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# Synthesis and Characterization of Surfactants Based on Natural Products

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B.Sc.

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## ABSTRACT

The thesis deals with the synthesis and characterization of surfactants derived from natural products. Physico-chemical properties, such as solubility and melting points, and surfactant properties, such as dispersion, emulsification, wetting and foaming were investigated.

A number of surfactants was synthesized from sugars and natural hydrophobic compounds. Monosaccharides, incl. D-glucose, 2-deoxy-2-amino-D-glucose, D-fructose and D-(+)-glucono-1,5-lactone, were used for the hydrophilic moiety of the surfactants. The hydrophobic moiety consisted of steroids, monoterpenes, rosin acids, fatty acids and long chain alkyl groups, as well as aromatic compounds. In general, the synthetic procedures gave relatively high yields in few steps. Some novel surfactants were prepared in high yields in one simple, synthetic step.

A simple model could not rationalize the general structure-property relationship of the surfactants since no clear trends could be observed. All surfactant properties were compared to those of common commercial surfactants. The aqueous solubility follows the general trend expected from the HLB of the surfactant when considerations about the character of the head group and the connecting unit are added. Some surfactants were able to form macroemulsions between water and different oils. The emulsions were stable for several months. Surfactants with open sugar head groups, in contrast to closed sugar head groups, were found to be better dispersion agents. Increasing the size of the tail group, by using twin chain tail groups, increased the dispersion properties further. The wetting properties of the sugar-based surfactants were generally found to be poor. Foaming properties were low for surfactants with low aqueous solubility.

Some surfactants were found to be particularly interesting: 1-deoxy-1-octylamino-D-glucitol is a very good foaming and wetting agent, as well as a good dispersion and emulsification agent. PEG- and sugar-based surfactants of dehydroabietic acid are good foaming agents with fair wetting properties. The sugar-based one is also a particularly good dispersion agent.

**Keywords:** surfactants, surface properties, natural products, melting point, wetting, foaming, dispersion, emulsification, solubility



# ABBREVIATIONS AND SYMBOLS

**COSY-gs** – A 2D-NMR method, used to detect homonuclear couplings, e.g.  $^1\text{H}$  to  $^1\text{H}$

**DEPT** – An NMR method, used to describe the multiplicity of a carbon atom

**HMBC-gs** – A 2D-NMR method, used to detect 2-3-bond heteronuclear couplings, for example  $^1\text{H}$  to  $^{13}\text{C}$

**HMQC-gs** – A 2D-NMR method, used to detect 1-bond heteronuclear couplings, for example  $^1\text{H}$  to  $^{13}\text{C}$

**HPLC** – High Performance Liquid Chromatography

**IR** – Infrared Spectrometry

**m.p.** – Melting Point

**MS** – Mass Spectrometry

**NMR** – Nuclear Magnetic Resonance

**SANS** – Small Angle Neutron Scattering

# LIST OF SURFACTANT TYPES AND TERMS

**APG** – Alkyl polyglucoside

**Adhesion** – The property of a surfactant to adsorb and stick to a solid surface.

**AE and  $C_mEO_n$**  – A surfactant composed of a straight hydrocarbon chain of m carbon atoms connected to a polyethylene oxide chain of n units via an ether bond.

**Cloud Point** – That temperature of a solution at which a nonionic surfactant, particularly a PEG-based one, increases its hydrophobicity and micellar size, to the point of clouding the solution.

**CMC** – Critical Micellization Concentration, the concentration in water at which individual surfactant molecules start to aggregate. A high CMC value indicates that the surfactant is hydrophilic and vice versa.

**CPP** – Critical Packing Parameter is a geometrical measure of a surfactant that gives an indication of the micellar packing properties.

**Dispersion** – The action of the surfactant to disperse (i.e. solubilize) ordinarily insoluble particles into a solution. Measured as amount solubilized by amount of surfactant.

**Emulsification** – The ability of a surfactant to form emulsions (drop-inclusion phase within phase systems) between two solutions ordinarily insoluble in each other. Usually defined as oil in water (o/w) and water in oil (w/o) emulsions, both being time- and temperature-dependent.

**EOR** – Enhanced Oil Recovery is the last, tertiary step in the oil acquisition process, where additives are used for forming emulsions.

**Foaming** – The ability of a surfactant to reduce the surface tension so that foam can be produced. Usually separated into Foamability, the ability to produce foam, and Foam Stability, the time-dependent stability of the foam produced.

**HLB** – Hydrophilic-Lipophilic Balance is a measure between the molecular weight ratio between a surfactant's hydrophilic and hydrophobic moieties. This can be given as calculated according to Griffin (the HLBG) or Davies (the HLGD).

**LAS** – Linear *p*-alkylbenzenesulfonate ion ( $p-C_nH_{2n+1}PhSO_3^-$ )

**NPE** – Nonylphenolethoxylate ( $p-C_9H_{19}Ph(EO)_n$ )

**PEG** – Polyethyleneglycol or Polyoxyethylene ( $HO-(CH_2CH_2O)_n-H$  or  $(EO)_n$ )

**PIT** – Phase Inversion Temperature is the temperature at which an emulsion changes state between an o/w and a w/o emulsion.

**SDS** – Sodium dodecylsulfate ( $C_{12}H_{25}SO_4Na$ )

**Solubility** – The solubility limit of a certain compound in a solution at a given temperature.

**Wetting** – The ability of a surfactant to decrease the contact angle between a droplet of a surfactant solution and a surface and thus increase the spreading of the droplet area.

# LIST OF PUBLICATIONS

The thesis is based on the following publications and manuscripts:

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- i. **Synthesis and Characterization of Surface Active Compounds derived from Cholesterol Derivatives and Glucose**\*  
Styrbjörn Byström, Martin Svensson, Peter S Piispanen, Bengt Kronberg, Irene Blute and Torbjörn Norin  
Accepted by *Journal of Surfactants and Detergents*
- ii. **Synthesis and Characterization of Dehydroabiatic Acid Derivatives Suitable for Surfactants Synthesis**\*  
Peter S Piispanen, Björn Hedman and Torbjörn Norin  
Accepted by *Journal of Surfactants and Detergents*, 5, 165-168, April 2002.
- iii. **Syntheses and Surface Measurements of Surfactants Derived from Dehydroabiatic Acid**\*  
Peter S Piispanen, Björn Hedman, Mikael Kjellin and Torbjörn Norin  
Accepted by *Journal of Surfactants and Detergents*
- iv. **Synthesis and Characterization of Surfactants via Epoxidation of Tall Oil Fatty Acid**\*  
Björn Hedman, Peter S Piispanen, El-Ouafi Alami and Torbjörn Norin  
Accepted by *Journal of Surfactants and Detergents*
- v. **Surface Properties of Surfactants derived from Natural Products. Part 1: Syntheses and Structure/Property Relationships – Solubility and Emulsification.**  
Peter S Piispanen, Marcus Persson, Per Claesson and Torbjörn Norin  
Manuscript prepared for *Journal of Surfactants and Detergents*
- vi. **Surface Properties of Surfactants derived from Natural Products. Part 2: Structure/Property Relationships – Foaming, Dispersion and Wetting.** Peter S Piispanen, Marcus Persson, Per Claesson and Torbjörn Norin  
Manuscript prepared for *Journal of Surfactants and Detergents*
- vii. **An Improved Method for the Synthesis of 2-Alkylamino-2-deoxy-D-glucopyranose and 1,2-Dialkylamino-1,2-dideoxy-D-(N)-b-glucose**  
Peter S Piispanen and Torbjörn Norin  
Submitted to *Journal of Organic Chemistry*
- viii. **Supplementary Material**

\* Papers I – IV are reproduced with permission by the *Journal of Surfactants and Detergents*.



# SUMMARY OF PUBLICATIONS

Paper I describes the syntheses of some steroid glucosides, the study of their properties as co-surfactants and their traditional role as stabilizers of liposomes. The developmental synthetic work of designing precursors of surfactants based on dehydroabietic acid is described in Paper II. Paper III is a direct extension of this work. PEG esters of dehydroabietic acid are synthesized and their surface properties are characterized. A useful surfactant derived from other natural hydrophobes, the tall oil fatty acids, is extensively studied in Paper IV, where synthesis, clouding behavior, dynamic and equilibrium surface tensions and adsorption on surfaces are studied in detail. Collective data from this thesis work are summarized in Papers V and VI. Basic surface properties such as CMC, solubility, wetting, foaming, dispersion, emulsification and chemical properties of the natural product based surfactants are presented and compared. An improved synthesis of a new class of pH-sensitive surfactants, derived from D-fructose, is presented in Paper VII. Unpublished synthetical procedures for some surfactants are given in Paper VIII, as supplementary material.

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# INTRODUCTION

Surfactant properties play important roles in the performance of a wide array of industrial and consumer products, including detergents, paints, paper products, pharmaceuticals and cosmetics.<sup>1</sup> Surfactants are also used in diverse exotic roles as emulsifiers during enhanced oil recovery from deeply located oil wells.<sup>2</sup>

The last few years show an increased interest in work involving the preparation and study of surfactants based on natural products. Examples are surfactants based on sugars,<sup>3-9</sup> sterols<sup>10</sup> and fatty acids.<sup>11</sup> Such surfactants are interesting because they are generally easily biodegraded.<sup>12</sup> In industry there is a desire to find new surfactants with improved properties, in comparison to conventional surfactants. Additionally, there is a trend to move towards a more sustainable production, using renewable natural products instead of petrochemical ones.

## SCOPE AND GOAL OF THE THESIS WORK

The goals of this thesis work have been as follows:

1. The development of easy and cheap syntheses of surfactants based on natural products. Although industrial upscaling of the synthesis has not been included, large-scale industrial production has been considered. The goal during the development of the synthetic procedures has been to minimize the number of steps and, thereby, provide a base for the development of industrial applications.
2. To be able to predict structure-activity relationships for the surfactants derived. The size of the hydrophilic moiety has been limited to monosaccharide structures or PEG-chains, while the hydrophobic moiety has been of great diversity. It has been desirable to understand the physical characteristics and surface properties based on the structural elements of the hydrophobe.
3. The synthetic methods shall lead to surface-active compounds, whose properties can be tailor-made by changing the hydrophobic moiety or the connection between the hydrophile and the hydrophobe. This goal will provide possibilities for the development of easily degradable, renewable, cheap and easily synthesized surfactants.

## WHY SURFACTANTS DERIVED FROM NATURAL PRODUCTS ?

Why is it important to use naturally occurring starting materials for the syntheses of surfactants? The existing commercial surfactants are mostly based on slowly degradable compounds and in not too few cases they are, or at some point during their degradation become, harmful to the environment or to human beings. The reasons for choosing natural raw materials are several:

### 1. Renewable starting materials

Natural raw materials are renewable, since they are derived from continuous ecological cycles. They are constantly produced in nature and thus, in principle, available for commercial use with little risk of shortage.

### 2. Cheap starting materials

Materials produced in nature are sometimes easy to obtain and purify, which results in low prices. Examples are sucrose, lactose, D-fructose, D-glucose, fatty acids and terpenoids.

### 3. Lower toxicity, less environmental impact

Since nature provides the starting materials, there are microorganisms that are adapted to the degradation of the products. When the surfactants are degraded into their natural, smaller components (i.e. hydrophobic and hydrophilic ones) it is assumed that they are included into the natural ecological cycles, without any significant toxicological impact. Most natural product based surfactants are also believed to be degraded fast and should, therefore, pass the eco-tests for toxicity, bio-degradability and bioaccumulation, necessary for commercial products. Thus, they will, hopefully, not put a burden on the natural balances as many of the non-natural products based surfactants do. For example, sugar-based surfactants show good skin compatibility<sup>13,14</sup> and are widely used in a range of cleaning formulations, from all-purpose cleaners to laundry detergents.<sup>15</sup> It should, however, be noted that the fact that a compound is naturally occurring by no means automatically mean that it is non-toxic.

### 4. Commercially feasible

For the various reasons mentioned (cheapness, non-toxicity etc.) surfactants derived from natural products offer a good substitute for existing surfactant types. The combination of cheap processes leading to effective surfactants with little or no toxic effect is a very desirable principle to choose. Being marks of environmentally safe products, viable from both a PR and an ideological point of view, the *White Swan* (in the Nordic Countries)<sup>16</sup> and

the *Blue Angel* (in Germany)<sup>17</sup> are becoming desired symbols of environmental safety.

## APPROACH AND METHODOLOGY OF THE THESIS WORK

The goal during the synthetic work has been to minimize the number of steps of the synthesis of the product desired. Ideally, all optimized synthetic procedures should have taken place in one-pot syntheses. Another goal has been to find cost efficient procedures. Therefore, starting materials derived in bulk, such as common monosaccharides, rosin acids, fatty acids etc., being reasonably cheap, have been the main starting materials. The costs have mainly originated from solvents and specific reagents.

It is important to realize that there is no universal surfactant good for every possible application. Different surfactants are needed for different applications, e.g. for wetting and foaming. That is the reason why so many different commercial surfactants are in use. The surfactants studied in this work have different useful properties.

The synthetic routes to surfactants are presented in **Chapter 1**, while the structure-activity relationships are studied and discussed in **Chapter 2**. Some conclusions are presented in **Chapter 3**.

## STARTING MATERIALS

The number of natural products is large, but only a limited number of them are suitable for being transformed into surfactants. Some compounds are too expensive for general use. It is also important that the starting materials possess the molecular handles needed for useful chemistry.

### *The Hydrophile*

In this work, the hydrophile is limited to monosaccharides, when surfactants based on natural products are prepared. A common, but not naturally derived hydrophilic group is the polyethylene oxide chain. A number of surfactants with this hydrophilic group are also prepared for comparisons. D-Glucose and D-fructose are useful monosaccharides, which offer suitable chemical properties. The disaccharide D-sucrose is not suitable, because its anomeric carbon atoms are locked up against a use as molecular handles, but bio-enzymatic esterification or similar could still produce defined and useful surfactants. The preparation of glycosides traditionally consists of the steps protection, activation, coupling and deprotection.<sup>18</sup> For technical applications, glucosides are prepared in one step

according to the Fisher glycosidation, which results in alkyl polyglucosides (APGs). Certain sugars, such as the monomer of chitosan, the 2-deoxy-2-amino-D-glucose (also a component of the natural surfactant Emulsan<sup>TM</sup> and believed to be the most abundant carbohydrate in nature), contain the most useful amino group, which is a strong nucleophile, as a molecular handle. They offer clear-cut, kinetic synthetic routes that yield useful products in one step.

### *The Hydrophobe*

Fatty acids are useful building blocks for the hydrophobic moiety of surfactants since they contain the useful, reactive carboxyl group, while the rest of the molecule is basically inert. Steroids with a hydroxyl or a keto group can also easily be employed for preparing surfactants, for similar reasons. Terpenes and diterpenes with a hydroxyl, aldehyde or carboxyl group are also useful. Simple alkanes are not suitable for surfactant preparations. Simple alkenes, however, may be used after introduction of an electronegative substituent onto the double bond, thus providing a molecular handle. Similarly, simple alkynes can be transformed to good hydrophobes.

### *The Connecting Bond*

The chemical bond between the hydrophobic and hydrophilic moieties plays a most vital role as to the properties of the natural product-based surfactants. It is usually desirable that the bond be stable towards hydrolysis during its applications, but that it can still be degraded in nature after disposal. The bond also has to have some degree of freedom of rotation to allow efficient packing of the surfactant molecules next to each other. Carbon-carbon bonds will be too stable for environmental degradation. The useful choices are the ether, amine, ester and amide bonds. Ether bonds are strong bonds, with a high degree of rotational freedom, and are, unfortunately, not easily degraded in nature, neither by bacteria, nor by chemical activity. Amino groups offer a similar degree of rotational freedom and become cationic under acidic conditions. Ester bonds, including those in carboxylates, phosphates and sulfonates, are useful and flexible and are easily degraded in nature and in aqueous solutions at non-neutral pH-levels. They are sometimes too easily hydrolyzed for certain applications. The amide bond offers a stable connection between the moieties. It is exceptionally resistant to basic hydrolysis and has good resistance towards acidic hydrolysis. The drawback is that the bond is rigid, which increases the crystallization potential of the compound and decreases the solubility of the surfactant in water. As a connecting bond, the amide bond prevents the necessary free rotation between the moieties. However, the strength of the bond still makes it useful for many applications. Living organisms possess enzymes for breaking down the amide bond, so that the surfactants should be rather easily degraded. The connecting bond may also differ in polarity, which reflects in the total

polarity of the surfactant.

## THEORY OF SURFACTANTS AND SURFACE CHEMISTRY

In this thesis some major properties of surfactants are briefly discussed. This account is prepared in order to provide a suitable background for the discussions in Chapter 2 of this thesis. The presentation is based on a recent comprehensive description of surfactant and polymer properties<sup>19</sup> as well as on information provided elsewhere.<sup>20, 21</sup>

Surfactant molecules, defined as surface-active agents, consist of a hydrophobic and a hydrophilic moiety that are clearly separated in the molecular structure. The polar part engages in electrostatic interactions (hydrogen bonding, dipolar interactions, ionic bonding etc.) with surrounding molecules, e.g. water and ions. The non-polar part, on the other hand, associates with neighbouring non-polar structures *via* hydrophobic and van der Waals interactions. The associated structures first formed when the surfactant concentration in an aqueous solution is increased are typically closed structures that are relatively small. Such structures are called micelles and they can exist in various sizes and shapes depending on surfactant concentration, surfactant structure, pH, ionic strength, temperature etc. The self-association process starts at a well-defined concentration, the micelle concentration, *CMC*. Thus, surfactants associate with both polar and non-polar compounds, but different parts of the surfactant are involved in the association with molecules of different polarity. Surfactants are usually classified according to their polar head group as anionic, cationic, nonionic or zwitterionic. This review pertains to the general properties of nonionic surfactants, unless otherwise stated.

### *Surface Tension*

The molecules of a liquid attract each other due to dispersion, dipole-dipole and dipole-induced-dipole forces, as well as hydrogen bonding. In the bulk liquid a molecule senses the same attractive and repellent forces in all directions, while for a molecule at the surface those forces are lacking in one direction. This asymmetry of forces is the origin of the surface energy or equivalent the *surface tension*. For example, there is a surface tension between water and air of the order of 73 dynes/cm (a unit that has a conversion factor of unity with mN/m, erg/cm<sup>2</sup> and mJ/m<sup>2</sup>). For the reasons mentioned above, a compound will possess higher surface tension, the more polar it is. Likewise, two liquids are immiscible if the surface tension between them is large, but for entropic reasons they are miscible if that tension is low enough. Then practically, what a surfactant does, is to lower the surface tension. This leads to increased solubility of non-polar molecules in aqueous solutions (e.g. solubilization of micelles). Surfactants can

also improve the stability of dispersions, emulsions and foams. There is, of course, a practical limit to how low the surface tension can be. With special formulations, so-called *ultra low interfacial tension*, values in the range of  $10^{-3}$  mN/m or lower can be reached. Such microemulsion systems are of interest for the purpose of *enhanced oil recovery* (EOR). A summary of the surface tension values of some liquids is found in Table 1.

**Table 1**

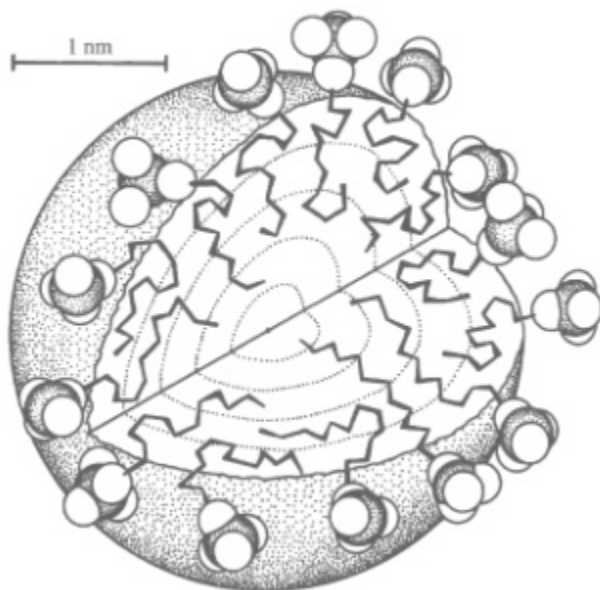
Surface tension values (in mN/m) of some liquids at 25 °C	
Water	72-73
10 % aq. NaOH	78
Aqueous surfactant solution	28-30 (at or above CMC)
Ethanol	22
Chloroform	27
Bromoform	45
Hexane	18
Octane	22
Dodecane	25
Hexadecane	27
Diethyl ether	17
Mercury	480

### *CMC and Micellar Growth*

When added to an aqueous solution, surfactant molecules minimize their energy by creating a monolayer on the air-water surface. This is a slow process with large molecules, for example polymers (equilibrium times can vary from seconds to days), but considerably faster for surfactants (ms-s). In order to minimize their free energy, the hydrophobic parts of the surfactants are directed towards the less polar air, while the hydrophilic groups are directed towards the polar water molecules. Upon increased surfactant concentration, the surface becomes increasingly saturated by surfactant molecules, which decrease the surface tension of the solution. In other words, the surface tension will decrease



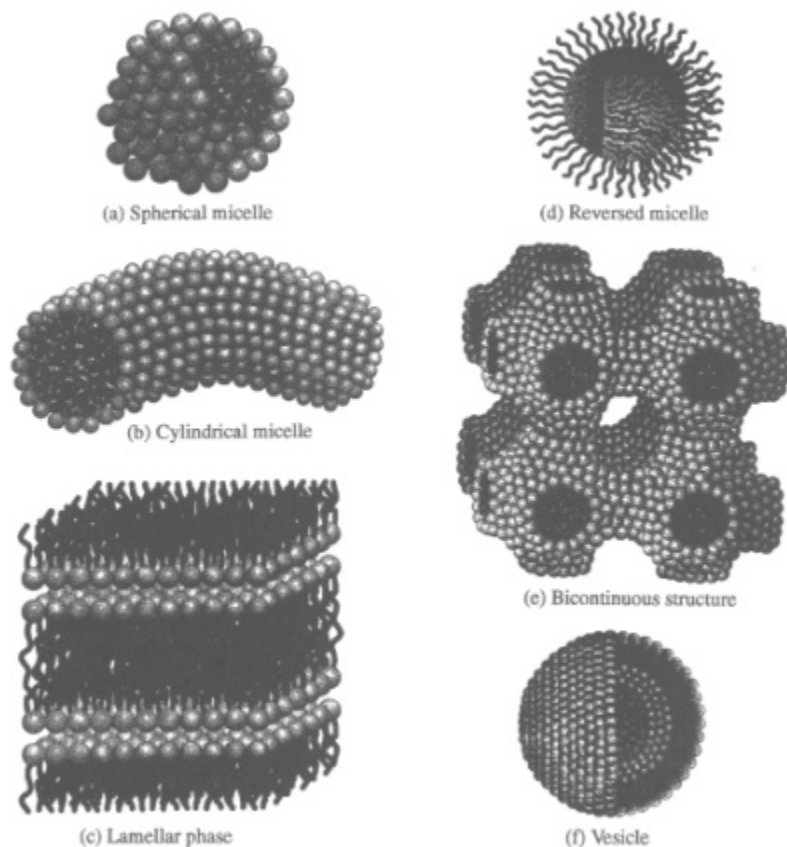
upon the addition of surfactants. The kinetic process can be followed by so-called *dynamic surface tension* studies. The low-concentration kinetics can be described by the *Ward-Tordai* equation, which assumes diffusion from the bulk and adsorption at the interface, here *NMR diffusion* experiments can be useful for determining the diffusion coefficient, using the *Stokes-Einstein equation*,<sup>22</sup> of the surfactant. The equilibrium situation is more commonly studied, and results in, among other things, the acquisition of the CMC value (see below), which is an important characteristic of the surfactants. The surface tension is commonly studied by means of a *Wilhelmy plate tensiometry apparatus*. The minimum surface tension reachable is determined by how effective the packing of the surfactants is at the surface and on the interactions between the surfactants at the interface; different hydrophobic and hydrophilic groups thus create different minimum surface tensions. With concentrations above the saturation point, called the critical micellization concentration, *the CMC*, the freely dissociated surfactant molecules in the water bulk phase start to form closed *micellar structures*, that can be spherical, oblate, prolate, tablet shaped or rod-like, with a hydrophilic surface and a hydrophobic interior (Figure 1). Such micelles usually have *hydrodynamic radii*,  $R_H$ , ranging from 20 to 400 Å. High accuracy measurements of the force between two solid interfaces coated with surfactants can be made by means of a *MASIF apparatus* (Measurement and Analysis of Surface Interaction Forces) or other surface force instruments.



**Figure 1.** An illustration of a spherical micelle (of dodecyl sulfate) emphasizing the liquid-like character with a disordered hydrocarbon core and a rough surface. (Redrawn from Jönsson, B., Lindman, B., Holmberg, K. and

Kronberg, B., Surfactants and Polymers in Aqueous Solution), ©1998 John Wiley & Sons Ltd., Chichester, Reprinted in April 2001, p. 36, Reproduced with Permission)

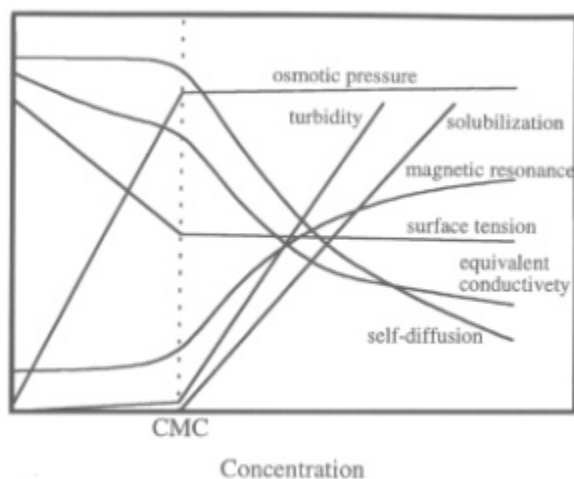
The CMC of polyoxyethylene-based surfactants decreases with increasing temperature. Sugar-based surfactants, as well as SDS, seem to exhibit minimum CMC values at given temperatures. The favorable decrease in energy gained from micelle formation further increases the solubility of the surfactant molecules themselves, as it also does with any non-polar organic compound trapped in the micellar interior.<sup>23</sup> At the CMC, usually in the order of  $\mu\text{M}$ - $\text{mM}$ , almost all further surfactant molecules are incorporated into the micellar structures and hence the adsorption to surfaces is also saturated. No noticeable decrease in surface tension is gained by increased surfactant concentrations above the CMC. Thus, the CMC can easily be determined, by application of the *Gibbs isotherm*, from a plot of the logarithmic surfactant concentration (often in  $\text{mM}$ ) vs. the surface tension ( $\gamma$ , often in  $\text{mN/m}$ ) of the solution. From such a plot it is also possible to calculate the adsorbed amount of surfactant at the interface, with the adsorbed amount being proportional to the slope of the surface tension isotherm (up to the CMC). For practical formulations, the CMC itself can be lowered by the addition of a molecule that is more hydrophobic than the surfactant itself, since the formation of micelles is then stimulated. Small rather hydrophobic compounds such as short chain alcohols also interact with surfactants. They affect the packing of the surfactant at the interface (e.g. affecting the foam stability). So-called *hydrotropes* are often small molecules with bulk hydrophobic groups and/or charged polar groups. They interfere with the packing of the surfactant and affects a range of properties, e.g. for ethylene oxide-based surfactants they increase the cloud point (the temperature at which the surfactant solution turns turbid due to a liquid-liquid phase separation). The actual radii of the micelles formed are determined by surfactant concentration and surfactant geometry. The size and shape can be effectively measured, for example by using a *SANS apparatus* (Small Angle Neutron Scattering). With further increased concentration the micelles increase in size, forming rod- or sponge-like structures instead, and begin to pack into lamellar, hexagonal or cubic structures (see Figure 2).



**Figure 2.** Surfactant self-assembly leads to a range of different structures, a few of which are shown here. (Redrawn from Jönsson, B., Lindman, B., Holmberg, K. and Kronberg, B., *Surfactants and Polymers in Aqueous Solution*, ©1998 John Wiley & Sons Ltd., Chichester, Reprinted in April 2001, p. 34, Reproduced with Permission)

This phenomenon, which is also temperature-sensitive is often described for surfactant-water mixtures by means of binary or ternary phase diagrams. Furthermore, increased temperature induces a decrease in the *hydration number* of the head group of the ethylene oxide-based surfactants, rendering it more hydrophobic. Sugar-based surfactants are less affected by temperature variations. Thus, with increased hydrophobicity, the ethylene oxide-based surfactant will, when mixed with oil, gradually go from promoting oil droplets in water to

forming water droplets in oil. This change in structure can be described as a result of changes in the *spontaneous curvature*,  $H$ , a parameter that describes surfactant packing at different temperatures in a given system, with positive values giving oil-in-water emulsions and negative values giving reversed micelles (water-in-oil emulsions). The temperature at which the  $H$ -parameter is 0, meaning exact balancing of hydrophobicity and hydrophilicity, is referred to as the *phase inversion temperature (PIT)* of the surfactant in that particular system. Mixtures of surfactants working synergistically are often characterized in ternary phase diagrams, showing the various phases of different molar ratios, molar fractions, weight fractions or weight percentages of the three components involved. A number of phenomena, including wetting, dispersion, emulsification and foaming, can be explained by the formation of micelles and the minimizing of free energy of the systems. Several physical properties of a solution are concentration-dependent on the presence of a micelle-forming surfactant, see Figure 3.



**Figure 3.** Schematic representation of the concentration dependence of some physical properties of solutions of a micelle-forming surfactant. (Redrawn from Jönsson, B., Lindman, B., Holmberg, K. and Kronberg, B., *Surfactants and Polymers in Aqueous Solution*), ©1998 John Wiley & Sons Ltd., Chichester, Reprinted in April 2001, p. 36, Reproduced with Permission)

## *Solubility and Krafft Point*

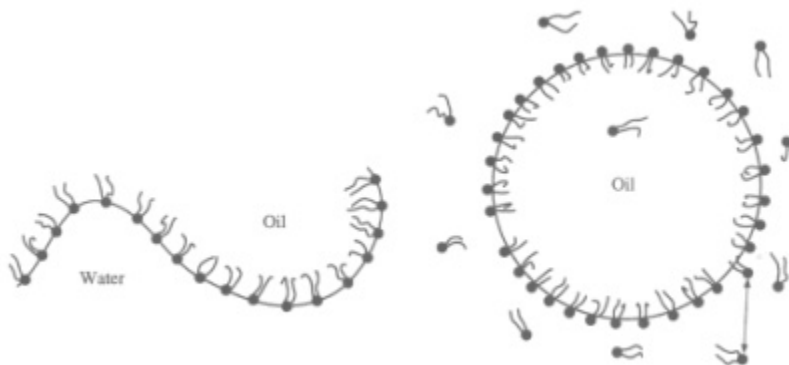
Since surfactants are designed as amphiphilic molecules, which interact with both hydrophobic and hydrophilic interfaces. They have limited solubility in all types of solvents. Surfactants have limited aqueous solubility, which needs to reach the level of the CMC of the surfactant to allow maximum performance. The point, at which the temperature-solubility curve of the surfactant crosses the temperature-CMC curve, is called the *Krafft point*. The Krafft point increases irregularly with increased alkyl chain length. The Krafft point can also be increased by added salt or decreased by other cosolutes. Some surfactants are not soluble enough ever to reach a critical micellization concentration. Certain surfactants, depending on the balance between hydrophilic and hydrophobic moieties, named the hydrophilic-lipophilic balance (*HLB*), are soluble in solvent mixtures with different dielectric constants ( $\epsilon$ ), but not in the pure solvents. The HLB concept, designed by Griffin<sup>24</sup> (the *HLBG*) and Davies<sup>25</sup> (the *HLBD*), is a numerical value that can be calculated for each surfactant, since each structural constituent is given a numerical value. The HLBG is restricted to non-ionics and is defined as the weight % of the surfactant's hydrophilic part divided by 5. The HLBD value takes the contribution of each individual group into account and is defined as  $7 + S$  (hydrophilic group numbers) +  $S$  (lipophilic group numbers). The HLBG number of the surfactant indicates for which properties the surfactant may be useful. For instance the following applications has been suggested: w/o emulsifier (HLBG of 3-6), wetting agent (7-9), o/w emulsifier (8-18), detergent (13-15) and solubilizer (15-18). A low value indicates a hydrophobic surfactant, while a high number indicates a hydrophilic surfactant. Naturally, many surfactants with low aqueous solubility can be found to be more soluble in solvents such as methanol or ethanol. Excessively fat surfactants, those with a low HLB, are thus soluble only in nonpolar solvents. For practical purposes, it is in most applications necessary that surfactants be designed to be soluble up to their CMC values.

## *Foaming*

*Foaming* depends on the stability of liquid-gas interfaces. Foaming studies are often performed according to the *Ross-Miles* method,<sup>26</sup> in which a surfactant solution is poured onto an identical surfactant solution, after which the height of the foam produced is measured (often during some minutes). The initial foam height is a measure of foamability and the decay of the foam with time is a measure of foam stability. Another common method is the *Bikermann* method,<sup>27</sup> in which a stream of air is bubbled through a surfactant solution at increasing speed until the rate of foam breakdown is equal to the rate of foam production. Both foamability and foam stability are of interest in different applications.

## Emulsification and the CPP

*Microemulsions* are macroscopically homogeneous and thermodynamically stable mixtures of a surfactant, oil and water. On a microscopic level, they consist of oil-domains separated from water-domains by a surfactant film (see Figure 4).

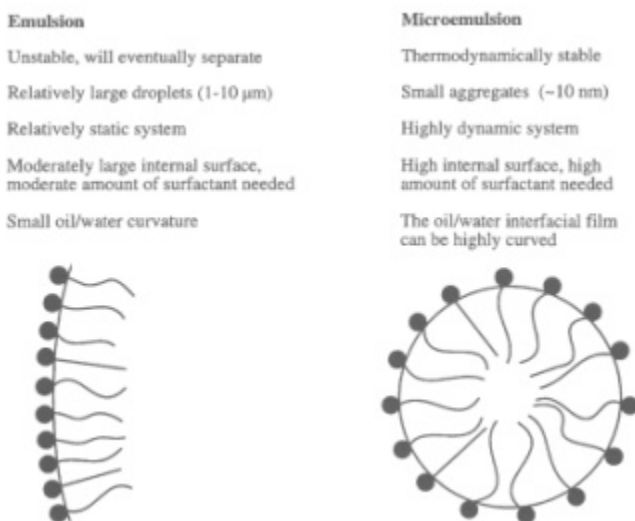


**Figure 4.** A micelle with solubilized oil is characterized by a positive spontaneous curvature. In general, a surfactant film between oil and water is flexible with regions of both positive (towards oil) and negative (towards water) curvatures. (Redrawn from Jönsson, B., Lindman, B., Holmberg, K. and Kronberg, B., *Surfactants and Polymers in Aqueous Solution*), ©1998 John Wiley & Sons Ltd., Chichester, Reprinted in April 2001, p. 86, Reproduced with Permission)

Emulsification thus involves the formation of a liquid-liquid interface. Microemulsions contain both non-polar and polar domains, allowing many applications. Microemulsions are good solvents of both organic and inorganic compounds, which is a useful property, for example, in catalyzing the hydrolysis of fat compounds. They can be characterized using a range of methods such as NMR, *rheology* or *turbidimetry* measurements.

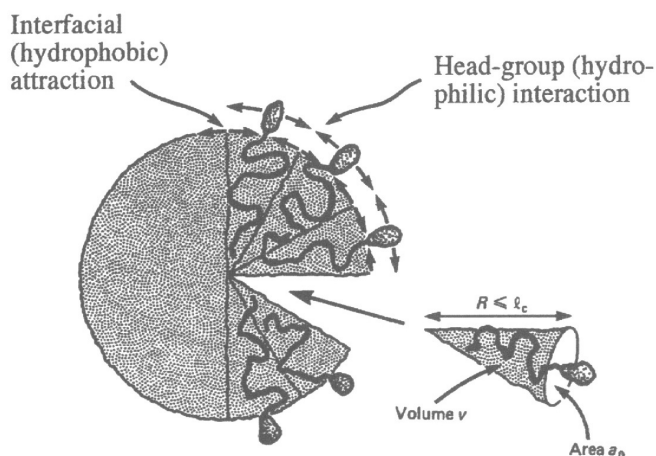
Macroemulsions (often called just emulsions), on the other hand, are not thermodynamically stable. Here, surfactants are used to retard the breakdown process. The emulsification properties of a surfactant can be predicted relatively well using the HLB concept described above. Two surfactants of different HLB values (one low and one high) are often used in emulsification formulations. This gives the best possible performance, since the surfactants can complement each other's properties. In practical formulations, the emulsion stability and character is also temperature dependent. When ethylene oxide-based surfactants are used, the emulsion possesses a phase inversion temperature, PIT. The PIT depends on

the surfactant structure and the character of the oil. Above PIT the emulsion is of the water in oil type and below the PIT of the oil in water type. The HLB-value is, thus, a property of a surfactant molecule in isolation, while the PIT describes a certain emulsification system. Together, they are most useful tools for selecting an emulsifier. Formation of thermodynamically stable microemulsions requires that the surface tension is extremely low (often formed from surfactants having a low CPP-value) or else that emulsions may form instead (see Figure 5). A *w/o microemulsion* in equilibrium with excess oil is called a *Winsor I* system, a *o/w microemulsion* in equilibrium with excess water is called a *Winsor III* system and a microemulsion in equilibrium with both excess water and oil is called a *Winsor II* system.



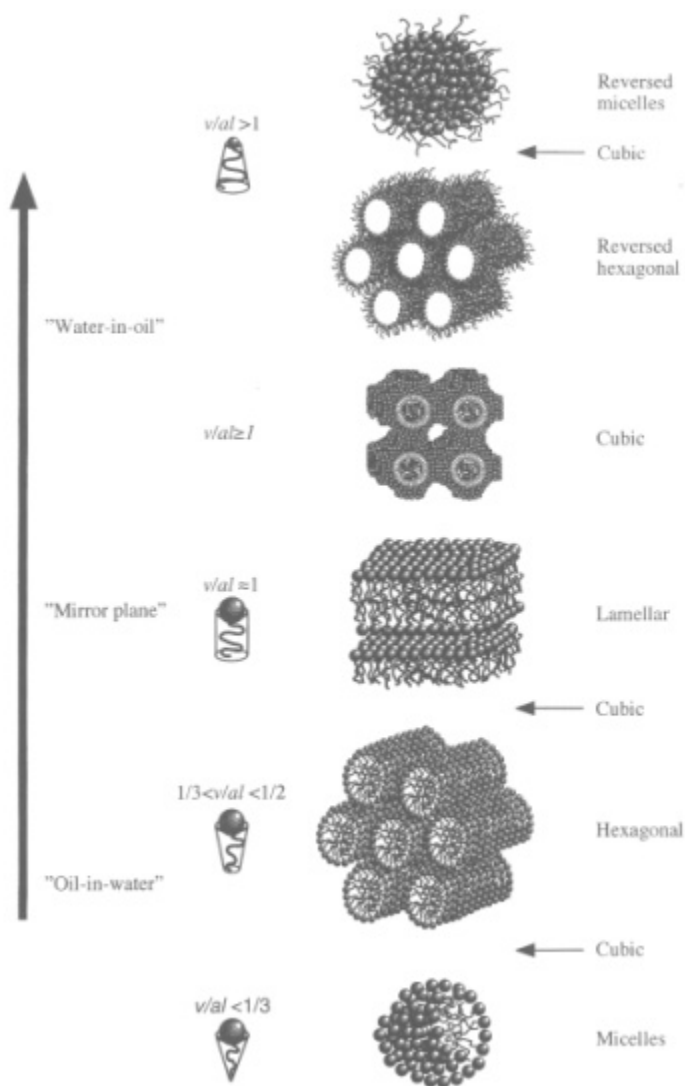
**Figure 5.** Characteristic differences between emulsions and microemulsions. (Redrawn from Jönsson, B., Lindman, B., Holmberg, K. and Kronberg, B., *Surfactants and Polymers in Aqueous Solution*), ©1998 John Wiley & Sons Ltd., Chichester, Reprinted in April 2001, p. 366, Reproduced with Permission)

The *CPP*, according to Israelachvili,<sup>28</sup> is a geometrical concept that is defined as the volume of the hydrophobic part of the surfactant divided by the product of the optimal area of the head group and the length of the hydrocarbon chain, that is as  $v/(a \cdot l)$  (see Figure 6). Thus, the *CPP* is a geometrical parameter that doesn't take electrostatic, or other long-range forces, into account. The *CPP* heavily influences the phase-behavior of the surfactant. A low ( $<1/3$ ) *CPP* indicates that spherical micelles can be formed (favoring o/w emulsions), while a high ( $>1$ ) *CPP* favors the formation of reversed micelles (thus forming w/o emulsions). An intermediate *CPP* ( $1/3 - 1$ ) will favor the formation of hexagonal, lamellar and cubic phases (see Figure 7). Hydrophobic surfactants will thus have high *CPP* values and less hydrophobic (i.e. hydrophilic) surfactants will have lower *CPP* values. Addition of smaller hydrophobes to the surfactant solution can increase the *CPP*. The *CPP* and the *PIT* are also connected, since an increase in the *CPP* decreases the *PIT*. Extremely unfavorable packing possibilities might result in an inability of some amphiphilic compounds to form micelles; such compounds have no CMCs, and are not surfactants in a traditional sense, but might, for example, still serve as hydrotropes.



**Figure 6.** The critical packing parameter (*CPP*) or surfactant number relates the head group area ( $a$ ), the extended length ( $l_{\max}$ ) and the volume of the hydrophobic part of a surfactant molecule ( $v$ ) to a dimensionless number  $CPP = v/(l_{\max}a)$ . (Redrawn from Jönsson, B., Lindman, B., Holmberg, K. and Kronberg, B., *Surfactants and Polymers in Aqueous Solution*), ©1998 John Wiley & Sons Ltd., Chichester, Reprinted in April 2001, p. 83, Reproduced with Permission)





**Figure 7.** The surfactant self-assembly structures of non-ionic surfactants are mainly governed by the temperature and the number of oxyethylene groups. Only selected structures are presented. (Redrawn from Jönsson, B., Lindman, B., Holmberg, K. and Kronberg, B., *Surfactants and Polymers in Aqueous Solution*, ©1998 John Wiley & Sons Ltd., Chichester, Reprinted in April 2001, p. 100, Reproduced with Permission)

## *Detergency and Dispersion stability*

The ability of a surfactant to solubilize ordinarily insoluble particles or aggregates of molecules is called the *dispersion* ability. This means that the hydrophobic solid is covered by surfactant molecules giving it a hydrophilic surface, which makes the enclosed particle water-soluble. Thus, for particulate soils the surfactant acts at a liquid-solid interface. The dispersion ability of a surfactant can, for instance, be estimated in terms of amounts of particles/aggregates per amount of surfactant (gram per gram) that can be dispersed. This quantity is, of course, not affected only by the surfactant but also by the nature of the solid particle. Dispersion can be studied by e.g. turbidimetry or rheology measurements. To understand the mechanism behind the surfactant actions, surface force measurements are able to provide useful information on the types of forces acting between surfactant-coated surfaces, their distance dependence and also on the structure of the adsorbed layer. Even more detailed information on the adsorbed layer structure can be obtained using *AFM-imaging* or *neutron reflectivity* measurements. Dispersing particulate soil and solubilizing oily soil, with mechanisms of adsorption and desorption, are the basic phenomena responsible for the very important *detergency* processes. Detergency, that is the removal of soil from fabric, acts by *in situ* formation of emulsions (of oily soils), solubilization (of oily soils) and by creating repulsive forces between fabric and particulate soils. This emulsification is best performed at the PIT of that particular oil-water-surfactant system. For practical formulations the PIT can be decreased by addition of shorter hydrophobes.<sup>29</sup>

## *Adsorption and Wetting*

Surfactants become adsorbed on surfaces, often forming complete bilayers or bilayers aggregates on hydrophilic surfaces (examples: glass, silica) and monolayers on hydrophobic surfaces (example: mica clay). To describe the *adsorption* process on solid surfaces is rather complex since one has to take into account interactions between surfactant and surface as well as between adsorbed surfactants. Common, but highly simplified approaches, are to use the *regular solution theory* and the *Langmuir equation*. Adsorption studies are often performed using reflectometry or *null ellipsometry*, a polarimetric method. The methods require that complete saturation of the surfactant and the surface occurs, but this is a rare case with large, bulky and kinetically slow molecules. Cationic surfactants, of course, interact more strongly with anionic surfaces than with non-ionic ones. Since the total amount adsorbed can be determined by these methods, it is easy to calculate the total area that each molecule occupies on the surface, the area per molecule.

A small droplet of pure water, unaffected by gravitational forces, will, due to the balance of three interfacial tensions (between liquid and air, liquid and solid

and air and solid), have an inner angle (the angle between the surface and the droplet surface) of  $110^\circ$  on hydrophobic surfaces, such as hydrocarbon, and  $98^\circ$  on parafilm. This angle will decrease with added surfactant, down to an optimum minimum of  $0^\circ$ , which means complete droplet spreading. The process itself is called *wetting* and is useful, for example, in detergency, in commercial painting products and in mineral flotation. In the latter application a high contact angle is required in order to allow the air bubbles to attach to the mineral particle and lift them to the top of the flotation chamber where they can be collected. It is known that adsorption increases as the CPP increases, although that is not always the case. Generally, an increase in the hydrophobicity of a surfactant will increase the wetting function of the surfactant towards a hydrophobic surface. The *advancing* and *receding wetting angles* can be measured using a Wilhelmy plate wetting tensiometer.

*On life's journey faith is nourishment, virtuous deeds are  
a shelter, wisdom is the light by day and right mindfulness  
is the protection by night. If a man lives a pure life, nothing  
can destroy him.*

- Buddha, 568-488 BC

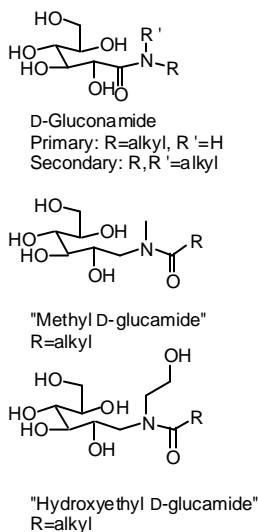
# CHAPTER 1

## SYNTHESIS

Syntheses of sugar derivatives, as which most of the surfactants in this thesis would be classified, often follow the route of protection, activation, coupling and deprotection. While this would be acceptable with industrial preparations of specific substances, such as bio-chemically active agents used as medicines or transmitters thereof, it is not a cheap and fast enough route for bulk preparations of general surfactants. Not only is increased price a common result of many reaction steps, but these also lead to low total yields of the product desired. In the detergency industry, technical mixtures are often used and even desired (since the mixtures of surfactants often possess increased properties due to synergistic effects of the components). In this case, a few consecutive synthetic steps are acceptable, but a limited number of purification steps is a requisite. Surfactants used in bio-medical applications, on the other hand, have to be pure and, if they are chiral, also be enantiomerically pure. The production of such compounds may need several synthetic steps and careful purification.

Several structural types of sugar-based surfactants are included in this thesis. Common building blocks have been used in most of the compounds in order to give the potentially most viable commercial surfactants. The structural categories are all presented below in appropriate groups. The results gained from surface characterizations of the compounds can be found in Chapter 2.

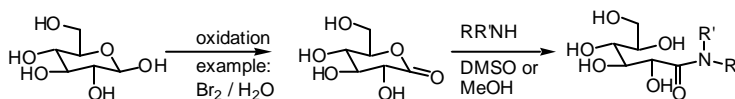
## 1.1 Gluconamides



**Figure 8.** The structures of D-gluconamides and common derivatives. Trivial names are given within quotation marks.

Gluconamides have long been known and used in consumer products, but they no longer are. Two methods of preparation are commonly used, differing in the solvents and temperatures only. The starting material is the commercially available D-(+)-glucono-1,5-lactone (or the aqueous equilibrium form D-gluconic acid). The lactone is aminolysed into a D-gluconamide by an amine in MeOH or DMSO.<sup>30</sup> Many gluconamides, including the *N*-octyl and *N*-decyl derivatives, have been used commercially as surfactants. Gluconamides with a fatty acid chain containing a heteroatom have been used as the surface-active agents in certain shampoos, since they have

good foaming properties.<sup>31</sup> The properties of primary gluconamides are quite well understood, while there is a notable lack of data on secondary gluconamides. D-gluconamides are generally prepared from D-glucose according to Scheme 1.

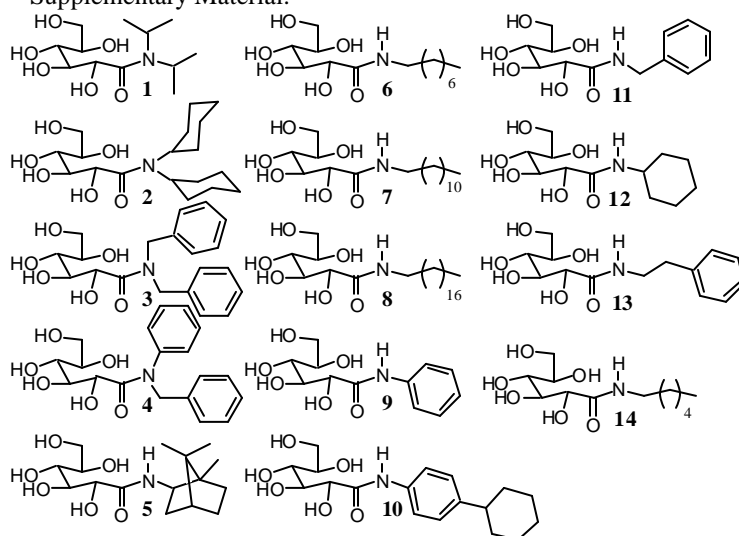


**Scheme 1.** The common synthetic route to alkyl/aryl-D-gluconamides.

Although structurally quite similar, the two types of analogs named “methyl glucamides” and “hydroxyethyl glucamides” (see Figure 8) differ in their properties from the primary gluconamides. Generally, primary D-gluconamides have low aqueous solubilities. Exchanging the hydrogen atom of the amide nitrogen for a methyl group can increase the solubility, probably due to disturbed packing in the crystalline state. Likewise, exchanging hydrogen for a hydroxyethyl group will decrease the solubility, since packing in the crystalline state is then favored instead. The aqueous solubility of both N-methyl glucamides is similarly greater than that of the non-methylated analogs.<sup>32</sup>

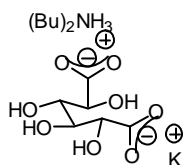
Commercial methyl glucamides are prepared by reductive amination of glucose with methylamine, followed by aminolysis of an activated fatty acid. Hydroxyethyl glucamides are prepared similarly, using 2-hydroxyethylamine instead of methylamine.<sup>33</sup> Very recently, the structurally similar *N*-alkanoyl-*N*-methylactitolamines were synthesized.<sup>34</sup>

A large number of D-gluconamides were prepared and their surface properties characterized. Most often, DMSO was used as solvent, although certain compounds required the use of MeOH for successful syntheses. Purification often consisted of evaporation of the solvent and recrystallization of the compound one to three times. A few compounds had to be purified chromatographically, e.g. *N,N*-dicyclohexyl-D-gluconamide. Secondary gluconamides required more purification work than primary ones. It was found that many of the secondary D-gluconamides were not stable in aerobic environments and oxidized gradually. All gluconamides synthesized for this thesis work are presented in Figure 9 below. The procedures used for synthesis, purification and characterization of the gluconamides can be found in Paper VIII – Supplementary Material.



**Figure 9.** The gluconamides.

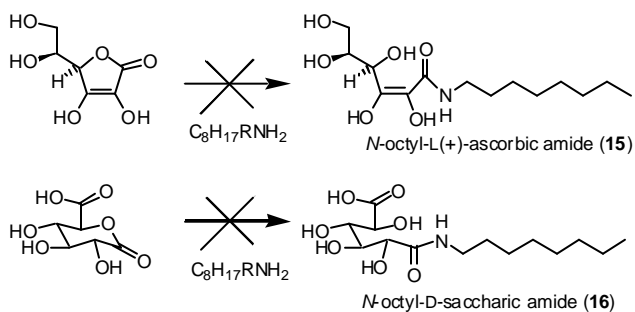
The compounds were prepared in yields ranging from 1 to 91 %. The pure gluconamides were surface characterized by surface tension measurements and several surface-screening tests, including wetting, dispersion, foaming and emulsification. With few exceptions they were found to be good hydrotropes, although some had certain other interesting surface properties.



Mucic acid salt

**Figure 10.** The structure of mucic acid.

We tried to prepare the *N*-octyl-D-saccaric amide (or its sodium salt), but our attempts failed and yielded a yellow product with properties similar to those of mucic acid (see figure 10).<sup>35</sup>

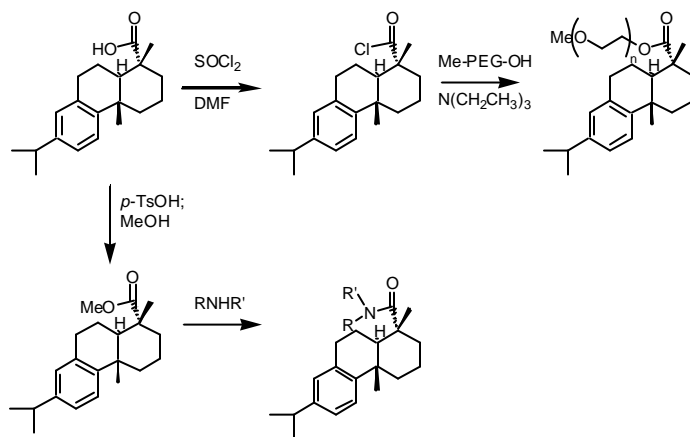


**Scheme 2.** Failed attempts at preparing some amides.

The same method could not be applied for the preparation of *N*-octyl-L-(+)-ascorbic amide either (Scheme 2). The formation of ammonium salts seemed to prevent the amide formation.

## 1.2 Dehydroabietic acid derivatives and surfactants

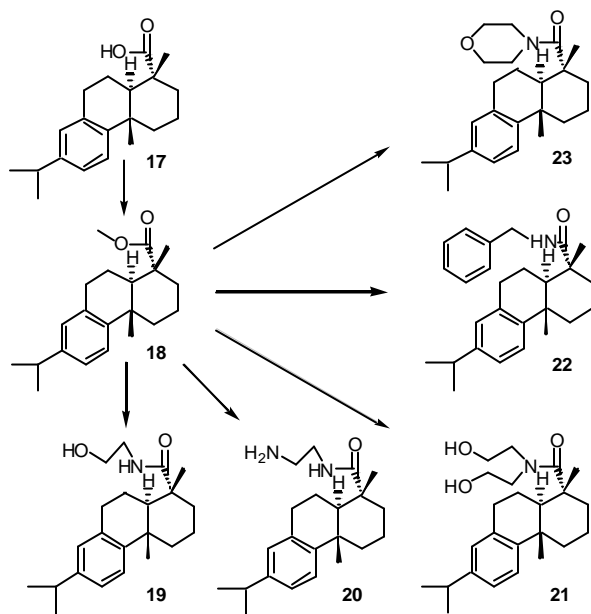
Distillation of by-products, e.g. tall oil, from the pulping industry yields rosin acids and tall oil fatty acids. Purification of rosin acids gives dehydroabietic acid, which is useful for surfactant synthesis. The synthetic methodology applied to dehydroabietic acid, for preparing both derivatives and surfactants, is outlined in Scheme 3 below.



**Scheme 3.** The synthetic methodology applied to dehydroabietic acid.

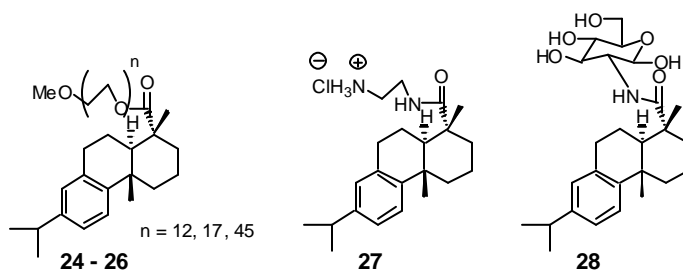
Starting from the methyl ester of dehydroabietic acid, some useful *N*-derivatives were prepared, from which several types of surfactants could potentially be synthesized. Such derivatives were easily purified by recrystallization, see Scheme 4. The details can be found in Paper II – Synthesis and Characterization of Dehydroabietic Acid Derivatives Suitable for Surfactant Synthesis.





**Scheme 4.** Prepared amides of dehydroabietic acid

Several surfactants were prepared from the acid chloride of dehydroabietic acid, see Figure 12. Chromatography or recrystallization were used for their purification. The details can be found in Paper III – Syntheses and Surface Measurements of Surfactants derived from Dehydroabietic Acid.



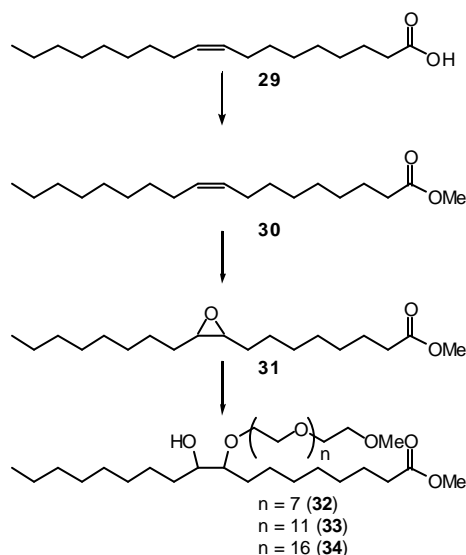
**Figure 12.** Prepared surfactants based on dehydroabietic acid

These compounds have been shown to possess many interesting properties as surfactants.

### 1.3 Fatty acid surfactants

Surfactants were derived from a tall oil fatty acid mixture of oleic acid rich 18-carbon carboxylic acids via methylation, epoxidation and coupling with a monomethylated PEG-chain. Chromatographic purification after the epoxidation gave the 9,10-monoepoxides of tall oil fatty acid methyl esters in high overall yields. The epoxides were opened with mono-methylated PEG-chains of different lengths, using a Lewis acid as catalyst. The resulting surfactant had the polyoxyethylene glycol-chain connected to either carbon 9 or carbon 10 of the fatty acid and was purified by chromatography. They were thoroughly surface characterized and several different surfactant properties were found.

A synthesis scheme is presented below in Scheme 5. The details can be found in Paper IV – Synthesis and Characterization of Surfactants via Epoxidation of Tall Oil Fatty Acid.

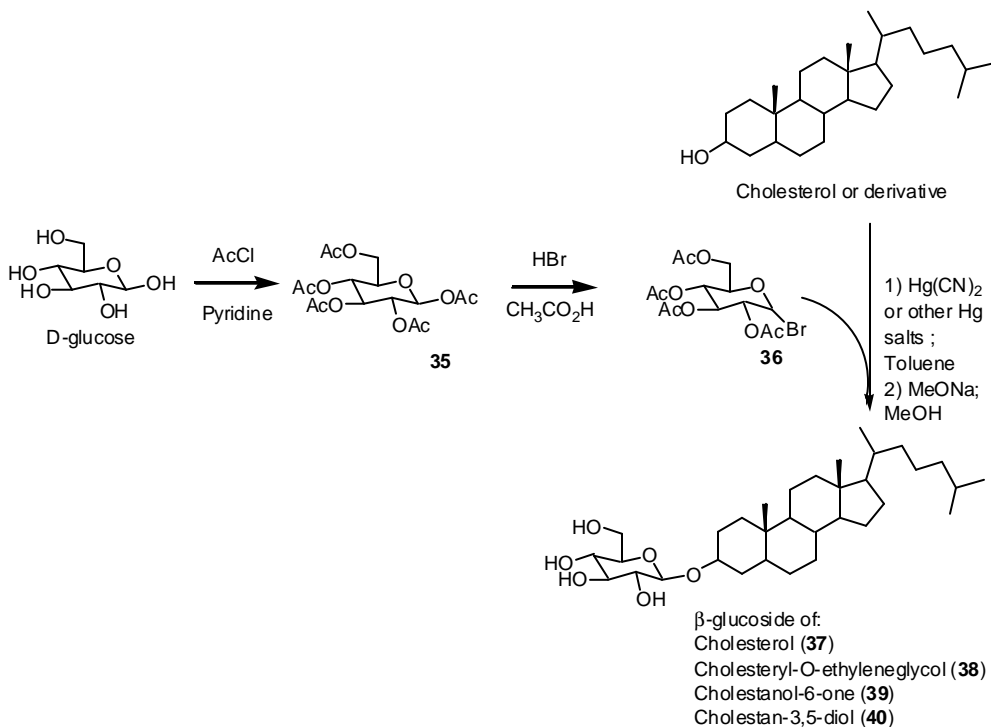


**Scheme 5.** Surfactants prepared from oleic acid from tall oil. The final surfactant is a mixture of the regioisomers having the polyoxyethylene oxide chain connected to carbon atom 9 or 10 of the fatty acid.

## 1.4 Steroid glucosides

The synthesis of steroid glucosides follows the regular route of protection, activation, coupling and deprotection. These four individual steps usually give high yields, resulting in a good total yield. The methodology is outlined in Scheme 6 below. It should be noted that while the glucosidation step is promoted by use of the  $\text{Hg}(\text{CN})_2$  salt, other Hg-salts are also useful. They differ, however, in their stereospecificity. Only  $\text{Hg}(\text{CN})_2$  yields the  $\beta$ -glucoside selectively, while other salts yield  $\alpha/\beta$ -glucoside mixtures. The details can be found in Paper I – Synthesis and Characterization of Surface Active Compounds derived from Cholesterol Derivatives and Glucose.

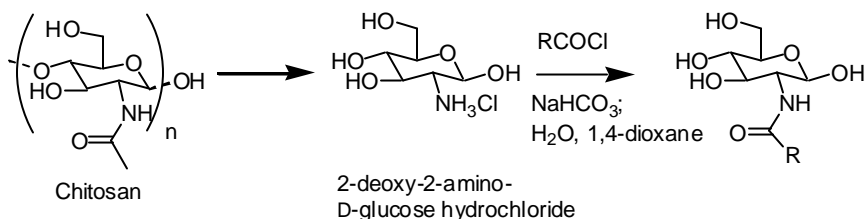
The reasonably similar 6-*O*-acyl- $[\beta]$ -D-glucosyl- $[\beta]$ -sitosterol isolated from *Ficus carica*, *Moraceae*, was recently found to be an anti-cancer agent.<sup>36</sup> The steroid glucosides presented in this thesis might also possess similar beneficial properties.



**Scheme 6.** Sugar-based surfactants prepared from cholesterol derivatives.

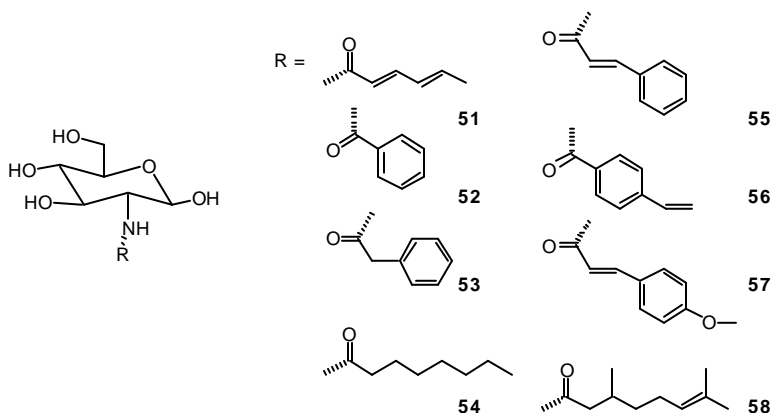
## 1.5 Aminoglucose amides

Interesting surfactants can be prepared from the hydrolysis product of the natural, sugar-based polymer chitosan, 2-deoxy-2-amino-D-glucose. The amino group of this commercially available sugar derivative can be used for the regio-selective production of amides from fatty acids. The general synthetic scheme is outlined in Scheme 7 below. The details of synthesis and characterization can be found in Paper VIII – Supplementary Material.



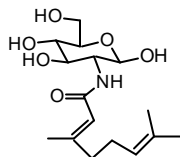
**Scheme 7.** General synthetic route to aminoglucose amide-surfactants.

The reaction generally proceeded fairly well (producing the surfactants presented in Figure 13), with yields around 50-60 % or more. Interestingly, the amidation reaction proceeds smoothly using an acid chloride in water/dioxane and from which the product crystallizes out.

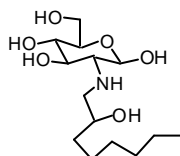


**Figure 13.** Synthesized amides of aminoglucose.

There were some synthetic difficulties with obtaining the 2-deoxy-2-geranic amido-D-glucopyranose. The method was, in our hands, not reproducible in this case. Using freshly distilled geranic acid instead of the bulk compound purchased provided the desired product. Difficulties were also observed for the 2-deoxy-2-(2'-hydroxy)-octylamino-D-glucopyranose (Figure 14).



2-deoxy-2-geranic amido-D-glucopyranose (**41**)



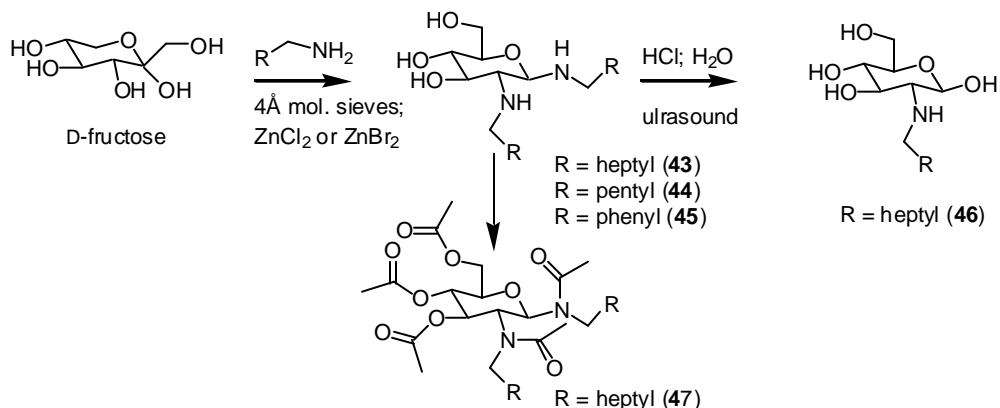
2-deoxy-2-(2'-hydroxy)-octyl-amino-D-glucopyranose (**42**)

**Figure 14.** Some special aminoglucose derivatives.

## 1.6 pH-sensitive surfactants

An improved method of preparing pH-sensitive surfactants from D-fructose was developed. In a straightforward fashion D-fructose was shaken with excess amine in the presence of a catalyst and molecular sieves. The product, formed via a rearrangement reaction, was a D-glucose unit connected with two alkylamino groups.

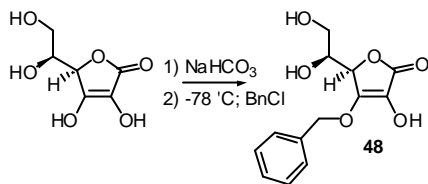
In its most pure form, such a compound is a non-ionic surfactant. When such a surfactant is immersed into a neutral or acidic aqueous solution its amino group becomes protonated and charges the surfactant molecule positively, thus giving it the characteristics of a cationic surfactant. Studies show that the surface activity of the molecule changes with the pH of the system studied. A general synthetic procedure for the preparation of these compounds is found in Scheme 8 below. The details can be found in Paper VII – An Improved Method for the Synthesis of 2-Alkylamino-2-deoxy-D-glucopyranose and 1,2-Dialkylamino-1,2-Dideoxy-D-(*N*)- $\beta$ -glucopyranoside. The fully acetylated derivative, **47**, serves characterization purposes.



**Scheme 8.** pH-sensitive surfactants prepared from D-fructose.

## 1.7 Miscellaneous natural product-based surfactants

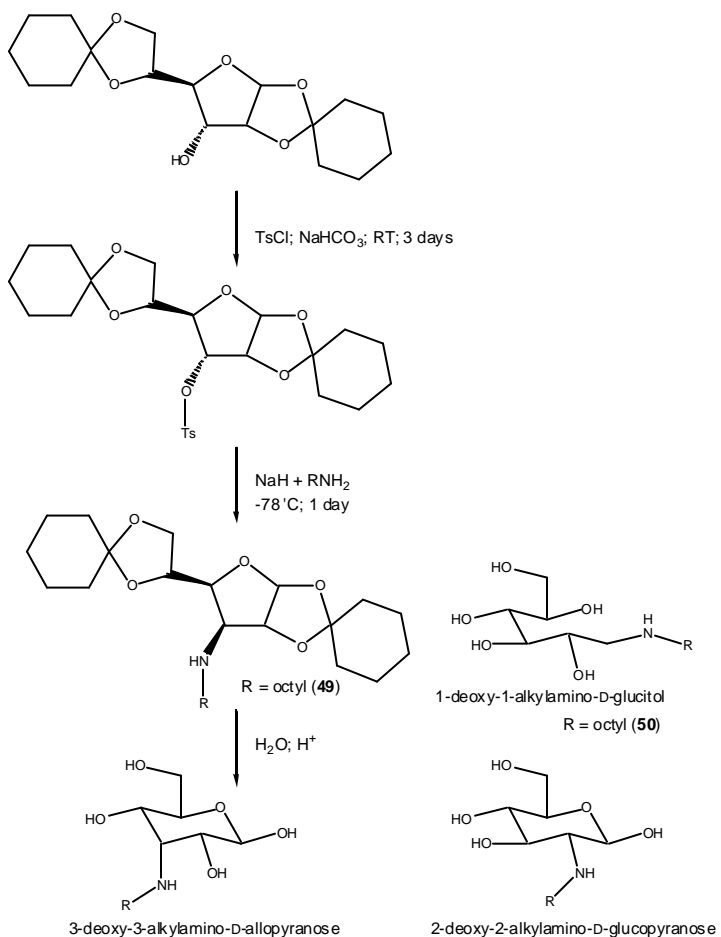
Some progress was made in attempts to prepare certain other natural product-based surfactants. For example, the peppermint smelling 3-*O*-benzyl-L-(+)-ascorbic acid could be prepared, albeit in low yield, according to scheme 9.



**Scheme 9.** Preparation of 3-*O*-benzyl-L-(+)-ascorbic acid.

It might prove interesting to study structural analogs of the 2deoxy-2-alkylamino-D-glucopyranoses and 1-deoxy-1-alkylamino-D-glucitols (the octylamine derivative was prepared for comparative studies; the results can be found in Papers V and VI). For this purpose a synthetic route was outlined for the preparation of 3-deoxy-3-alkylamino-D-allopyranose (all three types are found in scheme 10 below). This route, however, was neither tested with other amines than *N*-octylamine, nor was it pursued with the final deprotecting step.

Similarly, using the same synthetic route, the 3-*O*-geranyl- $\alpha$ -D-glucopyranose was found to be attainable from 1,2;4,6-diisopropylidene-3-*O*-geranyl- $\alpha$ -D-glucofuranose and geranyl bromide in DMF with NaH.



**Scheme 10.** Preparation of 3-deoxy-3-alkylamino-D-allopyranose.

*Tyger Tyger burning bright*  
*In the forests of the night*  
*What immortal hand or eye*  
*Dare frame thy fearful symmetry*  
 - William Blake



# CHAPTER 2

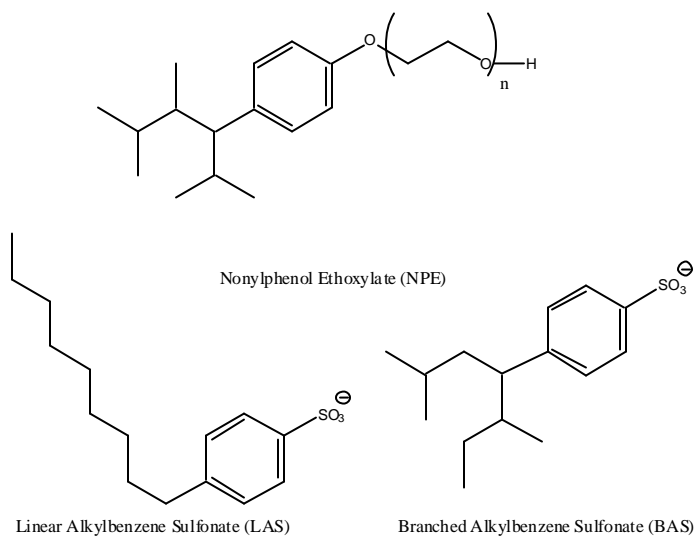
## CHARACTERIZATION

This chapter provides a brief discussion about the general properties of the current commercial surfactants. The surface properties of the surfactants discussed in this thesis are also presented. These surface properties can be found in Paper V – Surface Properties of Surfactants derived from Natural Products. Part 1: Synthesis and Structure/Property Relationships – Solubility and Emulsification, and in Paper VI – Surface Properties of Surfactants derived from Natural Products. Part 2: Structure/Property Relationships – Foaming, Dispersion and Wetting, as well as other sources as given in each subchapter. Some conclusions are presented in Chapter 3.

### Current Commercial Surfactants

Linear alkyl benzene sulfonate (LAS) was introduced in the 1960s to replace branched alkyl benzene sulfonate (ABS). ABS was not readily biodegradable and caused excessive foaming in sewage treatment plants, streams and rivers. LAS was to be considered the first green surfactant.<sup>37</sup>

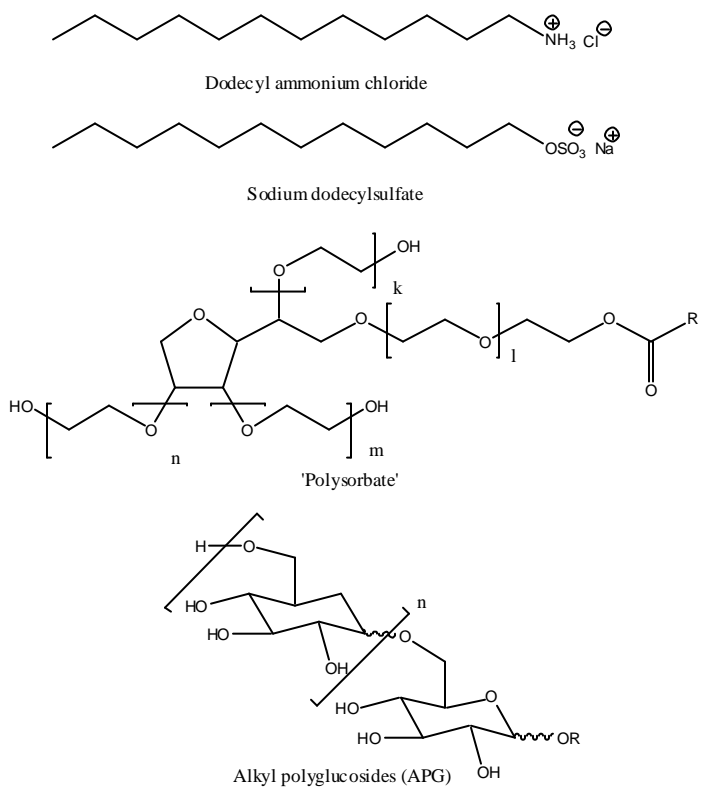
The more feasible alkyl benzene ethoxylates were introduced later on. The most common, still in use today, were the nonylphenol ethoxylates (NP-*n*) (see Figure 15 below).



**Figure 15.** Common commercial surfactants

This class of surfactants is used in a wide array of applications, including uses as wetting agents and dispersion agents. Other extremely common commercial surfactants are alkyl ammonium hydrochlorides (e.g. dodecyl ammonium hydrochloride) and alkyl sodium sulfates (e.g. dodecyl sodium sulfate), which are used as foaming agents and detergents. Both of these, however, have variable undesirable toxic or accumulative properties. It is, thus, desirable to exchange these for less toxic ones.

Sugar-based surfactants offer a viable option for such an exchange. There are some sugar-based surfactants in commercial use. Examples are polyoxyethylene sorbitan fatty acid esters (Tween, Polysorbate)<sup>38</sup> and alkyl polyglucosides (APGs),<sup>39</sup> prepared using the Fisher glucosidation process (see Figure 16 for structures).



**Figure 16.** Common Surfactants

## Properties of Sugar Surfactants

Sugar-based surfactants are compounds of a very broad range of structural diversities. Sugars (monosaccharides, disaccharides etc.) may be connected to the hydrophobe at any of its hydroxyl groups and by different types of connecting linkages. Secondly, the hydrophilicity of sugar can be changed by oxidation, reduction or addition of hydrophilic groups, such as a sulfonic acid residue or a polyoxyethylene chain. Thirdly, the hydrophobic moiety or moieties can also be subjected to a wide array of changes.

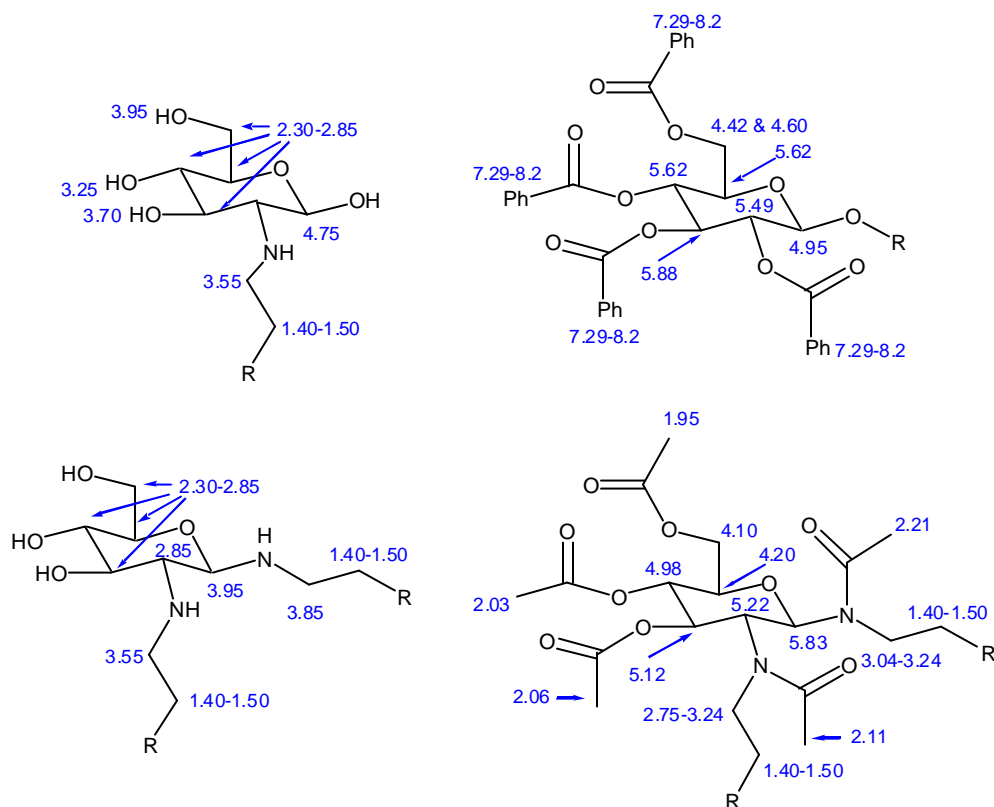
In this thesis it is shown that sugar surfactants have several rather flexible properties. Furthermore, sugar esters and sugar glycosides are generally non-toxic and non-cumulative. They are temperature insensitive as to their properties, in contrast to the like-wise non-ionic alkyl-PEG surfactants.<sup>40</sup> This means that sugar surfactants and other non-ionic surfactants complement each other in different applications. Non-ionic surfactants are not sensitive to the hardness of water.<sup>41-43</sup> The understanding of the surfactant properties of aqueous systems containing sugar surfactants is reasonably good and data about surface tensions, theoretical packing and CMCs exist for both the pure glycosides and mixtures with other surfactants or other compounds that affect the packing (often referred to as hydrotropes). The effects of structural elements on the CMC are known for non-ionics; the addition of two carbon atoms to the hydrocarbon chain of the surfactant decreases the CMC by a factor of 10, the addition of an ethylene oxide unit to PEG-based surfactants increases the CMC by a few percent and the addition of additional sugar head groups to sugar surfactants has only minor increasing or decreasing effects.<sup>44-46</sup> There are several indications that the complex isomerism of the sugar head group determines the physico-chemical properties of alkyl polyglucosides.<sup>47-50</sup> Sugar surfactants are generally known to be good foaming agents.<sup>51</sup> Although equilibrium surface tensions are well-known for several sugar surfactants, little is known of their dynamic surface tensions. The mechanisms of adsorption of sugar surfactants, which are the forces responsible for detergency processes, wetting and dispersion, are also not fully understood, since only one dialkyl chain gluconamide has been studied so far.<sup>52</sup> It is known that the best detergent properties are found in branched hydrophobe surfactants, while they are also the least biodegradable ones.<sup>53</sup> Sugar surfactants with small hydrophobic moieties are known to be good hydrotropes.<sup>54-55</sup> For example, gluconamides are traditional hydrotropes, but are no longer used. Sugar surfactants with block co-polymers are good for the formation of emulsions and these are non-toxic, efficient and cheap.<sup>56</sup>

Sugar surfactants are also known to be more lipophobic and hydrophilic than polyethylene oxide surfactants.<sup>57</sup> They have low organic solubilities and have low capacity of solubilizing the surfactant in oil media.<sup>58</sup> Sugar surfactants are known to be mild towards the skin<sup>59</sup> and possess lower hemolytic activity than other types of surfactants.<sup>60</sup> The structure-activity relationships of various glycosides are reasonably well understood and the differences in properties of  $\alpha$ - and  $\beta$ -glycosides and the effect of hydrophobe branching are explained.<sup>61</sup> Technical and biotechnological applications are expected to be of increasing importance.<sup>62</sup>

## Physico-Chemical Characterization of Surfactants Based on Natural Products

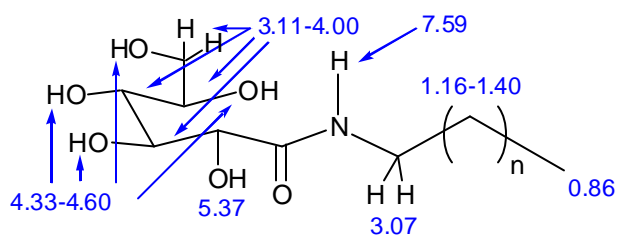
Within the field of surface chemistry, it is of interest to describe certain properties based on the molecular structure of the surfactant. It is, therefore, of interest to know the purity or composition of the surfactant studied. Remaining hydrophobic starting material or by-products are very often surface active and may thus affect the surface measurement studies. Such starting materials consist of smaller molecules, and are hence adsorbed at the air-water surface faster than the surfactant. Thus, any surfactant impurity will immediately show up during surface measurements. It is, however, a common opinion that technical grade surfactant mixtures are more efficient at surfactant work than the pure surfactant. The isolation of a pure surfactant and the study of its surfactant properties are, thus, mainly of academic interest.

The identity and purity of all surfactants presented in this thesis have been characterized by several methods. The methods of analysis have included <sup>1</sup>H-NMR, <sup>13</sup>C-NMR, IR, melting point and sometimes MS. Optical rotation has not been performed due to the often-low aqueous solubility of the surfactants. In addition to the standard chemico-physical analysis, some additional NMR-techniques were used for further characterization. COSY-gs, HMQC-gs, DEPT and HMBC were run, at 500 MHz, of surfactants, such as **43-46** and **50**. This made a total structural characterization of the compounds possible. An over-view of common spectral analysis data acquired from sugar-based surfactants is presented in Figures 17 and 18 below.



**Figure 17.**  $^1\text{H}$ -NMR spectral data of glucosides and *N*-glucosides, including the protected species, presented in this thesis. The signal ppm value is presented at each hydrogen position in the molecule and the solvent used is  $\text{CDCl}_3$ . Most of the shift data of hydroxyl and amine/amide protons are omitted in this presentation.

It is of special interest to note the relative ease of determining the stereochemistry of a glucoside ( $\alpha$ - or  $\beta$ -glucoside) by using  $^1\text{H}$ -NMR. As is well-known to sugar chemists,  $\beta$ -glucosides have the hydrogen atoms of sugar carbon atoms 1 and 2 trans to each other, which leads to a higher coupling constant between these two, than in  $\alpha$ -glucosides. For example, a fully acetylated  $\beta$ -glucoside in  $\text{CDCl}_3$  has the anomeric hydrogen atom at  $\delta$  4.95 (d,  $J=9$  Hz), while the  $\alpha$ -glucoside derivative is found at  $\delta$  5.25 (d,  $J=4$  Hz). Of course, the molecular ratio between  $\alpha$ - and  $\beta$ -glucosides in a mixture can also be determined by the same principle. This is how it was found that  $\text{Hg}(\text{CN})_2$  promotes the formation of  $\beta$ -glucosides of steroids (**37-40**) selectively (Paper I).



**Figure 18.**  $^1\text{H}$ -NMR spectral data for D-gluconamides, presented in this thesis. The solvent used is DMSO.

## Surface Chemical Characterization of Surfactants Based on Natural Products

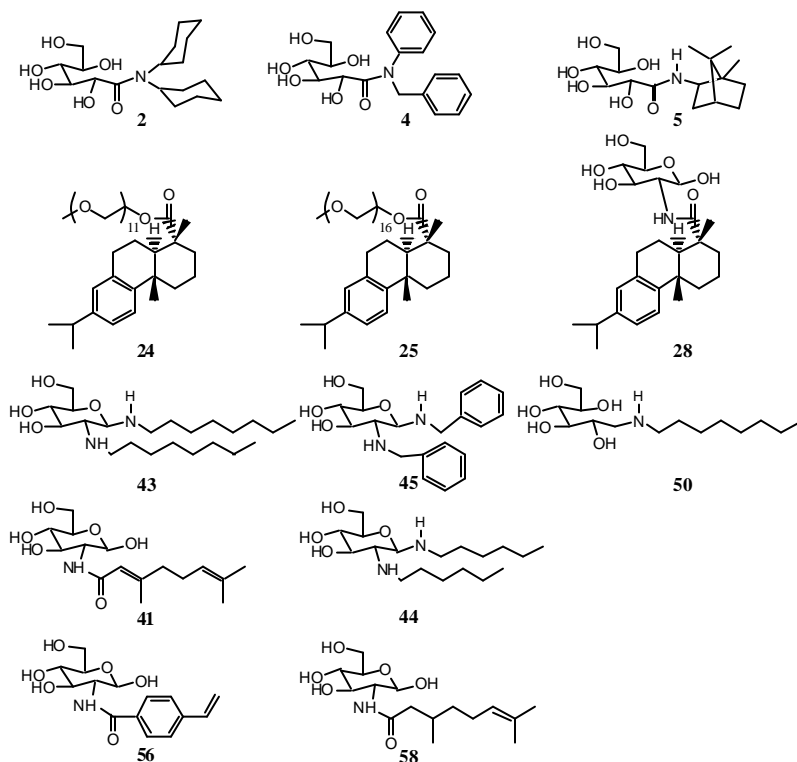
Many surfactants, derived from natural products, have been characterized as to their properties as surface-active agents. Emulsification, dispersion, wetting, solubility and foaming properties have been studied. A number of surfactants have been found to possess one or several useful properties. The characterization and results of the screening tests can be found in detail in Papers V and VI. The conclusions from these tests have been summarized below in tabular form for the sake of clarity (Table 2), with structures given in Figure 19.

**Table 2.** A short summary of the surfactant properties of the compounds from Papers V and VI <sup>a</sup>

<i><b>Surfactant no.</b></i>	<i><b>Foaming</b></i>	<i><b>Dispersion</b></i>	<i><b>Emulsification</b></i>	<i><b>Wetting</b></i>
2	Fair	Good	Fair	
4		Fair		
5	Fair			Fair
24	Good			Fair
25	Good			Fair
28	Fair	Very Good	Good	Fair
41		Fair		Good
43		Fair		
44			Fair	Fair
45				Fair
50	Very Good	Good	Fair	Very Good
56			Very Good	Fair
58		Fair	Fair	Fair

<sup>a</sup> Lacking descriptions indicate that the properties are weak or non-existent.





**Figure 19.** Surfactants with pronounced surface-active properties described in Papers V and VI.

The following pages give a more detailed account of the results gained from various surface measurements in appropriate subchapters (the exact details of the screening tests can be found in Papers V and VI).

## 2.1 CMC and surface tension

Some studies of the CMC value and the surface tension of aqueous solutions of some of the surfactants have been carried out. These are of importance when, for example, determining the compositions of a commercial formulation, since they give a measure of needed amount of surfactant for a given application. A short summary of some of the results acquired is presented in Table 3 below.

**Table 3.** CMC values and surface tensions of some surfactants. <sup>a</sup>

Surfactant number	Mw	Hydrophobic carbon atoms	CMC value (mM)	Approx. surface tension at the CMC (mN/m)	Surfactant type
<b>6</b>	307.38	8	6.5**	45	Gluconamide
<b>9</b>	271.269	6	10*	70	Gluconamide
<b>11</b>	285.296	7	10*	62	Gluconamide
<b>12</b>	277.317	6	16.7*	69.3	Gluconamide
<b>13</b>	299.323	8	9*	56	Gluconamide
<b>24</b>	843.09	20	0.071	36.1	Dehydroabietic acid surfactant
<b>25</b>	1063.36	20	0.069	36.1	Dehydroabietic acid surfactant
<b>26</b>	2296.83	20	0.17***	48.4	Dehydroabietic acid surfactant
<b>32</b>	696.95	18	2	33	Fatty acid surfactant
<b>33</b>	873.16	18	1	35	Fatty acid surfactant
<b>34</b>	1137.48	18	0.4	38	Fatty acid surfactant
<b>58</b>	331.408	10	7	37	Aminoglucose amide

<sup>a</sup> Legend: (\*) The surfactant does not possess any CMC value. The value given here is the concentration at which the Gibbs isotherm plot becomes planar. (\*\*) The Krafft point of the surfactant is at 40 °C, resulting in severe solubility problems in this measurement. The given surface tension is the value acquired for maximum saturation of the solution at room temperature. (\*\*\*) The surface tension is given at the solubility limit concentration, indicating that concentrations equaling the expected CMC cannot be reached.

## 2.2 Solubility

The aqueous solubility of the surfactants in this thesis follow the general trend expected from their hydrophilic-lipophilic balance according to Griffin's (HLBG). However, it is also clear that the nature of the head group and the structure of the non-polar part affect the solubility in a manner not captured in the standard HLBG concept. It is found that an ester or amine group as the connecting unit between the hydrophile and the hydrophobe leads to a more water-soluble surfactant as compared to the corresponding amide derivative. In general, it appears as if these sugar-based surfactants have relatively low organic solubilities. The solubility limits in water, ethanol and dodecane, at room temperature, for several surfactants can be found in Table 4 below. More detailed information can be found in Paper V).

**Table 4.** Solubility limits for several surfactants in water, ethanol and dodecane.<sup>a</sup>

Surfactant number	Mw	HLBG	Hydrophobic carbon atoms	Solubility Limits		
				Aqueous solubility (w/v%)	Ethanol solubility (w/v%)	Dodecane solubility (w/v%)
27	378.98	5.0	20	0.44	0.15 - 1	0.15 - 1
28	461.59	7.1	20	0.15	0.01 - 0.15	0.15 - 1
43	402.61	7.3	16	0.15 - 1	0.15 - 1	0.15 - 1
8	447.65	8.0	18	0.1	0.15 - 1	0.01 - 0.15
45	358.43	8.2	14	0.15 - 1	0.15 - 1	0.15 - 1
44	346.51	8.4	12	0.15 - 1	0.15 - 1	0.01 - 0.15
3	375.42	9.5	14	0.94	> 1	0.01 - 0.15
7	363.49	9.9	12	0.1	0.15 - 1	0.01 - 0.15
4	361.49	9.9	13	0.06	0.15 - 1	0.01 - 0.15
2	359.46	10.0	12	> 1	> 1	0.01 - 0.15
10	353.41	10.1	12	< 0.01	0.15 - 1	0.01 - 0.15
57	339.34	10.5	10	< 0.01	< 0.01	0.01 - 0.15
58	331.4	10.8	10	> 1	0.15 - 1	0.15 - 1
5	331.4	10.8	10	0.88	> 1	0.01 - 0.15
41	329.39	10.8	10	> 1	0.15 - 1	0.15 - 1
46	291.38	11.2	8	0.15 - 1	0.15 - 1	0.15 - 1
50	293.4	11.3	8	> 1	> 1	0.15 - 1
55	309.31	11.5	9	0.64	< 0.01	0.01 - 0.15
56	309.31	11.5	9	0.89	0.15 - 1	0.01 - 0.15
6	307.38	11.7	8	0.12	0.15 - 1	0.01 - 0.15
54	305.37	11.7	8	0.69	0.01 - 0.15	0.01 - 0.15
24	843.09	11.9	20	> 1	> 1	0.15 - 1
13	299.32	12.0	8	> 1	0.15 - 1	< 0.01
53	297.3	12.0	8	> 1	0.01 - 0.15	< 0.01
11	285.29	12.6	7	> 1	0.15 - 1	< 0.01
1	279.33	12.8	6	> 1	> 1	< 0.01
12	277.31	12.9	6	> 1	0.15 - 1	< 0.01
51	273.28	13.0	6	> 1	0.01 - 0.15	< 0.01
9	271.27	13.2	6	> 1	0.15 - 1	< 0.01
25	1063.4	14.4	20	> 1	> 1	0.15 - 1
Surfactant number	Mw	HLBG	Hydrophobic carbon atoms	Solubility Limits		
				Aqueous solubility (w/v%)	Ethanol solubility (w/v%)	Dodecane solubility (w/v%)
NP-6	498.69	11.6	15	0.15 - 1	> 1	0.15 - 1
NP-10	674.9	13.8	15	> 1	> 1	0.01 - 0.15
NP-20	1115.4	16.3	15	> 1	> 1	< 0.01

<sup>a</sup> The solubility was determined up to concentrations of 1 w/v% of surfactant in the solvent. Compounds having solubility limits in excess of 1 w/v% are given ‘> 1’ as their values. Aqueous solubility was determined gravimetrically for several surfactants. Ethanol and dodecane solubilities were determined at concentrations of 0.01, 0.15 and 1 w/v% with the result indicating up to which concentration the surfactant was fully soluble. From these tests the solubility range was determined for each surfactant.

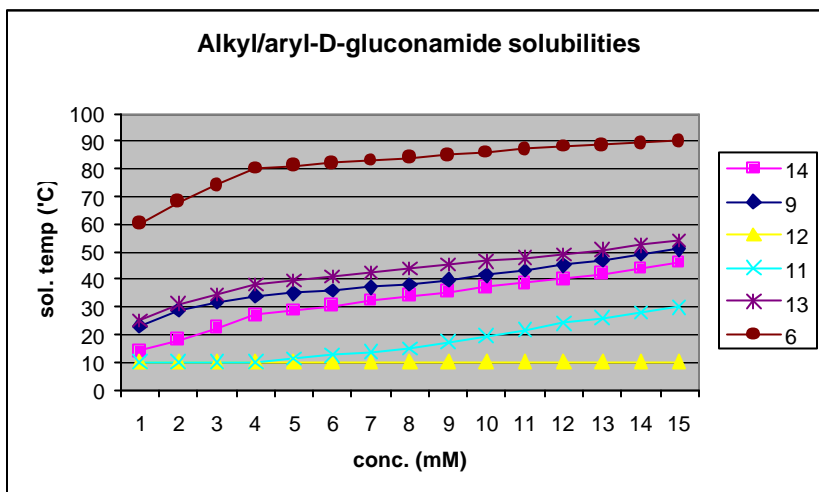
Aqueous solubilities were also tested for 2-deoxy-2-alkyl/aryl-amido-D-glucopyranoses in order to understand the effect that the structure of the hydrophobic moiety had on the solubility of this class of surfactants. Descriptions of the synthesis and preparation of these surfactants can be found in Paper VIII. Table 5 below summarizes the results of this simple, unpublished test.

**Table 5.** Aqueous solubilities of some 2-deoxy-2-alkyl/aryl-amido-D-glucopyranoses as a function of temperature.<sup>a</sup>

Surfactant number	Hydrophobic carbon atoms	Surfactant concentration (mM)	Soluble at temperature (°C)
<b>51</b>	6	40.3	25
<b>52</b>	7	38.8	46
<b>53</b>	8	37	54
<b>54</b>	8	36	96
<b>55</b>	9	35.6	82
<b>56</b>	9	35.6	96
<b>57</b>	10	32.4	100
<b>58</b>	10	33.2	46

<sup>a</sup> Each surfactant (11 mg) was mixed with distilled water (1.0 mL) in a small tube. The samples were slowly heated (~1 °C/minute), with shaking, from room temperature up to the boiling point of water. The temperature at which all surfactant was clearly dissolved was noted as the solubility temperature.

A measure of the aqueous solubility of the surfactants can be gained from their respective solubility temperatures. The relatively high solubility of the branched surfactant, **58**, and unsaturated one, **51**, is surprising. In another separate solubility experiment, the, to surfactant **58**, structurally similar surfactant **41**, was also found to have an unusually high aqueous solubility. This finding would seem to indicate that branching and unsaturation of the hydrophobe increases the aqueous solubility of the surfactant as they decrease its crystallization potential. It is of interest to compare with the structurally similar D-gluconamides. The solubility limit of some D-gluconamides at different temperatures is given in Scheme 11 below.



**Scheme 11.** Solubility curves of a series of D-gluconamides. Aqueous solutions (1.0 mL) of different concentrations of each surfactant were prepared. The solution temperature was slowly increased ( $\sim 1$  °C/minute) from around  $+2$  °C up to the boiling point of water, while the samples were slowly stirred. The temperature at which all of the surfactant was visibly dissolved was noted as the solubility limit temperature of the surfactant at that concentration.

A detailed study of the alkyl/aryl-D-gluconamides in the scheme indicates that the solubility is affected by factors such as conjugation with the amide bond, the presence of an aromatic ring and the number of hydrophobic carbons. The degree of branching of the hydrophobe dominated the solubility properties; the solubility increased when exchanging a straight hydrophobe with an aromatic hydrophobe and increased further when exchanging with a branched, saturated hydrophobe. For example, *N*-octyl-D-gluconamide **6**; m.p.  $153.9$  °C) is much less soluble than *N*-phenethyl-D-gluconamide **13**; m.p.  $154.3$  °C). The only exception to this rule is when the aromatic ring is conjugated with the amide bond, which increases the crystallization potential of the compound, and hence decreases the solubility. This is exemplified in the series of six carbon hydrophobes; *N*-hexyl-D-gluconamide **14**; m.p.  $178.9$  °C) is much less soluble than *N*-cyclohexyl-D-gluconamide **12**; m.p.  $134.5$  °C), but a little more soluble than *N*-phenyl-D-gluconamide **9**; m.p.  $166.5$  °C). At the same time, a gluconamide with a smaller hydrophobe will tend to have a higher melting point (since it is less ‘oily’, as evidenced by comparing surfactants **6** and **14**). Clearly, there is a delicate and subtle balance between the effects of the structure of the hydrophobe on the solubility of the surfactant.

Thus, there would seem to be a correlation between the aqueous solubility limits of both 2-deoxy-2-alkyl/aryl-amido-D-glucopyranoses and alkyl/aryl-D-gluconamides and the crystallization potential and structure of the compounds. Logically, this conclusion might be extendable to other sugar-based surfactants with other connecting bonds, but that requires experimental evidence.

## 2.3 Wetting

Some conclusions can be made from wetting studies of aqueous solutions of surfactants (1 w/v%). The results from the study done in Paper VI are presented below in Table 6 below. In general, most of the surfactants performed poorly as wetting agents. An exception is surfactant **1**, which consists of an open sugar connected to an octyl chain *via* a secondary amine. The charged character of this surfactant in water contributes to the good performance as a wetting agent. The structurally similar surfactants, **2-5**, are too poorly soluble to act as good wetting agents.

Approximate contact angles of the surfactants can be calculated by comparison to the reference surfactants' known angles in Table 6 below. Thus, the wetting abilities, as given in the table, will roughly correspond to 98° (for 0), 66° (for 1), 55° (for 2), 43° (for 3), 38° (for 4), 33° (for 5) and 0° (for 6). The margin of error of such calculations, however, is relatively large (+/- 5° for 1-5) in the middle ranges, and even larger at the extremes (+/- 15° for 0 and 6).

**Table 6.** Wetting properties of several surfactants.<sup>a</sup>

Surfactant number	Mw	Hydrophobic carbon atoms	Wetting ability	Sample concentration (mM)
			(0-6, 6 best)	
1	279.33	6	0	36
2	359.46	12	0	28
3	375.42	14	0	27
4	361.49	13	0	28
5	331.4	10	2	30
6	307.38	8	1	33
7	363.49	12	0	28
8	447.65	18	0	22
9	271.27	6	0	37
10	353.41	12	0	28
11	285.29	7	0	35
12	277.31	6	0	36
13	299.32	8	0	33
24	843.09	20	2	12
25	1063.4	20	2	9
27	378.98	20	0	26
28	461.59	20	2	22
41	329.39	10	4	30
43	402.61	16	1	25
44	346.51	12	2	29
45	358.43	14	2	28
46	291.38	8	-	34
50	293.4	8	6	34
51	273.28	6	0	37
53	297.3	8	0	34
54	305.37	8	1	33
55	309.31	9	0	32
56	309.31	9	0	32
57	339.34	10	-	29
58	331.4	10	2	30
Reference Surfactant	Mw	Hydrophobic carbon atoms	Measured contact angle	Sample concentration (mM)
			(degrees / ref.)	
NP-6	498.69	15	33 / 5	20
NP-10	674.9	15	43 / 3	15
NP-20	1115.4	15	66 / 1	9
Milli-Q water	-	N/A	98 / 0	-

<sup>a</sup> The wetting property of the surfactants are determined by comparison to commercial nonylphenol ethoxylates with 6, 10 and 20 polyoxyethylene units and pure water (NP-6, NP-10, NP-20 and Milli-Q water in the table). The wetting properties of the surfactants are given by values ranging from 0 to 6, where 6 is the most pronounced ability. The contact angles of the reference surfactants are given at the bottom part of the table, together with the defined reference value of the reference surfactant (5, 3, 1 and 0 for NP-6, NP-10, NP-20 and Milli-Q water, respectively) to be used in comparison to the studied surfactants. They have been measured by 4-5 repetitions by Marcus Persson by using a Goniometer.

## 2.4 Foaming

The foamability and foam stability of several of the surfactants in this thesis was studied by a fairly simple foaming test. The foamability, the ability to produce foam under given conditions, is studied by the initial amount of foam produced immediately after agitation. The foam stability is estimated by studying the remaining foam volume after some time.

It is noted, from the results (Table 7) that the foamability is low for surfactants with low solubility. It is assumed that the low monomer bulk concentration of such surfactants has a low rate of adsorption at the air-water interface, and hence leads to a lack of sufficient amounts of surfactants in the foam film to stabilize the foam. Thus, surfactants with high aqueous solubility are often good foaming agents. The only exception found, surfactant **28**, has a large hydrophobe and a single sugar group as hydrophile. The foamability of the surfactants with a high solubility ( $> 1$  w/v%) varies considerably. If the adsorption rate was the limiting factor for these surfactants one would expect to see an inverse relation between molecular weight and foamability. This is, however, not observed, but rather surfactants **24** and **25**, having high molecular weights, show good foaming properties. Large differences in long-range forces due to charging of the interfaces are not to be expected since the surfactants are non-ionic (with the exception of surfactants **27** and, in practice, **50**). Instead, it can be assumed that the observed differences between the surfactants are related to differences in short-range interaction and cohesive monolayer energy. The highest foamability and foam stability was observed for the charged surfactant **50**, which has small hydrophilic and hydrophobic moieties. At the air-water interface, the surfactant will be charged and thus stabilizing repulsive forces will be acting between the interfaces. The structurally similar surfactants **6**, **7**, **8**, **46** and **54** all show low foamability and low foam stability, the reason for which probably is their low solubility.



**Table 7.** Foaming properties of several surfactants.<sup>a</sup>

Surfactant number	Mw	Hydrophobic carbon atoms	Foaming			
			Foam volume (mm immediately)	Foam volume (mm after 1 minute)	Aqueous solubility (w/v%)	Head group
1	279.3	6	0	0	> 1	sugar, open
2	359.5	12	13	2.5	> 1	sugar, open
3	375.4	14	3	0	0.94	sugar, open
4	361.5	13	0.5	0	0.06	sugar, open
5	331.4	10	8	0	0.88	sugar, open
6	307.4	8	6	0	0.12	sugar, open
7	363.5	12	0.5	0	0.1	sugar, open
8	447.7	18	0	0	0.1	sugar, open
9	271.3	6	3	0	> 1	sugar, open
10	353.4	12	1	0	< 0.01	sugar, open
11	285.3	7	0	0	> 1	sugar, open
12	277.3	6	1	0	> 1	sugar, open
13	299.3	8	0.5	0	> 1	sugar, open
24	843.1	20	24	21	> 1	polyethyleneglycol
25	1063	20	28	20	> 1	polyethyleneglycol
27	379	20	2	0	0.44	cationic
28	461.6	20	12	0	0.15 - 1	sugar, ring-closed
41	329.4	10	1	0	> 1	sugar, ring-closed
43	402.6	16	2	0	0.15 - 1	sugar, ring-closed
44	346.5	12	2.5	0	0.15 - 1	sugar, ring-closed
45	358.4	14	4	0	0.15 - 1	sugar, ring-closed
46	291.4	8	3	0	0.15 - 1	sugar, ring-closed
50	293.4	8	60	55	> 1	sugar, open
51	273.3	6	1.5	0	> 1	sugar, ring-closed
53	297.3	8	1	0	> 1	sugar, ring-closed
54	305.4	8	4	0	0.69	sugar, ring-closed
55	309.3	9	7	0	0.89	sugar, ring-closed
56	309.3	9	4	0	0.64	sugar, ring-closed
57	339.3	10	0	0	< 0.01	sugar, ring-closed
58	331.4	10	8	2	> 1	sugar, ring-closed
Reference Surfactant	Mw	Hydrophobic carbon atoms	Foaming			
			Foam volume (mm immediately)	Foam volume (mm after 1 minute)	Aqueous solubility (w/v%)	Head group
NP-6	498.7	15	5	4	< 1	polyethyleneglycol
NP-10	674.9	15	32	30	> 1	polyethyleneglycol
NP-20	1115	15	28	27	> 1	polyethyleneglycol

<sup>a</sup> All samples consisted of a 40 mL aqueous solution with 0.1 w/v% surfactant. The cylinder containing the solution was turned around at a rate of 10 times during 20 seconds. The foamability and the foam stability of the surfactants and reference surfactants have been determined by measuring the formed volume of foam immediately after shaking and after 1 minute, in mm. The aqueous solubility limit of the surfactants is included for comparative purposes. The last column displays the different types of head groups; open or closed sugar-, cationic- and polyethylene glucol-based head group are the categories used.

## 2.6 Dispersion

Dispersion is the ability to solubilize ordinarily insoluble particles into a solution by forming micellar structures around those particles. In this thesis, the dispersion properties of a large number of surfactants were studied by solubilizing carbon black into water and then evaluating the turbidity of the solutions.

It was found that several surfactants had good dispersion properties. Two highly water-soluble surfactants, **2** and **50**, were found to be useful dispersion agents. The good dispersion abilities of the open-sugar surfactant **2**, might originate from a high non-polar absorption to carbon black. Surfactant **50**, on the other hand, becomes charged in water solution, and, therefore, the electrostatic double-layer repulsion contributes to the stability in this case. Interestingly, two less water-soluble surfactants, **11** and **28**, both having large hydrophobic groups, show good dispersion properties. This might be interpreted in two ways: a liquid crystalline phase may deposit on the particle surfaces and provide a stabilizing coating in the excess of that obtained for monolayer adsorption or the large hydrophobic group may give rise to high cohesive monolayer energy.

**Table 8.** Dispersion properties of several surfactants. <sup>a</sup>

Surfactant number	Mw	Hydrophobic carbon atoms	Dispersion ability (0-6, 6 best)	Head group	Tail group
<b>1</b>	279.3	6	1	sugar, open	double aliphatic
<b>2</b>	359.5	12	5	sugar, open	double aliphatic
<b>3</b>	375.4	14	0	sugar, open	double aromatic
<b>4</b>	361.5	13	3	sugar, open	double aromatic
<b>5</b>	331.4	10	1	sugar, open	single aliphatic
<b>6</b>	307.4	8	0	sugar, open	single aliphatic
<b>7</b>	363.5	12	0	sugar, open	single aliphatic
<b>8</b>	447.7	18	5	sugar, open	single aliphatic
<b>9</b>	271.3	6	2	sugar, open	single aromatic
<b>10</b>	353.4	12	2	sugar, open	single aromatic
<b>11</b>	285.3	7	0	sugar, open	single aromatic
<b>12</b>	277.3	6	0	sugar, open	single aliphatic
<b>13</b>	299.3	8	2	sugar, open	single aromatic
<b>24</b>	843.1	20	not measured	polyethyleneglycol	aromatic/aliphatic
<b>25</b>	1063	20	not measured	polyethyleneglycol	aromatic/aliphatic
<b>27</b>	379	20	2	cationic	aromatic/aliphatic
<b>28</b>	461.6	20	6	sugar, ring-closed	aromatic/aliphatic
<b>41</b>	329.4	10	3	sugar, ring-closed	single aliphatic
<b>43</b>	402.6	16	3	sugar, ring-closed	double aliphatic
<b>44</b>	346.5	12	2	sugar, ring-closed	double aliphatic
<b>45</b>	358.4	14	0	sugar, ring-closed	double aromatic
<b>46</b>	291.4	8	not measured	sugar, ring-closed	single aliphatic
<b>50</b>	293.4	8	5	sugar, open	single aliphatic
<b>51</b>	273.3	6	2	sugar, ring-closed	single aliphatic
<b>53</b>	297.3	8	not measured	sugar, ring-closed	single aromatic
<b>54</b>	305.4	8	1	sugar, ring-closed	single aliphatic
<b>55</b>	309.3	9	2	sugar, ring-closed	single aromatic
<b>56</b>	309.3	9	3	sugar, ring-closed	single aromatic
<b>57</b>	339.3	10	0	sugar, ring-closed	single aromatic
<b>58</b>	331.4	10	3	sugar, ring-closed	single aliphatic
Reference Surfactant	Mw	Hydrophobic carbon atoms	Dispersion ability (Defined as)	Head group	Tail group
<b>NP-6</b>	498.7	15	1	polyethyleneglycol	aromatic/aliphatic
<b>NP-10</b>	674.9	15	5	polyethyleneglycol	aromatic/aliphatic
<b>NP-20</b>	1115	15	3	polyethyleneglycol	aromatic/aliphatic

<sup>a</sup> The turbidimetry of the surfactant solutions was visually evaluated 5 minutes after preparation.

## 2.6 Emulsification

A large number of surfactants were studied as to their properties as emulsifying agents. Three systems were studied; rapeseed oil-water, diisopropyl myristate-water and dodecane-water. Most sugar-based surfactants were able to form macroemulsions of up to a maximum amount of oil of around 2 w/v%. The stability of many of these emulsions was very high, extending for months. The surfactants based on the dehydroabietic acid non-polar group (**24-28**) appear to be the most promising emulsifiers. By comparison between the PEG-based surfactants (**24-25**) to the sugar-based surfactants, it appears as if, indeed the high lipophobicity of sugar makes for lesser emulsification properties.

Surfactants that successfully emulsify all included oil probably have a potential capacity for even higher oil emulsification.

**Table 9.** Emulsification properties of several surfactants.<sup>a</sup>

Surfactant number	Mw	HLBG	Hydrophobic carbon atoms	Emulsification degree (%)			Emulsion sample conc. (mM)	Maximum emulsification of			Applications acc. to HLB
				Rape seed oil	Isopropyl myristate	Dodecane		Rape seed oil	Isopropyl myristate	Dodecane (mass%)	
27	379	5.0	20	28	44	31	6.6	1.32	2.11	1.45	w/o emulsifier
28	461.6	7.1	20	81	100	100	3.25	3.83	4.75	4.75	
43	402.6	7.3	16	81	61	53	6.21	3.83	2.9	2.51	
8	447.7	8.0	18	100	56	28	<u>2.23</u>	4.75	2.64	1.32	
45	358.4	8.2	14	61	53	44	6.97	2.9	2.51	2.11	
44	346.5	8.4	12	72	100	56	7.21	3.43	4.75	2.64	
3	375.4	9.5	14	22	81	44	6.66	1.06	3.83	2.11	
7	363.5	9.9	12	100	61	72	<u>2.75</u>	4.75	2.9	3.43	
4	361.5	9.9	13	<u>44</u>	<u>39</u>	<u>44</u>	<u>1.66</u>	2.11	1.85	2.11	
2	359.5	10.0	12	44	100	33	6.95	2.11	4.75	1.58	
10	353.4	10.1	12	64	50	100	0.28	3.03	2.38	4.75	o/w emulsifier
57	339.3	10.5	10	<u>17</u>	<u>44</u>	<u>11</u>	<u>0.29</u>	0.79	2.11	0.53	
58	331.4	10.8	10	75	100	81	7.54	3.56	4.75	3.83	
5	331.4	10.8	10	100	100	44	7.54	4.75	4.75	2.11	
41	329.4	10.8	10	22	44	44	7.59	1.06	2.11	2.11	
46	291.4	11.2	8	61	-	-	8.58	2.9			
50	293.4	11.3	8	100	89	0	8.52	4.75	4.22	0	
55	309.3	11.5	9	22	28	0	8.08	1.06	1.32	0	
56	309.3	11.5	9	<u>100</u>	<u>100</u>	<u>100</u>	8.08	4.75	4.75	4.75	
6	307.4	11.7	8	<u>22</u>	<u>44</u>	<u>0</u>	<u>3.5</u>	1.06	2.11	0	
54	305.4	11.7	8	<u>81</u>	<u>81</u>	<u>53</u>	8.19	3.83	3.83	2.51	Detergent
24	843.1	11.9	20	100	100	100	2.97	4.75	4.75	4.75	
13	299.3	12.0	8	33	61	28	8.35	1.58	2.9	1.32	
53	297.3	12.0	8	-	-	-	8.41				
11	285.3	12.6	7	33	53	22	8.76	1.58	2.51	1.06	
1	279.3	12.8	6	<u>81</u>	<u>72</u>	<u>22</u>	8.95	3.83	3.43	1.06	
12	277.3	12.9	6	<u>44</u>	<u>33</u>	<u>61</u>	9.02	2.11	1.58	2.9	
51	273.3	13.0	6	<u>33</u>	-	-	9.15	1.58			
9	271.3	13.2	6	<u>44</u>	<u>44</u>	<u>22</u>	9.22	2.11	2.11	1.06	
25	1063	14.4	20	80	80	90	2.35	3.8	3.8	4.28	
Reference Surfactant	Mw	HLBG	Hydrophobic carbon atoms	Emulsification degree (%)			Emulsion sample conc. (mM)	Maximum emulsification of			
				Rape seed oil	Isopropyl myristate	Dodecane		Rape seed oil	Isopropyl myristate	Dodecane (mass%)	
NP-6	498.7	11.6	15	100	100	100	5.01	4.75	4.75	4.75	
NP-10	674.9	13.8	15	100	100	95	3.7	4.75	4.75	4.51	
NP-20	1115	16.3	15	100	100	100	2.24	4.75	4.75	4.75	

<sup>a</sup> HLBG values are calculated according to Griffin. Composition of emulsification systems is water: oil: surfactant 95: 4.75: 0.25 w/v%. Surfactants with lower aqueous solubility limits than 0.25 w/v% were studied at their saturation concentrations (such samples are given in underscored italics in the concentration column; water was added in order to receive the same volume for all samples). The underscored emulsification degrees show that the sample concentration is below the approximated CMC value of that surfactant. Emulsification degrees in italics highlights that the maximum attainable emulsification was attained. The maximum possible amount of oil emulsified under the conditions is showed in mass% oil of the total volume.

*There is more to life than increasing its speed.*

- Mahatma Gandhi

# CHAPTER 3

## CONCLUDING REMARKS AND DISCUSSION

### Synthesis

Several novel and some previously known, mostly sugar-based, surfactants were synthesized and some of their surface properties were characterized and compared with those of commercial nonylphenol ethoxylates. The syntheses generally gave high yields in the very few steps necessary. Several of the synthetic procedures should be possible to scale up for industrial production. Generally, the starting materials and processes could be considered to be cheap.

### Characterization

A number of conclusions, as shown in Chapter 2, can be drawn from the results gained via various specific surface characterizations and screening tests. Several surfactant properties are investigated and the conclusions discussed in that chapter. It appears that some of the surfactants are good commercial candidates for both trivial and more complex applications. It should be noted that most surfactants tested are monosaccharide derivatives.

## Some Ideas for the Future

Several interesting results of this study deserve further scrutiny and analysis.

2-Deoxy-2-dehydroabiatic acid amido-D-glucopyranose (28). This compound is, as evident in Paper V, known to possess excellent ability to emulsify at least three water-oil systems.

According to recent reports, current estimates set the total oil reserve amounts of the world to a total of 1950 gigabarrels (gb) with a margin of error no greater than 10 %.<sup>63</sup> Currently, the rate of oil consumption is 27 gb per year, and is expected at 42 gb per year in the year 2020. At the current rate of consumption some current predictions suggest that oil will run out in about 50 years.<sup>64</sup> However, this is a topic of uncertainty and debate.<sup>65</sup> Unless new larger findings are made (the last great findings were done in the 1970s in the Northern Sea and in Alaska), new scientific break-throughs in energy production will have to be devised or radical changes of the global energy policy will have to occur (for example, by protocols set by the Department of Energy in the USA (DOE) or the members of the International Energy Agency (IEA)). Although the interest in EOR has been low in recent years, it might quickly increase in the future.

Primary oil recovery, performed by pumping action, nets 15-20 % of the oil in a well and secondary oil recovery, performed by water flooding, nets an additional 15-25 % of the oil.<sup>66</sup> To get at the remaining half of the oil, in the so-called enhanced oil recovery (EOR) step, additives, such as surfactants, need to be used. It would seem possible that the surfactant presented here could be used for EOR. For such a use in the oil industry, surfactants must fulfill several demands;<sup>66</sup> they must form Winsor III systems with reservoir oil and brine at reservoir temperatures, they have to be hydrolytically stable for extended periods of time, they should not precipitate in hard water and they should not be absorbed on mineral surfaces to any considerable extent. Furthermore, for environmental reasons, they should preferably be cheap, nontoxic and biodegradable. This particular surfactant should fulfill several of the requirements, such as hydrolytic stability, the Winsor III forming property and solubility in hard water, and its prerequisites of EOR applications should be tested. An interesting study would include the use of raw oil, or an alkane as model substance for emulsification studies, with the pure oil-water systems and with added salinity.

The aminoglucose amides (41, 51-58); it is of interest to compile and summarize findings about the synthesis/purification and surface properties of the amides of aminoglucose. Some promising surfactant properties were found in some of these (as seen in Chapter 2).

2-Deoxy-2-*p*-vinyl-benzoic acid amido-D-glucopyranose (56). Polymerizable surfactants are an interesting concept. The properties of surfactants are often needed at some stage in a process, but unwanted at the final stage. Examples are found within the paint industry, where surfactants are used as emulsifiers of the binder, as dispersants of the pigment and as wetting agents of the substrate. In the dried paint film, the presence of surfactants causes problems, decreasing the desired properties of the paint. The surfactant molecules will tend to migrate to the film-air interface, from the bulk, which increases surface soiling, water and chemical resistance and often also decreases the adhesion properties of the film, which leads to repaintability problems. This unwanted surfactant migration may be hindered or stopped by making the surfactant molecules polymerizable or hydrolysable, thus stopping motion or activity.<sup>67</sup> Surfactants that are sensitive towards auto-oxidative polymerization are useful. It is known that polymerization at the polar end generally gives low yields and requires rather severe conditions.<sup>67</sup> The surfactant presented here, however, has a polymerizable part in the hydrophobic moiety: the vinyl group. This moiety thus has a great resemblance to styrene, which is used for effective preparation of polystyrene. The surfactant itself is known to possess surprisingly good emulsification properties, and reasonably good dispersion and wetting abilities (see Papers V and VI). Hence, this surfactant is likely to be a useful compound in painting products, having the desired properties, including a considerable sensitivity towards auto-oxidation.

Dehydroabiatic acid (17). Dehydroabiatic acid is traditionally used for the preparation of adhesives by esterification with pentaerythritol. Dehydroabiatic acid usually occurs as esters in the crude tall oil. Simple purification procedures are needed for the production of the free acid. At present the esters are hydrolyzed in liquid, molten sodium hydroxide for up to three days, which is required for complete hydrolysis. Less severe reaction conditions, for hydrolysis of this neopentyl-type of esters, would be desirable. A much simpler hydrolysis method was found during the work with dehydroabiatic acid. Unfortunately, this hydrolysis was not found to be easily reproducible. Future work on this, however, could perhaps reveal the right experimental conditions for this reaction.

The alkyl/aryl-D-gluconamides (1-14). Much research has been carried out on the D-gluconamides, including syntheses, surface measurements, solubility tests and more. Some of the data are not yet compiled. Also, some preliminary results on research performed at the YKI, Stockholm, show that D-gluconamides with small hydrophobic moieties are good hydrotropes. The surfactants, which have been investigated, all have hydrophobic parts containing six carbon atoms. The surfactants are *N*-hexyl-D-gluconamide, *N*-cyclohexyl-D-gluconamide, *N,N*-diisopropyl-D-gluconamide and *N*-phenyl-D-gluconamide. It would be interesting to see the results in a continuation of this project, since cheap hydrotropes are always commercially interesting.

*Vi Veri Veniversum Vivus Vici*

- Immanuel Kant



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