Separation and Purification Technology 92 (2012) 168–173

Contents lists available at ScienceDirect

Separation and Purification Technology

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

Evaluation of low-pressure compressibility and permeability of bentonite sediment from centrifugal consolidation data

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A R T I C L E I N F O

Article history:
Available online 23 May 2011

Keywords:
Bentonite
Drilling mud
Analytical centrifugation
Consolidation
Compressibility
Specific cake resistance

A B S T R A C T

This paper discusses application of centrifugal consolidation technique for evaluation of the low-pressure compression–permeability characteristics of mineral sludge. The evaluation is based on analysis of consolidation kinetics and ultimate compression of the sediment measured at various centrifugal accelerations. Dependencies of the volume fraction of particles φ, specific cake resistance α and compressibility coefficient C of the sludge versus solid compressive pressure p_s were estimated and compared with those obtained from dead-end filtration experiments.

1. Introduction

Solid–liquid separation (filtration, sedimentation, or centrifugation) is accompanied by consolidation of particulate layer caused by solid compressive pressure p_s. The value of p_s varies with time and along the height of the compressed layer and affects the local values of particle volume faction φ and specific cake resistance α. Knowledge of local p_s, φ and α values and determination of functional dependencies $\varphi = \varphi(p_s)$ and $\alpha = \alpha(p_s)$ are essential for prediction of solid–liquid separations. These dependencies are frequently presented in the form of power law functions called constitutive equations [1,2].

$$\varphi = \varphi_o p_s^{\beta} \quad (1)$$

$$\alpha = \alpha_o p_s^{n} \quad (2)$$

where φ_o, α_o, β, and n are empirical constants.

Another important characteristic determining consolidation of particulate layer is consolidation coefficient C, which can be represented as [3,4]

$$C = G/(\alpha\mu\rho_s) \quad (3)$$

where $G = -\partial p_s/\partial e$ is the compressibility modulus and $e = (1-\varphi)/\varphi$ is the void ratio, μ is the viscosity of liquid, p_s is the density of solids.

A number of experimental methods were proposed for characterization of compressibility and determination of parameters of the constitutive equations. They are based on different techniques available for measurements of compression or permeability of suspensions: constant pressure filtration [5,6], compression–permeability (CP) experiments [7,8], gravity settling [4,9], and centrifugal consolidation [10,11]. Different experimental set-ups, such as pressure sensors, NMR, gamma and X-ray devices, were proposed for direct measurement of the local values of solid pressure and concentration of solids during consolidation [5,8].

Low-pressure compressibility of a concentrated suspension may be estimated from the centrifugal consolidation experiments. Centrifugation can be advantageous for measurements of compression as compared to other techniques: several samples may be studied simultaneously and centrifugal acceleration may be varied in the wide range corresponding to different compressive pressures. Murase et al. [10] have proposed a procedure for estimation of parameters of the constitutive Eq. (1) based on compression experiments with different centrifugal accelerations.

Recently, a new tool was developed for centrifugal sedimentation. It is so-called, analytical photocentrifuge [12,13]. It was applied for estimation of colloidal stability of mineral suspensions [12,13], characterization of sludge dewatering [14] and consolidation, packing and compression behavior of suspensions [15]. With this device sedimentation or consolidation of concentrated suspensions and sediments may be studied at various centrifugal rotation speeds corresponding to the low and moderate pressure range (from ≈200 Pa to ≈200 kPa). The height of sediments may be registered continuously during the centrifugation and twelve samples may be studied at the same time [12,13].

The analytical photocentrifuge was recently used for estimation of the specific cake resistance α on the basis of sediment consolidation experiments [16]. Curvers et al. [11] have proposed procedure

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1383-5866/$ - see front matter
doi:10.1016/j.seppur.2011.05.019

Notation

A	membrane surface area, m^2
C	consolidation coefficient, m^2/s
C_{av}	average modified consolidation coefficient, m^2/s
C_o	parameter of Eq. (17), m^2/s
d	diameter of particles, μm
e	void ratio, dimensionless
f	volume weighted distribution function
G	compressibility modulus, Pa
g	gravitational acceleration, 9.81 m/s^2
H	height of sediment in a centrifugal cell, m
H_o	height of sediment in a centrifugal cell before consolidation, m
H_∞	equilibrium height of sediment in a centrifugal cell after consolidation, m
k	local permeability of sediment, m^2
k_o	Kozeny's constant, dimensionless
L	filter cake thickness, m
n	parameter in Eq. (2), dimensionless
p_a	parameter of Eq. (18), Pa
p_s	local solid compressive pressure, Pa
$p_{s,max}$	maximal local solid compressive pressure corresponding to the bottom of sediment, Pa
$p_{s,av}$	average solid compressive pressure, Pa
Δp	filtration pressure, Pa
R	radial distance from the center of rotation to bottom of centrifugal cell, m
R_m	resistance of filtration membrane, m^{-1}
r_o	radial distance from the center of rotation to the surface of sediment, m
r	radial position, m
S	specific surface area of particles, m^2/g
t	time, s
T	light transmission, %
U	consolidation ratio, dimensionless
V	filtrate volume, m^3
w_c	weight fraction of solids in the filter cake, dimensionless
w_s	weight fraction of solids in the slurry, dimensionless
x	coordinate, m

Greek letters

α	specific cake resistance, m/kg
α_{av}	average specific cake resistance, m/kg
α_o	empiric constant in Eq. (2)
β	parameter of constitutive Eq. (1), dimensionless
γ	parameter of Eq. (17), dimensionless
δ	parameter of Eq. (18), dimensionless
μ	viscosity of liquid, Pa·s
ρ_l	density of liquid, kg/m^3
ρ_s	density of particles, kg/m^3
φ	volume fraction of particles, dimensionless
φ_o	parameter of Eq. (1)
Ω	angular rotational speed, rad/s
ω	height of solids measured from the bottom of the sediment, m
ω_o	total height of solids in the sediment, m

Abbreviations

CP	compression–permeability

for estimation of parameters of the constitutive Eq. (1) using the analytical photocentrifuge.

This work is devoted to application of analytical centrifugation for estimation of compressibility properties (volume fraction of particles, specific cake resistance and coefficient of compressibility). The estimation is based on analysis of two dependencies: ultimate height of the compressed sediment versus centrifugal acceleration and centrifugal consolidation kinetics versus centrifugal rotation speed.

2. Materials and methods

2.1. Bentonite sludge

Mineral sludge (provided by Horizontal Drilling International, France) was a thick non-settling aqueous suspension of sodium bentonite with solid content of 36.0 wt%. The suspension was conditioned by chemical additives (dispersants, lubricants and viscosifiers) for its use as a drilling mud. The density of bentonite particles ρ_s was equal to 2220 kg/m^3.

The particle size distribution function and specific surface area S of particles in the slurry were estimated from centrifugal sedimentation curves. They were measured using an analytical photocentrifuge LUMiSizer 610.0–135 (L.U.M. Gmbh, Germany) and analyzed using original SEPView 5.1 software for granulometric analysis. The analysis assumed that all the particles are spherical. The measurements required considerable dilution of the slurry (down to 10^{-4} wt%). The obtained volume-weighted distribution function f versus particle diameter (i.e., equivalent spherical diameter) d is presented in Fig. 1. Both individual particles (d < 0.5 m) and their aggregates (d 1.0 m) were present in the slurry. The mean diameter and specific surface area of particles estimated with the help of SEPView 5.1 software were of 0.35 ± 0.07 μm and 6.8 ± 1.3 m^2/g, respectively.

2.2. Centrifugal consolidation experiments

The samples of slurry weighting 2.02 g with initial volume fraction of particles φ = 0.204 were subjected to consolidation in an analytical photocentrifuge LUMiSizer 610.0–135 (L.U.M. Gmbh,

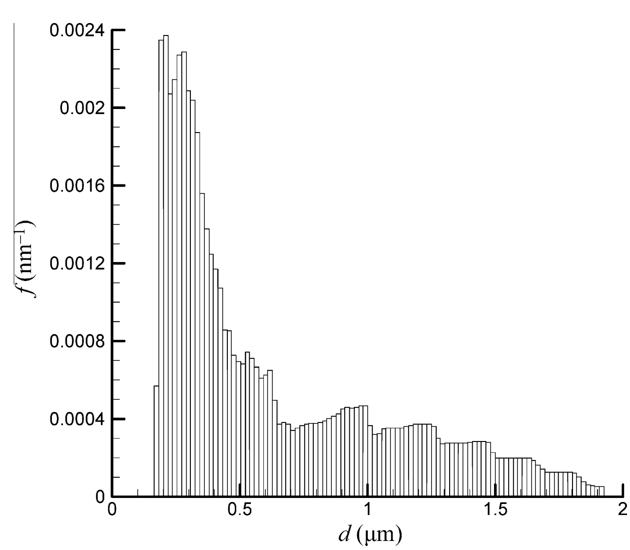

Fig. 1. Volume-weighted particle size distribution in the sludge.