Investigation of Effect of Adding Hydrophobically Modified Water Soluble Polymers on the Structure and Viscosity of Anionic Vesicle Dispersion

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ABSTRACT

This present study was conducted to investigate the effect of adding hydrophobically modified end-capped (HM) polymers with various polyethylene oxide (PEO) chain lengths on the structure and viscosity of anionic vesicles dispersion. A pronounced increase in viscosity was observed upon adding a few of such polymers. Based on the Dynamic Light Scattering (DLS) and Small Angle Neutron Scattering (SANS) analysis, 10 to 30 polymer molecules per vesicles can reach maximum viscosity and where polymer molecules can interconnect the vesicles without disrupting their structure. In addition, the kinetic stability of the vesicle dispersion also enhanced. From the measurement of the electrical conductivity of the dispersion, it was observed that the presence of the PEO and polypropylene oxide (PPO) group could induce the permeability of the vesicle membrane by altering their internal structure.

Keywords: *hydrophobically modified polymers; viscosity; structure of vesicles; chain length of polymer*

ABSTRAK

Penelitian ini bertujuan untuk mengetahui pengaruh penambahan hydrophobically modified end-capped (HM) polymers dengan variasi pada panjang rantai polietilen oksida terhadap struktur dan viskositas dispersi vesikel anionik. Peningkatan viskositas teramati dengan penambahan sejumlah kecil polimer. Analisis dengan menggunakan Dynamic Light Scattering (DLS) dan Small Angle Neutron Scattering (SANS) menunjukkan bahwa polimer ini dapat menghubungkan vesikel satu sama lain tanpa merusak struktur vesikel dan 10 sampai dengan 30 polimer per vesikel dapat menghasilkan viskositas yang maksimum. Stabilitas termodinamik dari dispersi vesikel juga meningkat. Pemeriksaan konduktivitas listrik menunjukkan bahwa adanya gugus PEO dan polipropilen oksida (PPO) dapat meningkatkan permeabilitas membran vesikel.

Kata Kunci: *hydrophobically modified polymers; viskositas; struktur vesikel; panjang rantai polimer*

INTRODUCTION

Vesicles exhibit an interesting morphology which is formed by self-aggregating amphiphilic molecules such as surfactant [1]. Vesicles are composed of closed bilayer shells and they may exist in the form of unilamellar or multilamellar vesicles with the radii ranging from 10 nm to 10 μm [1]. The formation of the vesicles is influenced by some factors such as packing parameter of the surfactants [2], the entropy of the dispersion [3] and the bending constants of the bilayer [4].

Vesicles are widely used in the biomedical, cosmetics and drug delivery field [5-7]. In these applications, the viscosity of the systems is important to stabilize the emulsion in a cosmetic formulation, to prolong drug contact with the targeted organ, and to control stability of the vesicle in biomedical application [8-10]. Nevertheless, control of viscosity is still a challenge in the development of vesicles system. By encapsulating a significant amount of water, the viscosity of the vesicle dispersion is generally higher than that of corresponding micellar solutions with the same surfactant concentration [11]. In the case of the spherical shape of the vesicles, the viscosity remains very low until they reach a packing fraction of around 40-50% [8]. Therefore, the vesicle formation itself is a very limited means of enhancing the viscosity.

One conceivable way to control the viscosity of the vesicle dispersion is the addition of a polymer that enhances the viscosity in aqueous phase without interacting with the vesicles [11]. However, the disruption of the structural integrity of the vesicles occurs commonly due to the unavoidable interference

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between the polymeric networks and vesicles. Another option is the addition of hydrophobically modified polymers that leads to the bridging of vesicles, the same way that they form networks by bridging micelles of microemulsions [12-13]. In the case of vesicles, its size and structure may change upon the polymer addition. In some cases, the addition of amphiphilic polymers leads to the stabilization of the dispersions due to the incorporation of anchoring hydrophobic domains into the vesicle bilayers [14-17].

This approach requires suitable amphiphilic polymers that are able to bridge the vesicles without disturbing their structure, which for instance can be polymers with the ethylene oxide (EO) groups. In order to interconnect the vesicles in solution by a bridging polymer, the number of the water-soluble EO groups of the polymer has to be of adequate chain length, as illustrated in Fig. 1. The relevant parameters for such mixed systems of vesicles and amphiphilic copolymers are the end-to-end distance (L_{ee}) of the bridging copolymers and the mean distance (d) between the vesicles with a membrane radii (R).

The aim of the current study was to investigate the effect of adding hydrophobically end-capped polymers (HM-polymers) on the physicochemical properties of an aqueous dispersion containing unilamellar vesicles of sodium oleate and octanol. The mixture of sodium oleate and 1-octanol was chosen as the vesicle model since previous studies have shown that this mixture spontaneously formed a small unilamellar vesicle with mean radii 20-25 nm and rather low polydispersity. However, the viscosity obtained was slightly higher than the water [18], unless the vesicles become sufficiently concentrated and then may form a vesicle gel, where this transition typically occurs over a rather narrow concentration range [19-20].

The HM-polymers were added into the dispersion contain hydrophobic oleic group at both ends and was based on the highly water soluble polyethylene oxide (PEO) group in the middle of the polymer molecule. The amount of added polymer is given by wt% of the dispersion and also by ratio xp = polymer/vesicle, i.e. the number of polymer molecules per vesicle, assuming that the spherical vesicles and the polymer are monodisperse. In addition, the kinetic stability of the dispersion and the effect of the presence of the PEO and polypropylene oxide (PPO) group on the permeability of vesicle membrane were also studied.

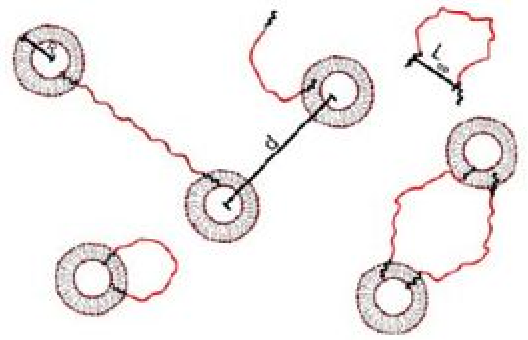

Fig 1. The relevant structural parameters in polymer-bridged vesicle systems investigated

EXPERIMENTAL SECTION

Materials

Oleic acid (Riedel De Haen, Germany), 1-octanol (Merck KGaA, Germany) and sodium hydroxide (Fluka, Germany) were used without further purification. Antil 141 and Rewopal 6000 DS (Evonik, Germany) were used as the hydrophobically modified (HM) water soluble polymers. Pluronic 10R5 and Pluronic L35 were supplied from BASF (Germany). The chemical structures are given in Fig. 2.

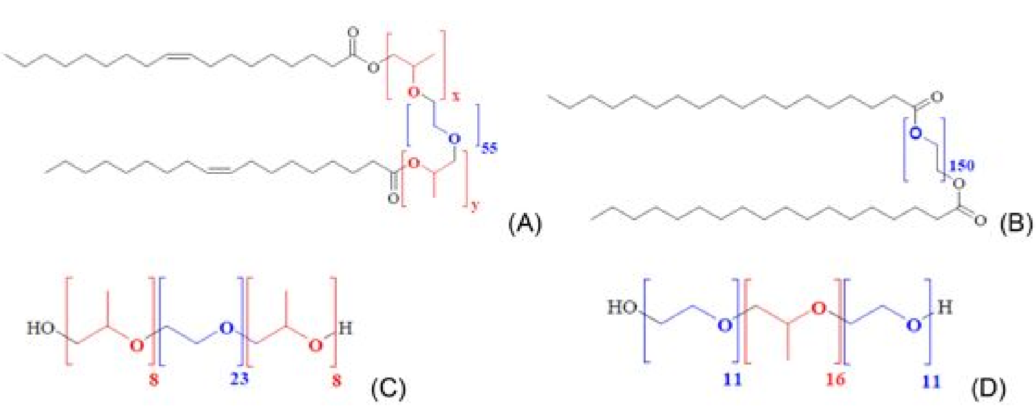

Fig 2. Chemical structure of : (A) Antil 141, (B) Rewopal 6000 DS, (C) Pluronic 10R5, (D) Pluronic L35

Table 1. Length parameters of the polymers employed

Polymer	Antil 141	Rewopal 6000 DS	Pluronic 10R5	Pluronic L35
M_w [g/mol]	3100	7100	1950	1900
L_c [nm]	22.2	60.6	9.0	8.8
L_{ee} [nm]	5.8	9.5	3.5	3.5

Instrumentation

The instrument used for viscosity measurement was a micro-Ostwald viscometer (Lauda Dr.R.Wobser GmbH & Co.KG, Germany). Dynamic light scattering (DLS) measurements were carried out with an ALV-5000 (ALV-GmbH, Germany). The small-angle neutron scattering (SANS) experiments were performed by using SANS Instrument V4. Conductivity of each vesicle system was measured using conductivity meter (Mettler Toledo, Int. Inc., Switzerland)

Procedure

Preparation of anionic vesicles and addition of the polymers

A stock solution of sodium oleate was prepared by equimolar addition of sodium hydroxide to oleic acid in Milli-Q-Water (R =18 MΩ·cm at 25 °C). After one day of stirring, the vesicle dispersion of sodium oleate/octanol was made by addition of octanol to the sodium oleate solution. The compositions of the vesicles used in this study were 50 mM sodium oleate/150 mM 1-octanol (50/150) and 60 mM sodium oleate/180 mM 1-octanol (60/180). The vesicle dispersions with various concentrations of the polymers were then properly homogenized. The concentrations of polymers applied were ranging from 0.0 to 0.5 wt%.

With regard to the polymer structure in an aqueous system, there are two important parameters of the polymers that need to be considered. Those parameters are the contour length (L_c) and especially for the end-capped ones, the end-to-end distance (L_{ee}) by which statistically their hydrophobic ends are separated. L_{ee} can be calculated according to the Equation 1 [21].

$$L_{ee} = \sqrt{C_\infty \cdot N \cdot L_m{}^2} \qquad (1)$$

where N is the number of monomer units, L_m is the length of one monomer unit, and C_∞ is a factor specific to the coiling properties of the polymer. The C_∞ value for the polymers used in this study is 4.2. Table 1 details the length parameters of Antil 141 and Rewopal 6000 DS.

Viscosity measurement

Measurements of the viscosity were done by using a micro-Ostwald viscometer at 25.0 ± 0.1 °C. Measurements were done in triplicate and reported as an average.

DLS measurement

For the purpose of DLS measurement, the samples were stored in a quartz cell tempered in a toluene bath. Autocorrelation functions obtained were analyzed by applying the CONTIN procedure [22]. The analysis yielded relaxation time distribution or the equivalent distribution of effective hydrodynamic radii.

SANS experiment

A wavelength of 6.1 Å was chosen and the data were recorded on a 64 x 64 two-dimensional detector. Following this, the data obtained was then radially averaged and converted into absolute units, or the differential cross-sections. This was done by comparison with the scattering of a 1 ml H_2O standard and proper correction for the detector background, the scattering of the empty cell, and the transmission of sample and cell. The constant incoherent background scattering was not subtracted from the intensity curves.

A model of homogeneous shells was employed to describe the scattering of the vesicle systems. For the limiting case of monodisperse systems, the experimental scattering intensity as a function of the magnitude q (in which, q = 4π·sin(θ/2)/λ; with θ and λ being the scattering angle and the wavelength, respectively) of the scattering vector is given as follows [23]:

$$I(q) = {}^1N \cdot P(q) \cdot S(q) \qquad (2)$$

where ${}^1N$ is the number density of the particles, P(q) the particle form factor, and S(q) is the structure factor that accounts for interparticle interferences and in this matter was taken as that of a hard sphere in the Percus-Yevick approximation [24]. The structure of the vesicles was then obtained from the SANS measurements as a function of the amount of polymer added. The particle form factor for a homogeneous spherical shell model is given as follows:

$$P_{ves}(q,R,D) = 16 \cdot \pi^2 \cdot \Delta\rho^2 \cdot \left((R + {}^{D}\!/_{2})^3 \cdot \frac{\sin(q \cdot (R + {}^{D}\!/_{2})) - q \cdot (R + {}^{D}\!/_{2}) \cdot \cos(q \cdot (R + {}^{D}\!/_{2})}{(q \cdot (R + {}^{D}\!/_{2}))^3} - (R - {}^{D}\!/_{2})^3 \cdot \frac{(q \cdot (R - {}^{D}\!/_{2})) - q \cdot (R - {}^{D}\!/_{2}) \cdot \cos(q \cdot (R - {}^{D}\!/_{2}))}{(q \cdot (R - {}^{D}\!/_{2}))^3} \right)^2 \qquad (3)$$

where Δρ is the difference of the scattering length densities of vesicle and solvent, R is the mean vesicle radius at the center of the vesicle shell, and D is the thickness of the shell. In this study, for a 3:1 molar ratio of 1-octanol to sodium oleate and assuming both amphiphiles only present in the vesicle bilayer, the Δρ is $65.6 \cdot 10^9$ cm^{-2}. This value was obtained as the scattering length density of the bilayer is $1.9 \cdot 10^{9}$ cm^{-2}, derived from the values of $2.0 \cdot 10^{9}$ and $3.2 \cdot 10^{9}$ cm^{-2} for the oleate and the 1-octanol, respectively.

Stability study of the vesicles

The vesicles, which already added with either Rewopal 6000 DS or Antil 141, were heated at an elevated temperature up to 60 °C and stored up to 24 days. Following this treatment, viscosities of the vesicles were measured and the changes of activation energy (Ea) in respect of the freshly prepared vesicle dispersion for a storage period of 15 and 24 days were calculated.

Permeability study of the vesicles

Six various concentrations of either Pluronic 10R5 or Pluronic L35 were subsequently added into the 50/150 and 60/180 vesicle dispersion. The concentrations added were ranged from 0.0 to 0.6 wt%. The conductivity of the vesicles after the addition of each polymer was then measured. Measurement of the radii of the vesicles was conducted using SANS.

RESULT AND DISCUSSION

Correlation between the Vesicle Size and Viscosity

Fig. 3 describes the profile of the dynamic viscosity in correlation with the polymer concentration. Having higher concentration of polymers, which means more presence of the bridging polymer, apparently, does not lead to a further viscosity enhancement. Based on the viscosity profile, the binding of charged vesicles to flexible polymers has been demonstrated to cause a characteristic change in the hydrodynamic properties of the solution. Particularly, upon adequate addition of the HM polymer to the vesicle dispersions, the viscosity increases to a maximum value, which is approximately a factor 2 higher than the one of the pure vesicle dispersion.

In the case of Rewopal 6000 DS addition, the magnitude of the increase in viscosity is more pronounced. An increase of vesicles concentration from 50/150 mM to 60/180 mM did not lead to further

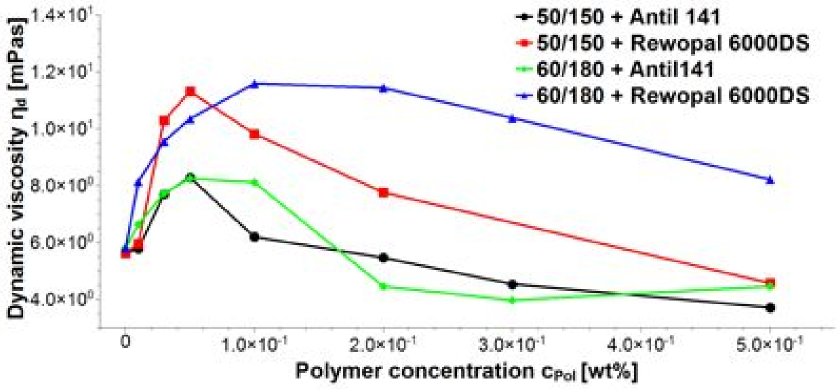

Fig 3. The viscosity of a vesicle dispersion composed of 50/150 and 60/180 vesicles as a function of various amounts of HM polymer added

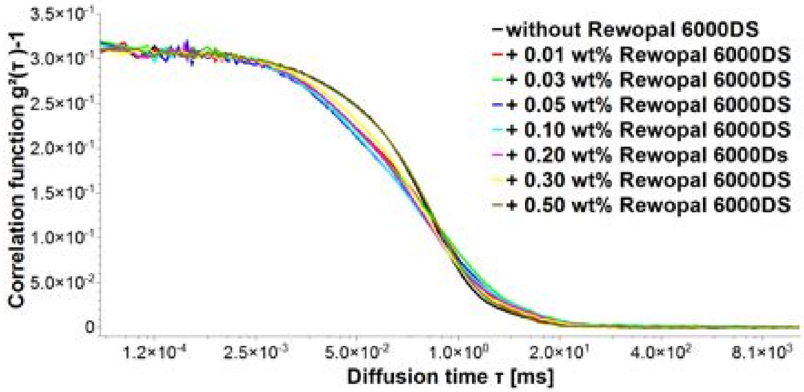

Fig 4. DLS intensity autocorrelations function $g^{(2)}(\tau)$ as a function of time for a sample of 50/150 with various amounts of added Rewopal 6000 DS

increase in the viscosity. The decrease in viscosity is observed at higher polymer concentration. An interesting feature of Fig. 3 is that the maximum point is almost the same.

It is interesting to ascertain whether they arise from bridging of vesicles or modifications of their structure, e.g. whether they might change in size or remain structurally unchanged. Accordingly, we investigated the structure of the vesicles by means of SANS measurements as a function of the amount of polymer added.

Based on the plot of SANS curves for vesicles of 50/150 mM and varying amounts of added Rewopal 6000 DS and Antil 141, a typical scattering pattern of rather monodisperse shell structures with a minimum 0.15 nm^{-1} was observed which indicates a vesicle radius of ~23 nm. One observes almost no change of the scattering curves (figure not shown), which demonstrates that the structure of the vesicles remains basically unchanged upon addition of these polymers. The thickness of the bilayer is comparable to the chain length of homologous series of alkyl rest (C18). This result confirms that the vesicles remain unilamellar at the concentration range up to 0.50 wt%.

In order to obtain further structural information about the Rewopal-vesicles systems studied, DLS experiments were performed. The intensity autocorrelation functions for the case of adding Rewopal 6000 DS is shown in Fig. 4. One can observe that increasing content of the added polymer results in no change at shorter times but at higher times, a slower relaxation mechanism becomes increasingly prominent. This would arise from a slower relaxation mechanism or the presence of larger aggregates or the formation of interconnected clusters.

This result becomes more evident in the Laplace transform of the autocorrelation functions that displays the relaxation spectrum given in terms of the hydrodynamic radius in $\tau > 1$ ms region. However, the SANS experiments indicate the absence of larger particles, whereas the vesicle radii with varying amount of added Antil and Rewopal remains approximately unchanged. This larger hydrodynamic radius does not correspond to larger particles or vesicles but can be due to a slower relaxation mechanism. Such slower relaxation modes are frequently observed for colloidal systems with aggregates interconnected by polymer chains and then correspond to a relaxation of the whole network.

It is concluded that the hydrophobic chains of HM-polymers incorporate within the vesicle bilayer without disrupting the membrane and vesicle structure. At higher polymer concentration, the effective repulsion between the vesicles becomes more pronounced due to its interaction with the EO groups, which leads to an increase in the number of the decorated vesicles and simultaneously to a decrease in viscosity.

One can hypothesize the general process of viscosity enhancement: Initially, the vesicles interact with the hydrophobic groups of the HM-polymer and at a certain HM-polymer concentration. Assuming that the spherical vesicles are monodisperse, the number of polymer molecules is sufficient so that the hydrophobic chain of polymer molecules can cross-link the vesicles. Furthermore, the number of polymer molecules per vesicle $x_{Pol/Ves}$ can be calculated using equation 7:

$$x_{Pol/Ves} = C_{Pol} \cdot \frac{N_A}{N \cdot M_{Pol}} \quad (4)$$

N_A is the Avogadro's number, C_{pol} is the polymer concentration, whilst M_{Pol} is the molecular weight of the polymer. ^1N is the particle number density of vesicles, which can be calculated from the ratio of the volume fraction of vesicle/volume of vesicle shell (for sodium oleate/octanol vesicle: ^1N (50/150 mM) = $3.2 \cdot 10^{15}$ vesicles/mL and ^1N (60/180 mM) =$3.8 \cdot 10^{15}$ vesicles/mL). The $c_{Pol,max}$ is the polymer concentration where the value of dynamic viscosity reaches its maximum. The value of $x_{Pol/Ves}$ for all polymer types is summarized in Table 2.

As shown in Table 2, fewer Rewopal molecules are needed to obtain the maximum viscosity compared to Antil. This effect is stronger in the case of 50/150. The increased length of the hydrophilic group of the polymer enhances the binding interaction with the vesicles. Therefore, using longer PEO groups is particularly advantageous. The information in Table 3 exhibits that about 10-30 molecules of bridging polymer are required to obtain a maximum of viscosity enhancement.

The average spacing between the vesicles has to be in the range of end-to-end distance of the bridging polymer (d) in order to get an effective bridging, as depicted in Fig. 1. The d value is equal to 2R+L_{ee}, where R is the radius and L_{ee} are the ends to end distance. The d value can be estimated from the equation:

$$d = \frac{4\pi R^2 D}{\varnothing} \quad (5)$$

where D is the bilayer thickness of the vesicles and ϕ the volume fraction of the vesicles. The volume fraction depends on the molar concentration of the vesicle dispersions. This has been similarly observed in the case of enhancing the viscosity of microemulsions by the addition of hydrophobically end-capped polymers [25]. The mean spacing between the bilayers of the vesicles db is equal to d-2R. The db values for 50 mM sodium oleate/150 mM 1-octanol and 60 mM sodium oleate/180 mM 1-octanol were 22.8 nm and 21.1 nm, respectively [18]. As shown in Table 1, by comparing

Table 2. The number of polymer molecules per vesicle at a maximum of viscosity for all polymer types

Polymer	50/150		60/180	
	$c_{Pol,max}$ [wt%]	$x_{Pol/Ves}$ [Polymer/Vesicles]	$c_{Pol,max}$ [wt%]	$x_{Pol/Ves}$ [Polymer/Vesicles]
Antil 141	0.05	32	0.05	27
Rewopal 6000 DS	0.05	13	0.10	22

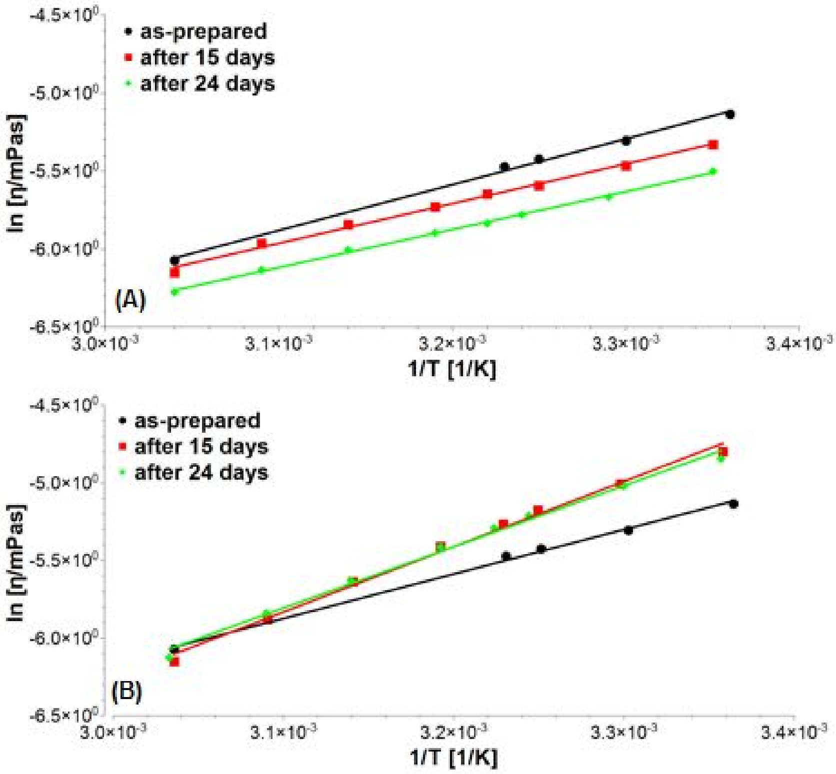

Fig 5. Arrhenius plots of the viscosity at the different times for the system: (A) 50/150; (B) 50/150 with Rewopal 6000 DS

these calculated values with the length of the hydrophilic chain of the polymer, it can be suggested that a better crosslinking of the vesicles is achieved by using Rewopal rather than Antil 141 because Rewopal 6000 DS consists of a greater L_{ee} (PEO) value with 9.5 nm compared to Antil 141 with 5.8 nm.

The comparison between Lee and db values has shown that none of the polymers are able to bridge the vesicles because of their length. In addition, the viscosity maximum occurs at the same polymer mass concentration for all polymers and not at the same number of polymers/vesicle. In any case, it seems that all polymers can interact with the vesicles by decorating them.

Enhancement of Stability Due to Polymer Addition

Fig. 5 shows the variation of the viscosity with and without fixed polymer concentration at temperature until 60 °C. It should be noted that PEO chain becomes less polar with increasing temperature and hence the chain contracts resulting in a decrease in viscosity [26]. As shown in this figure, the viscosity decreases with increasing temperature. This result seems consistent with previous studies [27-28].

Due to the Rewopal 6000 DS addition, an increase in viscosity of the dispersion is also observed with increasing temperature. This indicates the existence of the physical cross-link between the vesicles and the polymer. This physical cross-link is temporary and can be broken and re-established again. The PEO chains assume a more compact conformation at elevated temperatures [26], presumably because the poorer solvation of the PEO outweighs any weak electrostatic repulsion between the vesicles at a higher temperature.

As shown in Table 3, the viscosity increases over time while the activation energy decreases. The activation energy of the viscosity is comparable to the mean potential energy of intermolecular interactions.

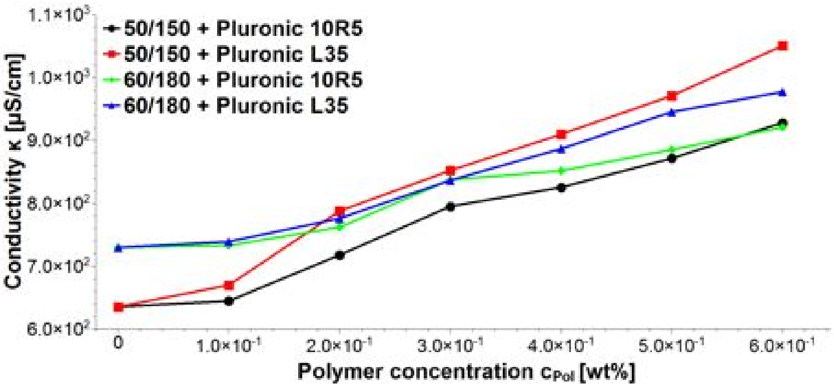

Fig 6. Conductivity of 50/150 and 60/180 samples as a function of the concentration of the pluronic polymers

Table 3. The activation energies of 50/150 **(left)** and with Rewopal 6000 DS addition **(right)** for different delays after preparation

Age of samples (days)	$\eta_{25\,°C}$ [mPas]	E_a [kJ]
0	0.31E-03	2.94.k
15	0.95E-03	2.55·k
24	1.16E-03	2.43·k

Age of samples (days)	$\eta_{25\,°C}$ [mPas]	E_a [kJ]
0	0.44E-05	4.32.k
15	1.07E-05	4.04.k
24	5.83E-05	3.45·k

Table 4. Structural parameters derived from the SANS measurements on vesicle samples based on 50/150 for various polymer concentrations c_p: Mean radius R and bilayer thickness D.

Polymer	C_p (wt%)	R (nm)	D (nm)
-	0.00	22.52	2.18
10R5	0.12	27.60	2.17
	0.61	30.52	2.16

The activation energy is higher with Rewopal 6000 DS due to an enhancement of the intermolecular interactions between vesicles-vesicles, vesicles-polymer, and polymer-polymer molecules. The change in activation energy with longer sample age of Rewopal 6000 DS is lower due to the enhancement of the stability of the system. The system is thermodynamically stable at least after 24 days and the appearance of the vesicle dispersions remains monophasic.

Enhanced Permeability of Vesicle

Further insight into the physical properties of the vesicles is the ion permeability of its membrane. The underlying idea is the interaction between ethylene oxide and the vesicles as well as propylene oxide and the vesicles unit can induce the membrane permeability. Based on their molecular structure, the PPO contains a methylene group additionally to EO groups, which enhances the hydrophobicity of the polymer molecules. In this work, the electrical conductivity of the vesicle system containing the polymer with ethylene oxide and propylene oxide unit is measured

In Fig. 6, the specific conductivity for the vesicles-polymer system is shown as a function of the amount of added polymer. Without polymer, the conductivity values of the vesicles at higher concentration regions are higher due to the degree of counterion binding [29]. In the case of higher vesicle concentration, the conductivity increase upon addition of Pluronic L35 is comparable to Pluronic 10R5. This increase is more pronounced at lower vesicle concentration whereas the Pluronic L35 with its PPO groups enhances this effect. Perhaps the PPO groups can be stronger adsorbed due to the hydrophobic interaction between them and the vesicles.

As shown in Fig. 6, we observed that a pronounced increase occurs in the case of adding Pluronic polymers. The electric conductivity of inorganic salt in neutral polymer solution provides the information of fluid dynamic resistance to the ion motion [30]. This means that the change of microstructure of vesicles associated with a polymer solution can be revealed by the change of the ion mobility. According to Kohlrausch equation, the conductivity is simply the sum of the current carried by individual ions which are also proportional to the concentration of ions and the ion mobility. Note that the used polymers are non-ionic species and do not give any direct contribution to conductivity. A decrease of conductivity may result accordingly in an increase in the radii of vesicle or alternatively, it may result in the cross-linking of vesicles. In order to obtain such information, the SANS measurement as a function of added polymer concentration is performed.

As shown in Table 4, in the case of Pluronic 10R5, a certain part of the conductivity increase is associated with the decrease in vesicle size due to high enclosed ions in the vesicle. The thickness of the bilayer remains constant and therefore the vesicles are still unilamellar upon the addition of the polymer. The reasonable interpretation for the increasing conductivity is an enhanced permeability for ion transport due to the interaction of the EO and PO groups with the vesicle bilayers. This might be due to the fact that for the Pluronic 10R5 one has a rather short PO unit incorporated into the vesicle bilayer and this could be a structural unit that facilitates the transport of ions across the bilayers. This result is consistent with previous work that the adsorption of Pluronics on bilayer induced considerable disturbance of the surfactant packaging [31].

It was observed that the interaction with such units caused an increment in the average vesicle radii. In the case of the addition of HM-polymers, the hydrophilic units (of Rewopal 6000 DS and Antil 141) have no effect on the vesicle size. Comparing this result with the Table 2, it can be expected that the hydrophobic interaction between the polymer and the vesicles stabilizes the curvature of the vesicles.

CONCLUSION

The effect of mixing commercially available hydrophobically modified (HM) polymers on the structure and viscosity of small unilamellar vesicles composed of sodium oleate (as a surfactant) and 1-octanol (as co-surfactant) was investigated in this study. The viscosity maximum of a dispersion containing 50 mM sodium oleate and 150 mM octanol was reached at a polymer concentration of 0.05 wt% for Antil 141 and Rewopal 6000 DS. The dynamic light scattering (DLS) and small angle neutron scattering (SANS) analysis showed that addition of the HM-polymers did not affect the vesicle structure since vesicles remained unilamellar and equal in radii (radii ~24.0 ± 2.0 nm, thickness ~2.2 nm). The addition of Pluronic polymers increased the vesicle radii without changing the membrane thickness. The Pluronic polymers above their critical concentration (~0.05 wt%) enhanced the permeability of the vesicles bilayer for ion transport, whereas the mean vesicle radii increased with the Pluronic concentration. In contrast, the PEO group of the HM-polymers did not affect the vesicle structure.

REFERENCES

[1] Weiss, T.M., Narayanan, T., and Gradzielski, M., 2008, Dynamics of spontaneous vesicle formation in fluorocarbon and hydrocarbon surfactant mixtures, *Langmuir*, 24 (8), 3759–3766.

[2] Šegota, S., and Težak, D., 2006, Spontaneous formation of vesicles, *Adv. Colloid Interface Sci.*, 121 (1-3), 51–75.

[3] Guida, V., 2010, Thermodynamics and kinetics of vesicles formation processes, *Adv. Colloid Interface Sci.*, 161 (1-2), 77–88.

[4] Bergström, L.M., 2006, Bending elasticity of charged surfactant layers: The effect of layer thickness, *Langmuir*, 22 (8), 3678–3691.

[5] Brinkhuis, R.P., Rutjes, F.P.J.T., and van Hest, J.C.M., 2011, Polymeric vesicles in biomedical applications, *Polym. Chem.*, 2, 1449–1462.

[6] Nohynek, G., Lademann, J., Ribaud, C., and Roberts, M., 2007, Grey goo on the skin? Nanotechnology, cosmetic and sunscreen safety, *Crit. Rev. Toxicol.*, 37 (3), 251–277.

[7] Samad, A., Sultana, Y., and Aqil, M., 2007, Liposomal drug delivery systems: An update review, *Curr. Drug Deliv.*, 4 (4), 297–305.

[8] Sinico, C., and Fadda, A.M., 2009, Vesicular carriers for dermal drug delivery, *Expert Opin. Drug Deliv.*, 6 (8), 813–825.

[9] Blanazs, A., Armes, S.P., and Ryan, A.J., 2009, Self-assembled block copolymer aggregates: from micelles to vesicles and their biological applications, *Macromol. Rapid Commun.*, 30 (4-5), 267–277.

[10] Tanner, P., Baumann, P., Enea, R., Onaca, O., Palivan, C., and Meier, W., Polymeric vesicles: From drug carriers to nanoreactors and artificial organelles, 2011, *Acc. Chem. Res.*, 44 (10), 1039–1049.

[11] Wolf, C., Bressel, K., Drechsler, M., and Gradzielski, M., 2009, Comparison of Vesicle Formation in Zwitanionic and Catanionic Mixtures of Hydrocarbon and Fluorocarbon Surfactants: Phase Behavior and Structural Progression, *Langmuir*, 25 (19), 11358–11366.

[12] Ramos, L., and Ligoure, C., 2007, Structure of a new type of transient network: Entangled wormlike micelles bridged by telechelic polymers, *Macromolecules*, 40 (4), 1248–1251.

[13] Penott-Chang, E.K., Gouveia, L., Fernández, I.J., Müller, A.J., Díaz-Barrios, A., and Sáez, A.E., 2007, Rheology of aqueous solutions of hydrophobically modified polyacrylamides and surfactants, *Colloids Surf., A*, 295 (1-3), 99–106.

[14] Lee, J.H., Agarwal, V., Bose, A., Payne, G.F., and Raghavan, S.R., 2006, Transition from unilamellar to bilamellar vesicles induced by an amphiphilic biopolymer, *Phys. Rev. Lett.*, 96 (4-3), 048102.

[15] Yu, W.W., Chang, E., Falkner, J.C., Zhang, J., Al-Somali, A.M., Sayes, C.M., Johns, J., Drezek, R., and Colvin, V.L., 2007, Forming biocompatible and nonaggregated nanocrystals in water using amphiphilic polymers, *J. Am. Chem. Soc.*, 129 (10), 2871–2879.

[16] Wang, Y., and Grayson, S.M., 2012, Approaches for the preparation of non-linear amphiphilic polymers and their applications to drug delivery, *Adv. Drug Delivery Rev.*, 64 (9), 852–865.

[17] Bressel, K., Muthig, M., Prevost, S., Gummel, J., Narayanan, T., and Gradzielski, M., 2012, Shaping vesicles–controlling size and stability by admixture of amphiphilic copolymer, *ACS Nano*, 6 (7), 5858–5865.

[18] Sandjaja, M., 2011, Einfluss von hydrophob modifizierter Polymere auf Struktur und rheologische Eigenschaften von Vesikeldispersionen, *Diplomarbeit*, Technische Universität Berlin.

[19] Antunes, F.E., Marques, E.F., Miguel, M.G., and Lindman, B., 2009, Polymer-vesicle association, *Adv. Colloid Interface Sci.*, 147-148, 18–35.

[20] Long, P., and Hao, S., 2010, A gel state from densely packed multilamellar vesicles in the crystalline state, *Soft Matter*, 6, 4350–4356.

[21] Flory, P., 1969, *Statistical Mechanics of Chain Molecules*, Interscience Publisher, New York.

[22] Provencher, S.W., 1982, A constrained regularization method for inverting data represented by linear algebraic or integral equations, *Comput. Phys. Commun.,* 27 (3), 213–227.

[23] Chen, S.H., 1987, Small angle neutron scattering studies of the structure and interaction in micellar and microemulsion systems, *Annu. Rev. Phys. Chem.*, 37, 351–399.

[24] Ashcroft, N., and Lekner, J., 1966, Structure and resistivity of liquid metals, *Phys. Rev.*, 145 (1), 83–90.

[25] Gradzielski, M., Rauscher, A., and Hoffmann, H., 1993, Hydrophobically cross-linked micellar solutions: Microstructure and properties of the solutions, *J. Phys. IV*, 3 (C1), 65–79.

[26] Mya, K.Y., Jamieson, A.M., and Sirivat, A., Effect of Temperature and Molecular Weight on Binding between Poly(ethylene oxide) and Cationic Surfactant in Aqueous Solutions, 2000, *Langmuir,* 16 (15), 6131–6135.

[27] Zhangfeng, Z., 2010, Rheology and Phase Change of Polymers and Vesicles, *Master Thesis*, National University of Singapore.

[28] Choudhary, S., and Sengwa, R.J., 2011, Dielectric spectroscopy and viscosity studies of aqueous poly(ethylene oxide) and poly(vinyl pyrrolidone) blend, *Indian J. Phys*., 85 (11), 1591–1602.

[29] Cametti, C., and Truzzolillo, D., 2011, Many facets of the polyelectrolyte and oppositely charged colloidal particle complexation: Counterion release and electrical conductivity behavior, *J. Phys. Chem. B*, 115 (22), 7248–7255.

[30] Wang, S.C., and Tsao, H.K., 2004, Ion migration through a polymer solution: Microviscosity, *Macromolecules,* 36 (24), 9128–9134.

[31] Chieng, Y.Y., and Chen, S.B., 2009, Interaction and complexation of phospholipid vesicles and triblock copolymers, *J. Phys. Chem. B*, 113 (45), 14934–1494.