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Preparation and gelling properties of sugar-contained low-molecular-mass gelators: Combination of cholesterol and linear glucose

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ABSTRACT

Four novel amphiphilic cholesterol-based and sugar-contained low-molecular-mass gelators (LMMGs) were designed and prepared. According to the structures of the linkers, which are ethylenediamine, 1,3-propanediamine, 1,4-butanediamine, and 1,6-hexane- diamine, these compounds are denoted as **1**, **2**, **3** and **4**, respectively. Gelation tests revealed that **2**, **3** and **4** start to gel xylene at concentrations of 0.090%, 0.022%, and 0.016% (w/v), respectively, which are typical 'super-gelators'. Moreover, these xylene gel systems also possess film formation property. Scanning electron microscopy (SEM) measurements demonstrated that the aggregation behaviors of the compounds are greatly affected by the structures of the linkers. ^{1}H NMR spectroscopy studies revealed that intermolecular hydrogen bonding formation plays an important role for the formation of the gels. X-ray diffraction (XRD) studies showed that **1** possesses a layered structure in its 1-pentanol gel, a similar structure to that of it in solid state. Gelator **3** also possesses a similar structure in its THF gel, but different from that of it in solid state. Transmission electron microscopy (TEM) observation revealed the helical nature of the nanobelt assemblies of **1** in its 1-pentanol gel.

1. Introduction

Unlike chemical gels, physical gels only involve non-covalent interactions (e.g., hydrogen bonding, π–π stacking, van der Waals interaction, coordination interaction, etc.) between gelator molecules. Generally speaking, these gels are thermo-reversible and display fascinating properties of both fundamental and practical values including drug delivery devices,[1] gel electrolyte based batteries,[2] scaffolds for tissue engineering,[3] and mild separation,[4] etc.

Within the physical gels, the gelators could be polymers, inorganic micro- nano- particles, and low-molecular mass compounds, which are called low-molecular-mass gelators (LMMGs). LMMGs are more attractive than others due to a number of reasons: (1) dissolution of the gels formed by them may result in solution of similar viscosity to pure solvent; (2) these gelators are much easier to be modified and created, and thereby much more gelators and gels can be developed; (3) these gelators are, at least in theory, degradable and combustible, which bring gels more chances in real-life applications.

According to the nature of driving forces of molecular aggregation, LMMGs can be classified into two categories: non-hydrogen-bond based gelators and hydrogen-bond based gelators. Some cholesterol-based gelators, falling within the former group, have attracted great attention in recent years.[5] This is because cholesterol is hydrophobic and possesses a rigid skeleton, several sterogenic centers, and a strong tendency to form aggregates via van der Waals interactions.[6] Sugar-contained gelators, having rich OH groups, are typical hydrogen-bond based gelators.[1f,7] Linear sugar, which contains five free OH groups, has been used to make special amphiphilic gelators. The first LMMG containing linear sugar was reported by Helfrich and co-workers.[8] They found that the compound possesses different assembled structures in different solvents. The helices of unknown multiplicity were seen in its hydrogels and the rolling up of multilayer sheets were seen in its 1,2-xylene gels. George and co-workers prepared a series of gelators containing linear sugar, and these gelators demonstrated very special self-assembling behaviors both in protic and aprotic solvents.[9] They generated a library of assemblies ranging from fibers that lacked structural regularity to highly uniform nanotubes. Kimizuka and co-workers prepared a series of compounds containing linear sugar, and demonstrated that these compounds can gel ionic liquids.[10] Morphological studies showed that the gelator molecules self-assembled into three-dimensional fibrous structures. Based upon these discoveries, it is reasonable to anticipate that combination of cholesterol–cholesterol interaction and hydrogen bonding interaction between sugar molecules may result in gelators with improved properties, particularly uncommon ambidextrous gelators, which gel both protic and aprotic solvents. Shinkai and co-workers reported some disaccharide

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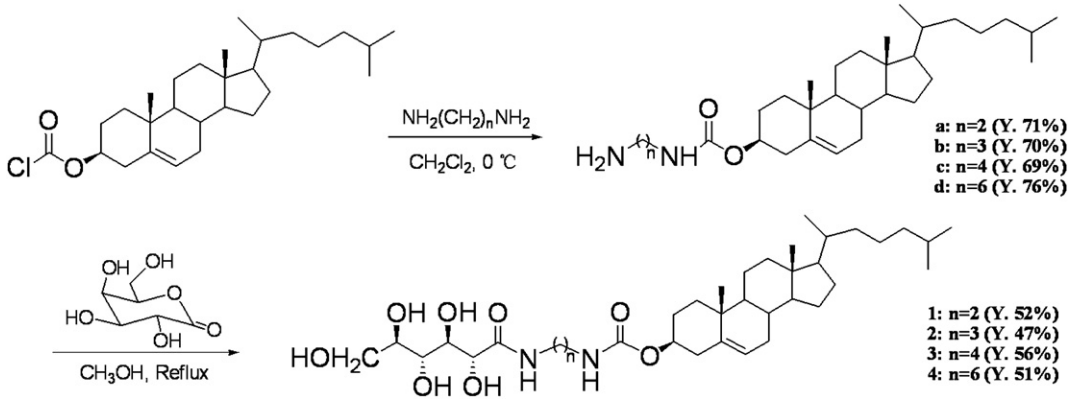
amphiphiles containing cholesterol residue and examined their hydrogelation abilities.[11] They employed a combinatorial method to solve the difficult to clarify how the OH groups in the saccharide moiety take part in the intermolecular hydrogen-bond formation. They found that cholesterol-saccharide conjugates can act as excellent gelators. Recently, our group reported a compound containing cholesterol unit and a linear sugar unit, which exhibits certain gelation behaviors and gels as formed are transparent.[12] However, the gelation behavior of this compound is not as great as we expected. Meanwhile, to our knowledge, there is no more report about gelators containing both a cholesterol unit and a sugar unit, and thereby four new cholesterol-based and sugar-contained compounds were designed and prepared (cf. Scheme 1). The gelling performances of these compounds were investigated. This paper reports the details.

of them. Furthermore, increasing the linker length also increases the possibility to form transparent gels. For example, **1**/xylene is a turbid gel, but similar systems of **2**, **3**, and **4** in xylene are transparent gels. In fact, among the systems studied, the number of transparent gels formed by compounds **1**, **2**, **3**, and **4** are 0, 1, 4, and 6, respectively. A gel with a shorter linker must be turbid if a similar gel containing a gelator with a longer linker is turbid. In other words, only the later gel is transparent, the former one has a chance to be transparent.

To further understand the gelation behavior of the compounds, their critical gelation concentrations (cgc) in benzene, $CHCl_3$, toluene, and xylene were studied. The results are listed in Table 2. Reference to the Table, it is shown that the cgc values for **2**, **3**, and **4** in xylene are only 0.090%, 0.022%, and 0.016% (w/v), respectively, which are significantly lower than 0.1% (w/v), a well recognized



Scheme 1. Schematic representation of the synthesis of the sugar-contained compounds.

2. Results and discussion

2.1. Molecular design

The amphiphilic compounds designed as potential gelators are composed of three parts: the cholesteryl unit, the diamine-contained linker unit and the linear-glucose unit. The sugar unit is intentionally introduced in order to bring more hydroxyl groups into the compounds, which are expected to increase the solubility of the final compounds in polar solvents and to create sites for hydrogen bonding formation. As demonstrated in literatures, cholesterol has a strong tendency to aggregate in various organic solvents through van der Waals interaction between the molecules containing it.[5b,6,14] Diamine was applied both for the purpose of systematic adjusting the space between the cholesteryl unit and the sugar unit, and for the convenience of chemical combination of the two units as mentioned. On the basis of the above considerations, four novel amphiphilic cholesterol-based and sugar-contained low-molecular-mass gelators (LMMGs) with organic diamines, which are ethylenediamine, 1,3-propanediamine, 1,4-butanediamine, and 1,6-hexanediamine, respectively, as linkers connecting the two units were designed and prepared. According to the structures of the diamines, these compounds are denoted as **1**, **2**, **3** and **4**, respectively.

2.2. Gelation behaviors of the compounds

The gelation behaviors of compounds **1**–**4** were tested in 26 solvents at a concentration of 2.5% (w/v), and the results are summarized in Table 1. Reference to the Table, it can be seen that compound **1** gels 12 solvents including both protic and aprotic solvents, such as alcohols, xylene, and DMF. Compounds **2**, **3**, and **4** also show similar gelation behaviors. The number of solvents gelled by the compounds increases along with increasing the linker length

Table 1
Gelation behaviors of compounds **1**–**4** in various solvents (2.5%, w/v)

Solvents	1	2	3	4
$CHCl_3$	I	I	G(rt)	TG
Benzene	I	I	I	TG
Toluene	I	I	TG	TG
Xylene	G	TG	TG	TG
DMF	G	S	S	S
Ethyl acetate	I	I	PG	PG
TEA	I	I	G	G
THF	I	G	TG	TG
Methanol	G	PG	G	PG
Ethanol	G	PG	G	PG
1-Propanol	G	PG	G	PG
1-Butanol	G	PG	G	G
1-Pentanol	G	G	G	G
1-Hexanol	G	G	G	G
1-Heptanol	G	G	G	G
1-Octanol	G	G	G	G
1-Nonanol	G	G	G	G
1-Decanol	G	G	TG	TG
p-Xylene	G	TG	TG	TG
o-Xylene	G	G	TG	TG

TG=transparent gel, I=insoluble, S=solution, PG=partial gel, P=precipitate.
Xylene used in the test is a mixture of *o*-xylene, *m*-xylene, and *p*-xylene (6.7, 85.3, and 7.8%, v/v).

Table 2
Critical gelation concentrations (cgc, %, w/v) of gels of compounds **1**–**4** in different solvents

Solvents	1	2	3	4
Benzene	—	—	—	0.03
$CHCl_3$	—	—	2.30	0.30
Toluene	—	—	0.16	0.13
Xylene	1.20	0.09	0.022	0.016

critical value for 'super-gelators'.[15] Meanwhile, compound **4** is also a 'super-gelator' of benzene. It is to be noted that **3** gels $CHCl_3$ at room temperature. The cgc values and the number of solvents gelled demonstrate clearly that the longer the linker the stronger the gelling ability of the compound is (cf. Tables 1 and 2). This result may be understood by considering the balance between dissolution and precipitation, which is a necessity for the formation of gel networks. Clearly, longer linker contains more methylene unit, which favors dissolution of the compound in hydrophobic solvents. This explanation is supported by the experimental results shown in Table 2. It is seen that **1** and **2** are insoluble in three of the four hydrophobic solvents tested, **3** insoluble in one of the solvents tested, but **4** forms gels in the solvents. This explanation is also supported by the gelation test conducted in DMF (cf. Table 1). It can be seen that **1** gels the solvent, but the others are soluble in it, suggesting destroy of the dissolution and precipitation balance, a possible result of too many methylene units. More interestingly, supramolecular gel films can be easily prepared by injecting a hot xylene solution of **2**, **3** or **4** into a film mold and then cooling the system to room temperature. These films are stable in wet state, and even can be slightly stretched as shown in Figure 1, a third example of LMMGs-based supramolecular gel films reported.[16]

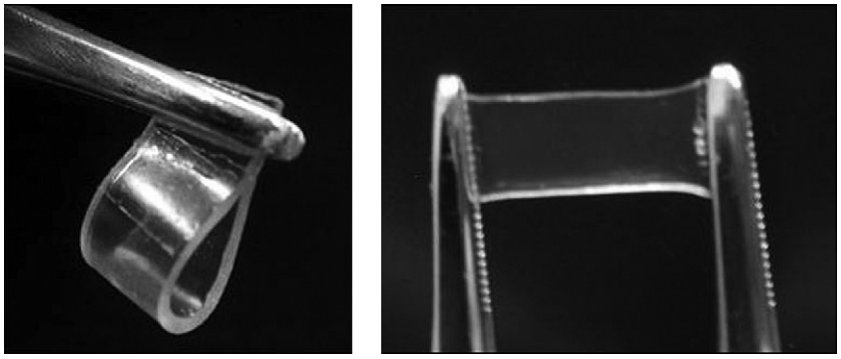


Figure 1. Photographs of the gel films of **2**/xylene.

2.3. Thermostability studies

Good thermostability is necessary for real-life applications of a gel. For a specific system, this stability can be expressed by its solution-to-gel or gel-to-solution phase transition temperature (T_{gel}). As examples, the T_{gel} values of **1**, **2**, **3**, and **4** in xylene were measured as functions of gelator concentrations. Figure 2 shows the results of the measurements. Examination of the plots reveals that the stability of each gel is very dependent upon the concentration of the gelator. For the systems and gelator concentrations studied, the T_{gel} for each gelator increases linearly along with increasing its concentration in the system. Further examination of the data shown the plots, it is seen that the thermostability of the gel systems containing **4** are always superior to those containing other gelators. For example, at a concentration of 2.5% (w/v), the values of T_{gel} for **1**/xylene, **2**/xylene, **3**/xylene and **4**/xylene are 80 °C, 108 °C, 116 °C and 120 °C, respectively. Again, compound **4** is a superior gelator to others.

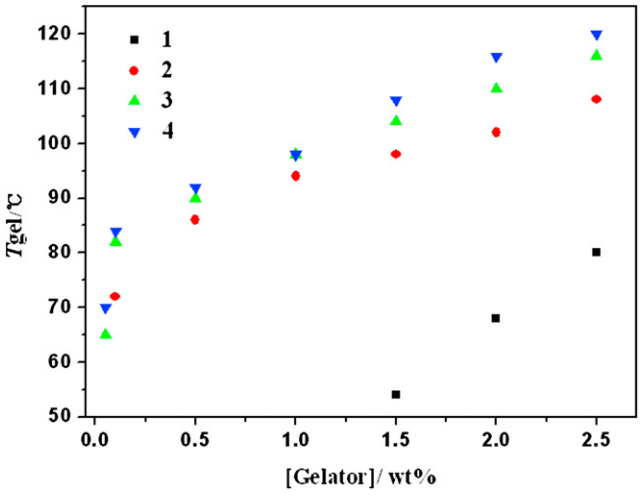


Figure 2. Gel-to-sol transition temperatures (T_{gel}) as functions of gelator concentrations in xylene.

2.4. SEM studies

The network structures of the gels were studied by SEM observation of their xerogel morphologies. Some typical SEM images of them are shown in Figure 3. Examination of the images reveals that **1** aggregated into long, rigid nanobelts in its xylene gel (cf. Fig. 3a), but **2** aggregated into plicate entangled network structures in the same solvent (cf. Fig. 3c). With further increasing the length of the linkers, the xerogel losts entangled structure, but instead occupies a flat, structure-less morphology (cf. Fig. 3e). For **4**/xylene system, the xerogel is characterized by interwoven fibrous structures as shown in Figure 3f. These observations may be understood by considering the length of the linker between the cholesterol unit and the glucose unit of a gelator, which are the two main structures determining the aggregation of the gelator molecules. It should be no difficult to understand that a longer linker must provide the molecules more freedom to form stable aggregates, a necessity for the formation of gel networks. This explains also the stronger gelation abilities of the compounds of longer linkers. Further examination of the morphologies of the xerogels indicates that the nature of the solvents has little effect upon the structures of the gel networks as evidenced by the similarities between the morphology of **1**/xylene and that of **1**/1-pentanol or between **2**/xylene and **2**/1-pentanol. This dominate effect can be attributed to the strong interaction between the gelator molecules.

2.5. Rheological studies

To evaluate the effect of linker length upon the mechanical properties of the gels formed in the same solvent, the rheological properties of the gels of **1**, **2**, **3**, and **4** in xylene (1.5%, w/v) were examined. The storage modulus, G', was measured as a function of shear stress at room temperature. The results are shown in Figure 4. Comparison of the G' values of the gels indicates that generally speaking the storage modulus of a gel increases along with increasing the linker length of the gelator. Among them, it is apparent that the value of **4** is apparently larger than that of **1**.

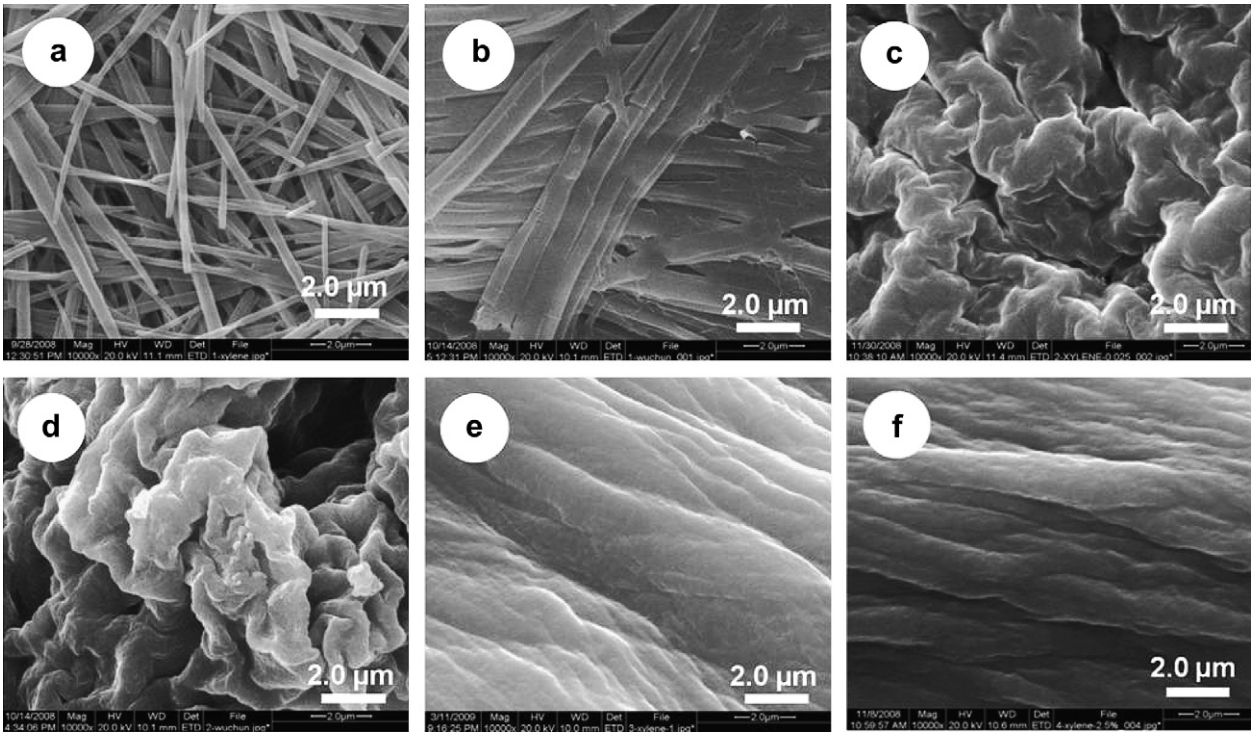


Figure 3. SEM images of the xerogels from **1**/xylene (a), **1**/1-pentanol (b), **2**/xylene (c), **2**/1-pentanol (d), **3**/xylene (e) and **4**/xylene (f) gels (2.5%, w/v).

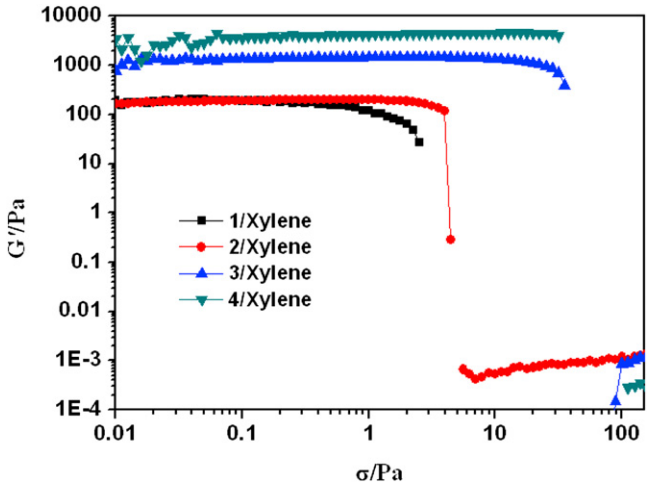


Figure 4. Evolution of G' as a function of the applied shear stress. Samples used are the gels of **1**, **2**, **3**, and **4** in xylene (1.5%, w/v).

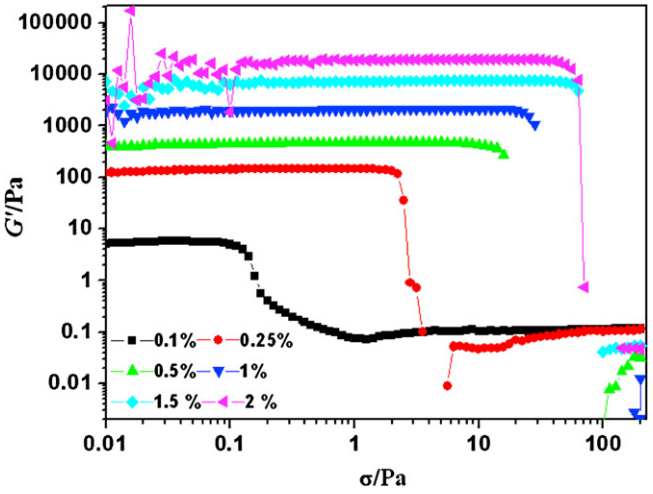


Figure 5. Evolution of G' as a function of the applied shear stress at different concentrations of **4** in xylene.

Furthermore, the yield stresses of the gels are also dependent upon linker lengths of gelators. Similarly, longer linker corresponds to larger value of the yield stress. But, there is a limit as shown by the fact that the yield stress of the gel system of **3**/xylene is almost the same with that of **4**/xylene. These results demonstrate clearly that the linker length of the gelators has a significant effect upon the mechanical properties of the resulting gels.

To further elucidate the importance of gelator concentration to the rheological properties of a supramolecular gel, the G' values of **4** in xylene at different concentrations are measured as a function of shear stress and the results are shown in Figure 5. From the Figure, it can be seen that the value of G' increases from a few Pas to more than ten thousand Pas along with the gelator concentration increases from 0.1% to 2% (w/v). Likewise, the yield stress changes from 0.12 to 63.08, indicating that both the stability of the gel network and the elastic property of the gel well depend upon the concentration of the gelator in the solvent. It is to be noted, however, that the stability (yield stress) of the gel does not increase further when the concentration of the gelator exceeds a critical value. For present system of **4**/xylene, the value is close to 1.5% (w/v).

2.6. ^{1}H NMR studies

It is well known that, similar with other non-covalent interactions between molecules, hydrogen bonding is a commonly encountered driving force for the formation of supramolecular gels of LMMGs.[17] Considering the molecular structures of the gelators prepared in the present work, it is anticipated that hydrogen bonding might have played some roles for the formation of the gels listed in Table 1. To elucidate this hypothesis, temperature- and concentration-dependent ^{1}H NMR measurements of **3** in THF-d_8

were conducted as these techniques can provide valuable information on the formation of hydrogen bonding between gelator molecules within a self-assembled supramolecular structure.[18] The results are shown in Figures 6 and 7. It is clear that at 298 K, the two amide protons exhibited NMR signals at δ=7.37 and 6.22 ppm, respectively. But the signals shifted to δ=7.31 and 6.12 ppm, respectively, at 308 K. The hydroxyl proton exhibited NMR peak at 4.85 ppm, but the signal shifted to δ=4.78 ppm. These changes indicate that the two amide protons and some hydroxyl protons have taken part in some interactions, an indication of presence of hydrogen bonds between neighboring gelator molecules in **3**/THF gel. This tentative conclusion was further supported by the result from concentration-dependent ^{1}H NMR spectroscopy studies of the gel system at 298 K. As shown in Figure 7, with increase of the concentration of **3**, the signals of the two amide protons and one of the hydroxyl protons gradually but significantly shifted to downfield, a definite evidence of intermolecular hydrogen-bond formation. The conclusion is further supported by the FTIR studies of the assemblies of **4** in $CDCl_3$ and in xylene (xerogel) as shown in Figure S1 (Supplementary data).

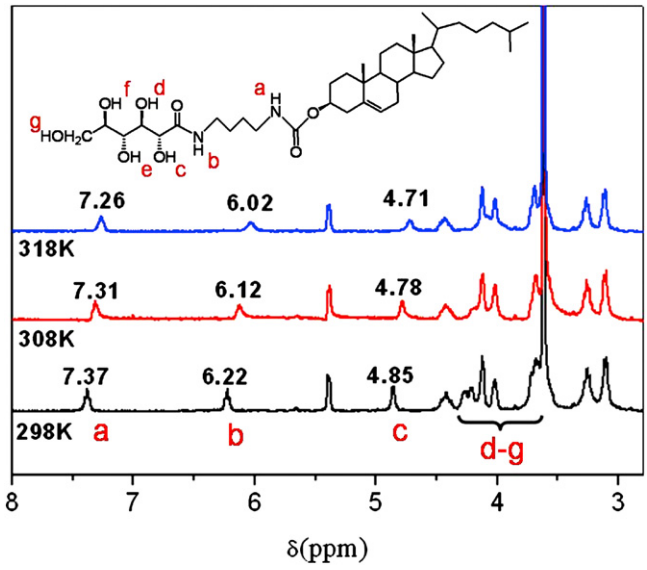


Figure 6. Partial ^{1}H NMR spectra of **3** in THF-d_8 at different temperatures (1%, w/v).

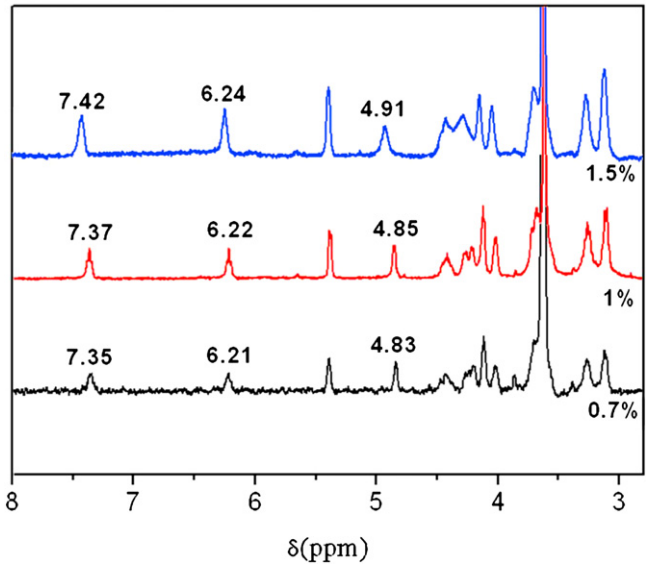


Figure 7. Partial ^{1}H NMR spectra of **3** in THF-d_8 at different concentrations at 298 K.

2.7. XRD studies

To reveal the detailed molecular packing modes of the gelators in the gels as prepared, XRD analyses of the powder sample of **1** and its xerogel from 1-pentanol were conducted. The results are depicted in Figure 8. As shown in the Figure, the XRD trace of powder **1** is characterized by three sharp reflection peaks, and the corresponding spacings (d) are 4.03, 1.99, and 1.32 nm, respectively, almost exactly following the ratio of 1:1/2:1/3, indicating that the powder **1** possesses a layered structure. The xerogel of **1** from 1-pentanol, also shows three reflection peaks but in the larger angle region compared with the powder, and the obtained spacings (d) are 3.83, 1.92, and 1.29 nm, respectively, which also follows the ratio of 1:1/2:1/3, a strong evidence of layered structure. Similar structure is also found for the assembly of **3** in its THF gel (cf. Fig. S2, Supplementary data).

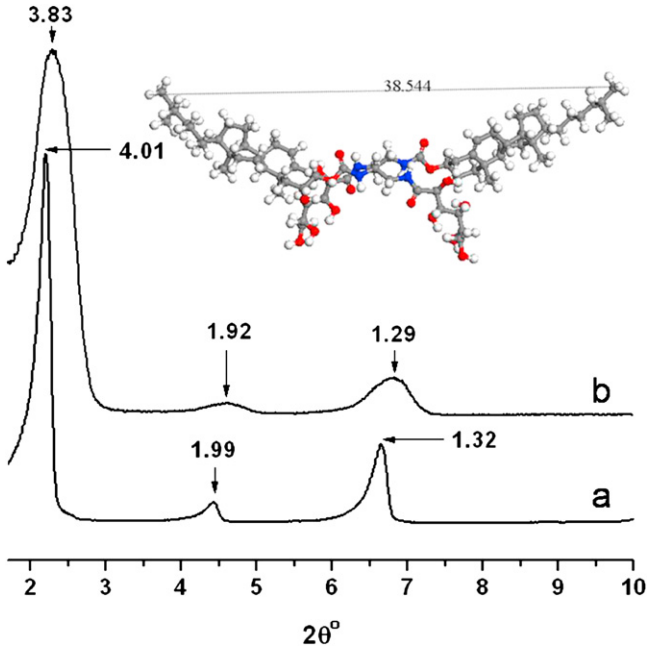


Figure 8. XRD profiles of **1** in powder state (a), and in xerogel state (from its 1-pentanol gel) (b) recorded at room temperature.

It is to be noted that as a normal practice XRD reveals only the primary molecular packings rather than the morphology of the packings, and thereby it is not necessarily identical to the findings from SEM or TEM observations. This is because the morphologies observed in SEM or TEM studies may be results of further packing of the primary assemblies as revealed by XRD studies. This explains why a helical structure was observed in TEM studies and CD measurements of the assembly of **1** in 1-pentanol (cf. Fig. 9 and Fig. S3, Supplementary data). A similar argument was also employed by other groups[18b,19] for the explanation of the inconsistence of the results from XRD and SEM or TEM studies.

Considering the main interactions between the gelator molecules, and the structure of the assembly of **1** in its 1-pentanol gel or solution as discussed above, a structural model was proposed to describe the formation of the assembly (cf. Fig. 10). With reference to the cartoon, it is seen that the model is characterized by the presence of hydrogen bonds between the hydrophilic part of the gelator including the linker and the glucose residues and the aggregation of the hydrophobic part-cholesteryl unit. It is worth mentioning that the width of the elemental fiber is 3.85 nm, which is a result of Molecular Dynamics modeling, very close to the value of 3.83 nm as revealed by XRD analysis. It is these elemental fibers

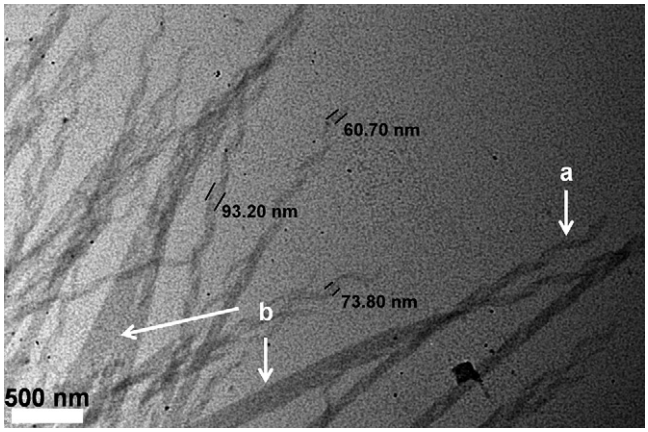


Figure 9. TEM image of the aggregates of **1** prepared from its 1-pentanol solution (0.1%, w/v).

4. Experimental section

4.1. Materials

Cholesteryl chloroformate, ethylenediamine, 1,3-propanediamine, 1,4-butanediamine, 1,6-hexanediamine, and D-(+)-gluconolactone were purchased from Alfa Aesar and used as received. All solvents used in the synthesis were purified in a general way.

*4.1.1. Preparation of **1**, **2**, **3**, and **4**.* The cholesterol derivatives, **a**, **b**, **c**, and **d** (cf. Scheme 1) were synthesized by using a method reported earlier.[13] Gluconolactone (0.356 g, 2 mmol) and **a** (0.946 g, 2 mmol) were added to methanol (150 mL), and the mixture was stirred and refluxed for 10 h. After the reaction, the mixture was filtered and the residue was washed with methanol for three times, and then hot acetone for another three times. Finally, the purified product was dried in vacuum to give white crystals (0.68 g) in 52% yield. Melting

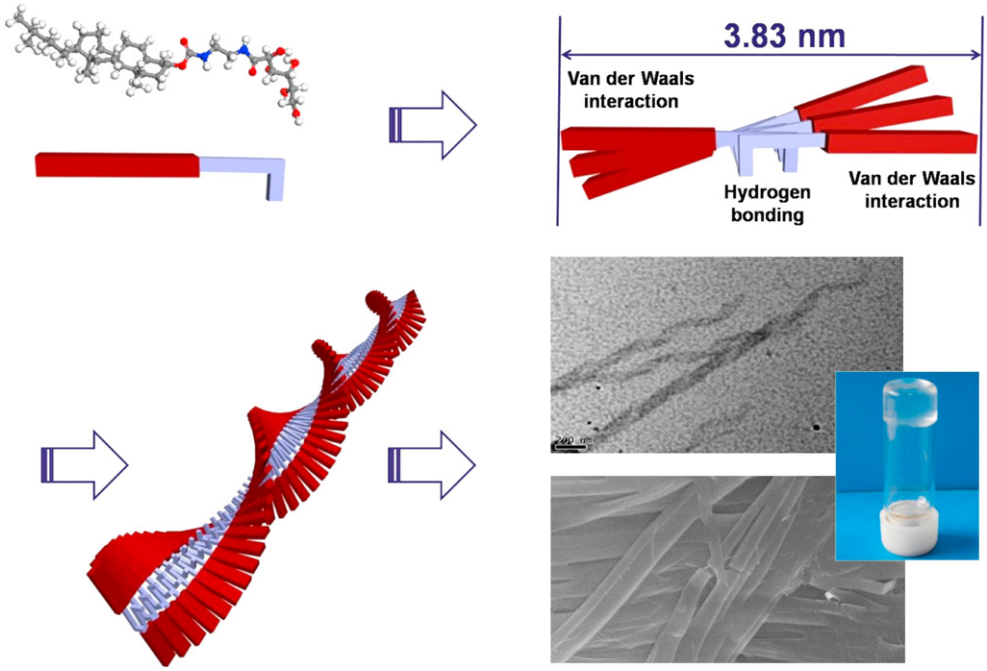


Figure 10. A proposed structural model of the assembly of **1** in its 1-pentanol gel.

that could pile up into thicker fibers (cf. Fig. 9a) via further interactions between the primary fibers as indicated by TEM studies, leading to final nanobelts as revealed by SEM images.

3. Conclusion

In conclusion, four novel and effective cholesterol-based and sugar-contained LMMGs have been designed and prepared. Gelation tests in various solvents revealed that a small variation in the linker length could produce a dramatic change in the gelation behavior and gel properties of the compounds. Interestingly, all the compounds as prepared gel both protic and aprotic solvents. Furthermore, compounds **2**, **3**, and **4** are super-gelators to xylene with cgcs significantly lower than 0.1% (w/v). More interestingly, supramolecular gel films based upon any one of the **2**, **3**, and **4**/xylene gels can be produced by employing a simple solution casting method. SEM studies revealed that the linker length has a great effect upon the aggregation mode of the gelators and the structures of the gel networks. ^{1}H NMR measurements revealed that hydrogen bonding between gelator molecules plays an important role for the formation and maintenance of the gels.

point (mp): 140.2–141.5 °C; ^{1}H NMR (DMSO/Me_4Si, 300 MHz): δ (ppm) 7.74 (s, 1H, OCONH), 7.02 (s, 1H, CONH), 5.32 (s, 2H, alkenyl), 4.50–3.30 (m, 11H, glucosyl protons), 3.12 (s, 2H, NCH_2), 3.03 (s, 2H, NCH_2), 2.26–0.63 (m, 43H, cholesteryl protons). ^{13}C NMR (DMSO/Me_4Si, 300 MHz): δ (ppm) 173.2, 156.2, 140.2, 122.3, 73.9, 72.7, 71.9, 70.5, 63.8, 56.6, 56.0, 49.9, 42.3, 40.7, 40.5, 40.2, 39.9, 39.7, 39.4, 39.1, 38.8, 35.6, 31.8, 28.2, 27.8, 23.6, 23.1, 22.8, 19.4, 19.0, 12.1. FTIR (cm^{-1}): 3297 (NH, OH), 2943 (CH), 1692 (C=O, O), 1643 (C=O, –NH), 1549 (NH). MS (MALDI-TOF): *m*/*z* calcd for [$(M+Na)^+$]: 673.43, found: 672.33. Anal. Calcd for $C_{36}H_{62}N_2O_8$: C, 66.43; H, 9.60; N, 4.30. Found: C, 66.58; H, 9.48; N, 4.05.

Similarly, **2**, **3**, and **4** were obtained from **b**, **c**, and **d**, respectively, by employing a condensation reaction with gluconolactone. The characterization data for **2** are as follows: mp 147.5–149.0 °C; ^{1}H NMR (DMSO/Me_4Si, 300 MHz): δ (ppm) 7.70 (s, 1H, OCONH), 7.00 (s, 1H, CONH), 5.39 (t, J=4.2 Hz, 2H, alkenyl), 5.33 (s, 1H, HOCO), 4.53–3.33 (m, 10H, glucosyl protons), 3.08 (s, 2H, NCH_2), 2.97 (s, 2H, NCH_2), 2.26–0.65 (m, 45H, CH_2, cholesteryl protons). ^{13}C NMR (DMSO/Me_4Si, 300 MHz): δ (ppm) 173.0, 156.1, 140.2, 122.3, 74.0, 72.8, 71.9, 70.5, 63.8, 56.6, 56.1, 49.9, 42.3, 40.8, 40.5, 40.2, 39.9, 39.6, 39.4, 39.1, 36.5, 36.1, 35.7, 31.8, 27.8, 23.7, 23.1, 22.8, 19.4, 19.0,

12.1. FTIR (cm^{-1}): 3345 (NH, OH), 2940 (CH), 1679 (C=O, O), 1634 (C=O, –NH), 1540 (NH). MS (MALDI-TOF): *m/z* calcd for $[(M+Na)^+]$: 687.45, found: 687.51. Anal. Calcd for $C_{37}H_{64}N_2O_8$: C, 66.84; H, 9.70; N, 4.21. Found: C, 67.29; H, 9.74; N, 3.93. The data for **3**: mp 131.0–132.5 °C; ^{1}H NMR (DMSO/Me_4Si, 300 MHz): δ (ppm) 7.60 (s, 1H, OCONH), 6.99 (s, 1H, CONH), 5.32 (s, 2H, alkenyl), 4.52–3.31 (m, 11H, glucosyl protons), 3.05 (s, 2H, NCH_2), 2.92 (s, 2H, NCH_2), 2.24–0.63 (m, 47H, CH_2CH_2, cholesteryl protons). ^{13}C NMR (DMSO/Me_4Si, 300 MHz): δ (ppm) 172.7, 156.1, 140.2, 122.3, 74.1, 72.8, 71.9, 70.5, 63.8, 56.6, 56.0, 49.9, 42.3, 40.8, 40.5, 40.2, 39.9, 39.7, 39.4, 39.1, 38.3, 36.5, 35.6, 31.8, 27.8, 23.6, 23.1, 22.8, 19.4, 19.0, 12.1. FTIR (cm^{-1}): 3377 (NH, OH), 2940 (CH), 1686 (C=O, O), 1641 (C=O, –NH), 1539 (NH). MS (MALDI-TOF): *m/z* calcd for $[(M+Na)^+]$: 701.47, found: 701.56. Anal. Calcd for $C_{37}H_{66}N_2O_8$: C, 67.22; H, 9.80; N, 4.13. Found: C, 67.06; H, 9.76; N, 3.79. And the data for **4**: mp 143.0–144.5 °C; ^{1}H NMR (DMSO/Me_4Si, 300 MHz): δ (ppm) 7.61 (d, *J*=5.4 Hz, 1H, OCONH), 7.00 (s, 1H, CONH), 5.34 (d, *J*=4.2 Hz, 2H, alkenyl), 5.33 (s, 1H, HOCO), 4.55–3.32 (m, 10H, glucosyl protons), 3.08 (s, 2H, NCH_2), 2.93 (s, 2H, NCH_2), 2.26–0.65 (m, 51H, $CH_2CH_2CH_2CH_2$, cholesteryl protons). ^{13}C NMR (DMSO/Me_4Si, 300 MHz): δ (ppm) 172.6, 156.0, 140.2, 122.2, 74.1, 72.9, 71.9, 70.5, 63.8, 56.6, 56.1, 49.9, 42.3, 40.8, 40.5, 40.2, 39.9, 39.7, 39.4, 36.5, 35.7, 31.8, 29.5, 27.8, 26.5, 23.7, 23.1, 22.8, 19.4, 19.0, 12.1. FTIR (cm^{-1}): 3345 (NH, OH), 2940 (CH), 1691 (C=O, O), 1643 (C=O, –NH), 1535 (NH). MS (MALDI-TOF): *m/z* calcd for $[(M+Na)^+]$: 729.51, found: 729.43. Anal. Calcd for $C_{37}H_{70}N_2O_8$: C, 67.95; H, 9.98; N, 3.96. Found: C, 67.59; H, 9.92; N, 3.63.

4.2. General methods

4.2.1. Gelation test. A weighted amount of potential gelator and a measured volume of selected pure solvent were placed into a sealed glass tube (10 mm i.d.), and the system was heated in an oil or water bath until all solid materials were dissolved. The solution was cooled to room temperature in the air, and finally, the test tube was turned upside down to observe if the solution inside could still flow. A positive test is obtained if the flow test is negative. It is to be noted that some of the gels obtained are turbid (G), but some are transparent (TG). In some cases, solution and gel may coexist within a system and they are referred to as 'partial gels' (PG). Systems in which only solution remained until the end of the tests are referred to as solutions (S). Systems that are clear solutions when they are hot but precipitation or crystallization occurs when they are cooled down to room temperature are denoted by P (precipitation) and R (re-crystallization), respectively. Insoluble systems, in which the potential gelator could not be dissolved even at the boiling point of the solvent, were also found, and they are labeled as insoluble (I).

4.2.2. Gel-to-sol transition temperature (T_{gel}) measurement. Temperatures of gel-to-sol transition (T_{gel}) were determined by using a conventional 'falling ball' method.[20] In the test, a small glass ball (diameter ≈3 mm) was carefully placed on the top of the gel to be tested, which was produced in a test tube (¼ 10 mm). The tube was slowly heated (0.5 °C/min^{-1}) in a thermostated water or oil bath until the ball fell to the bottom of the tube. The temperature corresponding to the end of the falling process was recorded and taken as the T_{gel} of the system.

4.2.3. SEM measurement. SEM pictures of the xerogel were taken on a Quanta 200 scanning electron microscopy spectrometer (Philips-FEI). The accelerating voltage was 15 kV, and the emission was 10 mA. The xerogel was prepared by freezing the gel formed in concerned solvent at a concentration of 2.5% (w/v) in liquid nitrogen and then evaporated by a vacuum pump for 12–24 h. Prior to examination, the xerogel was attached to a copper holder by using conductive adhesive tape, and then it was coated with a thin layer of gold.

4.2.4. FTIR measurement. All FTIR measurements were performed on a Brucher EQUINX55 spectrometer in an attenuated total reflection (ATR) mode with ZnSe as sample slot. The KBr pellets mixed with samples were measured on the transparent mode.

4.2.5. Rheological measurement. Rheological measurements were carried out with a stress-controlled rheometer (TA instrument AR-G2) equipped with steel-coated parallel-plate geometry (20 mm diameter). The gap distance was fixed at 1000 μm. A solvent-trapping device was placed above the plate to avoid evaporation. All measurements were made at 25 °C.

4.2.6. ^{1}H NMR measurement. ^{1}H NMR and ^{13}C NMR data of samples were collected on Bruker AVANCF 300 MHz spectrometer.

4.2.7. MS measurement. MALDI-TOF mass spectra were recorded in a Kratos' AXIMA-CFR plus instrument by using 2,5-dihydroxybenzoic acid (DHB) as a matrix.

4.2.8. XRD measurement. XRD data of samples were collected on a D/Max-2550/PC with Cu KR X-ray radiation generated under a voltage of 40 kV and a current of 40 mA. The scan rate was 0.5°/min. The xerogel was prepared by freezing the gel in liquid nitrogen and then evaporated by using a vacuum pump at a low temperature (−60 °C) for 12–24 h.

4.2.9. TEM measurement. TEM was performed on a JEOL-2000, NEC at 200 keV. Test samples were prepared by placing hot solution of compound onto a carbon coated copper grid (400 meshes) and then evaporated at room temperature.

4.2.10. CD measurement. CD spectra were obtained by using a circular dichroism spectrometer (Chirascan). In the measurement, gelator concentration was maintained at 0.5% (w/v). Sample was prepared by heating a gel sample, then poured into a quartz cell, and then cooled to room temperature. Finally, the measurements were started from lower temperatures to higher temperatures.

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Supplementary data

FTIR spectra of **4** in $CDCl_3$ (solution, a) and xylene (xerogel, b) (Fig. S1), XRD profiles of **3** in powder state (a) and in its THF xerogel state (b) (Fig. S2), and CD spectra of **1** in pentanol (Fig. S3). Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.tet.2010.02.070.

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