DOI: 10.1002/masy.200851006

The Formation of Middle-Phase Microemulsions of Polar Oils

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Summary: Middle-phase microemulsions exhibit the unique properties of an ultra-low interfacial tension and a bicontinuous structure formed from the water and oil components. New developments exploiting these properties are described. In designing such systems, it is important that the spontaneous transition of the oil droplets from Winsor II through Winsor III to the Winsor I state is brought about by diffusion or chemical reaction. The selection of the hydrophobic and lipophilic surfactants is critical when low-energy emulsification systems for highly polar oils are being developed.

Keywords: bicontinuous structure; microemulsion; nano-emulsion; spontaneous emulsification; ultra-low interfacial tension

Introduction

The behavior of water/oil/surfactant systems has been widely studied by conventional techniques. The technology of mixing water and oil is extremely important from an industrial standpoint.[1] The processes by which small oil droplets are dispersed in water to form O/W emulsions are generally classified as mechanical emulsification or low-energy emulsification. In mechanical emulsification the emulsion is formed mechanically by stirring a surfactant/oil/water mixture. The drawback of this technique is that the energy requirement is relatively high. In the alternative low-energy emulsification process, the emulsion is obtained with little energy by using phase changes in the surfactant/oil/water system. The ultra-low surface tension of middle-phase emulsions makes this approach extremely efficient in comparison with mechanical emulsification. The development of processes to carry out nano-emulsion formation (droplet size < 1 micron) with minimum energy consumption is important industrially, and is of relevance to academic and environmental chemistry.

In this paper, the author explains phase behavior in water/oil/surfactant systems and the basic principles of low-energy emulsification, before presenting information on the design of a spontaneous emulsification system as the ultimate form of low-energy emulsification. He follows this by describing phase behavior in polar oils (used as efficient solvent for functional organic compounds) and their low-energy emulsification. The control of middle-phase microemulsions is important in such systems.

Experimental Part

Ingredients

SDS (Sodium Dodecylsulfate), AOT (Aerosol OT: Di(2-ethylhexyl) Sulfosuccinate Sodium Salt), SDBS (Sodium Dodecylbenzenesulfonate), Benzethonium Chloride and Ethyl Acetate (all supplied by Tokyo Chemical Industry), ALKANOL XC (supplied by Aldrich), Tricresyl phosphate and Tri-isononyl phosphate (supplied by Daihachi Chemical Industry), Deionized Water with MILLIPORE Milli-Q System.

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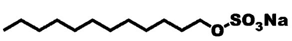
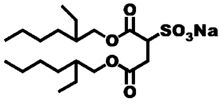
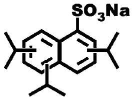


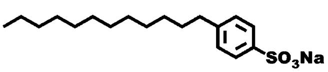
SDS



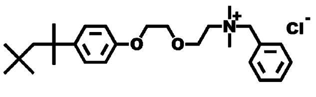
AOT



ALKANOL XC



SDBS



Benzethonium Chloride

The Phase Behavior of the Water/Surfactant/Ethyl Acetate Systems

Quantities of deionized water (2.35g), containing predetermined amounts of NaCl (0–2.0g), ethyl acetate (2.35g) and surfactant (0.3g), were placed in test tubes and thoroughly mixed after sealing tightly. They were then allowed to stand at 25 °C for a week, and the volume fractions of the aqueous phase, ethyl acetate phase and middle phase calculated from the position of the interfaces.

Other samples were prepared in a similar manner using the same quantities of aqueous NaCl solution and ethyl acetate, but with the surfactant concentration comprising from 0 to 12% of the entire weight. The phase behavior was observed.

The Phase Behavior of the Ethyl Acetate/Magenta Dye/ALKANOL XC/Water System

Magenta dye (1.6g: synthetic dye manufactured by Fujifilm), tricresyl phosphate (6.0g) and tri-isononyl phosphate (10.0g) were dissolved in 82.4g of ethyl acetate. 2.3g of water containing a predetermined amount of NaCl (0–2.0g) and 0.2g of ALKANOL XC were added to 2.5g of the resultant solution. The mixture was placed in a test tube, sealed tightly and mixed. It was let stand at 25 °C for a week, and the volume fractions of the aqueous phase, ethyl acetate phase and middle phase calculated based on the position of interfaces.

The Emulsification of Ethyl Acetate containing Magenta Dye

- **Preparation of Solution A-1**: Deionized water (19.9g) was added to gelatin (0.1g). It was heated at 50 °C to dissolve gelatin, and cooled to room temperature. A gel was obtained. The gel (2.0g) and a 1.0N aqueous NaOH solution (10.0g) were then dissolved in deionized water (60.0g) containing a saturated amount of ethyl acetate.
- **Preparation of Solution A-2**: Magenta dye (1.6g), tricresyl phosphate (6.0g) and tri-isononyl phosphate (10.0g) were dissolved in ethyl acetate (82.4g). 49.0g of ethyl acetate were added to 1.0g of the resultant solution, forming Solution A-2.
- **Preparation of Solution A-3**: Solution A-2 (5.0g), ALKANOL XC (0.4g), 2N hydrochloric acid (0.2g) and deionized water (0.3g) were mixed.
- **Preparation of Sample A**: 7.2g of Solution A-1 and a stir bar were placed in a sample bottle. While stirring at 1200rpm using a magnetic stirrer, 0.5g of Solution A-3 were added dropwise over 1 minute, followed by stirring for another minute. The whole operation was carried out at 25 °C. Emulsification was observed. The aqueous phase, Solution A-1, consists of deionized water containing a saturated amount of ethyl acetate. The ethyl acetate-based Solution A-3 does not therefore dissolve in Solution A-1 as the emulsion forms.

- **Preparation of Solution B-1**: ALKANOL XC (0.04g), 2N hydrochloric acid (0.02g) and deionized water (0.03g) were added to 8.5g of the Solution A-1.
- **Preparation of Solution B-2**: Magenta dye (1.6g), tricresyl phosphate (6.0g) and tri-isononyl phosphate (10.0g) were dissolved in ethyl acetate (82.4g). 1.0g of the resultant solution was diluted with 49.0g of ethyl acetate, forming Solution B-2.
- **Preparation of Sample B**: Solution B-1 (7.2g) and a stir bar were placed in a sample bottle. While stirring at 1200rpm using a magnetic stirrer, 0.5g of Solution B-2 were added dropwise over 1 minute, followed by stirring for another minute. The whole operation was carried out at 25 °C. Emulsification was observed. The aqueous phase, Solution B-1, consists of deionized water containing a saturated amount of ethyl acetate. The ethyl acetate-based Solution B-2 does not therefore dissolve in Solution B-1 as the emulsion forms.

The average particle size of the resultant emulsions were measured using Master Sizer X manufactured by Malvern Instruments Ltd.

Results and Discussion

Basis of Low-Energy Emulsification

Typically, the phase behavior shown by systems in which a surfactant is dissolved in sufficient water and oil are of three types, depending on the hydrophile-lipophile balance (HLB) of the surfactant.[2]

1. When the surfactant is hydrophilic, a two-phase state consisting of an O/W microemulsion and excess oil is produced (Winsor I).
2. When the surfactant is lipophilic, a two-phase state consisting of a W/O microemulsion and excess water is produced (Winsor II).
3. When the hydrophilicity and lipophilicity of the surfactant are balanced, a three-phase state consisting of a middle-phase microemulsion, excess water and excess oil is formed (Winsor III).

The middle-phase microemulsion formed with a balanced HLB is unique. It has a

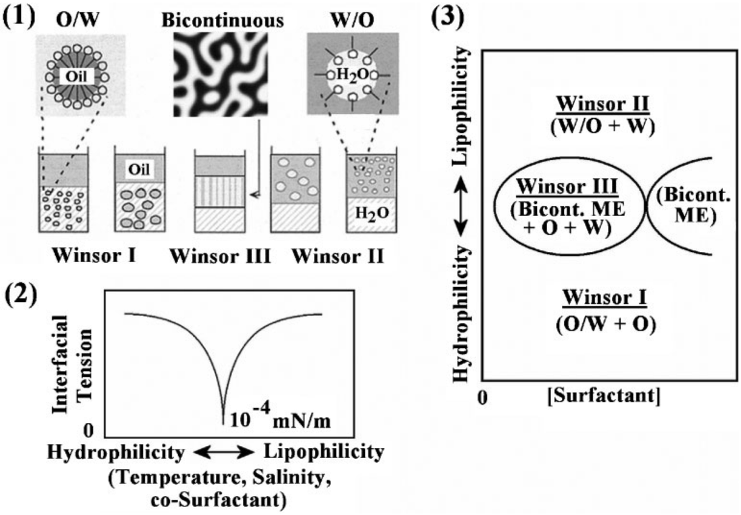


Figure 1.

(1) Existing states of water and oil, (2) interfacial tension between oil and water interfaces and (3) phase behavior, when the hydrophilic-lipophilic balance in a water/oil/surfactant system differs.

bicontinuous water-oil structure, and an interfacial tension between the oil and water interfaces that is almost zero ('ultra-low' interfacial tension).

Shinoda *et al.* have found that low-energy emulsification was feasible using the ultra-low interfacial tension provided by a nonionic surfactant/n-alkane/water system.[3] Since the HLB of a nonionic surfactant varies with temperature, the system is in a Winsor I state at low temperature, Winsor II at high temperature and Winsor III at the temperature at which the hydrophilicity and lipophilicity are balanced (phase inversion temperature (PIT)). The nonionic surfactant/n-alkane/water system has ultra-low interfacial tension at the phase inversion temperature, making it is possible to produce nano-emulsions having a submicrometer droplet size with little energy input at that temperature. However, the reverse process of emulsification, coalescence, also takes place easily at the phase inversion temperature. To overcome this problem, emulsification is carried out at around the phase inversion temperature and, once formed, the emulsion is cooled and stored at a temperature low enough to prevent coalescence of emulsion from occurring. The technique combines both nano-emulsion formation and stabilization, and is called ''the phase inversion temperature (PIT) emulsification method''. It is a method of emulsification brought about by a state of ultra-low interfacial tension a balanced HLB (Winsor III), and the preservation of the O/W emulsion so obtained in a highly hydrophilic state (Winsor I). The principle is used in the design of low-energy emulsification systems.

Designing a Spontaneous Emulsification System

Emulsification that proceeds using the thermal energy present at room temperature, without the application of external mechanical energy, is called ''spontaneous emulsification''. It is the ultimate form of low-energy emulsification.[4] The HLB of a surfactant/oil/water system varies according to the additives present (such as cosurfactants and salts). So it is theoretically possible for a spontaneous emulsification system to be created by simply changing the amount of additives. The PIT emulsification method could be used to achieve this, or an emulsification process that relies on the ultra-low interfacial tension brought about by a balanced HLB (Winsor III), followed by preservation in a highly hydrophilic state (Winsor I).

The process is more difficult than this, however. Emulsification in the presence of additives, giving a Winsor III state, followed by preservation as a Winsor I emulsion, in which the additives have been removed, is more complex and cannot be achieved by simply raising or lowering the temperature of the system. Miller *et al.* overcame these difficulties by the positive use of diffusion at the oil-water interface.[5] This involved the use of a surfactant that is insoluble in water, a cosurfactant that is soluble, and the injection of the surfactant/cosurfactant/oil system into water. The percentage of water increased as the percentage of the cosurfactant in oil decreased, due to diffusion into the water. Accordingly, when oil droplets with a proper composition come into contact with water, the state transition from Winsor II → Winsor III → Winsor I is enabled, as diffusion takes place. In such systems, the oil and aqueous phases together form the Winsor III continuous phase, after which the aqueous phase alone becomes the continuous phase. As a result, supersaturated oil is spontaneously formed as a nano-emulsion, using only the thermal energy present at room temperature. This mechanism is described as ''spontaneous emulsification through the use of diffusion'' (Figure 2).

Nishimi and Miller developed the concept, and invented a spontaneous emulsification system using the natural change in the HLB brought about by diffusion of inorganic salts.[6] Kunieda *et al.* have reported that the HLB of an ionic surfactant varies with the strength of added salt, and that the AOT/n-alkane/brine system exhibited Winsor-type phase behavior as

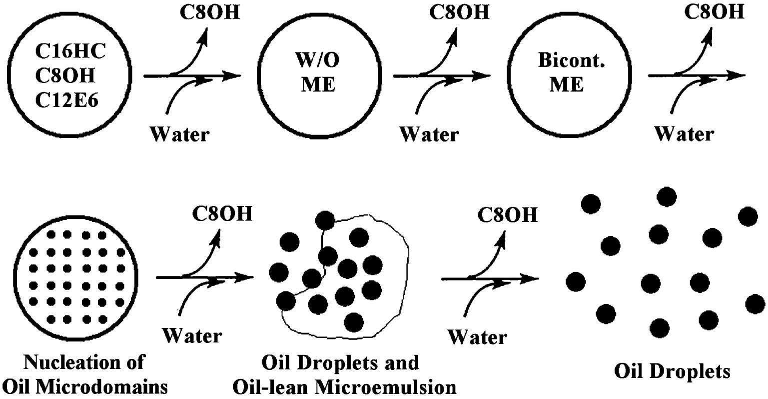


Figure 2.
Mechanism of spontaneous emulsification through the use of diffusion.

the salt strength was changed.[7] According to these finding, designing a spontaneous emulsification system is achievable by bringing about the Winsor II → Winsor III → Winsor I transition by injecting oil droplets consisting of AOT/n-alkane/brine into water, so reducing the salt concentration in the oil droplets by diffusion. This is demonstrated by injecting oil droplets with a composition of AOT/n-octane/0.5% NaCl aqueous solution (30%/60%/10%) into water. The oil droplets emulsify spontaneously as if they had undergone cell division.

Kunieda *et al.* have reported that the HLB of AOT depends on the ratio of AOT and water.[8] When the amount of water is low, AOT is lipophilic; it becomes hydrophilic as the amount of water increases. This indicates that the HLB can be controlled by changing the water content of the oil droplets containing AOT, and suggests that a spontaneous emulsification system might be achievable by increasing the water content of the oil droplets by diffusion. To test this, oil droplets with an AOT/n-octane/water (30%/60%/10%) composition were injected into water. Spontaneous emulsification was observed. A similar phenomenon was observed when oil droplets with a composition of AOT/n-hexane/water (20%/70%/10%) were injected into water.

A systematic study on an AOT/n-alkane/brine system showed that two conditions are necessary in designing a spontaneous emulsification system: making the transition from Winsor II → Winsor III → Winsor I by diffusion; and solubilizing a large amount of water and oil in a Winsor III state. The two major advantages of the AOT/n-alkane/brine system are: (1)

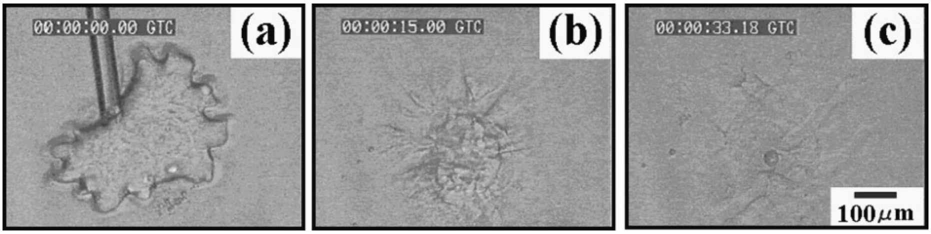


Figure 3.
Photographs taken through an optical microscope after injecting into water oil droplets having a composition of AOT/n-octane/water (30%/60%/10%). (a) immediately after injection, (b) 15 seconds after, (c) 33 seconds after.

coalescence of the emulsion is unlikely because AOT is an ionic surfactant, and (2) when optimized, spontaneous emulsification proceeds, even when no additive is present. Such spontaneous emulsification systems can be designed in various ways using other combinations of surfactants and oil, in addition to the AOT/n-alkane/brine system.

Molecular self-organization in water and the effect of changing the hydrophilic/ hydrophobic balance of a surfactant by chemical reaction have been actively investigated. The application to a drug delivery systems and the like has been studied.[9–11] The result, for example, is the transition from vesicle to micelle. Nishimi and Miller have successfully formulated a new spontaneous emulsification system that uses an HLB transition triggered by chemical reaction.[12] In this case, it is the transition from Winsor II → Winsor III → Winsor I as the chemical reaction proceeds, that is the driving force of the spontaneous emulsification process.

The Development of Low-Energy Emulsification Systems using Polar Oil

If low-energy emulsification could be carried out when a functional organic compound is dissolved in a polar oil, it would be possible to produce a nanoemulsion containing that functional organic compound. The low energy requirement for such a process suggests that it might have an important role in industrial applications. No conventional work on the ultra-low interfacial tension of polar oil has been disclosed, however.

It is reported in a study on nonalkane-based microemulsions that Winsor-type phase behavior is exhibited only when fluorine-based surfactants are used for fluorine-based oils[13] and when silicone-based surfactants are used for silicone-based oils.[14] These experimental facts indicate that, in order to carry out efficient solubilization, a hydrophobic group of a surfactant must be hydrophobic and also lipophilic. Although the terms hydrophobic and lipophilic are occasionally used imprecisely, without clear distinction between the two, hydrophobic denotes only a low affinity for water. It does not necessarily ensure high solubility in oil (or lipophilicity). A surfactant with a hydrophobic group that is insoluble in both water and oil, i.e. a structure with low hydrophilicity and lipophilicity, cannot serve as an effective solubilizing agent. Such thinking led to a surfactant containing aromatic rings to be chosen for having hydrophobic groups that have high solubility in polar oil. The phase behavior of the surfactant in an ethyl acetate/water system was studied, and Winsor-type behavior was observed for the first time in such systems.[15]

The positions of the water/ethyl acetate interface with SDS and AOT as the surfactants are shown in Figures 4 (a) and (b). Neither SDS nor AOT contain aromatic rings. Both systems exhibit only two phases at all salt concentrations. With SDS as the surfactant, the position of the interface remains unchanged regardless of the salt strength, whereas with AOT it moves as the salt concentration is increased. We believe this is because SDS is a water-soluble surfactant and remains dissolved in the aqueous phase in this salt concentration range. In contrast, AOT stays in the aqueous phase when the NaCl concentration is 0.3% or less, but moves to the ethyl acetate phase when the salt concentration exceeds 0.3%. Note that even at the point of balance between hydrophilicity and lipophilicity, a three-phase state, typical in ultra-low interfacial tension, is not observed.

Such behavior contrasts with systems using surfactants containing aromatic rings, such as ALKANOL XC, SDBS and Benzethonium Chloride. Figure 4 (c) shows the situation using ALKANOL XC as the surfactant. The ALKANOL XC is dissolved entirely in the aqueous phase when the NaCl concentration is 0.7% or less. A two-phase state is formed (Winsor I). High NaCl concentrations (above 1.0%) cause the ALKANOL XC to move to the ethyl acetate phase. Again, a two-phase state is formed (Winsor II). Between NaCl con-

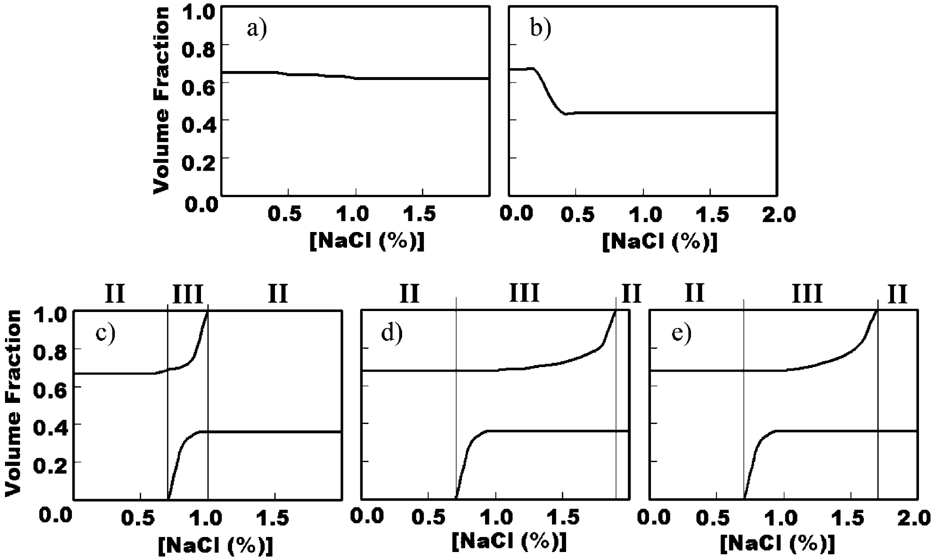


Figure 4.
Volume fractions of brine, ethyl acetate, and middle-phase microemulsion as a function of wt% NaCl at a water-to-ethyl acetate ratio of 1.0 for (a) the SDS-brine-ethyl acetate system, (b) the AOT-brine-ethyl acetate system, (c) the ALKANOL XC-brine-ethyl acetate system, (d) the SDBS-brine-ethyl acetate system, (e) the Benzethonium Chloride-brine-ethyl acetate system, at 25 °C and 6 wt% surfactant in brine.

centrations of 0.7% and 1.0%, a three-phase state appears due to the ultra-low interfacial tension brought about by the hydrophilicity and lipophilicity of the system being in balance (aqueous phase + middle phase + ethyl acetate phase: Winsor III).

The same phenomenon was observed when SDBS (Figure 4 (d)) and Benzethonium Chloride (Figure 4 (e)) were used as surfactants. Three-phase states occurred when the NaCl concentration was between 0.7% and 1.9% in the former, and between 0.7% and 1.7% in the latter.

The phase behavior of ALKANOL XC, SDBS and Benzethonium Chloride in water/ethyl acetate systems was also studied as a function of surfactant concentration. All three exhibited Winsor-type behavior. The results are shown in Figure 5.

A three-phase state (Winsor III) was obtained with ALKANOL XC when the HLB was balanced by the addition of 3.5-10.0% NaCl. This reduced to a two-phase state (Winsor II) when the concentration of ALKANOL XC was 11.0% or more. Under these conditions the ALKANOL XC dissolved in the organic phase even in the absence of NaCl.

A three-phase state (Winsor III) was also observed for SDBS when the HLB was balanced by addition of NaCl to give a concentration of 1.0–10.0%. In this case the system reduced to a single-phase state after balancing the HLB with NaCl when the SDBS concentration was 11.0% or more. This indicates that both water and ethyl acetate are completely solubilized in the bicontinuous phase under such conditions.

The same result was obtained with Benzethonium Chloride. A three-phase state (Winsor III) was observed with Benzethonium Chloride when the HLB was balanced by addition of 1.0–13.0% NaCl. At concentrations above 13.0% Benzethonium Chloride, a single-phase state was observed after balancing the HLB with NaCl.

These are the first examples that demonstrate Winsor-type phase behavior using a highly polar organic solvent such as ethyl acetate.

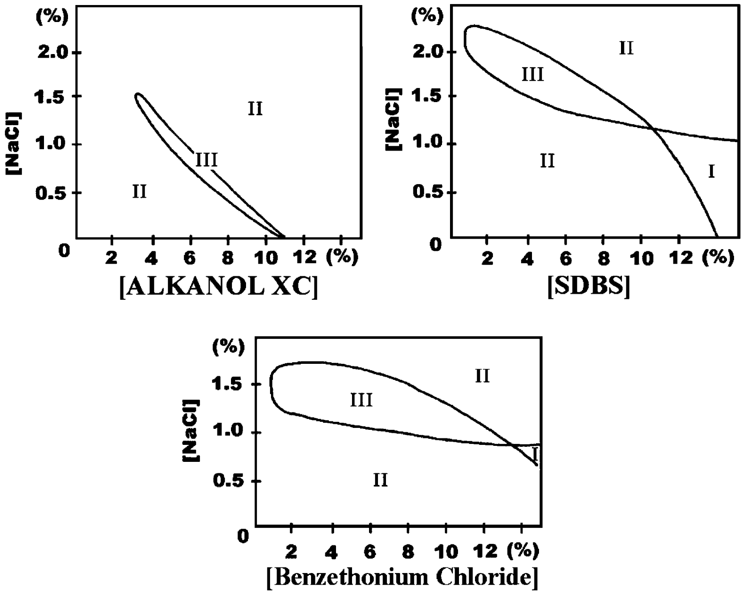


Figure 5.
Phase diagrams of surfactants with aromatic rings in the hydrophobic part of the molecules/ethyl acetate/brine system at 25 °C

The same phase behavior is observed when a magenta dye (synthetic dye manufactured by Fujifilm) is dissolved in ethyl acetate[16]. The three phases were obtained when the NaCl concentration was in the range 0.3–0.6%. This suggests that the water/ethyl acetate/ALKANOL XC system might be able to achieve a state of ultra-low interfacial tension in the presence of a magenta dye.

We therefore attempted the low-energy emulsification of ethyl acetate containing the magenta dye. The experiment was carried out with water containing a saturated amount of ethyl acetate, in order to prevent ethyl acetate from dissolving in the aqueous phase and from emulsifying. Gelatin was added to the aqueous phase as a protective colloid (Figure 7). ALKANOL XC was used as a surfactant. The emulsification behavior was compared when ALKANOL XC was added to the aqueous phase (Sample A) and to the ethyl acetate phase (Sample B) (Figure 7).

In sample A, the surfactant, ALKANOL XC, is in the aqueous phase throughout the emulsification process. Since the aqueous phase is alkaline, the sulfonic acid portion of the ALKANOL XC is in a dissociative state at all times, i.e., a state of high hydrophilicity. This ensures that the system remains in a Winsor I state during the entire emulsification process. It is not able to form an ultra-low interfacial state (Winsor III) and, as a result, has a relatively

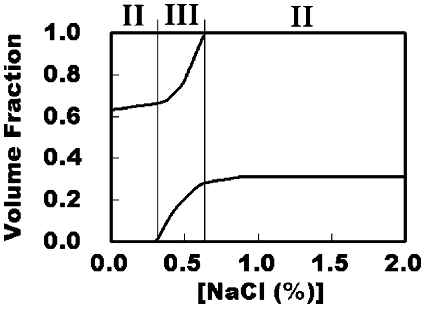


Figure 6.
Volume fractions of brine, ethyl acetate with magenta dye, and middle-phase microemulsion phase as a function of wt% NaCl. Refer to the Experimental Part for the detailed composition of the ethyl acetate phase.

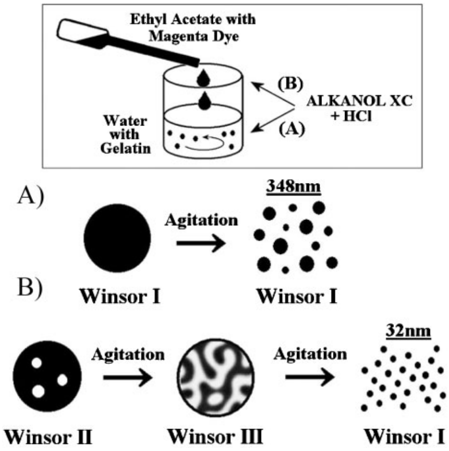


Figure 7.
Pattern diagrams of emulsification behavior when a magenta dye is dissolved in ethyl acetate solution. Sample A: ALKANOL XC in aqueous phase. Sample B: ALKANOL XC in ethyl acetate phase.

large average emulsion particle size of 348nm.

In sample B, the ALKANOL XC is present in the oil phase at the initial stage of the emulsification process, and only moves to the aqueous phase in the final stage. Since the ALKANOL XC is added to the oil phase together with hydrochloric acid, the sulfonic acid portion of the ALKANOL XC is initially in a non-dissociative state, i.e., a state of low hydrophilicity (Winsor II). In contrast, in the final stage of the emulsification process, the sulfonic acid portion of the ALKANOL XC is in a dissociative state, i.e., a state of high hydrophilicity (Winsor I). A phase change from the state of low hydrophilicity (Winsor II) to the state of high hydrophilicity (Winsor I) has therefore taken place during the process of emulsification. To do this, it would have passed through a Winsor III state of ultra-low interfacial tension. This would enable the low-energy emulsification process to take place, producing the observed small average particle size of 32nm in the resultant emulsion.

Thus, although the final composition of the emulsions is identical, the ultra-low interfacial tension achieved in sample B has brought about low-energy emulsification.

We believe that this approach can be applied more generally, and expect that it can be used in the emulsification of highly polar solutions of functional organic compounds, such as dyes, pigments, UV filters, cosmetic and pharmaceutical compounds.

Conclusion

In this paper, the design principles required for the spontaneous emulsification of polar oils are presented. The key point is that the oil droplets need to make the spontaneous state transition from Winsor II → Winsor III → Winsor I by means of diffusion or chemical reaction. The selection of a surfactant with hydrophobic as well as lipophilic properties is essential in the design of a low-energy emulsification system for highly polar oils.

Although middle-phase microemulsions are well-known structures, the application of discriminative properties such as the ultra-low interfacial tension and the bicontinuous water-oil structure will undoubtedly allow them to be developed further, not just in the fields mentioned in the present paper.[17–20] To do this, it is important to precisely understand the phase behavior of the water/oil/surfactant system, as well as understand the self-organizing interfacial structure at the molecular level. By deepening our understanding, further development of the present field can be expected.

Acknowledgements: In conducting the present study, the author received guidance and comments from Professor Clarence A. Miller of Rice University. He also received kind support from the staff of FUJIFILM Corporation. He would like to take this opportunity to express his heartfelt appreciation.

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