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Note

Fragmentation of wastewater sludge floc by planar ice front

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Abstract

Floc size has substantial impact on sludge dewaterability, which might be increased or reduced after freezing and thawing. It is commonly assumed that floc size would be increased by low-speed freezing, with a planar ice front rejecting most flocs ahead of it to form large aggregates. We demonstrate in this work that an advancing planar ice front can not only engulf an activated sludge floc of size 3030 μm, but also fragment it. During floc freezing, when the ice engulfed a thin layer of floc, the latter would be pulled apart vertically by the action of the former. This particular portion of floc was then axially elongated and fixed in the frozen layer, with accumulated force pushing upward. In the present test the floc's vertical length was increased by over 92% and its width decreased by 37% over freezing. The force measurement and floc morphology tracking revealed that the force gradient that pulled apart the floc was 0.0027 N/m. The floc under investigation was fragmented at the point where the normal stress acting on the interior network exceeded 8 Pa.

Keywords: Freezing; Thawing; Floc; Interface; Force

1. Introduction

Freeze/thaw treatment is an effective sludge dewatering technique, thereby having attracted a certain attention [1–5]. The employment of the freeze/thaw treatment can significantly improve certain sludge dewatering characteristics [6], (irreversibly) change a floc structure into a more compact form [7], and reduce sludge bound water content [8]. When an ice front advances in a suspension containing particles, the ice may repel, pierce, break, or entrap the solid particles ahead [9]. Uhlmann et al. [10] proposed the first systematic analysis of the solid–solidifying front interaction, demonstrating the existence of a critical velocity (V_c) above which all particles would be trapped in the moving front, since a liquid bridge was not maintainable between the particle and the ice front by the surrounding liquid.

The dewatering efficiency for freeze/thawed sludge decreases with increasing freezing speed [11]. Parker et al. [12] noted three distinct freezing behaviors in their alum sludge freezing test: at low freezing speeds all flocs were rejected by the ice front of planar shape; at high freezing speeds all flocs were trapped and pierced by the ice front of dendrite shape; and at intermediate freezing speeds, the ice front is rough in shape and part of the flocs could be trapped by the ice. These authors claimed that the ice front could fragment the flocs at intermediate and high freezing speeds. Chu et al. [13] and Martel [14] noted that the presence of dissolved NaCl could facilitate dendrite formation, hence deteriorating the efficiency of freeze/thaw treatment of sludge. Vesilind and Martel [2] hypothesized that the floc would increase in size at low freezing speeds because of floc–floc contact at the freezing ice front, which is of planar shape. Parker et al. [12] claimed that the floc would decrease in size since the dendrite formed at high freezing speeds could pierce and fragment the floc. At intermediate freezing speeds, a "rough" ice front was noted to engulf and fragment part of the sludge flocs. Hence, if one noted increased floc size after freezing and thawing, the freezing speed should be "low" to produce a planar ice front. If the floc size were reduced, in contrast,

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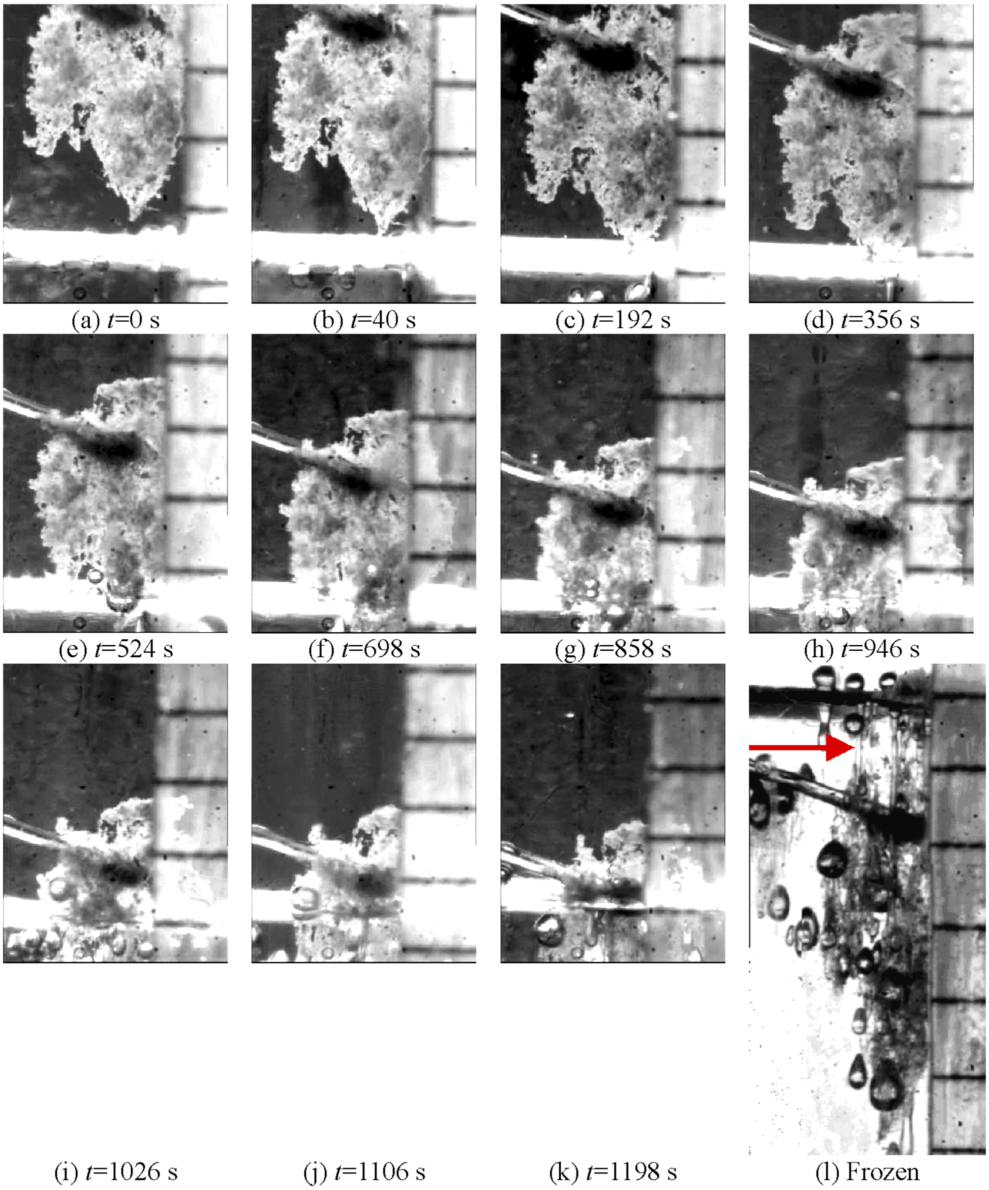

Fig. 1. Unidirectional freezing test at 4.4 µm/s. Arrow in (h) denotes the position where the floc has been torn apart.

the freezing speed should be "high" for dendrite formation. Hung et al. [7] estimated the floc size of activated sludge after freezing and found compact and larger aggregates and loose and small particles. Martel [14] noted that his alum sludge flocs were mostly contained in ice as inclusion bodies rather than at the ice boundary, hence yielding no significant floc fragmentation. However, highly turbid supernatant is frequently noted for freeze/thaw activated sludge, indicating the formation of small particles from the compactly agglomerated aggregates.

As mentioned above, the planar ice front is commonly assumed to reject the flocs for interfacial agglomeration or to include them without floc fragmentation. Floc size always increases with a planar ice front. However, we demonstrated in this work that a planar ice front could not only engulf but also fragment the floc. Tao et al. [15] measured the force exerted on a polystyrene (PS) sphere under constant-speed freezing. We utilized the apparatus of Tao et al. to measure the force exerted by an ice front on a floc, and quantitatively interpreted the full-apart action by ice on the floc.

2. Experimental

The experimental setup used here resembled that adopted in [15], with temperature gradient built along the vertical direction. The testing chamber, made of optical glass of size 150 (L) × 50 (W) × 5 mm (T), was immersed into the freezing pool (HAAKE C35) of −30 °C with ice growing upward at constant speed (4.4 µn/s in this test).

The flocculated activated sludge flocs were collected at the recycled stream of the wastewater treatment plant of