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Strings of Vesicles: Flow Behavior in an Unusual Type of Aqueous Gel

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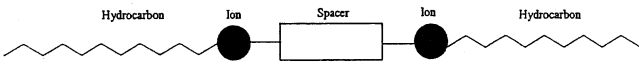
Abstract: This is a study of 10 asymmetric gemini surfactants that self-assemble into vesicles which, in turn, self-assemble into gels. The geminis have the following general structure: long-chain/phosphate/2-carbon spacer/quaternary nitrogen/short-chain. Dynamic light scattering and transmission electron microscopy (TEM) demonstrate that in dilute aqueous systems these compounds self-assemble into vesicles. The vesicles are cohesive as proven by cryo-high resolution electron microscopy (cryo-HRSEM) images that reveal a "pearls on a string" morphology. These strings of vesicles create a complex network that rigidifies the water. The one gemini in the study that does not form a gel is also the only vesicle system that, according to cryo-HRSEM and TEM, assembles into clumps rather than chains. It is proposed that the vesicles are cohesive owing to protrusion of short chains from the vesicle surfaces, thereby creating hydrophobic "patches" whose intervesicular overlap supersedes the normal membrane/membrane repulsive forces. Analogous geminis having two long chains, neither of which are thought capable of departing from their bilayers, also form vesicles, but they are noncohesive (as expected from the model). Rheological experiments carried out on the gels show that gelation is mechanically reversible. Thus, if an applied torque breaks a string, the string can rapidly mend itself as long as the temperature exceeds its calorimetrically determined T_m value. Gel strength, as manifested by the yield stress of the soft material, was shown to be particularly sensitive to the structure of the gemini. All three individual components of the systems (geminis, vesicles, and gels) have widespread practical applications.

Introduction

Our initial goal was rather simple: connect vesicles to other vesicles. In so doing we hoped to link vesicles into long polymer-like chains ("strings of vesicles"). Although the required vesicle−vesicle junctures could, in principle, be either covalent or noncovalent in nature, only the latter will be encountered in this paper. But, before delving into all that, we must ask why anyone would want to make strings of vesicles—why organic chemists (as ourselves) would want to color outside the lines of traditional organic chemistry. Perhaps the main reason is that we had no firm idea of what to expect by way of the strings' properties, particularly their rheological properties. Thus, familiarity, that enemy of vision, was not a risk factor. By the same token, we recognized the need for an apprenticeship to ensure our full share of pleasure and information from the rheology experiments. The results of such an apprenticeship (where we examined the flow characteristics of an amino acid-based gel) have already been published.[1] We now report on lipids that self-assemble into vesicles that themselves self-assemble. Solvent (water) is thereby trapped within a vesicle network to form an unusual type of gel.

Let us begin by defining terms, starting with the molecular component of our systems, a so-called gemini surfactant. Gemini surfactants were given that name[2] because they resemble a "twin" surfactant composed of (in sequence): a hydrocarbon chain, an ionic group, a spacer, an ionic group, and a hydrocarbon chain. Vesicles (formed here from our geminis)



are defined as spherical particles in which at least one lipid bilayer shell encloses a volume of space. Even a living cell might be considered a vesicle because its plasma membrane consists of a bilayer (containing phospholipids and other components). Although vesicle walls are only two molecules thick, they are extraordinarily resistant to mechanical disruption, topological change, and permeation. Gels (formed here from self-assembled vesicles) are easy to recognize but difficult to define. We arbitrarily consider a soft material to be a gel if it does not flow out of an inverted l cm vial over the course of several minutes. The work that is about to unfold unifies all three concepts: the gemini surfactant, the vesicle, and the gel.

Because the gemini surfactant, the vesicle, and the gel each own a prodigious literature, it is possible to cite here only reviews along with selected practical applications. Practical aspects seem relevant because without them any scientific field, sooner or later, will fade.

Gemini surfactants, despite their youth, are already the subject of reviews[3,4] and over one hundred patents. A family of geminis, given the trade name of EnviroGem (Air Products and Chemi-

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cals), is a fine example of green chemistry because the surfactants are biodegradable, and because they are made exclusively from natural substances with no byproducts.[5] In one of the most exciting developments, the European Network on Gemini Surfactants has shown that certain cationic geminis with low toxicity have a superior ability to introduce genes into cells.[6,7]

Vesicles (also called liposomes) have a long history; for general information on the subject, three old but still useful books may be consulted.[8−10] Reviews are also plentiful.[11] One of the most intensely investigated aspects of vesicles relates to their ability to encapsulate drugs within their bilayer shells. For example, a successful treatment of fungal infection with vesicular amphotericin has been reported.[12] Enzymes have been entrapped in vesicles and, by this means, inserted into cells.[13] Vesicles, loaded with methotrexate, have been conjugated to antibodies and thereby targeted to tumor cells.[14] Acne, arthritis, and AIDS[15] have all been treated with vesicular drug carriers. Technical problems remain to be solved, but the continued prospects for vesicles in the field of medicine are encouraging.

Many gels consist of long fibers or crystallites that cross-link noncovalently, or simply entangle with one another, creating a three-dimensional network that imparts rigidity to the system. The gelator (i.e., gelating substance) can be an inorganic, a macromolecule, or a small organic molecule that self-assembles. Most of the recent chemical literature deals with gelated organic solvents, a subject that has been reviewed recently.[16] References to aqueous gels are also available.[1] Gels are among the most useful colloidal systems with wide applications in photography, drug delivery, cosmetics, sensors, and food processing to name a few. "Smart" gels have been developed that bind guest molecules via multiple-point noncovalent interactions.[17] When the gel expands upon heating, the binding diminishes to only a single-point interaction, and the gel-guest affinity decreases accordingly. The potential for controlled release processes is obvious.

In summary, we brokered the tripartite marriage between gemini surfactants, vesicles, and gels in the belief that it would be a happy one.

Experimental Design

The initial question was how to join vesicles into strings, i.e., into a morphology resembling pearls on a necklace. One possibility was to synthesize a molecule having two widely spaced vesicle-binding units. In the absence of looping (that would place the two units within a single vesicle), the molecule should be capable of cross-linking vesicle systems. This approach will be considered in another paper; our concern here was to develop a mechanism based upon direct vesicle/vesicle association. Vesicle populations composed solely of either negatively or positively charged lipids were not an option because the resulting electrostatic repulsion would certainly impede adhesion. To avoid this problem, we synthesized a set of zwitterionic (but electrically neutral) geminis whose general structure is: $ROPO_2^-OCH_2CH_2N^+(CH_3)_2R'$ (where R and R′ are hydrocarbon chains). Geminis are known to self-assemble into neutral vesicles (among other morphologies).[4]

Having an overall zero net charge on our geminis did not guarantee their assembling into vesicles that cohere. Classical theory[18] tells us that vesicle cohesion, and colloid stability in general, depend on a competition between attractive van der Waals forces and repulsive electrostatic forces. Although electrostatic forces have been minimized in our gemini-based vesicles, an additional factor, the so-called hydration force (embodying the need to desolvate groups prior to contact) also comes into play.[19] Within a distance of about 3 nm, the hydration force is actually the primary barrier limiting the close approach of phospholipid membranes. Cohesion, therefore, was predicated upon overcoming both electrostatic and hydration forces. Ca^{2+} obviously does this well because it promotes the tight adhesion of negatively charged phospholipid bilayers.[20] Calcium ion operates by binding to anionic headgroups, an effect that (a) neutralizes the repulsive negative charge and (b) dehydrates the anionic headgroups of the phospholipids. In our case, it was clear that if our gemini-based vesicles were to link together, they would need a cohesive element (such as hydrophobic attraction) that promoted adhesion despite repulsive hydration energies.

Repulsive forces were not our only problem in designing vesicle strings. If, at the other extreme, the vesicles were endowed with an excess of cohesive elements, then undesirable clumping of the vesicles, possibly followed by precipitation, was a likely outcome. In addition, strong cohesion can sometimes precede another complicating and undesirable event: fusion.[21] These considerations made it clear that we needed to exploit judiciously any attractive force incorporated into our gemini vesicles for cohesion purposes.

We were in the process of confronting the problems mentioned above when a fortuitous event occurred. While screening (in combinatorial fashion) a large family of new zwitterionic geminis,[22,23] we happened to synthesize surfactants with a high degree of asymmetry; one chain was much longer than the other. Drawn below is a typical example of such a gemini (abbreviated $C_{18}-C_8$; note that $C_{18}-C_8$ and C_8-C_{18} are different compounds). According to electron microscopy, these geminis formed gels composed of vesicle strings. We inadvertently

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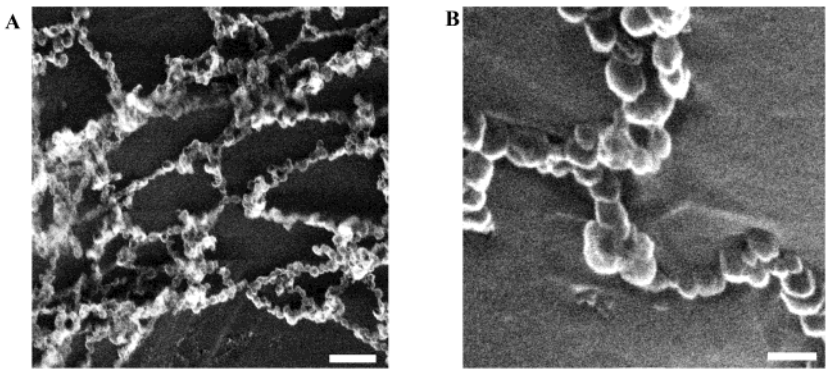


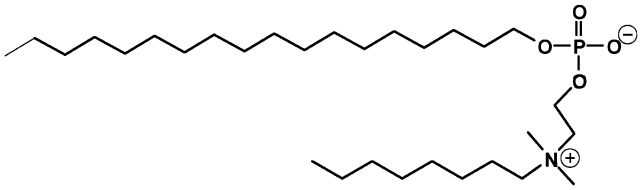
Figure 1. Cryo-HRSEM images of (A) $C_{14}-C_8$ (bar = 200 nm) and (B) $C_{18}-C_8$ (bar = 66.7 nm) in water at −110 °C.

Table 1. Properties of Gels from Zwitterionic Geminis

gemini[a]	T_m, °C[b]	min. gel	vesicle conc, mM	appearance[e] diam, nm[d]
$C_{14}-C_8$	<10	86	30	clear
$C_{18}-C_6$	<10	c	30	clear
$C_{18}-C_7$	<10	79	50	clear
C_8-C_{18}	27	58	30	clear
$C_{18}-C_8$	<10	38	30	clear
$C_{20}-C_6$	19	58	10	opaque
$C_{18}-C_9$	28	37	60	clear
$C_{20}-C_8$	<10	36	30	clear
$C_{22}-C_6$	34	55	10	opaque
$C_{22}-C_8$	27	52	10	clear

[a] Geminis arranged in order of total number of carbons in two chains. [b] Transition temperature determined by DSC. [c] Jelly. [d] Determined by DLS, ± 5 nm. [e] At the minimum gel concentration.

stumbled across the very system for which we had been searching! In the next section, we describe the gels' properties.



C_{18}-C_8

General Properties. Ten zwitterionic geminis, C_A-C_B, were investigated (Table 1). They differ in hydrophobicity with the total number of chain-carbons ($A + B$) varying from 22 to 30. They also differ in asymmetry with the number of the long-chain carbons minus that of the short-chain carbons (A − B) varying from 6 to 14.

Gels were obtained by immersing the solid geminis in water (without sonication) for several hours. Four geminis in Table 1 with gel transition temperatures (T_m, to be discussed later) greater than 25 °C were warmed gently and vortexed to achieve homogeneity. No organic solvents were ever used.

A useful parameter describing a gel, namely the minimum gelator concentration (MGC) necessary to form the gel, can only be approximated. To a large extent, the parameter depends on the experimental method. Ours consisted of preparing aqueous solutions of the gelators at various concentrations in 1.0 cm diameter vials. The lowest concentration required to retain the material (for at least 10 s) in an inverted vial was designated as the MGC. Table 1 lists MGC values for the 10 geminis along with the gels' appearance at the MGC (clear or opaque to the eye). With the exception of $C_{18}-C_6$ (which forms a fluid "jelly" up to 10% concentration), all the geminis begin to gelate within a fairly narrow concentration range (36−79 mM or 2−4 wt-%).

Dynamic light scattering gave the first indication that aqueous gemini solutions might contain vesicles or, at least, vesicle-sized structures. Thus, measurements at l mM gelator (almost 2 orders of magnitude more dilute than the MGCs) indicated the presence of particles with hydrodynamic diameters ranging from l0−60 nm (Table 1). The larger particles (30−60 nm) fall within the size-range of small unilamellar vesicles. This is consistent with published work on symmetrical zwitterionic geminis that, at concentrations as low as l mM, also self-assemble into vesicles.[22] Because the smaller particles (10−20 nm) lie at the border between micelles and vesicles, their morphology cannot be precisely defined here by light scattering. Confirmatory proof that vesicle formation does indeed occur, and information on vesicle self-assembly, are provided next.

Electron microscopy allowed direct visualization of our gemini systems. We made use of two complimentary methods: cryo-high-resolution scanning electron microscopy (cryo-HRSEM)[24] and transmission electron microscopy (TEM). Simply stated, cryo-HRSEM involved plunge-freezing aqueous gemini solutions in liquid ethane to embed the colloidal particles in vitreous ice. The specimen, coated with a l nm layer of Cr on a freshly fractured surface, was then transferred to the upper stage of a field emission SEM. Images of $C_{14}-C_8$ and $C_{18}-C_8$, traced at −110 °C, are given in Figure l. It is evident that the samples consist of a network of interconnected vesicle-sized particles (occasional single vesicles and vesicle clumps were also seen). Linear strands (our sought-after "pearls on a string"!) can reach l μm in length before they branch. Diameters of the strings' vesicular constituents are consistent with the dynamic light scattering data.

TEM was also used although it has a disadvantage not present with cryo-HRSEM: water removal from a TEM sample under high vacuum risks an unwanted morphological change. Nevertheless, TEM provided valuable information. As seen in a TEM of a 0.1 mM sample of $C_{18}-C_8$ (Figure 2), several vesicles have burst (no doubt to release internal water within them). The bursting proves that the geminis are indeed forming hollow vesicles rather than mere solid particles.

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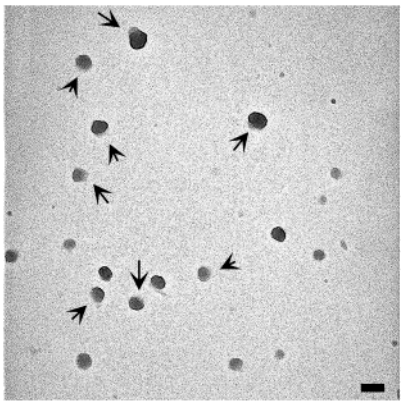


Figure 2. TEM of vesicles in a 0.1 mM aqueous solution of $C_{18}-C_8$. Arrows indicate the "broken" side of vesicle. Bar = 100 nm.

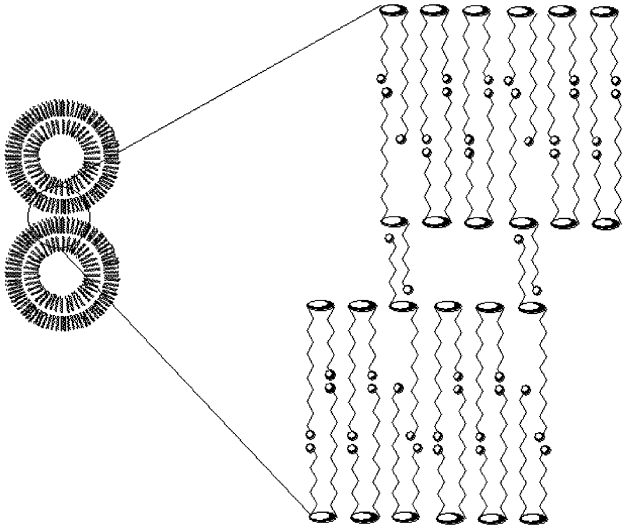


Figure 3. Proposed mechanism of vesicles cohesion.

$C_{18}-C_6$ is an unusual gemini in that it is the only one of the 10 geminis that forms a fluid "jelly" rather than a gel (Table 1). Cryo-HRSEM images (not shown) tell us why. Even at l.0 mM the $C_{18}-C_6$ gemini prefers to form 200 nm to 2 μm clumps as opposed to elongated strings. This supports the notion that vesicle networks are in fact necessary for gelation. Note in this connection that Hoffmann et al. have gelated water using high concentrations (5−15 wt-%) of octanol/oleate mixtures.[25] These authors have suggested that vesicles assume a dense hexagonal packing as in a cubic lattice. It is possible that a string morphology gradually converts into a liquid crystalline array of the Hoffmann type as the concentration increases. The viscosity increases accordingly.

One final interesting but complicating feature of the gemini family is seen from their T_m values listed in Table 1. Thus, when heated in a differential scanning calorimeter, the gels displayed broad endothermic peaks centered at their T_m values. Six gels have T_m values below 25 °C, whereas four gels have T_m values above 25 °C. Because there is no obvious correlation between T_m and structure, the parameter is poorly understood on a molecular level. Yet T_m is important because the gels become metastable *below* their T_m; even modest mechanical stress leads to a nonviscous turbid suspension.

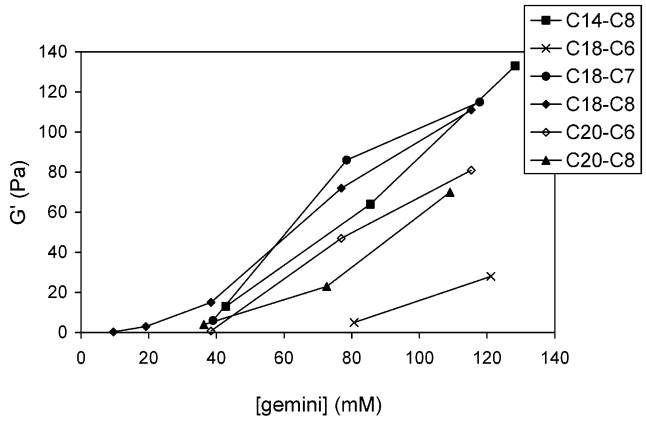
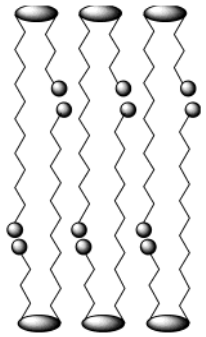


Figure 4. Elastic modulus G' at 25 °C for several geminis as a function of concentration. The lines are merely eye guides.

Most of our work was done with the gels having T_m values far below 25 °C so that room-temperature instability was not a problem.

Mechanism of Gelation. The key observation is that the asymmetric geminis in Table 1 ($C_{14}-C_8$, $C_{18}-C_7$, $C_{22}-C_6$, etc.) form "sticky" vesicles. In contrast, previous work has shown that geminis with greater symmetry ($C_{14}-C_{12}$, $C_{12}-C_{12}$, $C_{14}-C_{16}$, etc.) form noncohesive vesicles.[22] Why the difference? What attractive forces among the asymmetric geminis could compensate for the electrostatic and hydration factors that tend to keep vesicles separated? To answer these questions, we postulate that the asymmetric geminis self-assemble into bilayers with interdigitated chains as shown below (the terminal methyls being emphasized as dark circles). Other packing modes are conceivable, but they entail costly gauche conformations and/or hydrocarbon exposure to water, neither of which is present in our proposed model. Interdigitation (which is also found in certain phospholipid systems)[26] is attractive because the chains effectively fill the interior space of the bilayer.



When two asymmetric gemini vesicles approach, an interesting thing can happen: A short chain in each vesicle exits its bilayer and projects into the aqueous medium. These two short chains then associate hydrophobically, thereby noncovalently attaching one vesicle to the other (Figure 3). The close proximity of the vesicles may prompt other short chains to cooperatively follow suit, forming a cohesive "patch". Of course, this mechanism for cohesion creates a defect in the bilayers. Molecular reshuffling might help the vesicles accommodate a defect by distributing the disorder over many molecules. But

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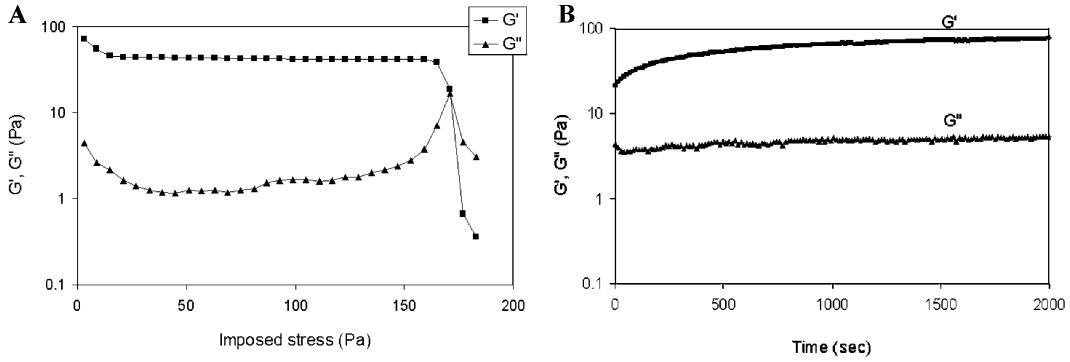

Figure 5. (A) Elastic modulus G' and viscous modulus G'' (1 Hz, 25 °C) for 77 mM $C_{18}-C_8$ as a function of imposed stress. The yield stress is defined as the crossover point. (B) Recovery of G' and G'' after gel was broken at ca. 175 Pa; compare with (A).

owing to the defect problem, a vesicle cannot sustain an abundance of intervesicular binding sites. Were it otherwise, the gemini-based vesicles would probably assemble into rather uninteresting clumps at low concentrations (and, as mentioned, $C_{18}-C_6$ does in fact do so). Vesicles made from symmetric or near-symmetric geminis (e.g., $C_{12}-C_{14}$) do not cohere because, we presume, partitioning of a long chain into the water is unfavorable and, in addition, loss of a long chain from the bilayer would leave behind a destabilizing "injury". In summary, it is proposed that hydrophobic association between two sets of short chains, one set from each vesicle, opposes normal repulsive forces and leads to a "pearl necklace" morphology.

Rheology. Vesicle strings can be regarded as a type of polymer whose "monomer" component is a vesicle. Our "monomers" are joined not by covalent bonds, as with most conventional polymers, but by weak hydrophobic forces. A question arises, therefore, as to the fragility of the vesicle strings that, conceivably, might break under an applied stress. If the strings do break, then a second question arises with regard to the rate of string repair. Because broken strings would be expected to weaken the gel, such questions can be addressed via the flow characteristics of the gel. This then takes us into the realm of rheology. Rheology has been often called "a difficult subject",[27] but we have found that mastering a few basic principles, outlined in the next paragraph, sufficed for our purposes.

We used a Bohlin controlled-stress rheometer employing a cone-and-plate configuration. Thus, a thin layer of gel (ca. 1.2 mL) is positioned between a round flat plate at the bottom and a round conical plate (40 mm diameter, 4° cone angle), fixed to a rotatable shaft, at the top. The cone oscillates at a constant torque that the rheometer converts directly into the important "stress" parameter (expressed in Pascal units). A position sensor on the oscillating shaft measures the amplitude of the gel's deformation to provide a unit-less "strain". A complex modulus G^* is defined as the ratio of stress-to-strain as the cone oscillates. G^* is in turn comprised of two useful components which will be plotted in our graphs: (a) G', the elastic modulus that represents the ability of a deformed material to "snap back" to its original geometry and (b) $G"$, the viscous modulus that represents the tendency of a material to flow under an applied stress. The rheometer automatically provides G' and G'' in Pascal units. For an ideal solid, $G'' = 0$; for an ideal liquid, $G' = 0$. Gels generally have finite values for both parameters, the relative values of which reveal whether the gel is "solidlike" or "liquidlike". Most runs were conducted at an oscillation frequency of 1 Hz and a constant target strain of 0.001. G' and G'' values, determined with an error of less than 5%, were independent of the oscillation frequency from 0.1 to 4 Hz.

At an oscilation frequency of 1 Hz or greater, and at 77 mM gemini surfactant, the elastic modulus G' (with typical values of 50−100 Pa) always exceeded the viscous modulus G''. This difference reached an order of magnitude for $C_{18}-C_8$, $C_{18}-C_7$, and $C_{20}-C_8$. Thus, the elastic (or "solidlike") behavior of the gels dominates over their viscous (or "liquidlike) properties. This is another way of saying that G' resembles G^*. Because G' and G^* are, on an absolute basis, rather small, the gels can be categorized as "weak" (although the distinction between weak and strong gels has not been clearly defined). For comparison we can cite $G' = 10^5$ Pa for some of our L-cystine gels, whereas $G' = 100$ Pa for the relatively nonrigid (but commercially important) xanthan gum gels.[28] Figure 4 shows that the elastic modulus G' increases smoothly with concentration.

The yield stress, designated σ_y, refers to the applied stress above which the gel starts to flow. Usually this point is determined by measuring the stress value at which G'' becomes larger than G' (in a so-called amplitude sweep experiment). An example of such an experiment is shown for 77 mM $C_{18}-C_8$ in Figure 5A. The gel succumbs to the applied stress and begins to flow at about 170 Pa. At a constant 100 mM concentration, five gemini gels display a "strength" according to the following order: $C_{18}-C_8 > C_{20}-C_8 > C_{14}-C_8 > C_{18}-C_7 > C_{18}-C_6$. For example, the yield stress of $C_{18}-C_8$, $C_{18}-C_7$, and $C_{18}-C_6$ are 250, 75, and 10 Pa, respectively. Lengthening the nitrogen-bound chain from six to eight carbons can, therefore, strengthen the gel by a remarkable factor of 25. Although a six-carbon chain likely leaves its bilayer "home" more readily than can an eight-carbon chain, chains with eight carbons achieve a greater hydrophobically driven overlap during the cohesive attachment. Of course, when the both chains becomes long (as in $C_{12}-C_{14}$), then the chains remain in the bilayer, and no cohesion at all is observed. In summary, cohesion appears to exist in a delicate balance: If one of the chains is too short, then its intervesicular attraction to another short chain weakens. And if both chains are too long, then they remain in the bilayer. Intermediate lengths, however, fortuitously promote cohesion.

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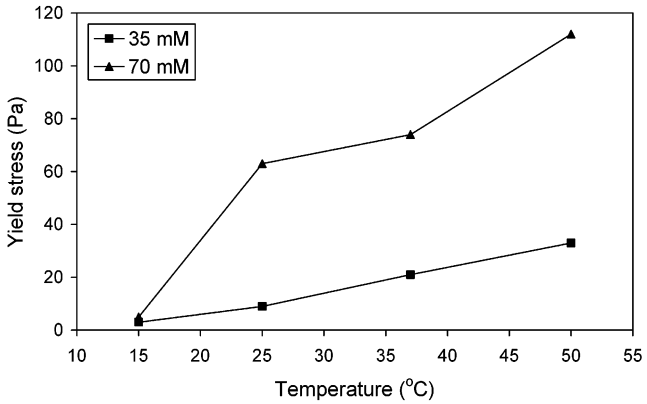

Figure 6. Yield stress for $C_{22}-C_8$ at two concentrations as a function of temperature. The lines are merely guides to the eye.

We next addressed the question of reversibility. If a vesicle network is mechanically disrupted, and the gel is destroyed, will the vesicles reassemble back into a gel? Figure 5B shows that a $C_{18}-C_8$ gel (77 mM, 4 wt %), subjected to a destructive torque exceeding the yield stress, recovers within 0−2 min at 25° C. Fast recovery was also found for $C_{18}-C_6$, $C_{18}-C_7$, $C_{14}-C_8$, $C_{20}-C_6$, and $C_{20}-C_8$ (all gels with T_m values below 25 °C). Clearly, above the T_m the broken vesicle strings can rapidly mend themselves spontaneously. One might thus regard the strings as self-healing polymers. Many known small-molecule gels are, of course, mechanically irreversible. If, for example, gels are formed from interlocking crystallites,[1,29] then the crystallites, once broken, usually remain that way.

The four gels in Table 1 with $T_m > 25$ °C are indeed destroyed irreversibly at 25° C by mechanical stress. We speculate that below the T_m the gemini molecules are more rigidly structured within their bilayer and thus less prone to "share" chains with a neighboring bilayer. As a consequence, the vesicle network, formed initially by warming above the T_m, becomes fragile below it. Once this network is broken, it will not reform unless the temperature is once again raised above the T_m.

G' and G'' turn out to be complicated functions of temperature which differ for each gel. Fortunately, the data can be adequately summarized by means of two pertinent observations. The first one involved slowly heating of the gels from 25° to 85 °C while subjecting them to a small, discontinuous (2 s on, 10 s off) oscillating stress (1 Hz and 3 Pa). The point at which the viscous modulus G'' exceeds the elastic modulus G' was taken as the "gel-to-sol" transition temperature T_{GS}. We found a particularly sensitive dependence of T_{GS} (at 35 mM gemini) on gemini structure: $C_{14}-C_8$ (28 °C); $C_{18}-C_8$ (69 °C); and $C_{20}-C_8$ (>85° C). In other words, at a constant length of the short chain, the longer the "permanent" chain, the more robust the gel. Because the T_m of $C_{20}-C_8$ is <10° C (Table 1), it seems unlikely that the high-temperature stability of the $C_{20}-C_8$ gel reflects the fluidity of its vesicular bilayer. More likely, the longer chains impart to the vesicle a greater propensity to share a vesicle's short chain with another vesicle (which, according to our model, is the event leading to gel formation). In anthropomorphic terms, a vesicle with long chains, such as C_{20}, can better afford to be generous with its short chains whose departure would cause a lesser overall disruption to the bilayer packing.

A second point from the temperature data is also revealing. Figure 6 shows the yield stress of $C_{22}-C_8$ as a function of temperature at two concentrations. Recall that the yield stress is the stress at which the gel "breaks". As long as T_{GS} is not exceeded, the "strength" of the gel is seen to actually increase with temperature. Whether this is a general phenomenon with the other geminis remains to be determined, but Figure 6 beckons for an explanation nonetheless. Within the context of our model, it would seem reasonable that a higher temperature facilitates the departure of the short chains from the vesicle interior (an effect that, apparently, more than compensates for the disruptive effect that a temperature rise generally has on aggregation processes). It is, of course, the intervesicular overlap of the short chains that induces string formation and the subsequent gelation of the water.

Final Remarks

If, as the texts write,[26] rheology is a difficult subject, then it is also fair to say that gels are elusive materials. To illustrate, take the example of gel-strength among our geminis. According to the yield stress criterion, $C_{18}-C_8 > C_{20}-C_8$. But according to T_{GS}, the transition temperature, $C_{20}-C_8 > C_{18}-C_8$. Another puzzling feature of our gels is their high sensitivity to rather modest changes in structure. For example, $T_{GS} = 28$ °C for $C_{14}-C_8$, whereas $T_{GS} = 69$ °C for $C_{18}-C_8$. And $T_m <$ l0° C for $C_{18}-C_8$, whereas $T_m = 19$ °C for $C_{20}-C_6$ (although both have a total of 26 chain carbons). Gel formation and properties depend on a complex combination of factors including some, such as packing constraints, of which we have only a distant understanding. Although a great deal has been learned about our gemini gels, and we can even make a reasonable case for a gelation mechanism, only the beginning of the story is being written. Those who assert that chemistry has nowhere to go[30] should contemplate the gel.

Experimental Section

Synthesis. The gemini surfactants in Table 1 were synthesized as described previously.[22,23] The compounds were characterized by ^1H, ^{13}C, and ^{31}P NMR, HRFAB-MS, and elemental analysis.

Instrumental Methods. Dynamic light scattering measurements were performed on an N4 Plus Coulter particle sizer. Measurements (taken at a 90° angle, at temperatures exceeding the particular T_m, and at 1 mM concentrations) were repeated three or four times while collecting data for 30 min each. Cryo-high-resolution scanning electron microscopy was carried out at −110° C as described in the text using the upper stage of an ISI DS-130F field emission scanning electron microscope. Transmission electron microscopy involved negatively stained samples on carbon-coated grids imaged with a JEOL-1210 at 80 kV. Transition temperatures T_m were obtained with a Hart Scientific differential scanning calorimeter upon heating suspension of zwitterionic geminis (1−10 mg/mL) at the rate of l0 °C/h. The suspensions were prepared by alternately heating and vortexing the surfactants in Milli-Q water until opaque suspensions were produced. Rheological experiments were carried out on a Bohlin controlled-stress rheometer as described previously [1] and in the text.

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