sustainable chemistry

Article

# Lysine-Based Silicone Surfactants

**Abygail Camacho Ramirez [1], Miguel Melendez-Zamudio [2], Antonio Guerra Contreras [1] and Michael A. Brook [2],***

[1] Department of Chemistry, Division of Natural and Exact Sciences, University of Guanajuato, Noria Alta S/N, Col. Noria Alta, Guanajuato C.P. 36050, Gto., Mexico
[2] Department of Chemistry and Chemical Biology, McMaster University, 1280 Main St. W, Hamilton, ON L8S 4M1, Canada
* Correspondence: mabrook@mcmaster.ca

**Abstract:** Highly efficient silicone surfactants are typically based on polyether hydrophiles. As part of a program to increase the natural content of silicones, we describe the synthesis of silicone surfactants with amino acid hydrophiles (cysteine, arginine, and lysine). The compounds were prepared using a radial thiol–ene reaction with vinylsilicones for cysteine derivatives and a catalyst-free aza-Michael reaction with arginine and lysine. Short chain surfactants with silicone monomer:hydrophile ratios of 5:1 or less (e.g., telechelic silicones of lysine-linker-$(Me_2OSi)_n$-linker-lysine n = 10) were ineffective at stabilizing emulsions of silicone oil ($D_4$): water. However, excellent surfactants were realized as the chain length (n) increased to 25 or 50, stabilizing water-in-oil emulsions with high water content (80% or 90%). The surfactants, especially the longer chain compounds, were stable against pH except <4 or >9 and survived freeze/thaw cycles. These surfactants contain 12–25% natural materials, improving their sustainability compared to those containing synthetic hydrophiles.

**Keywords:** surfactants; silicone; lysine; W/O emulsions

**Citation:** Camacho Ramirez, A.; Melendez-Zamudio, M.; Guerra Contreras, A.; Brook, M.A. Lysine-Based Silicone Surfactants. *Sustain. Chem.* **2023**, *4*, 197–208. https://doi.org/10.3390/suschem4020015

Academic Editors: Valeria La Parola and Leonarda Liotta

Received: 18 March 2023
Revised: 26 April 2023
Accepted: 28 April 2023
Published: 4 May 2023

## 1. Introduction

There are strong moral, scientific, and commercial reasons to make more sustainable chemical products. One approach to achieving this involves the use of natural feedstocks and/or the inclusion of natural materials within a product. In certain industries, such as personal care, this trend is particularly strong. Several additional strategies may be considered to achieve this goal as encoded in the 12 principles of Green Chemistry [1].

Silicone surfactants are widely used in many technical areas, ranging from agriculture, where they facilitate the spreading of pesticides/herbicides on leaf surfaces [2], to urethane foams [3], where they aid in controlling bubble density and size [4]. These surfactants possess very unusual properties because, among other things, of the much lower surface energy of the silicone component than analogous hydrocarbons. While silicone oils have an acceptable end-of-life performance—they degrade to $CO_2$, water, and sand; evidence for rapid degradation of agricultural adjuvants in the environment has also been reported [5,6]. Countervailing this argument for sustainability, however, is the significant energy input required for silicone synthesis [7].

The traditional hydrophiles in silicone surfactants—either trisiloxane super wetters or rake-type polymers with a silicone backbone and pendent hydrophiles—are poly ethers, particularly polyethylene glycol (PEG) and polypropylene glycol [4,8–10]. Concerns have been raised about PEG-type molecules because, among other things, they may have an immunological impact on humans. The wide trisiloxane agricultural adjuvants have been linked to issues in pollinators, like bees [11], although it is currently unclear what the mode of action is. There is, therefore, a desire to develop surfactants, including those derived from silicones, that have low levels of toxicity, rapid degradation in the environment to benign materials, and overall improved sustainability. One strategy to attempt to address these goals would utilize natural hydrophiles in place of polyethers.

We have previously reported the preparation of silicone surfactants derived from sugars [12]. More attractive are silicones based on amino acids, as one would predict the ability to tune surfactancy based not only on the specific residues—hydrophobic and hydrophilic—but also on the pH of the emulsions, as these materials would have free amines and/or carboxylic acids. Organic amino acid surfactants have been noted for their green character [13]. Several groups have prepared silanes [14] or silicones utilizing amino acids, including atypical amino acids [15], hydrogels [16], and silicone, with which peptide chemistry was possible [17]. However, an examination of the surface chemistry of these materials is lacking.

We report the preparation of ionic and zwitterionic silicone amino acid surfactants based on cysteine, arginine, and lysine and report the ability of the surfactants to stabilize emulsions of low molecular weight silicone oil ($D_4$ $(Me_2SiO)_4$, D = $Me_2SiO$) in water.

## 2. Results

### 2.1. Making Surfactants

### 2.1.1. Cysteine

The thiol–ene reaction is an effective way to crosslink or introduce hydrophiles into silicone polymers [18–20]. These processes typically involve radically mediated processes in which a sulfur radical adds to a vinylsilicone during a radical chain process. Commercial vinylsilicone copolymers were reacted with cysteine HCl in the presence of 2,2-dimethoxy-2-phenylacetophenone (DMPA) under the irradiation of UV light (Figure 1A). Good yields required using an excess of cysteine; residual cysteine was removed using dialysis in water, which is inconvenient.

### 2.1.2. Lysine and Arginine

Acrylate-modified silicones readily undergo the aza-Michael reaction in high yield [15], particularly if there is a hydrophile proximal to the acrylic carbonyl [21]; catalysts are not required (Figure 1B). A small library of lysine- and arginine-derived surfactants was created in which the length of the central telechelic silicone chain ranged from 10–50; the reaction involved stirring at room temperature in an alcohol-water mixture; at the reaction's end, small quantities of residual solvent were removed by evaporation at 60 °C under vacuum. Most of the study focused on well-behaving lysine surfactants. A comparison was made of the impact of surfactant packages formed from an amino acid-rich or acrylate-rich starting ratio, respectively. For example, for **LYS10** 1:2 and 3:1, acrylate to amine mixtures were prepared. The mass of amino acid and silicone precursors were held constant and, therefore, as the molar mass of the telechelic silicone increased (i.e., a higher fraction of D units, D = $Me_2SiO$), these ratios fluctuated (Table S1). Note that lysine possesses 2 amine groups, of which the epsilon amine is typically more reactive. Aza-Michael reactions can therefore involve single or double reactions with acrylates (**1**, **2** (Figure 1)). Thus, in all cases described below, there were mixtures of compounds in the surfactant package.

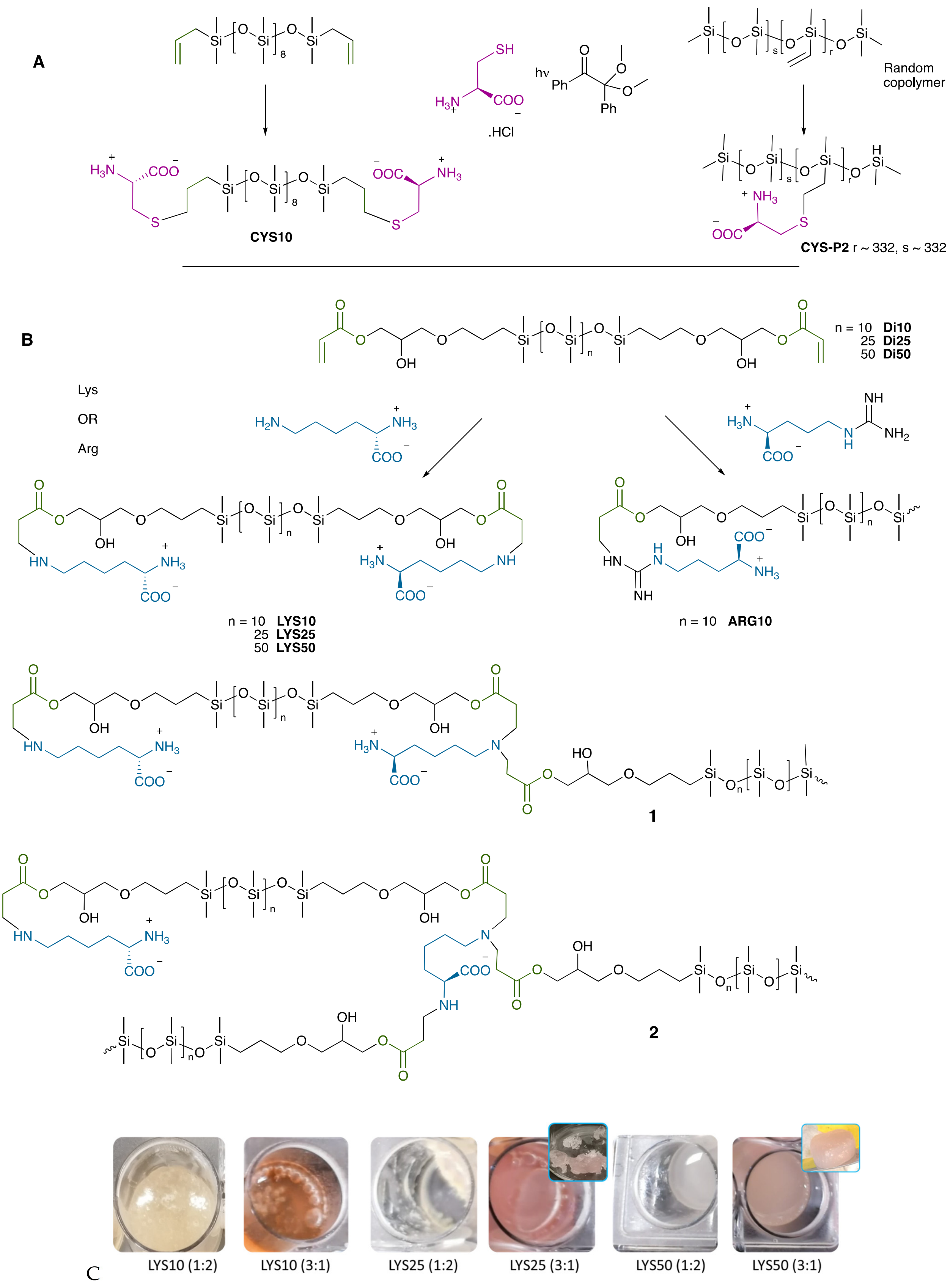


**Figure 1.** Synthesis of (**A**) cysteine-derived and (**B**) lysine-derived silicone surfactants. (**C**) Photographs of selected dispersions (note the pink coloration in the 3:1 dispersions is due to the presence of a very small quantity of dye that, it was hoped, would facilitate optical characterization but didn't).

### *2.2. Solvency*

The ability of the amino acid/silicone surfactants to stabilize emulsions was tested with a mixture of water and low molecular weight silicone oil, $D_4$. Therefore, the surfactants were initially examined for their solubility in various solvents, including water and $D_4$. These data and the calculated hydrophilic-lipophilic balance HLB and 3D-HLB [22], a term particularly useful for silicone surfactants that may have silicone components that are neither hydrocarbon lipophilic nor hydrophilic, are presented in Table 1 (for a discussion of HLB/3D-HLB, see SI).

**Table 1.** Behavior of surfactants in various solvents.

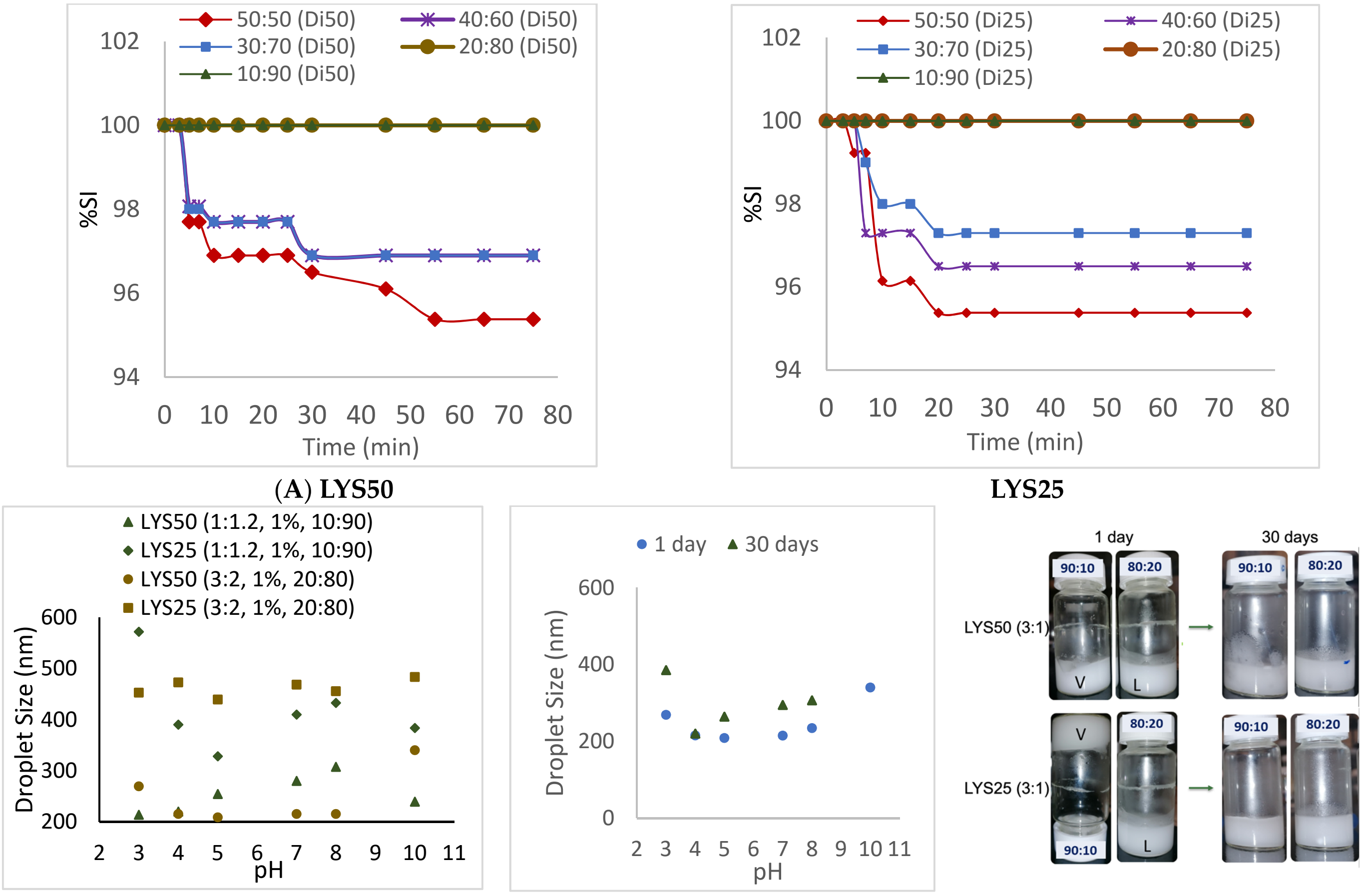
| **Sample** | **Solubility** [(a)] | | **Solubility in Organic Solvents** | **HLB** | **3D-HLB** | **Predicted Emulsion Type by 3D HLB** |
|---|---|---|---|---|---|---|
| | $D_4$ | $H_2O$ | | | | |
| **CYS10** | N | N | – | – | – | – |
| **CYS-P2** | N | N | EtOH P [(a)]<br>MeOH P | 4.61 | 4.61, 15.38 | W/O |
| **ARG10** | | | | | | |
| (1:2) [(b)] | N | N | EtOH S<br>MeOH S | 8.8 | 8.8, 11.1 | W/O |
| (3:1) | N | N | EtOH S<br>MeOH S<br>$CHCl_3$ S<br>TOL [(c)] S | | | W/O |
| **LYS10** | | | | | | |
| (1:2) | | N | EtOH S<br>MeOH S | 8.4 | 8.4, 11.6 | W/O |
| (3:1) | N | N | EtOH S<br>MeOH P | | | W/O |
| **LYS25** | | | | | | |
| (1:2) | P | N | TOL P | 4.6 | 4.6, 15.3 | W/O |
| (3:1) | S | N | $CHCl_3$: MeOH (1:1) P<br>TOL P | | | W/O |
| **LYS50** | | | | | | |
| (1:2) | P | N | TOL S | 2.7 | 2.7, 17.8 | W/O |
| (3:1) | S | N | $CHCl_3$: MeOH (1:1) P<br>TOL S | | | W/O |

[(a)] N Not soluble, S soluble, P partly soluble. [(b)] The ratio in parentheses is the ratio of mmol acrylate:mmol lysine in the formulation (Table S2). [(c)] TOL—toluene.

### *2.3. Surfactancy*

#### 2.3.1. Emulsion Types

Survey experiments were performed using the surfactants on emulsions ranging from $D_4$/water 100:0 → 0:100 in 10% increments; surfactant concentrations in these mixtures varied from 0.1–5 wt%. The ability to create emulsions depended, in particular, on the specific surfactant. Some of the compounds synthesized were essentially insoluble in either phase (Table 1, Table S2), although, in some cases, these materials could be encouraged to form emulsions by the temporary use of alcohol cosolvents (Table S2). However, it quickly became apparent that many of the materials prepared were not useful surfactants for either W/O (water in oil) or O/W (oil in water) emulsions due to insufficient solubility in either phase. In particular, short-chain silicone surfactants (a ratio of D:surface active silicone monomer < 10:1 ($s/r < 10$ or $n < 20$, Figure 1)) were ineffective. Most importantly, stable emulsions were only formed at a high water loading: 20:80 or 10:90 $D_4$:water (Figure 2A). Although the mixtures were mostly water, silicone was the continuous phase in these W/O emulsions (as could be seen by adding a drop of $D_4$ without shear).



**(A) LYS50** **LYS25**

**(B)** **(C)**

**Figure 2.** (**A**). Emulsion stability based on the index sedimentation over time for **LYS50** (1:1.2) and **LYS25** (3:2) at room temperature (SI = sedimentation index, see Section 4.5.1). (**B**). Droplet size as a function of pH for emulsions using **LYS50** and **LYS25**. (**C**). Emulsion stability at room temperature of **LYS50** (1:1.2, 1%, 80:20) as a function of pH and time.

### 2.3.2. Cysteine

The cysteine surfactant—a pendent material with ~50% cysteine-bearing and ~50% $Me_2SiO$ monomer species—was not soluble in MeOH or dispersible in water after purification and could not be tested. This was surprising, as analogous rake-type surfactants with polyether sidechains are frequently very effective surfactants [23]. **CYS10** was a very poor surfactant. It was not possible to prepare emulsions from formulations 1:3 or 2:1 (Table S1).

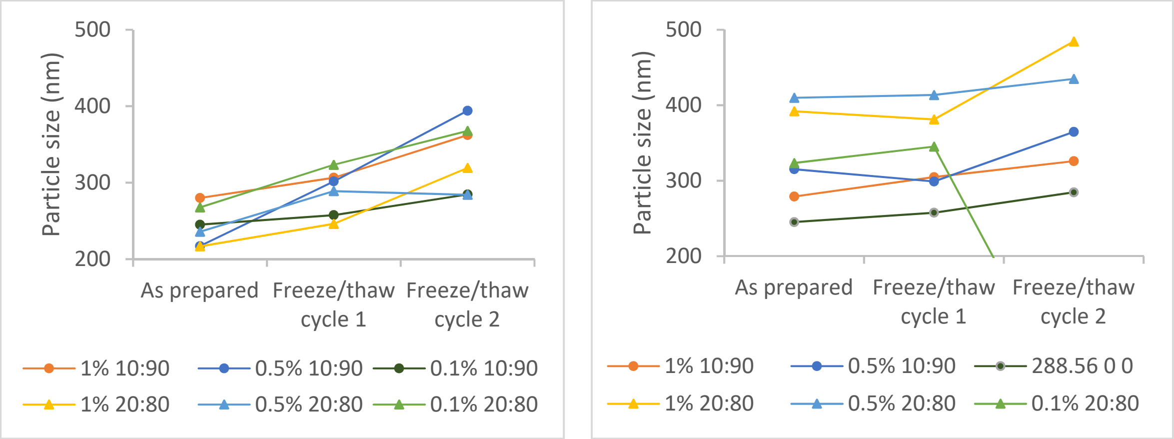
### 2.3.3. Lysine and Arginine

The short-chain telechelic derived from arginine **ARG10** was not an effective surfactant (Table S1). With lysine-derived surfactants, it quickly became apparent that emulsions rich in $H_2O$ were: more easily prepared; more stable; and that longer chain, telechelic silicone surfactants had better performance in stabilizing W/O emulsions, as judged using sedimentation over time. The shortest chain surfactant **LYS10** was not a very effective surfactant (Table S2), although better than either the short silicone chain surfactants **ARG10** or **CYS10**. Therefore, the remaining studies were undertaken with **LYS25** and **LYS50** (Figure 2A). Initially, experiments were undertaken with emulsions containing 1% surfactant in $D_4$/water emulsions to identify viable formulations. Once identified, the effect of surfactant concentration from 0.1 → 5% was examined. The stability of the emulsions was determined over time and after stresses that included changes in temperature and pH (Tables S1–S3).

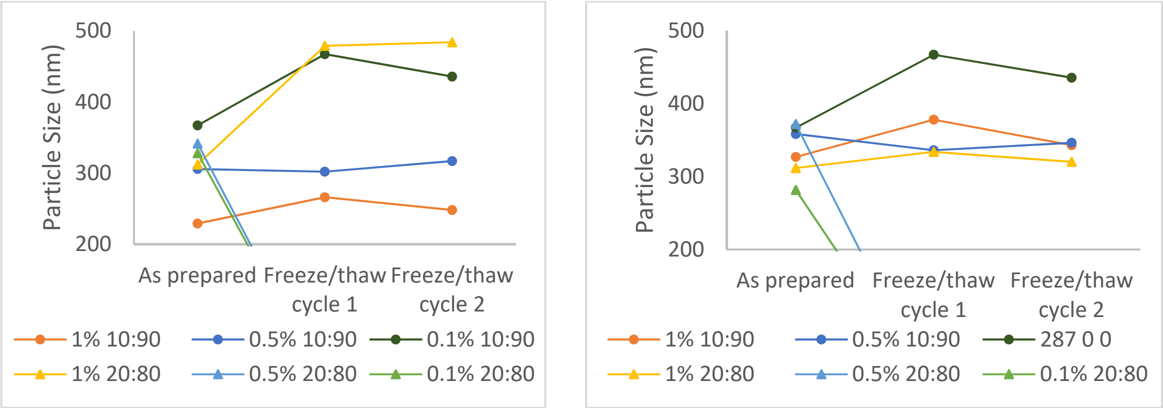
### *2.4. Emulsion Response to Stress: Droplet Size*

Droplet size was used to probe emulsion stability. Emulsions that appeared stable by eye were confirmed to be stable if only small changes in droplet size were observed. As an example, neither **LYS25** nor **LYS50** changed at pHs ranging from 3–10 over 2 days **LYS50** showed very little change over 30 days (Figure 2B,C). The latter observation is surprising in that silicones can undergo degradation/depolymerization at both low and high pHs [7]; only slight changes were noted at pH 3 and pH 10.

The emulsions were also subjected to the stress of freeze/thaw cycles. In these studies, a comparison was made between **LYS50** and **LYS25** at various concentrations in the $D_4$:water emulsions (Figure 3). Several trends are readily apparent: emulsions prepared with higher surfactant loading are typically more robust; the **LYS50** materials are more resilient than the **LYS25** surfactants; and the emulsions are typically more stable in 10:90 than 20:80 $D_4$:water mixtures.



(**A**) **LYS50** (1:1.2) (**B**) **LYS50** (1:7)



(**C**) **LYS25** (3:2) (**D**) **LYS25** (1:4)

**Figure 3.** Changes in particle diameter after freeze/thaw cycles as a function of surfactant, loading, and emulsions. (**A**,**B**) **LYS50** and (**C**,**D**) **LYS25**. The lines that migrate below 200 nm are indicative of broken emulsions.

## 3. Discussion

HLB and 3D-HLB are practical predictors for the behavior of surfactants at interfaces [22]. The very low surface energy of silicones dictates that, when considering hydrophobe content, a little goes a long way in a surfactant destined to emulsify silicone oil/water. Even with surfactants that had low D:amino acid ratios, the surfactants were expected to form W/O rather than O/W emulsions (Table 1) and, where emulsions did form—only with high ratios of water 20:80, 10:90 $D_4$:water—they were always W/O emulsions.

Several trends arise when examining the surfactancy of these silicone amino acid compounds, the most important of which is the fraction of silicone (D units, $Me_2SiO$) in the surfactant. Regardless of the 3 amino acids tested, short-chain silicones, with ratios of D:amino acid <5:1 did not perform well, regardless of whether they had telechelic or rake structures. Even with reasonable solubility (**CYS-P2** was insoluble in most solvents), these silicone-poor surfactants did not perform well. One possible explanation is that bridging between adjacent droplets with these short bolaamphiphiles could facilitate droplet coalescence **3** → **4** → emulsion breaking (Figure 4) [24,25].

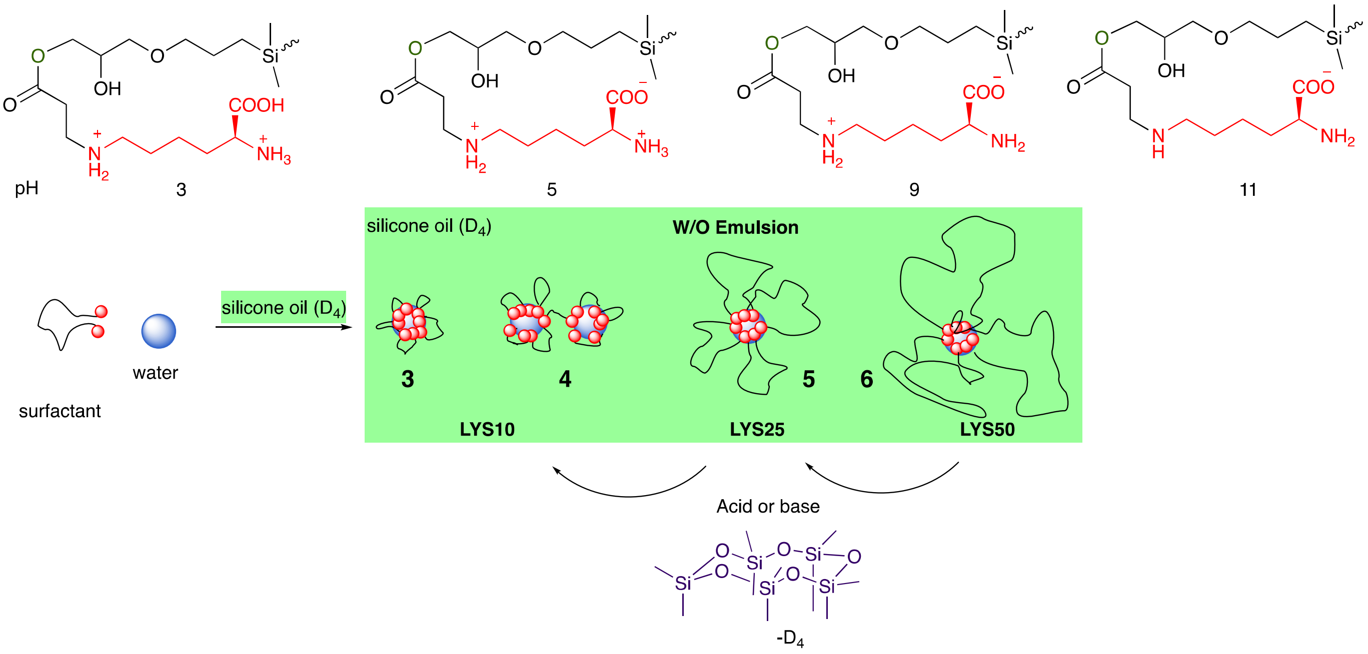


**Figure 4.** Model emulsions showing lysine chain ends at different pH; short-chain surfactants gain and loss of $D_4$ from surfactants at low/high pH.

Once longer silicone chains were involved, the emulsions were more highly stabilized, consistent with enhanced steric stabilization of the water droplets **5**, **6** (Figure 2A, Figure 4) [26]. This stabilization may arise simply because the droplet surface area is blocked and/or because the local viscosity of the interface will increase with increasing surfactant molar mass, which would additionally provide kinetic stabilization.

Droplet size was used as a surrogate for emulsion stability. That is, the interfacial area that can be stabilized by a given surfactant is linked to its efficiency; smaller droplets arise from better surfactants at a fixed surfactant concentration. Any action that changes the chemical nature of the surfactant, particularly its interfacial activity, will be reflected in droplet size changes. Regardless of pH, the LYS surfactants will be ionic. However, depending on pH, they could be cationic, anionic, or zwitterionic (Figure 4). Over short periods and based on droplet size, there were essentially no differences in interfacial stability for **LYS50** or **LYS25** surfactants, except at pH 3 and 10, where small deviations were observed (Figure 2B). Still, even after 30 days at these pH conditions, the surfactancy was resilient (Figure 2C).

It is well known that at more extreme pHs, silicones begin to equilibrate, leading to shorter (surfactant) chains and $D_4$ (Figure 4) [7]. That is, longer surfactant chains will become shorter, which eventually would be accompanied by lower effectiveness at interfaces, as shown with the **LYS10** compounds. Under these pH and time conditions, however, the level of degradation was low. The lysine residues that anchor the silicone surfactant to the aqueous surface may also provide local buffering. Neither water nor salts are very soluble in silicone oil, and the stability of the surfactant may be a consequence of the challenges the acids/bases face in actually reaching the silicone part of the surfactant within the $D_4$ silicone medium.

Freeze/thaw cycles are an excellent way to stress emulsions. It can be seen that **LYS50** performed better than **LYS25**, as judged by the lower number of broken emulsions. The higher viscosity **LYS50** may provide a better kinetic barrier to droplet aggregation—they are better steric stabilizers. The role of surfactant packages with an excess or deficit of lysine is unclear. It was anticipated that extended structures (e.g., **1**, **2** Figure 1) formed by multiple aza-Michael additions would significantly impact surfactancy. Within the ranges of acrylate:lysine tested, there were no strong differences in emulsion behavior.

One of the goals of this work is to migrate away from traditional polyether-based silicone surfactants. Green Chemistry principle 7 encourages the increasing use of natural feedstocks. **LYS50** and **LYS25** contain approximately 12 and 25 wt% natural materials (lysine/glycerol), respectively. Most amino acid syntheses require single or multiple protection, with attendant deprotection sequences. The approach used avoids the need for protection, which fits Green Chemistry principle 8. The data presented indicates that ionic lysine residues can serve as effective hydrophiles in silicone/water emulsions and improve the sustainability of the surfactants while doing so.

## 4. Materials and Methods

### 4.1. Materials

*L*-Lysine (LYS), *L*-arginine (ARG), *L*-cysteine hydrochloride (CYS·HCl), 2,2-dimethoxy-2-phenylacetophenone (DMPA), deuterated methanol ($D_3COD$), deuterated chloroform ($CDCl_3$), isopropanol (IPA), ethanol (EtOH), methanol (MeOH), and mineral oil and toluene were purchased from Sigma-Aldrich. Pendent poly(dimethyl,vinylmethylsiloxane, $Me_3SiO(Me_2SiO)_a(MeViSiO)_aSiMe_3$, a~332, **Vi2** molar mass ~50,000 g·mol$^{-1}$, 5000 cSt, VDT 5035), vinyl-terminated dimethylsiloxane ($ViMe_2SiO(SiMe_2)_8OSiMe_2Vi$ DMS-V03 **Vi10** molar mass 500 g·mol$^{-1}$) were purchased from Gelest. Octamethylcyclotetrasiloxane ($D_4$) was provided by Dow Corning (now Dow). Acrylate-terminated polydimethylsiloxane (**Di10**, molar mass = 550 g·mol$^{-1}$, **Di25**, 1000 g·mol$^{-1}$, and **Di50**, 2000 g·mol$^{-1}$, Figure 1 were kindly provided by Siltech Corporation. Buffer solutions (2 mM) were prepared using reagents purchased from Sigma-Aldrich. The pHs of buffers were adjusted with NaOH and HCl solutions: pH 3 (buffer: citric acid/sodium citrate), pH 4 and 5 (buffer: sodium acetate/acetic acid), pH 7 and pH 8 (buffer: potassium phosphate dibasic/potassium phosphate monobasic, and pH 10 (buffer: sodium bicarbonate/sodium carbonate). A dialysis bag (3.5 kD cutoff) was obtained from Spectra Por (Spectrum Laboratories), and a 14.5 k cutoff from Sigma Aldrich.

### 4.2. Characterization

$^1H$ and $^{13}C$ NMR spectra were recorded at room temperature on a Bruker Avance 600 MHz nuclear magnetic resonance spectrometer using deuterated solvents $CDCl_3$, toluene-*d8*, or MeOH-*d4*. The experiments were recorded in deuterated MeOH and toluene solvents. The spectral data were processed using Bruker Topspin software. Infrared spectroscopy was conducted using a Thermo Scientific Nicolet 6700 FT-IR spectrometer equipped with a Smart iTX attenuated total reflectance (ATR) attachment on thin films. Droplet size and zeta potentials were obtained using dynamic light scattering (DLS) with a Brookhaven 90 plus nanoparticle size analyzer, carried out at a scattering angle of 90° and a temperature of 25 °C.

### 4.3. Synthesis of Emulsifiers

#### 4.3.1. Cysteine-Derived Silicones

**CYS10** (Table S1): An excess of CYS·HCl (2.23 g, 14.2 mmol) was dissolved in MeOH (10 mL) and DMPA (36 mg, 0.14 mmol, 2.5%), then **Vi10** (4.0 g, 5.66 mmol) dissolved in THF (20 mL) was added. The solution was stirred at room temperature (RT), and then a 1:2 *v/v* solution of MeOH/THF was added until a transparent solution was obtained. The solution was irradiated for 2 h with a UV lamp (Analytik Jena (UVP-B-100AP), 100 watts, 1.27 W·cm$^{-2}$) at 365 nm. After the removal of solvents in vacuo, **CYS10** was obtained as a brown powder that contained unreacted CYS, which was removed by dialysis. First, **CYS10** (0.1 g) was dissolved in MeOH (5 mL), then deionized water (DIW) was slowly added dropwise with stirring. After the MeOH was removed using a rotary evaporator, the aqueous solution of **CYS10** in water was put inside of 3.5 kDa dialysis bag and placed in the dialysis medium (DI water 250 mL) at RT for 24 h. The dialysis medium was changed each 4 h. After 24 h, the now clean **CYS10** was lyophilized to obtain a white powder (Figure S1 and S9) $^1$H NMR data of the crude showed 100% conversion but, after isolation by dialysis, 75%.

**CYS10**: $^1$H-NMR (MeOH-d$_4$, 600 MHz): δ 4.18 (m, 2H), 3.21–3.14 (m, 2H), 3.10–3.03 (m, 2H), 2.70–2.65 (m, 4H), 0.95 (t, 4H, *J* = 8.7), 0.17–0.06 (m, 54H).

**CYS-P2** was prepared using the same procedure: **Vi2** (2 g, 12.5 mmol); MeOH (15 mL); DMPA (0.16 g, 0.62 mmol, 5.0%); THF (45 mL); 100% conversion of the vinyl products was observed after the irradiation process. The product was dissolved in water and placed in a 14 kDa cutoff dialysis bag (see preceding procedure) to give **CYS-P2** (for NMR, see Figure S1). Small batches (100 mg) were purified, from which 55 mg (55% yield) of pure product were obtained. For IR of the CYS samples, see Figure S2.

**CYS-P2**: $^1$H-NMR (MeOH-d$_4$, 600 MHz): δ 4.23–4.15 (m, 1H), 3.23–3.12 (m, 2H), 2.79–2.67 (m, 2H), 1.02–0.89 (m, 2H), 0.28–0.10 (m, 10H).

#### 4.3.2. Arginine-And LYSINE-Derived Silicones

Shown for **LYS10**. **Di10** (0.25 g, 0.454 mmol acrylate) was dissolved in methanol (0.25 mL, Table S1). LYS (0.13 g, 0.889 mmol) was dissolved in DIW (deionized water, 0.25 mL). The two solutions were mixed with manual stirring or a magnetic stir bar at room temperature (RT) to obtain the samples **LYS10** after 24 h reaction time. The products were concentrated under a vacuum. The same process was used to make **LYS25** and **LYS50**. For NMR, see Figures S3–S6; for IR, see Figures S7 and S8.

The lower solubility of ARG in IPA, toluene, DCM, and THF, called for a modified methodology. ARG was dissolved in DIW, a mixture of alcohol (EtOH: MeOH; 1 mL:1 mL) was added dropwise, and then acrylate **Di10** (0.25 g, 0.454 mmol) dissolved in MeOH (2 mL) was added with stirring at RT. Additional EtOH was added until complete solubilization was observed. After 12 h, the product solution was concentrated under a vacuum. The product was obtained as a white solid for 1:2 and a viscous liquid for a 3:1 molar ratio (Figure S9).

### *4.4. Emulsion Preparation*

Emulsions were prepared using concentrations (0.1%, 0.5%, 1%, 5%, *w/w*) of different emulsifiers. Volume ratios of the aqueous phase and oil phase (normally silicone oil, D$_4$) ranged from 10:90 to 50:50 (Table S2). The methodology used was based on the solubility of emulsifiers. As an example, in a round-bottomed flask equipped with a magnetic stir bar, **LYS50** (1:1.2) was dissolved in D$_4$, and then, with stirring for 1 h, water was added drop by drop to produce the emulsion at RT at 1600 rpm. Emulsions could also be prepared using ultrasonication, with modifications of mixing time and rpm (see Tables S2 and S3). The nature of mixing was not particularly important—emulsions formed in all cases.

For the low molecular weight surfactants based on **Di10**, and also for **Vi2**, it was necessary to use a cosolvent method to solubilize surfactants in the D$_4$ oil. As an example, **CYS10** (1:2) was dissolved in MeOH and D$_4$ or dissolved in MeOH. Then, water was added drop by drop with stirring (1600 rpm) at RT. Finally, the MeOH was removed by slow evaporation in an oven (60 °C). It is important to note that for high surfactant loadings, e.g., 5% in 20:80 or 10:90 D$_4$:H$_2$O, it was necessary to use IPA or MeOH as cosolvents.

### *4.5. Emulsion Characterization*

#### 4.5.1. Visual Stability

Emulsion stability was measured by visual observation over time function to obtain a% of sedimentation index [27,28] using the formula

$$\%S = \frac{Hc}{Ht} * 100$$

where $\%S$ is the sedimentation index, $Hc$ is height change over time, and $Ht$ is the total height of volume emulsion. The samples were allowed to sit at room temperature for 30 days, and then emulsion stability was noted via changes in particle size (Figure 3).

#### 4.5.2. Particle Size Analysis

Freshly prepared mixtures were diluted tenfold to obtain an emulsion with a surfactant concentration of 0.5 $\text{mg}\cdot\text{mL}^{-1}$. Particle size and distribution were measured using dynamic light scattering (DLS using a Brookhaven 90 plus nanoparticle size analyzer, carried out at a scattering angle of 90°) at 25 °C. Droplet size as a function of various parameters is reported in Figure 3, Tables S3–S5.

### *4.6. Stressing the Emulsions*

#### 4.6.1. pH

The impact of pH on emulsion stability was measured at pHs ranging from 3 to 10. To perform the experiment, an appropriate quantity of fresh emulsion was put in contact with a respective buffer (~100 mg in 10 mL buffer), and the samples were diluted tenfold to obtain a stock emulsion from which was prepared an emulsion of 0.5 $\text{mg}\cdot\text{mL}^{-1}$. Stability measurements were made 2 days after the emulsions were prepared. The same procedure was carried out for the sample **LYS50** after 1 month of storage. All measurements reflect the average of 3 replicates (Figure 2, Table S2).

#### 4.6.2. Temperature

A selection of those samples judged to be stable were subjected to 2× freeze/thaw cycles that involved: cooling to −10 °C overnight; moving the sample to room temperature until melting was complete; particle size characterization of the emulsions. The degree to which the emulsion broke, and could be reformed, was measured, as seen above in Table S3.

## 5. Conclusions

The synthesis of lysine-derived silicone surfactants is straightforward using an aza-Michael reaction that requires no catalyst and occurs under mild conditions. Useful surfactants for silicone water-in-oil emulsions were observed only at higher silicone/lysine ratios. The materials were surprisingly resilient to stresses, such as shifts in pH or temperature, inferring the ionic association of the ammonium carboxylate head groups.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/suschem4020015/s1, Selected NMR, IR spectra, and photographs of surfactants; Tables of preparative quantities, emulsion formation, emulsion particle sizes as prepared and after thermal stress, including Table S1. Preparation quantities for surfactants, Table S2: Formation of emulsions, Table S3. Droplet size after and before freeze/thaw (F/T) cycles temperature, Table S4. Droplet size at different pHs, and, Table S5. Emulsion preparation using Lys50 (3:1) by high energy methods.

**Author Contributions:** Conceptualization, M.A.B., A.G.C.; methodology, M.A.B., M.M.-Z., A.C.R.; validation, M.M.-Z., A.C.R.; formal analysis, M.A.B., M.M.-Z., A.C.R.; resources, M.A.B., A.G.C.; writing—original draft preparation, M.A.B.; writing—review and editing, M.A.B., M.M.-Z., A.C.R., A.G.C.; supervision, M.A.B.; project administration, M.A.B., A.G.C.; funding acquisition, M.A.B., A.G.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Natural Sciences and Engineering Research Council of Canada, Dirección de Apoyo a la Investigación y al Posgrado and División de Ciencias Naturales y Exactas-Universidad de Guanajuato, JuventudEsGto and CONACYT México.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The data presented in this study are available in the Supplementary Material.

**Acknowledgments:** We acknowledge with gratitude the financial support of the Natural Sciences and Engineering Research Council of Canada. We thank Tony O'Lenick for helpful discussions and Xiao Wu for assistance in running the particle size experiments.

**Conflicts of Interest:** The authors declare no conflict of interest.

**Sample Availability:** Samples of the compounds are not available from the authors.

## References

1. Anastas, P.T.; Warner, J.C. *Green Chemistry Theory and Practice*; Oxford University Press: Oxford, UK, 2000.
2. Stevens, P.J.G. Organosilicone surfactants as adjuvants for agrochemicals. *Pestic. Sci.* **1993**, *38*, 103–122. [CrossRef]
3. Snow, S.A.; Pernisz, U.C.; Braun, R.J. "Tying up loose ends"—Silicone surfactants as stabilizing agents for flexible polyurethane foam. *Silicon Chem.* **2006**, *3*, 1–10. [CrossRef]
4. Hill, R.M. *Silicone Surfactants*; Dekker: New York, NY, USA, 1999.
5. Bonnington, L.S. Analysis of Organosilicone Surfactants and Their Degradation Products. Ph.D. Thesis, The University of Waikato, Hamilton, New Zealand, 2000.
6. Radulovic, J.; Sefiane, K.; Shanahan, M.E.R. Ageing of trisiloxane solutions. *Chem. Eng. Sci.* **2010**, *65*, 5251–5255. [CrossRef]
7. Brook, M.A. Silicones. In *Silicon in Organic, Organometallic and Polymer Chemistry, Chapters 9 and 12*; Wiley: New York, NY, USA, 2000; pp. 256–308, 381–458.
8. Svitova, T.; Hoffmann, H.; Hill, R.M. Trisiloxane surfactants: Surface interfacial tension dynamics and spreading on hydrophobic surfaces. *Langmuir* **1996**, *12*, 1712–1721. [CrossRef]
9. Stoebe, T.; Lin, Z.X.; Hill, R.M.; Ward, M.D.; Davis, H.T. Surfactant-enhanced spreading. *Langmuir* **1996**, *12*, 337–344. [CrossRef]
10. Hill, R.M. Superspreading. *Curr. Opin. Colloid Interface Sci.* **1998**, *3*, 247–254. [CrossRef]
11. Chen, J.; Mullin, C.A. Characterization of Trisiloxane Surfactants from Agrochemical Adjuvants and Pollinator-Related Matrices Using Liquid Chromatography Coupled to Mass Spectrometry. *J. Agric. Food Chem.* **2015**, *63*, 5120–5125. [CrossRef]
12. Lusterio, A.; Brook, M.A. Naturally Derived Silicone Surfactants Based on Saccharides and Cysteamine. *Molecules* **2021**, *26*, 4802. [CrossRef]
13. Morán, M.C.; Pinazo, A.; Pérez, L.; Clapés, P.; Angelet, M.; García, M.T.; Vinardell, M.P.; Infante, M.R. "Green" amino acid-based surfactants. *Green Chem.* **2004**, *6*, 233–240. [CrossRef]
14. Provatas, A.; Matisons, J.G.; Smart, R.S.C. α-Amino Acid−β-Hydroxysiloxanes on E-Glass Fibers. *Langmuir* **1998**, *14*, 1656–1663. [CrossRef]
15. Genest, A.; Portinha, D.; Pouget, E.; Lamnawar, K.; Ganachaud, F.; Fleury, E. Zwitterionic Silicone Materials Derived from Aza-Michael Reaction of Amino-Functional PDMS with Acrylic Acid. *Macromol. Rapid Commun.* **2021**, *42*, 2000372. [CrossRef]
16. Xu, C.; He, R.; Xie, B.; Ismail, M.; Yao, C.; Luan, J.; Li, X. Silicone hydrogels grafted with natural amino acids for ophthalmological application. *J. Biomater. Sci. Polym. Ed.* **2016**, *27*, 1354–1368. [CrossRef] [PubMed]
17. LaRonde, F.J.; Brook, M.A.; Hu, G. Amino acid and peptide chemistry on silicones. *Silicon Chem.* **2002**, *1*, 215–222. [CrossRef]
18. Lucas, P.; Fleury, E.; Estur, J.-F.; Lapinte, V.; Robin, J.-J. Peroxide-Grafted PDMS: Hydrosilylation Reaction and Thiol-Ene Chemistry as an Alternative Pathway. *Macromol. Chem. Phys.* **2009**, *210*, 1933–1941. [CrossRef]
19. Zheng, S.; Zlatin, M.; Selvaganapathy, P.R.; Brook, M.A. Multiple modulus silicone elastomers using 3D extrusion printing of low viscosity inks. *Addit. Manuf.* **2018**, *24*, 86–92. [CrossRef]
20. Hoyle, C.E.; Bowman, C.N. Thiol-Ene Click Chemistry. *Angew. Chem. Int. Ed.* **2010**, *49*, 1540–1573. [CrossRef]
21. Lu, G.; Yepremyan, A.; Godfrey, S.; Mohr, C.; Herrlein, M.; Brook, M.A. Aza-Michael silicone cure is accelerated by β-hydroxyalkyl esters. *J. Polym. Sci.* **2021**, *59*, 1935–1941. [CrossRef]
22. O'Lenick, A.J., Jr.; Parkinson, J.K. Three-Dimensional HLB: This revolutionary development helps formulators choose surfactants for stable oil, water and silicone emulsions. *Cosmet. Toilet.* **1996**, *111*, 37–44.
23. O'Lenick, A.J., Jr. Silicone emulsions and surfactants. *J. Surfactants Deterg.* **2000**, *3*, 387–393. [CrossRef]
24. Zhang, X.; Wang, C. Supramolecular amphiphiles. *Chem. Soc. Rev.* **2011**, *40*, 94–101. [CrossRef]
25. Mansuri, E.; Zepeda-Velazquez, L.; Schmidt, R.; Brook, M.A.; DeWolf, C.E. Surface Behavior of Boronic Acid-Terminated Silicones. *Langmuir* **2015**, *31*, 9331–9339. [CrossRef] [PubMed]
26. Pelton, R.; Osterroth, A.; Brook, M.A. Silicone stabilized poly(methyl methacrylate) nonaqueous latex: 2. Flocculation by degradation of the steric layer. *J. Colloid Interface Sci.* **1991**, *147*, 523–530. [CrossRef]

27. Annan, W.S.; Fairhead, M.; Pereira, P.; Walle, C.F.v.d. Emulsifying performance of modular β-sandwich proteins: The hydrophobic moment and conformational stability. *Protein Eng. Design Sel.* **2006**, *19*, 537–545. [CrossRef] [PubMed]
28. McClements, D.J. Critical Review of Techniques and Methodologies for Characterization of Emulsion Stability. *Crit. Rev. Food Sci. Nutr.* **2007**, *47*, 611–649. [CrossRef]