)	1.79	167.0	$-x+1, -y, -z$
	C11–H11A···O5	3.250(4)	2.44	132.6	$x-1, y, z$
CTA·oPh·2CH$_3$OH	O6–H6o···O7	2.628(2)	1.61	175.4	$-x+2, -y, -z+1$
	O7–H7o···O8	2.625(2)	1.65	178.1	
	O8–H8o···N1	3.261(2)	2.55	129.3	
	O8–H8o···N2	2.755(2)	1.85	153.5	
CTA·Bipy	O4–H101···N2	2.627(2)	1.62	169.5	$-x+1.5, y+0.5, -z-0.5$
	C17–H17···O3	3.804(2)	3.24	113.6	$-x+1.5, y-0.5, -z-0.5$
	O6–H102···O4	2.849(2)	1.92	150.4	$x, y, z+1$
	C2–H2A···O5	3.829(2)	2.74	173.5	$x, y, z-1$
CTA·APY	N3–H3A···O1	2.895(4)	1.91	165.7	
	N3–H3B···N1	3.166(4)	2.17	168.4	$-x+1, -y+1, -z+1$
	N2–H100···O2	2.647(4)	1.66	164.1	
CTA·HMTA	N3–H3N···O5	2.704(2)	1.71	166.2	

[a] Applied to acceptor atoms.



Scheme 3

side chains to the acid tapes. In CTA·An and CTA·oPh·2CH$_3$OH, zigzag acid tapes are formed *via* $R_2^2(8)$ carboxylic acid group dimers and only one carboxylic acid group of each CTA interacts with the base. The repeat distance of the carboxylic acid groups on each side of the acid tape is *ca.* 16.2 Å(Scheme 4). Two possible inter-tape arrangements are observed: adjacent CTA tapes can be linked together by the base, as in CTA·An, giving rise to large cavities and facilitating the interpenetration of networks; alternatively, side chains of the acid tapes can be terminated by the organic bases and adjacent tapes are close packed, stabilised by weak hydrogen bonds. In CTA·oPh·2CH$_3$OH, for example,the size of oPh, 8.8 × 5.3 Å, is suitable to fit these molecules into the gaps between adjacent carboxylic acid groups on CTA tapes.

In the co-crystal structures involving organic bases with two H-bond acceptors, linear tapes are observed. In CTA·Bipy, the repeat distance is *ca.* 8.7 Å and the vertical distance between adjacent organic bases is *ca.* 7.6 Å; the angle between the direction of propagation of the acid tapes and the carboxylic acid groups is *ca.* 61° (Scheme 4). With the existence of the APY dimers, whose length is *ca.* 10.5 Å, a longer repeat distance would be required in the crystal structure, and an alternative arrangement of the acid tape is observed in CTA·APY. The $R_2^2(16)$ hydrogen bond arrangement involved in the supramolecular tapes increases the repeat distance to *ca.* 14.4 Å so that close packing can be satisfied.

In contrast to the supramolecular tapes discussed above, CTA pseudo-networks are also observed as a class of acid motifs. In the crystal structure of CTA·HMTA, non-planar CTA molecules enable the formation of honeycomb structures, and in each hexagon, six acid molecules surround two HMTA molecules.

Conclusion

We discussed here the supramolecular architectures found in complexes of CTA with a range of organic bases containing one, two and four hydrogen bond acceptors. Various CTA co-crystal structures have been prepared and analysed and a variety of acid motifs have been observed, such as molecular linear and zigzag tapes, sheets and a 3-D network. This variety of arrangements gives rise to difficulties in predicting and designing specific CTA co-crystal structures. In crystal engineering, favoured building blocks are those molecules that can significantly reduce the number of possible intermolecular arrangements within crystals. The existence of various acid-acid arrangements is likely to result from the flexibility of

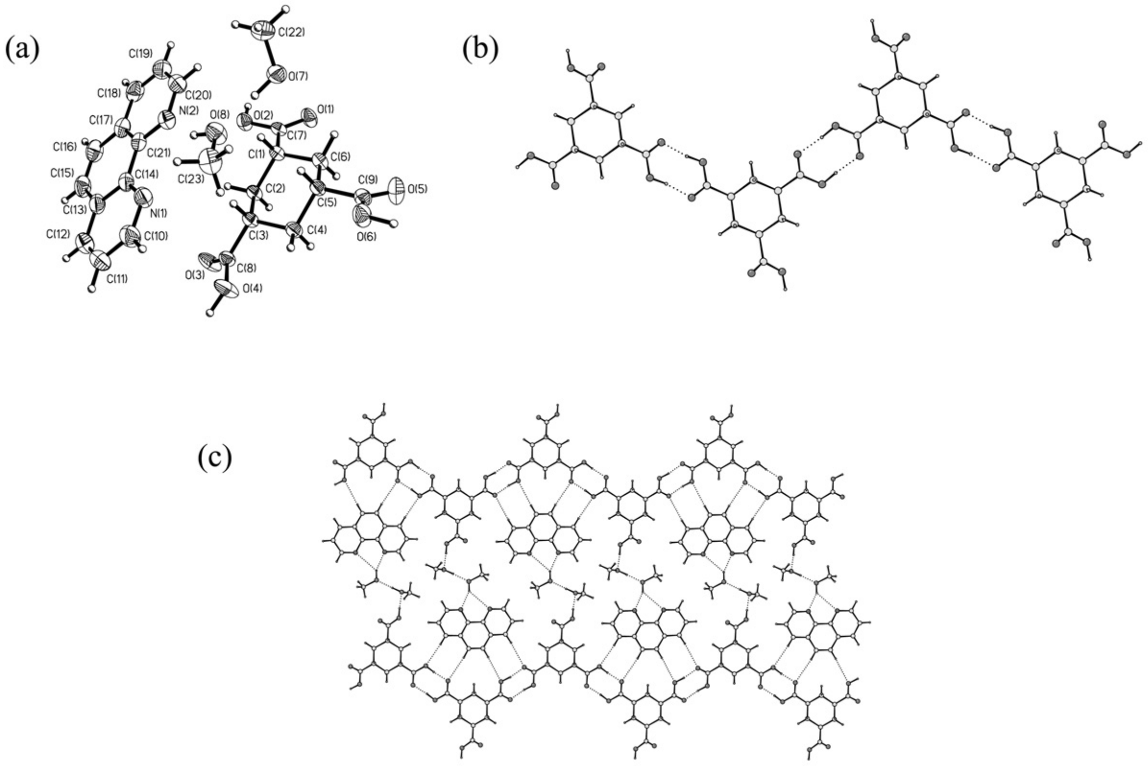


Fig. 2 (a) Atomic numbering scheme of CTA·oPh·2CH$_3$OH with displacement ellipsoids at the 50% probability level. (b) Supramolecular tape formed by hydrogen bonds involving $R_2^2(8)$ carboxylic acid group dimers. (c) CTA and oPh linked by O–H···O and O–H···N hydrogen bonds indirectly and supramolecular sheet formed by inter-tape C–H···O hydrogen bonds.

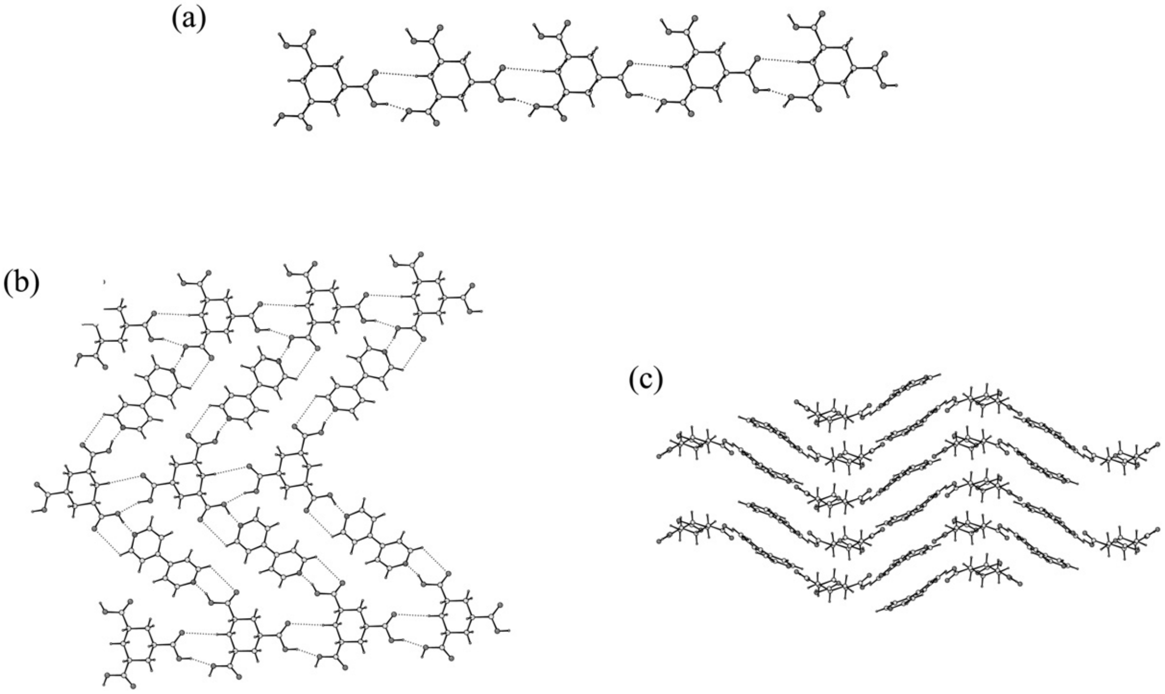


Fig. 3 (a) Supramolecular tape formed by hydrogen bonds in a CTA $R_2^2(9)$ arrangement. (b) Supramolecular sheet formed by supramolecular acid tapes with the linkage of Bipy. (c) Side view of CTA·Bipy supramolecular sheets and the close packing of the 2-D supramolecular sheets.

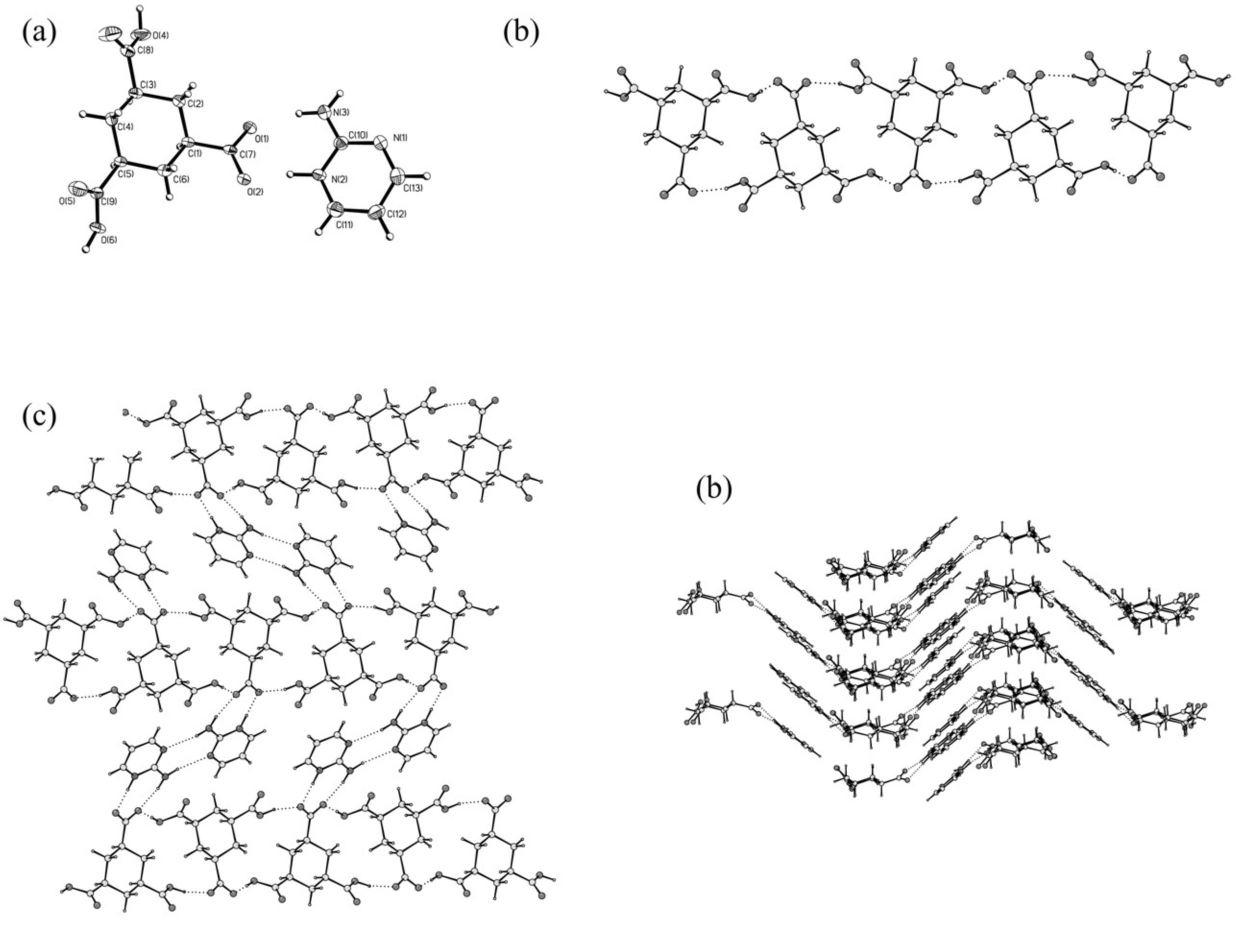


Fig. 4 (a) Atomic numbering scheme for CTA·APY with displacement ellipsoids at the 50% probability level.(b) Supramolecular tape formed by CTA in an ABAB arrangement. (c) Supramolecular sheet formed by APY dimers linking acid tapes. (d) Side view of the CTA·APY supramolecular sheets and the close packing of the 2-D supramolecular sheets.

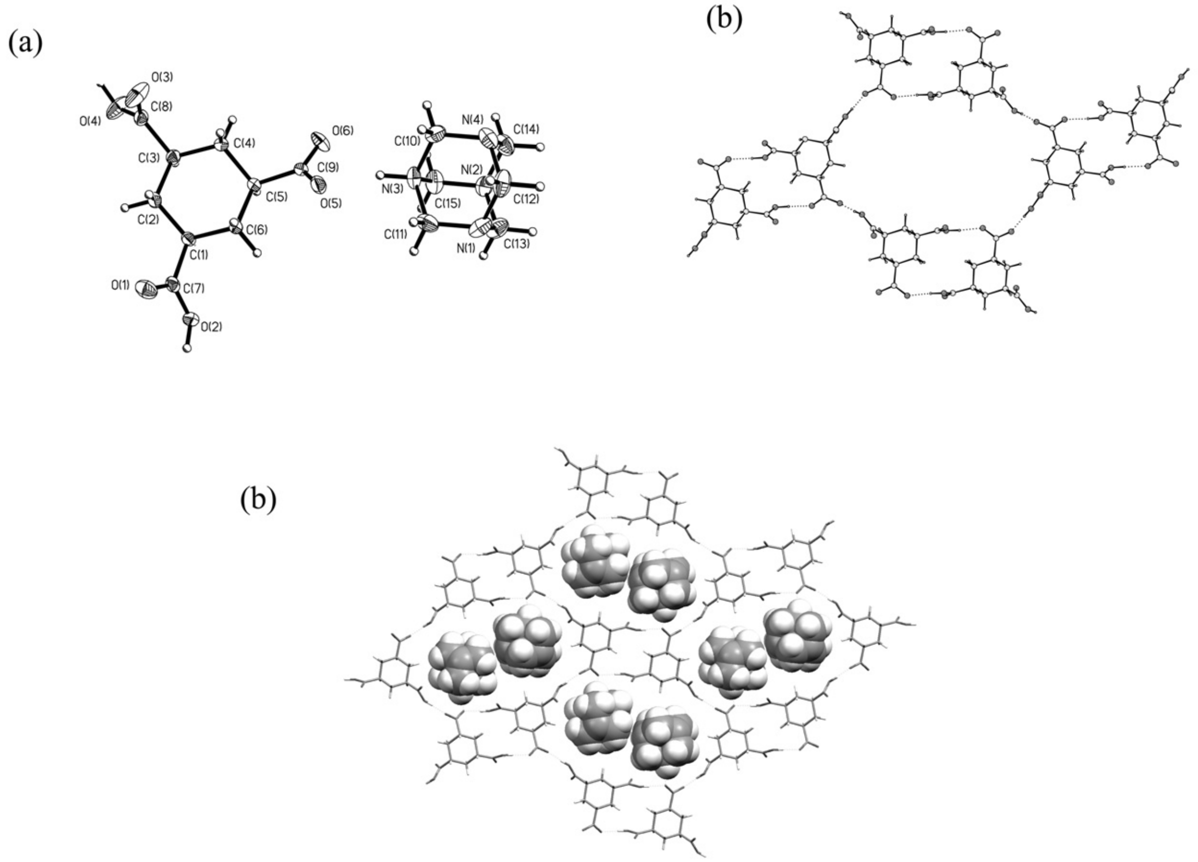
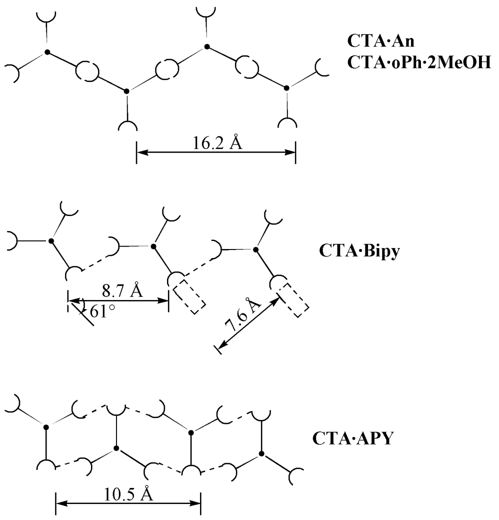


Fig. 5 (a) Atomic numbering scheme for CTA·HMTA with displacement ellipsoids at the 50% probability level. (b) Supramolecular acid network with honeycomb grid. (c) Supramolecular sheet formed by the hydrogen bonds between the acid and HMTA, in which HMTA fill the cavities.



Scheme 4

the CTA molecule itself—with several supramolecular acid-acid motifs being relatively low in energy. CTA might, therefore, be regarded as unsatisfactory as a building block. However, the studies of CTA·HMTA reveals that such co-crystals are still capable of producing novel molecular arrangements.

Acknowledgements

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