Sugar-integrated gelators of organic fluids: on their versatility as building-blocks and diversity in superstructures

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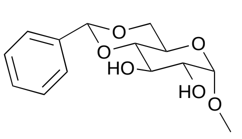
Three 1-*O*-methyl-4, 6-*O*-benzylidene derivatives of monosaccharides (D-glucose, D-galactose and D-mannose) were synthesised: they acted as versatile gelators of various organic fluids, indicating that saccharides are useful as potential building-blocks for molecular design of chiral gelators.

The development of new gelators of organic fluids has recently received much attention. They not only gelatinise various organic fluids but also create novel networks with fibrous superstructures which can be characterised by SEM pictures of the xerogels.[1–11] The gelators can be classified into two categories according to the difference in the driving force for the molecular aggregation, *viz*. hydrogen-bond-based gelators and nonhydrogen-bond-based gelators. Typical examples of the former group are the aliphatic amide derivatives,[1–4] whereas those of the latter group are cholesterol derivatives.[6–9] The superstructures of the organic gels of aliphatic amide derivatives show that they satisfy the complementarity of the intermolecular hydrogen-bonding interactions.[5–9] This observation stimulated us to use saccharides as a hydrogen-bond-forming segment in the gelators, because one can easily introduce a variety of hydrogen-bond-forming, chiral segments into gelators by selection from a saccharide library. In the literature examples of saccharide-containing gelators are very limited in spite of their high potential.[8,12] We synthesised glucose-based **1**, galactose-based **2** and mannose-based **3** and studied their gelation abilities. We found that the gelation properties, such as gel stability, superstructure and solvent-dependence, were profoundly related to the saccharide structure.



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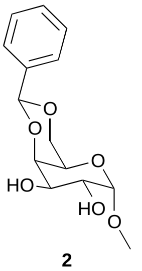

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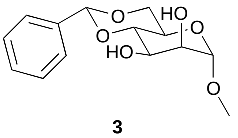

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The synthesis of **1** has already been reported.[13] Gelators **2** and **3** were synthesised in a similar manner by treatment of the saccharide with benzaldehyde and $ZnCl_2$. The products were identified by ^1H NMR and IR spectroscopy and elemental analyses.

The gelation test was carried out as follows: the gelator (**1–3**: 3.0 mg) was mixed with solvent (0.10 ml) in a septum-capped test tube and the mixture was heated until the solid dissolved. The solution was cooled to room temperature and left for 1 h (G in Table 1 denotes that a gel was formed at this stage). Some solutions gelatinised at a gelator concentration below 1.0 wt% (SG or super-gelator; Table 1). Solvents in Table 1 are those which were gelatinised by either **1**, **2** or **3**.[14] Table 1 reveals that, in general, **2** acts as an excellent gelator of many organic fluids. In contrast, comparison of the gelation ability for *n*-heptane and cyclohexane reveals that **1** is more cohesive and tends to form a precipitate, whereas **3** is more soluble than the other two gelators and is frequently unable to coagulate in solution.

What is the origin of the difference in their gelation ability? The sole structural difference among **1**, **2** and **3** is the absolute configuration of C-2 and C-4. It is reasonable to assume that **1**, **2** and **3** show a different ability to form a gel network because of the different intermolecular hydrogen-bonding interactions. In the FT-IR spectra, the gel solutions gave two peaks (3473–3240 and 3576–3659 cm^{-1}) in the ν_{OH} region which could be assigned to hydrogen-bonded OH and free OH groups, respectively. As shown in Fig. 1, the peak intensity ratio (R) of hydrogen-bonded OH *vs*. free OH abruptly increased at the sol-gel phase-transition concentration. Furthermore, the largest R value was observed for **2**, which also features the greatest gelation ability. In contrast, the peak arising from hydrogen-bonded OH groups was hardly observed for **3** up to 0.5 wt%, indicating that **3** is too soluble to use as a good gelator. These FT-IR spectral data consistently indicate that the gel network in the present system is primarily constructed by intermolecular hydrogen-bonding interactions. A computational study (MOPAC 93 included in CS CHEM3D) indicated that the

Table 1 Organic fluids tested for gelation by **1–3**[a]

Organic fluid	1	2	3
n-Hexane	SG	SG	SG
n-Heptane	P	SG	SG
n-Octane	SG	SG	SG
Cyclohexane	P	SG	SG
Methylcyclohexane	SG	SG	SG
Benzene	G	SG	P
Toluene	SG	SG	SG
p-Xylene	SG	SG	SG
CCl_4	SG	SG	P
CS_2	P	SG	SG
Et_2O	G	SG	P
Ph_2O	SG	SG	G
n-Octanol	S	G	S
Et_3N	S	G	S
Et_3SiH	P	Gp	SG
$(EtO)_4Si$	P	SG	P
H_2O	P	S	G

[a] G = gel; SG = supergel; Gp = partial gel; P = precipitation; S = solution.

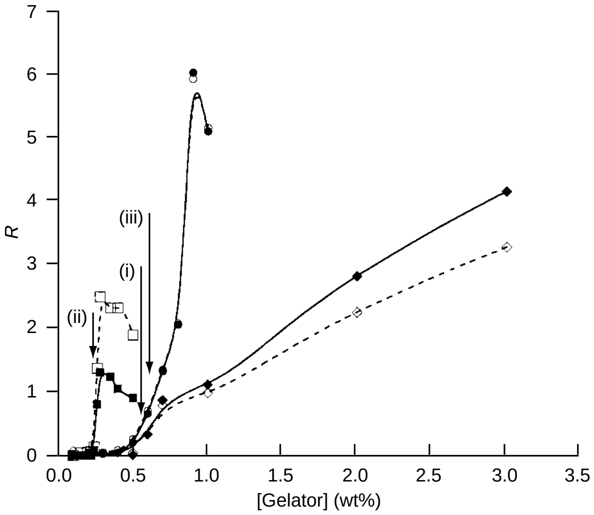

Fig. 1 Plot of the peak intensity ratio (*R*) of hydrogen-bonded OH groups *vs.* free OH groups as a function of [gelator] in toluene at 20 °C. There are two major peaks for hydrogen-bonded OH groups: the filled points were obtained from the intensities at ν_{OH} 3312–3240 cm^{-1}, whereas the open points are obtained from those at ν_{OH} 3473–3350 cm^{-1}; (○,●) **1**, (□,■) **2** and (◇,◆) **3**. The arrows indicate the sol-gel transition temperatures of (i) **1**, (ii), **2** and (iii) **3**.

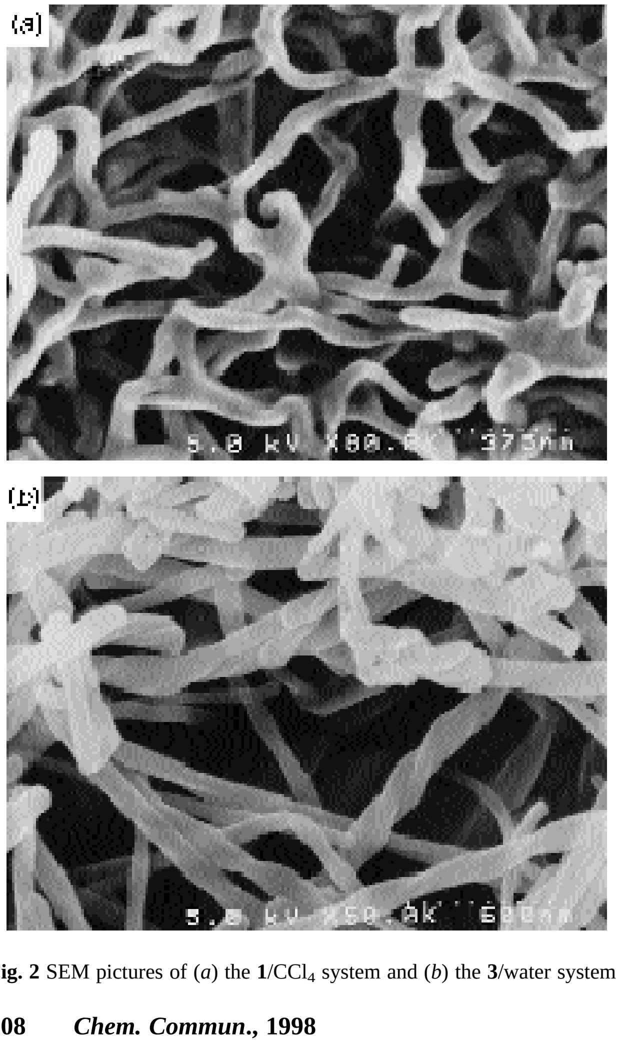

Fig. 2 SEM pictures of (*a*) the **1**/CCl_4 system and (*b*) the **3**/water system

intramolecular hydrogen-bonding distance (H···O) between 3-OH and 4-OR of the saccharides is not significantly different (*e.g.* 2.5 Å for **1** and 2.38 Å for **2**). This suggests that the differences in gelation ability are not due to the presence of a special OH group useful for intermolecular hydrogen-bonding, but rather is due to a structural preference in the molecular aggregation. We now consider that **2**, which has the benzylidene group and the pyranose ring arranged at almost a right angle, is able to enjoy both a benzene–benzene π–π stacking interaction and an OH–OH intermolecular hydrogen bonding interaction, whereas **1** and **3**, which are flatter than **2**, cannot enjoy both interactions simultaneously.

To obtain visual insights into the aggregation mode, we prepared a dry sample for SEM studies.[15] Fig. 2(*a*) shows a typical picture obtained from the xerogels of **1** or **2**. It is clear that the gelator forms a three-dimensional network with 50–200 nm frizzled fibrils. On the other hand, the fibrils obtained from the toluene gel of **3** are more linear (the picture is not shown here). Very interestingly, the fibrils obtained from the aqueous gel of **3** show a regular left-handed helical structure [Fig. 2(*b*)]. Presumably, in an aqueous system the balance between the hydrogen-bonding interaction and the hydrophobic interaction is different from that in other, organic media.

In conclusion, the present study has demonstrated for the first time that saccharides are promising building-blocks for new gelators with different gelation abilities and different three-dimensional network structures. We believe that such versatility of synthesis and diversity of products (including the creation of the helical structure) cannot be attained in a more simple fashion than with saccharides as building-blocks.

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14 The following solvents were also tested, but **1**–**3** were soluble in these solvents and gels were not formed: nitrobenzene, *m*-cresol, 1,2-dichloroethane, CH_2Cl_2, $CHCl_3$, THF, dioxane, MeOAc, diethyl malonate, acetone, ethyl methyl ketone, DMA, DMF, DMSO, NMP, MeCN, MeOH, EtOH, BnOH, AcOH, Ac_2O, $PrNH_2$, Et_2NH, $PhNH_2$, pyridine, 2,2,2-trifluoroethanol and glycerol.

15 For the preparation of dry samples for SEM observations, see ref. 7 and S. W. Jeong and S. Shinkai, *Nanotechnology*, 1997, **8**, 179.

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