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Organogels of Lignin-derived Stable Metabolic Intermediate, 2-Pyrone-4,6-dicarboxylic Acid (PDC), Bearing Cholesteryl Groups

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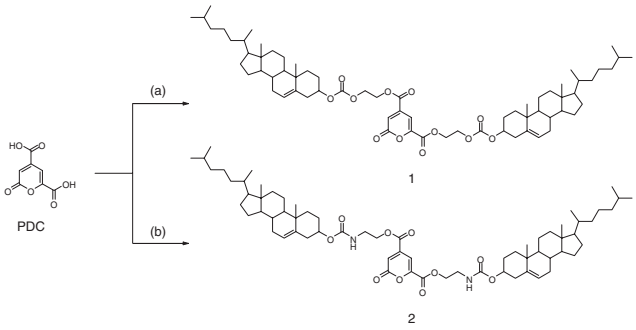
The organogelation behavior of a lignin-derived stable metabolic intermediate bearing two cholesteryl groups was examined for the first time, and it was found that the carbamate spacers possessing a hydrogen-bonding ability are essential for gelation of aliphatic or aromatic organic solvents.

Low molecular weight organogalators have attracted much attention because of their potential applications as new soft materials, gel electrolytes, photochemical templates, etc.[1,2] For such practical or industrial applications, it is important to consider the repeated circulation of carbon resources. One of the most promising approaches is the utilization of biomass, and there are many reports on the preparation of biomass-based functional materials.[3] In the past, we successfully established a massive production protocol of a small pseudo-aromatic ring molecule, 2-pyrone-4,6-dicarboxylic acid (PDC), from lignin biometabolic intermediates by transformed bacterium[4] and synthetic methods for a series of biodegradable PDC molecules and polymers.[5]

It is well known that organogels are formed through the 1D alignment of gelator molecules in terms of van der Waals, dipole–dipole, π–π, and hydrogen-bonding interactions.[6] Steroid and sugar derivatives are often employed as a source of van der Waals interactions. On the other hand, functional moieties, such as fluorescent dyes and redox active π chromophores, tend to self-assemble through dipole–dipole or π–π interactions, and most of them are usually synthetic substances. Our previous studies demonstrated the interesting fluorescent behavior of the PDC molecule, and X-ray crystallography of single crystals revealed the unusually short intermolecular contact between the 2-pyrone rings, indicating strong dipole–dipole interaction.[7] Therefore, to increase the content of natural carbon resources in functional organogelator molecules, we designed new PDC derivatives bearing two cholesteryl groups through either carbonate or carbamate spacers. We now report the synthesis and gelation ability of PDC-based organogelators.

Cholesterol-appended PDC derivatives, bis(2-{[(cholest-5-en-3-yloxy)carbonyl]oxy}ethyl) 2-oxo-2*H*-pyran-4,6-dicarboxylate (**1**) and bis(2-{[(cholest-5-en-3-yloxy)carbonyl]amino}ethyl) 2-oxo-2*H*-pyran-4,6-dicarboxylate (**2**), were synthesized from PDC by condensation, and unambiguously characterized by ^{1}H and ^{13}C NMR, FT-IR, MALDI-TOF-MS, and elemental analysis (Scheme 1).[8] In the ^{1}H NMR spectrum of **2**, a line-broadening effect originating from partial self-assembly was detected in $CDCl_3$ (10 mM) at 20 °C, whereas **1** did not show any such broadening.



Scheme 1. Synthesis of cholesteryl PDC derivatives. (a) Cholest-5-en-3-yl 2-hydroxyethyl carbonate, DIC, DMAP, THF, 20 °C, 1 h, 40%; (b) Cholest-5-en-3-yl (2-hydroxyethyl)-carbamate, DIC, DMAP, THF, 20 °C, 1 h, 46%.

Thermal analyses of both PDC derivatives were carried out by thermogravimetric and differential thermal analysis (TG-DTA) and differential scanning calorimetry (DSC). Neither derivative showed any decomposition at least up to 200 °C (Figure 1SI).[8] DSC measurements revealed a transition from a glass state to a liquid crystalline (LC) phase at 77.0 °C for **1** and 86.7 °C for **2** (Table 1SI), and the LC phase was determined to be smectic A from the polarized optical microscopy (POM) images (Figure 2SI).[8] The X-ray diffraction (XRD) patterns of the LC phases provided the layer distance of 43.63 Å for **1** and 44.62 Å for **2**, corresponding to single molecular sizes (Figure 2SI).[8]

The gelation properties of **1** and **2** were assessed in various organic solvents. It was found that **2** possesses an excellent gelation ability for hexane, cyclohexane, ligroin, and benzene at a minimum concentration of 10, 4.1, 3.7, and 7.4 wt %, respectively, whereas **1** did not show any gelation in the examined organic solvents (Figure 1a). This result implies that the carbamate spacers between PDC and the cholesteryl group play an important role in gelation in terms of the hydrogen bonds. The prepared organogels did not exhibit gel–sol transitions up to the boiling points of the employed solvents, indicating significantly high stability as a physical gel.

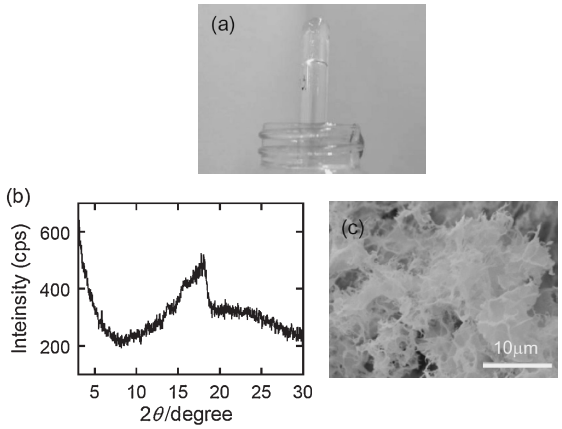


Figure 1. (a) Photograph of cyclohexane gel of **2** (4.1 wt %) in an NMR tube. (b) XRD diffraction pattern and (c) SEM image of the xerogel.

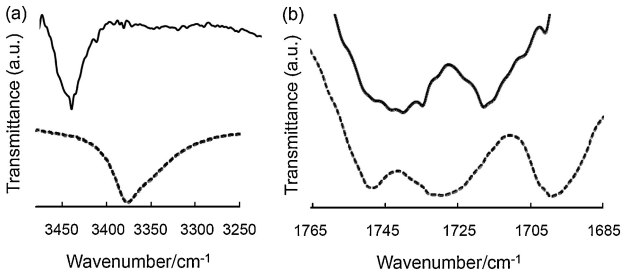


Figure 2. FT-IR spectra of **2** in a CH_2Cl_2 solution (solid line) and in the cyclohexane gel (4.1 wt %) state (dotted line).

The xerogels prepared by freeze-drying the cyclohexane gels of **2** were investigated by X-ray diffraction (XRD) analysis and scanning electron microscopy (SEM). The XRD analysis indicated a peak at $2\theta = 17.8°$ ($d = 4.98$ Å), suggesting the short intermolecular distance (Figure 1b). Since the *d*-spacing value was independent of the gelator concentration at >4.1 wt %, the gelation always occurs in the same process. The SEM image of the cyclohexane xerogel revealed the formation of a layered film-like structure (Figure 1c). Similar film-like structures were previously reported and explained by 2D organization of the gelator molecules.[9]

To elucidate the hydrogen-bonding interactions, the FT-IR spectra of **2** were measured in a CH_2Cl_2 solution and a cyclohexane gel. We noted the characteristic peaks of the NH and C=O groups of the carbamate and PDC moieties. In a CH_2Cl_2 solution, where no gelation was observed, **2** exhibited the NH stretching band at 3446 cm^{-1} (Figure 2a). However, the band shifted to 3377 cm^{-1} in the cyclohexane gel, suggesting a hydrogen-bond formation. Similarly, the C=O stretching band of the carbamate moieties observed at 1716 cm^{-1} in CH_2Cl_2 shifted to the lower energy of 1698 cm^{-1} in the cyclohexane gel (Figure 2b). This result again supports the hydrogen-bond formation, which stabilizes the self-assembled structure of **2** in a gel state. Moreover, the C=O stretching bands of the 2-pyrone ring and ester moieties are overlapped at around 1740 cm^{-1} in CH_2Cl_2 (Figure 2b). These bands were definitely split into two bands in the cyclohexane gel. The low energy shift to 1729 cm^{-1} is most likely associated with the dipolar interaction of the 2-pyrone ring.[7]

In conclusion, PDC-based organogels were described for the first time. Gelation of some aliphatic hydrocarbons and benzene was realized by the van der Waals interaction of the cholesteryl groups, dipolar interaction of the 2-pyrone ring, and hydrogen bonds of the carbamate moieties of **2**. Despite a similar thermal phase behavior, **1** with a carbonate spacer did not show any gelation in organic solvents. This result suggests the importance of the molecular design and control of the weak intermolecular interactions. Further diversification of this biomass-based novel organogelator is now underway.

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