

## Potential of polyethylene oxide solution as a fugitive dust palliative

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### **ABSTRACT**

The potential of polyethylene oxide (PEO) solution as a dust palliative was investigated using Na-montmorillonite as the model dust material. PEO with a molecular weight of  $8 \times 10^6$  and at aqueous concentrations ranging from 0.5 g/L to 10 g/L was mixed with 10 g of Na-montmorillonite (surface area =  $31.82 \pm 0.22 \text{ m}^2/\text{g}$ ) and desiccated. During 890 hrs of desiccation at 25 °C and 30 % relative humidity, liquid loss of about 0.44 kg/kg was recorded for 10 g/L PEO and 0.48 kg/kg for distilled water, respectively. Of the various concentrations, the lowest desiccation rate (0.0056 g/h) was obtained for a concentration of 2 g/L while distilled water showed a value of 0.0072 g/h. Generally, higher aqueous concentrations of PEO produced lower liquid losses from admixed clay than lower concentrations. It is postulated that higher concentrations of PEO increases the density of

PEO molecules in the pore spaces of Na-montmorillonite thereby producing a mesh that retards liquid movement to the evaporation surface.

## **INTRODUCTION**

Fugitive dusts can be generated by vehicular action on unpaved roads, wind action on exposed agricultural land and construction sites and mining operations. Soil-derived anthropodust can cause health problems such as asthma, and some forms of cancer, especially if such dusts are laden with contaminants. Peters et al. (2001) reported that human exposure to fine particles such as PM-2.5 could be the cause to frequent hospital admission and visits to the emergency room for heart and lung disease treatment.

Polymers have utility in soil stabilization against dusting due to its ability to bind fine particles together into sizes that may be too heavy to be airborne. The effectiveness of a polymer liquid or aqueous polymer solution on soil particles may be variable depending on soil mineralogy, polymer characteristics, and physico-chemical conditions. Greenland (1963) has studied polyvinyl alcohol stabilized soil aggregates. Helalia and Letey (1988) have cationic guar solution of 5 mg/L was effective in promoting flocculation of soil. Wallace and Wallace (1986) have investigated that polyacrylamide (PAM) can used for soil aggregation. It was mentioned that 0.0002% of clay amended with PAM in the soil could give stability to soil. Alince and Van de Ven (1997) have reported that when PEO was introduced into a mixture of fiber and clay, polymer bridging took place. Due to the PEO chain is generally considered as the hydrophilic, it shows water-soluble characteristic and operates as hydrogen bond acceptor in addition to PEO as known to be a good flocculant for clays (Rubio and Kitchener, 1976). It was

mentioned that flocculation is improved in the presence of 0.02M NaCl, which reduces the long-range double layer repulsion between silica particles upto 22 Å of double layer thickness to allow PEO molecules to bridge. Pelton et al. (1980) demonstrated that PEO with a molecular weight  $5 \times 10^6$  could be a good flocculant and enhance the critical solution temperature with clay. PEO molecules are adsorbed between surface and pore of clay matrix (Schamp and Huylebroeck, 1973). It can be explained that when polymer molecules gain unrestricted access to all the surfaces of Na-montmorillonite as well as interlayer. The other adsorption is occurred when the association of several unit layers into a crystal and the rearrangement of the crystals make a porous clay matrix.

However, the desiccation of soil amended with polymer under controlled environmental conditions has not been studied in detail. Understanding the desiccation with polymer solutions at the fundamental level enables the prediction of dust control potential when specific polymers are used. Dust suppressants must have criteria those are cost-effective, water soluble, non-toxic and biodegradable. The use of polymer solutions in soil stabilization requires studies not only the extend knowledge of fundamental physico-chemical interactions between polymer molecules and clay to the textural response of clay minerals to such interactions, but also polymer solution concentration ranges that have practical significance in the field need to be studied. The effectiveness of PEO solutions as a fugitive dust palliative will be explained with experimental data of desiccation in this paper. A key parameter is the desiccation rate of PEO solution of various known concentrations, from soil minerals.

The cumulative liquid loss from desiccating clay can be determined as follows:

$$W_c = \frac{W_i - W_t}{W_i - W_s} \times 100 \quad (1)$$

Where  $W_c$  is cumulative liquid loss (%);  $W_i$  is weight of the initial wet solid (clay + liquid) (kg);  $W_t$  is weight of the wet solid at time  $t$  (kg); and  $W_s$  is weight of dry solid (kg). The equilibrium liquid content and rate of desiccation are obtained as follows.

$$L_t = \frac{W_t - W_s}{W_s} \quad (2)$$

$$L_f = L_t - L_e \quad (3)$$

Where  $W_t$  is total weight (kg);  $W_s$  is solid weight (kg);  $L_t$  is free liquid content at each time,  $t$  (kg/kg);  $L_f$  is the liquid content at time (kg/kg);  $L_e$  is equilibrium liquid content (kg/kg);  $A$  is exposed surface area for desiccation ( $m^2$ ); and  $\Delta t$  is the corresponding time interval (h).

If the plot of the natural log of the final quantity of PEO solution versus time gives a straight line, then the desiccation follows first order kinetics. The rate constant,  $k$ , and half-life ( $t_{1/2}$ ) can be determined from the plot of the relation between the natural log of the final quantity of PEO solution versus time.

$$\ln(Q_t) = \ln(Q_0) - kt \quad (4)$$

In equation (4),  $Q_t$  is the final quantity of PEO solution (kg);  $Q_0$  is the initial quantity of PEO solution (kg);  $k$  is the rate constant (kg/h); and  $t$  is the duration of desiccation (h). From the slope of linear equation, the rate constant,  $k$ , can be obtained. The half-life, which is the time required for half of the PEO solution to evaporate from the wet soil, can be calculated from the rate constant as follows:

$$t_{1/2} = \frac{0.693}{k} \quad (5)$$

The rate of desiccation can be computed from the data of batch desiccation tests using the following equation (Greankoplis 1993):

$$R_d = \left( \frac{Q_s}{S_a} \right) \left( \frac{\Delta X}{\Delta t} \right) \quad (6)$$

In equation (6),  $R_d$  is the desiccation rate (kg H<sub>2</sub>O/m<sup>2</sup>h);  $Q_s$  is dry soil used (kg);  $S_a$  is exposed surface area (m<sup>2</sup>);  $\Delta X$  is weight loss for a  $\Delta t$  (kg); and  $\Delta t$  is the drying time interval (h).

## EXPERIMENTS

In order to control environmental conditions that affect liquid loss from wet soils, desiccation tests were performed in a chamber in which temperature and relative humidity can be controlled. Aqueous concentrations of PEO were produced at the

following concentrations: 0.5, 1, 2, 3, 4, 6, 8, 10 g/L. Free liquid loss of PEO was investigated by the measurements of viscosity and dielectric constant.

### **Materials and Polymer solution preparations**

The Na-montmorillonite was used in this research was obtained from the University of Missouri-Columbia, Missouri Clay Minerals Repository. The repository is the source of well-characterized clays that are frequently used by researchers nation-wide. The Na-montmorillonite consists of 62.9% SiO<sub>2</sub>, 19.6% Al<sub>2</sub>O<sub>3</sub>, 3.35% Fe<sub>2</sub>O<sub>3</sub>, 3.05% MgO, 1.68% CaO, 1.53% Na<sub>2</sub>O, 0.53% K<sub>2</sub>O, 0.32% FeO, 0.111% F, 0.090% TiO<sub>2</sub>, 0.05% S, 0.049% P<sub>2</sub>O<sub>5</sub>, 0.006% MnO, and the rest is loss on ignition, and cation exchange capacity (CEC) is 76.4 meq/100g. Sodium (Na<sup>+</sup>) with minor amounts of calcium (Ca<sup>2+</sup>) is the principal exchange cation. The surface area (using nitrogen adsorption method) was measured at 31.82 ± 0.22 m<sup>2</sup>/g as provided by the vendor.

Polyethylene oxide is a neutral polymer and typically exists as a clear solid powder. Its molecular structure is shown in Figure 1. It was supplied by Polysciences, Inc., Warrington.



Figure 1. The structure of polyethylene oxide

The configuration of the PEO molecule indicates that hydrogen bonding is likely the means of attachment of PEO onto clay. PEO solutions were prepared in the concentration ranges of 0.5, 1, 2, 3, 4, 6, 8, 10 g/L. Distilled water was used in all the experiments.

### **Chamber desiccation method**

Ten grams (10 g of Na-montmorillonite) was mixed with 50 mL of PEO solution and transferred to polystyrene tubes (22 mm internal diameter x 145 mm height). Then, the tube was weighed with a balance that is sensitive to  $10^{-4}$  g and left at room temperature to hydrate for one day. After 24 hrs of hydration, the samples were placed in an environmental chamber (Watlow Series 922, designed by Bryant Manufacturing Associates) that maintained constant temperature/humidity at 25 °C and 30% relative humidity. Weight measurements were then taken at various time intervals until the cumulative liquid content approached 100%. The measurements were made at one-day intervals and several times until the change in weight became less than 0.0100 g. Following this protocol, the duration of desiccation was found to be about 890 hrs for Na-montmorillonite with PEO in this research.

### **Measurements of viscosity and dielectric constant**

The viscosity of PEO solutions was measured using a rotational viscometer (Cole-Parmer, Vernon Hills, Illinois). For each test, an aliquot of 35 mL PEO solution was transferred into each polystyrene tube. The rotor was immersed in the PEO solution up to the groove marked on the rotor shaft. The value of viscosity was taken on the display panel after 1 min for stabilizing the viscometer.

Capacitance measurements were performed to determine the dielectric constants of PEO solutions. These tests were performed using a LCR Meter (Hewlett-Packard, Model 4261A) at a frequency of 1 kHz and a test signal of 1 V. A sample cell that made of parallel plates (30 mm width x 0.9 mm length x 15 mm height) was filled with PEO

solutions. Then, side of silver alloys was attached to internal surfaces of the sample cell and the other side was attached to electrodes, which connected the sample cell to the LCR meter. Before measuring the capacitance of the PEO solutions, the capacitances of air and water were measured for calibration of the measurements. The ratio of the capacitance of water to that of air was taken to be 78 at 25 °C.

## **RESULTS AND DISCUSSIONS**

### **Desiccation results**

During a desiccation duration of 890 hrs, about 99% of the initial liquid content was lost from Na-montmorillonite samples. This was observed at all aqueous concentrations of PEO. However, within this duration, there were drying rate variations for various PEO concentrations. The plot of cumulative liquid loss as a function of time is shown in Figure 2. It shows Na-montmorillonite amended with PEO solutions, lost liquid exponentially. This is a first-order reaction in which PEO liquid amount decreases exponentially within 550 hrs. The rate constant is determined from the plot of the relationship between the natural logarithm of liquid quantity and time,  $t$  (Figure 3). The lowest slope of the plot is  $-0.0056$  (g/hr) for an aqueous PEO concentration of 2 g/L and the highest slope is  $-0.0081$  (g/hr) for an aqueous PEO concentration of 8 g/L. Distilled water has a slope of  $-0.0072$  (g/hr). It is observed that the liquid is retained more and is lost slowly with 2 g/L solution than with distilled water after 550 hrs of desiccation. From the slope of the graph, the following rate constants were obtained: 0.0072 g/hr for distilled water; 0.0071 g/hr for 0.5 g/L; 0.0065 g/hr for 1 g/L; 0.0056 g/hr for 2 g/L; 0.0074 g/hr for 3 g/L; 0.0067 g/hr for 4 g/L; 0.0060 g/hr for 6 g/L; 0.0081 g/hr for 8 g/L;

and 0.0079 g/hr for 10 g/L. The rate constants and calculated half-lives of aqueous PEO desiccation from Na-montmorillonite are summarized in Table 1. The corresponding half-lives of various PEO concentrations are 96.2 hrs for distilled water; 97.6 hrs for 0.5 g/L; 106.6 hrs for 1 g/L; 123.7 hrs for 2 g/L; 93.6 hrs for 3 g/L; 103.4 hrs for 4 g/L; 115.5 hrs for 6 g/L; 85.5 hrs for 8 g/L; and 87.7 hrs for 10 g/L. These results imply that the PEO concentration of 2 g/L was retained the most by Na-montmorillonite.

### **Desiccation rate as a function of PEO free liquid from Na-montmorillonite**

Liquid loss data can be converted to the rate of Na-montmorillonite desiccation, which provides a useful basis for analysis of the effects of aqueous PEO concentration using equation (6). The steady state-period of Na-montmorillonite desiccation was observed as indicated in Figure 4. The notations a, b, and c represent the different desiccation stages (a: unsteady state-period, b: constant rate-period, c: falling rate-period). Greankoplis (1993) reported that the unsteady state adjustment period is usually quite short relative to other stages. The constant-rate period is shown in the middle of the desiccation graph. Subsequent to constant rate desiccation, the rate of desiccation falls more rapidly until the free liquid content equals zero. Bae and Inyang (2001) have identified three distinctive desiccation rate periods during the drying of aqueous polyethylenimine (PEI) solutions from Na-montmorillonite. The unsteady state-period was observed to be quite short, starting at 8 hrs after the beginning of drying and ending 26 hrs from beginning of drying. The constant rate-period began at 26 hrs and ended at 48.5 hrs.

In this research, during unsteady state adjustment period, the distilled water has the highest slope of 0.4899 (kg/m<sup>2</sup>h) and 6 g/L of PEO solution has the lowest slope (0.3045 (kg/m<sup>2</sup>h)). This implies that the concentrated PEO solution retains more free liquid than distilled water during the unsteady state adjustment period. The desiccation rates of PEO solution of various concentrations are summarized in Table 1. As shown in Figure 4, the constant-rate period starts at 128 hrs and ends at 530 hrs relative to the beginning of desiccation. Essentially, at the end of this period, the rate of liquid supply to the desiccating surface is equal to the rate of evaporation of liquids from the sample. With respect to the falling rate period shown, the amount of free liquid loss is less than that of the constant rate period. During this period, there is increased resistance to liquid flow through capillaries and voids of the clay. The liquid forms a meniscus across each pore. Unsaturated conditions develop even though the liquid is provided to the through the capillary movement. Consequently, desiccation rate decreases suddenly.

### **Free liquid loss versus viscosity and dielectric constant**

Relationship between viscosity and dielectric constant, and free liquid loss are shown in Figure 5-(a). The loss of free PEO liquid from Na-montmorillonite is less at higher aqueous concentrations than at lower concentrations.

The relationship between free liquid loss of PEO from Na-montmorillonite and dielectric constant of the liquid is shown in Figure 5-(b). As dielectric constant increases, the free liquid loss decreases. Flocculation is induced by the addition of polymer molecules to Na-montmorillonite. Such flocculation can result from electrostatic interactions between polymer molecules and clay particles or bridging of clay particles

together (Black et al. 1966; Roberts et al. 1974). The increases in the dielectric constant values of pore fluid cause the increase in diffuse double layer of clay particles. Thereby reducing the ease of flocculation, making it more difficult for liquid to move upward through soil to the evaporation surface.

## **CONCLUSIONS**

Aqueous PEO liquid at a concentration of about 2 g/L shows low liquid loss when the soil is exposed to a temperature of 25 °C and relative humidity of 30%. This is indicative of liquid retention capacity that would minimize the potential of dust release from exposed Na-montmorillonite-rich soils in the field. Although it is recognized that an actual soil, may other soil minerals and textures would be represented, these results provide a first-level indication of the reasonably good potential of low aqueous concentration of PEO as a dust palliative.

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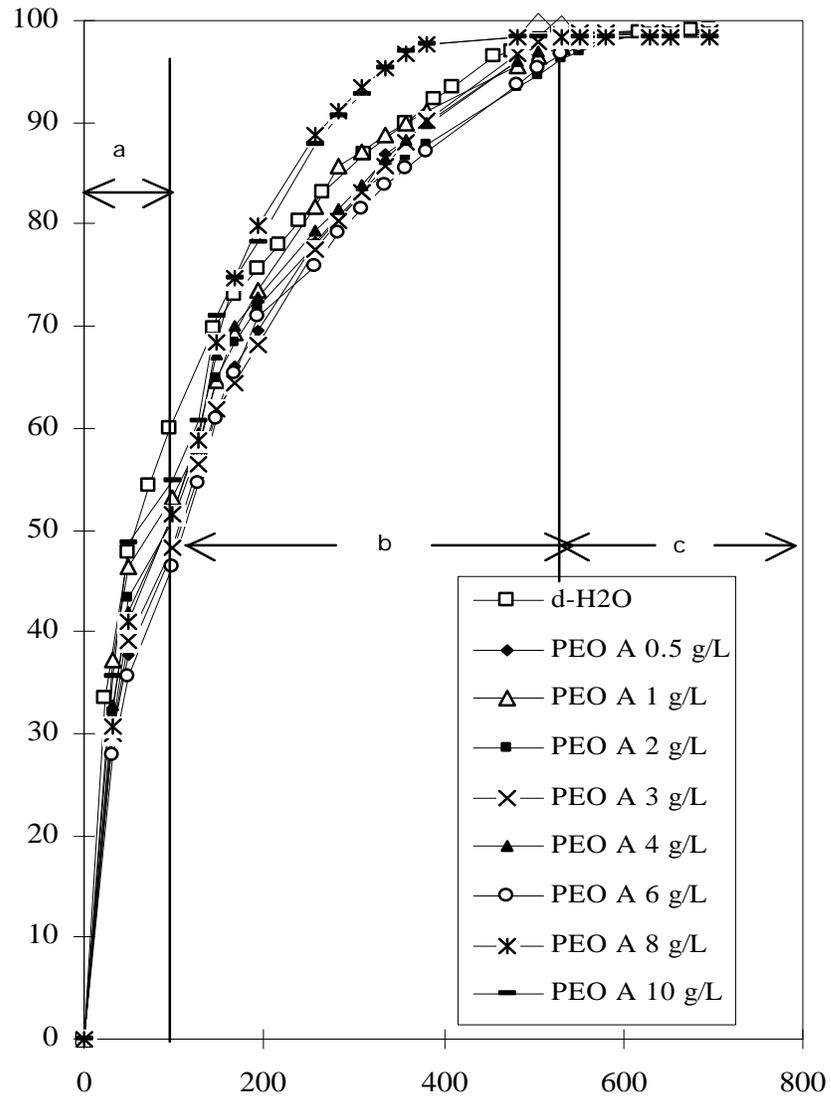


Figure 2. Desiccation profile of Na-montmorillonite with during 890 hrs duration

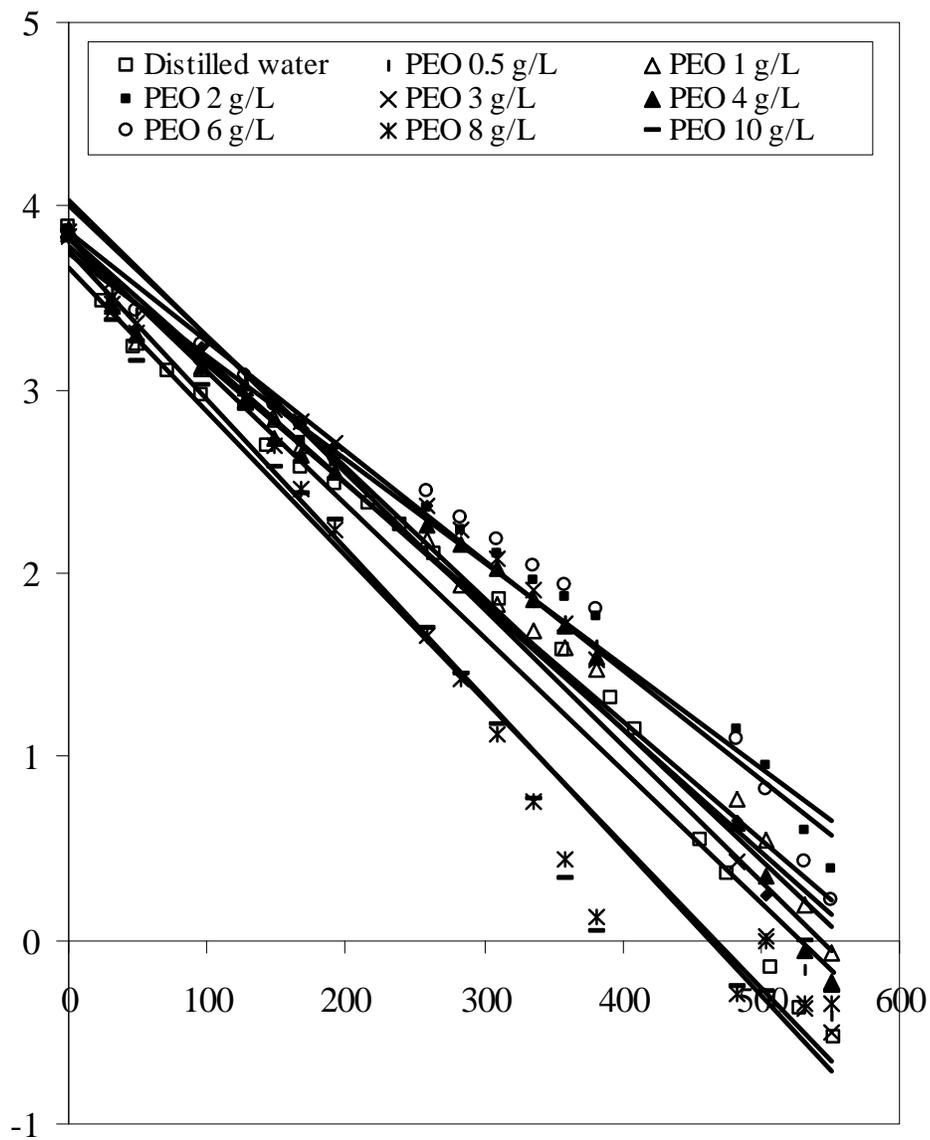


Figure 3. Desiccation of PEO on Na-montmorillonite to determine the first-order reacti

Table 1. The linear equation of cumulative liquid loss of PEO on Na-montmorillonite against time, rate constant, and half-lives obtained from the linear equation

Concentration of polymer solutions (g/L)	Linear equation	Rate constant (g/s)	Half-life (hr)	Desiccation rate / free liquid of PEO during unsteady state period
Distilled water	$y = -0.0072 x + 3.8224$	0.0072	96.2	0.4899
0.5	$y = -0.0071 x + 4.0097$	0.0071	97.6	0.3484
1	$y = -0.0065 x + 3.7779$	0.0065	106.6	0.4853
2	$y = -0.0056 x + 3.7390$	0.0056	123.7	0.3808
3	$y = -0.0074 x + 4.0289$	0.0074	93.6	0.3388
4	$y = -0.0067 x + 3.8404$	0.0067	103.4	0.3641
6	$y = -0.0060 x + 3.8567$	0.0060	115.5	0.3045
8	$y = -0.0081 x + 3.7588$	0.0081	85.5	0.3358
10	$y = -0.0079 x + 3.6664$	0.0079	87.7	0.4261

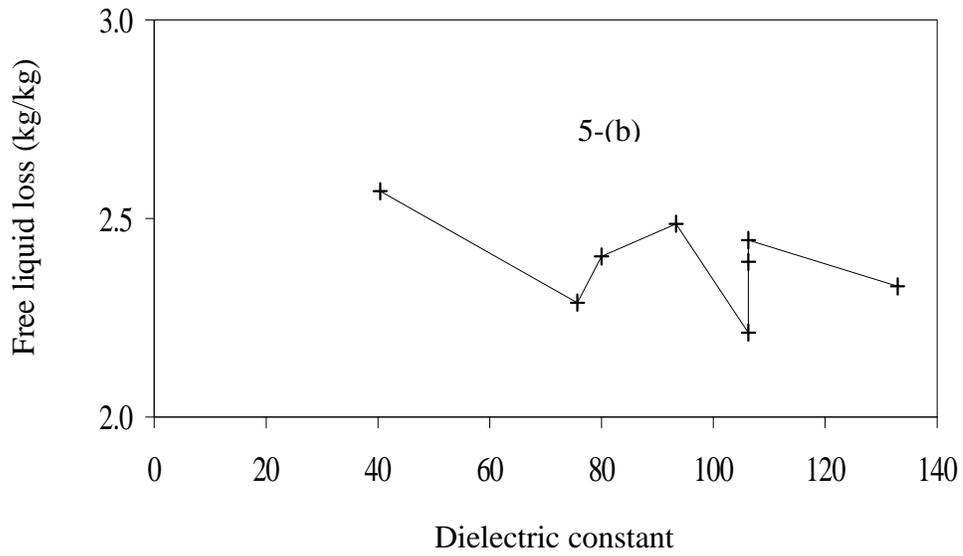
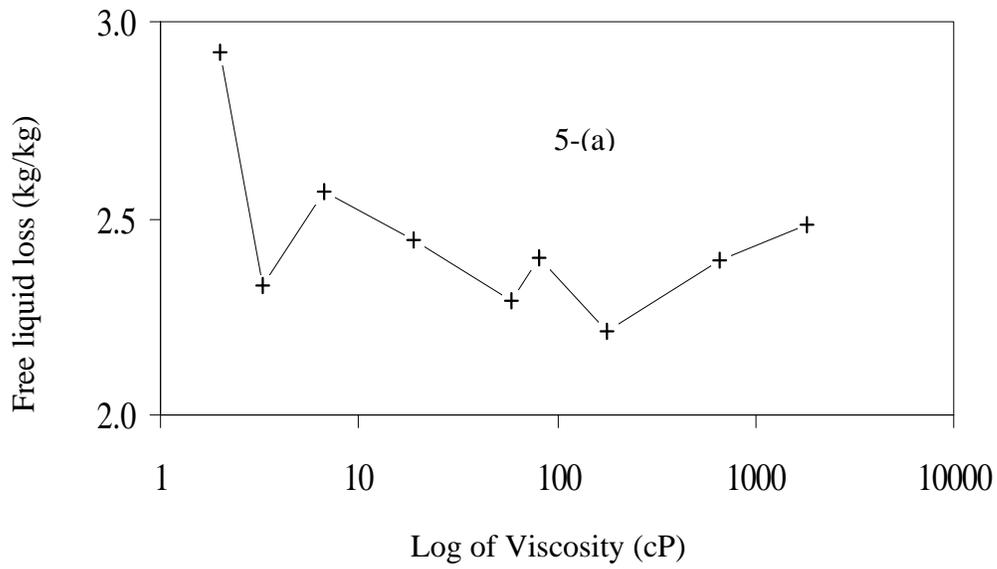


Figure 5. Free liquid loss of polyethylene oxide solutions on Na-montmorillonite versus viscosity and dielectric constant

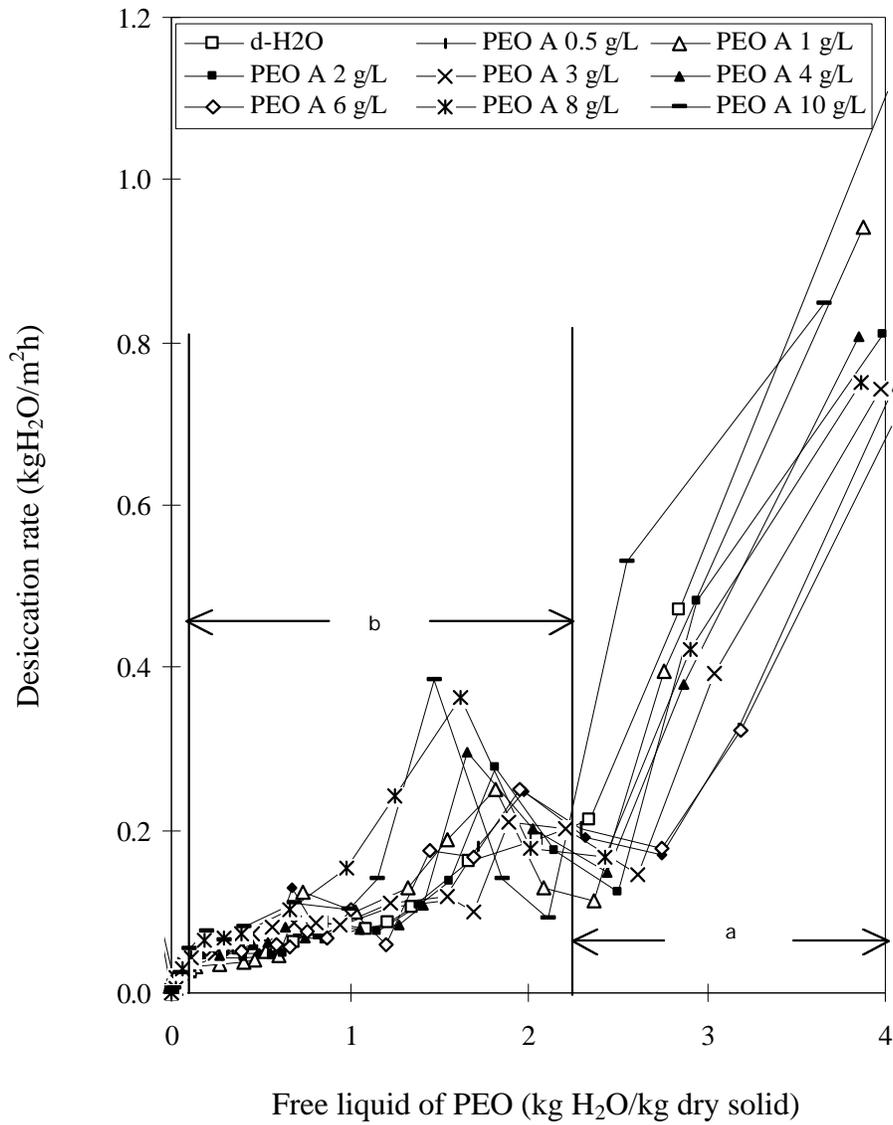


Figure 4. Desiccation rate versus free liquid loss of polyethylene oxide on Na-montmorillonite