Role of Lactose in Modifying Gel Transition Temperature and Morphology of Self-assembled Hydrogels

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Lactose, a low-value dairy byproduct, was investigated as a gelling agent that could be used to tune the gel transition temperature (T_{gel}) and morphology of self-assembled fatty acid and fatty amine gels prepared in a water/alcohol cosolvent. Palmitic acid−lactose and *n*-hexadecylamine−lactose gels were studied using Fourier transform infrared spectroscopy, atomic force microscopy, and scanning electron microscopy. Lactose was observed to lower the T_{gel} of the palmitic acid system while raising the T_{gel} of the *n*-hexadecylamine system. Pores ranging from ∼20 to 50 μm were observed for the *n*-hexadecylamine−lactose gel while ∼5−10 μm pores were observed for the palmitic acid−lactose gel. Compared to the pure palmitic acid, the infrared spectra of the palmitic acid−lactose system exhibit a 9 cm^{-1} shift of the carbonyl (C═O) stretching vibration and up to a 29 cm^{-1} shift of three hydroxyl (O−H) stretching vibrations, implying strong intermolecular hydrogen bonding. In contrast, a covalent conjugation is indicated for the *n*-hexadecylamine−lactose system by the disappearance of a sharp peak corresponding to a primary aliphatic amine stretching vibration (3337 cm^{-1}) and emergence of a weak peak corresponding to a secondary aliphatic amine stretching vibration (3431 cm^{-1}). Thus, lactose, either through covalent or physical conjugation to fatty amine and fatty acid, respectively, can be used as an effective agent to control the gel transition temperature for synthesis of thermally reversible hydrogels having a broad range of gel transition temperatures.

Introduction

Lactose is a disaccharide having low commercial value. Synthesis of lactose-based polymers hydrogels has been investigated by various groups in the past 2 decades as a means to construct novel materials from this dairy byproduct.[1−11] However, due to a number of protecting and deprotecting steps of the hydroxyl groups of lactose, the synthesis procedures are tedious and lead to additional byproduct formation.[2,8] Other disadvantages of traditional synthetic pathways for synthesis of hydrogels include poor control of polymer chain length, sequence, and three-dimensional structure.[12] Material synthesis through a controlled biomimetic approach, such as molecular self-assembly, is thus attractive.

In broad terms, self-assembly can be defined as highly convergent synthesis protocol extensively driven by noncovalent interactions.[13] The building blocks in self-assembly are generally amphiphilic molecules that have a strong tendency to self-aggregate and form simple, yet elegant, structures such as micelles, ribbons, vesicles, fibers, or sheets. At the next level of assembly, interaction among these structures (or colloids) may lead to the formation of a stable gel or a colloidal dispersion.[14] Gel formation through molecular self-assembly can be facilitated through addition of low molecular mass gelators (LMOGs).[14−16] Theses gelator molecules can be classified into two categories according to the difference in the driving force for molecular aggregation: hydrogen-bond-based gelators and non-hydrogen-bond-based gelators.[17] Anthracene-,[18] tetraline-,[19] anthraquinone-,[20] and steroid-based[21] gelators constitute the family of non-hydrogen-bond-based gelators in which self-aggregation is primarily driven by $\pi-\pi$ stacking and solvophobic effects. The self-assembly of the hydrogen-bond-based gelators is driven by the formation of highly directional hydrogen bonds[21] and therefore very important for water gelation. Of the hydrogen-bond gelators, carbohydrate-based

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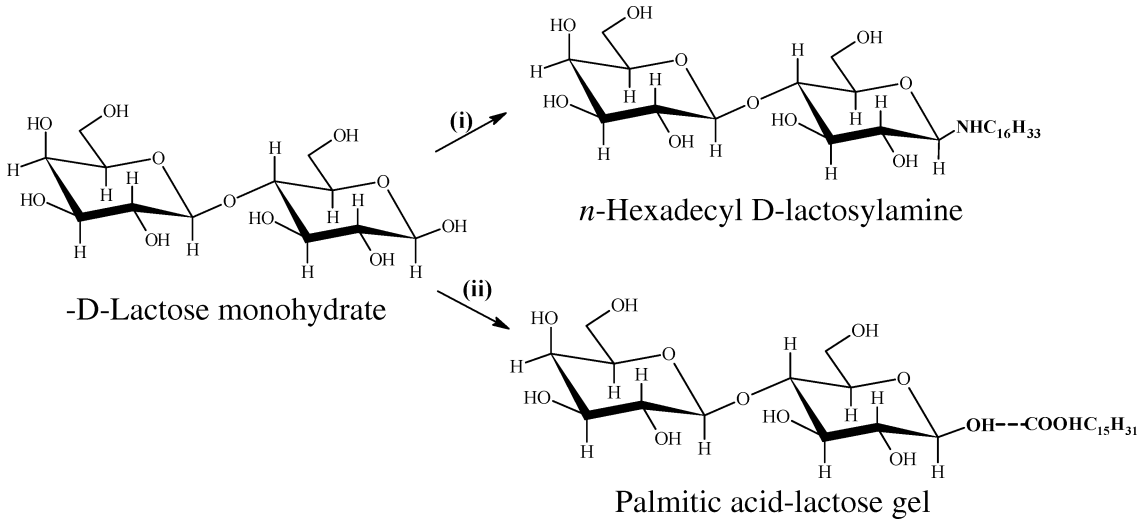
Scheme 1. Synthesis of Lactose-Based Gels[a]



[a] Conditions: (i) *n*-hexadecylamine or (ii) palmitic acid, in 2-propanol, stir, 24 h, with intermittent heating to a temperature just sufficient to eliminate turbidity (60 °C max.) followed by cooling to 20 °C and continued stirring and heating again when necessary to eliminate turbidity.

gelling agents are advantageous as carbohydrates provide a rich library of water-soluble chiral building blocks. In the case of lactose, these building blocks are also very economical.

A variety of sugar-integrating gelators has been described in the literature as successful organo and hydrogelators exhibiting high solubility in water and having a biodegradable nature.[14,17,22] Shinaki and co-workers have described methyl 4,6-*O*-benzylidene derivatives of monosaccharides as gelator of water as well as organic solvents.[23] Further, they have also shown that sugar-based gelators provide the unique possibility of modifying the gel transition temperature by changing the intermolecular aggregation due to the presence of highly directional intermolecular hydrogen bonds as a result of the multiple hydroxyl groups present on the saccharide molecule. Bhattacharya and Acharya also described the synthesis of a series of amphiphile molecules based on conjugating disaccharides to fatty amines, which self-assemble to form hydrogels in the presence of alcohol as cosolvent.[24] They demonstrated the necessity of maintaining an intact cyclic sugar in directing the intermolecular hydrogen bonding between amide N−H and carbohydrate OH groups, which improves gelation and resultant water-binding capacity.

Here, we further investigated the role of lactose in the formation of fatty amine gel following published methods of condensing alkylamines with sugars[24−26] that self-assemble in water and polar solvents to produce supramolecular networks with gelation properties. In addition to fatty amine we have also explored use of fatty acid as the hydrophobic segment in the synthesis procedure as well as explored the influence of excess of lactose on gel properties. The purpose of this study is to understand the interaction of lactose with surfactants and role of this disaccharide in altering the thermal and morphological properties of the resulting gel as a means of exploring profitable uses for a low-value product, lactose. The synthesized gels are advantageous because both the hydrophobic and the polar segments of the molecular building blocks are biodegradable and generally regarded as safe (GRAS) materials.

Experimental Section

Materials. *n*-Hexadecylamine (95%) (C_{16} fatty amine), palmitic acid (98%) (C_{16} fatty acid), 2-propanol (90%), and all other reagents were obtained from Sigma-Aldrich and used without further purification. α-D-Lactose monohydrate was provided by Proliant Inc. All other chemicals and solvents were reagent grade and used without further purification unless otherwise indicated.

Synthesis. Lactose was conjugated to *n*-hexadecylamine following published alkylamine−lactose condensation procedures.[24−26] The lactose/*n*-hexadecylamine stoichiometry was systematically varied to probe the influence of free (excess) lactose on resultant hydrogel gel transition temperature and morphology. To form palmitic acid−lactose hydrogel, *n*-hexadecylamine was substituted with palmitic acid and the same procedure was followed. Both procedures resulted in the formation of white gels. These synthesis procedures are shown in Scheme 1. ^{13}C NMR and ^{1}H NMR studies show the fatty amine conjugated to the hydroxyl group on the anomeric carbon of the lactose molecule.[24−26] Considering the higher tendency of the hydroxyl group on the anomeric carbon of lactose to react, authors simply speculate the fatty acid conjugation to the anomeric hydroxyl group of lactose.

n-Hexadecyl−D-lactosylamine. A solution of (250 mM) hexadecylamine in 10 mL of 2-propanol was added to a solution of α-D-lactose monohydrate (250 mM) in 10 mL of water. The mixture was stirred for 24 h with cyclic heating between 40 and 60 °C at regular intervals as and when the solution turned turbid. At the end of this period, a precipitate was formed, which was separated from the solvent by filtration. The crude residue was dried first under vacuum and then recrystallized from ethanol and then again freeze-dried to eliminate traces of water to avoid hydrolysis on prolonged storage.

Palmitic acid−lactose blend was prepared in the same way as described in the synthesis of *n*-hexadecyl−D-lactosylamine but

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instead of using *n*-hexadecylamine a 10 mL solution of 250 mM palmitic acid was used. Freeze-dried products were prepared only for IR analysis purposes.

Thin Layer Chromatography. Samples were prepared by dissolving 10 mg of freeze-dried synthesized compounds in 10 mL of methanol. Thin layer chromatography silica gel plates were used. A line of origin was traced 1 cm from the lower side of the plate, and the solvent front line was set at 8 cm from the origin. Two microliters of each solution was spotted onto the plate and dried thoroughly in an oven. Co-spotting, or double spotting, was also employed as a control to assess the interaction between the two starting reactants by placing 2 μL of pure α-D-lactose monohydrate and 2 μL of *n*-hexadecylamine (or palmitic acid) solutions onto exactly the same spot on the baseline. Methanol was used as the mobile phase. Plates were developed in 20 mL of the mobile phase at room temperature for 30 min. The plates were removed from the development tank and dried thoroughly in hot air prior to staining.

Two different staining solutions were used for the staining purpose. Staining solution A was prepared by adding 5 mL of concentrated sulfuric acid, 1.5 mL of glacial acetic acid, and 3.7 mL of *p*-anisaldehyde to 135 mL of absolute ethanol and mixed vigorously to ensure homogeneity. Staining solution B was prepared by adding 10 g of cerium sulfate, 20 g of molybdic anhydride, and 150 mL of concentrated sulfuric acid in 1.0 L of distilled water. Plates were first dipped in staining solution A and then sprayed with staining solution B, followed by heating at 100 °C for 5 min. Samples appeared as brown spots. The value of the retention factor (R_f) was determined by the distance traveled by the compound divided by the distance traveled by the solvent front. Distance traveled by the solute is defined from the center of the spot for calculating R_f values.

Gel Transition Temperature (T_{gel}). Gel transition temperatures recorded after the first heating cycle were determined for samples prepared over a range of fatty amine−lactose and fatty acid−lactose concentrations. The influence of subsequent heating/cooling cycles on the gel transition temperatures was also determined for equimolar ratios of fatty amine−lactose and fatty acid−lactose. Gel transition temperatures were measured by visual observation upon sample cooling from 60 °C at a rate of about 5 °C/min. The onset of gelling was indicated by the appearance of white particulates forming a band toward the bottom of the vial. Gel transition temperatures were determined from two observations for each sample and error bars calculated as the standard error of the mean. Gel transition temperatures were further verified by differential scanning calorimetry (DSC) studies of selected samples.

A TA instruments DSC(2910) differential scanning calorimeter was used to confirm the gel transition temperature of representative samples. Liquid samples (at 60 °C) were placed in DSC sample pans (Part PS1007, Instrument Specialists Inc.) and sealed with a hermetic lid (Part PS1011, Instrument Specialists Inc.) to avoid evaporation of solvent at higher temperatures. Thermographs were recorded during cooling from 60 °C at a scan rate of 5 °C/min. The gel transition temperature was taken as the onset temperature of the exothermic peak in the thermograph (representative data are included in the Supporting Information).

Infrared Spectroscopy. Infrared spectra were recorded using a Shimadzu FTIR 8400 spectrometer by collecting 32 scans at a resolution of 4 cm^{-1}. Absorption band intensities are expressed as transmittance percentage. Samples were analyzed by using the potassium bromide (KBr) pellet method. After complete mixing of sample and potassium bromide, the powder was compacted under pressure to form a transparent pellet, which was immediately analyzed.

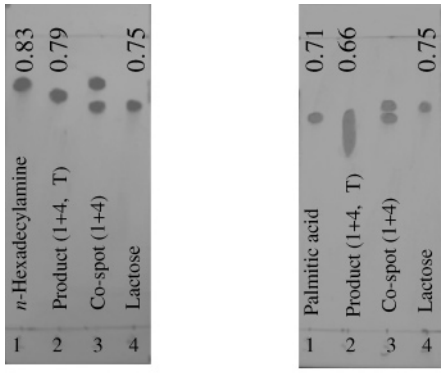

Figure 1. TLC analysis to assess reactant purity and product formation for (a) *n*-hexadecylamine−lactose product (2) gives a distinct band from *n*-hexadecylamine (1), α-D-lactose monohydrate (4), and co-spotting bands of *n*-hexadecylamine and α-D-lactose monohydrate (3) and (b) palmitic acid−lactose product (2) gives a distinct band from palmitic acid (1), α-D-lactose monohydrate (4) and co-spotting bands of palmitic acid and α-D-lactose monohydrate (3).

Microscopy. *Optical Microscopy.* Samples were prepared by heating above their T_{gel} and depositing 10 μL on an O_2 plasma cleaned cover slip, where it was allowed to gel. Ten microliter samples were sandwiched between a glass slide and a cover slip to maintain a native hydrated environment. The samples were examined using a Nikon (TE2000-S) phase-contrast light microscope with 10×ph1, 40×, and 100× objectives. Images were recorded by a color CCD video camera (Nikon DXM1200).

Atomic Force Microscopy (AFM). Following deposition of the sample on a cover slip, it was dried in an oven at 60 °C for 5 min and immediately imaged with a commercial atomic force microscope (Digital Instruments, Inc., Nanoscope IIIa) in contact mode using a Mikromash silicon nitride cantilever (force constant, 0.03 N/m). Images were flattened and plane fit using Nanoscope IIIa software, version 5.12r3.

Scanning Electron Microscopy (SEM). A field emission scanning electron microscope (Hitachi, F-4000) was used for SEM analysis. The 10 μL sample on the cover slip was frozen in liquid nitrogen, followed by drying under vacuum for 48 h to ensure removal of residual water. The dry sample thus obtained was sputtered-coated with gold and immediately analyzed. The accelerating voltage was 5 kV and the emission current was 10 μA.

Results and Discussion

Thin Layer Chromatography. The formation of products as depicted in Scheme 1 was assessed using TLC and the results are presented in Figure 1. It is observed that *n*-hexadecyl−D-lactosylamine product yields a distinct spot positioned between the spots corresponding to the pure and co-spotted starting reactants, which is an indication of covalent conjugation of lactose with *n*-hexadecylamine. For the analogous palmitic acid−lactose system a broad spot for the palmitic acid−lactose product suggests strong intermolecular hydrogen bonding exists between palmitic acid and lactose. Co-spotting gave two distinct bands for both systems, demonstrating that product formation is greatly enhanced through the heating−cooling cycles combined with stirring as expected.

Gel Transition Temperature (T_{gel}). The influence of excess lactose on the T_{gel} of *n*-hexadecyl−D-lactosylamine gels prepared at concentrations varying from 50 to 250 mM

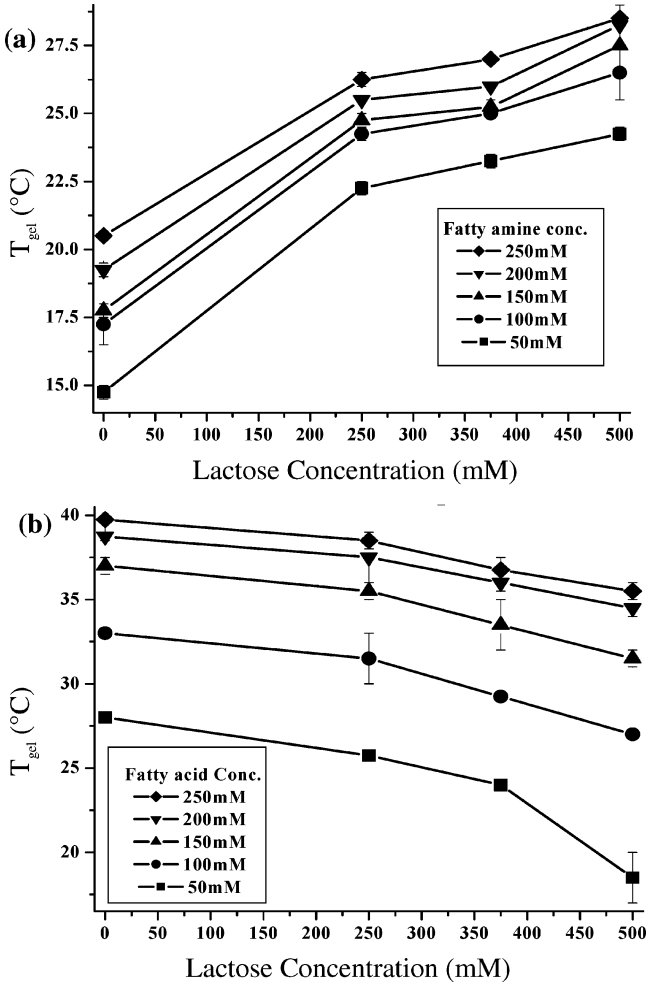

Figure 2. Gel transition temperatures of (a) *n*-hexadecylamine and (b) palmitic acid as a function of lactose concentration. (Error bars represent the standard error of the mean.)

is presented in Figure 2a. For all *n*-hexadecylamine−lactose gel concentrations, T_{gel} increases as the lactose concentration increases. However, the opposite is true for the analogous palmitic acid−lactose gel as shown in Figure 2b. We suspect that the lactose may be interfering with fatty acid hydrogen bonding. This hypothesis is also supported by the fact that the fatty acids have a natural tendency to self-assemble into a lattice structure and form a gel by virtue of having both hydrogen bond donor and acceptor ability, leading to head-to-head alignment in a linear fashion to form dimers.[27,28] Due to these extended lattice networks palmitic acid has strong gelling tendencies and has a higher T_{gel} than the corresponding fatty amine system. The increase in T_{gel} of *n*-hexadecylamine and decrease in T_{gel} of palmitic acid with an increase in lactose concentration indicates the role of lactose in assisting the intermolecular hydrogen bonding in *n*-hexadecylamine−lactose gel while hindering hydrogen bonding between two palmitic acid molecules. It is also observed from the data that as palmitic acid and *n*-hexadecylamine concentration increases T_{gel} increases.

The effect of cyclic heating−cooling treatments on the T_{gel} of *n*-hexadecyl−D-lactosylamine and palmitic acid−lactose gel systems are presented in Figure 3 over a 24 h period. Gel transition temperatures measured during heating−cooling treatment for both gel samples of equimolar ratios reveals that as the reaction precedes T_{gel} for *n*-hexadecyl−D-lactosylamine increases from 26.6 to 45.7 °C, while T_{gel} for the palmitic acid−lactose system decreases from 38.8 to 33.5 °C, which also supports the hypothesis of an opposite role of lactose in the fatty acid and fatty amine systems.

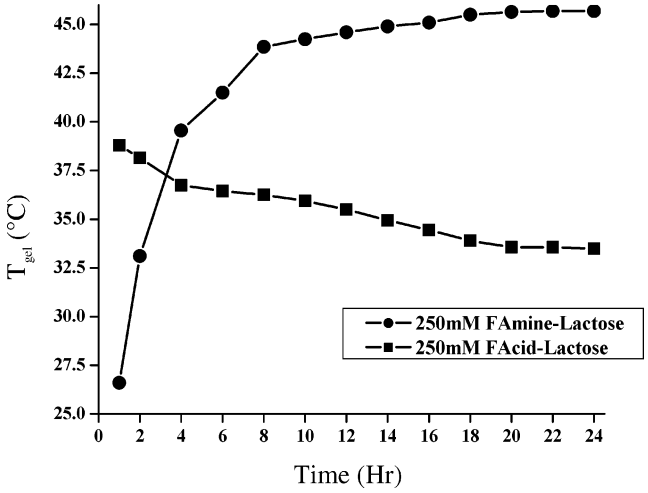

Figure 3. Gel transition temperatures of *n*-hexadecylamine−lactose (−●−) and palmitic acid−lactose (−■−) gel systems as a function of 24 h heating−cooling treatment.

Infrared Spectroscopy. Further insight into the role of hydrogen bonding in the fatty acid and fatty amine gel system was attained through FTIR analysis. The spectra of palmitic acid, lactose, palmitic acid−lactose mixture (precursor to gel without any thermal treatment), and palmitic acid−lactose gel (thermally cycled precursor, 1:1 stoichiometry) in the 1550−1800 cm^{-1} region are shown in Figure 4. The main band in these spectra is the carbonyl (C═O) stretching vibration that is observed to shift according to local environment. It is reported that two different IR absorptions can be observed for carbonyl stretching around 1700 cm^{-1} due to the partially restricted rotation.[29,30] One at 1706 cm^{-1} corresponds to intermolecularly hydrogen-bonded carbonyl moieties, and the other at 1732 cm^{-1} is from non-hydrogen-bonded carbonyl groups.[30−32] Indeed it is clear from the data that the palmitic acid carbonyl can be resolved into two peaks. The prominent band at 1700 cm^{-1} reflects the large proportion of hydrogen-bonded carbonyl vibration. In the palmitic acid−lactose gel, the carbonyl absorption shifts slightly to higher frequencies (9 cm^{-1}), which indicates the decrease in intermolecularly hydrogen bonded carbonyl moieties and the increase in other types of hydrogen-bonded carbonyl groups in blends.[32] For our system we can attribute the carbonyl shift to intermolecular hydrogen bonding between hydroxyl groups of lactose and palmitic acid, which is further supported by the dramatic reduction of the weak

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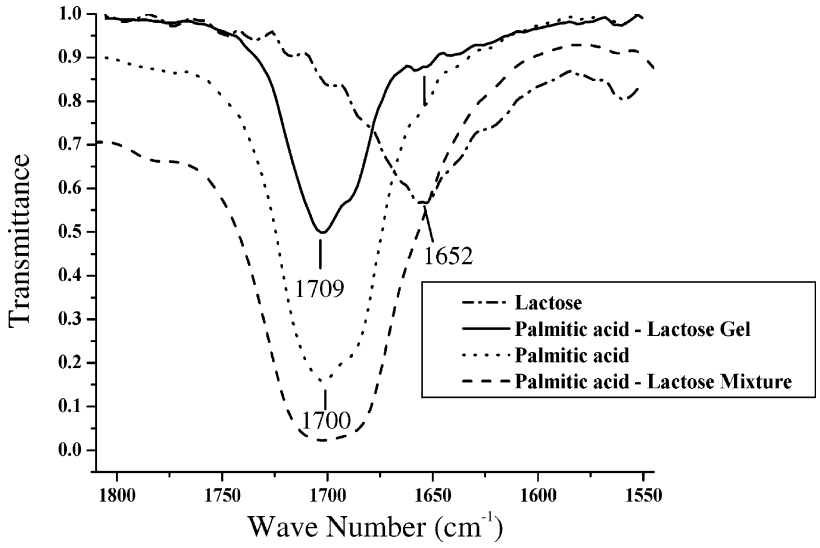

Figure 4. Infrared spectra in the 1550−1800 cm^{-1} region of palmitic acid, lactose, palmitic acid−lactose mixture without any treatment, and palmitic acid−lactose gel.

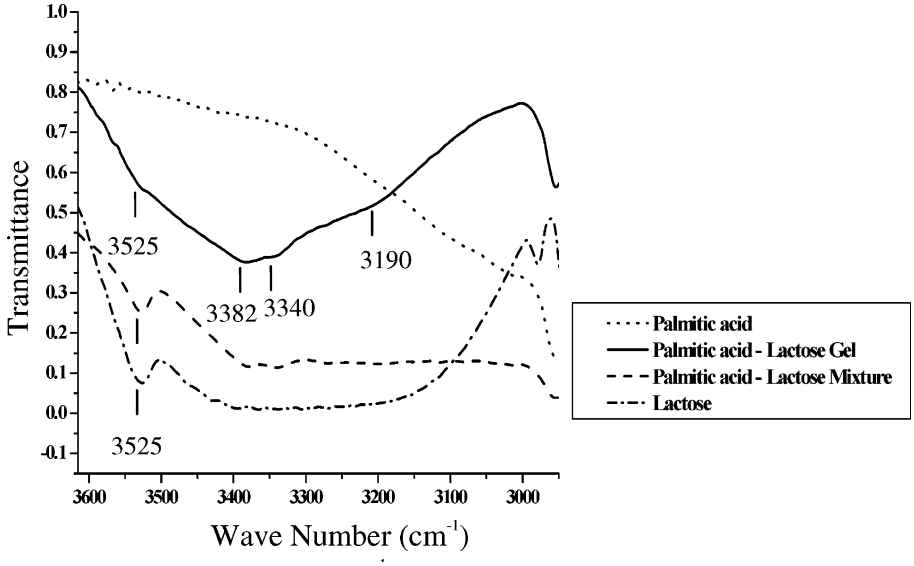

Figure 5. Infrared spectra in the 2950−3600 cm^{-1} region of palmitic acid, lactose, palmitic acid−lactose mixture without any treatment, and palmitic acid−lactose gel.

IR absorption band in the lactose spectrum at 1652 cm^{-1} assigned to the H−O−H bending vibration of the water of crystallization,[33−35] revealing a change in the surrounding local environment of lactose.

Intermolecular hydrogen bonding between the carboxylic acid (−COOH) moiety of palmitic acid and hydroxyl (−OH) moiety of lactose can be further demonstrated by spectral changes of hydroxyl stretching vibrations in the 3000−3600 cm^{-1} region, as shown in Figure 5. For fatty acids, the O−H stretching vibrations occur at 3490−3570 cm^{-1} for free hydroxyl groups and at 3000 cm^{-1} for acid cyclic dimer.[31,32] Here, we observed a broad absorption band in the 3000−3200 cm^{-1} region, which reveals the presence of a significant proportion of the intermolecularly hydrogen-bonded hydroxyl groups. For lactose, a very broad band from 3200 to 3800 cm^{-1} was observed with a sharp shoulder peak at 3525 cm^{-1}, which may reveal free and hydrogen-bonded hydroxyl groups present in crystalline and amorphous phases of lactose.[32,35] Infrared spectra of palmitic acid−lactose gel show a broad band in the 3000−3600 cm^{-1} region with a prominent peak at 3382 cm^{-1} and peaks on the shoulders at 3340, 3190, and 3525 cm^{-1}. These peaks are attributed to free and intermolecularly hydrogen-bonded O−H vibrations not visible in the pure lactose and pure palmitic acid spectra. The peak at 3525 cm^{-1}, clearly seen for pure lactose, is diminished in palmitic acid−lactose gel, but not in the "mixture" (precursor to gel), suggesting a change in the local environment of lactose as a consequence of the thermal cycling with palmitic acid, which leads to the formation of directional hydrogen bonds.

Figure 6 shows the infrared spectra of *n*-hexadecylamine, lactose, *n*-hexadecylamine−lactose physical mixture (precursor to gel), and *n*-hexadecyl−D-lactosylamine gel (thermally

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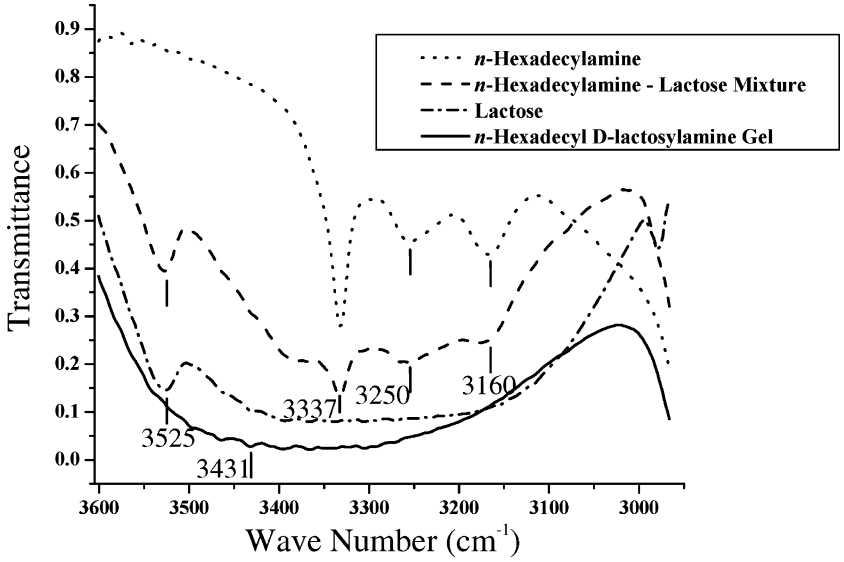

Figure 6. Infrared spectra in the 2950−3600 cm^{-1} region of *n*-hexadecylamine, lactose, *n*-hexadecylamine−lactose mixture without any treatment, and *n*-hexadecyl−D-lactosylamine gel.

cycled precursor) in the 3000−3600 cm^{-1} region. It is reported that primary aliphatic amines absorb in the 3250−3450 cm^{-1} region and may give two bands due to the N−H asymmetric and symmetric vibrations.[29] It is clear from the data that *n*-hexadecylamine gives three peaks, one sharp peak at 3337 cm^{-1} (antisymmetric $-NH_2$ stretch) and two smaller peaks at 3250 cm^{-1} (symmetric $-NH_2$ stretch) and 3160 cm^{-1} ($-NH_2$ bend overtone), which all disappear when reacted with lactose, suggesting conjugation of lactose with *n*-hexadecylamine and formation of *n*-hexadecyl−D-lactosylamine. A contrary argument for the absence of N−H stretching is due to the strong O−H stretching vibrations of lactose; however, this is disproved by the infrared spectrum of the physical mixture of *n*-hexadecylamine and lactose showing N−H as well as O−H stretching vibrations and the infrared spectrum of the *n*-hexadecyl−D-lactosylamine gel showing a weak peak at 3431 cm^{-1}, which may be assigned as a secondary aliphatic amine peak, suggesting lactose conjugation with *n*-hexadecylamine and conversion of the primary aliphatic amine to a secondary aliphatic amine.

Gel Morphology. Optical microscopy analysis (Figure 7a) of the hydrated *n*-hexadecylamine−lactose gel reveals a porous network structure, which is also apparent in the SEM image (Figure 7b) of the freeze-dried sample. The *n*-hexadecylamine−lactose gels form a network structure consisting of large pores (light features, Figure 7a) tens of micrometers in size, surrounded by a network of strands exhibiting secondary structural motifs such as fibers as well as spheroids as seen in the SEM image (Figure 7b). It is likely that the spheroids represent micelles of the lactose/fatty amine that have not completely coalesced and restructured during gelation to form the network strands. This is supported by the observation that many of the spheroids are interconnected, appearing to have a continuous membrane. We also cannot rule out artifact induced by the sample preparation method (complete drying under vacuum and sputter coating) where, upon dehydration, the gel may restructure.[14] This porous network structure provides pockets for holding water through surface tension, a hallmark of hydrogelation.[24] It is also clear

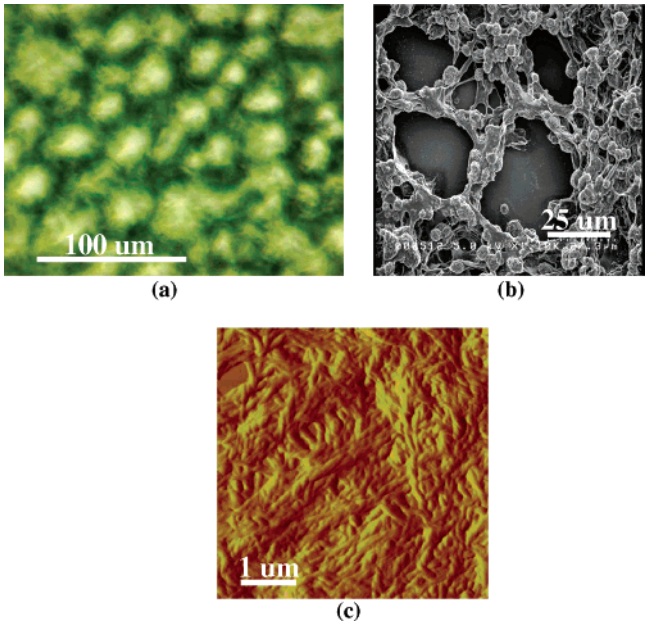

Figure 7. Morphological characteristics of fatty amine−lactose gel system. (a) Bright field image of 250 mM *n*-hexadecylamine−lactose gel (native state) in 50:50 water:2-propanol mixture. (b) SEM image of freeze-dried samples of 250 mM *n*-hexadecylamine−lactose gel. (c) Deflection AFM image of heat-dried samples of 250 mM *n*-hexadecylamine−lactose gel.

from the AFM image (Figure 7c) that the network-forming fibers exhibit secondary structural motifs such as coils and helices, which are characteristic of amphiphilic molecule self-assembly. Pure *n*-hexadecylamine does not form a gel (at 250 mM concentration) at room temperature (25 °C), demonstrating the important role of lactose in favoring gel formation for this system. In contrast, lactose interferes with gel formation of palmitic acid prepared under analogous conditions. Addition of lactose to palmitic acid dramatically changes the gel morphology as well. The palmitic acid−lactose gels (Figure 8a−c) reveal a more defined and confluent network structure as compared to the pure palmitic acid gel (Figure 8d), which exhibits net-like structure. The defined network structure of the palmitic acid−lactose gels as compared to the intricate net-like structure of the pure

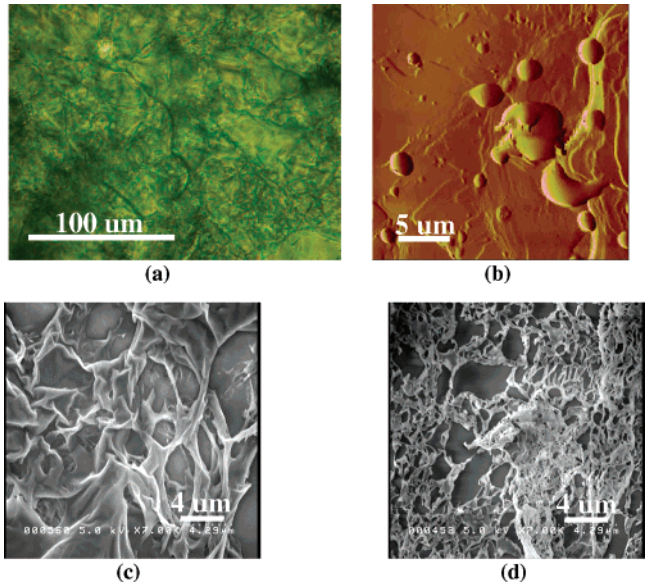

Figure 8. Morphological characteristics of fatty acid control and fatty acid−lactose gel systems. (a) Bright field image of 250 mM palmitic acid−lactose gel (native state) in 50:50 water:2-propanol mixture reveals mesoporous confluent structure. (b) Deflection AFM image of heat-dried samples of 250 mM palmitic acid−lactose gel reveals possible phase separation. (c) SEM image of freeze-dried sample of 250 mM palmitic acid−lactose gel. (d) SEM image of freeze-dried sample of 250 mM palmitic acid (control) gel.

palmitic acid gels is attributed to the role of lactose in disrupting the hydrogen bonding between two palmitic acid molecules and the tendency to hydrogen bond with the carboxylic acid moiety of palmitic acid.

In an attempt to understand the role of lactose in altering the morphological characteristics of fatty acid and fatty amine gels at nanoscale, we are investigating gel morphology in their native state using AFM under liquid.

Conclusion

From the present study based on the physical and chemical properties of the synthesized gel systems, we can suggest that lactose, a low-value dairy byproduct, can be used as a gel transition temperature modifier and consequently can be used in synthesizing thermally reversible gels for specific applications, where defined gelling temperature is required. Further, the porous network structure of these gels provides a high surface area-to-volume ratio to hold many times their weight in water, expanding potential use to an array of different applications, where self-assembled gels exhibit advantages over traditional cross-linked gels.

It is observed that, in the absence of lactose, *n*-hexadecylamine only forms gel at high concentrations and lower temperatures, but once conjugated with lactose, it tends to form a gel at higher temperatures with pores ∼20−50 μm in size. Here we illustrate that the opposite is true for palmitic acid systems. Our results reveal that palmitic acid itself has a strong tendency to hydrogen bond with each other and gel. Lactose interaction with palmitic acid reflects the competitive role of lactose in hydrogen bonding and consequently it lowers the gel transition temperature without any phase separation at equimolar ratios. Thus, pure fatty acid gels rapidly at higher temperature, resulting in a very intricate porous structure while the palmitic acid−lactose conjugate system gels at lower temperature, having a more defined mesoporous structure with pores ranging from ∼5 to 10 μm. To further understand the structural features and opposite behavior of lactose in *n*-hexadecylamine and palmitic acid system, FTIR studies were also carried out, the results of which revealed the noncovalent and covalent conjugation in the palmitic acid−lactose and *n*-hexadecylamine−lactose systems, respectively.

Varying fatty acid or fatty amine alkyl tail length provides further opportunities to tune gel properties, allowing a library of lactose-based surfactants exhibiting self-assembling and gelation properties to be developed, which is ongoing work in our laboratory.

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Supporting Information Available: Additional information (figures, text, and a table) on DSC thermographs and determination of T_{gel} by the observation-based approach. This material is available free of charge via the Internet at http://pubs.acs.org.

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