Supramolecular Chemistry
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713649759

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To cite this Article Weber, Edwin , Hager, Orm , Foces-foces, Concepcion and Llamas-saiz, Antonio L.(1998) 'Modular Crystalline Hosts Derived from Mandelic Acid. Host Synthesis, Inclusion Formation, and Xray Crystal Structures of Two Free Hosts and One Inclusion Complex with Methanol', Supramolecular Chemistry, 9: 2, 85 — 98
To link to this Article: DOI: 10.1080/10610279808034972
URL: http://dx.doi.org/10.1080/10610279808034972

SUPRAMOLECULAR CHEMISTRY, Vol. 9, pp. 85–98
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Modular Crystalline Hosts Derived from Mandelic Acid. Host Synthesis, Inclusion Formation, and Xray Crystal Structures of Two Free Hosts and One Inclusion Complex with Methanol

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(Received 29 May 1996)

Six new host compounds 2–5 (a, b) in optically resolved and racemic forms derived from mandelic acid and having particular lateral substituents were synthesized. Their properties in crystalline inclusion formation were studied and discussed relative to the unsubstituted parent molecules 1 (a, b). Crystal structures of two optically resolved free host compounds (2a, 3a) and of a respective methanol inclusion complex [2a · MeOH (1:1)] have been determined by Xray analysis [2a: a = 6.1641(2), b = 19.932(1), c = 14.3469(7) Å, orthorhombic, $P2_12_12_1$, D_c = 1.200 g · cm^{-3}, Z = 4, R = 0.051 for 1650 observed reflexions; 3a: a = 6.2828(3), b = 24.686(4), c = 15.000(1) Å, orthorhombic, $P2_12_12_1$, D_c = 1.149 g · cm^{-3}, Z = 4, R = 0.048 for 2154 observed reflexions; 2a · MeOH (1:1): a = 13.7316(7), b = 5.8722(2), c = 12.7330(6) Å, β = 99.278(4) °, monoclinic, $P2_1$, D_c = 1.149 g · cm^{-3}, Z = 2, R = 0.046 for 1823 observed reflexions]. In all compounds, the molecules are arranged in columns via OH···O hydrogen bonds. In the free hosts only one hydroxyl group acts as donor and the other one is involved in OH···phenyl interactions. However, in the complex, both hydroxyl groups of the host are connected through the methanol molecule by hydrogen bonds being responsible for the formation of the chains. Organic structures with R < 0.030 retrieved from the Cambridge Structural Database revealed the absence of correlation between the C—O bond length and the strength of the hydrogen bond (length of the O···O distance) in the C(sp^3)OH···OC(sp^3) fragments.

INTRODUCTION

Crystal engineering [1] involving organic molecules has emerged a major challenge in supramolecular science [2]. Both homomolecular and cocrystalline systems that selfassemble to give particular properties are in demand [3]. Selective inclusion crystallization of molecular guests into an organic lattice structure (host) is one important use [4]. These hosts may be designed according to some basic principles including a rigid framework and bulky substituents that make the compound difficult to crystallize without a suitable space filling guest thus forming a clathrate (crystalline hostguest com-

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plex) [5]. The clever installment of chirality is another point to control the inclusion property of the host lattice giving rise to high enantioselective clathrate formation [6]. Supramolecular synthons to create specific aggregate structures have been defined and proven successful [7]. Nevertheless, dealing with weak intermolecular interactions other than Hbonds [8] is still a problem considering potential relevance for a multitude of possible packing structures [7, 9].

Previously we have shown that mandelic acid when modified by addition of two phenyl rings to give **1a** and **1b** (optically resolved and racemic forms) yield crystalline host compounds displaying particular inclusion behaviour [10] (Tab. I). Binding schemes that characterize the packing structures have been discussed illustrating dimers and chains and the contribution of OH···phenyl contacts [10]. Lateral substituents attached to the phenyl rings of **1a** and **1b** are expected to have considerable consequences on both the packing structure and the host behaviour. Following this line, we became interested to study the compounds **25 (a, b)** that are derivatives of **1a** and **1b** containing substituents of different sizes and polarities.

Here we describe the preparation of the new compounds, discuss the properties of crystalline inclusion formation and report Xray structural studies of unsolvated hosts **2a** and **3a** and of the 1:1 (host:guest) methanol inclusion complex of **2a** considering the previous results [10].

RESULTS AND DISCUSSION

Synthesis

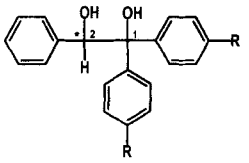
Compounds **2a, 2b, 3a, 3b, 4a** and **5a** were synthesized in a twostep process from (*S*), (*R*)

TABLE I Crystalline Inclusion Compounds (host:guest stoichiometric ratio)

Guest solvent[a]	Host compound							
	1a[b]	**1b**	**2a**	**2b**	**3a**	**3b**	**4a**	**5a**
MeOH	1:1		1:1					
1PrOH	2:1							
1BuOH	1:1							
*t*BuOH	2:1						1:1	
*c*PentOH	1:1	1:1						
*c*HeptOH	1:2	1:2						
3MecHexOH	1:1							
*i*BuNH$_2$	2:1		1:1		1:1		1:1	
2BuNH$_2$	2:1		1:1		1:1			
*c*PentNH$_2$	1:1		1:1		1:2			
*c*HexNH$_2$	1:1		1:1		1:1			
2MecHexNH$_2$	1:1		1:2				1:1	
3MecHexNH$_2$	2:3		1:3				c	
Cyclopentanone	1:1						4:3	
Cyclohexanone	1:1	1:1			1:2	1:2	c	1:1
3Methylcyclohexanone	1:1	1:1	1:1	1:1	1:1	1:1	c	1:1
Dimethylformamide	1:3	1:3	1:1	1:1	1:1	1:1		2:1
Dimethyl sulfoxide	1:1	1:1	1:1	1:1	1:1	1:1		1:1
1,4Dioxane	2:1						1:1	
Morpholine	1:1	2:3	1:1	1:2	1:1	1:2		
Piperidine	1:1		1:1		1:2		c	
3Methylpiperidine	3:2		1:1	1:2	1:2	1:2	c	
Pyridine	2:1	2:1						
3Picoline	2:1		1:1	1:1				1:1

[a] The following solvents yielded no crystalline inclusions: EtOH, 2PrOH, 2BuOH, *i*BuOH, *c*HexOH, 2MecHexOH, acetone, 2methylcyclohexanone, 4methylcyclohexanone, *β*butyrolactone, *γ*valerolactone, benzaldehyde, acetonitrile, propionitrile, butyronitrile, nitromethane, nitroethane, propylene oxide, tetrahydrofuran, 2methyltetrahydrofuran, 3methyltetrahydrofuran, toluene, xylene.
[b] Compound **1a** also yields crystalline inclusions with *γ*valerolactone and cycloheptanone.
[c] Difficult to crystallize.

and (*R, S*)mandelic acid, respectively, by conversion of the acid into the methyl ester followed by reaction with the corresponding aryllithium reagent to give the products in moderate to good overall yields. Inclusion compounds were obtained by recrystallization of the hosts from the respective guest solvent.



	R	
1a	H	(2 *R*)
b	H	(2 *R*, 2 *S*)
2a	Me	(2 *R*)
b	Me	(2 *R*, 2 *S*)
3a	*t*-Bu	(2 *R*)
b	*t*-Bu	(2 *R*, 2 *S*)
4a	Ph	(2 *S*)
5a	F	(2 *S*)

Inclusion Properties

In order to make a comparative study possible, the new potential host compounds **25** (**a** and **b**) were tested with the same variety of solvents used for **1a** and **1b** [10]. These include alcohols and amines of different molecular sizes and degrees of ramification, dipolar aprotic compounds of different polarities, heterocycles with different numbers and types of heteroatoms, as well as aromatic hydrocarbons (Tab. I).

The ability of the new compounds to form crystalline inclusions is evident. However, the range of these inclusions is in no case equal to **1a**, the optically resolved parent compound for the reported modifications. Generally, the inclusion ability of the optically resolved form is always higher compared to the respective racemic host, also relating to **1b**. There is no case of an inclusion only yielded by the racemic form; in effect inclusion only occurs with solvents that are also enclathrated by the optically resolved host. Aside from this general facts specific differences and conformity in the inclusion ability of the new compounds **25** (**a** and **b**) relative to **1** (**a**, **b**) are as follows.

Alcohols are found a very inefficient class of guests for the new compounds, with the inclusions between **2a** and MeOH or **4a** and *t*BuOH being the rare exceptions. By way of contrast, **1a** gave crystalline inclusions with alcohols of different size and shape while **1b** seems to prefer cyclic alcohols. Another remarkable finding is for the amine class of guests. Among the new compounds only **2a**, **3a** and **4a**, decreasing in this order, are capable of forming inclusions with amines, whereas **5a**, just as **1b**, failed and **1a** is again superior. On the other hand, there is a block in Table I including aprotic polar solvents such as 3methylcyclohexanone, dimethylformamide and dimethyl sulfoxide that form inclusions with nearly all hosts irrespective of substituents and optical specification. 1,4Dioxane has proved a common guest molecule in lattice inclusion [11]. But not here since inclusion compounds of 1,4dioxane are only formed with **1a** and **4a** though with different stoichiometric ratios. And one last remark, apolar hydrocarbon molecules totally refuse to be accommodated.

Structural Studies

A reasonable way of understanding the consequences coming from a modification of substituents is to compare related species. Thus structural studies of free host lattices **2a** and **3a** and of the methanol inclusion complex of **2a** are quite obvious including the previous studies [10].

The main characteristics of the molecular and crystal structures of compounds **2a**, **2a**·**MeOH** (1 : 1) and **3a** are shown in Table II according to the numbering scheme depicted in Figure 1. The OH groups are in a *gauche* conformation in all compounds, however, significant differences between the lengths of both C—O bonds in the free host with respect to those in the complex

TABLE II Selected geometrical parameters (Å, °)[a]

Compound	2a	2a · MeOH (1:1)	3a
C(1)-C(2)	1.553(5)	1.551(4)	1.556(3)
C(1)-O(4)	1.425(4)	1.445(4)	1.425(3)
C(1)-C(11)	1.536(5)	1.525(4)	1.543(4)
C(1)-C(21)	1.532(4)	1.525(4)	1.532(3)
C(2)-C(31)	1.509(5)	1.516(4)	1.513(3)
C(2)-O(5)	1.444(4)	1.419(4)	1.444(3)
C(12)-C(11)-C(16)	117.8(3)	117.3(3)	117.3(2)
C(22)-C(21)-C(26)	118.5(3)	118.1(3)	116.7(2)
C(32)-C(31)-C(36)	118.1(4)	118.9(3)	119.7(2)
C(2)-C(1)-C(11)	113.1(3)	112.9(3)	107.9(2)
C(1)-C(11)-C(12)	124.8(3)	123.7(3)	121.9(2)
C(2)-C(1)-C(21)	108.0(3)	108.5(2)	111.4(2)
C(1)-C(21)-C(22)	119.8(3)	120.2(3)	122.7(2)
O(4)-C(1)-C(2)-O(5)	61.0(3)	62.9(3)	58.9(2)
C(21)-C(1)-C(2)-C(31)	56.3(4)	56.3(3)	57.3(3)
C(11)-C(1)-C(2)-C(31)	178.3(3)	178.4(3)	178.3(3)
C(1)-C(2)-C(31)-C(32)	−116.2(4)	−107.1(3)	−108.3(3)
C(2)-C(1)-C(11)-C(12)	−20.1(5)	−16.6(4)	−59.3(3)
C(2)-C(1)-C(21)-C(22)	64.9(4)	76.4(4)	46.9(3)

2a	X-H	X···Y	H···Y	X-H···Y
O(4)-H(4)···O(5)(−1/2+*x*,1/2−*y*,−*z*)	0.76(6)	3.077(4)	2.40(6)	150(5)
O(5)-H(5)···C(1116)(1/2+*x*,1/2−*y*,−*z*)	0.75(5)	3.631(3)	2.92(5)	161(5)
C(17)-H(171)···C(3136)(−1/2+*x*,1/2−*y*,−*z*)	0.93(8)	3.973(7)	3.27(8)	133(6)
C(27)-H(271)···C(2126)(1/2+*x*,1/2−*y*,1−*z*)	0.80(7)	3.910(7)	3.21(7)	148(6)
2a · MeOH (1:1)				
O(4)-H(4)···O(6)	0.95(4)	3.072(4)	2.14(4)	166(3)
O(5)-H(5)···O(6)(1−*x*,1/2+*y*,1−*z*)	0.83(6)	2.713(4)	1.89(6)	167(5)
O(6)-H(6)···O(5)	0.97(7)	2.657(4)	1.70(7)	172(6)
C(7)-H(72)···C(3136)(1−*x*,−1/2+*y*,1−*z*)	0.93(8)	3.625(5)	2.90(8)	136(5)
C(33)-H(33)···C(3136)(1−x,1/2+*y*,2−*z*)	0.96(5)	3.882(4)	3.03(5)	148(3)
C(15)-H(15)···C(1116)(−*x*,−1/2+*y*,1−*z*)	0.98(5)	4.106(4)	3.31(5)	140(3)
C(34)-H(34)···C(2126)(1−*x*,−1/2+*y*,2−*z*)	0.97(4)	4.176(4)	3.32(4)	147(3)
C(17)-H(173)···C(2126)(−*x*,1/2+*y*,1−*z*)	0.91(15)	3.618(5)	3.22(11)	109(8)
3a				
O(4)-H(4)···O(5)(−1/2+*x*,1/2−*y*,−*z*)	0.80(3)	2.848(2)	2.12(3)	151(3)
O(5)-H(5)···C(1116)	0.90(3)	3.801(2)	3.08(3)	138(3)
O(5)-H(5)···C(3136)(−1/2+*x*,1/2−*y*,−*z*)	0.90(3)	4.076(2)	3.36(2)	138(3)
C(301)-H(3013)···C(1116)(1/2+*x*,1/2−*y*,1−*z*)	0.97(−)	3.882(7)	3.11(−)	140(−)
C(292)-H(2921)···C(1116)(1/2+*x*,1/2−*y*,1−*z*)	0.93(−)	3.904(8)	2.97(−)	177(−)
C(301)-H(3012)···C(2126)(1/2+*x*,1/2−*y*,1−*z*)	0.82(13)	3.748(9)	3.05(13)	144(10)
C(292)-H(2923)···C(2126)(1/2+*x*,1/2−*y*,1−*z*)	0.92(16)	4.338(12)	3.45(10)	141(6)

[a]C(i1i6), i = 1,2,3 represent the centroids of the C(11)···C(16), C(21)···C(26) and C(31)···C(36) phenyl rings.

have been detected. For each compound, these differences [C(1)—O(4) vs. C(2)—O(5)], seem to be correlated with the strength of the hydrogen bond in which they are involved as measured by their O···O distances. The larger the C—O distance the weaker the interaction (larger O···X). This effect has also been observed in previous studies of mandelic and lactic acid derivatives [10, 12, 13]. In spite of the broad distribution, a linear correlation can be observed in Figure 2 (there are two points which present an anomalous behaviour).

Angular distortions at C(1), C(11) and C(21) are closely related to the spatial disposition of

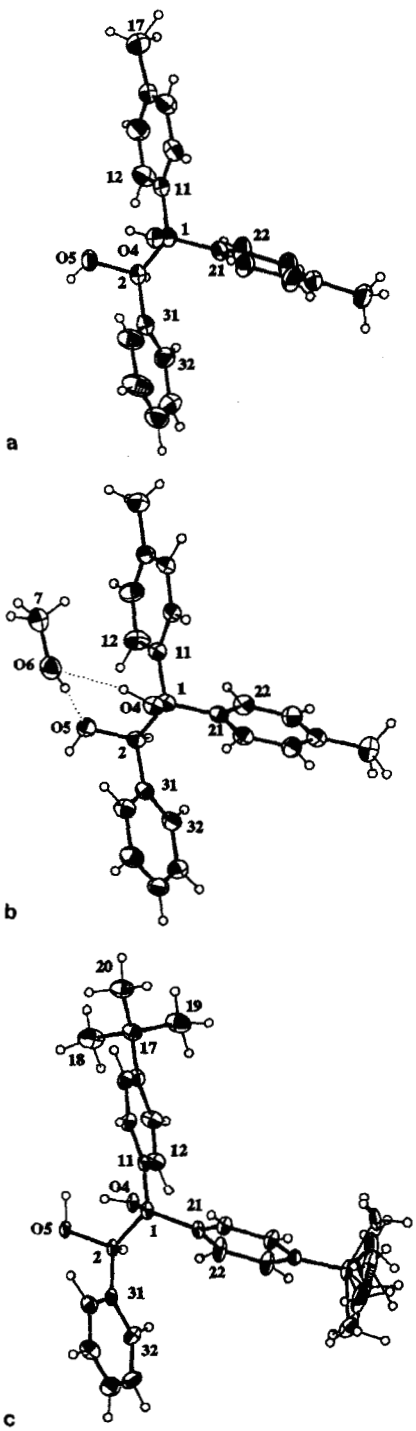


FIGURE 1 Molecular structures of (a) compound **2a**, (b) the asymmetric unit of **2a · MeOH** (1 : 1) (dotted lines specify hydrogen bonds) and (c) compound **3a** showing the disorder of one *t*butyl group. Displacement ellipsoids were drawn at 30 % probability level.

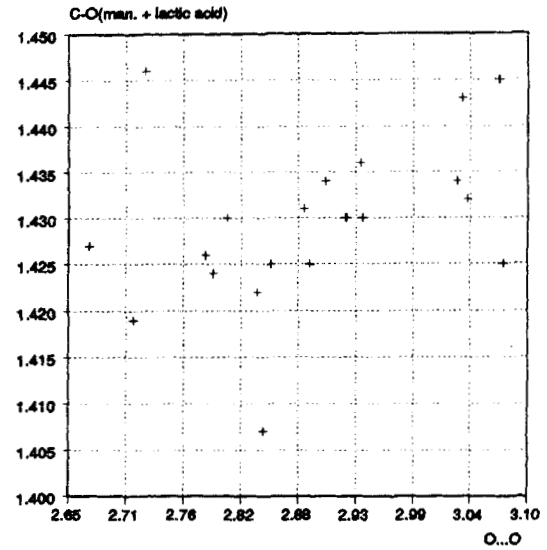


FIGURE 2 Scatterplot of the C—O (donor) *vs.* O···O distances for mandelic and lactic acid related structures (see text for references).

the corresponding phenyl rings with respect to C(2). The compounds **2a** and **2a · MeOH** (1 : 1), where the C(11)···C(16) and C(21)···C(26) rings are more and less coplanar with the C(2) atom, present the same pattern of bond angles. The opposite situation is observed in **3a**. In all phenyl rings, the *ipso* angle [C(i2)C(i1)C(i6); i = 1, 2, 3] reflects the influence of the σelectron withdrawing character of the substituent [14] (Tab. II).

Compounds **2a** and **3a** roughly display the same crystal packing. The hydroxy group at C(1) links molecules forming chains that are reinforced by OH···phenyl interactions [15] (Figs. 3a,b and Fig. 4). The hydrogen bond network around the twofold screw axes form chains of molecules along *a* that are quite similar in both crystals. The small differences are due to the conformation of the phenyl rings (Tab. II and Fig. 4) and also the disposition of the hydrogen at O(5)[H(5)O(5)C(2)C(1) = −165(5), 37(2)°, respectively]. The OH orientation in **3a** allows the formation of a three center hydrogen interaction, while in **2a** this interaction appears to be stronger and more linear. Besides that, the H···centroid distances and the O—H···centroid

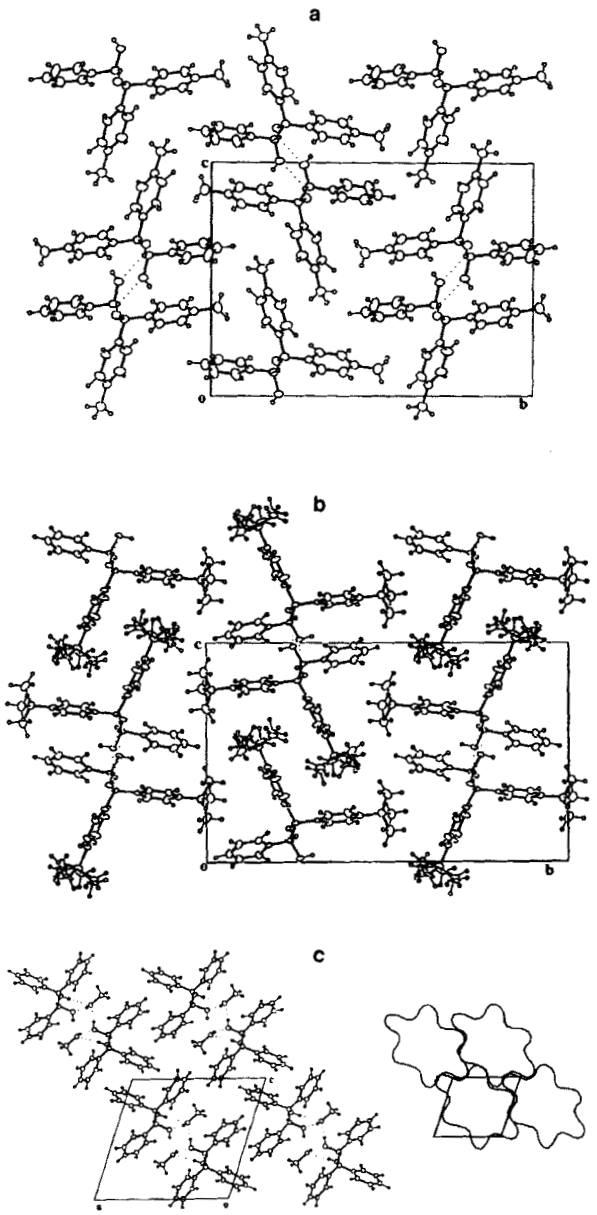


FIGURE 3 Crystal packing of (a) compound **2a** projected along the *a* axis; (b) **3a** projected along the *a* axis; (c) and (d) **1a**·**MeOH** (phenyl) (in ref 10) and **2a**·**MeOH** (*p*tolyl), respectively, projected along the *b* axis, together with a schematic representation of the crystal packing for both complexes.

angle place these interactions among those belonging to the small group of short and linear interactions observed in a statistical study for these type of contacts [10].

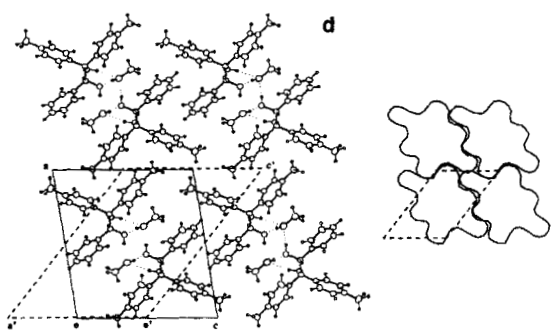


FIGURE 3 (Continued).

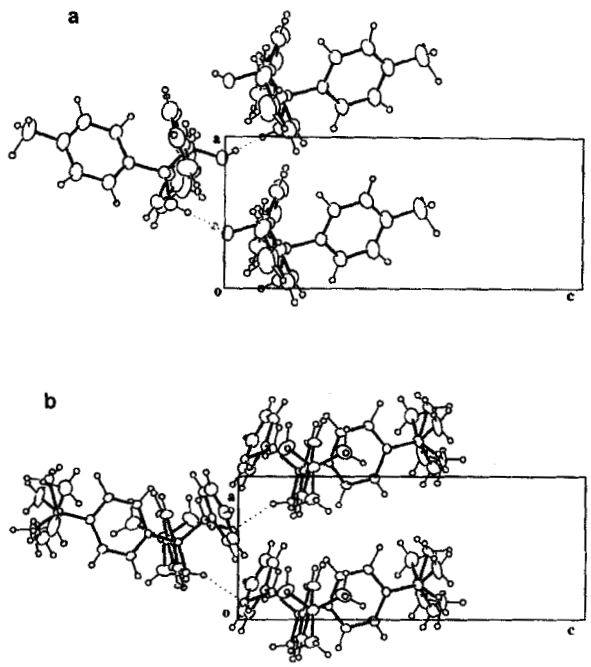


FIGURE 4 Projection along the *b* axis of one of the chains of molecules in compound (a) **2a** and (b) **3a**.

When comparing the crystal structures of the free hosts, the influence of the bulky substituent in *para* position is mainly reflected by the elongation of the *b* axis. The distances between the C(2126) planes related by a twofold screw axis along *a* and between the corresponding centroids increase [from 1.856(2) to 4.068(1) Å and from 5.527(3) to 6.335(2) Å, respectively] to accommodate a disordered *t*butyl group. However, similar C—H···phenyl contacts are pre-

sent (Tab. II) forming sheets of chains in the *ac* planes.

Host molecules related by twofold screw axes in **2a · MeOH** (1 : 1) are joined through hydrogen bonds that involve the methanol guest to from chains parallel to the *b* axis (Fig. 3d). The crystal packing of this complex can be related with that formed by the same guest and the parent host molecule **1a** without the lateral methyl groups [10] (Fig. 3c). The unit cell parameters used for the present crystal structure determination (see experimental part) could be transformed, for comparison purpose, according to $a = -a$, $b = b$ and $c = a + c$. The new values are a = 13.732, b = 5.872, c =17.155 Å and β = 124.65°. For both complexes, the previously described chains are almost identical and pack in a similar fashion to form sheets in the *ab* plane. A schematic representation of the packing modes are shown in Figures 3c and 3d. The presence of the methyl groups changes the surface topology of the sheets, hindering the way they interdigitate in the previously described compound [10] (Fig. 3). This change causes an expansion of the interplanar space between sheets (with the elongation of the *c* axis) and also a glide displacement along *a* to optimize the contact of the hydrophobic surface between sheets (with the opening of the β angle). In this new arrangement, the phenyl···phenyl, Ttype, interactions (Tab. II) are conserved inside each sheet but new contacts replace those ones that are lost in the interface between sheets. In all compounds described here, this kind of weak aromatic interactions (Tab. II) join together chains giving rise to the whole crystal.

There are no voids in the structures when using a model of interpenetrating spheres of van der Waals radii [16]. The total packing coefficients are 0.66 for both free hosts and 0.64 for **2a · MeOH** (1 : 1) while the local coefficient for the guest is 0.54. The methanol molecules were allocated in cavities that almost form channels. They are prolate in shape [16] with the maximum dimension along the *a* axis.

The O—H···O hydrogen interactions have been the subject of several studies [17]. It is well known that the O—H bond length increases with the shortening of the O···O distance. Besides, the C—O^- bond appears to be shorter than the corresponding C—O single bond if the proton is completely transferred. For example, that is the case in the picrate anion *vs.* the picric acid [18] or in phenolate compounds *vs.* phenol derivatives [19]. The differences in length observed between both C—O bonds in the present compounds lead us to perform a statistical study using the Cambridge Structural Database [20] in order to find out if there is any correlation between them and the O···O intermolecular distances. Organic structures with $C(sp^3)$—OH···O—$C(sp^3)$ fragments and a good degree of accuracy ($R < 0.030$), neither disorder nor errors and O—H···O angles larger than 130° have been retained (198 structures and 457 hits). Figure 5 shows the scatterplot of both distances, C—O(donor) vs. O···O (a), C—O(acceptor) *vs.* O···O (b) and their corresponding distributions together with that of the parameter [C—O(donor)C—O(acceptor)] and the O—H···O angle (c, d, e, f). In spite of the lack of correlation between the parameters in Figure 5a, there are two empty regions at the top left and the bottom right in the scatterplot. Δ values up to 0.06 Å have been observed. The values C—O(donor/acceptor) and O···O ranges are 1.3841.455 Å/ 1.3741.476 Å and 2.6173.026 Å (3.04 Å being the sum of van der Waals radii) [21] with average values of 1.423(11)/ 1.427(11) and 2.786(83) Å, respectively (the standard deviation of the sample being in parentheses). If the search (same fragment) is restricted to donor OH groups in which the O atom is not involved in other hydrogen bonds as acceptor, similar results are obtained for 97 structures and 110 interactions. In both cases, the shortest O···O distance (2.617 Å) [22] corresponds to similar C—O bonds (1.427 and 1.425 Å; CSD refcode: LIJPEZ). The histogram is quite symmetrical (skew parameter = −0.026) while the ones corresponding to C—O(donor/accep-

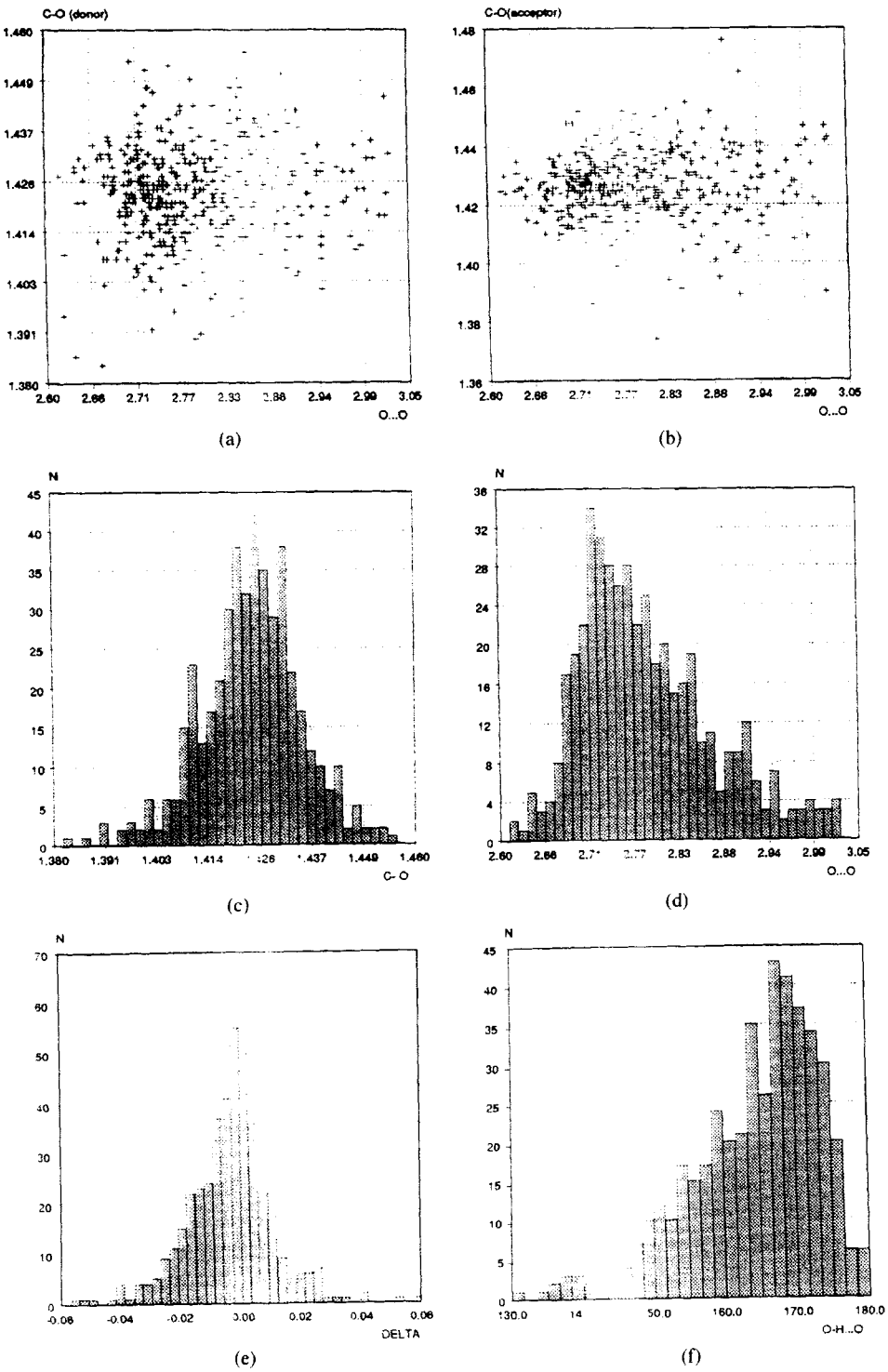


FIGURE 5 Statistical study of the C(sp^3)—OH···O—C(sp^3) fragment: (a) Scatterplot of the C—O(donor) *vs.* O···O distances, (b) same for C—O(acceptor) *vs.* O···O, (c) histogram of the C—O(donor) distance, (d) histogram of the O···O contacts, (e) histogram of (= difference values from the mean C—O distance) and (f) histogram of O—H···O angle.

tor), O···O distances and the O—H···O angle are not (skew = −0.251/−0.241, 0.729 and −0.862, respectively). Skewness and nonGaussian distribution of the values concerned here might indicate that some of the contacts in this ensemble derive from nonproductive interactions. Consequently this may smear correlation of C—O and O···O values in the data set assembled. The most probable values for the O···O and O—H···O parameters are 2.72 Å and 170°.

CONCLUSIONS

Laterally substituted derivatives of a previously introduced host compound **1** [10] derived from mandelic acid and produced in optically resolved and racemic forms **25** are shown to form crystalline inclusion complexes, thus establishing the framework of a new robust host family allowing for structural modification. Depending on the particular substituent (Me, *t*Bu, Ph, F) and on the optical species, the property of **25** to form hostguest inclusion complexes is rather different. However, in all cases the optically resolved compound is much more efficient compared to the racemic analogue, and none of the new compounds is able to compete with the unsubstituted parent host **1a** as far as the number of inclusion compounds is concerned. This illustrates superiority of **1a**, but from the selectivity point of view the substituted derivatives are more effective.

The superority of the optically resolved compounds may be interpreted from the structural results as follows. In the optically resolved free hosts (**1a**, [10] **2a**, **3a**), the molecules are arranged in columns via OH···O hydrogen bonds. However, only one hydroxyl group acts as donor and the other one is involved in OH···phenyl interactions. Thus, these structures do not meet the optimum hydrogen bonding rule in crystals recently defined by Etter [23] and others, [8] but exhibit a compromise between close packing and hydrogen bonding. In the alcohol complexes [**1a**·MeOH (1:1) [10] and **2a** Me · OH (1 : 1)], the situation improves since both hydroxyl groups of the hosts are connected through the alcohol molecules by hydrogen bonds being responsible for the formation of the supramolecular chains.

By way of contrast, in the structure of the free racemic host **1b**, previously reported, [10] hydrogen bonded dimers of enantiomeric host molecules are formed. It seems that this particular pattern is fairly stable allowing a relative densely packed crystal without having recourse to solvent molecules, thus explaining low inclusion behaviour of **1b** relative to **1a** and perhaps also of **2b** and **3b** relative to **2a** and **3a**. This is probably the situation in case of the racemic hosts and most of the strong hydrogen donor solvents (Tab. I), not competing with the dimer units, unlike the strong hydrogen acceptor solvents presumably overruling the dimer formation of hosts to give inclusion compounds. These findings suggest that other optically differentiated host compounds may have very distinct inclusion properties, such as here, stimulating further studies in this field.

EXPERIMENTAL

Synthesis

General

Melting points were taken with a Kofler hot stage apparatus. IR spectra were recorded on a Perkin-Elmer 1600 FTIR spectrometer; spectral bonds are reported in cm^{-1}. Proton NMR spectra were measured with a Varian T60A (60 MHz) spectrometer and ^{13}C NMR spectra with a Bruker MSL 300 (300 MHz) instrument; chemical shifts are reported in ppm downfield from tetramethylsilane as internal reference. Microanalyses were carried out by the Microanalytical Laboratory of the Technical University Bergakademie Freiberg.

Compounds **1a** and **1b** were prepared as described previously [10].

Compounds 2a, 2b, 3a, 3b, 4a and 5a

They were synthesized from optically resolved or racemic methyl mandelates [24] and aryllithium reagents analogous to **1a/1b** [10]. Specific details are given for each compound.

(R)2Phenyl1,1di(ptolyl)ethane1,2diol (2a)

(*R*)Methyl mandelate and 4bromotoluene were used; colourless crystals [from benzenecyclohexane, (1:1)], 34%, m.p. 150 °C, $[\alpha]^{21}_D$ + 205° (*c*1, $CHCl_3$). IR (KBr): 3510, 3476 (OH), 2922 (CH_3), 744, 700 (Ar). ^{1}HNMR (60 MHz, $CDCl_3$): 7.457.0 (m, 13H, Ar), 5.37 (s, 1H, CH), 3.02 (s, 1H, OH), 2.75 (s, 1H, OH), 2.21 (2s, 6H), MeH). ^{13}CNMR (75 MHz, $CDCl_3$): 20.9, 21, 77.8, 80.5, 126129.8, 136142.3 (19 signals). GCMS (m/z): 284 (5), 211 (100), 119 (99), 91 (40). Anal.: found: C, 83.03; H, 6.64; $C_{22}H_{22}O_2$ requires: C, 82,99; H, 6.96.

(R,S)2Phenyl1,1di(ptolyl)ethane 1,2diol (2b)

(*R,S*)Methyl mandelate and 4bromotoluene were used; colourless crystals, 55 %, m.p. 178°C. Spectroscopic data as given for the optically resolved species **2a**.

(R)1,1Bis(4tertbutylphenyl)2phenylethane1,2diol (3a)

(*R*)Methyl mandelate and 4*tert*butylbromobenzene were used; colourless crystals [from benzenenhexane, (1:1)], 62 %, m.p. 172 °C, $[\alpha]^{21}_D$ + 143° (c1, $CHCl_3$). IR (KBr): 3514, 3430 (OH), 1394, 1362 (*t*Bu), 749, 715 (Ar). ^{1}HNMR (60 MHz, $CDCl_3$): 7.467.0 (m, 13H, Ar), 5.53 (s, 1H, CH), 2.98 (s, 1H, OH), 2.45 (s, 1H, OH), 1.21 (d, 18H, *t*BuH). ^{13}CNMR (75 MHz, $CDCl_3$): 31.3, 31.4, 34.4, 34.4, 78.1, 80.6, 124128.1, 138149.9 (18 signals). GCMS (m/z): 355 (5), 295 (100), 297 (13), 161 (36). Anal.: found: C, 83.50; H, 8.04; $C_{28}H_{34}O_2$ requires: C, 83.54; H, 8.51.

(R,S)1,1Bis(4tertbutylphenyl) 2phenylethan1,2diol (3b)

(*R,S*)Methyl mandelate and 4*tert*butylbromobenzen were used; colourless crystals, 75 %, m.p. 196°C. Spectroscopic data as given for the optically resolved species **3a**.

(S)1,1Di(4biphenylyl)2phenylethane 1,2diol (4a)

(*S*)Methyl mandelate and 4bromobiphenyl were used; colourless crystals (from toluene), 40 %, m.p. 190 °C, $[\alpha]^{21}_D$ −194° (c1, $CHCl_3$). IR (KBr): 3570, 3456 (OH), 3030 (CH), 1486, 831702 (Ar). ^{1}HNMR (60 MHz, $CDCl_3$): 7.267.1 (m, 14H, BiPhH), 7.0 (s, 5H, ArH), 5.53 (s, 1H, CH), 2.43 (s, 1H, OH), 2.01 (s, 1H, OH). ^{13}CNMR (75 MHz, $CDCl_3$): 77.9, 80.6, 126131.8, 138144.1 (26 signals). GCMS (m/z): 334 (83), 257 (8), 181 (100), 152 (67). Anal.: found: C, 86.85; H 5.92; $C_{32}H_{26}O_2$ requires: C; 87.01; H, 6.23.

(S)1,1Bis(4fluorophenyl)2phenylethane 1,2diol (5a)

(*S*)Methyl mandelate and 4fluorobrombenzene were used; colourless crystals [from toluenecyclohexane (1:1)], 68 %, m.p. 133 °C, $[\alpha]^{21}_D$ −189° (c1, $CHCl_3$). IR (KBr): 3456 (OH), 3030 (CH), 1486, 831702 (Ar). ^{1}HNMR (60 MHz, $CDCl_3$): 7.686.75 (m, 13H, ArH), 5.45 (s, 1H, CH), 3.22 (s, 1H, OH), 2.44 (s, 1H, OH). ^{13}CNMR (75 MHz, $CDCl_3$): 77.9, 80.0, 114.2140.8, 163.2, 163.6 (signals). GCMS (m/z): 218 (28), 123 (100), 95 (63), 75 (21). Anal.: found: C, 73.27, H, 5.09; $C_{20}H_{16}O_2F_2$ requires: C, 73.16; H, 5.53.

Crystalline Inclusion Compounds

These were obtained by recrystallization of the corresponding host compound from a minimum amount of the respective guest solvent. The crystals formed were collected by suction filtration, washed with an inert solvent (hexane) and dried (0.5 h, 15 Torr, room temperature). The

hostguest stoichiometric ratio was determined by ^{1}HNMR integration. Data for each compound are given in Table I.

Xray Data Collection, Structure Determination, and Refinement

Single crystals of **2a**, **2a · MeOH** (1:1) and **3a** were prepared by slow evaporation of solvent from solutions of nitromethane and MeOH in the latter cases.

Crystal data, experimental details and refinement parameters are displayed in Table III. A crystal of **2a · MeOH** (1:1) was mounted in a glass capillary with solvent to prevent decomposition. Initial structure models for **2a**, **2a** · MeOH (1:1), and **3a** obtained by direct methods (SIR 92 [25]) were consecutively refined by fullmatrixleastsquares. One of the *t*butyl groups is statistically disordered in two positions with occupancy factors of 0.55(2) and 0.45(2). Hydrogen atoms were located in the

TABLE III Crystal analysis parameters

	2a	**2a · MeOH** (1:1)	**3a**
Crystal data			
Formula	$C_{22}H_{22}O_2$	$C_{22}H_{22}O_2 \cdot CH_3OH$	$C_{28}H_{34}O_2$
Crystal habit	Colourless prism	Colourless prism	Colourless prism
Crystal size (mm)	0.50 × 0.40 × 0.47	0.50 × 0.40 × 0.17	0.20 × 0.20 × 0.40
Symmetry	Orthorhombic, $P2_12_12_1$	Monoclinic, $P2_1$	Orthorhombic, $P2_12_12_1$
Unit cell determination	Leastsquares fit from 59 reflexions ($\theta < 45°$)	Leastsquares fit from 84 reflexions ($\theta < 45°$)	Leastsquares fit from 81 reflexions ($\theta < 45°$)
Unit cell dimensions (Å, °)	a = 6.1641(2) b = 19.932(1) c = 14.3469(7) 90, 90, 90	a = 13.7316(7) b = 5.8722(2) c = 12.7330(6) 90, 99.278(4), 90	a = 6.2828(3) b = 24.686(4) c = 15.000(1) 90, 90, 90
Packing: V(Å), Z	1762.8(1), 4	1013.3(1), 2	2326.6(4), 4
Dc(g/cm^3), M, F(000)	1.200, 318.42, 680	1.149, 350.46, 376	1.149, 402.58, 872
μ(cm^{-1})	5.56	5.59	5.10
T(K)	295	225	150
Experimental data			
Technique	Four circle diffractometer: Graphite monochromator: Detector apertures 1×1°;	Philips PW1 100, Bisecting geometry CuKα, $\omega/2\theta$ scans θ_{max} = 65°	
Scan width	1.5°	1.5°	1.5°
Scan speed	1 min./reflex.	0.5 min./reflex.	1.0 min./reflex.
Number of reflexions			
Independent	1733	1887	2290
Observed	1650 (3σ(I) criterion)	1823 (3σ(I) criterion)	2154 (3σ(I) criterion)
Standard reflexions	2 reflexions every 90 minutes		
	No variation	8.3%	2.5%
Solution and refinement			
Solution		Direct Methods: SIR92	
Refinement			
LeastSquares on Fo	full matrix	full matrix	full matrix
Parameters:			
Number of variables	305	338	442
Degrees of freedom	1345	1485	1712
Ratio of freedom	5.4	5.4	4.9
H atoms		From difference synthesis*	
Weightingscheme		Empirical as to give no trends in $\langle\omega^2F\rangle$ vs. $\langle\lvert Fobs\rvert\rangle$ and $\langle\sin\theta/\lambda\rangle$	
Max. thermal value (Å^2)	U11(C(17)) = 0.200(9)	U22(C(17)) = 0.101(3)	U11(C(302)) = 0.168(14)
Final ρ peaks (eÅ^{-3})	±0.20	±0.16	±0.23
Final R and Rw	0.051, 0.068	0.046, 0.053	0.048, 0.046

*See experimetal section.

TABLE IV Final atomic coordinates and Ueq[a]

Atom	*x*	*y*	*z*	Ueq
Compound **2a**				
C1	0.2626(6)	0.2298(2)	0.1687(2)	44(1)
C2	0.4281(6)	0.1955(2)	0.1024(2)	46(1)
C31	0.4451(6)	0.1205(2)	0.1149(2)	48(1)
C32	0.6370(8)	0.0925(2)	0.1447(3)	62(1)
C33	0.6596(11)	0.0232(2)	0.1550(4)	77(2)
C34	0.4880(12)	−0.0185(2)	0.1353(4)	82(2)
C35	0.2955(11)	0.0088(2)	0.1054(5)	91(2)
C36	0.2741(9)	0.0777(2)	0.0933(4)	73(2)
O4	0.0514(4)	0.2036(1)	0.1509(2)	48(1)
O5	0.3606(5)	0.2118(1)	0.0088(2)	53(1)
C11	0.2534(6)	0.3063(2)	0.1565(2)	46(1)
C12	0.4146(8)	0.3447(2)	0.1161(3)	65(1)
C13	0.3915(11)	0.4138(2)	0.1056(4)	79(2)
C14	0.2029(11)	0.4459(2)	0.1336(3)	74(2)
C15	0.0455(10)	0.4084(2)	0.1757(3)	71(1)
C16	0.0674(8)	0.3393(2)	0.1884(3)	59(1)
C17	0.1812(20)	0.5206(3)	0.1168(4)	111(3)
C21	0.3253(6)	0.2123(2)	0.2690(2)	44(1)
C22	0.5198(8)	0.2349(3)	0.3052(3)	67(1)
C23	0.5850(8)	0.2166(3)	0.3946(3)	71(1)
C24	0.4583(9)	0.1767(2)	0.4507(2)	60(1)
C25	0.2604(10)	0.1559(2)	0.4149(3)	71(1)
C26	0.1960(8)	0.1720(2)	0.3240(3)	59(1)
C27	0.5325(14)	0.1580(3)	0.5468(3)	87(2)
Compound **2a** · MeOH (1:1)				
C1	0.2968(2)	0.4903(6)	0.6494(2)	39(1)
C2	0.3948(2)	0.6259(6)	0.6607(2)	42(1)
C31	0.4688(2)	0.5631(6)	0.7581(2)	41(1)
C32	0.4858(2)	0.7133(7)	0.8430(2)	47(1)
C33	0.5558(2)	0.6657(8)	0.9313(3)	55(1)
C34	0.6098(2)	0.4677(8)	0.9358(3)	57(1)
C35	0.5935(3)	0.3159(7)	0.8518(3)	61(1)
C36	0.5230(2)	0.3632(7)	0.7628(3)	53(1)
O4	0.3174(1)	0.2500	0.6422(2)	45(1)
O5	0.4352(2)	0.5873(6)	0.5656(2)	56(1)
C11	0.2228(2)	0.5618(6)	0.5526(2)	41(1)
C12	0.2295(3)	0.7641(7)	0.4970(3)	58(1)
C13	0.1576(3)	0.8207(7)	0.4109(3)	62(1)
C14	0.0782(2)	0.6802(7)	0.3760(2)	52(1)
C15	0.0721(2)	0.4788(8)	0.4310(2)	52(1)
C16	0.1428(2)	0.4201(7)	0.5172(2)	47(1)
C17	0.0033(3)	0.7459(12)	0.2812(3)	71(2)
C21	0.2522(2)	0.5237(6)	0.7505(2)	40(1)
C22	0.2048(2)	0.7270(6)	0.7675(3)	50(1)
C23	0.1649(2)	0.7610(8)	0.8593(3)	56(1)
C24	0.1699(2)	0.5942(8)	0.9372(2)	55(1)
C25	0.2176(2)	0.3922(8)	0.9202(3)	56(1)
C26	0.2585(2)	0.3569(7)	0.8286(2)	48(1)
C27	0.1251(4)	0.6323(11)	1.0369(3)	79(1)
O6	0.3809(2)	0.2648(6)	0.4217(2)	65(1)
C7	0.3177(3)	0.3134(10)	0.3254(3)	72(2)
Compound **3a**				
C1	0.03665(36)	0.24701(10)	0.17363(13)	28(1)
C2	0.19295(37)	0.23220(9)	0.09697(13)	27(1)
C31	0.21001(40)	0.17239(10)	0.07602(14)	30(1)
C32	0.39448(48)	0.14452(12)	0.09922(18)	41(1)

TABLE IV (Continued)

Atom	x	y	z	Ueq
C33	0.41223(61)	0.08937(13)	0.07962(23)	53(1)
C34	0.24695(64)	0.06216(12)	0.03862(23)	55(1)
C35	0.06423(54)	0.09005(13)	0.01555(21)	50(1)
C36	0.04574(43)	0.14514(11)	0.03260(17)	39(1)
O4	−0.17337(23)	0.23008(7)	0.15104(10)	28(1)
O5	0.12004(24)	0.25889(7)	0.01696(9)	28(1)
C11	0.04352(38)	0.30903(10)	0.18632(13)	29(1)
C12	0.23104(42)	0.33608(12)	0.20779(21)	45(1)
C13	0.23456(43)	0.39198(13)	0.21771(22)	47(1)
C14	0.05353(41)	0.42364(11)	0.20606(15)	35(1)
C15	−0.13189(44)	0.39657(11)	0.18444(18)	40(1)
C16	−0.13764(39)	0.34027(11)	0.17440(16)	35(1)
C17	0.06486(49)	0.48574(12)	0.21547(21)	45(1)
C18	0.19841(69)	0.50821(13)	0.13790(30)	67(1)
C19	0.16994(65)	0.50068(15)	0.30365(27)	65(1)
C20	−0.15691(53)	0.51193(13)	0.21313(26)	56(1)
C21	0.09567(36)	0.21783(10)	0.26034(14)	28(1)
C22	0.30297(41)	0.21594(14)	0.29293(18)	46(1)
C23	0.34942(45)	0.19214(15)	0.37496(18)	47(1)
C24	0.19382(41)	0.16920(10)	0.42738(15)	31(1)
C25	−0.01112(41)	0.16816(11)	0.39156(18)	37(1)
C26	−0.05810(38)	0.19192(10)	0.31030(16)	33(1)
C27	0.24564(46)	0.14574(12)	0.51919(17)	41(1)
C281	0.06436(138)	0.11693(65)	0.56206(62)	85(4)
C291	0.41653(136)	0.09668(26)	0.49947(44)	64(2)
C301	0.35443(202)	0.18513(34)	0.57322(40)	80(4)
C282#	0.12269(158)	0.18443(39)	0.58999(38)	63(3)
C292#	0.47251(115)	0.15102(51)	0.54720(50)	72(3)
C302#	0.15322(344)	0.09219(39)	0.53218(73)	88(5)

[a]Ueq = $(1/3)\Sigma\ [Uij \cdot a_i^* \cdot a_j \cdot a_i \cdot a_j \cdot \cos(\mathbf{a}_i, \mathbf{a}_j)] \times 10^3$.
pp = 0.55(2), #pp = 0.45(2).

corresponding difference Fourier maps and were included isotropically in the last cycles of refinement. Some hydrogen atoms of the disordered *t*butyl group were kept fixed during the last cycles of refinement. Most of the calculations were carried out with the XRAY80 System [26] on a Vax 6410 computer. The final atomic coordinates are reported in Table IV. The atomic scattering factors were taken from the International Tables for XRay Crystallography [27].

Supplementary Material

Lists of the structure factors, atomic coordinates and thermal components for the nonhydrogen atoms and hydrogen atom parameters are available from the authors (CF).

Acknowledgements

Financial support from COST (No. CIPACT 930171) is gratefully acknowledged. E. W. also thanks the Fonds der Chemischen Industrie for financial support. O. H. thanks the State of Saxonia for a scholarship.

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