

Investigation of Gel Structure of Aluminum Hydroxycarbonate Gel Using a Tension Cell

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Received April 21, 1980, from the *Department of Industrial and Physical Pharmacy and the †Department of Agronomy, Purdue University, West Lafayette, IN 47907. Accepted for publication February 6, 1981.

Abstract □ A tension cell was designed to measure the gel structure of aluminum hydroxycarbonate gel. Equilibrium measurements of the total water outflow versus applied tension give insight into the rigidity of the gel structure. Dynamic measurements of the rate of outflow of water at various applied tensions yield the capillary conductivity of the gel, which is related to the apparent surface area, particle size, and porosity. An aluminum hydroxycarbonate gel with a high apparent viscosity exhibited an increase in viscosity upon aging at 25°, which was accompanied by an increase in the equilibrium tension of the water phase, an increase in $\Delta\bar{G}_{H_2O}$, and a decrease in capillary conductivity. In contrast, the apparent viscosity of a low viscosity aluminum hydroxycarbonate gel, which was precipitated from the same reagents but with different precipitation temperature, pH, and stirring speed, exhibited a decrease in equilibrium water tension, a decrease in $\Delta\bar{G}_{H_2O}$, and an increase in capillary conductivity during aging at 25°.

Keyphrases □ Aluminum hydroxycarbonate gel—gel structure measurement using a tension cell □ Gels—aluminum hydroxycarbonate, gel structure measurement using a tension cell □ Tension cell—gel structure measurement of aluminum hydroxycarbonate gel

Many physical properties associated with aluminum hydroxycarbonate gel are simply a reflection of the particular structural arrangement of particles within the gel¹. The specific structural arrangement is, in turn, a delicate function of various parameters such as particle size, shape, solids concentration, the nature and amount of any solutes present, and the various forces involved, *i.e.*, coulombic and van der Waals forces.

Viscosity is one of the most important physical properties of aluminum hydroxycarbonate gel. However, the viscosity of aluminum hydroxycarbonate gel varies widely, as evidenced by the availability of commercial aluminum hydroxycarbonate gels that are semisolids at 9% equivalent aluminum oxide content or that are pourable liquids at 9% equivalent aluminum oxide. The differences in apparent viscosity as well as the high water content of these systems suggest that considerable variation exists in the gel structure. For this reason, a series of experiments was performed utilizing a specially designed tension cell to obtain greater insight into the gel structure of aluminum hydroxycarbonate gel. The technique developed for this study was based on studies of clay systems (1) and offers the advantage of very little gel disruption during the experiment. The data obtained from the tension cell were compared to the results of more conventional measurements such as viscosity and rate of acid neutralization.

EXPERIMENTAL

Conditions for the precipitation of aluminum hydroxycarbonate gel by the reaction of aluminum chloride, sodium carbonate, and sodium bicarbonate were varied (Table I) to produce two aluminum hydroxy-

carbonate gels of significantly different apparent viscosity. The aluminum hydroxycarbonate gel prepared using the conditions described by Kerkhof *et al.* (2) will be termed the high viscosity aluminum hydroxycarbonate gel, and the aluminum hydroxycarbonate gel prepared by Beekman's method (3) will be referred to as the low viscosity aluminum hydroxycarbonate gel.

X-ray² (4) and IR³ (4) analysis confirmed that both the high and low viscosity aluminum hydroxycarbonate gels studied were amorphous aluminum hydroxycarbonate (5).

The rate of acid neutralization was determined by pH-stat titration⁴ at pH 3.0 and 25° (6).

Rheograms were obtained using a rotational viscometer⁵. After being stirred to ensure homogeneity, the sample was extruded through a 15-gauge needle into a 600-ml beaker and allowed to stand for 1 hr with the spindle in place prior to the viscosity determination.

The tension cell was a modification of pressure cells used in soil sciences to study the interaction of water with solids (7–9). Preliminary experiments with a pressure cell indicated that pressures of 0.5 atm (68 cm of water) or greater, which are used to characterize water–soil interactions, are too large for studying aluminum hydroxycarbonate gel. To obtain accurately the small driving force needed, a cell capable of applying a small negative pressure or tension to the aluminum hydroxycarbonate gel was developed.

Figure 1 shows the construction of the tension cell. A glass cover fit loosely over the sample chamber to protect the sample and to minimize evaporation. The sample chamber was a plexiglass tube 6.35 cm i.d. × 6.985 cm o.d. × 17.145 cm in length. A 0.9525-cm notch was machined into the outside wall of the sample chamber so that the top base piece could be securely attached. A rubber O-ring and a 0.45- μ m membrane filter were sandwiched between the sample chamber and the bottom base piece. An extracourse sintered-glass disk, 6.19 × 0.476 cm, fit into the base and served as a filter support. The bottom base piece was machined so a trough system would aid the flow of water to the two outlet ports⁶.

Figure 2 is a diagram of the complete tension cell apparatus. The tension cell was fastened to a movable plate⁷, which could be accurately positioned by means of a screw gear and vernier system. Water from the samples was collected into a buret that was closed with a stopper containing a capillary which maintained atmospheric pressure in the buret. A three-way stopcock was incorporated in the outlet tubing.

It is essential that the volume comprising the membrane filter's pore volume, the sintered-glass disk's pore volume, and the outlet tubing be completely filled with water before the aluminum hydroxycarbonate gel sample is introduced into the sample chamber. The following procedure was followed in conducting the tension cell experiments:

1. The tension cell was filled from the bottom by adding water through the three-way stopcock. Water was allowed to fill the sample chamber to a height of ~8 cm.

2. The sample chamber cover was replaced with a large one-hole rubber stopper. With the three-way stopcock adjusted to connect the cell to the buret, pressure was applied through the hole in the rubber stopper to remove any air bubbles in the system. The rubber stopper was replaced with the glass cover, and the position of the outlet port was adjusted using the screw assembly so that the outlet port was level with the membrane filter. At this position, the water in the outlet port had a flat surface; *i.e.*, neither a meniscus or a drop was present. The system was allowed to equilibrate for 4–5 hr.

² Kristalloflex 4 generator, type F diffractometer, Siemens AG, Karlsruhe, West Germany.

³ Model 180, Perkin-Elmer Corp., Norwalk, Conn.

⁴ PHM 26, TTT II, ABU 12 (2.5 ml), TTA 3, and SBR 2, Radiometer, Copenhagen, Denmark.

⁵ Model RVT, Brookfield Engineering Laboratories, Stoughton, Mass.

⁶ Swagelok 55-2-TA-OR-ST, Crawford Fitting Co., Solon, Ohio.

⁷ Model B2504B-B2530B, Velmen, Bloomfield, N. Y.

Table I—Precipitation Parameters ^a

Type	Temperature	End-Point pH	Stirring Speed, rpm	Moles of Aluminum Chloride per Liter of Washed Gel	Moles of Sodium Carbonate per Liter of Washed Gel	Moles of Sodium Bicarbonate per Liter of Washed Gel
High viscosity	25°	6.5	500	0.75	0.315	0.805
Low viscosity	4°	5.8	15	0.80	0.315	0.805

^a The AlCl₃·6H₂O (0.47 M) was added to a solution of 0.53 M NaHCO₃ and 0.23 M Na₂CO₃.

3. The stopcock was closed to prevent any water flow, and an accurately weighed sample was added to the chamber by extrusion through a 15-gauge needle.

4. The outlet port was raised so it was level with the top surface of the sample. A final adjustment was made in the position of the outlet port by opening the stopcock and adjusting the position of the outlet port to achieve a flat water surface at the outlet port. This was the zero-tension position. The sample was allowed to equilibrate for 30 min.

5. The tension cell was raised 2 cm, and the cumulative volume of water in the collection buret was recorded with time. To maintain a constant tension of 2 cm, the tension cell was raised 0.05 cm for every 1.5 ml of outflow. This manner of correction is permissible since it was observed in separate measurements that the volume change of the column of aluminum hydroxycarbonate gel is identical to the volume of water that has flowed from the aluminum hydroxycarbonate gel.

6. After the outflow from the sample was zero for 2 hr, the tension cell was raised by a predetermined increment (2-cm increments were used), and this step was repeated.

7. After the final tension increment, the sample remaining in the sample chamber was collected and accurately weighed. The sample was dried to constant weight at 110°. Loss during transfer never exceeded 0.05%.

RESULTS AND DISCUSSION

Both equilibrium and dynamic measurements are possible through the use of the tension cell. Each contributes unique information concerning gel structure so that structural differences are readily ascertained.

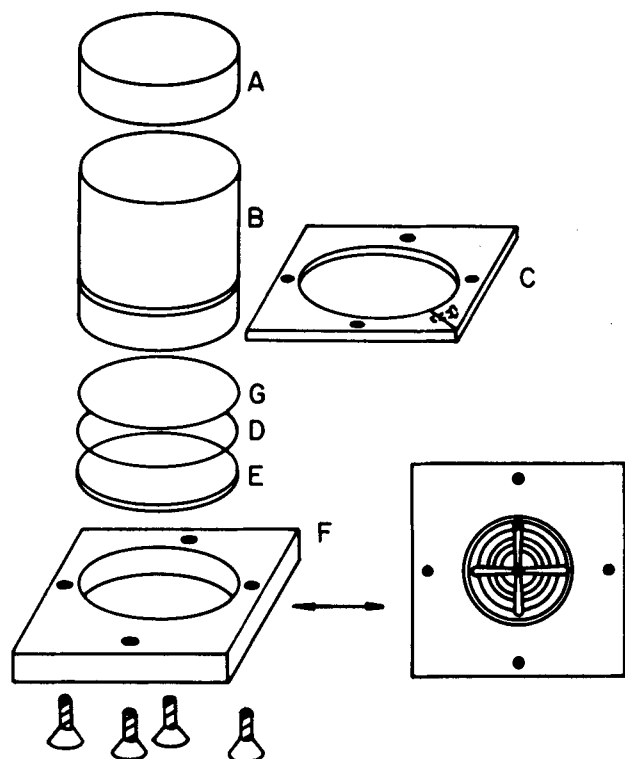


Figure 1—Components of tension cell. Key: A, cover; B, sample chamber; C, top base; D, O-ring; E, sintered-glass disk; F, bottom base; and G, membrane filter.

In the case of the simple and more easily treated equilibrium data, where total water outflow is examined as a function of applied tension, the particular gel characteristic examined is structural rigidity. Since the volume of water outflow is equal to the volume change of the aluminum hydroxycarbonate gel during the experiment, the ability of a gel to resist collapse of its structural framework may be directly observed by measuring the amount of water released as a consequence of an applied tension. The experiment may be analyzed either in terms of simply plotting the equilibrium water content of the aluminum hydroxycarbonate gel as a function of applied tension or in terms of the following thermodynamic quantity (10–15):

$$\Delta\bar{G}_{H_2O} = -\bar{v}\rho g\tau \quad (\text{Eq. 1})$$

where \bar{v} is the molar volume of water, ρ is the density of water, g is the gravitational constant, and τ is the tension increment. Thus, $\Delta\bar{G}_{H_2O}$ represents the work required per mole of water to remove water from the system with the accompanying compression of the particles into a smaller volume. If $\Delta\bar{G}_{H_2O}$ is large, the particles are pushed closer together only with difficulty due either to large cohesive forces between particles that prevent distortion of the gel structure or to repulsive forces (primarily coulombic repulsion) that prevent particle surfaces from approaching more closely. The latter force becomes much more pronounced only at higher solids concentrations.

Figure 3 shows the equilibrium water content of the high and low viscosity gels. As water was removed from either aluminum hydroxycarbonate gel, the further removal of water became increasingly more difficult. A greater rigidity of gel structure was indicated when the tension versus equilibrium water content curve rose more abruptly at low tension

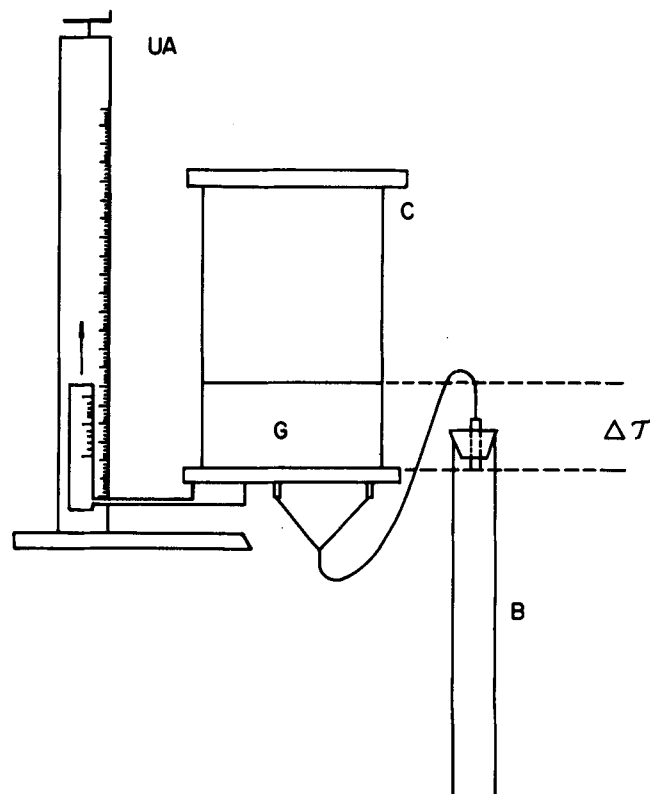


Figure 2—Schematic of tension cell apparatus. Key: C, tension cell; UA, moveable plate assembly; B, collection buret; and G, sample gel.

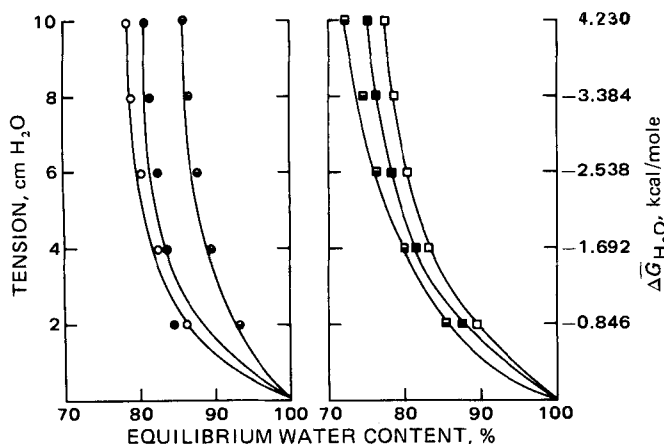


Figure 3—Effect of equilibrium water content on the water tension and change in partial molar Gibbs free energy, $\Delta\bar{G}_{H_2O}$. The high viscosity gel was aged 2 (○), 6 (●), and 14 (◐) weeks at 25°. The low viscosity gel was aged 2 (□), 10 (■), and 14 (◑) weeks at 25°.

values. The rigidity of the gel structure changed with age (Fig. 3). The high viscosity gel became considerably more rigid as it aged, whereas the low viscosity gel became less rigid with aging. These opposing trends demonstrate that different procedures of aluminum hydroxycarbonate gel preparation can lead to substantially different physical behavior both immediately after precipitation and during aging.

Dynamic measurements also are readily made with the tension cell. Darcy's law (1), which was developed to describe flow through porous media, provides the basis for analyzing the rate of water outflow at various applied tensions:

$$q = \frac{KA\tau}{L} \quad (\text{Eq. 2})$$

where q is the rate of flow through the solid phase (cubic centimeters per minute); K is the capillary conductivity (centimeters per minute); A is the cross-sectional area of the solid phase (centimeters squared); τ is the driving potential, i.e., tension head of water (centimeters); and L is the length of the gel slab (centimeters).

The apparent surface area of the gel, particle size, and porosity all are interrelated. A qualitative measure of these parameters is provided by examining the relative ease with which water may flow through the system. This examination involves time-dependent measurements, whereas only equilibrium measurements were involved in evaluating structural rigidity of the gel structure. The rate of water outflow is measured so that an estimate of capillary conductivity, K , may be obtained (8, 9, 16). This quantity reflects the resistance to water flow offered by the gel particles. A large K value implies a low resistance to water flow, which, in turn, indicates lower apparent surface area, larger particles, and higher porosity.

Figure 4 illustrates the capillary conductivity data obtained for the two aluminum hydroxycarbonate gels. With both gels, resistance to the flow of water through the system increased as the water content decreased. Opposite trends were again observed during aging. The high viscosity gel became more resistant to water flow as it aged, whereas the low vis-

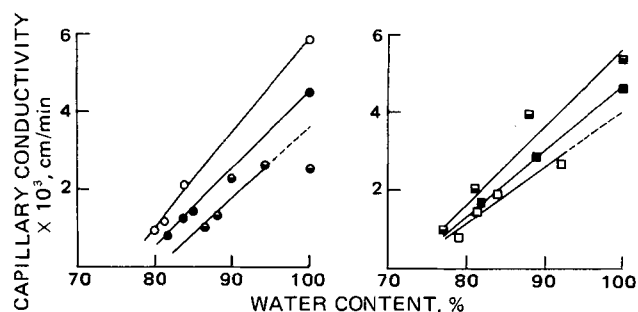


Figure 4—Effect of water content on capillary conductivity. For clarity, the data points are represented by straight lines to emphasize the trends. The R^2 values for the straight lines range from 0.64 to 0.99. The high viscosity gel was aged 2 (○), 6 (●), and 14 (◐) weeks at 25°. The low viscosity gel was aged 2 (□), 10 (■), and 14 (◑) weeks at 25°.

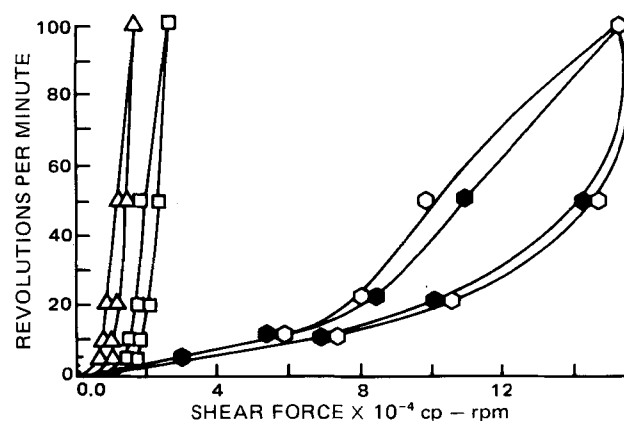


Figure 5—Rheograms of the high viscosity gel during aging at 25°. Key: Δ, 1 day; □, 4 weeks; ●, 8 weeks; and ○, 12 weeks.

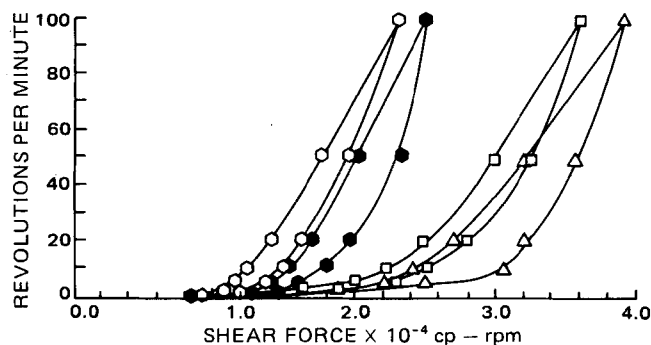


Figure 6—Rheograms of the low viscosity gel during aging at 25°. Key: Δ, 1 day; □, 4 weeks; ●, 8 weeks; and ○, 12 weeks.

cosity gel allowed water to flow more rapidly through its interparticle space upon aging. Both the equilibrium and dynamic measurements indicate that as the gels age, their behavior with respect to water removal changes, which is an important property to consider in the use of aluminum hydroxycarbonate gel dosage forms. The different gel structures exhibited by the two aluminum hydroxycarbonates also will influence manufacturing processes in which the solids concentration is changed, such as in concentrating or washing.

The rheograms for both the high and low viscosity aluminum hydroxycarbonate gels (Figs. 5 and 6, respectively) indicate thixotropic, shear-thinning systems. The apparent viscosity of the high viscosity gel and the degree of hysteresis increased during aging. In contrast, the low viscosity gel exhibited a decrease in viscosity with aging but no change

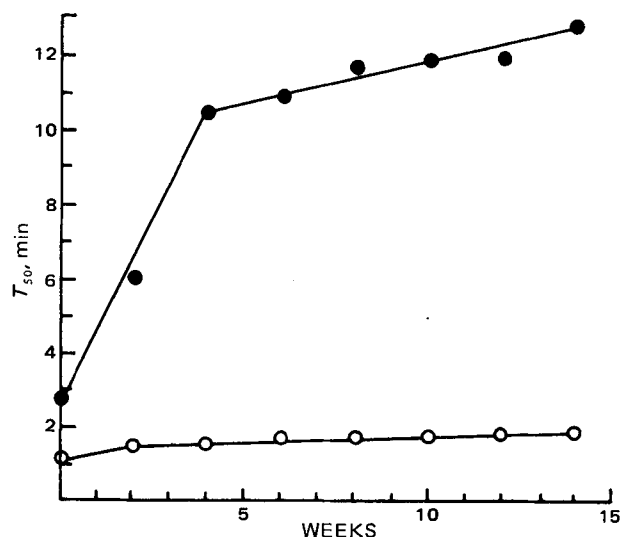


Figure 7—Effect of aging at 25° on the rate of acid neutralization of the high viscosity gel (○) and the low viscosity gel (●).

in the degree of hysteresis. These facts suggest a substantial increase in the cohesive forces operating between particles of the high viscosity gel and a decrease in the level of cohesion for the low viscosity gel.

Alteration of the degree of particle-particle cohesion due to changes in the level of particle charge was established previously (17). It was shown that additional charge provides sufficient coulombic repulsion to overcome the van der Waals attraction forces so that the apparent viscosity decreases. Examination of the rates of acid neutralization by the two aluminum hydroxycarbonate gels (Fig. 7) indicates a significant decrease in the rate of acid neutralization of the low viscosity gel but no appreciable change for the high viscosity gel. This behavior indicates that crystallinity develops in the low viscosity gel, eventually leading to the formation of a crystalline form of aluminum hydroxide such as gibbsite, which is free of carbonate (5, 18). The transformation to a carbonate-free aluminum hydroxide results in an increased zero point of charge (17) and, therefore, a buildup of charge on the low-viscosity gel. Thus, the apparent viscosity, gel structure rigidity, and resistance to water flow would be expected to decrease as was observed. With the high viscosity gel, the relatively stable rate of acid neutralization during the time period studied indicates that no buildup of charge occurs so that the natural tendency of a gel to form the most stable arrangement of particles with the maximum degree of particle-particle linking is observed. Thus, an increased apparent viscosity, an enhanced gel structure rigidity, and a decreased capillary conductivity are consistent with the proposed mechanism.

CONCLUSIONS

The tension cell is useful for examining the physical state of a gel, especially when compared to other methods such as viscosity measurement where large inputs of mechanical energy in the form of shear stress may disrupt the gel structure. The tension cell is capable of providing meaningful data with a firm basis provided by thermodynamic and kinetic theory. The data reported here were obtained with considerable difficulty because of the necessity for position readjustment of the tension cell to maintain a constant tension, the long duration of the experiments, and the frequent tabulations of data required for the dynamic measurements. Early experiments, in which adjustments to maintain a constant tension during water outflow were not performed, did not produce satisfactory data. The manual adjustment of cell position to maintain a constant tension was essential in obtaining meaningful results. However, some of the scatter observed in Figs. 3 and 4 may have been due to unavoidable mechanical disturbances of the gel structure through the manual repositioning of the tension cell. Consequently, various methods for automating the tension cell are being tested so that acquiring the necessary data will be more convenient and more precise data may be

obtained.

Future experiments are planned with the tension cell to give insight into various roles played by particle charge, size, and shape. The effects of surface charge and particle size on the compressibility of aluminum hydroxycarbonate gel are examined specifically in a subsequent report.

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ACKNOWLEDGMENTS

Supported in part by a David Ross Fellowship to E. A. Lipka. This report is Journal Paper 8071, Purdue University Agricultural Experiment Station, West Lafayette, IN 47907. The authors thank Professor D. Swartzendruber for stimulating this research.

Effect of Complex Formation between 4-Hexylresorcinol and Ethyl Myristate on Release Rate of 4-Hexylresorcinol from Petrolatum Base

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Received April 7, 1980, from the College of Pharmacy, University of Kentucky, Lexington, KY 40506.

Accepted for publication February 5, 1981.

Abstract □ The effect of ethyl myristate on the release rate of 4-hexylresorcinol from petrolatum base was studied at pH 7.4 and 37°. 4-Hexylresorcinol was analyzed spectrophotometrically at 278 nm. The release rate of hexylresorcinol from the ointments was directly proportional to the square root of time and depended on the percentage of ethyl myristate in the ointment base. For 0, 0.5, 1, 3, and 5% of ethyl myristate, the release rates were 29.6, 35.4, 38.3, 55.7, and 70.0 $\mu\text{g}/\text{hr}^{1/2}/\text{cm}^2$, respectively. The solubility of hexylresorcinol in the petrolatum base was determined as a function of ethyl myristate using partitioning techniques. The enhancement in hexylresorcinol solubility was rationalized on the basis of

1:1 and 1:2 complexes between hexylresorcinol and ethyl myristate. The complexation constants of these complexes were estimated to be $10 M^{-1}$ and $206.1 M^{-2}$, respectively. The diffusion coefficient of hexylresorcinol in the petrolatum base was estimated to be $1.31 \times 10^{-8} \text{ cm}^2/\text{sec}$.

Keyphrases □ Release rate—effect of ethyl myristate on release of 4-hexylresorcinol from petrolatum, quantitative analysis □ Ethyl myristate—effect on release rate of 4-hexylresorcinol from petrolatum, quantitative analysis □ 4-Hexylresorcinol—effect of ethyl myristate on release rate from petrolatum, quantitative analysis

Percutaneous absorption depends on both drug release from the vehicle and drug permeability through the skin.

Drug release depends on physicochemical factors, such as the drug's solubility and diffusion coefficient in the vehicle.