Summary and Conclusions

Surface active agents (Surfactants) possess a unique property to absorb at interfaces/surfaces. Surfactants have hydrophilic and hydrophobic parts which have tendency to adsorb and form micelles. These are commonly classified on the basis of charge on head group as anionic, cationic, nonionic and zwitterionic surfactants. The aggregation characteristics of surfactants are highly sensitive and can be easily modulated to the desired range by change in temperature, pH and concentration and in the presence of co-surfactants or co-solvent or additives. Micelles formed are of different geometry viz. spherical, ellipsoidal (prolate or oblate), rodlike, disclike and wormlike. Even vesicular dispersions and liquid crystalline phases can be seen. In the presence of two distinct amphiphilic molecules, mixed micelles are formed due to synergistic interaction and have practical importance.

Cationic surfactants belong to one of the most extensively studied class of surfactants which have overriding importance over other class of surfactants. A few studies on the aqueous solution and phase behavior of quaternary ammonium salt based cationic surfactants have been documented in this thesis. Some studies on the influence of electrolytes, glycol ethers, alcohols, aromatic solutes, polymers, Pluronics® and reverse Pluronics® on cationic surfactants have been reported in detail and some are taken as the base for further research.

Triton X-100 (TX-100) is a polyoxyethylene based alkyl aryl type well-studied nonionic surfactant. It finds numerous applications in diverse fields ranging from household to industrial formulations. Being biocompatible, it also finds usefulness in solubilization/separation of proteins and in DNA extraction. Detailed studies on solubilization of phenolic antioxidants from cinnamic acid family in TX-100 micelles have been done. Bile salts, the Nature’s anionic surfactants play a vital role in solubilization of fat in digestion process. Mixed systems containing TX-100 + bile salts are studied. Distinct effect of cinnamic acid analogues and bile salts is discussed in terms of their effect on size and shape of Triton X-100 micelles.

Pluronics® are commercially available PEO–PPO–PEO triblock copolymers and have been studied quite comprehensively due to their rich phase behavior, diversity of industrial as well as biomedical applications. In an aqueous medium, these copolymers form core–shell micelles made of core from
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hydrophobic PPO blocks and shell from hydrated PEO blocks. Aqueous solution properties of Pluronics® and Tetronics are quite sensitive to pH, temperature and in the presence of additives. Being biocompatible, Pluronics® are considered to be good carriers for poorly water soluble compounds/drugs due to their enormous solubilization ability. In this context, the influence of these substances on the aggregation characteristics of Pluronics® is therefore of overriding importance. A systematic study on solubilization and interaction of some hydrophobic alcohols in Pluronic® micelles is reported in detail.

The following Pluronics® were used during my research work.

<table>
<thead>
<tr>
<th>Pluronics®</th>
<th>Molecular formula</th>
<th>Molecular weight</th>
<th>% PEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>P123</td>
<td>EO$<em>{20}$PO$</em>{70}$EO$_{20}$</td>
<td>5750</td>
<td>30</td>
</tr>
<tr>
<td>P85</td>
<td>EO$<em>{26}$PO$</em>{40}$EO$_{26}$</td>
<td>4600</td>
<td>50</td>
</tr>
<tr>
<td>F87</td>
<td>EO$<em>{61}$PO$</em>{40}$EO$_{61}$</td>
<td>7700</td>
<td>70</td>
</tr>
</tbody>
</table>

This thesis is mainly divided into seven chapters covering several studies on the solubilization and aggregation behavior of different type of surfactants viz. cationic, nonionic (Triton X-100) and EO-PO block copolymers (Pluronics®) in aqueous media and their interaction with other surfactants, electrolytes, hydrotropes, polymers, alcohols, antioxidants and bile salts. Surfactant solution behavior has been examined using several techniques viz. cloud point, viscometry, UV-visible spectroscopy, cryo-TEM, $^1$H NMR, Dynamic light scattering (DLS) and small angle neutron scattering (SANS). The aggregation and morphological changes have also been scrutinized at different pH, temperatures and in the presence of salts. In order to meet all objectives, the contents of thesis chapters are summarized as follows.

**In chapter 1**, general introduction to the world of surfactants and their opportunity is provided. Brief description of ionic (cationic and anionic) and nonionic (Pluronics® and Triton X-100) surfactants alongwith their solution chemistry is provided. An overview of literature studies on phase and micellar characteristics viz. CMC, aggregation number, micelle size/shape intermicellar interaction and influence of external stimuli and additives on the surface and colloid-chemical behavior of ionic and nonionic surfactants is given. A list of
important and the most relevant research articles to the work are provided in this chapter.

**In chapter 2,** effect of hydrophilic PEO-PPO-PEO triblock copolymer on cetyltrimethylammonium tosylate (CTAT) solutions in water is examined. CTAT in water forms long flexible wormlike micelles at concentrations above 15 mM, leading to highly viscous solutions and viscoelastic stiff gels (above 70 mM). The hydrophilic water soluble PEO further increases the viscosity, while in the presence of a nonmicellar hydrophilic PEO–PPO–PEO triblock copolymer (Pluronic® F87) these wormlike micelles are transformed into smaller structures, as evident from a sharp decrease in viscosity and increase in specific conductance. These results are quantified by SANS measurements. Two break points in the typical specific conductance versus [CTAT] plot as a function of [F87] represent interactions between CTAT and F87.

In pure CTAT, the tosylate counterions remain close to the head group and facilitate the formation of rodlike micelles at lower concentrations and their existence is confirmed from cryo-TEM image. However, addition of Pluronic® F87 reduces the larger size of the rodlike micelles and converts them into smaller ones. The PPO middle block of Pluronic® F87 gets inserted in the CTAT micelle by forming a mixed micelle, the size and total aggregation number of CTAT/F87 mixed micelles decreases but the number of F87 molecules in the mixed micelles increases with an increase in [F87]. The penetration of PPO of F87 containing significant amount of water molecules attached to it, inside CTAT micelles decreases hydrophobicity of the core while the presence of PEO end blocks enhances hydrophilicity each favoring smaller micelles. SANS data on CTAT micelles in the presence of F87 show a progressive decrease in the aggregation number showing insertion of a few F87 molecules and releasing many CTAT molecules from the mixed micelles.

This work has been published in *Journal of Surfactants and Detergents 15 (2012) 377-385.*

**In chapter 3,** 1-alkanol induced microstructural changes in CTAT micelles have been examined by viscosity, cryo-TEM and SANS measurements. Special attention is provided on the effect of 1-hexanol. In 20 mM CTAT solution wormlike micelles accompanied by small spherical micelles are observed. In the
Summary and Conclusions

presence of small amount of 1-hexanol, wormlike micelles are elongated giving peak in viscosity which are then entangled resulting in lowering of viscosity. Further addition of 1-hexanol till a certain value leads to formation of vesicle micelles. A route of formation of vesicular structures from wormlike micelles of CTAT is successfully monitored by cryo-TEM microphotographs. It is further quantified by SANS measurements. Such microstructural changes are attributed due to the different location of 1-hexanol in the micelles.

In chapter 4, the solubilization of three weakly polar aromatic compounds viz. p-toluidine, p-toluic acid and p-cresol in cetyltrimethyl ammonium bromide micelles was examined to understand their effect on micellar growth/transition. Micellar growth depends on electrostatic and hydrophobic interaction between the surfactant and additives. Highly polar p-cresol strongly interacts with CTAB micelles compared to other two additives leading to micellar transitions. Viscosity and DLS provide clear evidence of micellar growth with progressive solubilization. The pH dependant protonation/deprotonation of phenolic/carboxylic/amino group of the additives and interaction with surfactant’s polar head group showed remarkable growth close to pKa value. New insight in this study is that polar aromatic compounds in less ionized form get solubilized more in micelle and cationic-π/electrostatic interaction induces micellar growth. NMR studies indicate pH dependant location of p-toluic acid in micelle. This study provides fundamental knowledge of pH modulated growth of micelles by weakly polar solubilizates which might be useful in developing surfactant based formulations and supportive for researchers in the field of colloid and surface science. This work has been communicated in Colloids and Surfaces A: Physicochemical and Engineering Aspects.

In chapter 5, solubilization of phenolic antioxidants from cinnamic acid family viz. cinnamic acid (CA), p-coumaric acid (PCA), caffeic acid (CFA), ferulic acid (FA) and sinapic acid (SA) on the aggregation characteristics of TX-100 micelles in aqueous medium has been investigated by viscosity, DLS, SANS and NMR experiments. These solubilizates influence the cloud point, viscosity and micelle size of TX-100 on account of their hydrophobicity. The solubility data for
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CA and its analogues in TX-100 micelles follow the order CA>PCA>FA>CFA>SA, a trend expected from their chemical structures.

Cinnamic acid, a biomedically useful compound, displayed maximum growth in micelles and was therefore studied in detail. Cinnamic acid alters micellar characteristics of TX-100 which is strongly dependant on pH. The behavior of CA as a hydrophobic solubilizate in acidic pH and a hydrotrope in alkaline pH dictates its location in micelles and a consequence changes micelle size and shape. SANS data shows that the micellar aggregation number increases with increase in concentration of CA. The formation of rodlike micelles on progressive solubilization of cinnamic acid and their transformation into spherical micelles in alkaline medium was also confirmed from SANS analysis. The increase in the cinnamic acid concentration, decrease in pH and the presence of sodium chloride favor the micellar growth at low temperature. NMR experiments reveal that CA is solubilized in palisade layer of TX-100 micelles. As cinnamic acid and related compounds are biologically important, this study might be useful for their surfactant based formulations in pharmaceutical and food industry. This work has been communicated in Colloids and Surfaces B: Biointerfaces.

In chapter 6, the effect of two bile salts namely, sodium cholate (NaC) and sodium deoxycholate (NaDC) on the phase behavior and micellar characteristics of aqueous solution of a nonionic surfactant Triton X-100 has been investigated at different pH, temperatures and in the presence of sodium chloride using cloud point (CP), viscosity, DLS and SANS measurements. Bile salts form spherical mixed micelles with TX-100. Formation of mixed micelles was confirmed from decrease in total aggregation number obtained from SANS experiments.

Our aim was to study the variation in microstructures of TX-100 micelles in the presence of bile salt and a special attention is provided on the effect of pH. The solution behavior of mixed micellar system is discussed in the light of synergism and protonation/deprotonation of carboxylic acid with a change in pH. SANS experiments reveal that the aggregation number and size of TX-100 + NaDC mixed micelles increase below pKa of NaDC which are in agreement with viscosity and DLS data. In acidic medium, spherical mixed micelles are transformed in to ellipsoidal shape with axial ratio of ~2. Temperature and salt-
induced micellar growth of TX-100 micelles diminished in the presence of bile salts. The size and viscosity of the micelles at low pH was a function of [bile acid]. With investigations on pH, electrolyte and temperature effects, our study might be useful for a better understanding on solution behavior of bile salts which are of prime importance in digestion process. This work has been communicated in *Colloids and Surfaces B: Biointerfaces*.

In *chapter 7*, the effect of addition of hydrophobic alcohols viz. 1-hexanol, 1-octanol and 1-decanol in the aqueous solutions of two Pluronics® (P85 and P123) has been studied by DLS, SANS, viscometry and fluorescence measurement techniques. Pluronics® are considered as good carrier for poorly water soluble substances on account of their superior solubilization capacity over other ionic and nonionic surfactants. Understanding the influence of these substances on the aggregation characteristics of Pluronics® is therefore of overriding importance. Both these Pluronics® exhibit sphere-to-rod micellar shape transition with increase in temperature, the dynamics of the transitions being significantly slower in the case of P123 because of its higher hydrophobicity and molecular weight.

The aim of our studies was to investigate the restructuring and growth of Pluronic® micelles upon addition of hydrophobic alkanols that have applications in the fields ranging from personal care/food products to pharmaceutical formulations. The studies show that alcohol induced micellar restructuring and growth for the two Pluronics® slows down as the concentration of the alcohols increases and their aqueous solubility decreases progressively from 1-hexanol to 1-decanol. These observations, which were manifested in decreasing rate of sphere-to-rod micellar growth, have been attributed to more effective dehydration of micellar core at higher level of solubilization and hydrophobicity of the alcohols. The results thus shed light on the specific role of additive induced dehydration of micellar core on restructuring and growth characteristics of micelles of both hydrophilic (P85) and hydrophobic (P123) Pluronics®. This work has been published in *Soft Matter 9 (2013) 7583-7591*.

In brief, this thesis presents the studies on colloid-chemical behavior of some surfactants viz. CTAB, TX-100 and Pluronics® in the presence of additives of different nature using different techniques viz. cloud point, viscosity, rheology,
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UV-visible spectroscopy, cryo-TEM, NMR, DLS and SANS. It was concluded that solution of surfactants display fascinating phase and micellar behaviour strongly dependant on their molecular characteristics which can be easily tuned in the presence of variety of additives viz. inorganic salts, alcohols (short, medium chain and higher chain), medicinally important antioxidants from cinnamic acid family, linear polymers, biological surfactants (sodium deoxycholate and sodium cholate) and hydrotrropes and in the absence and presence of external stimuli. This can be useful in optimizing properties of surfactant based products and drug delivery systems. Mixed surfactant systems (cationic-nonionic and anionic-nonionic) showed strong synergism. These can be of prime importance in designing surfactant based formulations.

In short, the whole work can be summarized as the studies on aqueous solution behavior of ionic, nonionic and block copolymeric surfactants. These studies can help in improving the performance based properties of surfactant or polymer solutions and in designing surfactant based formulations.