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# Cake Structure of Consolidated Biological Sludge

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# Cake Structure of Consolidated Biological Sludge

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## ABSTRACT

This work reported for the first time the cake structure of consolidated biological sludge in Compression-Permeability Cell (C-P cell) tests without the interference of sludge rebound after stress release. The filter cake equilibrated with the applied load was fixed in situ by agarose solution. Then the porosity of slices of cake was determined using image analysis tool. Both original and flocculated sludges were consolidated at a pressure of 128.3 kPa.

The cake structure is nonhomogeneous. The applied load and the action of wall-cake friction squeeze the cake toward, and yield the lowest porosity at the rim region on the septum. The flocculated sludge cake has a higher porosity than the original sludge. However, flocculation could produce a more elastic cake, which results in a completely different cake structure in C-P cell test.

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## INTRODUCTION

Ruth introduced the use of Compression-Permeability Cell (C-P Cell) tests for characterizing the cake rheological properties.[1] The validity of the C-P cell test relies on a basic assumption: the cake subject to compaction would deform in a one-dimensional manner, while the *average* porosity and *average* permeability of filter cake in C-P cell could represent their *local* counterparts in a real filter.[2] However, friction exists between the cake and the wall.[3] A cake with nonhomogeneous interior structure would lead to measurement errors in C-P cell test.[4–6] Zhao et al. presented a model to take into account the wall friction in a C-P cell test, by assuming the cake as a purely elastic body.[7] The prediction of cake structure becomes more complicated when the plastic role of filter cake has come into play.[8–12]

Despite the comprehensive framework established by theorists, some efforts had been devoted to probe the interior structure of the filter cake. These efforts include the use of embedded electrodes,[13–16] color staining,[17] or cake slicing[18,19] followed by microphotographic observation, or of radiation attenuation, such as γ-ray,[20,21] NMR,[22–24] and X-ray.[25–31] Detailed analysis of cake structure, particularly on the biological sludge cake, is still largely lacking. The occurrence is partially attributable to the fact that the sludge floc is rather weak and absorbs negligible radiation. For instance, work investigating sludge sedimentation process by CATSCAN technique was recently reported.[32–34]

Filter cake of sludge is a viscoelastic material.[32–34] Restated, the compressed cake would exhibit both elastic and plastic characteristics; with the former the cake would "rebound" after the release of the applied load.[35] Yen et al. demonstrated that the filter cake compressed in a centrifugal field might bound back by 100% in cake thickness after the cessation of centrifuge in certain tests with flocculation.[36] Measurements in situ are needed to obtain the cake behavior under stress. We adopted herein the slicing technique to observe the interior structure of a compressed biological sludge cake. For preventing the change in structure after the release of stress, the cake was fixed at consolidation. The spatial nonhomogeneity of porosity distribution in the consolidated biological sludge cake was presented for the first time.

## EXPERIMENTAL

### C-P Cell Test

The C-P cell and other supportive apparatus were reported by Wu et al.[37] The load at the top and the transmitted pressure to the bottom surface were

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measured together with the cake height during each test. The cylinder was made of acrylate, which has an inner diameter of 50.1 mm. Prior to C-P cell test the septum was first filled with filtrate. A 250-mL slurry was carefully poured into the cylinder and drained to form a saturated, wet cake. The piston was positioned at the top of the formed cake, through which the mechanical force (128.3 kPa) was applied.

## Samples and Flocculation Conditioning

Activated sludge samples (pH 6.8) were taken from the wastewater treatment plant in the Neili Bread Plant of Presidential Enterprise Co., Taoyuan, Taiwan. The tests were performed within 2 hs of sampling. The dried solid percentage of the sludge, determined by weighing and drying at 102°C, was 0.89% w/w. The true solid density was measured at 1,450 kg/m$^3$. The polyelectrolyte flocculant, polymer T-3052, obtained from Kai–Guan Inc., Taiwan, is a cationic polyacrylamide with an average molecular weight of $10^7$ g/mole and a charge density of 20%. Sample sludges were first mixed with 160 ppm polyelectrolyte using a stirrer operating at 200 rpm for 5 mins and then 50 rpm for 20 mins.

To fix the structure of the filter cake, 250-mL sludge was premixed with the same amount of high-melting-point agarose solution (melting point of 89°C and gelling point of 38°C) at 50°C. The cell was also maintained at 50°C by a thermostat. After the cake had reached mechanical equilibrium the jacket temperature was reduced to 30°C for solidifying the agarose gel. The embedded cake was removed from the C-P cell for further tests.

## Microtome Slicing

The agarose-embedded sludge cakes were sampled at nine positions over the half plane of filter cake, depicted schematically in Fig. 1. The sampled clumps were first fixed in a formalin buffer for 24 hs at 4°C. Dehydration was conducted by immersing the cake subsequently in ethanol/water solution of 50%, 70%, 90%, 95%, and 100%, respectively. The ethanol was then replaced by xylene/ethanol solutions of 50%, 70%, 90%, 95%, and 100%. The cake saturated with xylene was immersed in molten paraffin at 65°C overnight. Finally the paraffion-embedded cakes were cooled to 25°C in peel-off molds and then sliced into sections in thickness of 5 μm by microtome (Leitz Model 1400). The thin paraffin section was floated in a water bath and, afterward, transferred to a glass slide. The slide was dried in air. Then the slice was put in

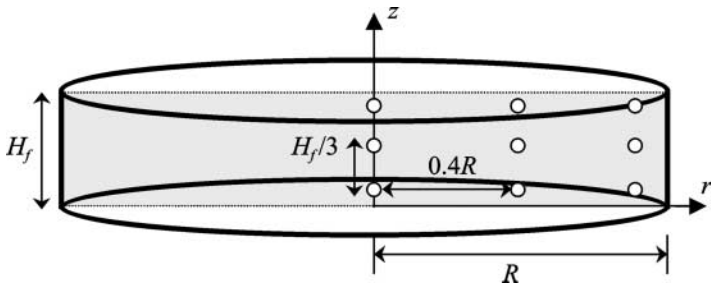


***Figure 1.*** The schematics of the sampling positions of filter cake. $H_f = 12.5\,\text{mm}, R = 25\,\text{mm}$. ○: Sampling points.

an oven at 70°C for 10 minutes to melt the paraffin and dewaxed with xylene. The final slice was stained by hematoxylin and eosin (H&E).[38]

### Image Processing

A phase-constract microscope (LEICA DME) and a digital camera (NIKON COOLPIX 995) recorded the image of slices at a constant luminescence light (Fig. 2a). The image was analyzed by *INSPECTOR* (Matrox). The images were first converted into a gray scale, from which the histogram for pixels versus luminescence intensity was constructed (Fig. 2b). A threshold intensity was chosen to divide the whole image into black (solids) and white (void) parts. The area fraction of white parts was taken as the "two-dimensional porosity." As Yang et al. suggested,[39] and discussed later by Baveye,[40] the chosen threshold value has a considerable impact on the estimated porosity data. We took the point exhibiting the highest slope on the curve of porosity vs luminescence intensity as the boundary separating the solid and liquid phase. The obtained porosity commonly exhibits a maximum relative error less than 5% for the same sample.

## RESULTS AND DISCUSSION

Figure 3 demonstrates the spatial distributions of cake porosity for original and flocculated sludges equilibrated with the applied load (128.3 kPa). Some observations were noticeable within experimental uncertainty. First, the cake has a nonhomogeneous structure at a porosity ranging from 0.445–0.495. Restated, the nonhomogeneity of cake structure is found unexceptionable in our tests. In an ideal, frictionless case the consolidated pressure over the entire

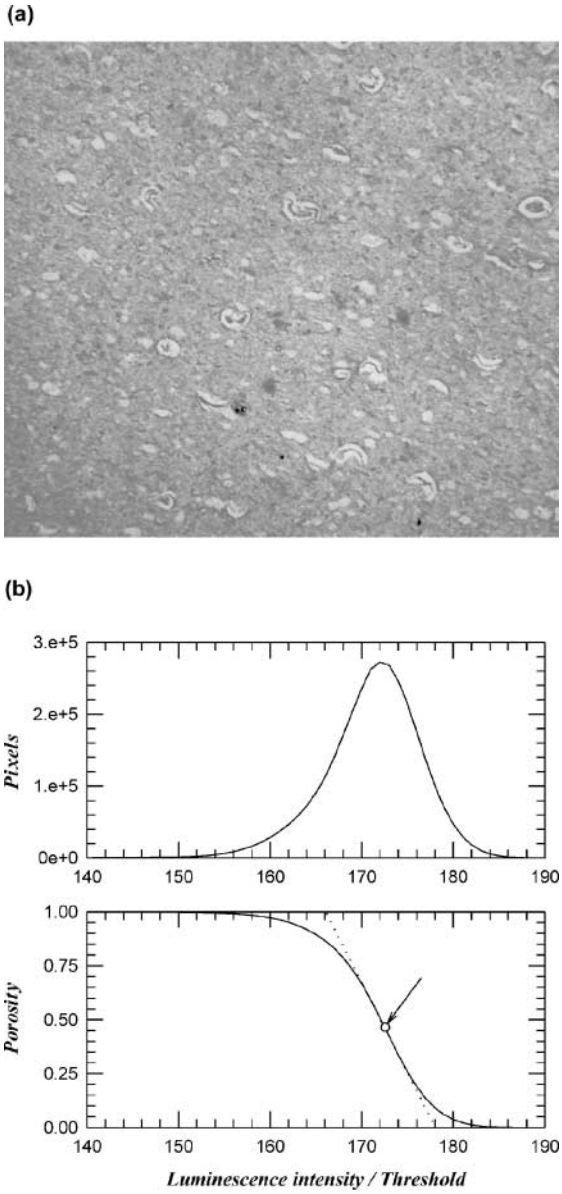


***Figure 2.*** (a) The demonstrative image of microtome slice. (b) The histogram and the porosity obtained under different threshold values. The arrow indicates the opted threshold value for the determination of 2-D porosity.

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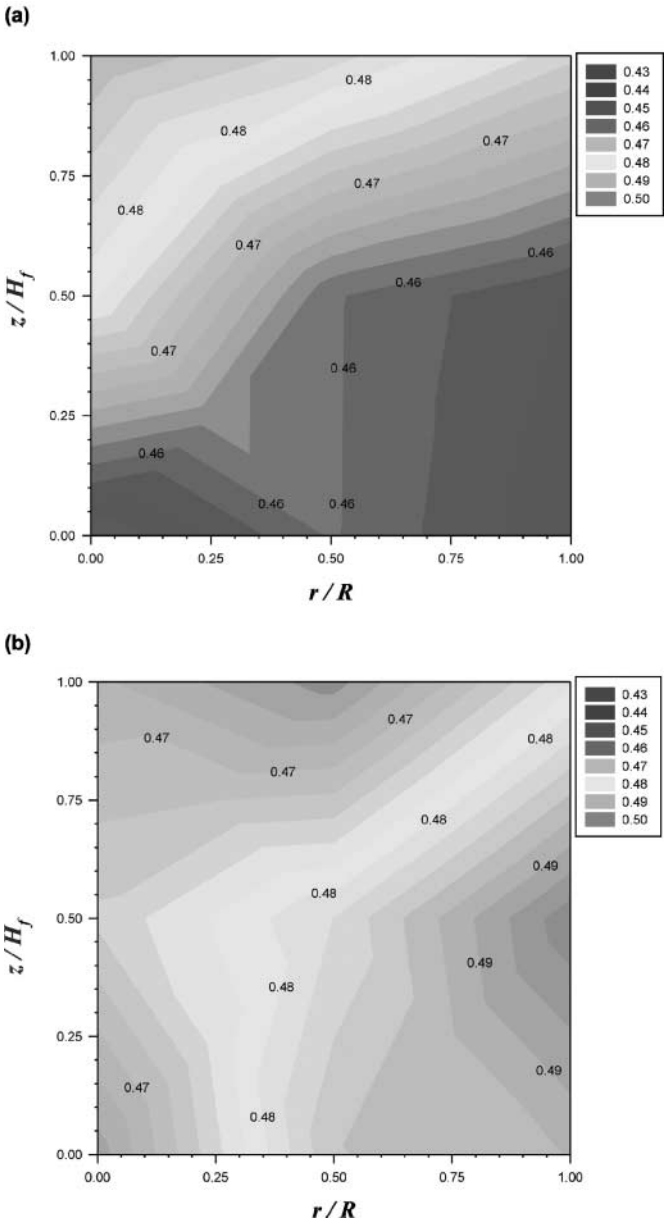


***Figure 3.*** (a) Porosity distribution for original sludge cake. (b) Porosity distribution of flocculated sludge cake.

cake should become the same at the end of consolidation. However, the presence of side-wall friction leads to an nonuniform pressure distribution, hence yielding nonhomogeneous cake structure. It is somewhat surprised to note a quite narrow porosity range (approx. 0.05) for the super-compactible filter cake like biological sludge over a pressure loss of 15–30% in the C-P cell test.[35] This observation indicated the significant role of plastic contribution during consolidation of biological sludge. The employment of purely elastic material function relating local porosity and compressive solid pressure is questionable.

Secondly, the cake structure for original sludge presents an almost symmetrical pattern along the line connecting $(z,\ r) = (H_f,\ 0)$ and $(0, R)$. Restated, the distribution of porosity skews counterclockwise in Fig. 3a, giving the loosest part at the central fraction on the upper cake surface $((z,\ r) = H_f,\ 0))$, and the tightest part in the rim region on the septum $((z,\ r) = (0,\ R))$. This occurrence should be attributable to the effect of wall friction, which retards the cake movement near cell wall and *skews* the cake mass counterclockwise in Fig. 3a.

Thirdly, the porosity distribution for flocculated sludge revealed in Fig. 3b gives a different pattern. The flocculated sludge cake exhibits a higher overall porosity than the original cake, which correlates with the commonly observed much better dewaterability for the latter than the former. However, just opposite to the original sludge test, the cake porosity for flocculated sludge *increases* rather than *decreases* when moving from cake surface along the $(H_f, 0)$–$(0, R)$ line. Restated, the cake becomes the loosest at the rim region on the septum and the tightest at the central fraction on the upper cake surface. Apparently, although the wall-friction is still effective in the flocculated sludge tests, however, the change in cake characteristics after polyelectrolyte flocculation has resisted the skewed-wise deformation as driven by the external force field. Lee demonstrated using rheological tests that the storage modulus for flocculated sludge is always greater than its loss modulus.[41] That is, the flocculated sludge samples yield near elastic solid-like behavior. This elastic contribution can resist deformation under applied load, and together with the retardation action of wall friction produces the porosity distribution depicted in Fig. 3b.

## CONCLUSIONS

This work aims to explore the cake structure of consolidated biological sludge without the interference of sludge rebound after stress release. We fixed the filter cake of a biological sludge in the Compression-Permeation Cell

(C-P cell) using agarose solution. Microtome slicing and microphotographic observation constructed the porosity distribution inside the cake. Both original and flocculated sludge (160 ppm cationic polyacrylamide of MW $10^7$ and charge density of 20%) were investigated at a consolidation pressure of 128.3 kPa.

The nonhomogeneous cake structure is found unexceptionable in our tests, ranging 0.445–0.485 for original sludge, and 0.47–0.495 for flocculated sludge cake. Because of the wall-cake friction, the original sludge exhibits a cake structure having a loosest part at the central fraction on the upper cake surface and the tightest part in the rim region on the septum. Moreover, although the flocculated sludge cake has a higher porosity than the original sludge, the former exhibits an opposite trend in porosity distribution to the latter. Restated, the flocculated sludge cake is loosest at the rim region on the septum and tightest at the central fraction on the upper cake surface. Despite the effect of wall friction, the change in cake elasticity should come into play to affect the equilibrated cake structure in C-P cell test.



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