WATER CONTENT AND ELECTRIC POTENTIAL DISTRIBUTIONS IN GELATINOUS BENTONITE SLUDGE WITH ELECTROOSMOTIC DEWATERING

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Key Words: Solid Liquid Separation, Gelatinous Sludge, Electroosmotic Dewatering, Water Content Distribution, Electric Potential Distribution

To analyze the electroosmotic dewatering process precisely, the variations of water content and electric potential distributions in the sludge are made clear. The distributions of water content and electric potential in gelatinous bentonite sludge with electroosmotic dewatering were studied experimentally under the conditions of both constant voltage and constant electric current. It is proved that the water content distribution is generally related to the electric potential distribution throughout the dewatering process. Electroosmotic dewatering under constant voltage is compared with that under constant electric current. Electroosmotic dewatering combined with vacuum dewatering is also discussed from the viewpoint of these distributions.

Introduction

Gelatinous sludge and sludge containing colloidal particles are very difficult to dewater by conventional mechanical methods. Electroosmotic dewatering is particularly effective for these hardly dewaterable sludges. In our previous papers,[3,4] electroosmotic dewatering of compressible sludge under the conditions of both constant electric current (abbreviated C.C.) and constant voltage (C.V.) was analyzed theoretically. The analysis was based on a simple model consisting of two characteristic layers such as a dewatering layer having an initial water content and a dewatered layer having an equilibrium water content corresponding to the applied electric field. But this model does not satisfactorily explain the dewatering process, because the actual distribution of water content in the sludge is inconsistent with that of the model.

The velocity of electroosmotic flow is theoretically proportional to the strength of the electric field, namely the electric potential gradient. Therefore, water content in the sludge varies with the electric potential gradient. Since it is considered that the electric resistance of sludge depends on its water content, the electric potential distribution in the sludge varies simultaneously with the variation of water content distribution because of Ohm's law. Accordingly, in order to analyze the electroosmotic dewatering process precisely, it is important to make clear the variations of water content and electric potential distributions throughout the dewatering process.

In this work, the water content and the electric potential distributions in the electroosmotic dewatering of gelatinous bentonite sludge under the conditions of both C.V. and C.C. were investigated experimentally. The electroosmotic dewatering process under C.V. is compared with that under C.C. condition. Electroosmotic dewatering combined with vacuum dewatering is also discussed from the viewpoint of these distributions.

1. Experimental

The apparatus used in this work was almost the same as used in the previous studies.[3,4] Platinum was used as the electrode. Bentonite powder and deionized water were mixed by stirring and a gelatinous bentonite sludge was prepared. The sludge, almost saturated with water, was packed in an acrylic resin cylinder with inside diameter of 72 mm. The upper electrode was set to contact the surface of the sludge bed, but the sludge was not compressed by the electrode.

The cylinder wall was provided with holes for the purpose of measuring water content and electric potential distributions in the direction of height of sludge bed. To measure local water content, a glass tube of 3 mm inside diameter was inserted into the sludge through the sampling hole and the sludge was taken out in turn from the upper side of sludge bed. The water content was obtained by measuring wet

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and dry weight of sample sludge. Water content of the sludge was defined as volumetric fraction of water, ε_w, and ε_w was calculated from $\varepsilon_w=(w_l/\rho_l)/(w_l/\rho_l+w_p/\rho_p)$. Here w_l and w_p are the weight of water and particles in the sludge, and ρ_l, ρ_p the density of water and particles, respectively. The electric potential was measured with a vacuum-tube voltmeter by using pin-type electrodes (stainless steel of 1.0 mm diameter) which were inserted into the sludge.

The initial concentration of particles in the sludge was 20.0 wt% and was hardly dewatered by gravitation. The initial value of ε_w, ε_{w0}, and the initial height of sludge bed, H_0, were 0.917 and 5.40 cm, respectively. The value of ρ_p was 2767 $\text{kg}\cdot\text{m}^{-3}$.

2. Results and Discussion

2.1 Relation between volume dewatered by electroosmosis Q_E and dewatering time t

Figure 1 shows the relation between Q_E and t under the conditions of C.V. and C.C., with E_0 as a parameter. In this figure, Q_E under C.V. gradually approaches a constant terminal value, $Q_{E\infty}$, at each E_0. The value of $Q_{E\infty}$ becomes maximum at a certain E_0, as shown in **Fig. 2**. Under the condition of C.C., it is found that a secondary dewatering process[3] appears after completion of the first. In the secondary dewatering process, Q_E can be further increased. However, it is difficult to continue the experiment because the voltage applied to the sludge is extremely large, as described later. Therefore, the end of dewatering under C.C. was regarded as that time when the experiment was stopped.

2.2 Relation between sludge bed height H_t and t

The relations between H_t and t under both operating conditions are illustrated by E_0 in **Fig. 3**. Each plotted key (○▲) shows the observed values, and the broken lines show the values calculated by $H_t=H_0-Q_E/A$ using Q_E shown in Fig. 1. The observed H_t is larger than the calculated value. This result suggests that an unsaturated sludge layer is gradually formed in the dewatered sludge. It is found that the observed H_t finally becomes constant and the final value of H_t at a large E_0 is slightly larger than that at a small E_0. Accordingly, it is considered that the formation of the unsaturated sludge layer is intensified with increasing E_0.

2.3 Variation of electric resistance of sludge bed with dewatering

The electric resistance of the sludge bed varies due to the variation of water content distribution with t. The variations of i_t under C.V. and V_t under C.C. were measured as shown in **Fig. 4**. In this figure, i_t increases in the early period, and after reaching a maximum it decreases with t. In the case of small E_0 values such as 40.1 $\text{V}\cdot\text{m}^{-1}$, however, i_t scarcely changes with t. By contrast, V_t decreases in the early period, and after reaching a minimum it increases rapidly with t. These results are considered to be

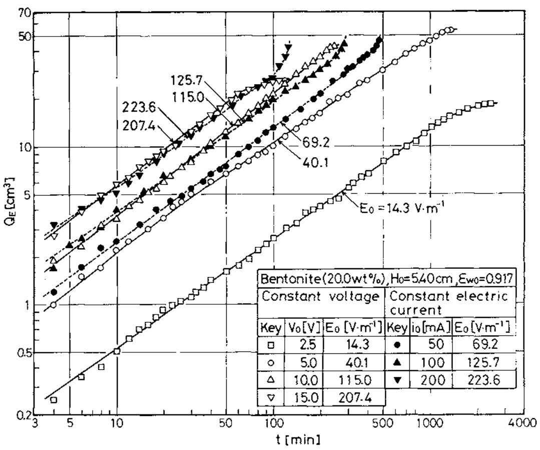

Fig. 1. Relations between Q_E and t under constant voltage and constant electric current.

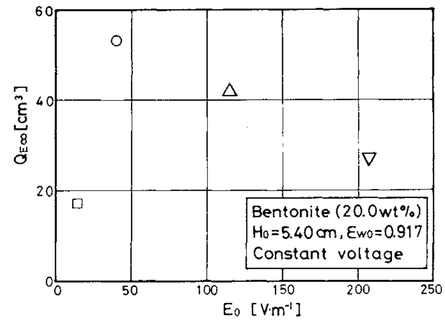

Fig. 2. Relation between $Q_{E\infty}$ and E_0 under constant voltage.

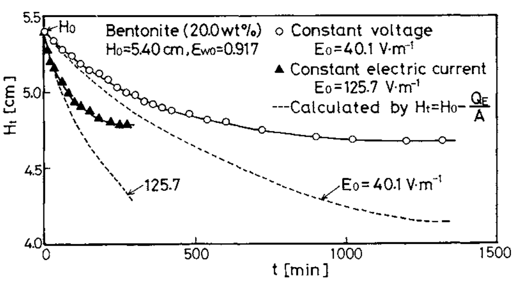

Fig. 3. Relations between H_t and t under constant voltage and constant electric current.

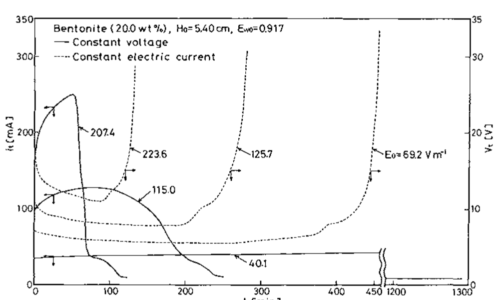

Fig. 4. Variation of i_t with t under constant voltage, and variation of V_t with t under constant electric current.

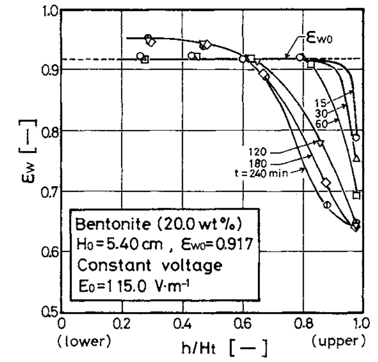

Fig. 5. Variation of water content distribution with time under constant voltage.

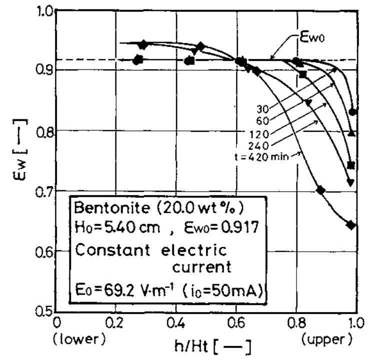

Fig. 7. Variation of water content distribution with time under constant electric current.

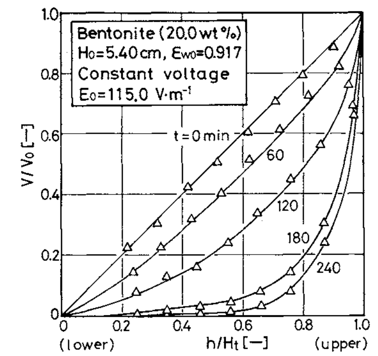

Fig. 6. Variation of electric potential distribution with time under constant voltage.

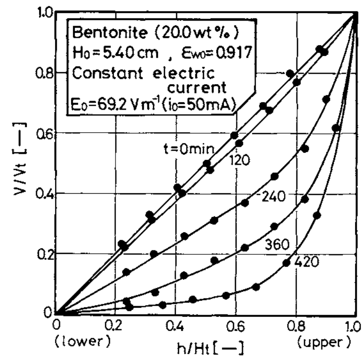

Fig. 8. Variation of electric potential distribution with time under constant electric current.

caused by the following reason. The electric resistance of the sludge bed decreases in the early period because H_t decreases with dewatering, and thereafter it increases under the influence of the unsaturated sludge layer formed in the dewatered sludge. The increase of electric resistance is also due to gas produced by electrolysis.

2.4 Distributions of water content and electric potential in sludge

Figure 5 shows the variation of ε_w distribution in the sludge with t under C.V. condition. In this figure, h/H_t of 1.0 expresses the top of the sludge bed irrespective of t. In the early dewatering period, ε_w near the top decreases rapidly to a certain terminal value while ε_w in the lower part remains substantially constant at ε_{w0}. The terminal value of ε_w is kept unitl the end of dewatering ($t = 240$ min). The value of ε_w in the lower part becomes slightly larger than ε_{w0} after a long time.

Figure 6 shows the variation of electric potential distribution in the sludge with t under the same condition denoted on Fig. 5. The electric potential is expressed by the dimensionless term V/V_0. The value of V/V_0 near the top decreases remarkably with t. That is, the electric potential gradient increases greatly in the upper part near the top. This phenomenon is explained as follows. As shown in Fig. 5, ε_w near the top begins to decrease with dewatering. An unsaturated sludge layer is gradually formed in the dewatered sludge. As local electric resistance of the unsaturated sludge layer increases, the electric potential gradient (namely, strength of electric field E) near the top is increased due to Ohm's law. The velocity of electroosmotic flow is proportional to E. Accordingly, both ε_w and V/V_0 in the upper part decrease simultaneously less and less. On the contrary, the electric potential gradient in the lower part decreases gradually with t because of C.V. condition. Therefore, ε_w in the lower part is scarcely decreased after a long time and becomes rather larger than ε_{w0}, as shown in Fig. 5.

Figures 7 and **8** show the variations of ε_w and electric potential distributions with t under C.C., respectively. The electric potential distribution under C.C. is expressed by V/V_t, as shown in Fig. 8. From these results, it is found that the variations of ε_w and V/V_t distributions under C.C. show a similar tendency to those under C.V. condition.

2.5 Final distribution of water content in sludge

The final distributions of ε_w under both operating conditions are shown with E_0 in **Fig. 9**. Under the condition of C.V., the final distribution varies with increasing E_0. That is, ε_w near the top decreases with increasing E_0 and is independent of E_0 when E_0 becomes large. In the case of large E_0 values such as 115.0 and 207.4 $V \cdot m^{-1}$, ε_w decreases exclusively in

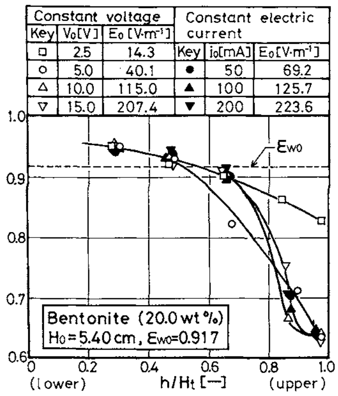

Fig. 9. Final distributions of water content under constant voltage and constant electric current.

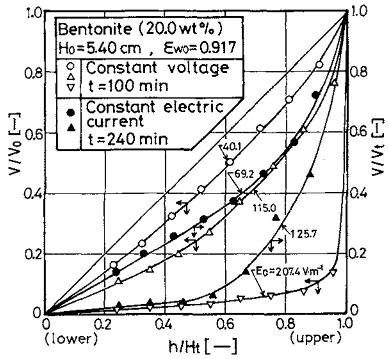

Fig. 10. Effect of E_0 on electric potential distributions under constant voltage and constant electric current.

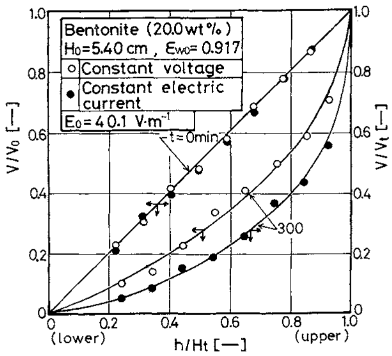

Fig. 11. Comparison of electric potential distribution under constant voltage with that under constant electric current.

the upper part near the top. The difference of the final distributions depending on E_0 is due to the following reason. In the case of large E_0, an unsaturated sludge layer is conspicuously formed near the top and the applied voltage drops extremely in this sludge layer. Consequently, the decrease of ε_w is restricted to the upper part near the top. Accordingly, there is an optimum E_0 in which $Q_{E\infty}$ becomes maximum, as shown in Fig. 2. On the other hand, the final distributions of ε_w under C.C. were independent of E_0 and almost agreed with the case of large E_0 under C.V., as shown in Fig. 9.

From the above results, the electroosmotic dewatering process can be described as follows. At the beginning of dewatering, water in the sludge is removed downwards throughout the sludge bed and ε_w near the top is decreased. At the same time, E near the top is increased due to Ohm's law. As the electroosmotic dewatering is enhanced with increasing E, ε_w in the upper part decreases gradually with the lapse of time. Finally, the applied voltage almost drops in the upper part and E in the lower part becomes very small. Therefore, ε_w in the lower part is hardly decreased.

Shirato *et al.*[1] reported the following fact. In the settling of thick slurry to which an electric field is applied, the electric potential gradient in the settling sediments increases greatly in the part consolidated electrically, namely the part having smaller water content. The result shown in this study is similar to the result cited above.

2.6 Effects of initial strength of electric field and operating condition on electric potential distribution

In both operating conditions, the electric potential distributions at a certain t are illustrated by E_0 in **Fig. 10**. In this figure, t is the same in each operating condition. It is found that the electric potential near the top decreases considerably with increasing E_0 in both operating conditions. This indicates that the applied voltage drops extremely in the dewatered sludge layer near the top when E_0 is large. Therefore, large E_0 is not necessarily effective for dewatering throughout the sludge bed, as described previously.

Figure 11 compares the electric potential distribution under C.V. with that under C.C. at the same elapsed time. The values of E_0 under both operating conditions are the same. The electric potential gradient in the upper part under C.C. is large compared with that under C.V. condition. This result means that ε_w in the upper part under C.C. is smaller than that under C.V. at the same elapsed time. Therefore, in the case of the same E_0, the dewatering rate under C.C. is larger than that under C.V. condition. Accordingly, the operating condition of C.C. is suitable for increasing dQ_E/dt compared with that of C.V., as described in the previous paper.[2]

From the results shown in Figs. 5–11, it was confirmed that ε_w distribution is generally related to the electric potential distribution. However, it was difficult to obtain a quantitative relation between these distributions, because the electric potential gradient is excessively influenced by the formation of the unsaturated sludge layer and by the variation of electrical characteristics of the sludge by electrolysis.

2.7 Electroosmotic dewatering combined with vacuum dewatering

For electroosmotic dewatering under C.V. com-

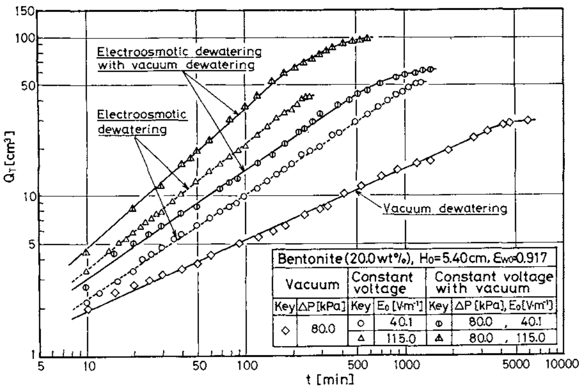

Fig. 12. Relation between Q_T and t under constant voltage combined with vacuum.

bined with vacuum dewatering, the relation between Q_T and t is shown in **Fig. 12**. In this figure, it is found that electroosmotic dewatering is very effective compared with vacuum dewatering. In the case of electroosmotic dewatering combined with vacuum dewatering, both dQ_T/dt and terminal Q_T are greater than in the case of electroosmotic dewatering only. The experimental result under C.C. combined with vacuum was also similar to that under C.V. combined with vacuum.

The final distribution of ε_w and the variation of electric potential distribution with t under C.V. combined with vacuum are illustrated in **Figs. 13** and **14**, respectively. In Fig. 13, the final distribution of ε_w under vacuum dewatering shows that ε_w in the lower part is very slightly decreased. Under the condition of C.V. combined with vacuum, ε_w near the top is almost the same but ε_w throughout the sludge bed is smaller, compared with C.V. condition. Therefore, electroosmotic dewatering combined with vacuum is effective for decreasing ε_w throughout the sludge bed. In Fig. 14, the solid lines express the results under C.V. combined with vacuum and the broken lines express the results under C.V. condition. The electric potential gradient in the upper part under C.V. combined with vacuum is smaller than that under C.V. at the same elapsed time. This indicates that the drop of applied voltage in the upper part under C.V. combined with vacuum is not so excessive as that under C.V. condition. In order to dewater electroosmotically throughout the sludge bed, it is advisable to make E uniform everywhere. Accordingly, electroosmotic dewatering combined with vacuum is effective for dewatering throughout the sludge bed, as shown in Fig. 13.

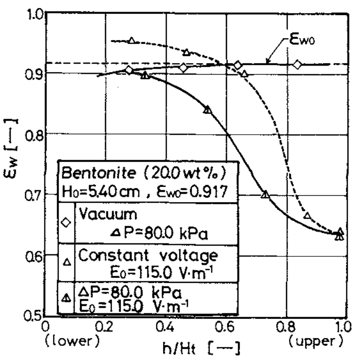

Fig. 13. Final distribution of water content under constant voltage combined with vacuum.

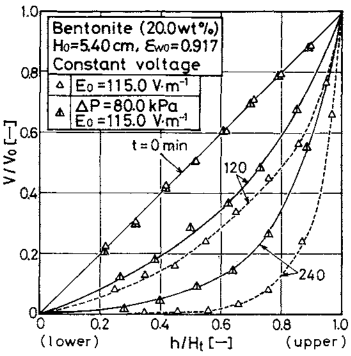

Fig. 14. Variation of electric potential distribution with time under constant voltage combined with vacuum.

Conclusion

The water content and electric potential distributions in sludge with electroosmotic dewatering under the conditions of C.V. and C.C. were measured. The conclusions are summarized as follows.

1) In the electroosmotic dewatering processes under both operating conditions, ε_w is remarkably decreased in the upper part in the direction of height of the sludge bed, and the electric potential gradient in that part is increased gradually due to on Ohm's law. As the electric potential gradient mostly depends on ε_w, ε_w distribution is generally related to the electric potential distribution throughout the dewatering process.

2) The terminal water content (the minimum value of ε_w) in the dewatered sludge bed is nearly equal under both operating conditions. Under the condition of C.V., large E_0 is not necessarily effective for dewatering throughout the sludge bed, so that $Q_{E\infty}$ becomes maximum at a certain E_0 with increasing E_0 and there is an optimum E_0 with regard to $Q_{E\infty}$. When E_0 is set the same under both operating conditions, dQ_E/dt under C.C. is gradually larger than that under C.V. condition.

3) Electroosmotic dewatering combined with vacuum is effective for dewatering throughout the sludge bed and can be used as an available application of electroosmotic dewatering.

Acknowledgment

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Nomenclature

A	=	cross-sectional area of sludge bed	[cm^2]
E	=	local strength of electric field in sludge bed	[$V \cdot m^{-1}$]
E_0	=	initial strength of electric field in sludge bed	[$V \cdot m^{-1}$]
H_0	=	initial height of sludge bed	[cm]
H_t	=	height of sludge bed at t	[cm]
h	=	distance from bottom of sludge bed to measuring point	[cm]
i_0	=	constant electric current passing through cross section of sludge bed	[mA]
i_t	=	electric current passing through cross section of sludge bed at t	[mA]
Q_E	=	volume dewatered by electroosmosis	[cm^3]
$Q_{E\infty}$	=	terminal value of Q_E	[cm^3]
Q_T	=	total volume dewatered by electroosmosis and vacuum	[cm^3]
t	=	dewatering time	[min]
V	=	electric potential at height of sludge bed	[V]
V_0	=	constant voltage applied to electrodes	[V]
V_t	=	voltage applied to electrodes at t	[V]
w_l	=	weight of water in sludge	[kg]
w_p	=	weight of particles in sludge	[kg]
ε_w	=	volumetric fraction of water content in sludge	[—]
ε_{w0}	=	initial value of ε_w	[—]
ρ_l	=	density of water	[$kg \cdot m^{-3}$]
ρ_p	=	density of particles	[$kg \cdot m^{-3}$]
ΔP	=	degree of vacuum	[kPa]

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KINETICS OF STRIPPING OF N-8-QUINOLYL-*P*-DODECYLBENZENESULFONAMIDE-COPPER CHELATE COMPLEX WITH HYDROCHLORIC ACID

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Key Words: Extraction, Stripping, Kinetics, Interfacial Reaction, Copper, LIX 34

A kinetic study concerning the stripping of copper chelate complex in toluene with hydrochloric acid was carried out at 303 K, using a stirred transfer cell and pure copper complex prepared from copper and synthesized N-8-quinolyl-*p*-dodecylbenzenesulfonamide.

It was found that the mechanism of copper stripping could not be explained as simply a reverse process of the copper extraction by this extractant from acetate buffer media, due to the reaction between the extractant and hydrochloric acid and the low solubility of the ion pair complex formed by this reaction. Moreover, it was confirmed that the stripping rate was determined by the first step of the interfacial reaction between the copper complex and the acid, and by mass transfer of the copper complex.

Introduction

Research into metal recovery with liquid membranes has rapidly expanded in the last decade, because of practical interest in the development of attractive hydrometallurgical processes.[1,2,4,10] To develop and design the liquid membrane process, it is important to elucidate the mechanism and kinetics of stripping of metal by the stripping solution, as well as extraction of metal by the extractant used as a carrier in the liquid membranes.

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Earlier investigations concerning the kinetics of stripping of copper complex with acid were mainly carried out with commercial extractants, that is, LIX 64N,[13] LIX 65N,[6,8,12] *anti*-2-hydroxy-5-nonylbenzophenone oxime[7] (henceforth *anti*-HNBPO) of the active component of LIX 65N and *anti*-2-hydroxy-5-nonylacetophenone oxime[5,11] (henceforth *anti*-HNAPO) of the active component of SEM 529. Several mechanisms for stripping of the copper complex with acid were proposed to account for each experimental result. Kojima *et al.*[6] measured the stripping rate of copper-loaded LIX 65N in Dispersol solution with sulfuric acid using a dia-