From Silica to Silicones: A Course Design Introducing Basic Concepts of Material Science into High School Chemistry Class

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Abstract

Silica- and silicone-based materials offer a wide range of applications in everyday life. Silica-based materials, for instance, are being used in scratch-resistant coatings on glasses, for the absorption of unpleasant odors in cat litter, act as gelling agents in food items like ketchup and serve as drying agents in the form of silica gel beads. Silicones on the other hand, are being used in the form of baking utensils and ice cube trays as well as lubricants, thermal or caulking compounds and in waterproofing treatments. On account of their useful properties such as thermal stability, resistance to weather, UV radiation, elasticity and flexibility, silicones are still of current interest in science research. Especially the recent use of microemulsions in templating procedures led to functional enhancements in monolithic materials with nanometer-range pores.[1-3]

In this contribution, we will present a teaching unit designed for schools and student laboratories, introducing basic concepts of material science on the example of silica and silicones. In addition to experiments demonstrating some of the characteristics of the above mentioned materials, the unit contains a simple synthesis of monolithic silicone as well as several experiments investigating some of its properties, such as thermal stability, hydrophobia and gas adsorption.[4]

In the course of this unit, students will encounter a number of topics consistent with curricular requirements. While the synthesis allows the revision and practice of reaction types such as hydrolysis and condensation, other chemical topics like surfactants and solubility can also be addressed.[1,5] Furthermore, these nonhazardous materials and chemicals allow high student participation during all experimental stages of the teaching unit.

1. Introduction

The study of materials and the enhancement of their properties has been one of the main focuses in science research for years. Especially recent progress in the field of nanotechnology has opened up a wide range of new research areas in the material sciences. Especially nanoparticles possess a number of new and modified properties compared to their respective bulk materials. Among these properties are different melting and boiling points, changes in electric conductivity, reactivity and magnetic properties as well as the occurrence of fluorescence. [6] Due to these properties, nanoparticles are already enhancing the UV protection of sunscreen lotions, increasing the scratch resistance of car paints and allowing the development of stain-resistant and antibacterial surfaces.

Two of the materials currently of interest are silica and silicones. Silica, also known as silicon dioxide, is most commonly found in nature as quartz. While silica is mostly being used in cement and necessary for the production of glass and optical fibers, it is also useful for odor absorption in cat litter, enhancement of the abrasion resistance of tires and as gelling agents in ketchup. Moreover, research focusing on silica-based nanomaterials led to the development of mesoporous silica. While this material appears as a white powder at the macroscopic level, it is composed of particles with an ordered pore system with pore-diameters ranging from two to ten nanometers at the submicroscopic level. Additionally, it is non-toxic and exhibits a high surface area as well as a high temperature stability and is therefore currently being tested as a carrier for catalysts and energy-storing substances.[1,2]

Silicones, on the other hand, are synthetic inorganic-organic polymers based on alternating silicon-oxygen chains with organic side groups attached to the four-coordinated silicon atoms (see Fig. 1) and can be differentiated by the number of cross-linkages within the molecule.

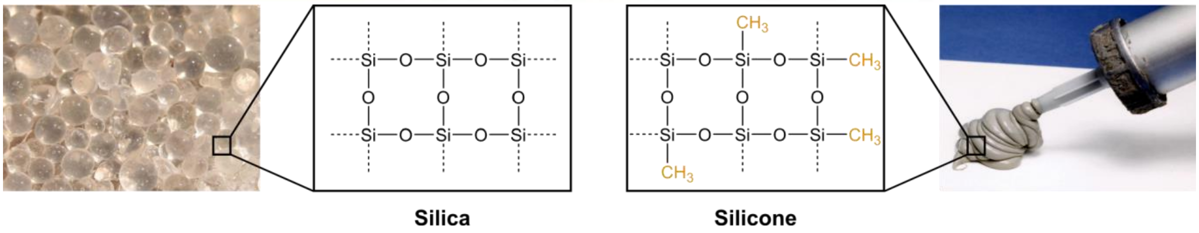


Fig. 1 *Typical molecular structure of silica vs. the structure of silicone*

Silicone properties are low viscosity for short-chained molecules and water repelling and electrically insulating properties for long-chained, linear molecules. Furthermore, high elasticity as well as heat and UV resistance can be achieved with a large amount of cross-linking within the molecules. As a result, the field of application is wide. Silicones are being used as lubricants, thermal and caulking compounds and defoamers. Furthermore, household objects such as flexible keyboard pads and kitchen utensils, e.g. bakeware and ice cube trays, are also made of silicone.

More recently, mesoporous silicones have been developed by using surfactants as templating agents. These easy to synthesize, non-toxic silicones with pores under 50 nm resemble marshmallows in morphology, color, texture and elasticity. Because of their large surface area, non-polar properties and high thermal stability, they can be used in separation processes. Areas of application include oil spills as well as grease fires.[4]

Given their prominence in everyday objects as well as their importance in current research, both silica and silicones offer great educational potential. Considering the synthesis of silica, for instance, reaction mechanisms such as hydrolysis and condensation can be addressed while the investigation of different types of silicones gives knowledge about the relationship between structure and properties.

2. Design of the Teaching Unit

In order to allow students to achieve deeper insight into current research endeavors, the presented teaching unit was based on the concept shown in Fig. 2. This concept suggests that in order to form a deeper understanding of scientific topics, subject-specific aspects need to be combined with students' prior knowledge. While researchers often assume scientific principles to be true, in school those principles need to be explained and embedded into contexts relevant to students' everyday life. In doing so, students are given the opportunity to develop greater concepts by understanding the underlying cognitive process.

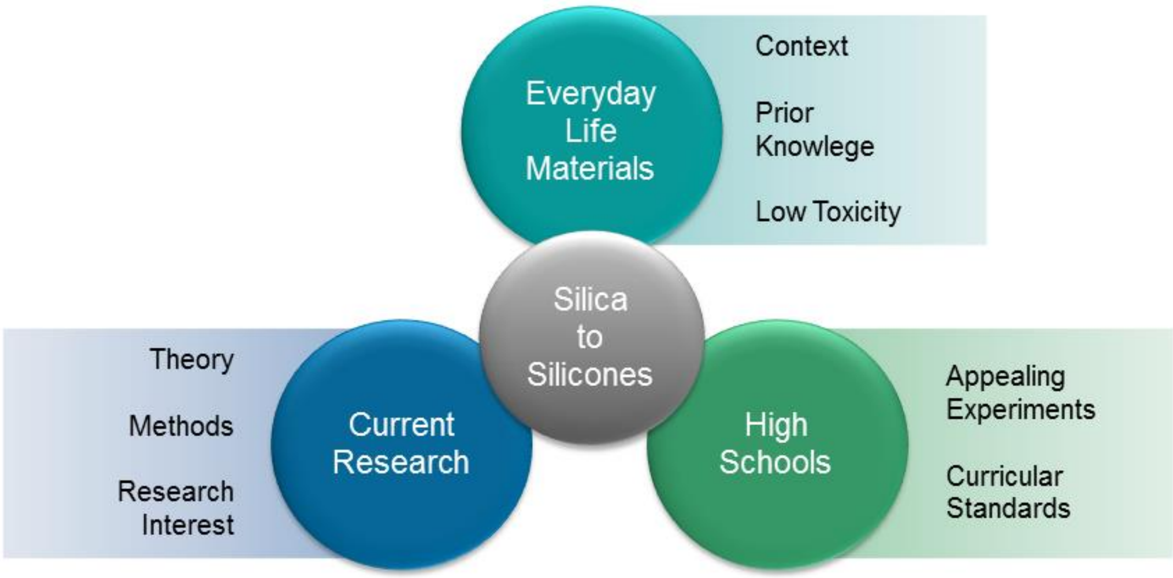
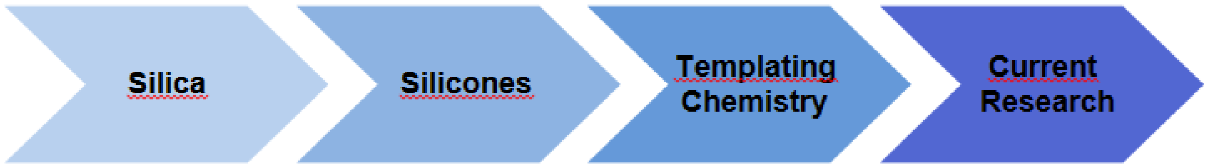


Fig. 2. *Concept for the Teaching Unit "From Silica to Silicone".*

By basing the unit on the concept above, further aspects such as curricular standards and teaching methods have to be considered. Therefore, the experiments embedded in the unit offer a number of topics consistent with curricular requirements. Understanding the underlying principles of the synthesis of monolithic silicones, for instance, requires knowledge about reaction mechanisms such as hydrolysis and condensation. Once synthesized, further topics like separation methods, hydrophobic and hydrophilic properties as well as micelle-formation can be explored and discussed. Moreover, all experiments were carefully chosen and modified to only require non-hazardous materials and chemicals so that students themselves can carry out the experiments.
The teaching unit “From Silica to Silicones” (

Fig. **3**) is divided into four consecutive sub-units illuminating different chemical traits of silica and silicones and leading up to the aforementioned current research. In order to adjust the unit to school routines, each of the sub-units is designed for a 90 or a 180 minute time frame.



- Natural Occurrence
- Applications
- Properties
- Detection
- Synthesis (hydrolysis, condensation, sol-gel chemistry)

- Properties of organic/ inorganic matter
- Structural properties
- Applications

- Templating processes
- Templating agents (surfactant chemistry)
- Nanodimension

- Synthesis of mesoporous silica and silicones
- Investigation of enhanced properties (hydrophobia, heat resistance, gas absorption)
- Possible areas of application (oil spills, grease fires, separation processes)

Fig. 3. *Course design for the teaching unit “From Silica to Silicones”.*

3. Selected Experiments

During the development of the teaching unit “From Silica to Silicones”, multiple experiments were chosen for the different sections described in

Fig. **3**. In the following section, three experiments concerning the synthesis of mesoporous silicones and the investigation of their properties will be presented. These are examples of experiments found in the last sub-unit ‘Current Research’.

3.1 Synthesis of a Mesoporous Silicone

1.5 g urea are dissolved in two respective beakers containing 4.5 mL of water. After the addition of 0.27 g of the surfactant cetyltrimethylammonium bromide (CTAB) to one of the two solutions, it is stirred for 20 minutes. The other solution acts as a reference. After adding 0.9 mL of dimethyldimethoxysilane (DMDMS) and 0.6 mL methyltrimethoxysilane (TMMS) to both solutions, the mixtures are stirred for another 60 minutes. Finally, both solutions are transferred into respective wide-necked jars which are tightly closed and heated to 80 °C for 9 h in an oven (see Fig. 4)
After a 3 hour cooling period, the excess liquid is drained and the product is carefully removed from the jar and transferred into a petri dish. In order to remove the surfactant from the silicone with the added CTAB, a water-ethanol mixture (1:1) is poured over the silicone which is then carefully squeezed out by hand. While the silicone synthesized with the help of a surfactant resembles a marshmallow in form, color and elasticity, the other silicone is rather flat and firm in nature.

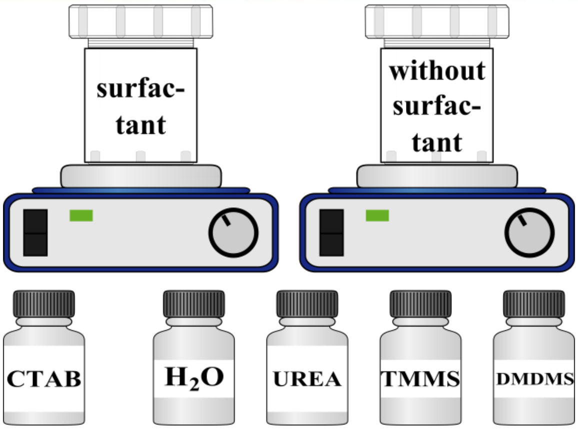


Fig. 4. *Experimental setup for the synthesis of mesoporous silicones.*

3.2 Hydrophobic Properties of Mesoporous Silicones

The hydrophobic properties of mesoporous silicones can be demonstrated by wetting its surface with polar and nonpolar solutions respectively. In order to better distinguish the liquids, the non-polar solution is dyed with sudan red. The observations reveal that while the polar solution forms droplets on the surface, the non-polar solution is absorbed immediately, dyeing the mesoporous silicone orange in the process (see

Fig. **5**). This can be explained due to the alternating inorganic silicon-oxygen chains of the silicone molecules being shielded by organic methyl groups, which are hydrophobic in nature.

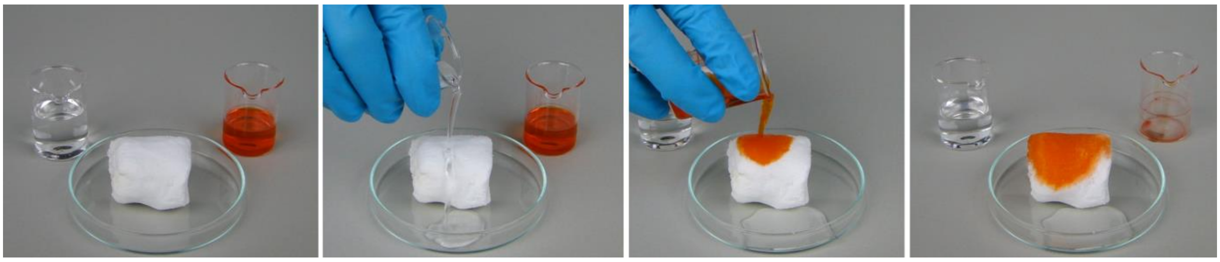


Fig. 5. *Demonstration of the hydrophobic properties of the mesoporous silicone with a polar (left) and a dyed non-polar solution (right).*

3.3 Heat Resistance of Mesoporous Silicones

In order to demonstrate the heat resistance of mesoporous silicones, a small piece of silicone is placed on a wire mesh on a tripod stand. By way of comparison, a small piece of an ordinary household sponge is placed next to the silicone. With the help of a gas burner, both pieces are heated equally as shown in

Fig. **6**. While the household sponge starts melting immediately, the silicone maintains its color and form. It takes a few minutes, in which the temperature increases, for the silicone to start glowing. After a short cooling period the silicone still maintains its form, but has lost its elasticity and is now brittle.

Fig. 6. *Demonstration of the heat resistance of a mesoporous silicone (right) in comparison to an ordinary household sponge (left).*

4. Conclusion

The unit “From Silica to Silicones” has the potential of introducing students to current research in material science including, for instance, the design of new materials, the enhancement of absorption capacities and hydrophobic properties. Moreover, with the help of selected experiments, students are enabled to understand the underlying principles needed for the synthesis of such new materials. Since silica and silicones are two materials with countless applications in students’ everyday life, an increase in student interest is expected. A further advantage of the unit is the non-hazardous nature of the experiments, allowing students to work autonomously. Additionally, the unit offers a number of topics consistent with curricular requirements, making it a potential unit for the chemistry classroom or an interesting project for both school and university settings.

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