

# Anion binding inhibition of the formation of a helical organogel†

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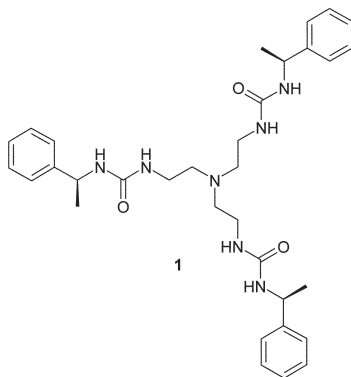
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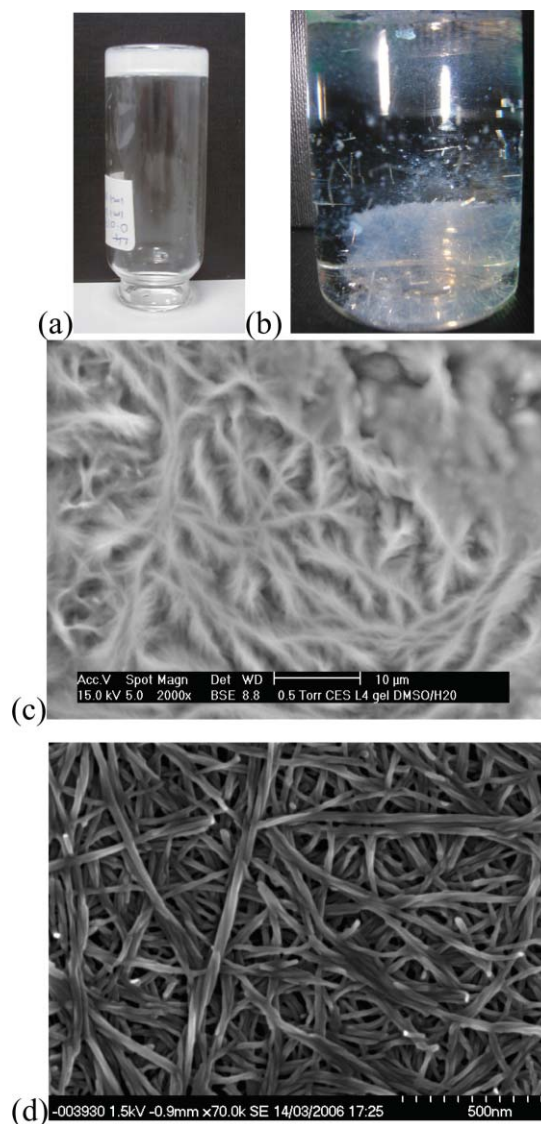
A chiral tris(urea) organogelator gels dmsO–water and methanol–water mixtures at low weight percent. The formation of the helical gel fibres is partially inhibited by addition of chloride, which is bound by the gelator, resulting in fully crystalline material characterised by X-ray crystallography

The phenomenon of gelation may be understood as a form of arrested or partial crystallisation.<sup>1</sup> Recently, there has been a surge of interest in low molecular weight gelators (LMWGs), a class of organic small molecules that form gels *via* supramolecular interactions.<sup>2–9</sup> Supramolecular two-component LMWG systems<sup>4</sup> and metallogels based on coordination complexes<sup>5,10–12</sup> have also been reported. In addition chiral LMWGs are known in which the molecular chirality results in nanoscale helicity in the gel fibres.<sup>2,13–19</sup> Bis- and tris(urea) LMWGs, particularly bearing long alkyl substituents, have proved to be highly effective gelators.<sup>8,9,20–23</sup> Unrelated to gel formation, the tris(urea) motif has also been used in a number of effective supramolecular hosts for anions.<sup>24–26</sup> We now report a system in which LMWG self-association and LMWG–anion interactions are in competition with consequent effects on the behaviour and properties of the gel phase.



The enantiomerically pure tris(urea) (**1**) was prepared by reaction of tris(2-aminoethyl)amine with (*S*)-(-)- $\alpha$ -methylbenzyl isocyanate. A chiral gelator was chosen in the anticipation that the chirality of the LMWG would be expressed in the gel structure yielding information about inter-gelator interactions. Compound **1** forms stiff, opaque thermoreversible gels in aqueous methanol and

aqueous DMSO (1 : 1 v/v) over a period of *ca.* 5 min above 0.3 wt% (Fig. 1(a)). This contrasts to a range of achiral tris(urea)s that do not gel DMSO or methanol but do gel other solvents.<sup>23</sup> The initiation of gel formation in the methanol system may be markedly accelerated by sonication,<sup>27,28</sup> however gelation does not go to completion in the ultrasonic bath, presumably because of



**Fig. 1** (a) Hydrogel formed from a solution of **1** in DMSO–water (1 : 1 v/v), (b) mixed gel and single crystal formed from water–methanol with NaCl, (c) ESEM image of the partially dried gel, (d) SEM of the xerogel showing the helical fibrous structure.

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shear stresses on the developing supramolecular gel network. The sol–gel transition temperature,  $T_{\text{gel}}$ , was measured using the ‘tilted tube’ method and increases regularly with concentration of **1** reaching a limit at 116 °C from a 0.0170 M gel of **1** in DMSO–water.

Frequency sweep rheometry measurements, with a small amplitude stress, indicate that the storage modulus,  $G'$ , remains constant with increasing angular frequency. Such linear viscoelastic behaviour is associated with classical gels, and supports the belief that these materials undergo a transition to a true gel state. The storage modulus scales with concentration,  $c$ , as  $G' \propto c^{1.9 \pm 0.1}$ , in good agreement with previous work.<sup>29,30</sup> The non-linear rheological response was probed using large amplitude stress sweep experiments, during which an oscillatory stress is imposed with a fixed frequency (1 Hz) over a range of shear stress amplitudes. Below a critical value of shear stress, the yield stress,  $\delta^*$ , the storage modulus remains constant. Above the yield stress,  $G'$  decreases rapidly, suggesting that the gel has collapsed. The yield stress scales with concentration as  $\delta^* \propto c^{1.4 \pm 0.03}$ , again in agreement with the work of Terech *et al.*<sup>29</sup>

Sangeetha *et al.*<sup>30</sup> discussed two quantitative theoretical frameworks for the mechanical properties of molecular gels, based on concepts developed to describe either colloidal gels or cellular solids. A colloidal gel is modelled as comprised of flocs with a fractal dimension,  $d_f$ , which reflects how the mass of colloidal material within a floc scales with floc size, connected by interfloc links.<sup>31</sup> The dependence of the mechanical properties on concentration is determined by the relative strength of interactions between flocs and within flocs. In the strong-link regime, the former dominate and the following is predicted,

$$G' \propto c^{(3+x)/(3-d_f)}; \delta^* \propto c^{-(1+x)/(3-d_f)} \quad (1)$$

where  $x$  is the fractal dimension of the elastically effective number of interactions within a floc. In the weak-link regime, intrafloc interactions dominate and the following is predicted,

$$G' \propto c^{1/(3-d_f)}; \delta^* \propto c^{1/(3-d_f)} \quad (2)$$

From eqn (1) and (2), it is clear that the strong-link model permits agreement with the experimentally observed scaling of the shear modulus, but only if  $x = d_f = 1$ .<sup>30</sup> Both these latter conditions are inconsistent with the model of an interconnected fractal colloidal gel,<sup>31</sup> which requires that (i)  $x$  be less than the fractal dimension,  $d_f$ , and (ii) in order to ensure connectivity between flocs,  $x$  must be greater than unity. Furthermore, neither model is able to correctly predict the scaling of the yield stress, regardless of the fractal dimension. Hence, we believe that the mechanical properties of small molecule gelators cannot be described by analogy with colloidal gels.

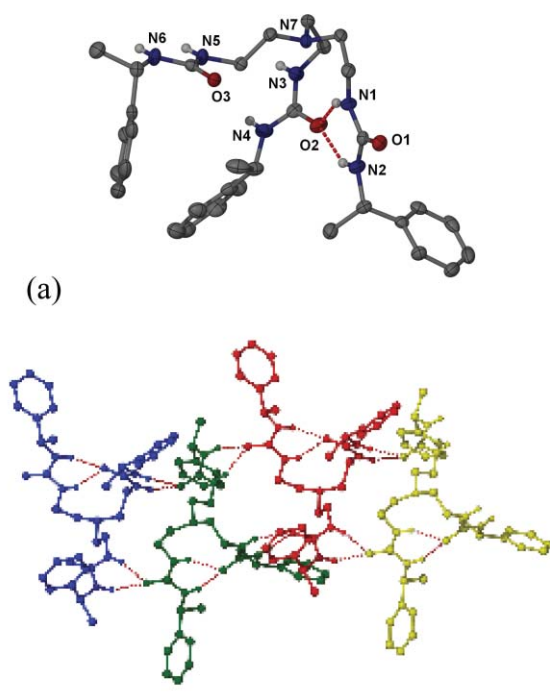
The cellular solid model<sup>32</sup> appears a more promising framework. For open-cell cellular materials, which consist of, load-bearing struts interconnected *via* crosslinks or junction points, which deform by bending, this model predicts  $G' \propto c^2$ , in good agreement with our observations. For a wide range of materials with a wide range of cellular concentrations,  $G' \approx 3E_S(c/\rho_S)^2/8$ ,<sup>33</sup> where  $E_S$  is the Young’s modulus of the struts and  $\rho_S$  the density within the struts. From the crystallographic data (*vide infra*),  $\rho_S = 1.171 \text{ g cm}^{-3}$ . The Young’s modulus of the individual fibres is  $E_S \sim 1.2 \text{ GPa}$ , comparable to values associated with the

macroscopic mechanical behaviour of semi-crystalline polymers. The scaling of the yield stress with concentration according to the mechanism of failure of the cellular material has been studied.<sup>32,33</sup> If the struts buckle during deformation (elastic collapse), then  $\delta_{\text{el}}^* \approx 0.05E_S(c/\rho_S)^2$ , whereas if plastic collapse occurs (*i.e.*, the struts exhibit plastic deformation), then  $\delta_{\text{pl}}^* \approx 0.3\delta_S(c/\rho_S)^{1.5}$ , where  $\delta_S$  is the plastic yield stress of the individual struts. By comparing the two scaling laws with our results, and by noting that our values for the yield stress are roughly an order of magnitude less than the predicted yield stress for elastic collapse, it seems that the mechanism of plastic collapse agrees well with our observations and hence  $\delta_S \sim 1.4 \text{ MPa}$ .

The partially dried gels were imaged by environmental SEM which shows a well-defined dendritic, feathery type structure (Fig. 1(c)). The dried xerogel was also examined by SEM which shows a network of monodisperse left handed helical fibres *ca.* 30 nm wide, some grouped into larger bundles, Fig. 1(d). The helical pitch is variable in the larger scale bundles although there is some sign of very small pitch helicity within the smallest fibres. It is unclear whether the helical twisting arises from the molecular chirality or an anisotropy of the interfacial energy.<sup>21</sup> Low-temperature DSC measurements on the methanol–water gel showed a glass transition at –46 °C. Two distinct freezing exotherms at –122 and –81 °C were observed during the cooling cycle which might be attributable to free solvent (sharp peak at –122 °C) and solvent included within the gel matrix (broader peak at –81 °C) (see ESI†).

Anion binding by **1** was probed by <sup>1</sup>H NMR titrations with the tetrabutylammonium salt of  $\text{Cl}^-$  in DMSO- $d_6$  solution. The binding isotherm was fitted readily to a 1 : 1 binding stoichiometry. Compound **1** binds  $\text{Cl}^-$ ,  $K_{\text{assoc}} = 1154 \text{ M}^{-1}$ , in line with previously reported related compounds.<sup>24,34</sup> The effect of anion binding on the gelation process was monitored by repeating the gelation experiments in the presence of stoichiometric amounts of NaCl at various concentrations, and in excess. The NaCl markedly retarded the rate of the gelation process and decreased the amount of the solvent incorporated into the gel phase. Surprisingly concomitant formation of gel and crystalline material was invariably observed (Fig. 1(b)). The crystalline material was characterised by X-ray crystallography which revealed it to comprise solely ligand **1**. Thus the  $\text{Cl}^-$  binds to the gelator **1** (as indicated by the NMR experiments) and promotes crystallisation but the material does not crystallise as the NaCl complex under these conditions.

The X-ray structure of **1** is shown in Fig. 2.‡ Compound **1** adopts a needle morphology, crystallising in the chiral space group  $P2_12_12_1$  forming polar stacks of molecules along the crystallographic  $b$  direction, without any molecular symmetry. Molecules within the stacks are linked by two six-membered hydrogen bonded ring interactions involving two pairs of urea groups, reminiscent of the urea tape motif. The third urea group is involved in an intramolecular hydrogen bonded ring of the same type, aligned in the same direction. This type of interaction has been postulated to be responsible for gel fibre formation in bis(urea)s.<sup>21</sup> If the X-ray crystal structure is taken as a starting model for the gel fibres then the fibres of width 30 nm would comprise collinear bundles of *ca.* 15–25 stacks of unit cell cross section  $1.25 \times 2.0 \text{ nm}$ . The fact that the chirality of the individual stacks is reflected in the left handed helicity of the fibres (Fig. 1(d))



**Fig. 2** (a) Molecular structure of **1** determined by X-ray crystallography (50% ellipsoids), (b) crystal packing in **1** to give chiral stacks linked by a single urea hydrogen bond.

suggests that all of the stacks are orientated in the same direction. It is thus possible to propose a model for gelation in which gel fibre growth along the stack axis, promoted by strong urea–urea hydrogen bonding interactions, is very rapid and results in fibres long enough to entangle in the time taken to reach the optimum fibre width by van der Waals packing. Fibre branching to produce a dendritic 3D network (Fig. 1(c)) is possible by occasional cross-linking involving breaking the intramolecular urea–urea hydrogen bond to form a second intermolecular interaction. Dynamic chloride binding to the three urea groups would significantly retard the rate of stack growth along the fibre axis resulting in the observed needle crystals with a much lower length : diameter ratio. Face indexing of the crystal confirmed that the *b* axis along which the urea hydrogen bonding is orientated corresponds to the long axis of the needle shaped sample.

In conclusion we have demonstrated that molecular properties such as anion binding affinity and chirality are reflected in the gelation behaviour of LMWG compound **1**. Addition of  $\text{Cl}^-$  tips the system from gelation into full crystallisation and suggests a close correspondence in the gel fibre and single-crystal structures. The mechanical properties of these kinds of small molecule gel systems cannot be described by analogy with colloidal gels and a cellular solid model is more appropriate. This research offers an insight in to new ways to manipulate, control and understand the phenomenon of gelation by low molecular weight compounds and paves the way for tailored gels with novel properties.

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‡ See ESI for crystallographic data. CCDC 604537. For crystallographic data in CIF or other electronic format see DOI: 10.1039/b606373j

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