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FACILITATED CO-TRANSPORT OF Ag(I), Cu(II), AND Zn(II) IONS BY USING A CROWN ETHER AS CARRIER: INFLUENCE OF THE SLM PREPARATION METHOD ON IONS FLUX

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ABSTRACT

This article reports and discusses the study of facilitated co-transport of silver(I), copper(II), and zinc(II) ions through a supported liquid membrane (SLM) containing a specific extractant of metals: dibenzo-18-crown-6 (DB18C6) in chloroform as solvent. Mode and duration of immersion of the macroporous support in the organic phase, physical characteristics of the support (porosity, pore size, and thickness) as well as wettability of the SLM that influence the transport have been

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examined. Three preparation modes of the SLM (vacuum impregnation, impregnation by immersion in a high-vacuum chamber, simple impregnation by immersion (SI)) were compared and the best result was obtained with SI. In the last case, the obtained results showed that full impregnation of the support in the organic phase can take a long time (26 days) for obtaining high fluxes, if DB18C6 concentration is above $5 \times 10^{-3}\,M$ because of the difficulty in impregnation due to carrier aggregation and precipitation. After 26 days, the support degrades under the action of the solvent. In fact, Fourier transformed-infrared spectroscopy showed support degradation while scanning electron microscopy observations showed that porosity and pore size were reduced with increasing impregnation time. On the other hand, at DB18C6 concentration below $5 \times 10^{-3}\,M$, impregnation took less time (30–60 min) because of the reduced ability of the carrier to form aggregates. Transport experiments showed an order of permeability, Ag(I) > Cu(II) > Zn(II). The Cu(II) flux, using 1 hr impregnation time, reached the highest value when the organic solution was made by dissolving $10^{-3}\,M$ DB18C6 in $CHCl_3$. The flux for the above-mentioned ions increased with the increasing pore size and porosity of the polymeric support and decreasing thickness.

Key Words: Supported liquid membranes; Stability; Impregnation methods; Copper; Silver; Zinc; DB18C6

INTRODUCTION

Despite the advantages of supported liquid membranes (SLMs) (1–4), they are not used yet on an industrial scale. The principal reason is the low stability or the short lifetime of the membrane, which is unable to provide efficient application on an industrial scale (5–7). Another important aspect is the method of preparing the SLM, which generally consists of impregnating the support with the organic phase. The preparation method is very important because it is directly linked to the stability of the membrane, the quantity of extractant immobilized inside the membrane pores and, therefore, to the value of transport flux.

The methods of support impregnation vary with the authors. Lee et al. (8) placed the support in a vacuum to evacuate the air contained in the pores, impregnated the support with an organic phase, and then returned it to the atmospheric pressure. Duffey et al. (9) submerged the support into the organic phase, then placed it under vacuum conditions and repeated the operation several times. Largman and Sifniades (10) placed the support into the transport cell first, and then injected the organic phase into the pores of the support by placing the cell under vacuum. Many other authors prepare the SLM by simple impregnation of the membrane support into the organic phase (11–14).

Using the Laplace equation, Kemperman et al. (15) showed that SLMs made from supports having small pore size are more stable than those with larger pores. Neplenbroek et al. (16) showed that Accurel SLMs, which present various physical characteristics (porosity, pore size and distribution, pore geometry, tortuosity and interconnection of the pores, thickness, etc.) different from Celgard, are more stable than Celgard SLM. Thicker membrane support gives more stable SLM (long life duration) (17,18), but the fluxes are very low. Danesi et al. (19) recommended the utilization of supports with small pore size having high porosity for obtaining high fluxes. Zha et al. (20) recommended the use of supports with small, interconnected pores. Another important characteristic of the SLMs is the wettability of the support. When it is sufficiently wetted by the organic phase, the release of carrier and solvent into the aqueous phase is reduced. The organic phase must have a surface tension lower than the critical surface tension of the support (21,22). The composition of the organic phase also influences membrane stability and fluxes (23–25).

Since various parameters influence SLM operations, e.g., preparation, stability, flux, etc., a case-by-case experimental study is required to obtain good performance of the SLM itself.

In the present paper, a study of the influence of membrane support on facilitated co-transport of silver(I), copper(II), and zinc(II) ions through an SLM containing a macrocyclic polyether as the carrier has been undertaken. The influence of SLM preparation method on transport flux of Ag(I), Cu(II), and Zn(II) ions has been studied together with the SLM stability and support resistance to organic solvent using three polypropylene macroporous supports with different physical characteristics.

THEORY

An SLM comprises an organic solution of an agent (carrier) absorbed on a thin hydrophobic polymer macroporous support. The SLM separates the aqueous solution containing the diffusing species (feed) and the solution into which the species will diffuse (strip). The species are accumulated in the strip at a concentration generally greater than that found in the feed. The permeation of the species is due to a chemical potential gradient (the driving force of the process) that exists between the feed and the strip.

The transport of silver(I), copper(II), and zinc(II) ions through an SLM containing DB18C6 as a carrier obeys the principles of facilitated co-transportation (3).

The charged species diffuse through the liquid membrane as a noncharged complex in the presence of a second oppositely charged species. The general chemical complexation reaction is as follows:

$$\mathrm{M}^{n+} + \bar{\mathrm{L}} + n\mathrm{A}^- \Leftrightarrow \overline{\mathrm{MLA}_n}$$

where M^{n+} represents a metal ion; L, the carrier where the bar indicates that the species is in the organic phase; A^-, the negatively charged co-ion giving an ion-pair for complexation (in this work, NO_3^-). The chemical potential gradient is achieved by a concentration difference of NO_3^- between the feed and strip solution. At the feed membrane interface, the complexation reaction of DB18C6 and the metal ions takes place, the complex MLA_n diffuses through the membrane reaching the other side where the stripping of the metal ions with the co-ion is realized due to a low NO_3^- concentration and the carrier diffuses back. Formation of complexes between the carrier and the metal ions and their stability depends on the size of the carrier cavity, charge, and size of the metal ion (26). For DB18C6, the average diameter of the cavity is 260–320 pm, while the ionic radius of Ag(I), Cu(II), and Zn(II) are 126, 69, and 72 pm, respectively.

Mass fluxes J ($\mathrm{mol\,cm^{-2}\,sec^{-1}}$) of metal ions through the membrane from feed side to strip side can be determined applying its definition:

$$J = -\frac{\Delta n}{S\Delta t}$$

where Δn represents the variation in number of moles of metal ions in the solution during the reference time, S, the membrane surface, and Δt, the reference time.

Membrane flux is also related to variation in concentration dC of metal ion during time dt in the feed phase, volume V of this phase, and surface S of the membrane by:

$$J = -\frac{\mathrm{d}C}{\mathrm{d}t}\frac{V}{S} \tag{1}$$

Integration of this equation gives:

$$\mathrm{Ln}\,\frac{C}{C_0} = -\frac{S}{V}Pt \tag{2}$$

where C_0 ($\mathrm{mol\,dm^{-3}}$) is the initial concentration of the metal in the feed phase, and $P(=J/C)$ ($\mathrm{cm\,sec^{-1}}$) is the permeability coefficient for a low C concentration so that a linear relationship between J and C exists.

The slope of straight lines Ln (C/C_0) vs. t allows the permeability values of the various ions to be obtained.

EXPERIMENTAL

Materials and Methods

Supports for the liquid membranes were macroporous films made by polypropylene (Celgard, Celanese Corporation) having different physical characteristics (Table 1). The carrier was dibenzo-18-crown-6 (DB18C6) (Aldrich) whose molecular weight is 360.41 ($\mathrm{g\,mol^{-1}}$) (Fig. 1). The solvent was chloroform (a product of Fluka). Feed solutions (0.01 M) were prepared from copper, silver, and zinc nitrates (from Fluka) dissolved in distilled water. Strip solutions consisted of distilled water. All chemicals were of reagent grade purity and were used as received without further purification.

The cell used in all transport experiments is shown in Fig. 2. It consisted of two Teflon compartments, each of volume 45 mL. The effective membrane surface area was 8.04 $\mathrm{cm^2}$. Solutions were agitated by two synchronized motors relayed to generators of a variable tension with a stirring rate of 800 rpm measured with a phototachometer from Cole Parmer Instruments Company. The stirring rate was sufficiently high to minimize boundary layer resistances (24). The temperature was maintained at 25°C by placing the cell in a thermostatted water bath.

Three methods of impregnation of the support with the organic phase were tested.

(a) Vacuum impregnation (VI)

The apparatus used was a classical vacuum analytical filtration unit (from Sartorius). The membrane was placed in the apparatus and the organic phase was

Table 1. Physical Characteristics of the Supports

Support	Porosity (%)	Effective Pore Size (μm)	Thickness (μm)
Celgard 2500	45	0.04	25
Celgard 2400	38	0.02	25
Celgard 2402	38	0.02	50

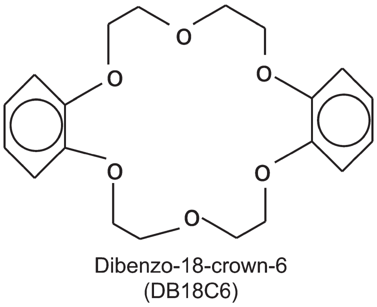


Figure 1. Structural formula of the macrocyclic polyether.

sucked by means of a water vacuum pump. It was then immersed into the organic phase for 24 hr. The membrane was finally used for transport tests.

(b) Impregnation by immersion in a high-vacuum chamber (IHVC)

As reported in the Introduction, air contained in the pores of the support or dissolved in the organic solution could influence the amount of impregnated liquid. So, degasing of the organic phase and the support was carried out prior to impregnation.

The organic phase was previously degased twice by freezing it in a bath of liquid nitrogen in order to prevent evaporation, and evacuating the noncondensable gas by means of a vacuum pump (10^{-5} atm); after which it was brought back to an ambient temperature. The support was subjected to a high vacuum, 10^{-5} atm, following the same process applied for the organic phase for evacuating the air contained in its pores. Next, the organic phase was transferred into a glass flask containing the support, maintaining all the systems under high vacuum. After a night, the SLM was finally placed in the transport cell.

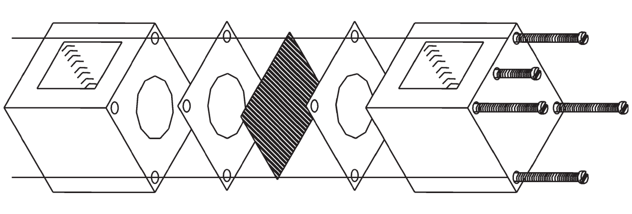


Figure 2. Setup of the transport cell.

(c) Simple impregnation by immersion (SI)

The support was immersed in the organic phase at room temperature and pressure for varying time (30–60 min or from 1 to 43 days) depending on the tests to be carried out and then was placed in the transport cell.

After impregnation by one of the three methods, the macroporous supports were placed between the two compartments of the transport cell (Fig. 2) and the two aqueous phases (feed and strip) were then introduced and stirred; $t = 0$ was the starting time of stirring.

Samples of 1 mL each were withdrawn from the two compartments at regular time intervals and then analyzed by an atomic absorption spectrophotometer (Perkin Elmer 2380) using the characteristic wavelengths of copper, silver, and zinc that were 324.7, 328.1, and 213.9 nm, respectively.

For each experimental run, about 10 samples were collected; so the feed and strip volumes decreased accordingly but the membrane support was always covered by solution. Furthermore, to calculate the metal ion flux, the volume at time t was used in Eq. (1) where dC/dt was evaluated as $\Delta C/\Delta t$.

RESULTS AND DISCUSSION

The impregnation methods, (a) and (b) described previously, are quite difficult to apply in the case of a large membrane module; however, they have been studied in order to gain information with respect to the optimum impregnation technique.

All SLM permeation experiments were completed in a small-volume cell and membrane setup because they were easy to run on a laboratory scale.

Influence of the Impregnation Method of the Support on the Mass Transport

Figures 3 and 4 show plots of the concentration of Ag^+ and Cu^{2+} in the strip phase, respectively, vs. time using a 0.01 M DB18C6/chloroform organic solution, for the three methods of impregnation described earlier. Impregnation by simple immersion of support in the organic phase was the most efficient method. Low efficiency of the other two methods can be attributed to some difficulty of the organic solution to occupy the support pores, especially the more tortuous cavities (27), and due to the low penetration rate of the carrier into the pores caused by its precipitation in the organic phase (15). In fact, other than the dissolution of the organic phase into aqueous phase as a cause of low membrane

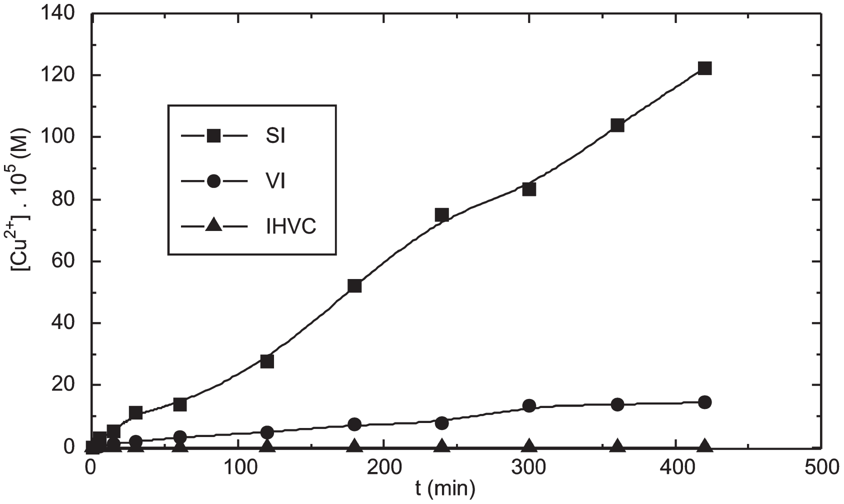


Figure 3. Concentration of copper in the strip vs. the time changing the impregnation mode. (SI = simple impregnation by immersion, VI = vacuum impregnation, IHVC = impregnation by immersion in a high-vacuum chamber). SLM: organic phase 0.01 *M* DB18C6/chloroform, support: Celgard 2500; feed: solution of $Cu(NO_3)_2$ in water $[Cu^{2+}] = 0.01\,M$; strip: distillate water.

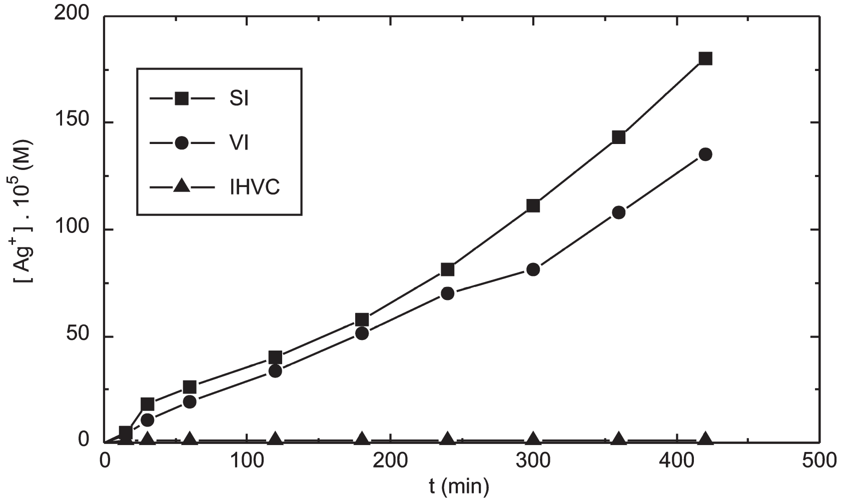


Figure 4. Concentration of silver in the strip vs. the time changing the impregnation mode. (SI, VI, IHVC). SLM: organic phase 0.01 *M* DB18C6/chloroform, support: Celgard 2500; feed: solution of $AgNO_3$ in water $[Ag^+] = 0.01\,M$; strip: distillate water.

flux (24), a low carrier solubility in the organic phase can also cause its precipitation (28) and consequently lead to aggregate formation that plugs the support pores. The hypothesis of carrier aggregation can explain why a low or no concentration increase with time is observed in Figs. 3 and 4 for VI and IHVC methods when compared with the SI method. In fact, in the VI method as the organic phase is sucked into the pores, only the dissolved carrier molecules are able to penetrate into pores but not the aggregates that can occlude part of the support pores reducing the membrane flux; on the other hand, the carrier should penetrate by diffusion in the IHVC method, but this is hindered if a precipitated carrier is present.

In both SI and IHVC methods, carrier molecules should penetrate by diffusion into membrane pores. An equilibrium exists between single carrier molecules and aggregates; so it is shifted vs. progressive dissolution of aggregates as soon as single molecules move into the support pores. Different trends observed in Figs. 3 and 4, where experimental errors are within 10% could be explained with more stable aggregates obtained by the IHVC method compared to the SI method, after freezing and thawing of the organic solution. We did not investigate further on aggregate characteristics as the aim of the work was to choose an efficient impregnation method. However, to confirm the obtained results, the amount of impregnated organic phase was determined by weighing the supports before and after impregnation.

Table 2 lists a collection of the weights of supports and their increase after impregnation using two concentration values of DB18C6. It can be seen that using the SI mode of impregnation, the organic phase fills the support pores better at low concentration of DB18C6. Table 2 also reports on the impregnating behavior using 0.001 *M* carrier concentration for comparison; however most of the work was done using a 0.01 *M* concentration to study the problems involved when relatively high-carrier concentration is used.

Table 2. Weight of the Celgard 2500 Support After Impregnation in the Organic Phase Using the Three Methods. Initial Support Weight = 26.0 mg

	[DB18C6] = 0.01 *M*		[DB18C6] = 0.001 *M*	
Impregnation Method	Weight of the Support After Impregnation (mg)	Weight Increase (mg)	Weight of the Support After Impregnation (mg)	Weight Increase (mg)
SI	30.0	4.0	29.6	3.6
VI	26.9	0.9	33.3	7.3
HVIC	26.0	0.0	32.0	6.0

Influence of the Impregnation Time

To date, few studies have considered the dependence of metal ion fluxes through SLMs as a dependence of impregnation time of support with the organic phase. Most authors immerse the support for a short time (few minutes or hours) and then place it into the transport cell.

In the present work, a systematic study on the evolution of fluxes of silver ions vs. impregnation time of the support has been carried out.

Figure 5 shows that mass fluxes of Ag^+ ions increases notably with time of impregnation and reach a maximum when the support is immersed for 26 days. This behavior could be explained considering the equilibrium between the carrier and aggregate and the diffusion mechanism (before mentioned) involved in support impregnation. The fall in flux values after 26 days can be explained due to degradation of support under the action of solvent, which is due to the chemical- and physical interactions between the solvent molecules and the support.

Analysis of the support by Fourier transformed-infrared (FT-IR) spectroscopy (organic phase was removed by evaporation prior to analysis) before- and after 14 days of impregnation followed by its utilization (Fig. 6) revealed the absence of carrier peaks in all wavelengths range and a significant increase in the intensities of the signal. This behavior is due to an increase in the

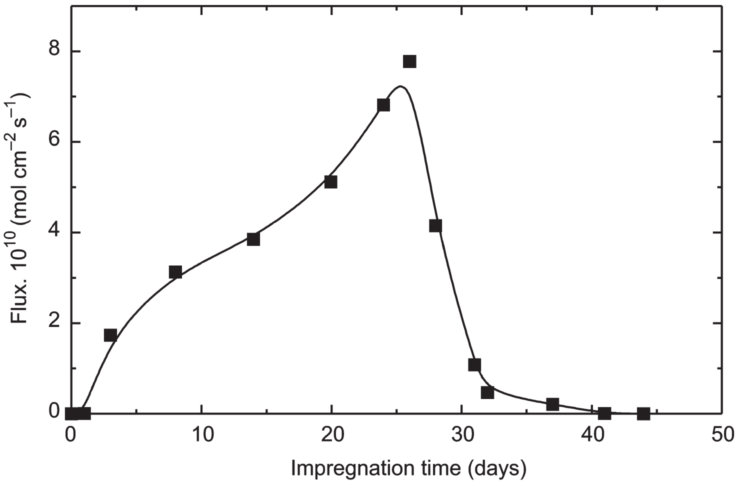


Figure 5. Mass flux of silver vs. the duration of impregnation of the support. SLM: organic phase 0.01 *M* DB18C6/chloroform; support: Celgard 2500; feed: solution of $AgNO_3$ in water: $[Ag^+] = 0.01\,M$; strip: distillate water.

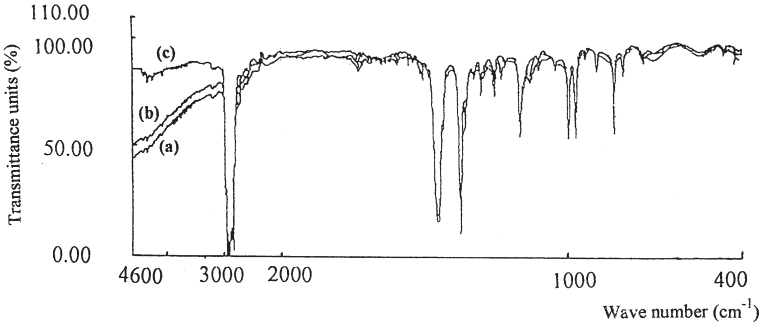


Figure 6. The FTIR spectra of Celgard 2500 support: (a) before utilization (b) after impregnation during 14 days, (c) after transport using organic phase 0.01 *M* DB18C6/chloroform; feed: solution of $AgNO_3$ in water $[Ag^+] = 0.01\,M$; strip: distillate water.

polymer support thickness, which means degradation of the support under the action of the solvent as shown in Fig. 7a and 7b obtained by scanning electron microscopy (SEM) of Celgard 2500 support—before and after impregnation in a 0.01 *M* DB18C6/chloroform solution during a period of 2 months, respectively. It can be seen that porosity and pore-size decrease drastically when impregnation time increases; the same behavior was observed on a micrograph taken after 26 days, but it was less marked. These results seem to confirm the degradation of this type of support in contact with the organic phase after a certain time.

The results obtained agree with the study of Chaiko and Osseo-Asare (29), who showed using SEM observations that the surface of Celgard support loses its porosity after 52 days of impregnation.

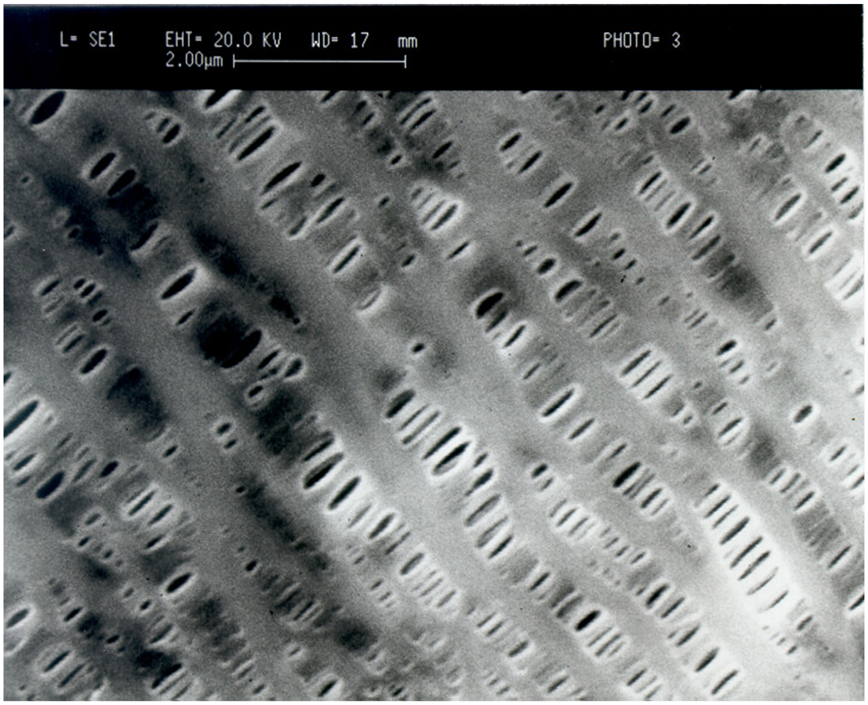
Influence of the Support Characteristics

Thickness, pore-size, and porosity of the support are some of the fundamental parameters that act on mass fluxes of metallic ions and on SLM stability. The influence of these parameters has been studied using three supports with different characteristics. The obtained results, reported in Table 3, show for all three ions, that the initial fluxes: (i) decrease with increasing support thickness, (ii) increase with increasing pore size of the support, and (iii) increase with increasing porosity of support.

These results, which agree with that reported in literature (29,30), showed that Celgard 2500 membrane with highest porosity and pore-size and lowest thickness is the one that gives highest mass fluxes for silver, copper, and zinc ions.

Permeability Factors

Figure 8 and Table 4 give values of P, calculated by Eq. (2), as a function of carrier concentration and support characteristics, respectively. It can be observed that permeability increases with increase in the concentration of the carrier and reaches a maximum at a concentration of $5 \times 10^{-3}\,M$; beyond this value, it is a constant. The observed behavior can be explained by an increase in the carrier molecules acting as a shuttle in the liquid membrane; above $5 \times 10^{-3}\,M$, the carrier molecule precipitates (see "Study of Carrier Precipitation in the Organic Phase") and so the free molecules in the liquid membrane do not increase effectively and the permeability reaches a maximum. With variation in the types of support, permeability varies in the same way as described before.



(a)

Figure 7. Scanning electron micrographs of a Celgard 2500 support: (a) before impregnation, (b) after impregnation in a 0.01 M DB18C6/chloroform solution during 2 months.

(b)

Figure 7. Continued.

Study of the SLM Stability

Repeated transport tests of silver were carried out for characterizing the stability of the SLMs. Feed and strip phases were renewed every 24 hr without changing the membrane. For each test, the average flux during 24 hr, before

Table 3. Initial Mass Fluxes of Silver, Copper, and Zinc Ions for Various Liquid Membrane Supports. Supported Liquid Membrane: DB18C6/Chloroform 0.01 *M*, Support Impregnated During 14 Days by Simple Immersion. $[\mathrm{Ag}^+]_\mathrm{i} = [\mathrm{Cu}^{2+}]_\mathrm{i} = [\mathrm{Zn}^{2+}]_\mathrm{i} = 0.01\,M$

Support	$J_{\mathrm{Ag}^+} \times 10^{10}$ (mol cm^{-2} sec^{-1})	$J_{\mathrm{Cu}^{2+}} \times 10^{10}$ (mol cm^{-2} sec^{-1})	$\mathrm{J}_{\mathrm{Zn}^{2+}} \times 10^{10}$ (mol cm^{-2} sec^{-1})
Celgard 2500	4.42	2.533	1.031
Celgard 2400	1.50	0.755	0.298
Celgard 2402	0.58	0.204	0.128

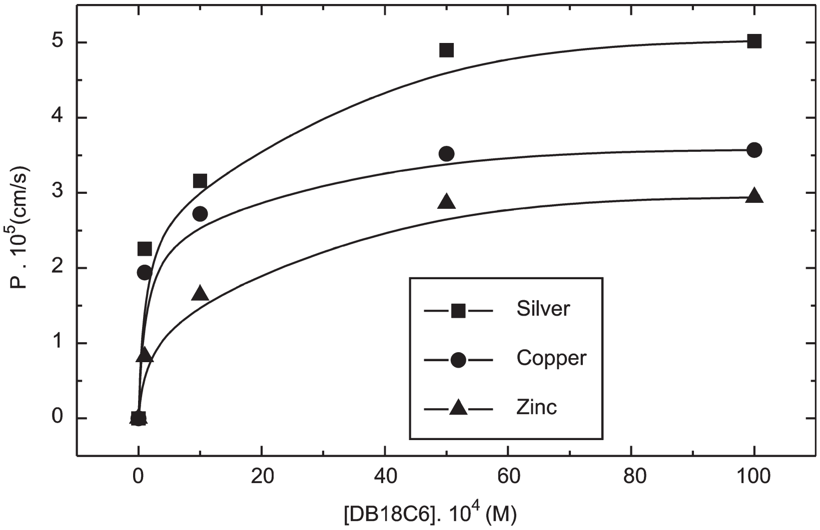


Figure 8. Permeability of Ag(I), Cu(II), and Zn(II) ions vs. extractant concentration. SLM: organic phase DB18C6/chloroform, support Celgard 2500 impregnated during 14 days; feed: solutions of $Cu(NO_3)_2$, $Zn(NO_3)_2$, and $AgNO_3$ in water $[Cu^{2+}] = [Zn^{2+}] = [Ag^{+}] = 0.01\,M$; strip: distillate water.

renewing solutions was measured and plotted as shown in Fig. 9. Quite constant fluxes were obtained during the observation time (15 days). In many cases, the decay can be attributed to (30–33):

—specific interactions between the organic diluent, carrier, and the support;

—decrease of membrane porosity due to pore plugging;

Table 4. Variation of the Permeability vs. the Type of the Support. Supported Liquid Membrane: DB18C6/Chloroform 0.01 *M*, Support Impregnated During 14 Days by Simple Immersion. [Metal] = 0.01 *M*

	$P \times 10^5$ (cm sec^{-1})		
Support	Ag^{+}	Cu^{2+}	Zn^{2+}
Celgard 2500	5.02	3.57	2.94
Celgard 2400	1.1	0.77	0.3
Celgard 2402	0.36	0.205	0.129

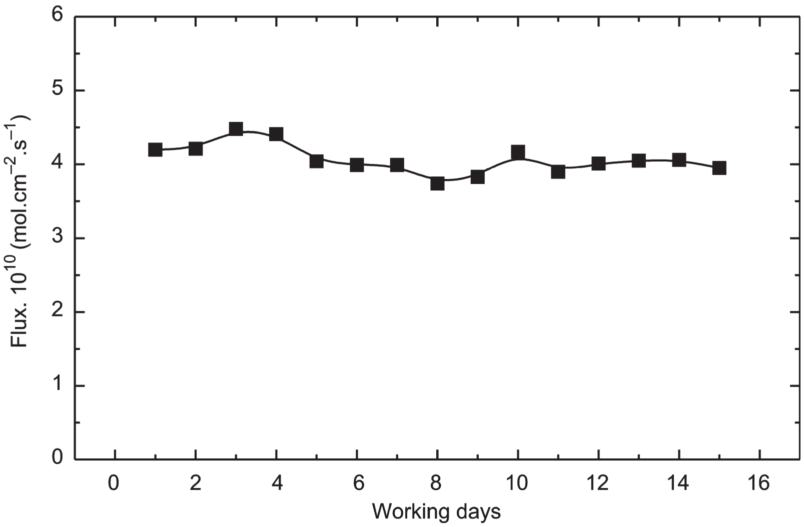


Figure 9. Mass fluxes of silver ion vs. the time changing feed and strip each 24 hr. SLM: organic phase 0.01 *M* DB18C6/chloroform; support: Celgard 2500 impregnated during 14 days, feed: solution of $AgNO_3$ in water $[Ag^+] = 0.01$ *M*; strip: distillate water.

—change in viscosity of the organic phase caused by the formation of metal–carrier complex;

—loss of liquid membrane phase from support pores (e.g., by dissolution in aqueous phase).

Figure 9 shows that the measured fluxes do not decrease significantly after 15 days; therefore, the Celgard 2500 membrane presents a lifetime greater than 15 days for the system studied.

Study of Carrier Precipitation in the Organic Phase

An increase in flux with impregnation time as shown in Fig. 5 could be caused by the presence of aggregated carrier molecules in the organic solution used for preparing the SLMs (precipitation by low solubility, 6.94×10^{-2} *M* as found in literature, which is a value close to the concentration used: 0.01 *M* DB18C6 in chloroform). In this case, equilibrium exists between the free molecules in solution and aggregate particles. The aggregate particles cannot penetrate into the support pores (size of particles less than 150 μm was measured by optical microscope) but free molecules can, as can be seen from the previous results reported in Table 2 where a weight method was used. Owing to low concentration of free carrier molecules in the organic solution, a longer diffusion time was required to reach the inside of pores; on the other hand, the molecules from dissolved aggregates penetrate into the support and all these require a longer immersion time.

To find the optimum concentration of DB18C6 above which precipitation (or aggregation) occured, the absorbance (to which turbidity can be revealed) of DB18C6 solutions at various concentrations in chloroform at a wavelength of 400 nm was measured using chloroform as the blank reference. The obtained results, repeated twice because low absorbance values were measured (Fig. 10), thereby showing that absorbance increased a little when the concentration of DB18C6 was in the range 1×10^{-4}–5×10^{-3} M; in this range, the solutions were very clear. Above 5×10^{-3} M, a little turbidity was observed in the organic phase and the absorbance had a higher value. This concentration value is attributed to the solubility limit above which precipitation or aggregation starts and it is a little lower than that reported previously from literature.

Supplementary experiments were carried out to see the influence of carrier concentration at a fixed time of impregnation of the support by the organic phase. Figure 11 shows the mass fluxes of copper ions through the SLM vs. carrier concentration using the impregnation method by simple immersion of support for 1 hr in the organic phase. The results obtained show that with increasing carrier

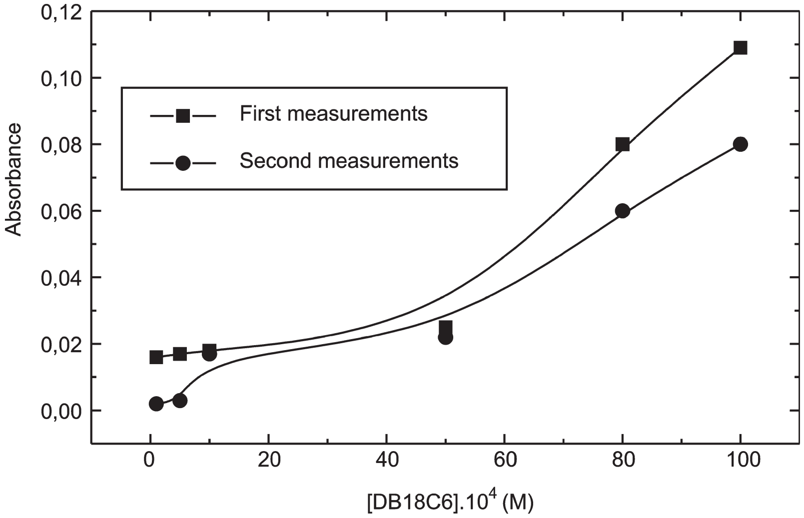


Figure 10. Absorbance of the organic phase vs. DB18C6 concentration at a wavelength of 400 nm; reference: chloroform.

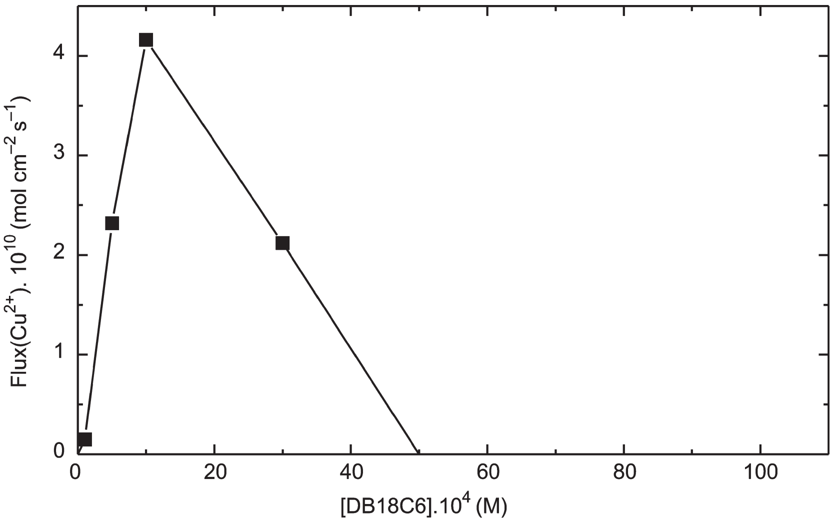


Figure 11. Mass fluxes of copper vs. carrier concentration. SLM: organic phase $1 \times 10^{-4} - 100 \times 10^{-4}\,M$ DB18C6/chloroform; support: Celgard 2500 impregnated during 1 hr by SI method; feed: solution of $Cu(NO_3)_2$ in water $[Cu^{2+}] = 0.01\,M$; strip: distillate water.

concentration, mass flux increases, then it decreases till it reaches a zero value above $5 \times 10^{-3}\,M$ carrier concentration confirming the behavior described previously. Indeed, from Fig. 5, it can be seen that at higher concentration ($0.01\,M$ DB18C6), a flux of Ag^+ greater than zero can be obtained but a significantly longer time was required (26 days). As longer time is the limiting factor for practical applications, and an accurate choice of carrier concentration is needed to avoid long impregnation time for SLM preparation.

CONCLUSIONS

Three preparation modes of SLM using organic solutions containing a crown ether (DB18C6) in chloroform were studied for the facilitated co-transport of silver(I), copper(II), and zinc(II) ions. Comparison of the three preparation modes (VI, IHVC, SI) showed higher mass fluxes were obtained using the SI method. Impregnation time of 1 hr is interesting for practical applications but at least 14 days were required for obtaining high ion flux when a concentration higher than $2 \times 10^{-3}\,M$ was used. This behavior was attributed to aggregate formation by precipitation of the carrier molecules at a concentration above $2 \times 10^{-3}\,M$. So, for obtaining significant flux, through the SLM, studied using short impregnation time (e.g., 1 hr), a carrier concentration below $2 \times 10^{-3}\,M$ must be used.

Long impregnation time of polypropylene Celgard 2500 support (above 26 days) resulted in degradation. Of the three types of supports (2500, 2402, 2400), Celgard 2500 with lower thickness, higher pore size, and higher porosity gave higher mass fluxes for all the three ions. The Celgard 2500 support gave stability higher than 15 days during the transport of silver ions.

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