Colloids and Surfaces A: Physicochem. Eng. Aspects 440 (2014) 116–121

Contents lists available at ScienceDirect

Colloids and Surfaces A: Physicochemical and Engineering Aspects

journal homepage: www.elsevier.com/locate/colsurfa

Constant-current electroosmotic dewatering of superabsorbent hydrogel

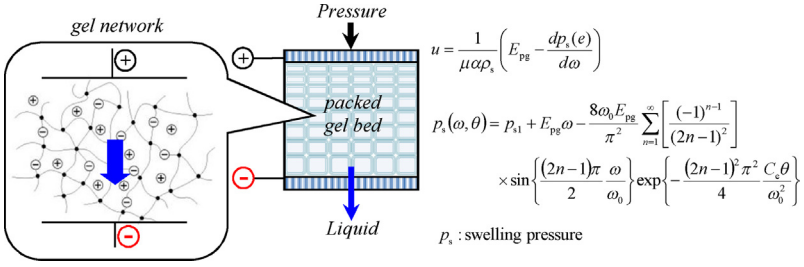
Takanori Tanaka[a], Kenji Fujihara[a], Mohammed Saedi Jami[b], Masashi Iwata[a,*]

[a] Department of Chemical Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai-shi, Osaka 599-8531, Japan
[b] Department of Biotechnology Engineering, Faculty of Engineering, International Islamic University Malaysia, Kuala Lumpur, Malaysia

HIGHLIGHTS

- The progress of EOD of hydrogel is expressed by the average consolidation ratio.
- The apparent liquid velocity can be represented by swelling pressure gradients.
- The mechanical properties of gel can be represented by the Terzaghi–Voigt model.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 June 2012
Received in revised form 4 October 2012
Accepted 8 October 2012
Available online 16 October 2012

Keywords:
Electroosmotic dewatering
Effective osmotic pressure gradient
Swelling pressure gradient
Superabsorbent gel

ABSTRACT

The electroosmotic dewatering (EOD) behaviors of gelatinous materials, such as superabsorbent hydrogels or swelling clay, are discussed. The apparent liquid velocity through the materials can be represented in terms of effective-osmotic, electroosmotic and swelling pressure gradients. Taking the creep deformation of the materials into consideration and assuming that the mechanical properties of the materials can be represented by the Terzaghi–Voigt combined model, the basic differential equation expressing EOD of gelatinous materials is solved. The progress of EOD is represented by an average consolidation ratio U_c as in mechanical expression. The agreement between calculated and experimental U_c is satisfactory when the creep deformation of the material is considered. The disagreement between theory and experiment in the latter part of EOD may be due to the change of the property of hydrogel caused by dissolution of Fe(III) from stainless steel electrode.

1. Introduction

Electroosmosis is the motion of liquid induced by an applied electric field across a porous material, capillary tube, membrane, microchannel, or any other flow channel. Electroosmosis has been used for sludge dewatering since the early 1900s [1,2] and this engineering technique was named "electroosmotic dewatering (EOD)". EOD is especially effective in removing liquid from sludge of colloidal particles for which conventional mechanical dewatering is not very successful. That is, such sludge is usually highly compressible, and mechanical dewatering is impeded due to a very high hydrodynamic resistance of the sludge. On the other hand, the high surface charge density of colloidal particles leads to a high electroosmotic flow rate under an applied electric field.

In our previous papers [3,4], the basic differential equation that describes the progress of an EOD of solid/liquid mixture was presented, considering the creep deformation of the mixture. EOD is used for reducing moisture content of gelatinous materials, such as sewage sludge or swelling clay. Since gelatinous materials show osmotic swelling behavior, an understanding of EOD process of such materials is essential for the process improvement. In this study, we extend our theory for expressing EOD of superabsorbent hydrogel as a model substance of gelatinous materials.

A superabsorbent hydrogel is a macromolecular polymer network immersed in water. Some superabsorbent hydrogels swell to

* Corresponding author. Tel.: +81 72 254 9302; fax: +81 72 254 9306.
E-mail address: iwata@chemeng.osakafu-u.ac.jp (M. Iwata).

0927-7757/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.colsurfa.2012.10.020

several hundred times their original volume. Various works have been reported concerning the swelling behaviors of hydrogels. Tanaka and Fillmore [5] developed a theoretical analysis of kinetics of gel swelling, which is driven by an osmotic pressure change. Iwata et al. investigated the compression and expansion processes of cross-linked sodium polyacrylate hydrogels under mechanical pressure [6] and have also reported on the analysis of dewatering process under centrifugal field [7]. Likewise, many research results regarding the response of gel properties to changes such as mechanical pressure [8–11], temperature, solvent composition and electric field [12–16] have appeared in the literature.

The progress of EOD of superabsorbent hydrogel is expressed by the average consolidation ratio as in mechanical expression. In the following sections, first the experimental procedure is explained. Then a theory is developed which explains the swelling pressure distribution in packed gel bed as a function of time and position. Finally, a comparison is made between experimental observations and theoretical predictions.

2. Experimental

The experimental apparatus consists essentially of a piston and a cylinder (inner diameter: 0.1 m), both made of acrylic resin (Fig. 1). Cross-linked sodium polyacrylate (Dia Wet A3, Mitsubishi Chemical Corp.) was used as an experimental material. The dry gel particles were mixed with deionized water. The resulting hydrogels have spherical shape. After the hydrogel volume reaches a stable value, the gels were sieved. Gel particles with diameter of 1.7–2.0 mm were employed in the experiment. In each test, 64 g of the superabsorbent hydrogel was poured into the cylinder. The gel was pre-consolidated in the apparatus under a pressure p_{s1} of 16.5–91.4 kPa. Then, D.C. voltage was applied between the electrodes, both made of stainless steel. A stainless steel wire-mesh was used as a sacrificial electrode. The electric current density i was held constant for each experimental run (1.0–10.0 A/m^2). The preconsolidation pressure p_{s1} was maintained in the apparatus during the electroosmotic dewatering test to ensure that the material was in good contact with the electrodes. The change in thickness of the material with time θ was measured by a dial gauge fitted on the cylinder. The elemental contents in the removed liquid from the gel particles were detected using ICP-AES (Seiko SPS 7800).

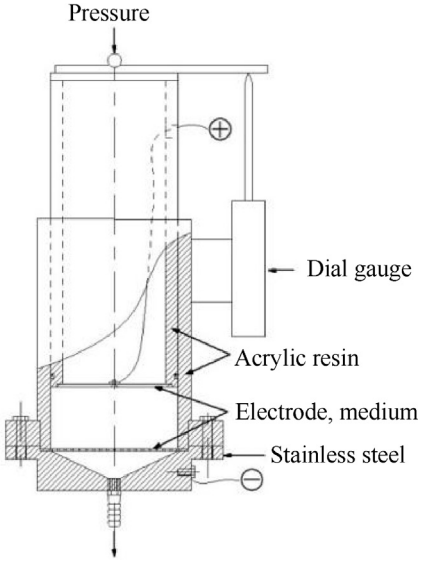


Fig. 1. Schematic diagram of experimental apparatus.

3. Theory

3.1. Electroosmotic flow through a capillary and porous media

The electroosmotic flow induced in a capillary tube has been modeled in a variety of ways. Kobayashi et al. [17] solved the Navier–Stokes equation, taking into account the applied electric field strength E_o and the electric field strength in the double layer E_i caused by the contact potential difference ψ. Eq. (1) is the solution of the Navier–Stokes equation combined with the Gauss theorem for electric flux density.

$$v_{z\cdot av} = \frac{D\zeta E_{oz}}{\mu} f - \frac{(R-\delta)^2}{8\mu}\frac{dp_L}{dz} \tag{1}$$

where

$$f = \frac{2}{\kappa(R-\delta)}\frac{I_1\{\kappa(R-\delta)\}}{I_0\{\kappa(R-\delta)\}} - 1 \tag{2}$$

Here $v_{z\cdot av}$ is the average velocity; D, the dielectric constant of liquid; ζ, the zeta-potential; E_{oz}, the electric field strength along the z-axis of the capillary; μ, the viscosity of liquid; R, the capillary radius; δ, the thickness of slip plane; p_L, the liquid pressure; and f, a factor denoted by Eq. (2). κ in Eq. (2) is the Debye–Hückel parameter; I_1 and I_0, the modified Bessel functions of the first kind of order one and zero, respectively. Rice and Whitehead [18] obtained similar equations with Eqs. (1) and (2), neglecting the thickness of slip plane δ.

Eq. (1) can be extended to describe electroosmotic flow through porous media in much the same way as the derivation of the Kozeny–Carman equation. The apparent liquid velocity u through the porous media is represented by Eq. (3). This is a kind of Darcy's equation under an electric field.

$$u = \frac{1}{\mu\alpha\rho_s}\left(E_{pg} + \frac{dp_L}{d\omega}\right) \tag{3}$$

where

$$E_{pg} = \frac{f_S\varepsilon\alpha\rho_s D\zeta f}{\tau} i\rho_E \tag{4}$$

Here α is the specific hydrodynamic resistance; and ρ_s, the true density of solid. ω is the moving material coordinate and denotes the net solid volume per unit cross-sectional area extending from the drainage surface up to an arbitrary position in the material. E_{pg} is the driving force of flow due to the electric field denoted by Eq. (4), where f_S is the shape factor of the flow path; ε, the porosity; τ, the tortuosity of the flow path; i, the electric current density; and ρ_E, the specific electric resistance of the porous media. Here, we refer to E_{pg} as an electroosmotic pressure gradient. In our theory, it is assumed that the thickness of slip plane δ is zero. Eq. (3) can be represented as follow:

$$\mu\alpha\rho_s u d\omega = E_{pg} d\omega + dp_L \tag{5}$$

This equation implies that the viscous dissipation energy is offset by electric and pressure energies.

When the flow path is so narrow that the liquid is considered as homogeneously charged (Fig. 2a), then E_{pg} can be represented by Eq. (6)

$$E_{pg} = \frac{\sigma_s}{\varepsilon} i\rho_E \tag{6}$$

where σ_s is the surface charge density per unit volume of solid.

On the other hand, if the double layer thickness is neglected ($1/\kappa = 0$, Fig. 2b), $f = 1$ in Eq. (2). Therefore, E_{pg} is represented by Eq. (7).

$$E_{pg} = \frac{f_S\varepsilon\alpha\rho_s D\zeta}{\tau} i\rho_E \tag{7}$$