A SIMPLE METHOD FOR SMALL SCALE WASTEWATER TREATMENT PLANTS FOR THE THICKENING OF SLUDGES: MESH FILTER AND FOAM FILTER

by

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A SIMPLE METHOD FOR SMALL SCALE WASTEWATER TREATMENT PLANTS FOR THE THICKENING OF SLUDGES: MESH FILTER AND FOAM FILTER

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Dedicated to my family……..

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ABSTRACT

The ultimate disposal of wastewater sludge (biosolids) continues to be one of the most difficult and expensive problems in the field of wastewater engineering. Wastewater treatment plants generate different sludges, like primary settled sludge, waste activated sludge, chemical sludge and anaerobic sludge, according to their operating systems. These excess sludges have to be managed by reducing their volume and stabilizing them before their ultimate disposal. Generally used volume reduction methods are thickening and dewatering that are usually coupled with conditioning.

Sludge thickening and dewatering require either a big capital investment or a big surface area. Moreover, most of the mechanical dewatering technologies use polymers to condition the sludge before dewatering. These polymers have high cost rendering the mechanical dewatering uneconomical.

Small-scale wastewater treatment facilities play an important role in the aquatic environment in many countries. Although sludge treatment is essential for overall wastewater treatment, it is difficult and non-economical for small-scale treatment plants to use mechanical equipments. Considering these points, there is therefore a need for alternative technologies for high performance and easy to operate small-scale wastewater treatment facilities.

In this study, mesh filter and foam filter are used as a liquid-solid separator instead of the conventional equipments like gravity sludge thickener, dissolved air flotation or centrifuge. By this way, it is possible to reduce the water content of the sludge as mechanical devices and make thickening process economical.

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ÖZET

Atık sulardan kaynaklanan çamurların uzaklaştırılması atıksu mühendisliği sahasının en zor ve en pahalı problemi olmaya devam etmektedir. Atıksu arıtma tesisleri, kullanılan sisteme göre ön çöktürme çamuru, aktif çamur, kimyasal çamur veya anaerobik çamur gibi farklı çamurlar üretmektedir. Bu artık çamurlar, uzaklaştırılmadan önce hacimlerinin azaltılması ve stabilize hale getirilmesi gibi işlemlere tabi tutulmak zorundadırlar. Bunun için genellikle kullanılan yöntemler koşullandırmayla birleştirilmiş yoğunlaştırma ve susuzlaştırmadır.

Çamur yoğunlaştırma ve susuzlaştırma ya büyük bir ilk yatırım ya da büyük bir yüzey alan gerektirmektedir. Bundan başka, mekanik ekipmanlar susuzlaştırma işleminden önce polimer takviyesine ihtiyaç duymaktadırlar. Bu polimerler masrafı mekanik yoğunlaştırma ve susuzlaştırmayı ekonomik olmaktan uzaklaştırmaktadır.

Küçük ölçekli arıtma tesisleri bir çok ülkede akuatik ortamın korunmasında büyük bir rol oynamaktadır. Genel olarak çamur arıtımı, atıksu arıtımının bir parçası olmasına rağmen küçük ölçekli atıksu arıtma tesisleri için mekanik aletler kullanmak zor ve pahalı bir yoldur. Bu noktaları dikkate alarak, küçük ölçekli arıtma tesisleri için yüksek performanslı ve kullanımı kolay teknolojilere ihtiyaç vardır.

Bu çalışmada, ağ filtre ve sünger filtre, genelde kullanılan çamur yoğunlaştırma tankı, hava ile yüzdürme veya santrifüj yerine katı-sıvı ayrımı için kullanılmıştır. Bu sayede, çamurun su muhteviyatını mekanik aletler gibi azaltmak mümkün olmuş ve ayrıca yoğunlaştırma işlemi ekonomik şekilde yapılmıştır.

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LIST OF SYMBOLS/ABBREVIATIONS

Symbol	Explanation	Units used
u_s	Absolute solid velocity	m/s
$Ø_s$	Solid volumetric concentration	%
ε_{sav}	Average volume fraction of solids	-
ν	Filtrate volume / unit area	m^3/m^2
u_{sR}	Solid velocity relative to liquid	m/s
ω_c	volume of inert solids / unit area	m^3/m^2
L	Cake thickness	m
ϕ_l	Limiting solids flux	$m^3/m^2.d$
ϕ_f	Input flux	$m^3/m^2.d$
c_d	Dilute blanket concentration	mg/l
c_f	Actual concentration	mg/l
c_l	Limiting concentration	mg/l
c_r	Recycled concentration	mg/l
Q	Feed flow rate	m^3/d
C_0	Feed solids content	mg/l
Q_e	Exit flow rate	m^3/d
C_e	Effluent solids content	mg/l
Q_u	Underflow flow rate	m^3/d
C_u	Underflow solids content	mg/l
H’	Final settled height	m
X	Initial biomass concentration	g/l
Ho	Height of the column	m
X_m	Solids concentration at the bottom	g/l
SBH	Sludge blanket height	m
X	Input MLSS	g/l
H_o	Side depth	m
X_r	Underflow solids concentration	g/l
t	Hydraulic residence time in the bottom	h
DS	Dry Solids	ton, kg

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EU	European Union	-
MLSS	Mixed liquor suspended solids	mg/l
COD	Chemical oxygen demand	mg/l
TSS	Total suspended solids	mg/l
TS	Total solids	%
ISKI	Istanbul Su ve Kanalizasyon İdaresi	
µm	micron meter	-
SS	Suspended solids	mg/l
DAF	Dissolved air flotation	-
EPA	Environmental Protection Agency	-

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1. INTRODUCTION

Sludge processing and disposal is one of the most essential and important steps in wastewater treatment, due to the huge amount of sludges (biosolids) produced as a residue of the biological wastewater treatment plants. Inappropriate sludge treatment causes serious environmental problems. Thickening and dewatering are the common processes for sludge treatment; sludge is reduced or disposed directly or after insulation, etc. Considering the overall cost of wastewater treatment including biosolids treatment, the efficiency of the solid-liquid separation process is a key factor in wastewater treatment (Dentel, 2001). The cost of the dewatering step in municipal treatment plants, including conditioning agents, typically accounts for 30-50% of the annual operating costs (Mikkelsen and Keiding, 2001). Sludge dewatering was also pointed out as one of the most expensive processes (Burris, 1979, Bruus et al., 1992). Therefore, many researchers (Krofta and Wang, 1986; Tokunaga et. al., 1986; Vesilind, 1995) focused on improving the efficiency of the dewatering and thickening systems.

In small-scale wastewater treatment facilities, it is difficult to carry out the sludge treatment on site. In many cases the excess sludge is transported to the other sludge processing facilities. Sludge volume reduction is an important issue in terms of transport costs and energy saving. It is then worthy to develop a sludge thickening and dewatering system specific for small-scale wastewater treatment facilities.

Gravimetric thickening, dissolved air flotation and centrifugation are the most common processes used for sludge thickening. Gravimetric thickening is commonly used in wastewater and water treatment facilities because of the simple structure and low energy requirements of the apparatus. On the other hand, the gravimetric thickening process requires a large volume thickening tank and long operation period. In addition, the supernatant from the gravimetric thickening tank contains a high level of suspended solids and needs to be recycled to the water treatment plant for small-scale facilities. Some other mechanical thickening processes may not be applicable for small-scale facilities their high costs and low working rates.

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This study introduces mesh and foam filters as a liquid-solid separator instead of the large conventional sedimentation basins. By this way, it is possible to reduce the water of sludge as mechanical devices and make thickening process economical.

Mesh filtration is based on catching the solid particles in the pores of the filter and using these blocked pores to form a sludge layer over the filter medium and make the sludge itself a filter medium and percolate only water under the filter medium, then decrease the sludge volume.

Foam filtration is used as an upper step of mesh filtration with the same principle. The pore sizes changes between 200 – 250 µm and they do not follow a regular pattern in 10mm thick foam, this fact enhances solid caking. Also water can percolate from the pores easily. Using foam as a filter medium has several advantages on mesh filtration. It provides better sludge caking and effluent standards, and can operate in a wider range of flow rates than mesh filter.

Two phenomena take place simultaneously during thickening. They are namely retention of solids in the foam and expulsion of water. They are affected by various parameters; the major factors being gradation of solids in the sludge, water content of sludge, and pore size of the foam. Another important aspect that needs to be taken care of during thickening is the permeability of the foam. Permeability of the media does not remain constant throughout the process. It decreases with time. Decrease in permeability of the media is the result of clogging of the pores. Clogging is a function of gradation and therefore, the decrease in permeability is also a function of gradation. However, pore size of foam and water content of sludge are other variables that have significant influence on the thickening process.

In the literature, there is no study on the foam filtration of the waste activated sludges. In this study, sludge properties are determined before and after the thickening operation with polyether foam and mesh filter to obtain full information about the behavior of the sludge samples.

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This study introduces the mesh and foam filters as tools for sludge thickening and dewatering for small scale wastewater treatment facilities, investigates the effect of mesh opening size, filter area, operation type, raw sludge type, and sludge concentration on their process performance.

Study also investigates the effect of mesh and foam filtration on the conditioning requirements of the sludges.

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1.2. Backgroun d

Common place requirements in many processing plants are to minimize the amount of wastewater generated or to reduce the concentration of contaminants in the wastewater, and there are often underlying problems related to dewatering and handling of the sludge. A number of methods are used to reduce the amounts of sludge disposed. These include thickening and dewatering technologies that minimize the amount of water content in the sludge.

Thickening is the process by which biosolids are condensed to produce a concentrated solids product and a relatively solids-free supernatant. Thickening wastewater solids reduces the volume of residuals, improves operation, and reduces costs for subsequent storage, processing, transfer, end use, or disposal. For example, thickening liquid-solids (slurry) from 3 to 6 percent will reduce the volume by 50 percent (EPA, 2003).

The volume reduction obtained by sludge concentration is beneficial to subsequent treatment processes, such as digestion, dewatering drying, and combustion from the following standpoints:

1. Capacity of tanks and equipment required,
2. Quantity of chemicals required for sludge conditioning and,
3. Amount of heat required by digesters and amount of auxiliary fuel required for heat drying or incineration, or both (Metcalf & Eddy, 2003).

For large facilities where sludge must be transported to a significant distance, such as to a separate plant for processing, a reduction in sludge volume may result in a reduction in pipe size and pumping costs. For smaller facilities, the requirements of a minimum practical pipe size and minimum velocity may necessitate pumping of significant volumes of wastewater in addition to sludge, thereby diminishing the value of volume reduction. Volume reduction is very desirable when liquid sludge s transported by tank trucks for direct application to land as a soil conditioner (Metcalf & Eddy, 2003).

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Solids thickening can be improved beneficially at most wastewater treatment plants. However, solids thickening characteristics are unique to each wastewater treatment plant and facilities should develop a biosolids management plan to evaluate thickening technology options, including gravity thickening, DAF, centrifuge thickening, and gravity belt thickening. All of these technologies are commonly used, but they vary in performance criteria, such as solids concentration, achieved solids capture, odors, power demand, labor requirements, sensitivity to changing temperatures, and solids characteristics (EPA, 2003).

1.2.1. Gravity Thickener

Gravity thickeners consist of a circular tank (usually with a conical bottom) that is fitted with collectors or scrapers at the bottom. Primary and/or secondary solids are fed into the tank through a center well, which releases the solids at a low velocity near the surface of the tank. The solids settle to the bottom of the tank by gravity, and the scrapers slowly move the settled, thickened solids to a discharge pipe at the bottom of the tank. A V-notch weir located at the top of the tank allows the supernatant to return to a clarifier. In addition, many systems also use a skimmer to collect and remove any floatables and grease that have accumulated at the top of the tank. The biosolids concentration and thickening that occurs in the tank is achieved through three different settling processes, which include gravity settling, hindered settling, and compaction settling. Gravity settling occurs when solid particles travel downward due to their weight. Settlement continues as solids begin to concentrate near the bottom of the tank, but the settlement rate decreases as the solids concentrations increase. This is known as “hindered settling.” Compaction settling occurs when bottom solids are further concentrated due to the pressure of solids on top of them (EPA, 2003). Typically sludge with a water content of 0.8 % can be thickened up to 3-4%.

1.2.2. Centrifugal Thickening

Centrifugal thickening and dewatering is a high speed process that uses the force from rapid rotation of a cylindrical bowl to separate wastewater solids from liquid (U 1987). Centrifuges have been used in wastewater treatment since 1930s. Thickeni digestion or dewatering reduces the tank volume needed for digestion and s

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removing water. Dewatering removes more water and produces a drier material referred to as “cake” which varies in consistency from that of custard to moist soil. Centrifuges operate as continuous feed units which remove solids by a scroll conveyor and discharge liquid over the weir. The bowl is conical-shaped which helps lift solids out of the liquid allowing them to dry on an inclined surface before being discharged (Kemp, 1997). Typically sludge with a water content of 0.8 % can be thickened up to 6-7 %.(EPA, 2000)

1.2.3. Gravity Belt Thickener

Gravity Belt Thickener employs gravity drainage through a filter belt to thicken polymer conditioned sludge prior to digestion, mechanical dewatering, or trucking to a land application site or disposal site. Dilute sludge (typically 0.5% to 1.0%) is introduced at the feed end of a horizontal filter belt. As the slurry makes its way down the moving belt free water drains through the porous belt. The solids are continuously turned, encouraging the drainage of more water. Drainage System actually holds back the solids while causing constant movement throughout the entire sludge blanket allowing optimal drainage of free water. Sludge is discharged at the end of the horizontal filter belt as a pumpable thickened sludge (EPA, 2003). Typically sludge with a water content of 0.8% can be thickened up to 6-7%.

1.2.4. Dissolved Air Flotation (DAF)

Dissolved Air Flotation (DAF) is a process for the removal of fine suspended material from an aqueous suspension. The term "flotation" indicates something floated on or at the surface of a liquid. Dissolved Air Flotation provides the needed energy for effective flotation in the form of extremely fine air bubbles which become attached to the suspended material to be removed. The attraction between the air bubbles and particles is a result of adsorption forces that are functions of the characteristics of the particle surface, or physical entrapment (enmeshing) in the particle. This attachment of bubbles to the particle "reduces" the density of the particle resulting in increased buoyancy, thus effecting flotation. Chemical conditioning is often used to increase the effectiveness of the air flotation process (EPA, 2003).

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The most reliable and positive method of producing bubbles of the proper size is to dissolve air into water under pressure and then reduce the pressure of the solution. As the pressure is reduced, the air comes out of solution in the form of microbubbles (EPA, 2003). Typically sludge with a water content of 0.8% can be thickened up to 2-4%.

1.3. Dewatering Systems

1.3.1. Mechanical Plate and Frame Filter Presses

Mechanical plate and frame filter presses, recessed plate presses, and membrane plate presses are all used to dewater sludges. Filter plates are supported on side beams or suspended from sidebar filter press an overhead beam; filter plates of 1.5m×1.5m are typical, but 2m×2m plates are increasingly common—and larger plates are being developed.

For wastewater applications, 80 chambers in a recessed plate press or 60 chambers in a membrane plate press is not uncommon. The ability of membrane plate presses to utilize the compressible nature of the sludge makes them particularly useful for sludge dewatering applications. Typical sidebar filter press is represented in Figure 1.1.



Figure 1.1. Sidebar filter press (www.tradeget.com)

A typical filtration cycle for dewatering is: (i) slurry feeding; (ii) cake squ
inflating the membranes; (iii) air blow through the cake; (iv) core wash and/or b
cake squeeze is affected by diaphragms that are pressurized up to 16 bar in orde

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cake moisture content (or, increase the volume of liquid recovered from the feed). Cake moisture content reductions are dependent on its compressibility properties, but moisture contents more than 25% can be achieved on a conventional filter press are not uncommon.

Although membrane presses are significantly more expensive than conventional filter presses, the additional capital and operating costs are often justified by shorter cycle times (and hence greater sludge throughout) and the more easily handled cake that is produced (Wakeman, 2007).

The data of the filter press for different type of sludges is given in Table 1.1.

Table 1.1. Recess plate filter press operating data for some municipal sludges (Water Env. Federation, 1992)

Sludge type feed solids	Concentration (%)	Cake solids concentration (%)	Typical cycle time (h)
Raw primary sludge + activated sludge	3–8	45–50	2–2.5
Raw primary sludge + activated sludge + $FeCl_3$	5–8	40–45	3–4
Primary sludge + activated sludge + $FeCl_3$ +digested sludge	6–8	40	3
Tertiary sludge + lime sludge	8	55	1.5

1.3.2. Belt Filters

Belt filters are characterized by two continuous, tensioned filter cloths. Flocculated sludge is fed to the lower cloth (belt); initial dewatering is under gravity as the belt carries the sludge into a consolidation zone where it is progressively squeezed under pr the upper and lower belts moving towards each other to form a closed "envelope"

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The cake is then squeezed under increasing pressure as the cloths move over a sequence of successively smaller diameter rollers. As the two belts pass over the rollers there is a relative movement of the belts, causing liquid to be removed by a combination of expression and shearing to produce a dry, crumbly cake. Figure 1.2 a typical belt pres machine is presented.

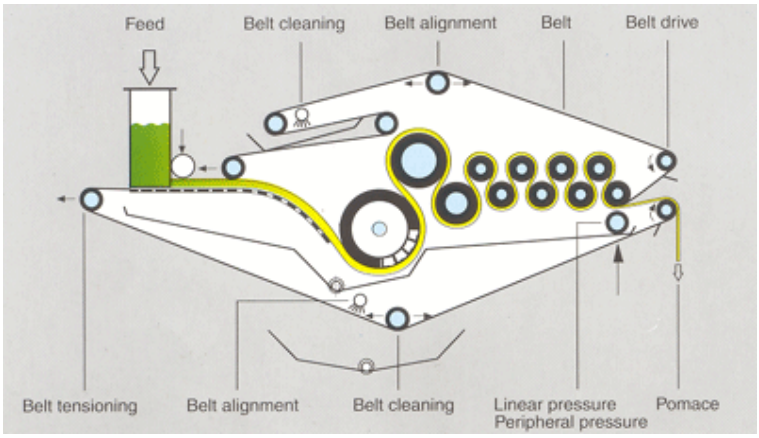

Figure 1.2. Belt press (www.tistr-foodprocess.net)

A key to successful operation of a belt press is that the feed must be flocculated, to avoid blinding of the filter belt and facilitate gravity drainage when it is initially fed to the belt. Conditioning is carried out by polyelectrolyte immediately before the drainage zone. Special care must be taken with belt washing, carried out on the belt return cycle with rinse water flow rates as high as 50 – 200% of that of the sludge. For good machine operation a feed sludge concentration 3 – 4% has been recommended (Spinosa, 1986) to have water content of 18 -20% in the dewatered sludge (Wakeman, 2007).

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In Table 1.2, belt press operating data is given for different municipal sludges.

Table 1.2. Belt press operating data for some municipal sludges (Spinosa, 2007).

Sludge type	Input solids concentration (%)	Cake solids concentration (%)	Polyelectrolyte dosage (kg/t)
Raw primary sludge	3–10	25–44	0.6–4.5
Raw activated sludge	0.5–4	12–32	1.0–6.0
Raw primary sludge + activated sludge	3–6	20–35	0.6–5.0
Aerobically digested sludge	1–8	12–30	0.8–5.0
Anaerobically digested sludge	3–9	18–34	1.5–4.5
Thermally conditioned sludge	4–8	38–50	–

1.3.3. Rotary Drum Filter

Vacuum filters have operational and process limitations that can be the most important criteria for choosing a filter for sludge dewatering.

By definition, the driving force for dewatering is limited by the vacuum that can be applied; in practice, a vacuum of not more than 0.25 bar absolute can be applied. For this reason vacuum filters are not usually employed in systems where most of the particle sizes are smaller than about 5 m; in turn, vacuum filters are rarely used to dewater municipal sludges but are more often suitable for some types of industrial ones. When vacuum filters are used, rotary drum filters are the preferred choice and their continuous operation and virtually no operator intervention during the normal operating cycle can be advantage (Wakeman, 2007). A typical representation of a rotary drum filter is Figure 1.3.

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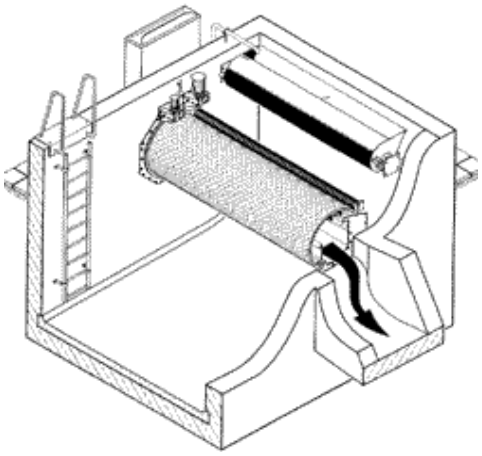

Figure 1.3. Rotary drum filter (www.ongov.net)

1.3.4. Decanter Centrifuges

Decanter centrifuges are used to mechanically dewater environmental and biosolids sludges and are often a preferred choice of equipment due to: the high forces of 2000 – 4000 g applied directly to the feed solids, enabling lower solids moisture contents (the "ultimate" cake dryness depends on the given sludge); its ability to handle higher solids content feeds; its continuous operation, with solids throughputs up to about 90 kg/h; the solids handling capabilities intrinsic through its design, with solids conveyed co-currently along the walls of the bowl by a helical screw. The centrifuge can be over-torque due to the flow properties of the thickened solids, or due to plugging by accumulation of unconveyed solids in the bowl. A typical operation of a decanter centrifuge is given in Figure 1.4.

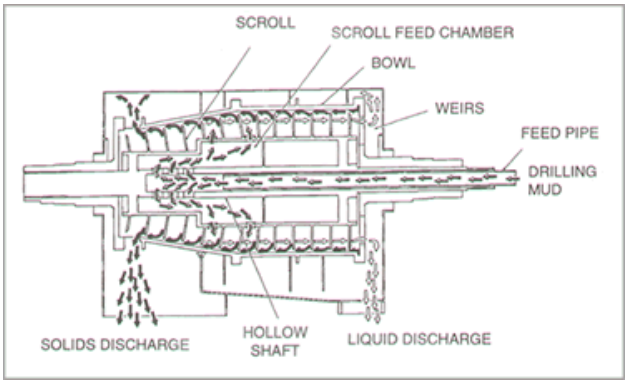

Figure 1.4. Decanter centrifuge (www.mudcontrolequipment.com)

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Important innovations in decanter technologies are the CentriDry which combines centrifugal dewatering and thermal drying in the same machine, and the compound beach and adjustable gate centrifuges (Schlip et all., 2000). The compound beach profile has a steep conical beach followed by a 0° cylindrical beach, with an adjustable gate located near to the solids discharge end of the machine to meter the cake. In this way, only the driest cake layer adjacent to the bowl wall which is subjected to the maximum compressive solid pressure is skimmed for discharge while the wet cake layer near the cake surface is recycled back upstream. This is an attempt to increase solids capacity whilst not compromising cake dryness, as tends to happen in the conventional decanter centrifuge.

The data for different municipal sludges of a decanter centrifuge is given in Table 1.3.

Table 1.3. Decanter centrifuge operating data for some municipal sludges (Schlip et all., 2000)

Sludge type	Feed solids concentration (%)	Cake solids concentration (%)	Conditioner dosage (kg/t)	Solids recovered (%)
Raw primary sludge	5–8	25–36, 28–36	0.5–2.5, 0	90-95 , 70-90
Raw activated sludge	0.5–3	4–12	5.0–7.5	85-90
Raw primary sludge + activated sludge	4–5	18–25	1.5–3.5	90-95
Digested primary sludge + activated sludge	2–4, 4–7	15–18, 17–21	3.5–5.0, 2.0–4.0	90-95,90-95
Thermally conditioned primary sludge + activated sludge	9–14, 13–15	35–40, 29–35	0, 0.5–2.0	75-85

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1.4. Drying Beds

1.4.1. Sand-Drying-Bed

Sand-drying-bed processes were used earlier with wastewater to dewater sludge, but their use declined with wide scale implementation of mechanical units. Sand beds are usually used for small industrial or community waste treatment plants. The sludge can be dewatered on open or covered sand beds. The method is very simple and requires minimal operator attention. They also require a considerable amount of land, and are subject to such uncontrolled variables as rainfall, temperature, humidity, and drainage rate. They cause odor problems, which increase in severity as long as sludge production increases. Sand drying beds are less complex, easier to operate, and require less operational energy than mechanical dewatering systems. They easily produce a sludge cake with 25 – 40 percent solids and can exceed 60 percent solids with additional drying time. A typical conventional sand bed is represented in Figure 1.5.

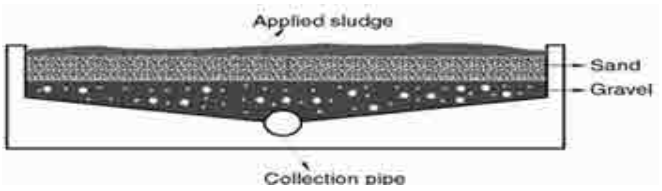

Figure 1.5. Conventional sand bed (www.builditsolar.com)

1.4.2. Paved Drying Bed

Paved drying bed is a drying bed constructed with a concrete or asphalt pavement that involves applying the sludge to the paved bed, decanting water after the settling of solids, and allowing the sludge to dry. Figure 1.6 is representing the section of a paved bed.

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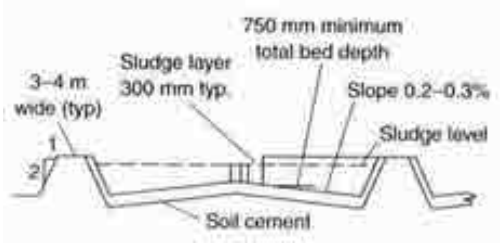

Figure 1.6. Paved drying bed section (www.pavingexpert.com)

After the surface crust is formed, the sludge is turned and aerated, to accelerate the drying process. The paved drying bed works best in warm, arid and semi-arid climates since water loss depends on evaporation. In arid climates, a 12-inch layer of sludge can attain a solid content of 40 to 50% in 30 to 40 days. In the same climate, it might require 100 to 250 days for a 3 feet thick sludge layer to reach 50% solids. The performance of the paved drying bed may be severely limited by rain falling on the loosened sludge. Because of large voids in the loosened sludge, rainfall will be retained in the sludge except during extremely intense rainfall, after which excess water may be decanted. The proportion of rainfall requiring evaporation would be 70 to 100% of the annual rainfall, which greatly increases the total time to achieve the desired solids content. Therefore, the paved drying bed requires a very large area to treat a large volume of sludge (Metcalf & Eddy, 2003).

1.4.3. Drying Lagoon

A drying lagoon is very similar to a sand bed except that the drainage is provided by the natural sand deposit at the bottom of the lagoon and the sidewall is an earthen dike. Sludge is applied to the lagoon in 24 to 48 inch depths and allowed to drain by gravity and to dry by evaporation. Lagoon drying is relatively inefficient, requiring several months to one year per cycle of drying, and therefore requires large land areas. Dilute liquid sludges with about 5% solid content are placed in these facilities and allowed to drain and to dry to a solid content between 25 and 40%. Dewatered sludge is removed by mechanical equipment. Drained water enters the ground water body and degrades the ground water quality. Drying lagoon is represented in Figure 1.7.

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Figure 1.7. Drying lagoon (www.teriin.org)

Because of its impact on the ground water quality, this method is no longer a viable method of sludge dewatering (Metcalf & Eddy, 2003).

1.4.4. Vacuum -Assisted Drying Bed

Vacuum-Assisted Drying Bed system utilizes a rigid, porous surface in a vacuum tight concrete bed. Polymer treated sludge is fed into the bed to a depth much greater than conventional drying beds. Filtrate passes through this porous surface through the bed under drain, and is collected in a sealed wet well and pumped away by a submersible pump. Vacuum is applied to this wet well, increasing the drainage of the thickening liquid, resulting in a stiff cake similar to a mechanical dewatering system. Due to the Net Positive Suction Head requirement of this type of pump the maximum possible vacuum was 8-10" Hg.

In the 1990s, the standard filtrate/vacuum system was revised to eliminate the filtrate pump, replacing it with simpler under drain level sensors/controls removing the filtrate from the Vacuum Bed by use of a motor operated valve. This allowed complete closure of the vacuum control valve, providing as much as 26" Hg vacuum for dewatering the solids to dryer cakes in a 24 hour cycle time. The dewatered sludge typically has a solid content of 15-20 %.

The effect of the vacuum in dewatering the cake is significant with regard
liquid loadings, shorter cycle times, and higher resultant cake dry solids while ma
low power and chemical consumption rates. This approach in removing the lic

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sludge should no longer be referred to a "Drying Bed", it subject to effects of climate; this is the "Vacuum Dewatering Bed System" (Metcalf & Eddy, 2003). A typical vacuum drying bed is given in Figure 1.8.

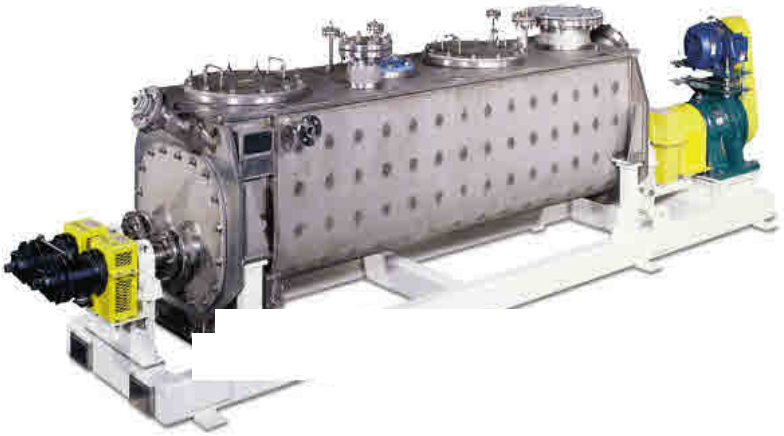

Figure 1.8. Vacuum drying bed (www.komline.com)

1.4.5. Artificial - Media Beds

Artificial - media can be used such as stainless - steel wedge wire or high - density polyurethane formed into panels. In a wedge wire drying bed, liquid sludge is introduced onto a horizontal, relatively open drainage medium. The medium consist of small stainless -steel wedge - shaped bars with the flat part of the wedge on top. The slotted openings between the bars are 0.25 mm (0.01 in) wide. The wedge wire is formed into panels and installed in false floor. An outlet valve is used to control the drainage. Figure 1.9 represents an artificial media bed.

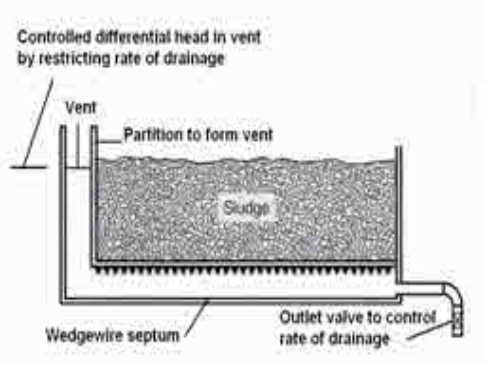

Figure 1.9. Artificial - media beds (www.rideau-info.com)

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Advantages cited for this method of dewatering are (1) no clogging of the wedge wire, (2) drainage is constant and rapid, (3) throughput is higher than sand beds, (4) aerobically digested sludges can be dried, and (5) beds are relatively easy to maintain. The principal disadvantage is that the capital costs are higher than for conventional drying beds. Typical solids loadings rates are 2 to 5 kg/m^2 cycle. The number of operating cycles varies depending on local climatic conditions. Typically the biosolids will dry to 8 to 12 percent solids after 24 h of drying.

In the high–density polyurethane media system, special 300 mm – (12 in) square interlocking panels are formed for installation on a sloped slab or in prefabricated steel self – dumping trays. Each panel has an eight percent open area for dewatering and contains a built – in underdrain system. The system can be designed for installation in open or covered beds. Advantages of this method of dewatering are (1) dilute sludges can be dewatered including aerobically digested waste – activated sludge, (2) filtrate contains low suspended solids, and (3) fixed units can be cleaned easily with a front – end loader. Drying rates are comparable to those of wedge wire media (Metcalf & Eddy, 2003).

1.4.6. Solar Drying Beds

Solar Drying beds are used to enhance the dewatering and drying of liquid, thickened, or dewatered biosolids. The solar drying system, which is a sophisticated ‘greenhouse’, consists of a rectangular base structure, translucent chamber, sensors to measure atmospheric drying conditions, air louvers, ventilation fans, a mobile electromechanical device (called a ‘mole’) that agitates and moves the drying biosolids, and a microprocessor that controls the drying environment. The system’s main source of drying energy is solar radiation. A closed solar drying bed is given in Figure 1.10.

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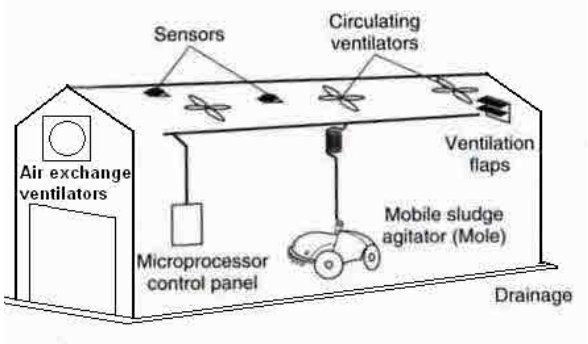

Figure 1.10. Closed solar drying beds (www.jcwinnie.biz)

The microprocessor evaluates the number of climatic variables and then initiates one or more operations that optimize the moisture–absorbing potential of the ambient air. Ventilating fans provide circulating air movement to exhaust the moisture–laden air. The mole tills the sludge bed, bringing moist biosolids to the surface to accelerate drying. Ultimately, a dry pelletized material is produced with solid content as high as 90 percent (Metcalf & Eddy, 2003).

1.4.7. Reed Beds

Reed beds can be used for biosolids dewatering at treatment plants with capacities up to 0.2 m^3/s (5 Mgal/d). Reed beds are similar in appearance to subsurface flow constructed wetlands, which consist of channels or trenches filled with sand or rock to support emergent vegetation. The difference between reed beds used for biosolids application and subsurface flow wetlands is that liquid biosolids are applied to the surface of the beds (as compared to subsurface application) and the filtrate flows through the gravel to underdrain. A typical reed drying bed is given in Figure 1.11.

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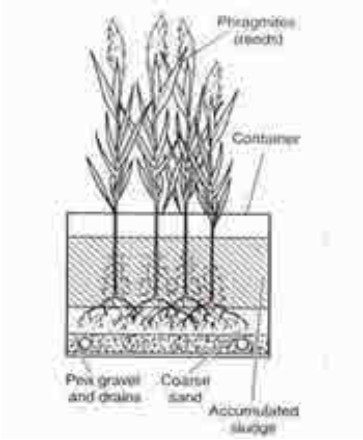

Figure 1.11. Reed drying beds (www.reedbed.com)

Typically, reed beds are constructed of washed river–run gravel in the following layers: (1) a 250 mm (10 in) deep drainage layer composed of 20 mm (0.8 in) washed gravel, (2) a 250 mm (10 in) deep layer composed of 4 to 6 mm (0.16 to 0.24 in) washed gravel, (3) a 100 to 150 mm (4 to 6 in) layer of sand (0.4 to 0.6 mm). Sometimes an even coarser bottom layer is used. At least 1 m (3 ft) of freeboard above the sand layer is provided for a 10 – year accumulation of sludge. Phragmites (reeds) are planted on 300 mm (12 in) centers in the gravel layer just below the sand. Other wetland vegetation can also be used, although reeds are the most popular. The first sludge application is made after the reeds are well established. Harvesting of the reeds is practiced typically in the winter by cutting the tops back to a level above the sludge blanket. Harvesting is necessary whenever the plant growth becomes too thick and restricts the flow of sludge. The harvested material can be composted, burned, or landfilled.

The purpose of the plants is to provide a pathway for continuous drainage of water from the sludge layer. Movement and growth of the plants create pathways for water to drain from the biosolids into the underdrain. The plants also absorb water from the sludge. Oxygen transfer to the plant roots assists in the biological stabilization and mineralization of the sludge. The reed bed system is a form of passive composting. The design loading rates for reed beds range from 30 to 60 kg/m^2.yr (6 to 12 lb/ft^2.yr). Loading rates a
100 kg/m^2 yr (20 lb/ft^2.yr) have been used, depending on the nature of the sl
climatic conditions. The liquid sludge is applied intermittently, as in sand drying

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typical sludge depth applied is 75 to 100 mm (3 to 4 in) every week to 10 d (Metcalf & Eddy, 2003)

1.5. Sludge Management in Turkey

Turkey, with a population around 71 million people, has approximately 1911 municipalities with 1421 served with sewer systems (Turkish Statistical Institute, 2005). According to the data of 2004, 2.77 billion m^3 of wastewater was discharged from the sewer system of which 60% is treated at the wastewater treatment plants (Turkish Statistical Institute, 2005). Figure 1.12 shows the relative use of the methods for treatment of wastewaters generated at Turkey in 2004. Figure 1.12 is representing the treatment methods of wastewaters at Turkey in 2004.

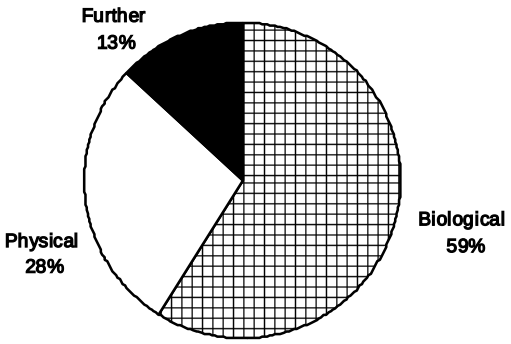

Figure 1.12. The relative use of methods for treatment of wastewaters in 2004 at Turkey (Turkish Statistical Institute, 2005)

Thirty seven percent of the total population was served with wastewater treatment services in 2004. The municipal wastewater treatment plants summed up to 165 in 2004, in Turkey. The population served with wastewater treatment plants is estimated to
60–80% by the year 2020, during the European Union integration process of Tur
result, the production of municipal sludge from the Turkish wastewater treatmen
estimated to increase up to more than one million tons DS per year, in 2020. T

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was estimated by using the value of 60 g of dry solids obtained from the average data of existing facilities in the EU (International Solid Waste Association, 1997). Centrifuging, filter presses, and especially belt presses are the most commonly used sludge dewatering methods, in Turkey. Sludge has a very limited use as fertilizer in agriculture. The general trend is liming the sludge after mechanical treatment and dumping or sanitary landfilling. The Ministry of Environment and Forestry issues the statutory order governing the use and applications of waste, including sludge, in Turkey. The Ministry published a circular allowing the sewage sludge to be incinerated at cement factories. Considering the emission problem and other environmental factors that may occur, limited incineration studies have been conducted for industrial sludge for testing purposes. Only four cement factories have licenses to incinerate sludge. Careful steps should be taken in this field since the incorporation of the sludge to the fuel of cement kiln may affect the quality of the cement (Salihoglu et al., 2006)

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2. STATEMENT OF THE PROBLEM

The ultimate disposal of wastewater sludge (biosolids) continues to be one of the most difficult and expensive problems in the field of wastewater engineering. Wastewater treatment plants generate different types of sludges, like primary settled sludge, waste activated sludge, chemical sludge and anaerobic sludge, according to their operating systems. These excess sludges have to be managed by reducing their volume and stabilizing them before their ultimate disposal. Generally used volume reduction methods are thickening and dewatering that are usually coupled with conditioning.

Sludge thickening and dewatering require either a big capital investment or a big surface area. Moreover, most of the mechanical dewatering technologies use polymers to condition the sludge before dewatering. These polymers have high cost rendering the mechanical dewatering uneconomical.

Small-scale wastewater treatment facilities play an important role in the aquatic environment in many countries. Although sludge treatment is essential for overall wastewater treatment, it is difficult and non-economical for small-scale treatment plants to use mechanical equipments. Considering these points, there is therefore a need for alternative technologies for high performance, easy to operate and economically feasible for small-scale wastewater treatment facilities.

This study evaluates the filter mesh and foam filter as a tool for sludge thickening and dewatering for small scale wastewater treatment facilities by investigating the effect of mesh opening size, filter area, raw sludge type, sludge concentration, quality of the filtrate, and the coagulant addition on the process performance.

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3. RELATED THEORY

3.1. Filtration Theory

Solid/liquid separation operations involve relative movement of solids and liquids in both slurries and porous compactible beds. Thickening, filtration and centrifugation are governed by the simultaneous flow of liquid through and compaction of porous particulate beds. In the relative motion, the liquid may have a higher velocity than the solids as in filtration or the reverse as in thickening and sedimentation. Movement of liquid is accompanied by a simultaneous collapse of the structure of the cakes and sediments under mechanical, centrifugal, gravitational, and fluid induced frictional stresses (Tiller and Hsyung, 1993).

A unified approach to solid-liquid separation with cake formation requires the solution of two simultaneous equations. The first rate equation (Darcy-Shirato) involves the gradient of the liquid pressure and the velocity of the liquid relative to the solid. The second stress balance equation contains the gradients of both the liquid pressure and the induced stress on the solid matrix.

A slurry or suspension provides feed for separation operations. The slurry can be classified under several broad categories depending principally on the size and concentration of the particles. No sharp lines of demarcation separate the various classes. Concentration is related to movement (gravitational, centrifugal, or diffusional) of particles as individual entities or as a mass in “zone” form. In dilute slurries, containing particles of different sizes and densities, the particles settle individually with different velocities. As the concentration increases, the motion of each particle is affected by its neighbours; and ultimately a concentration is reached where zone settling prevails, and all of the particles move with the same bulk velocity. Zone movement is divided into (1) freely sedimenting suspensions and (2) cakes with structures capable of supporting stresses. In simple rheological terms, the presence of a yield stress marks the boundary betv sedimentation and compaction or compression zones (Tiller and Hsyung, 1993).

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In zone "free" settling, it is generally assumed that the settling velocity relative to the liquid is a unique function of the concentration for a given degree of flocculation. Sediments formed from flocculated suspensions compact under the influence of gravity. Zone velocities of particles in sediments are not uniquely related to the local concentration. The particles can have velocities for a given concentration ranging from zero in quiescent, completely compacted beds to a maximum value in an overload thickener.

In all cases of filters and centrifuges, suspensions are converted into cakes and sediments. Where flow is downward in a vertical direction (thickeners or filtration on horizontal surfaces) or in centrifugation, the particle velocity will equal the liquid velocity plus the relative solid velocity which depends on the concentration. In the simplest case, batch sedimentation in a cylinder is governed by a transient material balance in which the absolute solid velocity u_s is presumed to be a unique function of the solid volumetric concentration $\emptyset_s$. The following first order partial differential equation governs gravitational sedimentation in the suspension region (Tiller and Hsyung, 1993).

$$\frac{\partial \phi_s}{\partial t} + \upsilon \frac{\partial \phi_s}{\partial x} = 0; \qquad \upsilon = \frac{\partial}{\partial \phi_s}(u_s \phi_s) \tag{3.1}$$

Where t = time, ν = filtrate volume / unit area and x = distance measured down from initial slurry surface.

Hyperbolic equations (Eqn.3.1) involve characteristics of the forms $x = f(t)$ along which $\emptyset_s$ is constant. The characteristics play a fundamental role in gravitational (laboratory sedimentation in cylinder) sedimentation. The characteristics which emanate from the point at which the sediment forms (bottom of the laboratory cylinder) effect changes in the suspension concentration. The return flow of liquid from the origin of characteristics results in a slowing down of the solids gravity sedimentation with increase in suspension concentration above the sediment.

In down-flow filters, the downward liquid flow interacts with the characte
the filtrate flow is sufficiently large, no liquid return flow occurs; and the chara

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are “buried” in the sediment. For batch Nutsch-type filters operating with a fixed initial charge and “buried” characteristics, the slurry concentration will remain constant.

However, the solid velocity will be larger than the liquid velocity; and the usual case in which the average solidosity, ε_{sav} (average volume fraction of solids) is assumed constant, the rate of deposition is given by

$$\frac{d\omega_c}{dt} = \frac{\phi_s}{1-\phi_s/\varepsilon_{sav}}\frac{dv}{dt} + (u_{sR} + \frac{dL}{dt})\phi_s \qquad (3.2)$$

Where ω_c = volume of inert solids/unit area, v = filtrate volume / unit area, u_{sR} = solid velocity relative to liquid, and L = cake thickness. In the usual analysis of filtration operations, the last term in Eqn.3.2 is neglected.

3.2. Compactibility

Compactibility or compressibility of particulate networks is prime factor in the behaviour of thickeners, filters, centrifuges, and expression equipment. A highly aggregated structure is easily compacted and leads to a high degree of compressibility. Flocs arising in normal processing or in pre-treatment operations are deposited at a cake or sediment surface at the critical or null stress concentration. If the cake is continually covered by new particles, porosity at the surface always retains its null-stress value. Developing stresses transmitted through the particulate network compact the inner layers and lead to a uniform porosity distribution (Tiller and Hsyung, 1993).

Principal sources of stress are (1) unbuoyed weight of solids in gravity thickeners, (2) centrifugal forces, (3) pump pressure converted into Darcian drag, and (4) surface forces developed by pistons or pressure-actuated impermeable membranes. When a specific stress is applied to a bed of flocculated particles, the porosity is reduced until the particles have so arranged themselves that no further movement occurs.

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3.3. Darcy-Shirato Equation

In flow through fixed incompressible beds, the solid velocity is zero; and only the liquid velocity enters the conventional Darcy equation. In solid-liquid separation, the solid velocity is frequently not negligible. Shirato and his co-workers (1969) introduced the relative velocity into Darcian equation for cake filtration and batch sedimentation. Whereas solid velocities are generally small in filtration, they are of primary importance in thickening and expression. Particles flow downward more rapidly than the liquid in thickening operations. In expression, particles are squeezed into the open interstices replacing liquid (Tiller and Hsyung, 1993).

In thickening, particles enter the sediment with their maximum velocity. Their motion is retarded by the slower moving liquid which picks up speed as it moves toward the bottom of the thickener. At the bottom, the velocities are usually assumed to be equal when a sediment is present. However, when no sediment is present and freely settling prevails, the solid leave the bottom with a higher velocity than the liquid.

In filtration, the liquid velocity in the slurry drops suddenly at the growing cake interface. The porosity at any given location in the cake decreases with time, and the liquid originally deposited at the cake surface is slowly squeezed out. As the liquid passes through the cake, the liquid being squeezed out is added to the main flow and the velocity increases. The solid velocity is a maximum at the cake surface and decreases to zero at the supporting medium. In most filtration theory, the solid velocity is neglected even though it frequently amounts to several per cent of the liquid velocity.

In general, the flow rate equations may be written in spatial or material coordinates (μ = viscosity, K = permeability, ω = volume of solids/unit area, α = specific resistance)

$$\frac{\partial}{\partial x}(driving force) = \frac{\mu \varepsilon_L}{K}(u_L - u_s) \tag{3.3}$$

$$\frac{\partial}{\partial \omega}(driving force) = \mu \alpha \varepsilon_L (u_L - u_s)$$

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The material and spatial coordinates are reduced by

$$d\omega = \varepsilon_s dx \tag{3.5}$$

$$K\alpha(d\omega / dx) = K\alpha\varepsilon_s \tag{3.6}$$

Where Eqn.3.6 arises from combining Eqs.3.3 – 3.5, only two of K, α, ε_s are independent. In contrast to electrical and thermal transport, the resistance is not the exact reciprocal of the conductivity because Darcy used superficial rather than pore velocity. The later introduction of α on the basis of moving material coordinates led a situation in which K is not the reciprocal of α.

3.4. Solids Flux

In a settling basin that is operating at steady state, a constant flux of solids is moving downward as shown in Figure 3.1. Within the tank, the downward flux of solids brought about by gravity (hindered) settling and by bulk transport due to the underflow being pumped out and recycled.

General flux theory can be written as following:

$$G = V.C = (m/h)*(kg/m^3) = kg/h.m^2 \tag{3.7}$$

G_u is independent from solids concentration. If there is no sludge or solids, there will be still G_u as shown in Figure 3.2.

$$\text{Solids Balance} = Q_0.C_0 = Q_u.C_u \tag{3.8}$$

$$\text{Liquid Balance} = (Q_0)_{slurry} - (Q_0)_{solids} = Q_e + [((Q_0)_{slurry} - (Q_0)_{solids})]$$

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Where

Q = feed flow rate	C_0 = Feed solids content
Q_e = Exit flow rate	C_e = effluent solids content
Q_u = Underflow flow rate	C_u = underflow solids content

$$Q_{solids} = Q_{0slurry} * C/\rho_s \tag{3.10}$$

$$(Q_0)_{slurry} - [(Q_0)_{slurry} * C_0/\rho_s] = Q_e + (Qu)_{slurry} - [(Q_u)_{slurry} * C_u/\rho_s] \tag{3.11}$$

If we solve this equation by replacing Q_e by V.A, we end with (Chancelier et all., 1996).

$$Gi = \frac{Q_0 C_0}{A} = \frac{v_i}{\frac{1}{c_i} - \frac{1}{c_u}} \tag{3.12}$$

As a result, the thickener is designed for;

$$G_L = \frac{v_L}{\frac{1}{c_L} - \frac{1}{c_U}} \tag{3.13}$$

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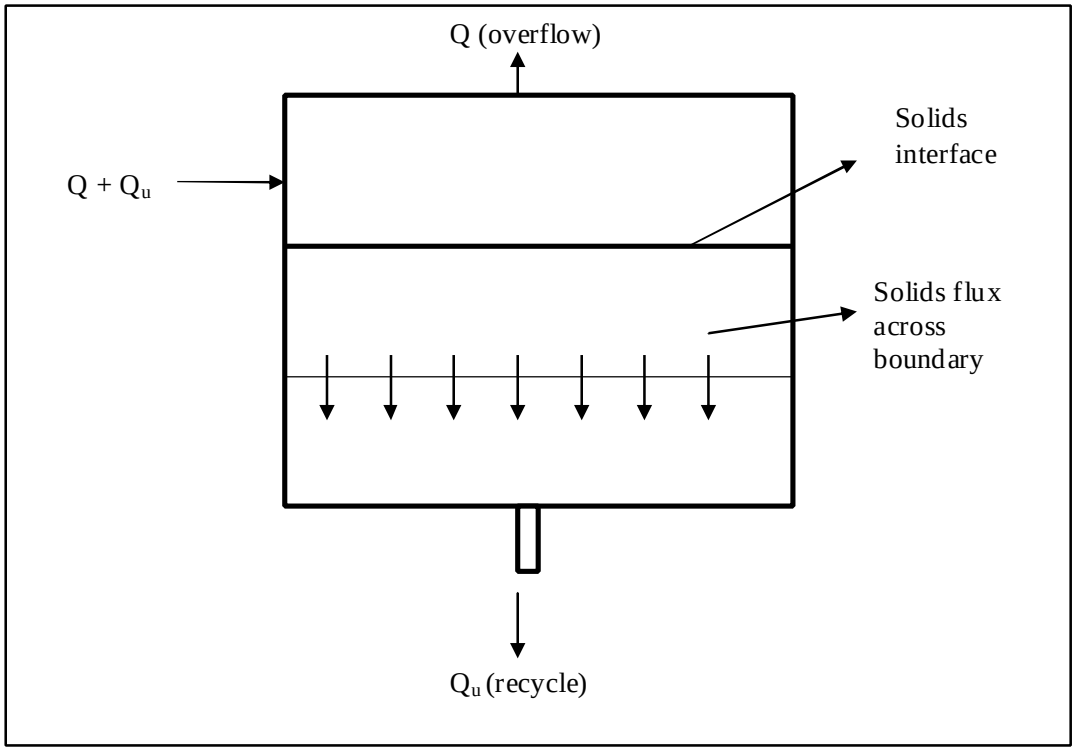

Figure 3.1. Definition sketch for a settling basin operating at a steady state

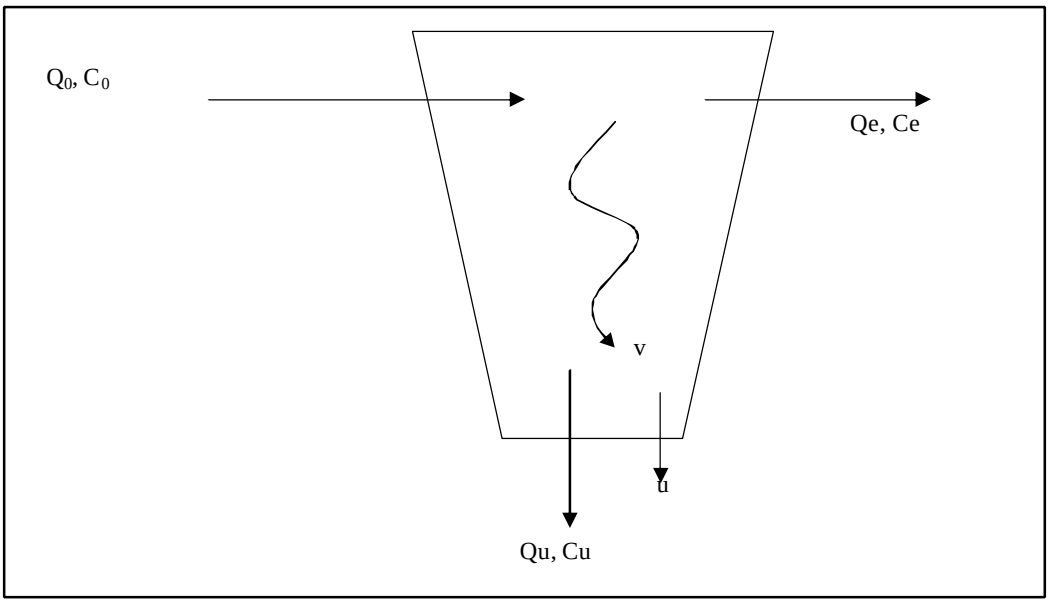

Figure 3.2. Solids flux sketch

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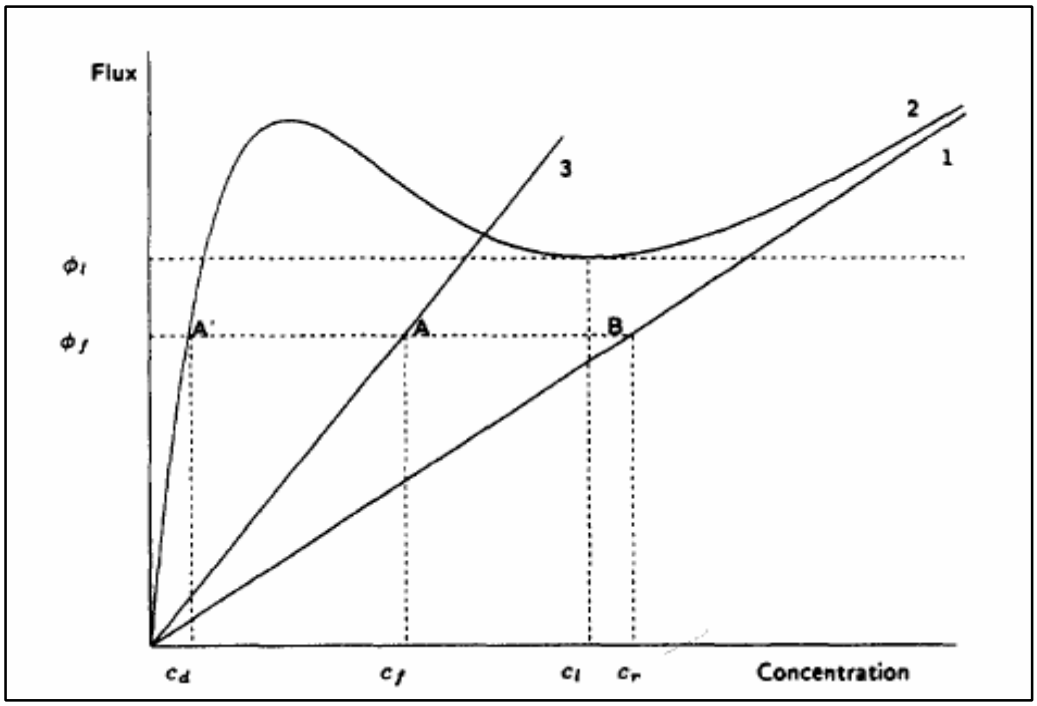

Figure 3.3. Typical solids flux representation (Chancelier et al., 1996)

In Figure 3.3, ϕ_l = limiting solids flux, ϕ_f = input flux, c_d = dilute blanket concentration, c_f = actual concentration, c_l = limiting concentration, c_r = recycled concentration, A' = underload point , A = operating point, B = the point for which the input flux is conveyed to the recycle flow alone, Line 1 = underflow flux, Line 2 = total flux, Line 3 = effluent flux

3.5. Batch Reactor Theory for Thickening

The traditional approach for analyzing clarifier design and performance is based on the application of the solids flux theory. This approach provides good graphical tools which describe the settling process at steady-state operating conditions and satisfactorily predicts the thickening performance of full-scale clarifiers that are not limited by their capability to convey settled solids to the return activated sludge withdrawal point. More specifically, this approach is well suited for studying the effect of real limitations (relating to the clarifier surface area) but it does not adequately address the effect of hydraulic limitations. For this reason, several investigations have been performed in
integrate the solids flux theory based on simplifications or improvements of t
approach. However, most of these approaches either do not consider hydraulic li

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or require the use of complicated mathematical (mostly differential) equations, which are arduous to solve numerically. Despite the fact that reliable numerical algorithms exist at present that can simulate the exact mathematical solutions of such mechanistic and complex dynamic models, their use is still limited for design purposes, as it would often be too time consuming for comparing different process configurations or for a first estimation of the settlers efficiency. Coupled analysis of the aeration and settling tanks has also been proposed as an integrated method for the assessment of the overall treatment process. These approaches though do not usually account for the solids storage function of the settlers. One dimensional models, based on solids flux theory, have been shown to satisfactorily account for the observed behaviour of secondary clarifiers in terms of both clarification and thickening performance. These models divide the settling tank into a number of layers and describe the sludge concentration profile (downwards and/or upwards) within the settler. However, they add new physical phenomena (diffusivity, by-pass) thereby incorporating more parameters, which require extensive and cautious calibration (Giokasa et all., 2001).

In the theory, a simple empirical method is pursued for the analysis and design of the continuously operating full-scale secondary clarifiers. The proposed approach rests on the phenomenon of dilution of the incoming activated sludge in the feeding well of the settling tanks while provides several types of modified models for its quantitative estimation. The parameters of the overall approach include almost all of the operational variables, which are readily ascertained in the routine analysis performed in a wastewater treatment plant, thereby minimizing sampling and experimental effort (Giokasa et all., 2001).

By this theory, the sludge blanket height can be predicted before the operation.

$$H' = X*Ho/X_m \qquad (3.14)$$

Where;

H’ = final settled height (m)

X = initial biomass concentration (g/l)

Ho = height of the column (m)

X_m = solids conc. at the bottom (g/l)

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Assuming X_m is X_{sb} (sludge blanket solid conc.) and H' is the sludge blanket height, Eqn.1 can be written as:

$$SBH = X*Ho / X_{sb} \quad (3.15)$$

Where;

SBH = sludge blanket height (m)

X = input MLSS (g/l)

H_o = side depth (m)

$$X_r = a\,(t + \Delta t)b \quad (3.16)$$

Where;

X_r = underflow solids conc. (g/l)

t = hydraulic residence time in the bottom (h)

a, b and Δt are empirical coefficients

$a = 2.065\ X^{0.382}$

$b = 0.545\ SVI^{-0.152}$

$\Delta t = 0.545\ X^{2.234}$

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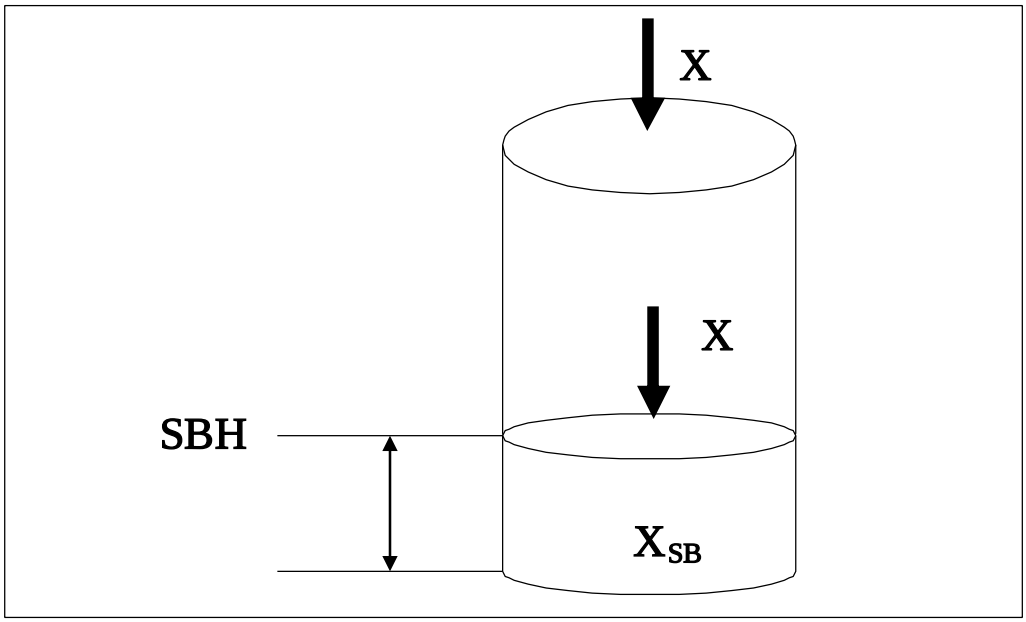

Figure 3.4. Sketch of thickening in a batch reactor

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4. MATERIALS AND METHODS

4.1. Sludges

In this study, experiments were conducted on both biological and chemical sludge samples. Biological sludge samples were taken from "Paşaköy Advanced Wastewater Treatment Plant" located at Paşaköy in the Anatolian side of Istanbul. The treatment plant operated with an average flow rate of 125,000 m^3/d, mainly municipal sewage, and employs bio-P removal, nitrification and denitrification processes. The sludge used was "Return Activated Sludge" from Secondary Clarifier and was received weekly in plastic barrels of 30 liters. The solid content of feed sludge varied over time between 0.26 and 2.10%.

Chemical sludge samples were obtained from a metal processing industry "Aksan Metal" located at Kartal, Istanbul. The treatment plant capacity is 300 m^3/d and sludge was taken from a silo which was located just before the filter press of the treatment plant. The initial solids concentration of the raw sludge varied between 2.1 and 2.7%.

4.2. Cationic Polymer

SNF FLOERGER (5880S) cationic polymer was used for the conditioning of the sludge samples. The dosage of the polymer applied to the sludge samples was 1 mg/l. Polymer is kept in refrigerator at 5°C.

4.3. Apparatus

For mesh thickening, a lab-scale cylindrical tank with inner diameter of the tank is 26 cm and the height 40 cm was equipped with a mesh filter having mesh openings of 100 and 200 µm.

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For foam thickening, a galvanized metal stand 40 cm x 40 cm in length and width covered with a 10 mm thick polyether foam fitted on the same lab-scale cylindrical tank used in the mesh thickening experiments.

A peristaltic pump was used to feed the sludge into the system. The sludge samples were completely mixed by using a magnetic stirrer. The schematic view and the photos of the system are given in Figures 4.1 to 4.4.

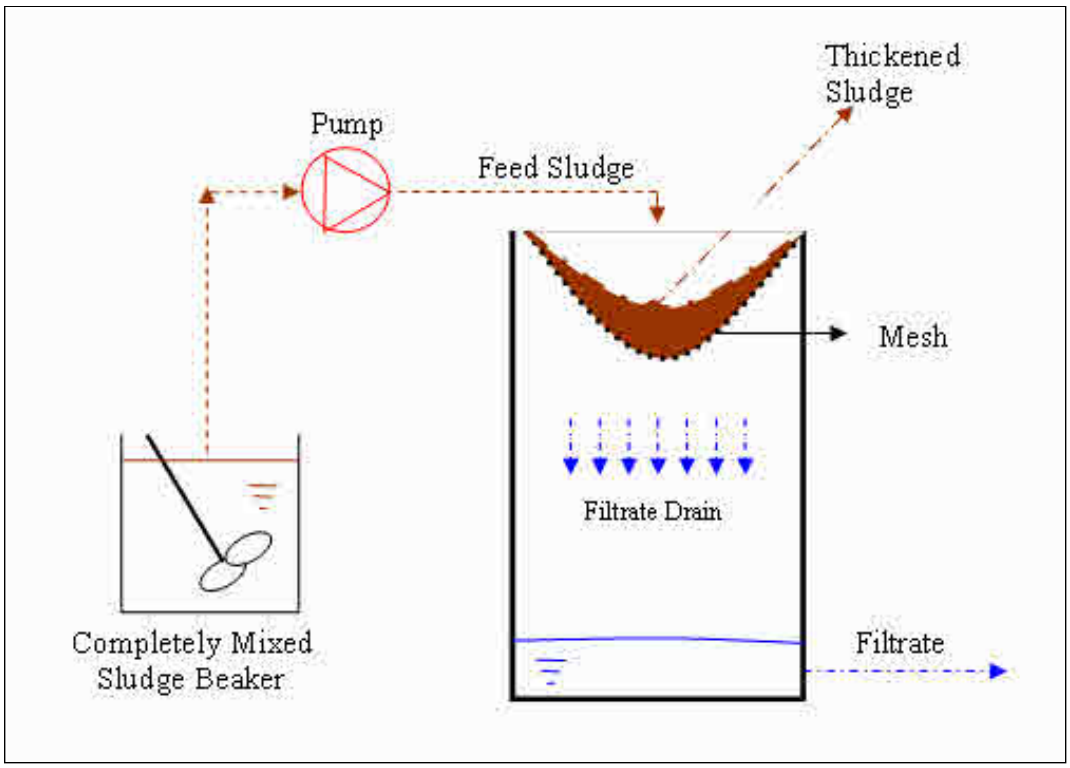

Figure 4.1. Schematic view of the mesh thickening system

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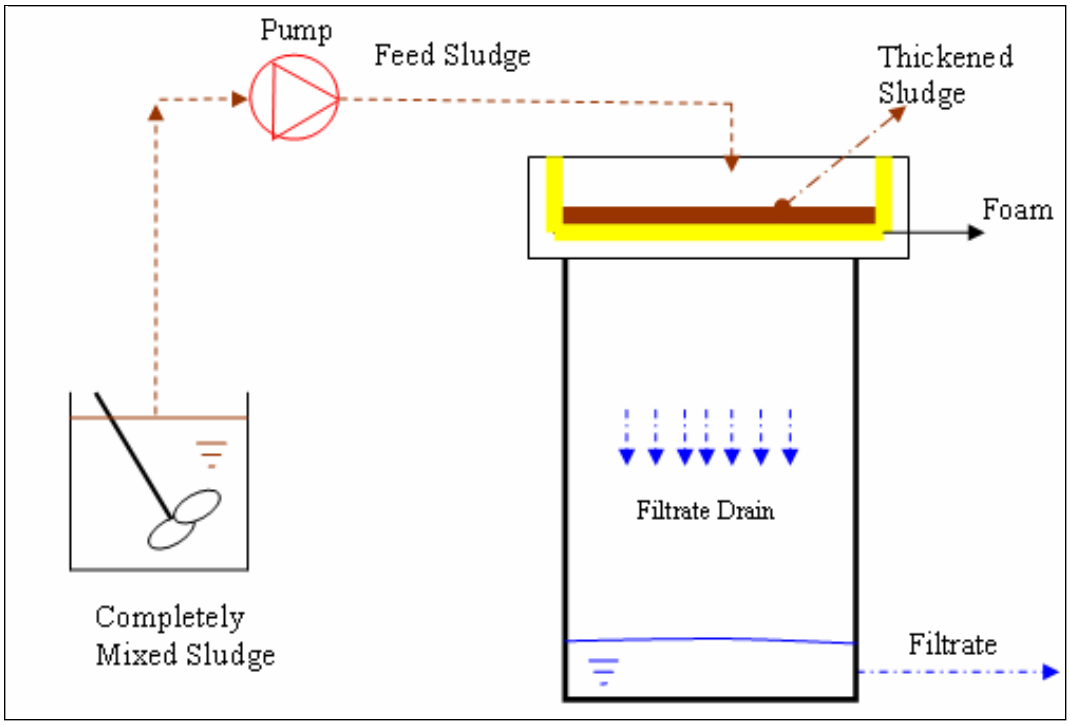

Figure 4.2. Schematic view of the foam thickening system

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Figure 4.3. Experimental setup of the mesh thickening system

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Figure 4.4. Experimental setup of the foam thickening system

4.4. Experimental Analysis

In this study, measurements of Total Solids (TS), Chemical Oxygen Demand (COD) and Total Suspended Solids (TSS) were done in order to control the key parameters. All of the measurements were done according to the Standard Methods for the Examination of Water and Wastewater (1995) were carried out.

COD measurements were done according to Method 5220 D (Closed Reflux, Colorimetric Method) of the Standard Methods for the Examination of Water and Wastewater (1995).

TSS measurements were done according to Method 2540 D (Total Suspend
Dried at 103-105°C) of the Standard Methods for the Examination of W
Wastewater (1995).

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TS solids measurements were done according to Method 2540 B of the Standard Methods for the Examination of Water and Wastewater (1995).

4.5. Reagents

4.5.1. Sulfuric acid reagent

The reagent used in the COD analysis is prepared by adding Ag_2SO_4 (crystal or powdered) to the concentrated H_2SO_4 in the range of 5.5 g Ag_2SO_4/ kg H_2SO_4 and waited for 1-2 days for the complete dissolution of Ag_2SO_4.

4.5.2. Digestion solution

Digestion solution was also used for COD analysis. It was prepared by dissolving 10.216 g $K_2Cr_2O_7$ primary standard grade previously dried at 103°C for 2 hours, and 33.3 g $HgSO_4$ in 167 ml concentrated H_2SO_4 and then adding 500 ml distilled water in it. The solution was cooled to room temperature and diluted to 1000 ml.

4.6. Procedure

The operation type was semi-batch which is the most appropriate feeding method for the small-scale treatment plants. The experiments were carried out in two phases. The first one started with a 30 minutes of feeding and 15 minutes of draining period. The second one started again with a 30 minutes of feeding followed by 30 minutes of ultimate draining period. Samples were taken in every 15 minutes to measure the solids percent obtained on the filter mesh or foam.

The sludge flow rates were changed from 20 ml/min to 100 ml/min in the mesh thickening experiments and from 40 ml/min to 180 ml/min in foam thickening experiments. During the mesh thickening at biological sludge samples, the solids varied between 2.06 to 55.70 kg/m^2.d for 100 µm and from 8.31 to 48.91 kg/m^2. µm mesh openings.

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For chemical sludge, the solids loadings fell into a range of 9 to 55 kg/m^2.d for 100 µm and 10 to 56 kg/m^2.d for 200 µm mesh openings. The effect of the polymer addition on mesh thickening was also investigated by adding 1 mg/l cationic polymer for 100µm and 200 µm mesh sizes. For foam thickening, solids loading differed from 4.57 kg/m^2.d to 22.17 kg/m^2.d.

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5. RESULTS AND DISCUSSIONS

The results of this study were presented in three different groups including thickening of the biological sludge with mesh filter, thickening of the chemical sludge with mesh filter and lastly, a new way of thickening in the literature, thickening of biological sludge with foam.

The results of the thickening experiments were compared according the applied sludge flow rates, solids loadings, mesh opening size, effect of polymer on the thickening and finally filtrate quality at the end of thickening operation.

The control parameter was obviously the total solids concentration for the thickening process, total suspended solids (TSS) and chemical oxygen demand (COD) for the final filtrates.

The importance of the total suspended solids concentration measurements for thickening experiments was to evaluate the efficiency of the process and to make a comparison with the real case operations. Moreover, by measuring the TSS and COD parameters of the sludge samples, a comparison would be done with the sewage discharge regulations of local district, Istanbul Water and Sewerage Administration, ISKI.

5.1. Thickening of Biological Sludge with Mesh Filtration

The used mesh opening sizes for the thickening process were 100 µm and 200 µm.

The sludge feeding flow rates were between 20.5 and 100 ml/min. In this range, five different flow rates were used. The operation type was semi-batch which is the most appropriate feeding method for the small-scale treatment plants. The experiments were carried out in two phases. The first phase started with a 30 minutes of feeding and 15 minutes of draining period. The second phase started again with a 30 minutes c followed by 30 minutes of ultimate draining period. Samples were taken in minutes to measure the solids concentration obtained on the mesh filter.

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A recovery period was investigated in the biological sludge thickening experiments. This recovery period occurred at the 45th minute of the thickening process. According to the used batch feeding system, at this minute, second feeding period started and the bulk sludge over the mesh became less concentrated. This phenomenon was in accordance with the filtration theory that was defined in Related Theory section 3.1.

The biological sludge used for the thickening studies was taken from return sludge line of Paşaköy Advanced Wastewater Treatment Plant. Due to some operational changes in the treatment plant, the initial solids concentrations varied from 1.0% to 1.8% for 100 µm mesh size and from 1.0% to 1.5% for 200 µm mesh size.

Solids loadings changed depending on feed sludge flow rate and initial solids concentration applied to the system. Solids loadings ranged between 5.57 kg/m^2.d and 38.51 kg/m^2.d for 100 µm mesh and 6.79 kg/m^2.d and 35.86 kg/m^2.d for 200 µm mesh. The usual range of solids loading for gravity thickeners used in treatment plants for extended aeration process was changing from 24.4 to 34.2 kg/m^2.d and obtained thickened sludge concentration was 2-3% (Metcalf and Eddy, 1997).

The filter mesh was designed to have a conical surface instead of a plain surface. The conical surface increased the surface area and thus the active filtration of the filter mesh. The surface area of the conical shape filter was 2.36 times higher compared to the plain surface and lead to application of higher hydraulic loadings.

The effect of polymer addition was also investigated in this study by adding 1.0 mg/l cationic polymer into the biological sludge samples.

The total suspended solids and chemical oxygen demand of the filtrates were determined to compare with the discharge limits of ISKI.

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5.1.1. Effect of Mesh Size and Flow Rate

5.1.1.1. 100 µm Mesh Size Experiments. The first experiments were started by using 100 µm mesh opening size. In this part, the results obtained from thickening with this mesh size were presented in Table 5.1 and Figure 5.1. The Table 5.1 was consists of parameters mesh opening, flow rate, solids loading, initial solids concentration, final solids concentration and sludge volume reduction. The figure represented the trend of solids concentration increase over the mesh with respect to time.

Table 5.1 summarizes the biological mesh thickening results of biological sludge samples.

Table 5.1. Summary of mesh thickening results of biological sludge samples for 100 µm mesh size

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)
100	20.5	5.57	1.0	7.1	86
100	41	10.86	1.0	7.4	87
100	61.6	18.41	1.1	6.4	82
100	80	38.51	1.8	7.2	75
100	100	29.0	1.1	6.5	83

As seen in the Table 5.1, at the lowest flow rate of 20.5 ml/min, solids loadings of the 5.57 $kg/m^2.d$, final solids concentration increased from 1.0% to 7.1% leading to 85% sludge volume reduction. Increasing the sludge flow rate from 20.5 ml/min to 41 ml/min, solids loading became higher, 10.86 $kg/m^2.d$, and sludge volume reduction improved to 86%. Further increase in flowrate to 61.6 ml/min caused to a slight decrease in the sludge volume reduction. At 80 ml/min flow rate, the beginning solids concentration v and the calculated solids loading was 38.51 $kg/m^2.d$. The final solids concentrati

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mesh was 7.2 %. The sludge volume reduction was calculated to be 75%. The total increase in thickening from the start point to the end was 3 folds of the initial value.

At the maximum sludge feeding flow rate of a 100 ml/min, initial solids concentration was 1.1% and the solids loading was 29.0 kg/m^2.d. During the thickening process, solids concentration was increased from 1.1% to 6.5%. The obtained final sludge concentration of 6.5% was not high as previous experiments. This can be attributed to the higher flow rate applied to the system.

In agreement with Park (2004), the thickening of biological sludge samples by mesh filtration, formation of sludge cake depended on solids loading. In the first interval, where the cake started to form, the higher solids loading experiments resulted with an initial solids concentration close to the final solids concentration. On the other hand, when the solids loading rates were low, there were big differences in the initial and final solids concentrations.

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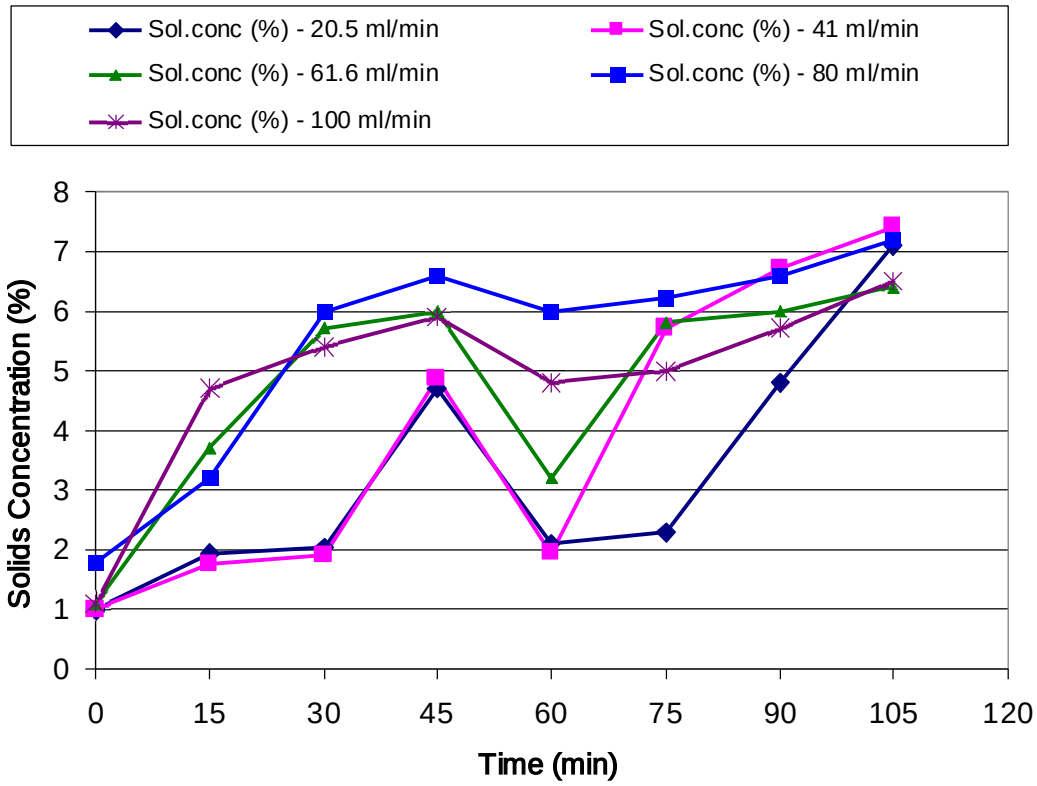

Figure 5.1. Solids concentrations with respect to time for 100 µm mesh size

Generally, in the fist phase of thickening, especially for high solids loadings greater than 15 kg/m^2.d, there was a quick cake formation and, in the second phase the increase of sludge concentration over the mesh was not noticeable. The differences in solids concentrations between two phases were bigger when the solids loading were less than 10 kg/m^2.d. When the solids loadings were low, both formation and clogging of the pores occurred at a longer time. After the clogging, the cake formation became stable and remained nearly constant throughout the experiments.

Park (2004) explains the time to create a film on mesh as the time for cake formation and it happens in the first a few minutes. However, in this study, the cake formation period named as the time that the solids concentration became less variable. There was no definite time determined but the time that less changes in solids concentration were observed was named as cake formation time.

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The results of mesh filtration thickening of biological sludge showed that, even in the worst case, final solids concentration reached was higher than that of a conventional gravity sludge thickener. As mentioned before, conventional sludge thickener sludge of an extended aeration system can obtain solids concentration of 2 – 3%. In this study, it was seen that the final solids concentrations ranged between 6.4% and 7.4% for 100 µm mesh size openings.

In the 100 µm mesh size experiments, the final solids concentrations obtained on the mesh was higher than the 200 µm mesh size. This can be easily attributed to the mesh size. The smaller openings of mesh favored quicker cake formation and the sludge can retain on the mesh longer time. The final solids concentration for 100 µm mesh size varied from 6.4% to 7.4%. The overall sludge volume reduction was calculated as 82% where as the maximum sludge volume reduction was 86%, on the other hand, the minimum sludge volume reduction was 75%. The solids loading changed by the hydraulic loading and initial solids concentration and they ranged between 5.57 $kg/m^2.d$ and 38.51 $kg/m^2.d$. It is necessary to indicate that the general solids loadings for a conventional gravity thickener were from 24.4 to 34.2 $kg/m^2.d$ for such a sludge system (Metcalf and Eddy, 2003).

As it can be seen in the Figure 5.1, there was a recovery period for the reformation of the sludge cake. This period started at 45th minute of the experiment and ended 60th minute. The reason of this recovery period was explained by Tiller (1993) as the bulk sludge over the mesh became less concentrated by the start of the second period. The difference between the concentrations of the bulk sludge and the cake sludge needed to be balanced and then, the solids concentration of the cake increased. The recovery period was also in accordance with Kiso et al. (2000). They have also experienced same difficulties but stable fluxes were obtained in 10 – 15 minutes.

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5.1.1.2. 200 µm Mesh Size Experiments. The second part of the experiments was done to find out the effect of a greater mesh size in the thickening of biological sludge. The results are given by the graphics. In order to compare the findings with the 100 µm mesh, same hydraulic loadings were applied and because the sludge's initial concentration can not be controlled due to real case sludge, percent volume reduction was a better definition for the efficiency of the system.

Table 5.2. Summary of mesh thickening results of biological sludge samples for 200 µm mesh size

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)
200	20.5	6.79	1.2	5.1	77
200	41	15.64	1.4	5.5	74
200	61.6	24.8	1.5	6.0	75
200	80	21.73	1.0	5.4	81
200	100	35.86	1.3	6.9	86

As seen in the Table 5.2, lowest flow rate of 20.5 ml/min, solids loadings of the 6.79 $kg/m^2.d$, final solids concentration increased from 1.2% to 5.1% leading to 77% sludge volume reduction. Increasing the sludge flow rate from 20.5 ml/min to 41 ml/min, solids loading increased to 15.64 $kg/m^2.d$, and sludge volume reduction reduced to 74%. At 80 ml/min flow rate, the beginning solids concentration was 1.0% and the calculated solids loading was 21.73 $kg/m^2.d$. The final solids concentration on the mesh was 5.4%. The sludge volume reduction was calculated to be 81% and this sludge volume reduction was higher than the experiment with 61.6 ml/min.

The maximum hydraulic loading application was done for 200 µm mesh size by a flow rate of 100 ml/min. Solids concentration before the start was measured as increased to 6.9 percent at the end of the experiment. The solids loading for this

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was 35.86 kg/m^2.d. Among the five different flow rate applications, the highest cake solids concentration was reached at this run leading to highest sludge volume reduction of 86%.

Park (2004) investigated that there was no big differences in the sludge volume reduction rates between 100 and 200 µm mesh sizes. In agreement with the Park, the sludge volume reduction ranged between 75 – 86% and 74 – 86% in the mesh filtration experiments performed with 100 and 200 µm mesh sizes, respectively. Sludge volume reduction was not affected by mesh opening size.

Kiso (2000) concluded that in the formation of sludge cake over the mesh differed by the mesh opening size. The sludge concentration over the mesh increased during the filtration operation when 100 µm mesh used and on the other hand, the sludge concentration over the mesh remained nearly unchanged for 200 µm mesh. As it can be seen from the Figure 5.2, once the cake was formed in the first 15 minutes of the experiment, the concentration of the sludge over the mesh did not increase much when compared to the final solids concentration except for the solids loading less than 10 kg/m^2.d.

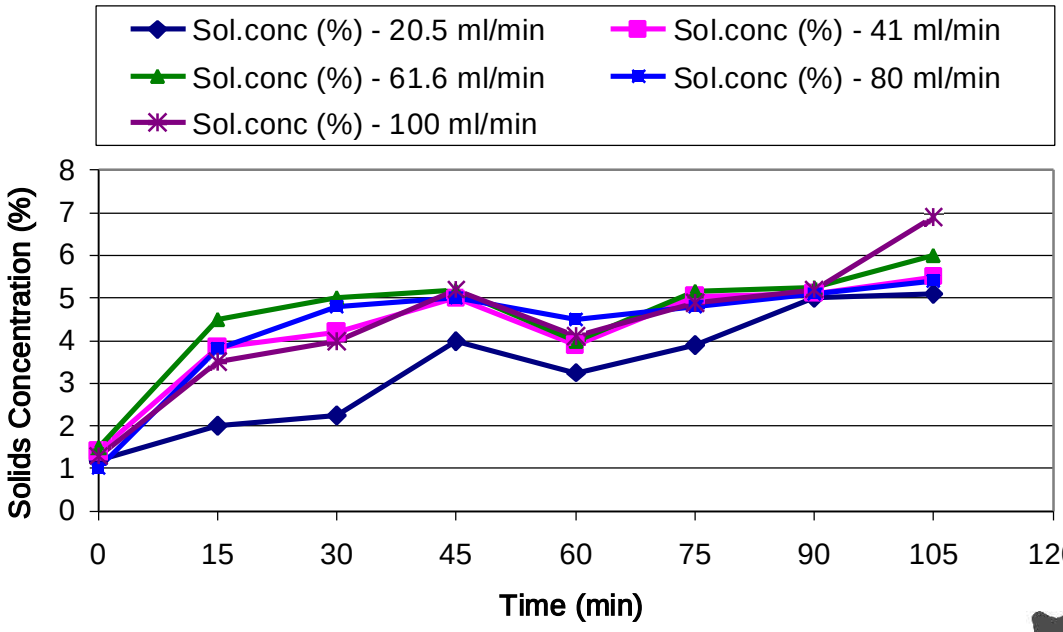

Figure 5.2. Solids concentrations with respect to time for 200 µm mesh siz

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Park (2004) investigated that the cake formation time was highly depended on the solids loadings and this lead to differences in initial and final solids concentrations. In the thickening of biological sludge samples with mesh filtration, the trend that Park (2004) explained was seen clearly again in the 200 µm mesh size. In the fist phase of thickening, especially for high solids loadings greater than 15 $kg/m^2.d$, there was a quick cake formation and, in the second phase the increase of sludge concentration over the mesh was not noticeable. The big differences between two phases were apparent when the solids loading were less than 10 $kg/m^2.d$. This can be explained with the clogging occurring of a longer time leading to slower cake formation. After the clogging, the cake formation became stable and remained nearly constant throughout the experiments.

The sludge thickening performance of the 200 µm mesh size was better than a conventional sludge thickener. In this study, it was seen that the final solids concentrations ranged between 5.1% and 6.9% which was greater than that of the conventional gravity sludge thickeners for an extended aeration system.

5.1.2. Effect of Polymer

The effect of polymer addition was also investigated in this study. For all the samples, 1 mg/l cationic polymer added and same hydraulic loadings were applied on meshes, 100 µm and 200 µm. The polymer effect was seen clearly on low solids loadings especially.

5.1.2.1. 100 µm Mesh Size Experiments. The results of 100 µm mesh thickening experiments with 1 mg/l polymer addition. In this part, the results obtained from thickening with this mesh size were given in Table 5.3.

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Table 5.3. Summary of polymer added mesh thickening results of biological sludge samples for 100 µm mesh size

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)
100	20.5	1.45	0.26	7.7	97
100	41	8.58	0.77	7.7	90
100	61.6	18.75	1.1	7.67	85
100	80	21.74	1.0	5.3	81
100	100	24.72	0.9	4.5	80

As seen in the Figure 5.3, the lowest flow rate, 20.5 ml/min was applied to the system. The initial solid concentration was 0.26%. The solids loading was very low due to initial feed concentration and it was calculated as 1.45 $kg/m^2.d$. The resulted final solid concentration reached to 7.7% and the sludge volume reduction was 97%.

In the Figure 5.3, the result of the 41ml/min flow rate was given. At the beginning, the solids concentration given to the system was measured as 0.77% and the solids loading was 8.58 $kg/m^2.d$. The final solid concentration at the end of experiment was 7.7%. The resultant percent volume reduction was very high, 90% approximately.

The flow rate was increased to 61.6 ml/min. The solids loading became greater due to initial solids concentration and flow rate. It was 18.75 $kg/m^2.d$. At the beginning, the solids concentration was 1.1% and the final solids concentration reached at 7.67%. The overall sludge volume reduction was calculated as 85%.

When the flow rate was 80 ml/min and the solids loading was 21.74 $kg/m^2.d$. It was seen that the initial solid concentration was 1.0% and the final solid concentratio to 5.3%. The sludge volume reduction was observed as 81%.

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The maximum hydraulic loading was used and the sludge feeding rate was 100 ml/min. The solids loading calculated as 24.72 kg/m^2.d. At the beginning, the solids concentration was 0.9% and at the end of thickening operation, it was reached to 4.5% with an overall sludge volume reduction of 80%.

As shown in the Figure 5.3, through all the experiments, the same trend of polymer application was seen. There was no big difference between two phases of the experiment. In the second phase, 15 minutes of recovery period was investigated. In the first phase, an increase in solids concentration can be observed but in the second phase, there was no improvement in solids concentration.

It can be concluded that, polymer addition had an absolute positive effect for low solids loadings. In this situation, a quick sludge cake formation was observed in the first phase, then, the solids concentration remained nearly same as before after recovering period. On the other hand, when solids loading increased more than 20.0 kg/m^2.d, the effect of polymer was not noticeable. This could be due to insufficient dosage of polymer and this problem could be managed by adding higher dosages of polymer. Experiments by applying higher dosages were done and the final solids concentrations obtained were higher but on the other hand, the cost of polymer would be very high and not be economically feasible. The results of the higher dosages of polymer application will be given after.

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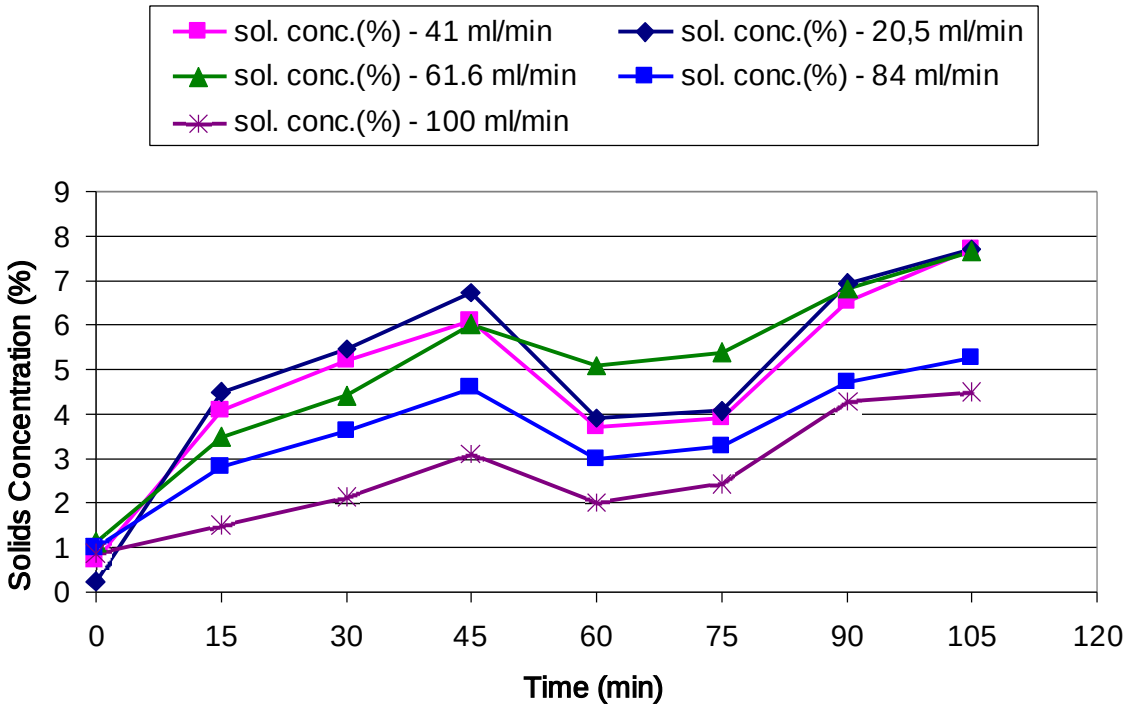

Figure 5.3. Solids concentrations with respect to time for 100 µm mesh size with 1 mg/l polymer addition

Park (2000) reported that coagulant addition retarded the cake formation and the cake was not properly formed and separation of sludge was not effective. On the other hand, this study showed that the coagulant addition had a positive effect on the formation of sludge cake and improvement of the solids concentration over the mesh. Moreover, the sludge cake formation time decreased, in other words sludge cake formed quicker. Once the cake formed, concentration of solids increased over the mesh more than that of the experiments without polymer addition.

In order to clarify the effect of polymer addition, additional experiments were carried out under same conditions. The results are given in Figure 5.5 and 5.6.

5.1.2.2. 200 µm Mesh Size Experiments. The same hydraulic loadings were appl
200 µm mesh size in order to compare with the 100 µm mesh. The results were
the following figures from Figure 5.16 to Figure 5.20.

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Table 5.4. Summary of polymer added mesh thickening results of biological sludge samples for 200 µm mesh size

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)
200	20.5	2.0	0.4	7.8	95
200	41	2.8	0.3	7.6	97
200	61.6	25.0	1.5	3.5	59
200	80	29.7	1.3	4.8	81
200	100	43.4	1.6	3.4	53

As seen in the Figure 5.4, the lowest flow rate, 20.5 ml/min was applied to the system. The initial solid percent was 0.4. The solids loading was very low due to initial sludge concentration and it was calculated as 2.0 $kg/m^2.d$. The resulted final solid concentration reached to 7.8% and the percent volume reduction increased to 95%.

For a flow rate of 41ml/min, at the beginning, the solids concentration given to the system was measured as 0.3% and the solids loading was 2.80 $kg/m^2.d$. The final solid concentration at the end of experiment was 7.6%. The resultant percent volume reduction was very high, 97% approximately.

The flow rate was increased to 61.6 ml/min. The solids loading became greater due to initial solids concentration and flow rate. It was 25.0 $kg/m^2.d$. At the beginning, the solid percent was 1.5 and the final solids concentration reached at 3.5%. The overall sludge volume reduction was calculated as 59%.

In the Figure 5.4, it was seen that the initial solid concentration was 1.3% and the final solid concentration reached to 4.8%. In this experiment, the flow rate was 80 ml/min and the solids loading was 29.7 $kg/m^2.d$. The sludge volume reduction was ob 81%.

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The maximum hydraulic loading was used and the sludge feeding rate was 100 ml/min. The solids loading calculated as 43.4 kg/m^2.d. At the beginning, the solids concentration was 1.6% and at the end of thickening operation, it was reached to 3.4% with an overall sludge volume reduction of 53%.

It can be said that 100 µm mesh results were better than 200 µm mesh. It is clear that the size of the openings of mesh had an effect on this.

The application 1 mg/l polymer for high solids loadings did not improve the solids concentration on mesh but the positive effect of the polymer addition was seen on recovery period. In the experiments without polymer addition, a sharp decrease of solids concentration over the mesh seen. In polymer added applications, the recovery period was again investigated but the sharp decrease of the solids concentration was not noticeable for high solids loadings. This can be due to the sludge cake formation time. When the solids loading was low namely less than 20 kg/m^2.d, sludge cake was formed later when compared to the solids loadings greater than 20 kg/m^2.d. For higher solids loadings with polymer addition, sludge cake formed quickly and once the cake formed, sharp decrease solids concentration over the mesh did not change much.

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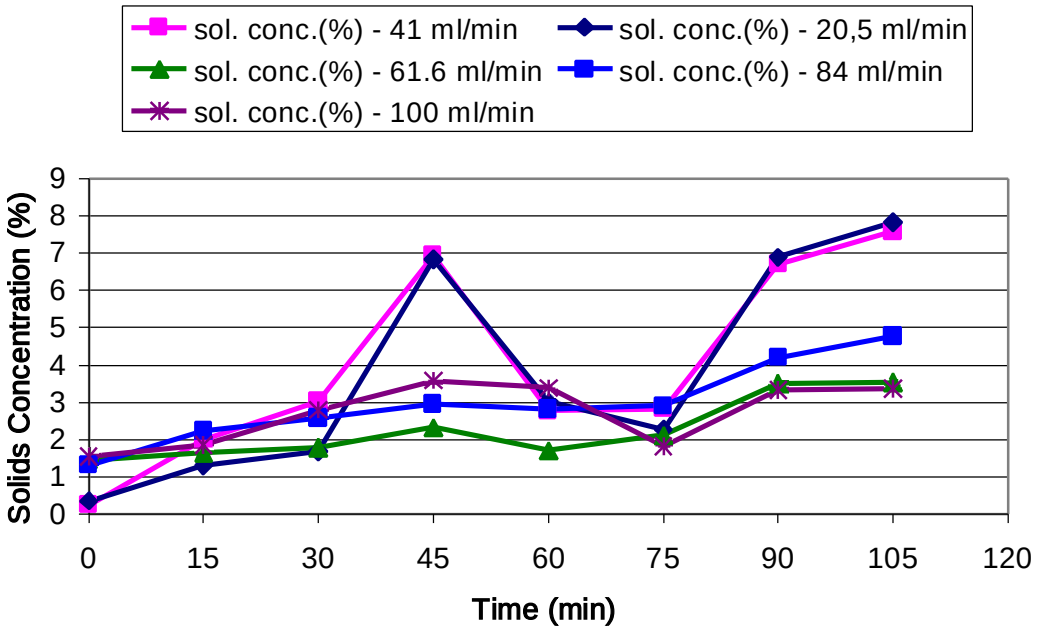

Figure 5.4. Solids concentrations with respect to time for 200 µm mesh size with 1 mg/l polymer addition

It can be concluded that, polymer addition had an absolute positive effect for low solids loadings. In this situation, a quick sludge cake formation was observed in the first phase, then, the solids concentration remained nearly same as before after recovering period. On the other hand, when solids loading increased more than 20.0 kg/m^2.d, the effect of polymer was not noticeable. This could be due to insufficient dosage of polymer and this problem could be managed by adding higher dosages of polymer. Experiments by applying higher dosages were done and the final solids concentrations obtained were higher but on the other hand, the cost of polymer would be very high and not be economically feasible. The results of the higher dosages of polymer application will be given after.

Effect of polymer addition for low solids loadings can be seen in the Figure 5.5 and Figure 5.6 for the same flow rates and for different mesh sizes.

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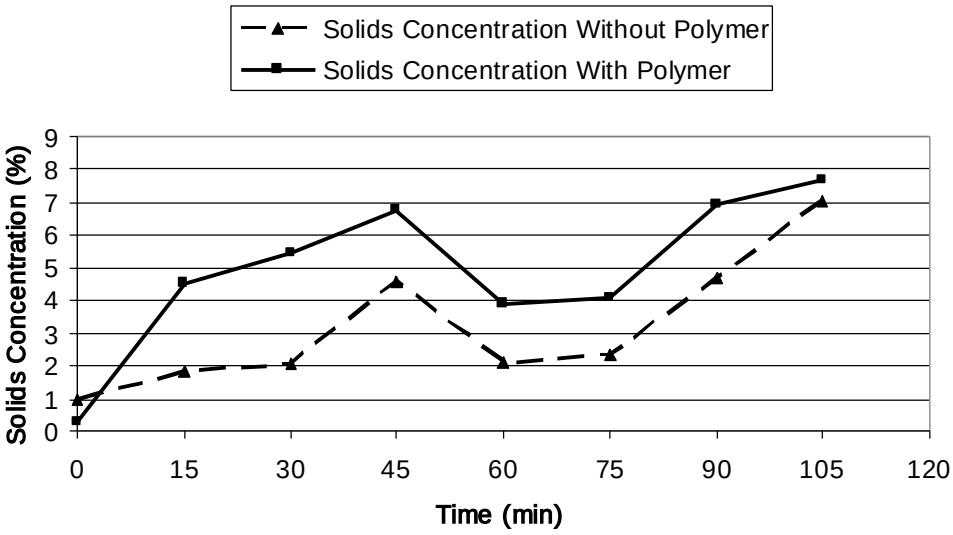

Figure 5.5. Effect of polymer addition on 100 µm mesh for 20 ml/min

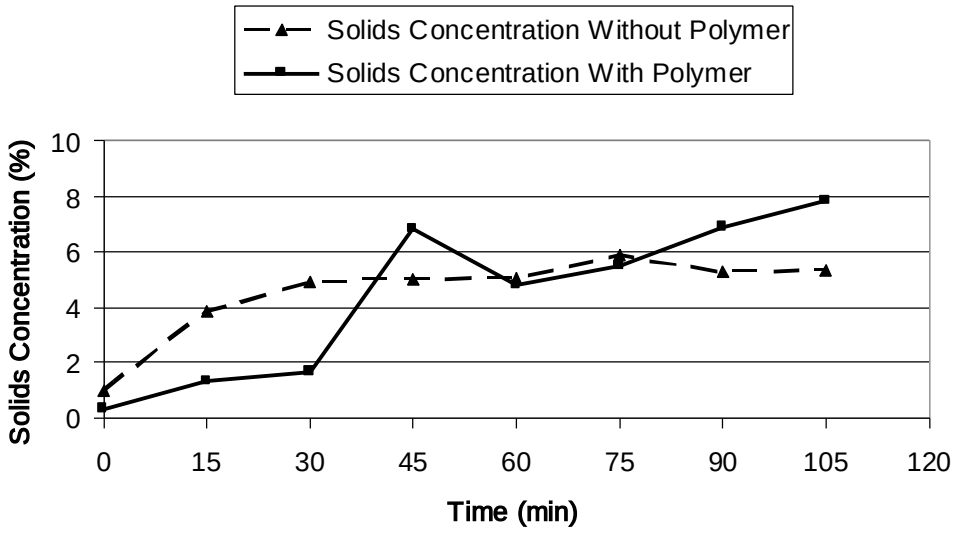

Figure 5.6. Effect of polymer addition on 200 µm mesh for 20 ml/min

As seen in the Figures 5.5 and 5.6, for low solids loadings, when the experiment results were evaluated, it can be observed clearly that polymer had a positive effect on sludge thickening.

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5.1.3. Effect of Solids Loading

The effect of solids loading was a very important criterion for the thickening of sludges. In order to compare with real case gravity sludge thickeners and to find out the efficiency of the mesh thickening, and optimum solids loading, the graphics of solids loading versus sludge volume reduction (in folds) were plotted. In the graphics, 100 µm and 200 µm mesh sizes with and without polymer addition were investigated.

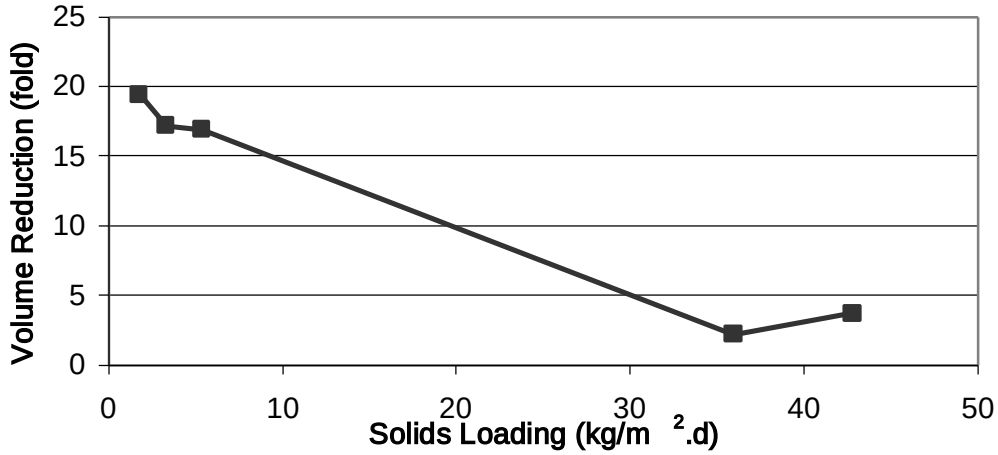

Figure 5.7. Sludge volume reduction with respect to solids loadings for 100 µm mesh

In the Figure 5.7, the effect of solids loading on the 100 µm mesh size could be seen. The general trend was a decreasing volume reduction with an increasing solids loading as expected. The point that should be focused on these sets of experiments, all the values of final solids concentrations was higher than that of the conventional thickener of a large scale treatment plant. The end value of thickened sludge, as mentioned before, was 2-3% generally for gravity thickeners. In small scale treatment plants which were the subject of this study, the solids loadings would be much less than these values (from 24.4 to 34.2 $kg/m^2.d$).

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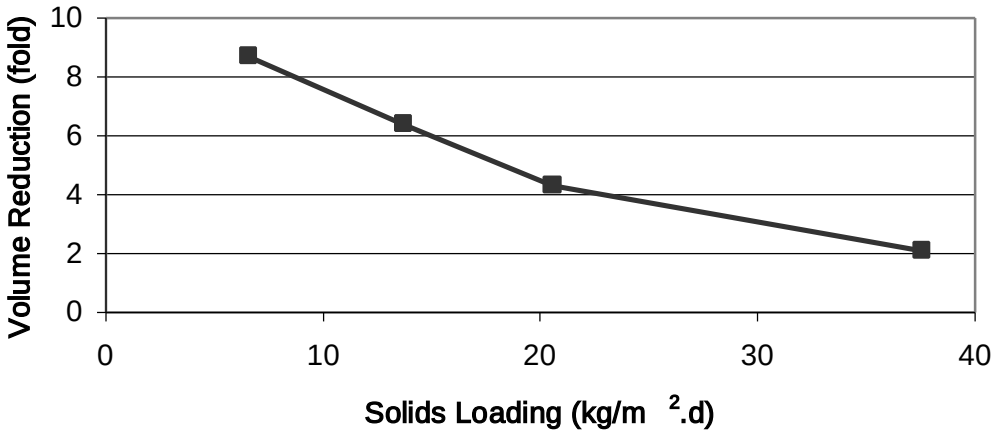

Figure 5.8. Sludge volume reduction with respect to solids loadings for 200 µm mesh

In the Figure 5.8, the effect of solids loading on 200 µm mesh size could be observed. Although the reached values were less than the 100 µm mesh, the results were quite satisfying for a thickening operation. The trend of the sludge volume reduction was very similar to the 100 µm mesh, as the loading increased, the volume reduction decreased.

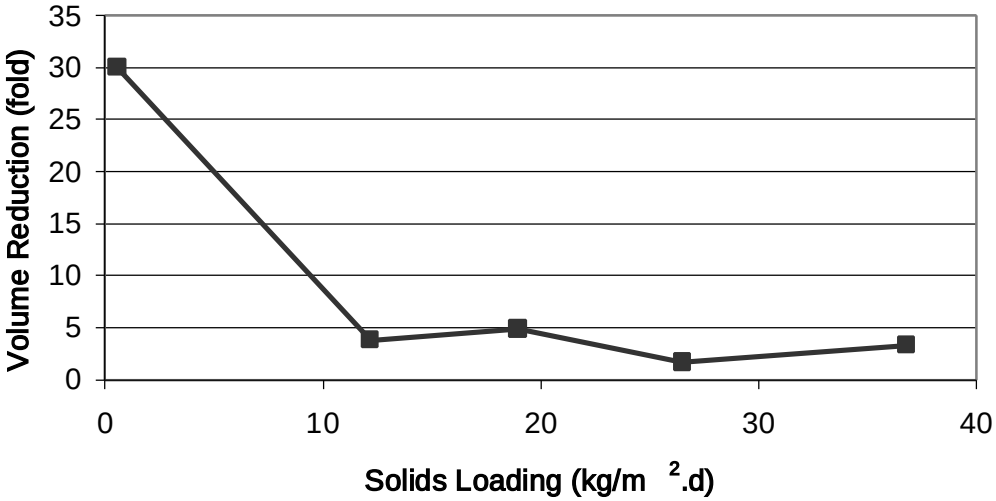

Figure 5.9. Sludge volume reduction with respect to solids loadings with 1 mg/l ca
polymer addition for 100 µm mesh

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In the Figure 5.9, the effect of polymer addition on 100 µm mesh size could be investigated. The figure showed that the polymer was very effective for low solids loadings and as the loading increased, the effect was not noticeable. This was due to low polymer dosage added to the system. The trend was not different from the Figure 5.7 and Figure 5.8. During 100 µm mesh size thickening without polymer reached at a maximum value of approximately 20 folds of its initial value whereas in the polymer added application the solids concentration reached to 30 folds of the initial solids concentration.

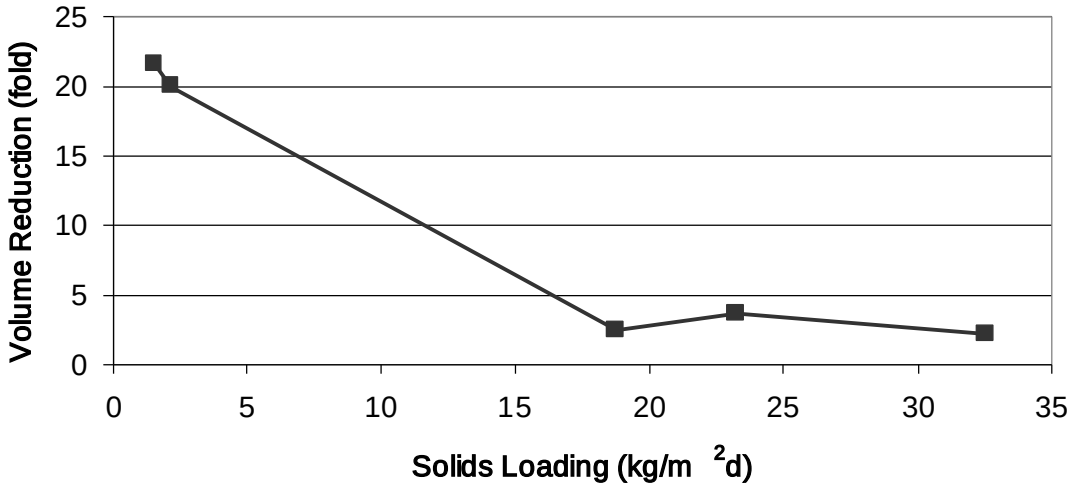

Figure 5.10. Sludge volume reduction with respect to solids loadings with 1 mg/l cationic polymer addition for 200 µm mesh

In the Figure 5.10, the effect of polymer addition on 200 µm mesh size was shown. As in the previous figure, the efficiency of polymer was very important for low solids loadings. The overall percent volume reduction was less than the 100 µm mesh size because of the smaller size of openings. For the low solids loadings, polymer addition increased the volume reduction up to 22 folds whereas it was about 9 folds for the not polymer added application for the same mesh. Parallel to all solids loading versus volume reduction trends, the decrease could be seen for high solids loadings. The dosa polymer could be increased but this would not be an economical solution.

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It can be concluded that, for all solids loadings, the mesh thickening could manage to obtain a solids concentration at the end greater than 3%, even in no polymer added applications. Polymer addition was a good solution for low solids loadings but, in high solids loadings, the dosage of 1 mg/l was not enough.

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5.2. Thickening of Chemical Sludge with Mesh Filtration

The used mesh opening sizes for the thickening process were 100 µm and 200 µm. 5 different flow rates were applied to the system. The sludge feeding flow rates were between 20.5 and 100 ml/min.

Thickening of chemical sludge with meshes was a new method for thickening. In the literature, mesh thickening was only applied for biological sludges.

The chemical sludge used for the thickening studies was brought from a metal processing industry. The sludge was taken from the silo just before the pressure filter of the treatment plant of the facility. The raw sludge's initial solids concentration varied between 2.1% and 2.7% during the experiments.

Solids loadings changed according to feed sludge flow rate and initial solids concentration applied. During the experiments, solids loadings applied to the system were from 9.0 to 55.1 kg/m^2.d for 100 µm mesh and from 9.6 to 57.0 kg/m^2.d for 200 µm mesh.

The effect of polymer addition was also investigated in this study by adding 1.0 mg/l cationic polymer.

The total suspended solids and chemical oxygen demand of the final filtrates were measured to compare with the discharge values of ISKI.

5.2.1. Effect of Mesh Size and Flow Rate

Chemical sludge thickening with mesh was a new study which was not found in the literature. This study was done because small scale wastewater treatment plants were using usually chemical treatment and the volume reduction of sludge was a big problem both for dewatering and transportation issues. For example, if the sludge concentration could be increased from 2% to 4%, this meant that the transportation cost would be reduce simply, and this was a great cost decrease for these plants.

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5.2.1.1. 100 µm Mesh Size Experiments. As in the biological sludge experiments, 100 µm mesh size was used firstly. The following figures will give results for different flow rates of sludge feeding to the system and moreover, initial and final solids concentrations obtained on the mesh, solids loadings and the trend of solids concentration increases will be mentioned. Lastly, the results of the final sludge concentration showed that they were in the line between thickening and dewatering because it was generally said that dewatering started after 15% sludge concentration.

Table 5.5. Summary table of the mesh thickening of chemical sludge with mesh opening of 100 µm

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)
100	20.5	9.0	2.1	11.9	82
100	41	18.0	2.1	12.1	83
100	61.6	32.0	2.5	11.9	79
100	80	45.0	2.6	12.5	80
100	100	55.0	2.6	11.2	77

The first flow rate for the experiment was 20.5 ml/min. It can be seen from the Figure 5.11, initial solids concentration was 2.1% and the final solids concentration was measured as 11.9% at the end. During the procedure, 9.0 $kg/m^2.d$ solids loading was applied and the sludge volume reduction occurred as 82%.

The flow rate increased to 41 ml/min and as a result of higher flow rate, solids loading rose to 18 $kg/m^2.d$. Initial solid concentration was 2.1% and reached to a value of 12.1% at the end of experiment. The overall volume reduction was 83%.

A sludge flow of 61.6 ml/min was used. At the beginning, the solids con was measured as 2.5% and at the end, the result was 11.9% with a solids load $kg/m^2.d$. The volume reduction of sludge was 79%.

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The next flow used was 84 ml/min. The solids loading was calculated as 45 kg/m^2.d. The obtained solids concentration was 12.5% and it improved from 2.6%. The overall sludge volume reduction was 80%.

In the Figure 5.11, it can be seen that the maximum hydraulic loading was used, 100 ml/min. Initial solids concentration was 2.6% and at the end of thickening operation, it was 11.2%. This result obtained by applying 55 kg/m^2.d solids loading. The overall sludge volume reduction was 77%.

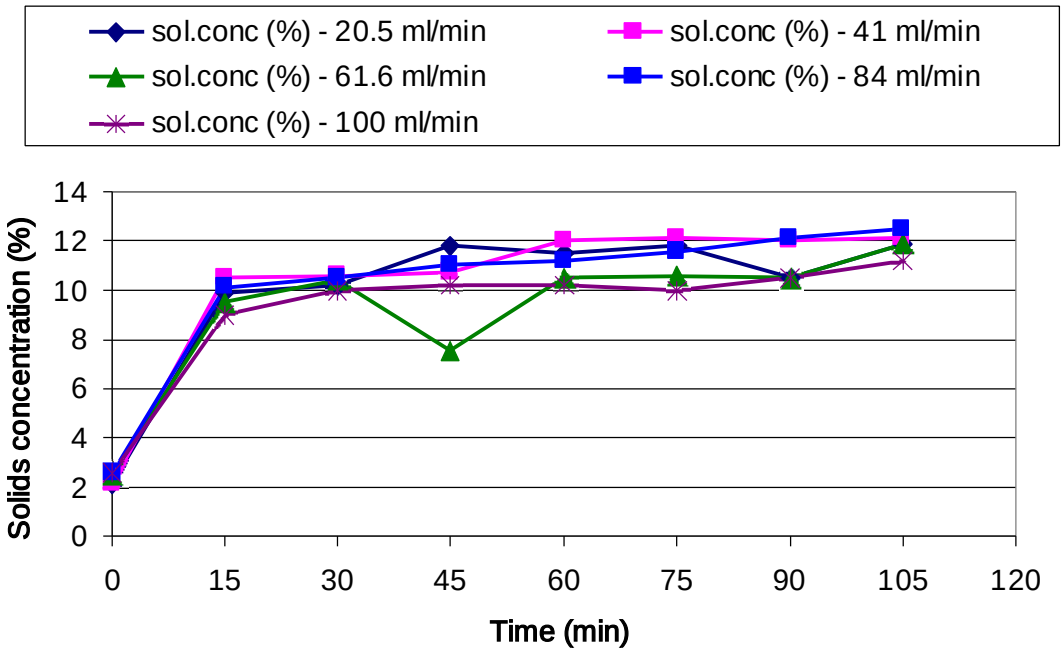

Figure 5.11. Solids concentrations with respect to time for 100 µm mesh size

The general trend of chemical sludge thickening can be seen in Figure 5.11. In the first phase, a quick increase of solids concentration was observed and than it remained nearly unchanged during whole procedure. In the first phase, the solids concentration increased between four and fives folds when compared with the initial concentration. In the second phase, there was approximately no improvement. At the end of procedure, the resultant solids concentrations were nearly the same with that of the value reach end of first phase. The increases were less than one fold generally.

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The flocs of the chemical sludge were less porous and less irregular than the flocs of the biological sludge (Perez et al., 2006). Regularity of the flocs of the chemical sludge provides more compacted sludge (Keijzer and Loch, 2001). The chemical flocs block the pores of the mesh quicker than the biological flocs and once the pores are blocked with regular sized chemical flocs, the concentration of solids did not improved after the first phase. In the second phase, compaction mechanism became more important. Thus the sludge cake height increased more than the expected values. The ratio of chemical sludge cake height measured to the theoretical sludge cake height was more than that of the biological sludge. Sludge cake height will be discussed in Section 5.5.

The reason for higher final solids concentrations of the chemical sludge at the end of thickening than the biological sludge can be explained by the concentration of Al^{3+} because high concentration of Ca^{2+}, Mg^{2+}, Fe^{3+} and Al^{3+} had significant improvement for dewaterability (Jin et al., 2004). It was mentioned in the Materials and Methods section that the chemical sludge was gathered from a metal processing industry which was using alum as a coagulant. The concentration of Al^{3+} improved the dewaterability and hence the thickening of chemical sludge.

The recovery period needed for the biological sludge thickening was not necessary for the thickening of chemical sludges with mesh filtration. As it can be seen from the Figure 5.11, there were no sharp decreases of solids concentrations on the mesh. This can be explained by the compaction of chemical sludges and regular pattern of the flocs.

5.2.1.2. 200 µm Mesh Size Experiments. As in the biological sludge experiments, 200 µm mesh size used after 100 µm. Flow rates used were same and the results were given by the following figures. The general pattern of the solids concentration increase was very similar and the results of the final solids concentration were very close to the 100 µm mesh ones.

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Table 5.6. Summary table of the mesh thickening of chemical sludge with mesh opening of 200 µm

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)
200	20.5	9.6	2.3	11.4	80
200	41	20.0	2.4	10.4	78
200	61.6	32.0	2.5	10.9	77
200	80	47.0	2.7	12.3	78
200	100	56.0	2.7	12.8	79

The same trend between phases of thickening was developed in the 200 µm mesh size as it was in the 100 µm mesh size. From the Figure 5.12, it can be seen that there is a quick increase of solids concentration till the end of first phase and there was nearly no further increase in the solids concentrations. The differences in solids concentration values were less than two percent between first and second phase of the thickening process. The obtained results of the final solids concentrations of the 200 µm mesh size were very close to the 100 µm mesh size results. The pore blocking occurred in the first 15 minutes of the experiment. Quick formation of the sludge cake removed the difference between pore sizes of the mesh.

As it is showed in the Figure 5.12, the recovery period was not necessary in the thickening with 200 µm mesh size also as it was in the 100 µm mesh size. The compaction of the chemical sludge provided that there was no need for recovery time.

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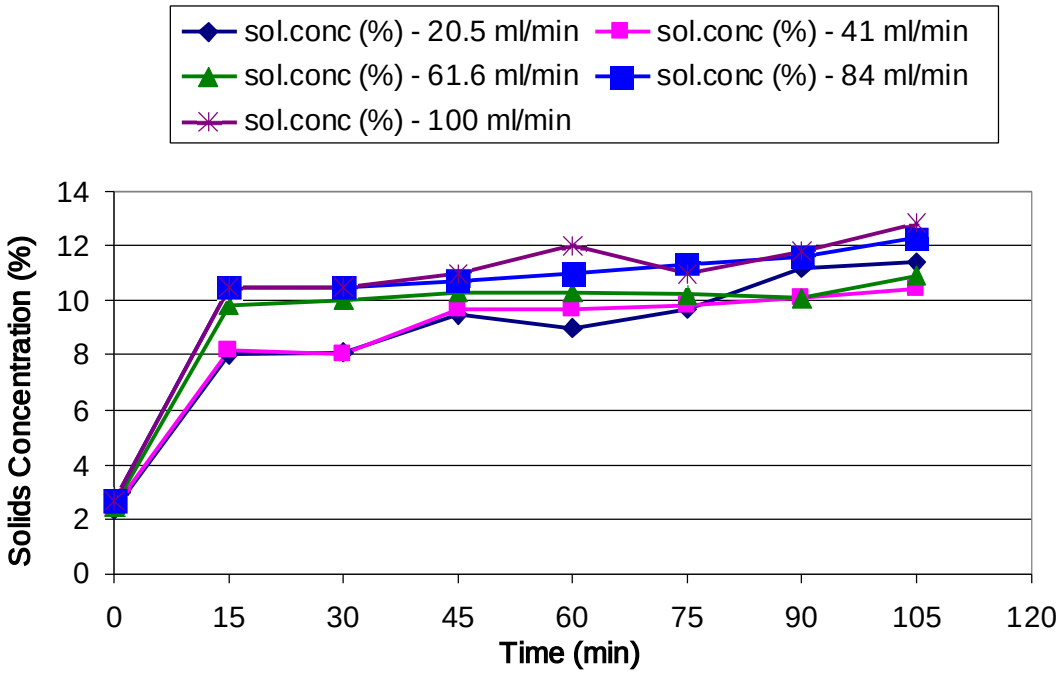

Figure 5.12. Solids concentrations with respect to time for 200 µm mesh size

Chemical sludge thickening with mesh showed very successful results in all cases. Both mesh size could thicken the sludge for all solids loadings and hydraulic loadings. 100 µm mesh was more efficient according to 200 µm mesh because of the smaller pore size. During the whole experiments, the trend of sludge thickening was very similar. There were no big differences between two phases of procedures. Quick cake formation was investigated and it was occurred generally at 15th minute and remained stable throughout the experiment. In the opposite of biological sludge, a recovery period was not needed due to restart of the feeding period.

In the 100 µm mesh experiments, the average percent volume reduction was 80.2% where the maximum reduction was 83% and the minimum 77%. The final solids concentrations were very close to each other and they were ranged from 11.2% to 12.5%. Solids loadings were higher than the biological applications and the results obtained showed better efficiency.

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In the 200 µm mesh experiments, the average of sludge volume reduction was 78.4% and they were fallen into a range between 77% and 80%. The minimum final solids concentration obtained was 10.4 and the maximum was 12.8. Solids loading were similar to the 100 µm mesh and they were again higher than biological applications.

5.2.2. Effect of Polymer Addition

5.2.2.1. 100 µm Mesh Size Experiments. As in the all experiments, flow rates were from 20.5 ml/min to 100 ml/min. 1 mg/l cationic polymer was added to the sludge feed. The results were given by the help of following table and figure. Final solids concentrations were incredibly high especially for low solids loadings.

Table 5.7. Summary table of the polymer added mesh thickening of chemical sludge with mesh opening of 100 µm

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Content (%)	Final Solids Content (%)	Sludge Volume Reduction (%)
100	20.5	9.2	2.1	21.0	90
100	41	18.0	2.1	16.1	87
100	61.6	28.0	2.2	15.9	86
100	80	43.0	2.7	16.2	83
100	100	54.0	2.6	17.1	85

Park (2001) investigated that the addition of a coagulant was a retardant factor for the sludge cake development and had a negative effect on the cake. Addition of 1 mg/l cationic polymer increased the final solids concentration of the thickening process as it is showed in Table 5.7 when compared to the thickening experiment without polymer addition. However, it can be seen from the Figure 5.13 that the occurrence of the sludge cake and stability (no further improvement of the solids concentration) retarded after the a the polymer which was not investigated in the none polymer added application polymer addition, the cake developed quickly in the first 15 minutes and remain

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constant during the rest of the experiment. In the polymer added experiment, although the final solids concentrations reached higher values, sludge cake occurrence was late. On the other hand, unlike Park (2001), the addition of the polymer had an absolute positive effect on the final solids concentration. The reason can be the usage of polymer type.

At low solids loadings, the positive effect of the polymer addition was very clear that the final solids concentration reached to 21.0 %. At high solids loadings, the differences between solids concentration percents were also higher than the experiments without polymer addition but the increases were not much. The reason can be the insufficient dosage of polymer.

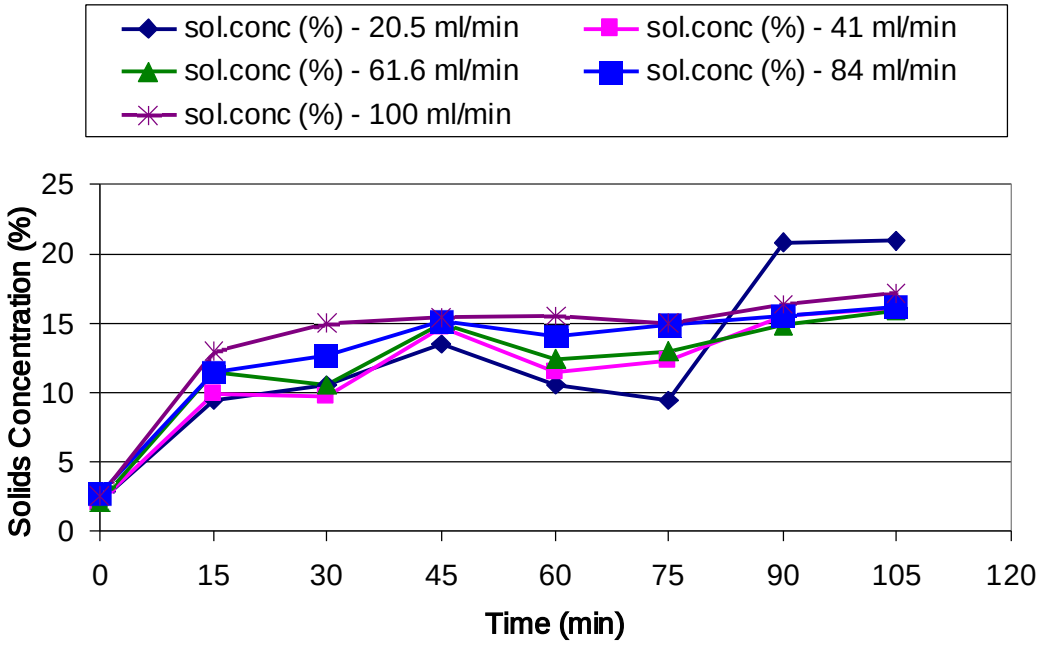

Figure 5.13. Solids concentrations with respect to time for 100 µm mesh size with 1 mg/l polymer addition

5.2.2.2. 200 µm Mesh Size Experiments. As in the all experiments, flow rates were from 20.5 ml/min to 100 ml/min. 1 mg/l cationic polymer was added to the sludge feed. The results were given by the help of following table and figure. Final solids concentrations were very high especially for low solids loadings.

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Table 5.8. Summary table of the polymer added mesh thickening of chemical sludge with mesh opening of 200 µm

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)
200	20.5	10.0	2.3	21.1	89
200	41	21.0	2.5	14.5	83
200	61.6	32.0	2.7	14.3	81
200	80	46.0	2.7	12.6	79
200	100	56.0	2.7	12.3	78

The same effect of polymer was seen in the 200 µm mesh size as in the 100 µm mesh size. The cake occurrence retarded and the solids concentration increased through the experiment as it is showed in Figure 5.14.

At low solids loadings, addition of polymer increased the solids concentration when compared to the thickening without polymer but at higher solids loadings, the effect of polymer addition was not clear. The retardation of the sludge cake occurrence decreased the effect of polymer addition. The obtained final solids concentrations were not much different than that of the without polymer added experiments. The dosage of the polymer was insufficient and the final solids concentrations can be increased by applying higher dosages.

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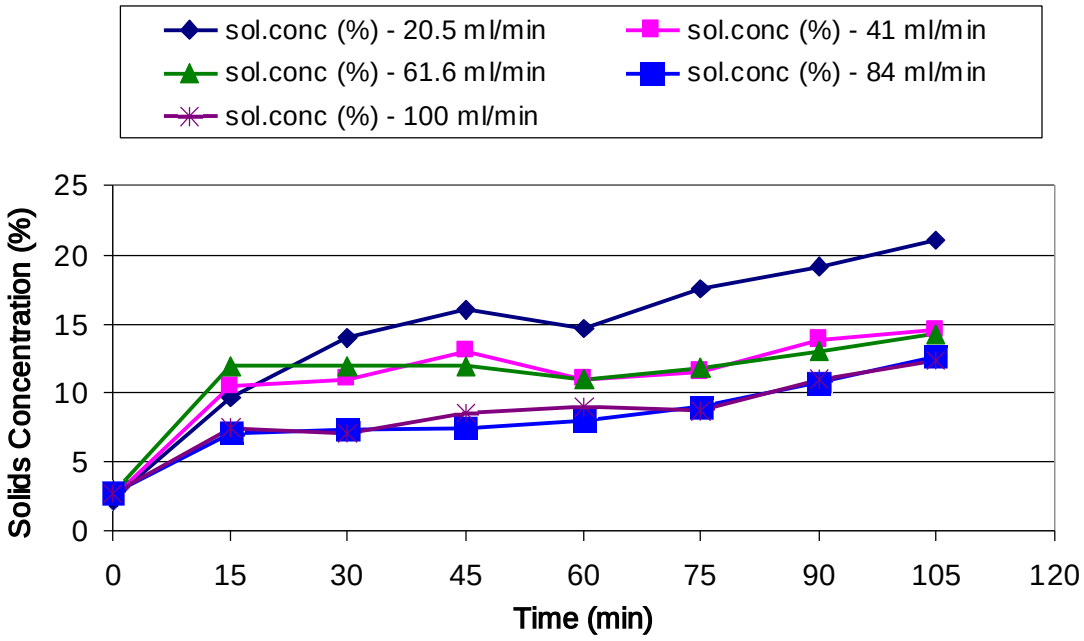

Figure 5.14. Solids concentrations with respect to time for 200 µm mesh size with 1 mg/l polymer addition

The polymer effect on the thickening of chemical sludge was seen clearly especially in 100 µm mesh size. All the values of final sludge concentration obtained were higher than the no polymer added applications.

In 100 µm mesh size, without polymer addition, the most concentrated final sludge was 12.5% where as in the polymer added applications; the minimum value was 15.9%. The solids concentration over the mesh was reached up to 21.0%. The average sludge volume reduction was 87%. It was generally seen that the cake formed in the first phase and endured through the all experiment. Solids loadings were higher than the biological applications but the results obtained much better.

In 200 µm mesh size, the results obtained were higher than the without polymer addition applications except the maximum hydraulic loading. As the solids loadings were higher, the effect of polymer was not noticeable. On the other hand, the obtai
solids concentrations on the mesh was higher when compared to the without

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experiments. The average sludge volume reduction was 81.4%. Especially, in low solids loadings, 200 µm mesh worked efficiently, and reached up to 21.1% solids concentration.

In order to investigate the dosage of polymer, additional experiments were carried out by adding 2 mg/l and 3 mg/l cationic polymer. The results were given in the following Figure 5.15 to Figure 5.18 and in the summary Table 5.9.

As it can be seen from the graphics and Table 5.9, increasing the dosage of the polymer, improved the sludge volume reduction clearly but the increase in the reduction when compared to the 1 mg/l polymer added applications, was not worth to apply this amount of polymer. If the economical comparison was done between gain and cost, it can be concluded that addition of more polymer dosage was not a feasible method for the thickening of chemical sludge with mesh.

Table 5.9. Summary table of the different polymer dosages effect on mesh thickening of chemical sludge

Mesh Opening (µm)	Flow rate (ml/min)	Polymer Dosage (mg/l)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)
100	41	1	2.1	16.1	86
100	41	2	1.66	15.5	89
100	41	3	1.74	17.5	90
100	61.6	1	2.2	15.9	86
100	61.6	2	1.66	14.5	89
100	61.6	3	1.84	16.5	90

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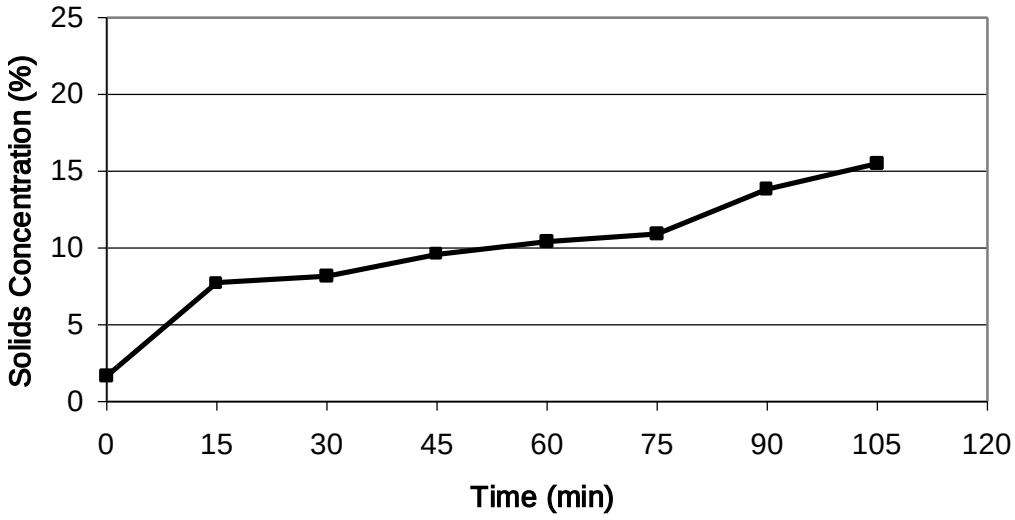

Figure 5.15. Solids concentrations with respect to time for 100 µm mesh size with 2 mg/l polymer addition for 41 ml/min

As in the Figure 5.15, the sludge volume reduction increased to 89%. In the 1 mg/l polymer added experiment with same flow rate and mesh size, the sludge volume reduction was 87%. Doubling the polymer dosage was not affected the sludge volume reduction as expected.

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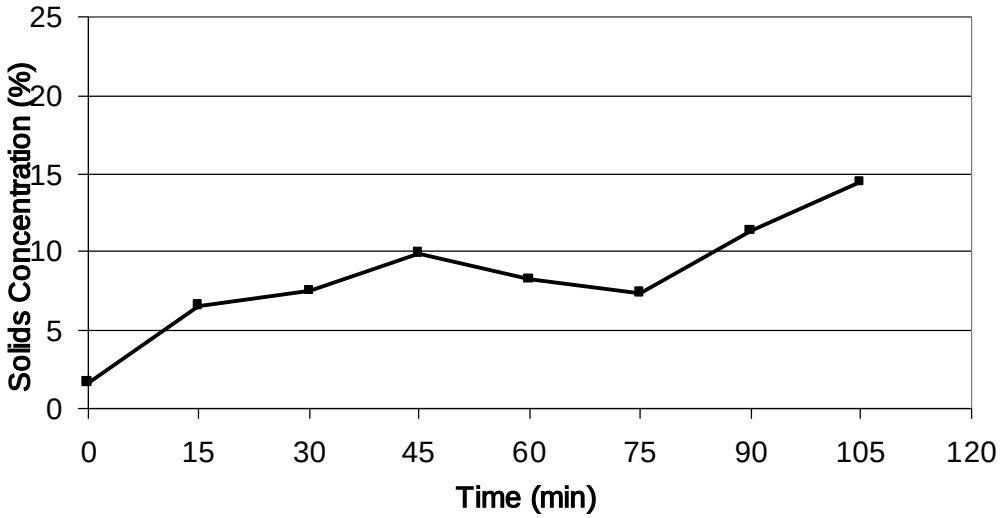

Figure 5.16. Solids concentrations with respect to time for 100 µm mesh size with 2 mg/l polymer addition for 61.6 ml/min

As it can be seen in the Figure 5.16, the experiment with 61.6 ml/min flow rate and 2 mg/l polymer addition, the sludge volume reduction obtained was approximately 89%. By applying same procedure for the same mesh and flow rate when 1 mg/l polymer added, the sludge volume reduction was 87%. Increasing the polymer dosage to 2 mg/l, did not improve the sludge volume reduction as expected.

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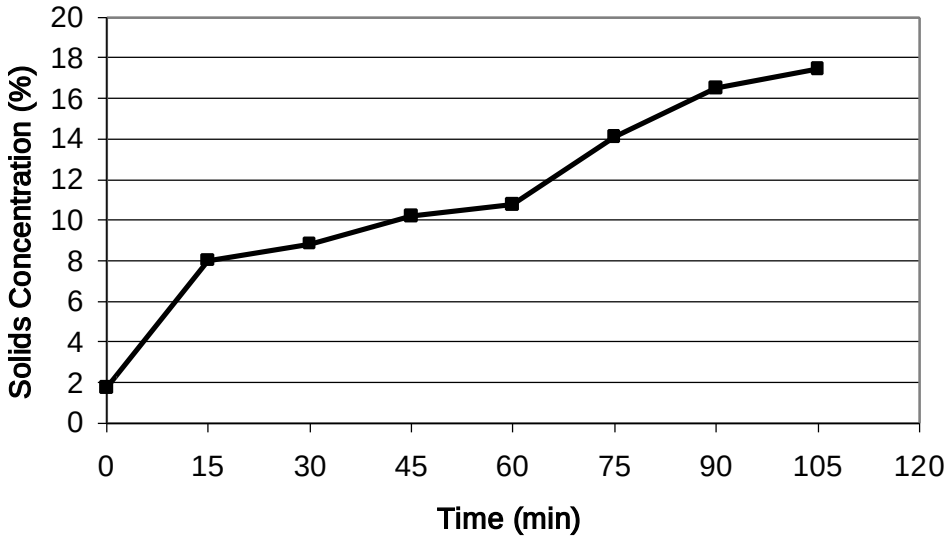

Figure 5.17. Solids concentrations with respect to time for 100 µm mesh size with 3 mg/l polymer addition for 41 ml/min

As in the Figure 5.17, the sludge volume reduction increased to 90%. In the 1 mg/l polymer added experiment with same flow rate and mesh size, the sludge volume reduction was 87% and 89% for 2 mg/l polymer dosage. Increasing polymer dosage to 3 mg/l improved the sludge volume reduction but the result was not high enough to decide to use this amount of polymer.

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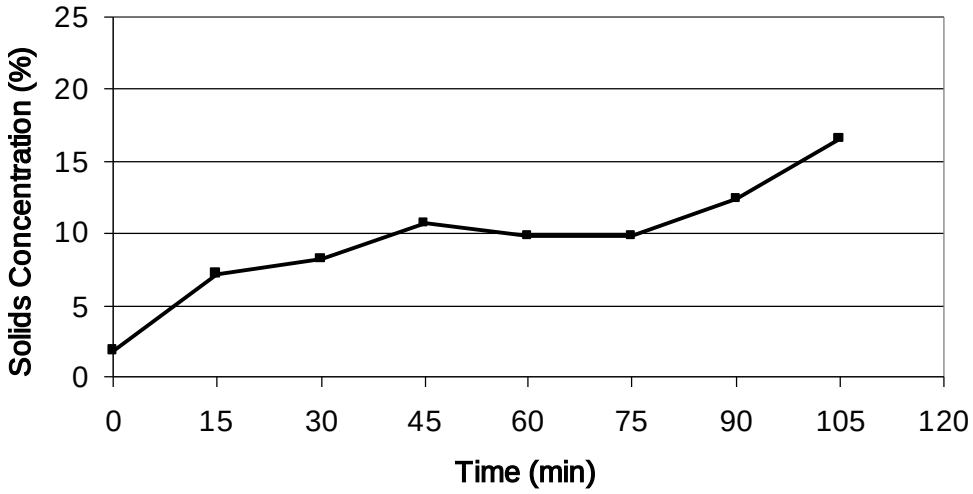

Figure 5.18. Solids concentrations with respect to time for 100 µm mesh size with 3 mg/l polymer addition for 61.6 ml/min

As it can be seen in the Figure 5.18, the sludge volume reduction, approximately 90%, was obtained. By applying same procedure for the same mesh and flow rate when 1 mg/l and 2 mg/l polymer added, the sludge volume reduction was 87% and 89%, respectively. Increasing the polymer dosage to 3 mg/l, did not improve the sludge volume reduction as expected.

5.2.3. Effect of Solids Loadings

The effects of solids loadings were also investigated for both meshes and with and without polymer addition. The following figures would provide to compare the mesh size efficiencies on solids loadings and effect of polymer on solids loadings.

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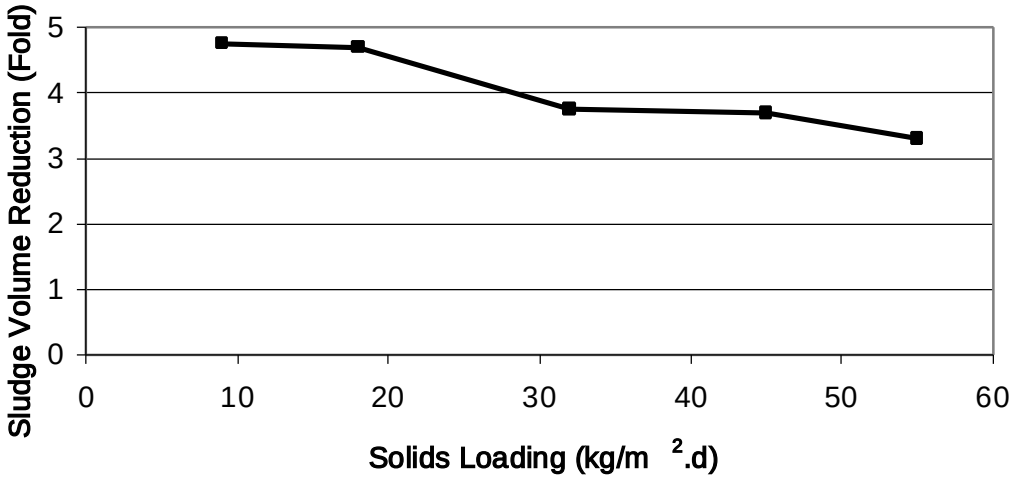

Figure 5.19. Effect of solids loadings on 100 µm mesh without polymer

From the Figure 5.19, it can be concluded easily that low solids loadings gave better results for the thickening of chemical sludge although there were no big differences for different solids loadings. The difference between 10 and 55 kg/m^2.d was just 1.5 folds. This could be explained by the uniform floc structure of the chemical sludge. The cake formed quickly and remained stable during the experiments.

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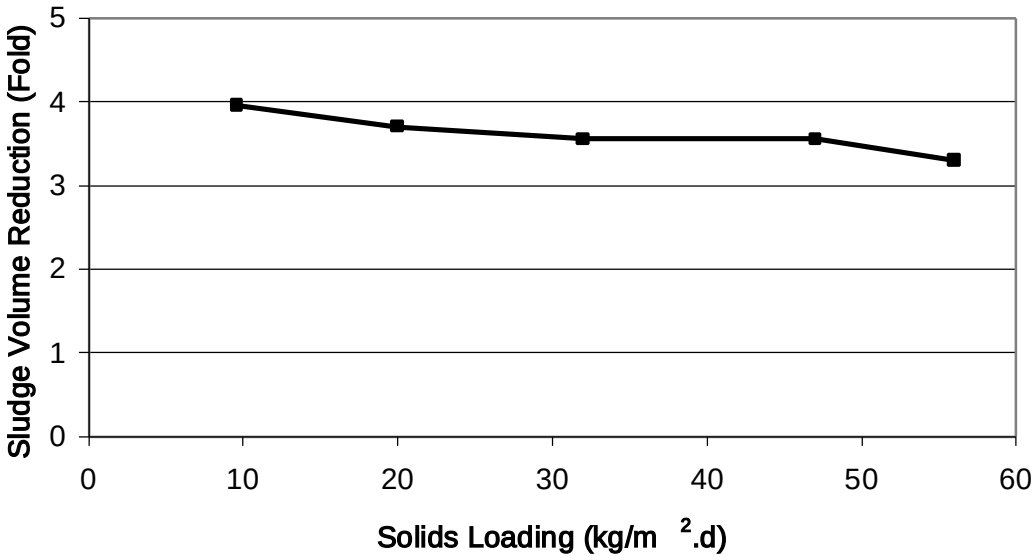

Figure 5.20. Effect of solids loadings on 200 µm mesh without polymer

As shown in the Figure 5.20, solids loading did not particularly affect the efficiency of thickening. Although at low solids loadings better results were achieved, general pattern of the thickening for different solids loading did not changed much. The results obtained for the final solids concentration of this mesh was lower than the 100 µm mesh. They were fallen into a range from 3.3 to 4.1 folds of initial solids concentration.

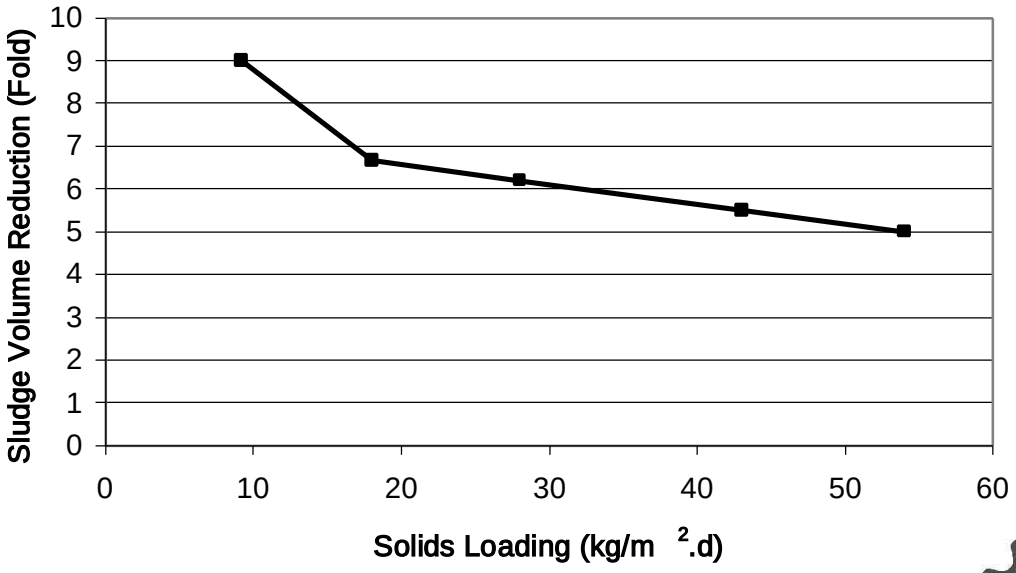

Figure 5.21. Effect of solids loadings on 100 µm mesh with 1 mg/l polymer ad

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As seen in the Figure 5.21, when compared with the application without polymer addition, obtained final sludge volume reductions were higher and almost doubled. Solids loadings effects were clear. As the loading increased, volume reduction decreased.

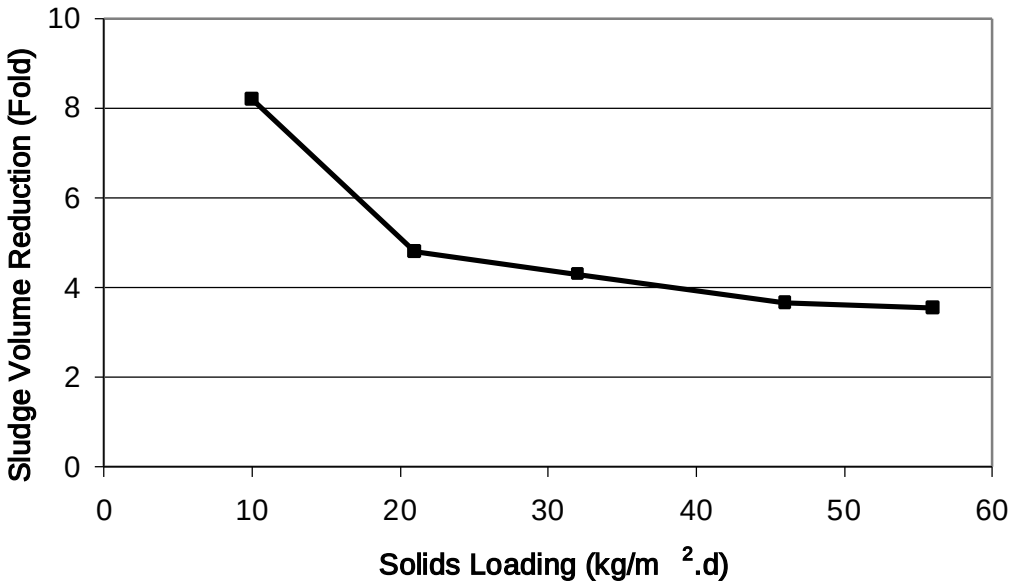

Figure 5.22. Effect of solids loadings on 200 µm mesh with 1 mg/l polymer addition

The solids loadings effect was more obvious in 200 µm mesh size as it is shown in the Figure 5.22. 200 µm mesh affected more than 100 µm mesh against solids loadings. There was a sharper decrease as the solids loadings increased. This can be explained by the smaller pore size of the mesh and retard of the sludge cake occurrence.

5.2.4. Comparison of Conventional Gravity Thickener with Mesh Filter

In this part, the conventional gravity thickener was compared to the mesh filter in terms of solids flux. According to solids flux theory, a typical performance of a gravity thickener was given in the Figure 3.3.

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Solids flux of a conventional thickener which hydraulic loading was 24 m^3/m^2.d was calculated and the result was given in Figure 5.23.

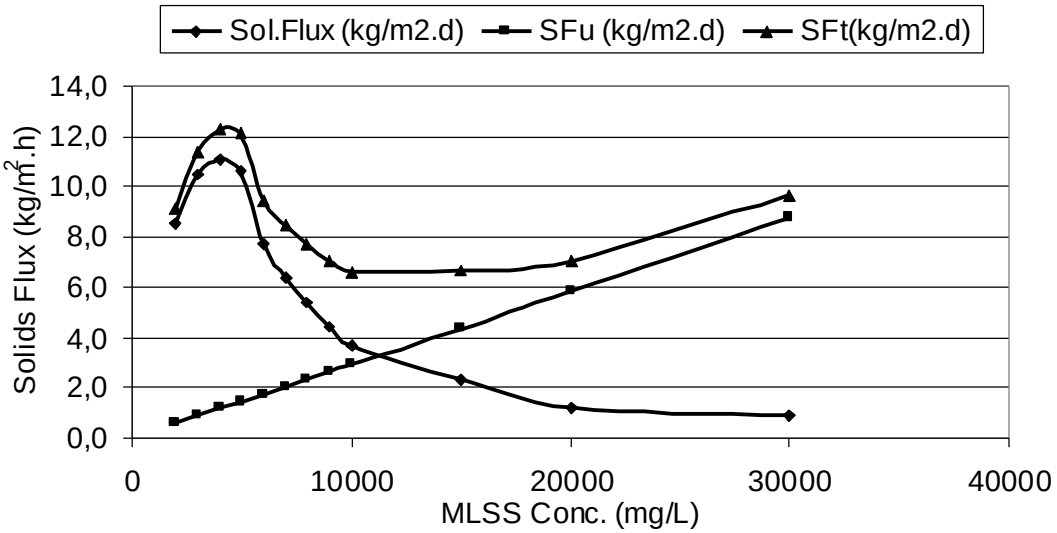

Figure 5.23. Solids flux of a conventional thickener with 24 m^3/m^2.d solids loading

If the same values except the flow rate were applied to the mesh filter with a flow of 100 ml/min (2.7 m^3/m^2.d), Figure 5.24 would be obtained.

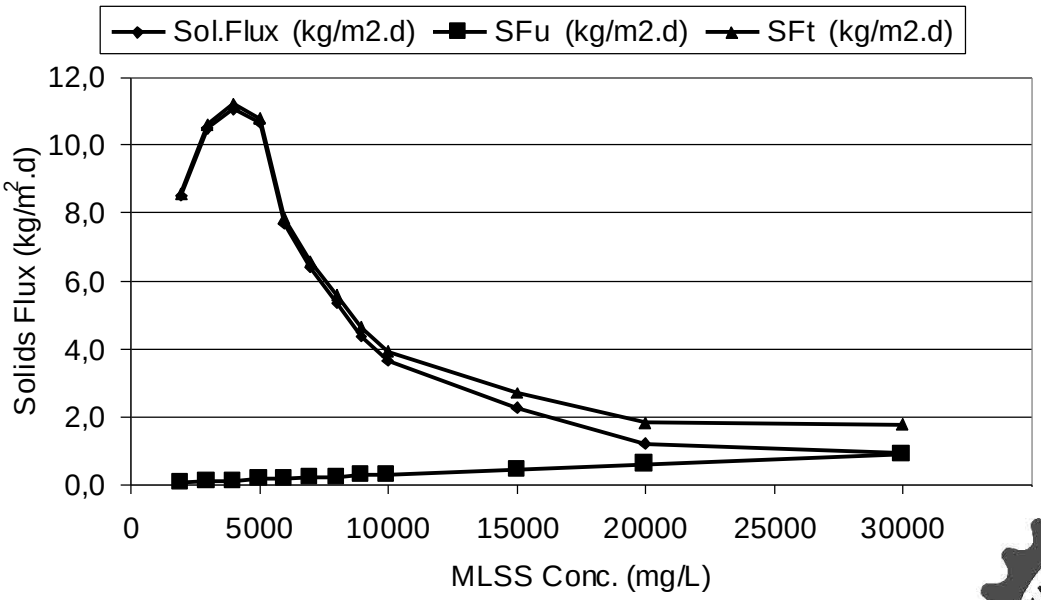

Figure 5.24. Solids flux of the mesh filter

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From the Figure 5.24, it can be calculated that the maximum solids flux would be 44.5 kg/m^2.d according the theory but the minimum solids loading for this flow rate in the mesh thickening was 48.9 kg/m^2.d. As a result, it can be said that the mesh filter's solids loading can be higher than a conventional gravity thickener.

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5.3. Foam Thickening

Thickening of sludges with foam was a new idea and not found in the literature. The purpose of this study was to find out an economical and easy was of thickening for small scale wastewater treatment plants. In order to save the money of the small industries, mesh thickening was investigated and was successful as mentioned in the previous sections but the question was if it could be a more economical solution and if there could be a way to increase sludge flow rate. Foam thickening was the answer of the question. Foam was a material which was cheaper than the steel mesh. As it would be shown in following section, the thickening efficiency was sufficient and moreover, the flow rates used were higher than the mesh applications. The foam could be used several times as mesh and it could be easily disposable when it became useless.

The sludge cake formation endured throughout the experiments in all operations. The flow rates used were from 40 ml/min to 180 ml/min and 8 different flow rates were investigated. The sludge used was brought from Paşaköy Advanced Wastewater Treatment Plant and taken from the recycle line of the return sludge as in the mesh thickening applications. The same procedure was used in foam thickening applications. The solid percent value at 120th minute was the result of the manual dewatering operation which was simply done by squeezing the foam by hand.

The same procedure was applied for the chemical sludge thickening but the cake formation could not be obtained and it was concluded that foam thickening was not an ideal solution for chemical sludge thickening.

The results obtained from the sludge thickening by foam filter were summarized at Table 5.10.

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Table 5.10. Summary table of the foam thickening of biological sludge

Flow Rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Sludge Volume Reduction (%)	Sludge Volume Reduction After Manual Dewatering (%)
40	4.57	1.3	5.4	76	86
61.6	5.54	1.0	5.6	80	90
84	7.92	1.1	6.3	82	85
100	11.70	1.2	6.4	81	88
120	16.85	1.6	5.3	70	84
140	19.40	1.5	4.1	62	80
160	22.17	1.5	4.8	69	82
180	13.28	0.8	4.7	83	Not applied

The foam thickening is a filtration operation which is the simulation of a slow sand filter with a different medium. Slow sand filters go through a ripening phase of a few weeks after their startup. During this phase a dense microbial zoogleal or gelatinous growth establishes itself in the upper layers of the filter. It is in this layer that the most of the removal of suspended and colloidal particles occurs (Droste, 1997). The filtration rate of a slow sand filter varies from 1 to 8 $m^3/m^2.d$ (Geyer and Okun, 1968). In the foam thickening, the filtration rate changed between 0.36 and 1.62 $m^3/m^2.d$. The filtration with foam uses the foam as a filter media instead of sand and the filtered material. The removed particles on the upper layer form a second layer after the pores are clogged and the collection efficiency of the filter increased. In this part of the experiment, straining occurred. Particulate material can be removed by straining when particles are larger than pore openings in granular media or sieve openings in screens. In addition, it is possible for particles smaller than pore size to be removed by straining due to collection of particulates on the surface of the media and closure of existing pore openings. At relati concentrations of solids, it is possible for several smaller particles to arrive at ar simultaneously, thus blocking or clogging the opening (Montgomery, 1985).

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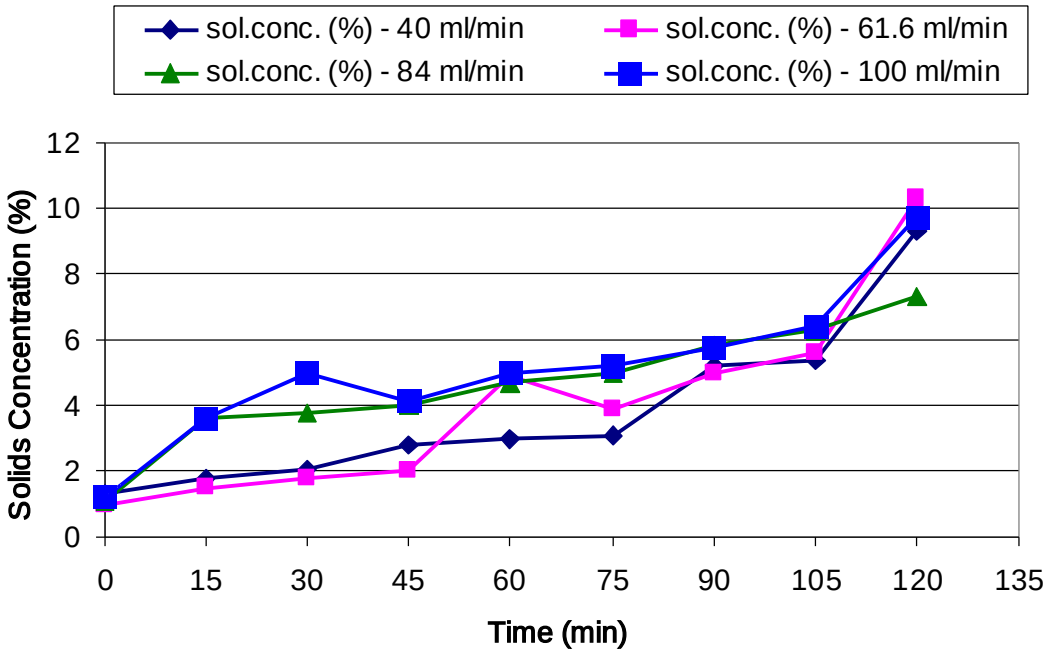

Figure 5.25. Sludge thickening by foam filter with the flowrates between 40 and 100 ml/min

The filter material in real case should be selected to minimize the straining phenomena (Boller, 1980). However, in the thickening of sludges by foam filter, straining was the most important mechanism. The floc size of the bacterial sludges was between 0.1 to 2.0 mm (www.eawag.ch/services/publikationen/eanews/news_60/en60e_manser.pdf.) The pore size of the foam filter was changing between 0.2 and 0.25 mm. Thus, the smaller flocs than the opening size were captured not on the surface of the filter but on the sludge layer obtained or in the filter. The varying pore size of the foam media develop the straining mechanism and increase the collection efficiency. As the collection efficiency increases, the final solids concentration on the foam increases also.

Various investigators have suggested that straining becomes an important removal mechanism when the ratio of the particle size to the media opening size is greater than 0.2 (Herzig et al., 1970; Boller, 1980). The average pore size of the foam media is 250 µm and the ratio is between 0.4 and 8. As the ratio of foam filter is greater than 0.2, occurred and the thickening on the foam developed and it is possible to im efficiency by using a foam media which has smaller size of openings. Other inv

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(Maroudas and Eisenklam, 1965 a, b; Tien at al., 1979) have reported that for particle size greater than approximately 100 µm, straining in media will become a dominant removal mechanism.

In the case of granular media filtration, straining is undesirable because head loss will increase rapidly due to the formation of a surface mat (Ives, 1982). However, rapid increase of head loss occurred due to clogging of pores and this mechanism is desired in thickening operation to form a sludge layer over the media. As the sludge layer forms quicker, the solids concentration on the media increases quickly. Moreover, in slow sand filters, when head loss increases to the cutoff point, a layer of medium is scraped of the top of the filter but in the foam filter, it is enough to wash the filter and use it again.

It can be easily seen from the Figures 5.25 and 5.26 that the solids concentrations increased during the experiments. It was the trend met at the biological sludge thickening with mesh filtration. The compaction of a biological sludge took more time compared to a chemical sludge due to its complex and more porous structure. The sludge cake continued to develop throughout the thickening procedure.

Unlike the mesh thickening of the biological sludges, the recovery period was not necessary for the foam thickening. The surface area was bigger and the shape was flat and these provided more time to the media to become diluted. The equalization of the concentrations of the sludge cake and the media over the foam was quicker and the recovery period was ether shorter or not necessary.

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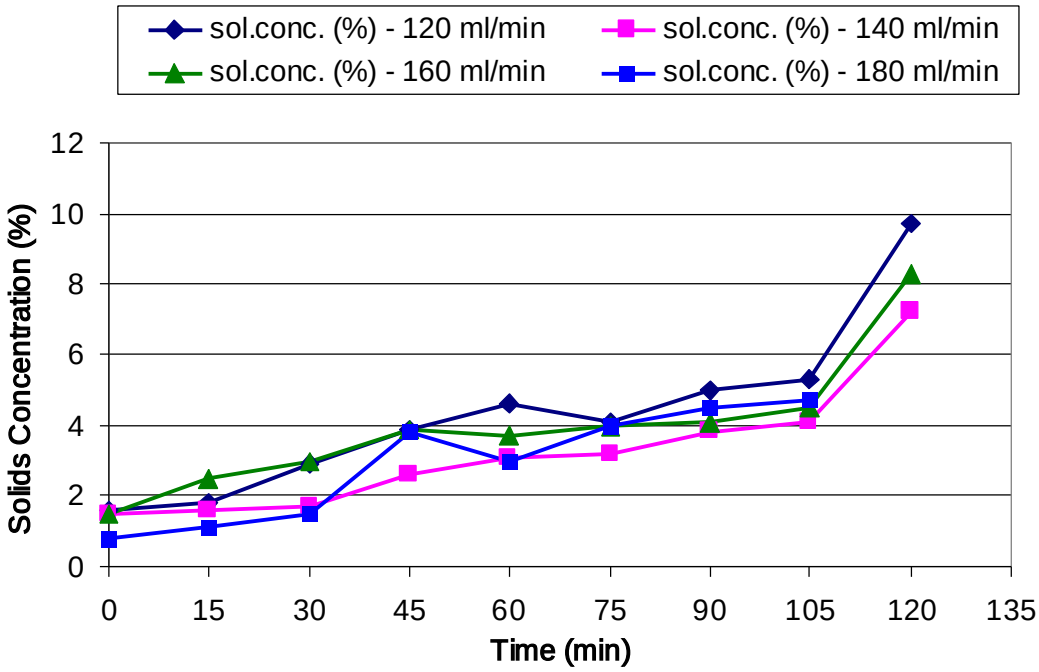

Figure 5.26. Sludge thickening by foam filter with the flowrates between 120 and 180 ml/min

As it can be noticed from the Figure 5.26, there was no manual dewatering for foam filter operating at 180 ml/min flow rate. Instead of this operation, at a sunny day, sludge sample was directly exposed to the sun for one day, and the obtained solids concentration was incredibly high, 54%. This procedure could be easily applied in all wastewater treatment plants. Dewatering step can simply be handled by this way without any dewatering equipment.

This procedure was repeated with the same flow rate during three rainy days. Final solids concentration of the cake was 5.9% before the exposition of sludge to the open atmosphere. But this time the sludge sample was covered with a plastic bag in order to protect the sludge cake against the rain. The concentrations of the sludge sample were measured during three days and the solids concentrations were 11%, 25%, and 43%, respectively.

The foam thickening was a new method to provide a more economica thickening and ease of operation. The material used in the foam thickening is very

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In the foam thickening, solids concentrations ranged between 4.1% and 6.4% which were higher compared to concentrations obtained from conventional gravity thickening. The average sludge volume reduction was about 65%. Manual sludge dewatering helped to gather more concentrated sludge cake which was a very easy method to be applied.

The solids loading were lower than the mesh application because of the increased surface area of the thickener but the used flow rates were higher.

The foam thickening method could be converted to dewatering by simply spreading the foam to the open atmosphere. In a sunny day, the sludge can be dewatered up to 50%.

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5.4. Filtrate Quality

In all of the filtration experiments, the filtrate quality in terms of COD and TSS was also investigated in order to compare with the discharge limits of ISKI regulation for treatment plants. In general, filtrate quality of the conventional thickeners does not meet the limits for direct discharge into to the local sewers. Moreover, returning the filtrate into the treatment system is not an economical due to the extra energy and equipment costs. It is known that the filtrate quality of the conventional thickeners is poor and the filtrate should be recycled to improve the quality of the effluent. The recycling of filtrates put an extra load on the treatment plant. Tables 5.11 and 5.12 summarize the quality of the filtrates obtained from thickening of chemical and biological sludge samples by using a mesh filter and the thickening of biological sludge samples by using a foam filter.

The obtained results were compared with the discharge values of ISKI given in the Table 5.11.

Table 5.11. Sewage Discharge limits (Wastewater Discharge Regulations of ISKI)

	Units	Facilities that End with Complete Treatment	Facilities that End with Deep Sea Discharge
TSS	(mg/l)	500	350
COD	(mg/l)	4000	600

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Table 5.12. Filtrate Quality of the Mesh Thickening

Filtrate Quality					
Sludge Type and Polymer Addition	Mesh Size (µm)	Initial COD (mg/l)	Final COD (mg/l)	Initial TSS (mg/l)	Final TSS (mg/l)
Chemical (no polymer)	100	10,110	603	18,800	222
Chemical (with polymer)	100	10,110	521	97,807	132
Chemical (no polymer)	200	10,110	713	18,800	2,365
Chemical (with polymer)	200	10,110	579	97,807	513
Biological (no polymer)	100	11,080	645	11,500	90
Biological (with polymer)	100	11,080	95	11,500	27
Biological (no polymer)	200	11,080	725	11,500	160
Biological (with polymer)	200	11,080	120	11,500	65

The results obtained from the same flow rate which was 61.6 ml/min. The filtration efficiency of the mesh was very successful. As seen in the Table 5.12, the effect of mesh size and polymer addition could be investigated clearly.

Park (2000) investigated the effect of mesh opening size on the TSS of the filtrates and found out that it affected the quality of the filtrate. The initial amounts of TSS that Park investigated were 3000 mg/l, 6000 mg/l and 9000 mg/l. The TSS recovery efficiencies were 88.2%, 91.2% and 97.8% respectively for 100 µm mesh openin 200 µm mesh opening, the TSS recovery were 77.3%, 83.4% and 90.7% res

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From the results, it is seen that using small mesh opening increased the TSS recovery percent.

Kiso (2000) showed also that the mesh opening size had an effect on the TSS concentration of the filtrates. 100 µm mesh opening decreased the TSS concentration of the effluent more than that of the 200 µm mesh opening. Moreover, Kiso measured the effluent BOD of the system and the results showed again that the 100 µm pore size decreased the effluent BOD of the system more than that of the 200 µm pore size.

In this study, the effect of mesh opening size on the filtrate quality was investigated both for chemical and biological sludges. The results agree with the results of Park (2000) and Kiso (2000) explained in the previous paragraph.

For chemical sludge, except one, all the results were under the limits of discharge value TSS (the limit was 500 mg/l). In the COD case, the limits were higher than the obtained filtrate values. The ISKI limit for the COD discharge for the treatment plants was 4000 mg/l. As it is shown in the Table 5.12, all the values of chemical sludge samples were under the limits. In filtration, the 100 µm mesh seemed more effective than the 200 µm mesh but only about 1%.

For biological sludge, the same trend was shown. COD removal was about 94% for 100 µm mesh and 93% for 200 µm mesh. TSS removal of the meshes was very sufficient also. For 100 µm mesh, the TSS removal efficiency was 99.2% without polymer addition and for 200 µm mesh, TSS removal was 98.6% without polymer addition.

The effects of the coagulant addition were examined also by Park (2000) on the TSS quality of the effluents. Park used powder coagulant and investigated that coagulant addition had an absolute negative effect on the effluent quality and TSS increased very high levels. On the other hand, in this study a liquid coagulant was used and the effect on the filtrate quality was positive.

For chemical sludge, the TSS recovery for 100 µm mesh was 98.8% without polymer addition and after polymer addition the recovery percent increased to 99.8%. Th

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quality of the 200 µm mesh showed polymer addition increased the recovery percent from 87.2% to 99.5%. The recovery for the COD was 94.0% for 100 µm mesh before polymer addition and it was 99.5% after polymer addition. Moreover, for 200 µm mesh, the recovery amount of COD was 92.9% without polymer addition and it increased to 94.3% after the polymer addition.

For biological sludge, the TSS recovery for 100 µm mesh was 99.2% without polymer addition and after the polymer addition the recovery efficiency increased to 99.8%. The effluent quality of the 200 µm mesh showed that the polymer addition increased the recovery efficiency from 98.6% to 99.4%. The COD recovery was 94.2% for 100 µm mesh before the polymer addition and it was 99.1% after the polymer addition. Moreover, for 200 µm mesh, the COD recovery was 93.4% without polymer addition and 98.9% after the polymer addition.

It can be concluded that the mesh thickening for biological and chemical sludge was very effective in filtrate quality. After the thickening operation, the filtrate can be discharged into the sewers without a problem because values obtained were lower than the ISKI discharge limits showed in Table 5.11.

Table 5.13. Filtrate Quality of the Foam Thickening

Flowrate (ml/min)	COD of the Raw Sludge (mg/l)	COD of the Filtrate (mg/l)	SS of the Raw Sludge (mg/l)	SS of the Filtrate (mg/l)
40	9950	689	11520	195
60	11200	185	11766	65
80	27850	447	14600	180
100	7250	640	11760	135
120	11000	55	12440	20
140	11500	110	13220	75
160	18100	190	13280	5
180	17600	160	13230	4

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The COD and SS values of foam thickening filtrates were shown in Table 13. All the filtrates of foam thickening were under the limits of ISKI as given in Table 5.11. The SS values were under 350 mg/l and COD values were under 800 mg/l. The minimum removal efficiency was 99.6% for SS where the maximum reached to 99.6%. In the COD part, the minimum and maximum values of removal were 91% and 99%, respectively. The straining mechanism which was the leading mechanism in foam thickening provided better filtrate values for foam than that of the mesh thickening. The escaped particles could be caught on the deeper section of the foam that could not be seen in the mesh thickening.

Foam thickening meets the ISKI values in SS and COD parameters which are the focused parameters on. The filtrate of the foam thickening could be discharged without any problem to the sewer system of ISKI such as mesh thickening filtrates.

5.5. Prediction of Estimated Sludge Cake Thickness

Sludge cake height can be predicted according to calculations given by Giokasa (2001). In the theory, a simple empirical method is pursued for the analysis and design of the continuously operating full-scale secondary clarifiers. The proposed approach rests on the phenomenon of dilution of the incoming activated sludge in the feeding well of the settling tanks while provides several types of modified models for its quantitative estimation. The parameters of the overall approach include almost all of the operational variables, which are readily ascertained in the routine analysis performed in a wastewater treatment plant, thereby minimizing sampling and experimental effort. In this study, the sludge cake height was measured after the thickening operation with mesh filter. The results showed that the sludge cake height was related with the initial solids concentration, the solids loading rate, the flow rate of the sludge and polymer addition for the biological sludge thickening and it was related with the initial solids concentration and polymer addition for the chemical sludge thickening. The opening size of mesh did not show a great effect on the sludge cake height. The results are shown in the Table 5.14, Table 5.15, Table 5.16, and Table 5.17.

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Table 5.14. Sludge Cake Height of the Biological Sludge Thickening by Mesh Filtration without Polymer Addition.

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Theoretical Sludge Cake Height (cm)	Measured Sludge Cake Height (cm)	Measured / Theoretical Sludge Cake Height Ratio
100	20.5	5.57	1.0	7.1	1.83	3.1	1.69
100	41	10.86	1.0	7.4	1.76	3.0	1.70
100	61.6	18.41	1.1	6.4	2.23	3.6	1.61
100	80	38.51	1.8	7.2	3.25	4.6	1.41
100	100	29.0	1.1	6.5	2.20	3.4	1.54
200	20.5	6.79	1.2	5.1	3.06	5.1	1.67
200	41	15.64	1.4	5.5	3.31	5.5	1.66
200	61.6	24.8	1.5	6.0	3.25	5.0	1.53
200	80	21.73	1.0	5.4	2.41	3.8	1.57
200	100	35.86	1.3	6.9	2.45	3.5	1.43

It can be seen from the Table 5.14 that the theoretical and measured sludge cake heights after the thickening operation was related with a ratio varied between 1.70 and 1.41 for 100 µm mesh size and 1.67 and 1.43 for 200 µm mesh size. Solids loading rate affected the height of the sludge cake inversely. As the solids loading increased, the final solids concentration decreased, and the effect of this phenomenon can be investigated in the sludge cake height also.

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Table 5.15. Sludge Cake Height of the Biological Sludge Thickening by Mesh Filtration with Polymer Addition.

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Theoretical Sludge Cake Height (cm)	Measured Sludge Cake Height (cm)	Measured / Theoretical Sludge Cake Height Ratio
100	20.5	1.45	0.26	7.7	0.44	0.8	1.82
100	41	8.58	0.77	7.7	1.30	2.4	1.85
100	61.6	18.75	1.1	7.67	1.86	3.3	1.77
100	80	21.74	1.0	5.3	2.45	4.4	1.80
100	100	24.72	0.9	4.5	2.60	4.4	1.72
200	20.5	2.0	0.4	7.8	0.67	1.2	1.79
200	41	2.8	0.3	7.6	0.51	0.9	1.76
200	61.6	25.0	1.5	3.5	5.57	9.0	1.62
200	80	29.7	1.3	4.8	3.52	5.6	1.60
200	100	43.4	1.6	3.4	6.12	9.5	1.55

Table 5.15 shows the effect of polymer addition the sludge cake height for the thickening of biological sludge. The results showed that the polymer addition affected the sludge cake height by increasing the size of the flocs and so the thickness of sludge layer formed on the mesh. The ratio between the theoretical and measured sludge cake height increased with the addition of polymer. The ratio changed between 1.85 and 1.72 for 100 µm mesh size and was between 1.79 and 1.55 for 200 µm mesh size. The addition of polymer was led to a greater measured / theoretical sludge cake height ratio and less fluctuations between the ratios.

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Table 5.16. Sludge Cake Height of the Chemical Sludge Thickening by Mesh Filtration without Polymer Addition.

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Theoretical Sludge Cake Height (cm)	Measured Sludge Cake Height (cm)	Measured / Theoretical Sludge Cake Height Ratio
100	20.5	9.0	2.1	11.9	2.29	4.8	2.09
100	41	18.0	2.1	12.1	2.26	4.7	2.07
100	61.6	32.0	2.5	11.9	2.73	5.7	2.09
100	80	45.0	2.6	12.5	2.70	5.6	2.07
100	100	55.0	2.6	11.2	3.02	6.2	2.05
200	20.5	9.6	2.3	11.4	2.62	5.5	2.09
200	41	20.0	2.4	10.4	3.00	6.2	2.07
200	61.6	32.0	2.5	10.9	2.98	6.2	2.08
200	80	47.0	2.7	12.3	2.85	5.9	2.07
200	100	56.0	2.7	12.8	2.74	5.7	2.08

Table 5.16 showed that the sludge cake height and ratios after the thickening of chemical sludge with mesh filtration. It can be easily seen that the prediction of the chemical sludge cake height was more precise when compared to the biological sludge cake height. The ratio of the measured / theoretical sludge cake height varied between 2.09 and 2.05 for 100 µm mesh size and between 2.09 and 2.07 for 200 µm mesh size. The final solids concentrations of the chemical sludge were very close although the feeding rates were different. The same effect can be seen on the sludge cake height also.

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Table 5.17. Sludge Cake Height of the Chemical Sludge Thickening by Mesh Filtration with Polymer Addition.

Mesh Opening (µm)	Flow rate (ml/min)	Solids Loading ($kg/m^2.d$)	Initial Solids Concentration (%)	Final Solids Concentration (%)	Theoretical Sludge Cake Height (cm)	Measured Sludge Cake Height (cm)	Measured / Theoretical Sludge Cake Height Ratio
100	20.5	9.2	2.1	21.0	1.30	3.2	2.46
100	41	18.0	2.1	16.1	1.70	4.2	2.47
100	61.6	28.0	2.2	15.9	1.80	4.42	2.44
100	80	43.0	2.7	16.2	2.17	5.4	2.49
100	100	54.0	2.6	17.1	1.98	4.9	2.47
200	20.5	10.0	2.3	21.1	1.42	3.5	2.46
200	41	21.0	2.5	14.5	2.24	5.5	2.45
200	61.6	32.0	2.7	14.3	2.45	6.1	2.49
200	80	46.0	2.7	12.6	2.79	6.8	2.43
200	100	56.0	2.7	12.3	2.85	7.0	2.46

Coagulants added are the reason for the increase of the floc size. Table 5.17 show the effect of polymer addition on the sludge cake height. The measured / theoretical sludge cake height ratios increased with the addition of polymer. It can be seen from the Table 5.17 that the ratios changed from 2.49 to 2.44 for 100 µm mesh size and changed between 2.49 to 2.43 for 200 µm mesh size. The addition of polymer increased the ratio of the measured / theoretical sludge cake height when compared to the non polymer added applications. Polymer addition has clearly positive effect on the sludge cake height increase due to the agglomeration effect of the sludge particles.

The results showed that the prediction of the sludge cake height can be ma the thickening operation by mesh filter. Moreover, the sludge cake height obtain

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mesh filtration was bigger than that of the conventional secondary clarifier of a wastewater treatment plant. The reason of that was the draining period of the thickening operation.

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6. CONCLUSIONS AND RECOMMENDATIONS

This study introduces mesh and foam filtration as new techniques for sludge thickening. Mesh and foam filtration thickening methods were applied to both biological and chemical sludge samples.

The results of the mesh filtration and foam thickening experiments can be summarized in four parts, namely, biological sludge thickening by mesh filtration, chemical sludge thickening by mesh filtration, foam thickening of biological sludge and lastly, quality of the final filtrates after the thickening operation.

Based on the results of the study, following conclusions can be drawn.

6.1. Mesh Filtration Thickening of Biological Sludge

- Mesh thickening showed better performance than a conventional gravity sludge thickener for all flow rates.
- According to solids flux theory, the solids loading of mesh filter was higher than a conventional gravity sludge thickener for the same loading conditions.
- Mesh size affected the efficiency of thickening process. Performance of mesh thickener with 100 µm mesh size was higher than the thickener with 200 µm mesh size.
- The solids loading also affected the performance of the mesh thickener. The final solid concentration was higher at lower solids loading rates, showing an inverse relationship between solids loading and the final solid concentration.
- The rate of cake formation depended on the initial solids concentration of the sludge sample. At the high initial solids concentrations, the cake formation was quick and the final solids concentration of the cake was high. The final solids concentrations did not show a considerable improvement between first and second phases, phases before and after the recovery period, of the experiment. At low initial solids concentrations, the cake formation was slower and the final solids concentrations showed improvement between first and second phases of the experiment.

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- A recovery period was needed during the experiments. After the start of the second phase following the 15 minute recovery period, the solids concentration of the cake was decreased due to dilution of the bulk sludge over the mesh by new sludge feed as mentioned in the filtration theory. A period of 15 – minute was enough to recover the cake.
- Conditioning of sludge samples with the addition of a cationic polymer increased the efficiency of mesh thickening and lead to a further increase in sludge volume reduction especially for low solids loadings. The sludge volume reduction was almost doubled for 100 µm mesh size and tripled for 200 µm mesh size after the conditioning of the sludge samples.
- At high solids loadings the polymer requirement of the sludge samples increased and the applied polymer dosage became insufficient to condition the sludge samples. Increasing the polymer dosage at high solids loadings did not cause to a major improvement in the sludge volume reduction. It seems that applying higher polymer dosages is not economically feasible.
- Measured sludge cake thickness values were greater than the theoretical values. The ratio of measured sludge cake thickness to theoretical cake thickness was found to be 1.5 for the biological sludge samples without polymer addition and about 1.7 for samples with polymer application.

6.2. Mesh Filtration Thickening of Chemical Sludge

- Thickening performance of mesh filter was better for chemical sludge compared to biological sludge.
- Mesh size affected the thickening efficiency. Performance of mesh thickener with 100 µm mesh size was higher than that of the thickener with 200 µm mesh size.
- For unconditioned sludge samples solids loading did not affect the thickening performance considerably, no matter which mesh size was used.
- The initial solids concentration of the sludge samples did not affect the rate of cake formation.
- A recovery period was not necessary in thickening of the chemical sludge unlike the biological sludge samples. The start of the second phase did not

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sludge cake formation as expected. The cake of chemical sludge formed quickly in the first phase and remained nearly unchanged during the second phase of the experiments.

- Conditioning of chemical sludge samples with a cationic polymer improved the thickening. At low solids loading rates, the application of polymer increased the final solids concentration incredibly. When the solids loading rate increased, the efficiency of conditioning decreased. Polymer dosage was insufficient for high flow rates and solids loadings. Higher dosages of polymer addition improved the sludge volume reduction but the improvement was not high enough to increase the polymer dosage in an economical way.
- At low solids loading rates, the final solids concentrations of polymer conditioned chemical sludge samples were higher than 20% that is much higher than the typical range of thickening.
- Measured sludge cake thicknesses were greater than the theoretical values. The ratio was 2.05 for the chemical sludge without polymer and about 2.45 for polymer applied chemical sludge samples.

6.3. Foam Thickening

- Straining was the effective mechanism during foam filtration. This mechanism was not wanted for the filtration operation due to increased head loss but in foam filtration, straining was required for the formation of quick sludge cake.
- Thickening of biological sludge with foam filter was a method more economical than mesh filtration.
- The thickening capacity of foam filter resembled with the capacity of the 100 µm mesh thickening.
- The cake formation in foam thickening operation endured throughout the experiments, the sludge cake concentration increased gradually.
- Solids loading rates were not so effective in foam thickening. The efficiency of the foam filter remained almost constant at all of the solids loading rates.
- The sludge concentrations were higher than that of conventional gravity sludge thickener for all flow rates and solids loadings.
- The foam can be operated at higher flow rates compared to mesh filters.

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- In the foam filters, expulsion of the sludge water takes more time compared to mesh filters and the foam media requires a head on top of it to release sludge water.
- Thickening of chemical sludge by using a foam filter was not successful. The sludge cake over the foam could not be formed. The sludge solids passed into the foam and stuck in it.

6.4. Filtrate Quality

- All of the filters were very effective to obtain good filtrate quality.
- The filtrate quality of the 100 µm mesh size was better than that of the 200 µm mesh size.
- The quality of the filtrate values obtained from mesh filter met the direct discharge regulations to the local sewer system.
- Polymer addition improved the filtrate quality.
- In the foam filtration, TSS and COD values of the filtrates were always lower than the discharge limits of ISKI for treatment plants.

Finally, Sludge Thickening with Mesh Filtration and Foam Filtration can be good alternatives for small-scale wastewater treatment plants. The obtained final solids concentrations showed that mesh and foam filters reached better performance according to Gravity Thickeners and according to Dissolved Air Flotation Thickeners due to their higher solids loading capacity. The filtrate quality of these filters was better when compared to the conventional thickeners.

Recommendations from this study are given as

- This study recommended the application of solar drying method after thickening to reach high sludge volume reduction. Drying process would lead to reduction of transportation, handling costs and also most probably reduce pathogen amount by UV.
- Working with different pore sized foams would be beneficial.
- The thickness of the foam could be another study project to work on.

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APPENDIX A . FIGURES OF THE EXPERIMENTS

A.1. Mesh Filtration of Biological Sludge

A.1.1. 100 µm Mesh Size Experiments without Polymer

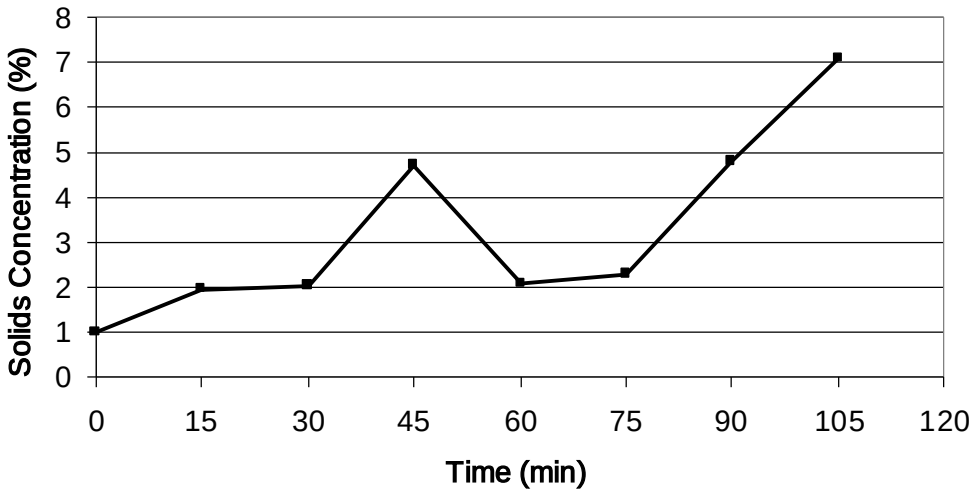

Figure A.1. Biological Sludge - 100 µm mesh – Batch type –20.5 ml/min

As seen in the Figure A.1, at the lowest flow rate applied, 20.5 ml/min, with 5.57 kg/m^2.d solids loading, final solids concentration increased from 1.0% to 7.1% at the end of the operation. The volume reduction obtained was 85%. In the first phase of the experiment, the increase was approximately 3.8 folds of its initial value (from 1.0% to 4.8%) and in the second phase, the increase was sharper and reached to a value of 7.1% and this triggered 6.1 folds more thickened sludge at the end. The decrease in solid content between 45th -75th minutes was mainly due to the start of the second feeding period that causes the dilution of the sample but the system recovered later.

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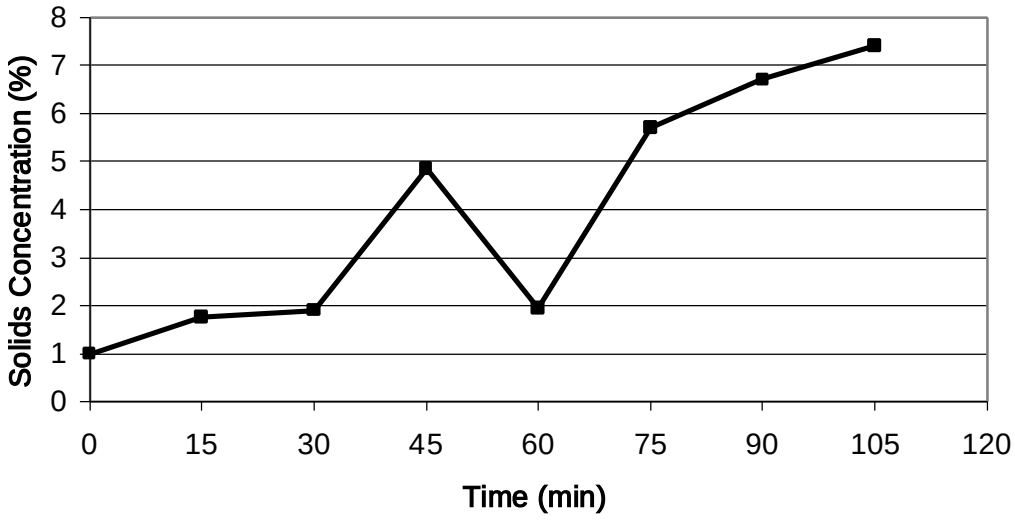

Figure A.2. Biological Sludge - 100 µm mesh – Batch type – 41 ml/min

The flow rate was increased from 20.5 ml/min to 41 ml/min and the solids concentration at the beginning was again 1.0%. Solids loading became higher as a result of the flow rate increment and was calculated as 10.86 kg/m^2.d. The final solid concentration increased to 7.4 at the end of experiment. Although flow rate and the solids loading were doubled, there was no distinct increase in sludge cake concentration. At the end of the experiment, volume reduction of 86% was obtained.

During the experiment, a sharp increase was investigated between the two phases as seen in the Figure A.2. In the first phase, concentration of the solids over the mesh increased up to 3.9 folds of its initial value (from 1.0% to 4.9%) and in the second phase, after a 15 minutes of recovering period, final solids content obtained was 6.4 folds more than initial solids concentration.

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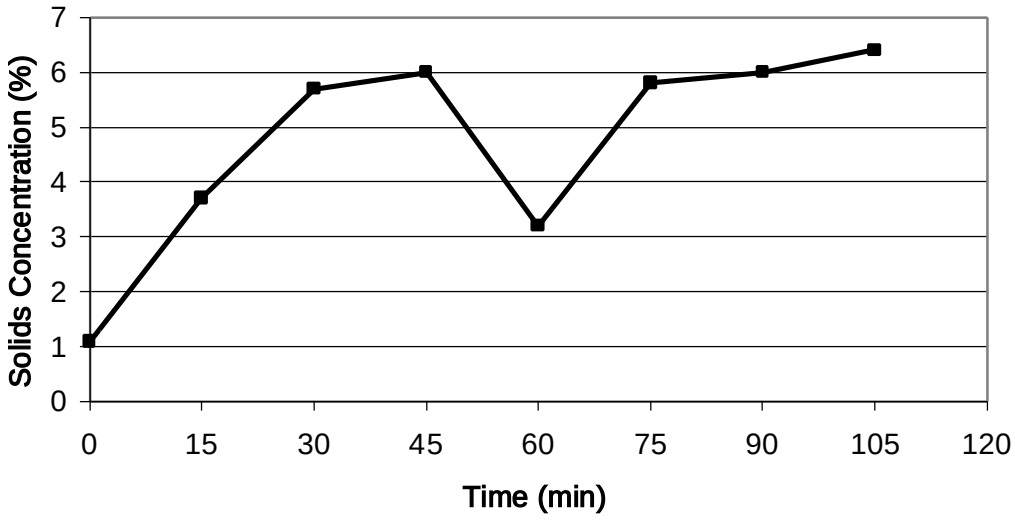

Figure A.3. Biological Sludge - 100 µm mesh – Batch type – 61.6 ml/min

It can be seen from the Figure A.3 that the flow rate was increased to 61.6 ml/min which led to a solids loading of 18.41 kg/m^2.d. Solid concentration before the start was measured as 1.1%. At the end of experiment, it was reached to 6.4%, and approximately 83% volume reduction, was obtained.

Between the two phases of procedure, there was no sharp increase in solids concentration gathered over the mesh. In the first phase, approximately 5 folds of increase was observed (from 1.1% to 6.0%) and then after a 15 minutes of recovery period of the sludge cake, final thickened solids concentration advanced up to 4.8 folds of its initial value.

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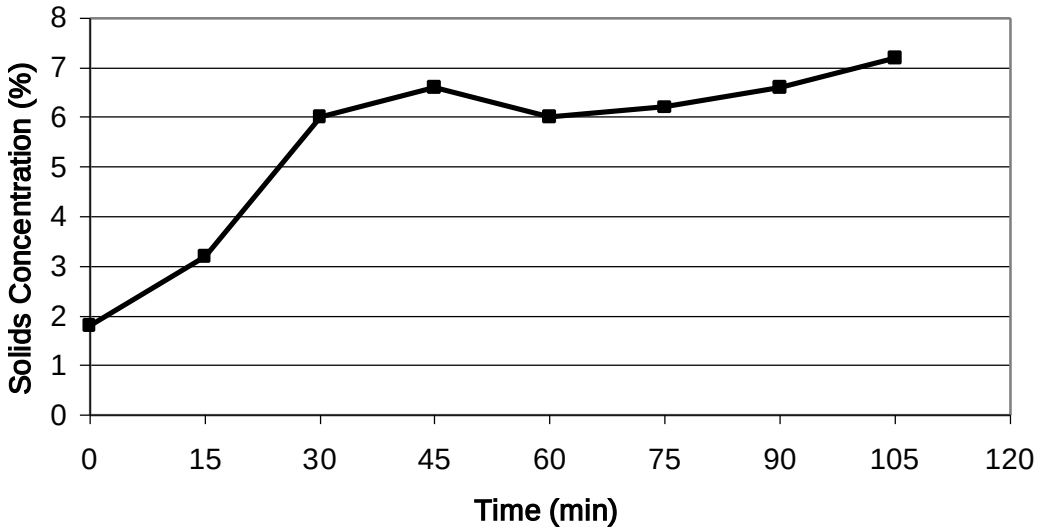

Figure A.4. Biological Sludge - 100 µm mesh – batch type– 80 ml/min

In the Figure A.4, it was seen that the flow rate was increased to 80 ml/min. At the beginning the solids concentration was 1.8% and the calculated solids loading was 38.51 kg/m^2.d. The final solids concentration on the mesh was 7.2 %. The total increase in thickening from the start to the end was 3 folds of the initial value and the sludge volume reduction reached approximately to 75%.

As in the previous experiment, there was no big difference between the phases of the operation. In the first phase, the solids concentration increased from 1.8% to 6.0% and then, the sludge cake concentration was very stable during second phase. The increase was only 0.4 percent more according to first phase and finally 4 times higher concentrated sludge was obtained.

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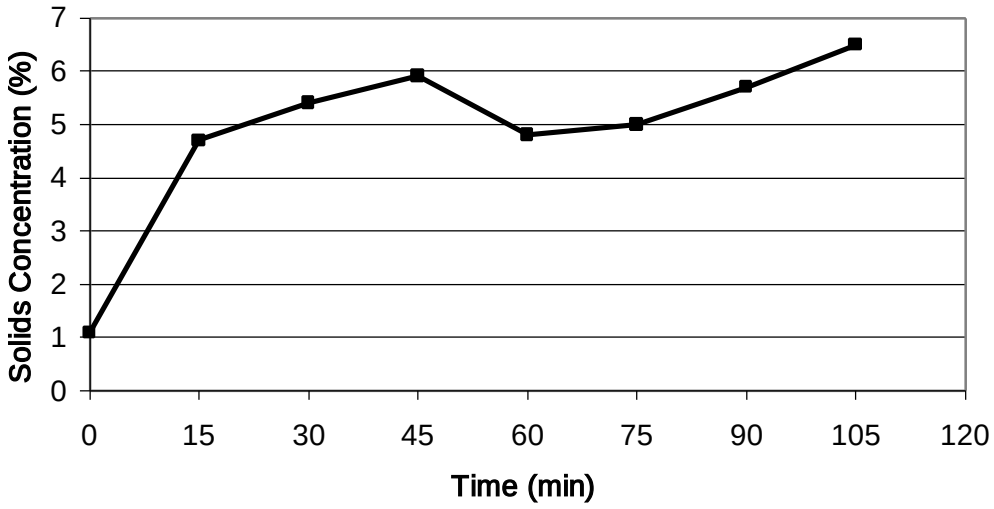

Figure A.5. Biological Sludge - 100 µm mesh – Batch type – 100 ml/min

The maximum sludge feeding flow rate of the experiments was carried out with a flow rate of 100 ml/min and the results were given in the Figure A.5. The solids loading was 29.0 kg/m^2.d. It is decreased although the flow rate increased because the initial solid concentration applied to the system. During the thickening process, solids concentration was increased from 1.1% to 6.5%. The obtained final sludge concentration was not high as previous experiments. This can be due to maximum flow rate.

As in the previous two tests, there were similar trends during two phases. In the first phase, approximately 3.5 folds of more solids percent measured on the mesh and after 15 minutes of recovery period, only 0.4% gain was observed in the second phase. The overall sludge percent reduction was 82%.

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A.1.2. 200 µm Mesh Size Experiments without Polymer

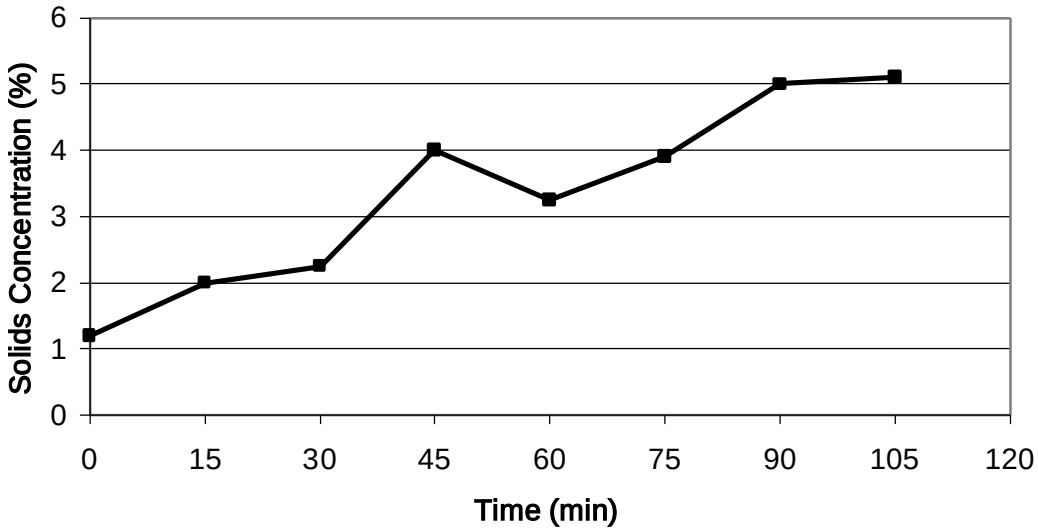

Figure A.6. Biological Sludge - 200 µm mesh – Batch type – 20.5 ml/min

As seen in the Figure A.6, at the lowest flow rate applied, 20.5 ml/min, the solids loading was 6.79 kg/m^2.d. At the end of the experiment, final solids concentration reached to a value of 5.1% where the beginning solids concentration was 1.2%. The volume reduction of the sludge occurred as 77%.

Although the trend of solid content increase was similar to the trend of 100 µm mesh, a lower solids percent value was achieved at the end of the thickening operation.

At the end of the 105 minutes period, the solid content of sludge became 3.2 times greater than the beginning solid content. There was a high increase of solids concentration on the mesh in the first phase (from 1.2% to 4%) which was 2.3 folds of its initial value and in the second phase, after 15 minutes of recovery, 1% more accumulation was seen. At the end of process, there was 3.25 folds of increase in solid percent obtained.

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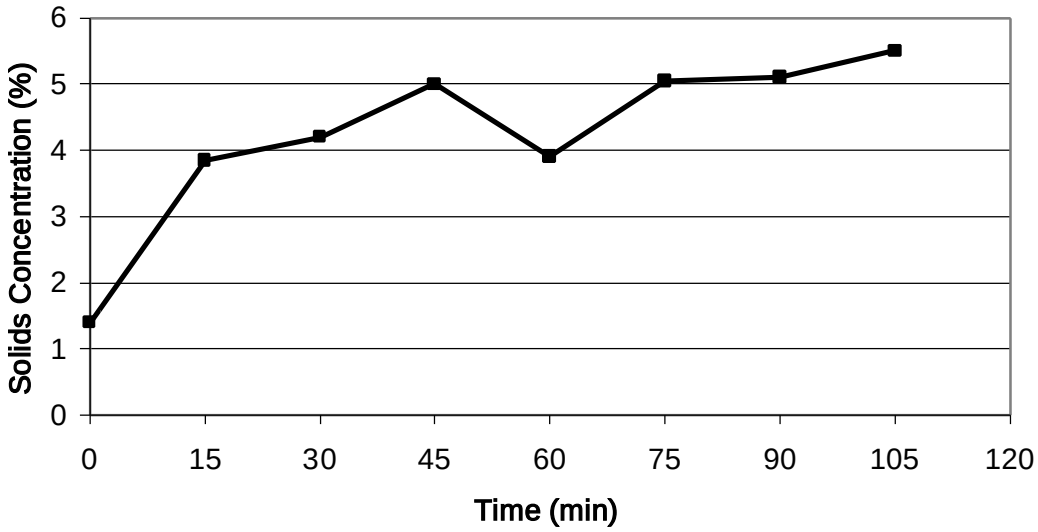

Figure A.7. Biological Sludge - 200 µm mesh – Batch type – 41 ml/min

The flow rate was increased to 41 ml/min for this mesh and solids percent at the beginning was 1.4. The solids loading increased to a value of 15.64 kg/m^2.d as a result of increased hydraulic loading. A sludge cake concentration of 5.5% was obtained at the end of experiment. The lowest sludge volume reduction for the 200 µm mesh was investigated, approximately 74%.

During the experiment, there was no sharp increase between two phases as seen in the Figure A.7. In the first phase, concentration of the solids over the mesh increased up to 2.5 folds of its initial value (from 1.4% to 5.0%) and in the second phase, after a 15 minutes of recovering period, final solids content obtained was 3.8 folds more than initial solids concentration.

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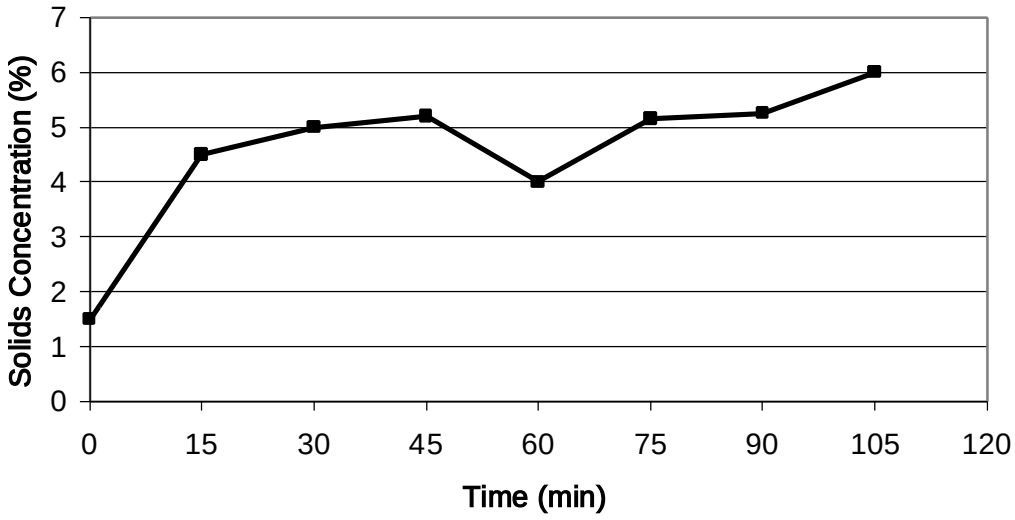

Figure A.8. Biological Sludge - 200 µm Mesh – Batch type – 61.6 ml/min

As it was seen in Figure A.8, the flow rate was increased to 61.6 ml/min. The solids loading was calculated as 24.8 kg/m^2.d. At the beginning of the experiment, initial solids concentration was 1.5%, and a final sludge cake concentration of 6.0% was achieved. Slightly higher sludge volume reduction, approximately 75%, was obtained with respect to previous thickening operation.

Between the two phases of procedure, there was no sharp increase in sludge concentration obtained over the mesh. In the first phase, 2.3 folds of increase was observed (from 1.5% to 5.0%) approximately, and then after a 15 minutes of recovery period of the sludge cake, final solids concentration advanced up to 3.0 folds of its initial concentration.

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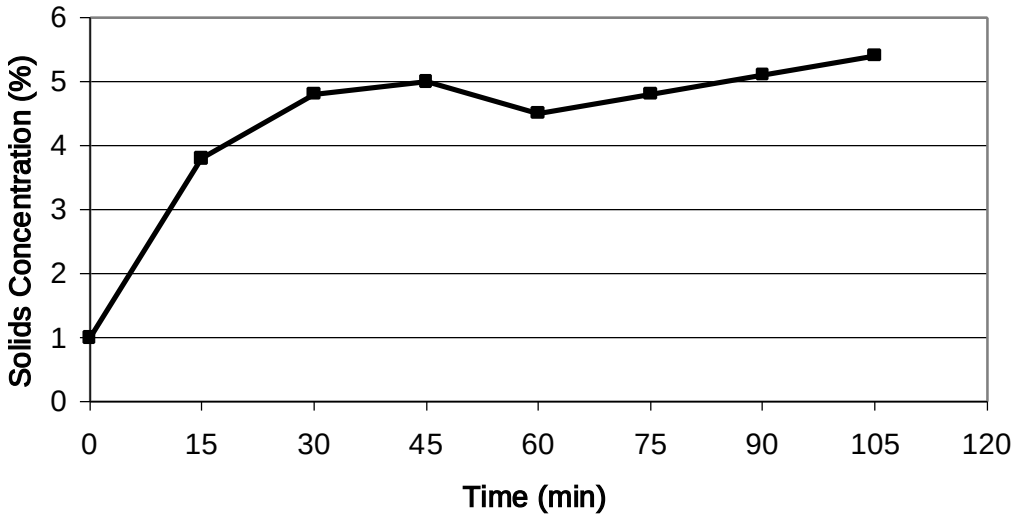

Figure A.9. Biological Sludge - 200 µm mesh – Batch type – 80 ml/min

In the Figure A.9, it can be seen that the flow rate was increased to 80 ml/min and solids loading was 21.73 kg/m^2.d for this experiment. Solid percent at the beginning was 1.0 and increased to 5.4 percent at the end of the experiment. The obtained sludge volume reduction was high, approximately 81%.

As it was observed in the previous experiments, the difference of solids concentration increase over the mesh between two phases of thickening was not so noticeable. In the first phase, a quick increase occurred in solid percent, from 1.0 to 5.0, and in the second phase, the concentration of solids was nearly stable, only 0.4 percent increase was investigated that brought a 4.4 folds of improvement when compared to the initial value.

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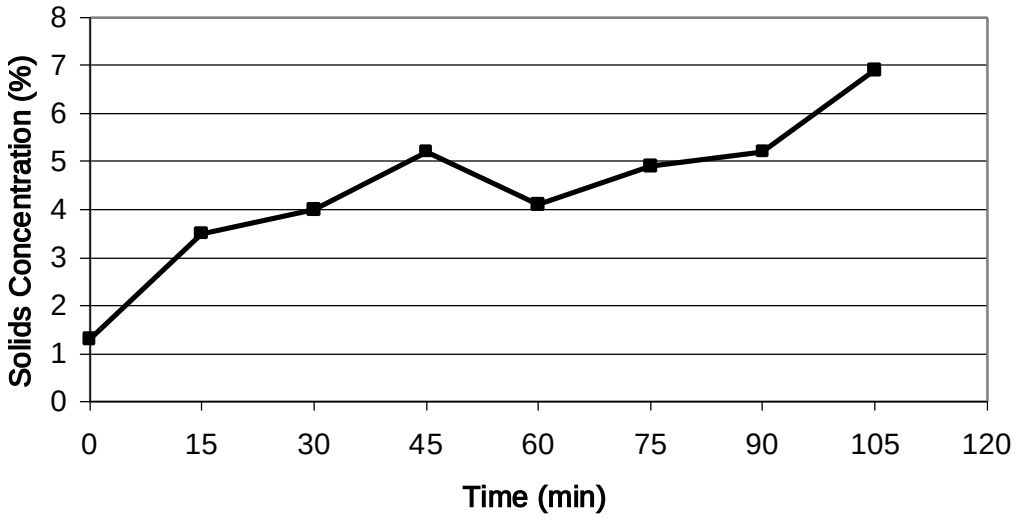

Figure A.10. Biological Sludge - 200 µm mesh – Batch type – 100 ml/min

The maximum hydraulic loading application was done for 200 µm mesh size. The flow rate was 100 ml/min. Solids concentration before the start was measure as 1.3% and increased to 6.9 percent at the end the experiment. The solids loading for this operation was 35.86 kg/m^2.d. The highest sludge percent value was reached at the end of the experiment period. Achieved sludge volume reduction, 86%, was obtained.

When compared to the previous applications, the trend of sludge concentration increase between two phases was different as seen in the Figure A.10. In the first phase, there was a quick improvement of solids concentration and then released stable. It was seen that the solid percent promoted 2.5 folds of its initial value and in the second phase continued to rise up to 4.3 folds when compared to the original value.

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A.1.3. 100 µm Mesh Size Experiments with Polymer

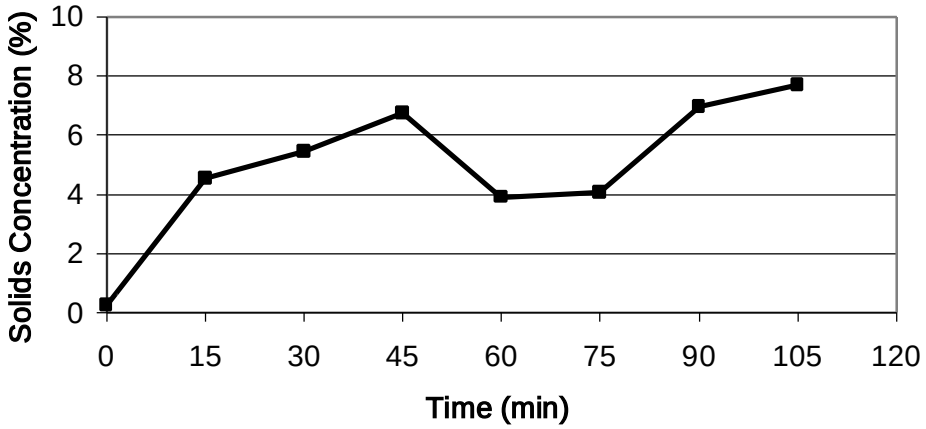

Figure A.11. Biological Sludge - 100 µm mesh - Batch Type - 1mg/l cationic polymer – 20.5 ml/min

As seen in the Figure A.11, the lowest flow rate, 20.5 ml/min was applied to the system. The initial solid concentration was 0.26%. The solids loading was very low due to initial feed concentration and it was calculated as 1.45 kg/m^2.d. The resulted final solid concentration reached to 7.7% and the sludge volume reduction was 97%.

In the first phase of the experiment, a great improvement of cake solids concentration was observed and approximately 25 (from 0.26% to 6.74%) folds of its initial value obtained especially between 30th and 45th minutes. In the second phase, after 15 minutes of recovery period, the sludge cake concentration over the mesh continued to rise and reached at the end 28.6 folds more according to initial solids concentration. The difference between two phases was not noticeable.

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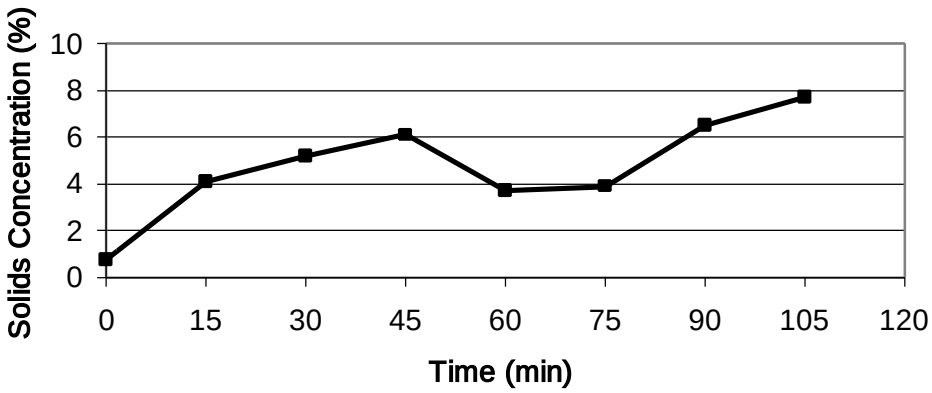

Figure A.12. Biological Sludge - 100 µm mesh - Batch Type - 1mg/l cationic polymer – 41 ml/min

In the Figure A.12, the result of the 41ml/min flow rate was given. At the beginning, the solids concentration given to the system was measured as 0.77% and the solids loading was 8.58 kg/m^2.d. The final solid concentration at the end of experiment was 7.7%. The resultant percent volume reduction was very high, 90% approximately.

The trend of sludge concentration increase was very similar to the previous experiment. As seen in the Figure 12, there was a quick increase, nearly 8 folds of the initial concentration and similar to 20.5 ml/min experiment, after 30 minutes of recovery, solids concentration reached to 7.7% and this was 9 folds of its initial value. The difference between two phases was not so important.

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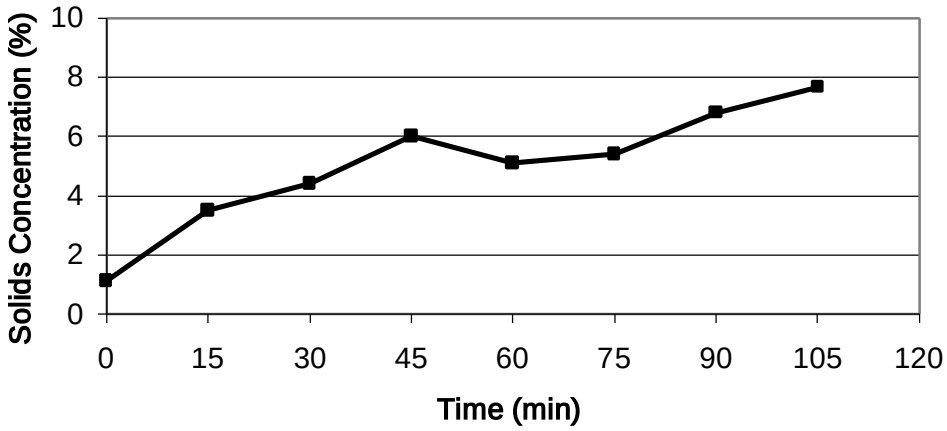

Figure A.13. Biological Sludge - 100 µm mesh - Batch Type - 1mg/l cationic polymer – 61.6 ml/min

The flow rate was increased to 61.6 ml/min. The solids loading became greater due to initial solids concentration and flow rate. It was 18.75 kg/m^2.d. At the beginning, the solids concentration was 1.1% and the final solids concentration reached at 7.67%. The overall sludge volume reduction was calculated as 85%.

In this case, as seen in Figure A.13, obtained sludge volume concentration at the end was lower when compared to the previous experiments. During the first phase, the increase of concentration of sludge cake was 4.9% and after 30 minutes of recovery, the concentration increased 6 folds of its original value. The general trend of polymer added experiments continued as it can be investigated from the figure.

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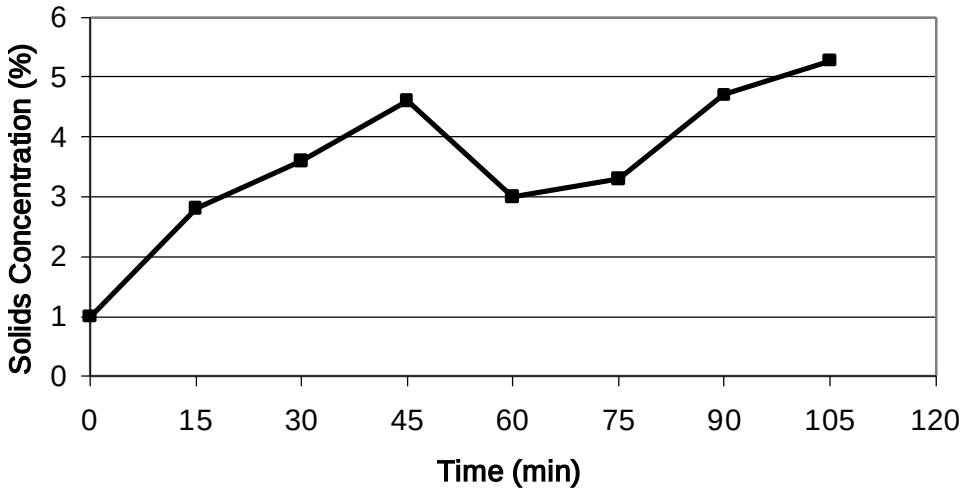

Figure A.14. Biological Sludge - 100 µm mesh - Batch Type - 1mg/l cationic polymer – 80 ml/min

In the Figure A.14, it was seen that the initial solid concentration was 1.0% and the final solid concentration reached to 5.3%. In this experiment, the flow rate was 80 ml/min, and the solids loading was 21.74 kg/m^2.d. The sludge volume reduction was observed as 81%.

The general trend of concentration increase was similar to the previous experiments. In the first phase, the solids concentration increased to 4.6% and this was 3.6 folds of its initial value. In the second phase, there was a recovery period and the solids concentration over the mesh became 5.3% which was 4.3 folds of the initial concentration. The effect of polymer was not noticeable again because of the insufficient amount of the polymer addition. The reason can be insufficient amount of the polymer.

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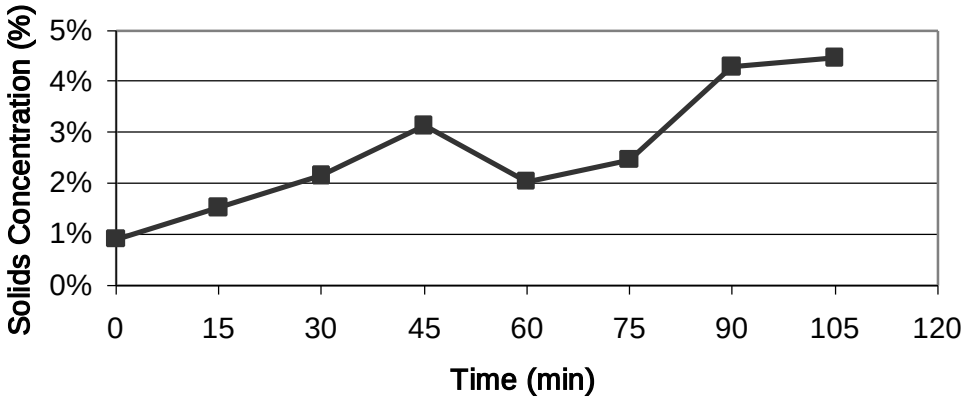

Figure A.15. Biological Sludge - 100 µm mesh - Batch Type - 1mg/l cationic polymer – 100 ml/min

In this experiment, the maximum hydraulic loading was used and the sludge feeding rate was 100 ml/min. The solids loading calculated as 24.72 kg/m^2.d. At the beginning, the solids concentration was 0.9% and at the end of thickening operation, it was reached to 4.5% with an overall sludge volume reduction of 80%.

As shown in the Figure A.15, the same trend of polymer application was seen. There was no big difference between two phases of the experiment. In the second phase, 15 minutes of recovery period was investigated. In the first phase, an increase in solids concentration can be observed but in the second phase, there was no improvement in solids concentration, 4 folds of increase could be obtained at the end according to initial concentration.

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A.1.4. 200 µm Mesh Size Experiments with Polymer

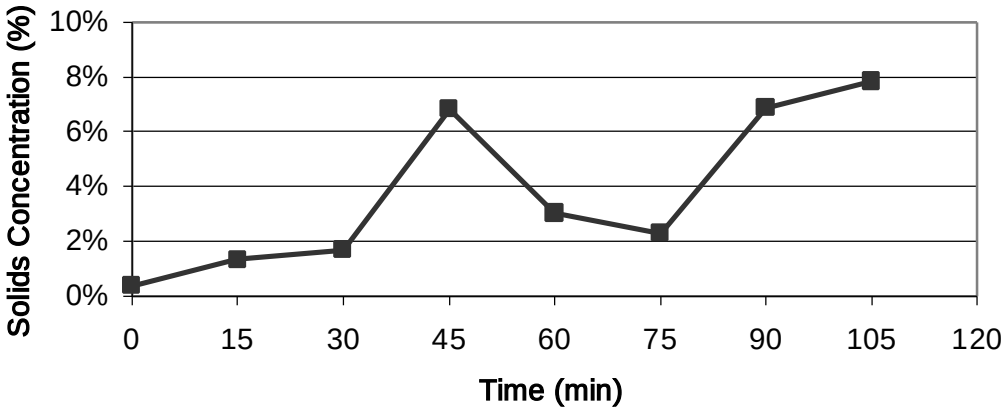

Figure A.16. Biological Sludge - 200 µm mesh - Batch Type - 1mg/l cationic polymer – 20.5 ml/min

As seen in the Figure A.16, the lowest flow rate, 20.5 ml/min was applied to the system. The initial solid percent was 0.4. The solids loading was very low due to initial sludge concentration and it was calculated as 2.0 kg/m^2.d. The resulted final solid concentration reached to 7.8% and the percent volume reduction increased to 95%.

In the first phase of the experiment, a great improvement of cake solids concentration was observed and approximately 16 (from 0.4% to 6.8%) folds of its initial value obtained especially between 30th and 45th minutes. In the second phase, after a longer recovery period which was about 30 minutes, the sludge cake concentration over the mesh continued to rise and reached at the end 18.5 folds more according to initial sludge concentration. The difference between two phases was not noticeable.

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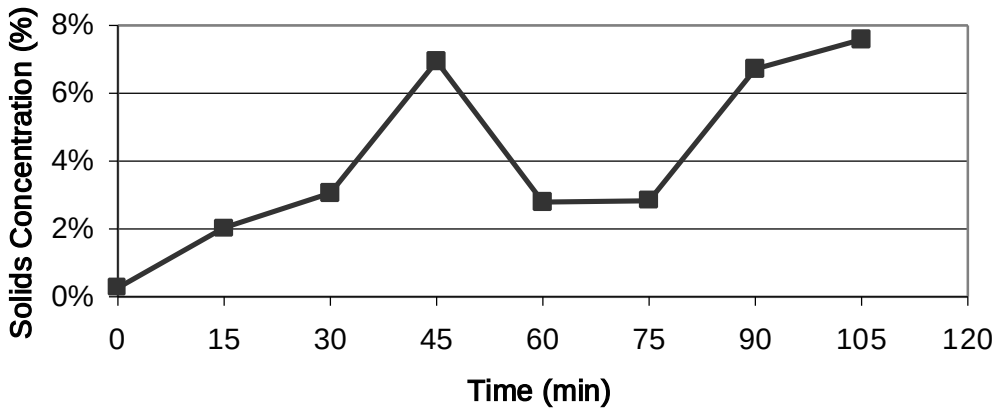

Figure A.17. Biological Sludge - 200 µm mesh - Batch Type - 1mg/l cationic polymer – 41ml/min

In the Figure A.17, the result of the 41ml/min flow rate was given. At the beginning, the solids concentration given to the system was measured as 0.3% and the solids loading was 2.80 kg/m^2.d. The final solid concentration at the end of experiment was 7.6%. The resultant percent volume reduction was very high, 97% approximately.

The trend of sludge concentration increase was very similar to the previous experiment. As seen in the figure 17, there was a quick increase, nearly 22 folds of the initial concentration and similar to 20.5 ml/min experiment, after a 30 minutes of recovery, solids concentration reached to 7.6% and this was 25 folds of its initial value. The difference between two phases was not so important.

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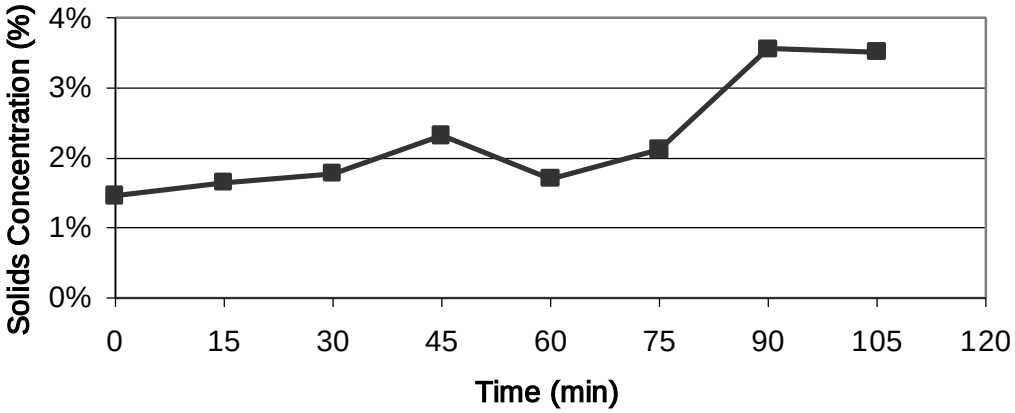

Figure A.18. Biological Sludge - 200 µm mesh - Batch Type - 1mg/l cationic polymer – 61.6 ml/min

The flow rate was increased to 61.6 ml/min. The solids loading became greater due to initial solids concentration and flow rate. It was 25.0 kg/m^2.d. At the beginning, the solid percent was 1.5 and the final solids concentration reached at 3.5%. The overall sludge volume reduction was calculated as 59%.

In this case, as seen in Figure A.18, obtained solids concentration at the end was not high when compared to the previous experiments. The reason can be insufficient amount of the polymer. Further researches were done by applying higher dosages. The results will be given after. During the first phase, the increase of concentration of sludge cake was only 0.8% and after 30 minutes of recovery, the concentration increased to 3.5%. The general trend of polymer added experiments continued again in this case also.

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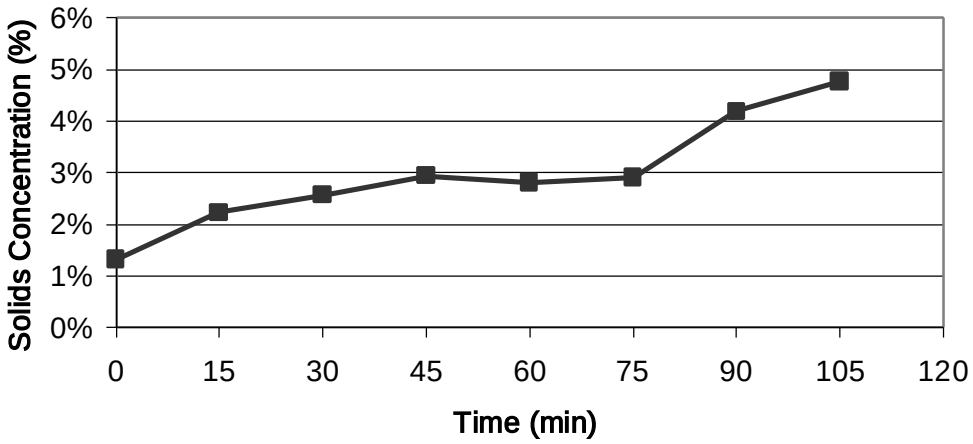

Figure A.19. Biological Sludge - 200 µm mesh - Batch Type - 1mg/l cationic polymer – 80 ml/min

In the Figure A.19, it was seen that the initial solid concentration was 1.3% and the final solid concentration reached to 4.8%. In this experiment, the flow rate was 80 ml/min, and the solids loading was 29.7 kg/m^2.d. The sludge volume reduction was observed as 81%.

Except the recovery time, the general trend of concentration increase was similar to the previous experiments.

In the first phase, the solids concentration increased to 3.0% and this was 1.3 folds of its initial value. In the second phase, there was no clear recovery period and the solids concentration over the mesh became 4.8% which was 2.7 folds of the initial concentration. The effect of polymer was not noticeable again because of the insufficient amount of the polymer addition.

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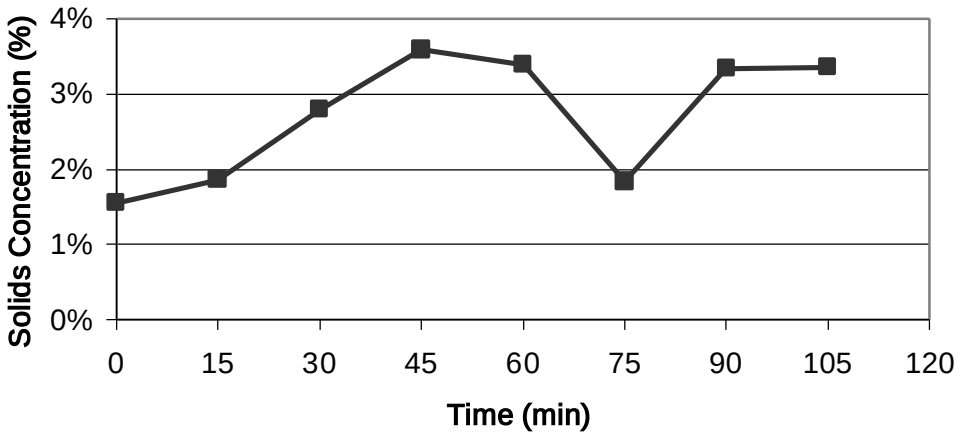

Figure A.20. Biological Sludge - 200 µm mesh - Batch Type - 1mg/l cationic polymer – 100 ml/min

In this experiment, the maximum hydraulic loading was used and the sludge feeding rate was 100 ml/min. The solids loading calculated as 43.4 kg/m^2.d. At the beginning, the solids concentration was 1.6% and at the end of thickening operation, it was reached to 3.4% with an overall sludge volume reduction of 53%.

As shown in the Figure A.20, the same trend of polymer application was seen. There was no big difference between two phases of the experiment. In the second phase, 30 minutes of recovery period was investigated. In the first phase, an increase in solids concentration can be observed but in the second phase, there was no improvement in solids percent. Only 1.1 folds of increase could be obtained at the end according to initial concentration.

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A.2. Mesh Filtration of Chemical Sludge

A.2.1. 100 µm Mesh Size Experiments without Polymer

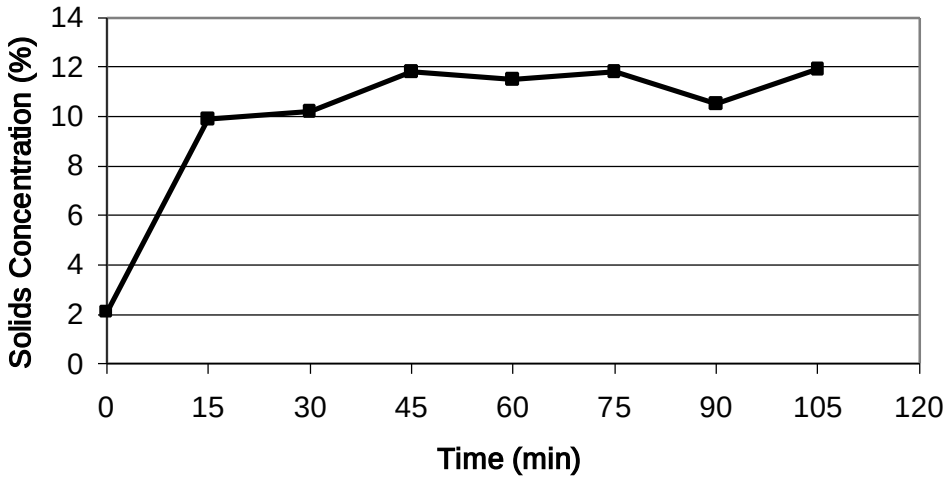

Figure A.21. Chemical Sludge - 100 µm mesh-Batch Type - 20.5 ml/min

The first flow rate for the experiment was 20.5 ml/min. It can be seen from the Figure A.21, initial solids concentration was 2.1% and the final solids concentration was measured as 11.9% at the end. During the procedure, 9.0 kg/m^2.d solids loading was applied and the sludge volume reduction occurred as 82%.

The general trend of chemical sludge thickening with mesh was seen. In the first phase, a quick increase of solids concentration was observed and than it remained nearly unchanged during whole procedure. In the first phase, the solids concentration increased to 11.5% which was 4.5 folds of the initial concentration. In the second phase, there was approximately no improvement. At the end of procedure, the resultant solids concentration was 11.9% and this was 4.7 folds of its initial value, only 0.2 folds of increase were seen. The obtained solids concentration in chemical sludge thickening could not be reached in biological sludge thickening applications.

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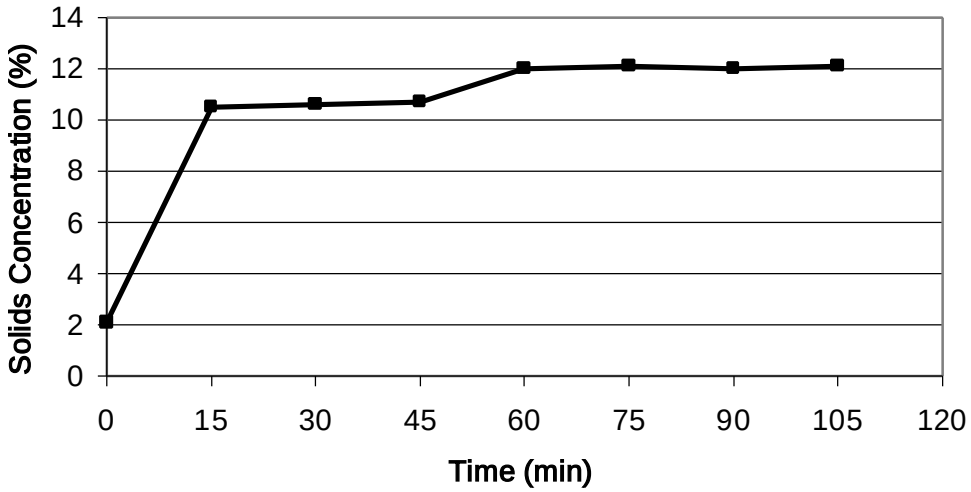

Figure A.22. Chemical Sludge - 100 µm mesh-Batch Type - 41 ml/min

As seen in the Figure A.22, the flow rate increased to 41 ml/min and as a result of higher flow rate, solids loading rose to 18 kg/m^2.d. Initial solid concentration was 2.1% and reached to a value of 12.1% at the end of experiment. The overall volume reduction was 83%.

In chemical sludge thickening with mesh showed always similar results as mentioned before. The pattern of sludge cake concentration over the mesh during the procedure did not show ups and downs. Once the cake formed and became stable, a straight line occurred in the graphics. In the first phase, after 15th minute, the cake arrived to a constant value which was approximately 11% and did not change during the second phase also. The difference between two phases was only 0.6 folds or in terms of concentration was nearly 1.1%. According to initial solids concentration, 4.8 folds of increase were observed.

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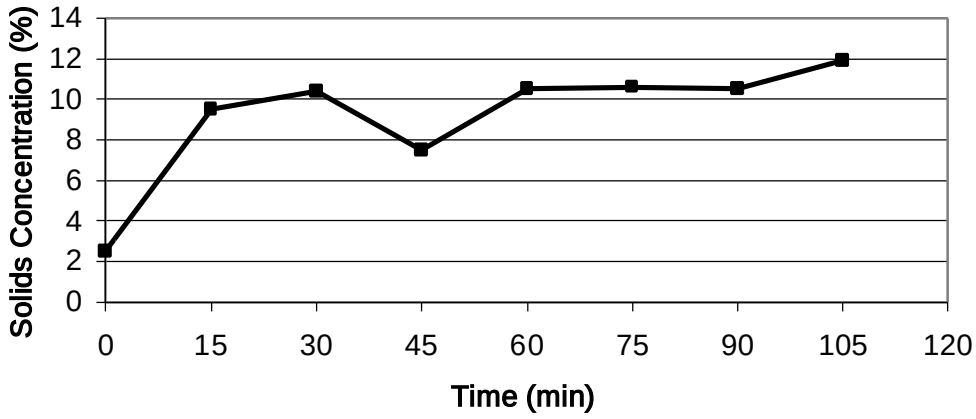

Figure A.23. Chemical Sludge - 100 µm mesh-Batch Type – 61.6 ml/min

In this experiment, a sludge flow of 61.6 ml/min was used. At the beginning, the solids concentration was measured as 2.5% and at the end, the result was 11.9% with a solids loading of 32 kg/m^2.d. The volume reduction of sludge was 79%.

In this case, sludge cake formed later, at 30th minute of the experiment as it can be seen in Figure A.23. A difference from the other procedures, in the 45th minute, solids concentration decreased. This was due to cake disturbances in sampling period but there was again no particular difference between two phases. In the first phase, the sludge concentration increased to 10.5% and in the second phase, the resultant concentration was 11.9% which was 3.8 folds according to initial value of sludge.

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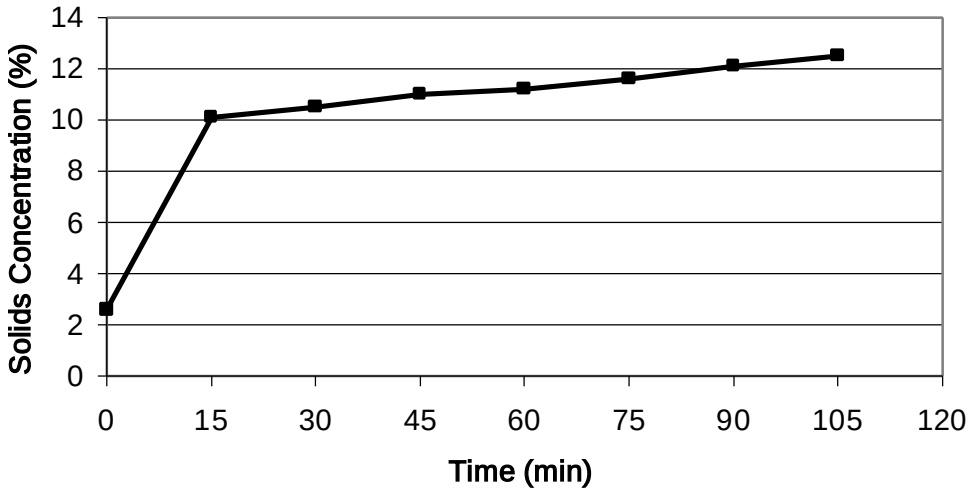

Figure A.24. Chemical Sludge - 100 µm mesh-Batch Type – 84 ml/min

The flow used in this experiment was 84 ml/min. The solids loading was calculated as 45 kg/m^2.d. The obtained solids concentration was 12.5% and it improved from 2.6%. The overall sludge volume reduction was 80%.

In the Figure A.24, it can be easily seen that, the cake formation completed almost at 15th minute of the experiment. From this point, the solids concentration over the mesh did not changed much. In the first phase, 3.2 folds of increase was investigated (from 2.6% to 11%) and in the second phase, the solid concentration reached to 12.5% which was 1.5% more compared to the first phase. The general pattern was very stable during the procedure.

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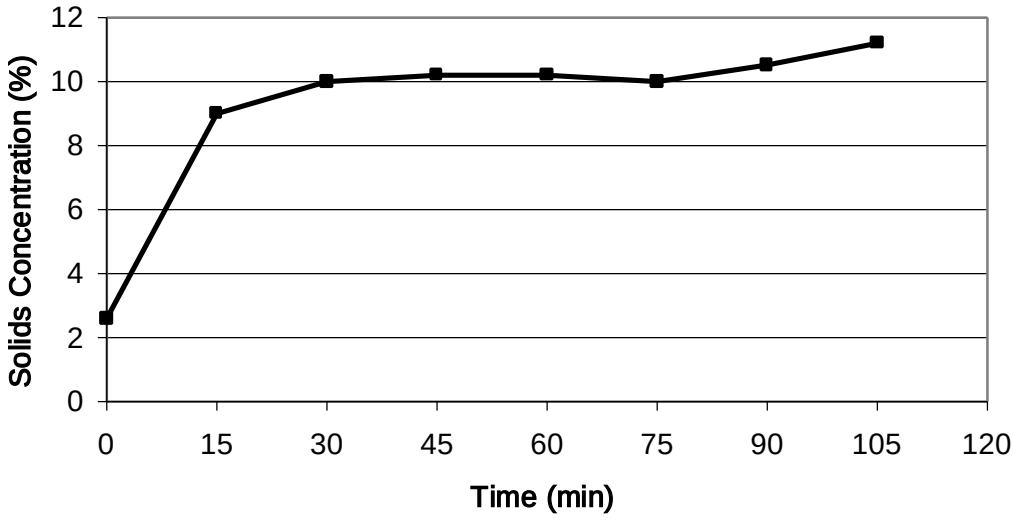

Figure A.25. Chemical Sludge - 100 µm mesh-Batch Type – 100 ml/min

In the Figure A.25, it can be seen that the maximum hydraulic loading was used, 100 ml/min. Initial solids concentration was 2.6% and at the end of thickening operation, it was 11.2%. This result obtained by applying 55 kg/m^2.d solids loading. The overall sludge volume reduction was 77%.

During all chemical thickening experiments, the same pattern was seen as in that case. Cake formation became stable in the 15th minute of the procedure and endured up to the end. In the first phase, the solid concentration was 10.5% approximately which was 3 folds of its initial value and in the second phase, the increase was 0.7% and it reached to 3.3 folds of initial solids concentration.

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A.2.2. 200 µm Mesh Size Experiments without Polymer

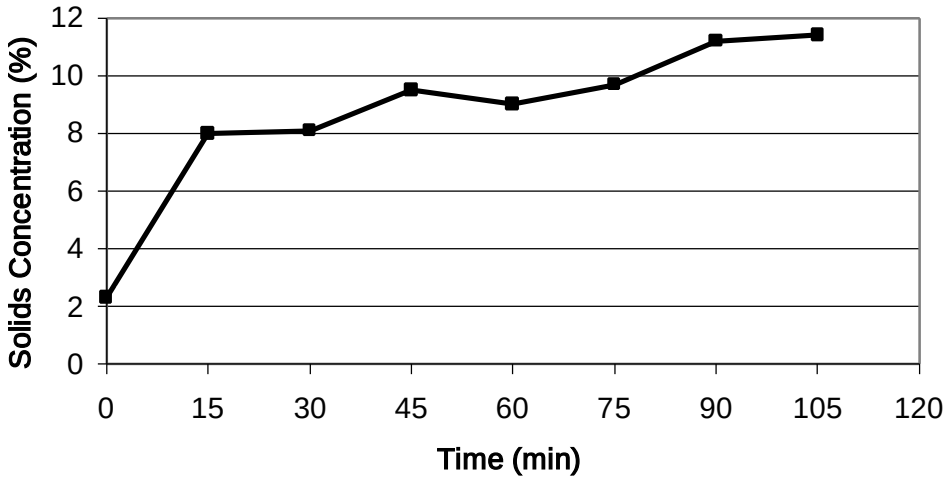

Figure A.26. Chemical Sludge - 200 µm mesh-Batch Type – 20.5 ml/min

The first flow rate of sludge feed was 20.5 ml/min. The solids loading for this experiment was 9.6 kg/m^2.d. The initial solids concentration measured as 2.3% and it reached to 11.4% at the end of procedure. The sludge volume reduction was 80%.

Although there can be seen a little difference between two phases of experiment as in the Figure A.26, there was about 2% sludge increase in the second phase. In the first phase, the sludge cake concentration rose up to 9.5% which was 3.1 folds of increase, the resultant sludge was 4 folds of the initial solid concentration. The late formation of sludge could be explained in 2 parts. The first, the mesh size opening was bigger and the second one was the low solids loading. Actually, both reasons caused such a late formation because, in the next sections of 200 µm mesh, this case could not be realized.

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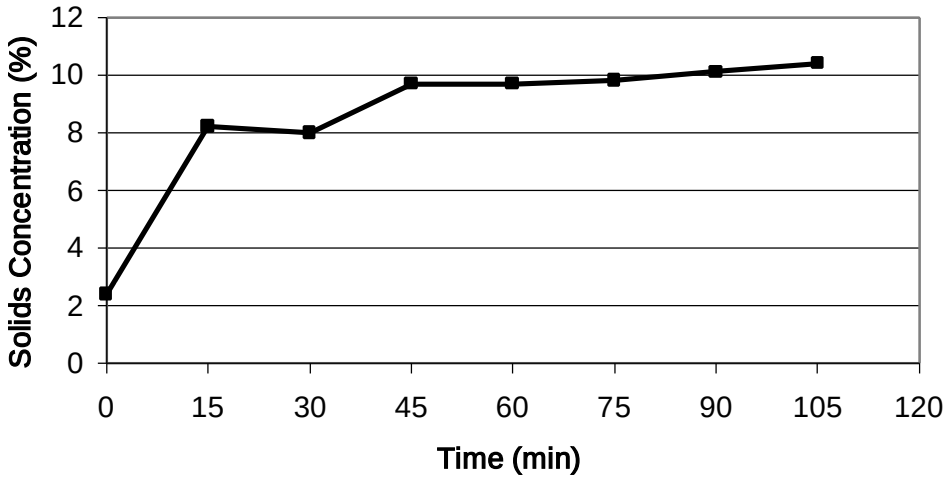

Figure A.27. Chemical Sludge - 200 µm mesh-Batch Type – 41 ml/min

The sludge feed increased from 20.5 ml/min to 41 ml/min and the solids loading was calculated as 20.0 kg/m^2.d. At the beginning, the solid concentration was 2.4% and it became 10.4% at the end of experiment. The sludge volume reduction was 78%.

From minimum to the maximum hydraulic loading, the same trend was seen. An early cake formation occurred in the first phase and it endured in second phase. In the first phase, the sludge cake concentration increased to 9% approximately as it can be seen in the Figure A.27, and during the second phase, a little difference was investigated. At the end of procedure, the sludge thickened by 3.3 folds of its initial value.

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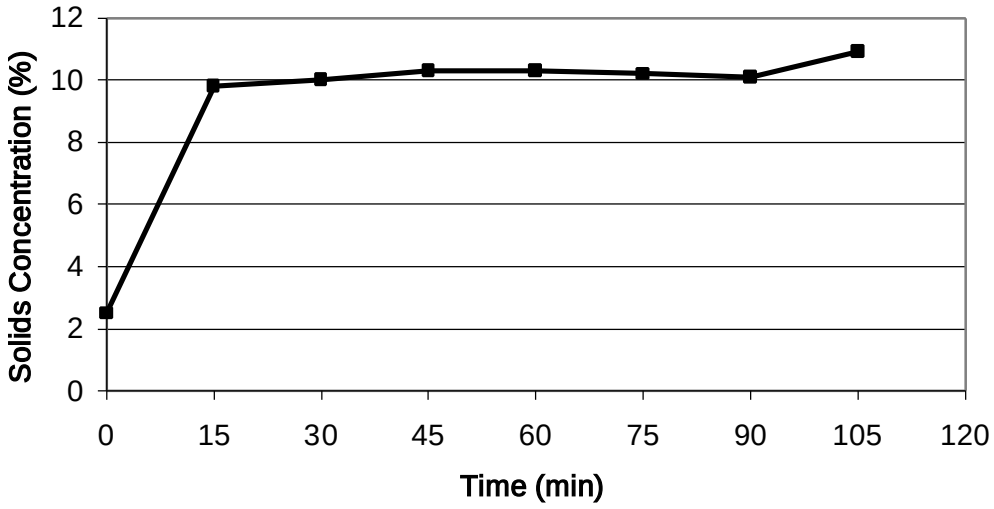

Figure A.28. Chemical Sludge - 200 µm mesh-Batch Type – 61.6 ml/min

As it can be seen in the Figure A.28, the flow rate of sludge feed was 61.6 ml/min. The solids loading was 32.0 kg/m^2.d and the initial solids concentration was 2.5%. The resultant sludge cake concentration on the mesh was calculated as 10.9%. The overall sludge volume reduction was 77%.

The pattern showed that sludge cake formed at 15th minute of the experiment and remained unchanged throughout the procedure. In the first phase, 3 folds of increase were investigated (from 2.5% to 10.1%) and in the second phase, 0.4 folds more of its initial value was obtained. By the increase of hydraulic loading, sludge started to form quicker and once it was formed, it remained stable.

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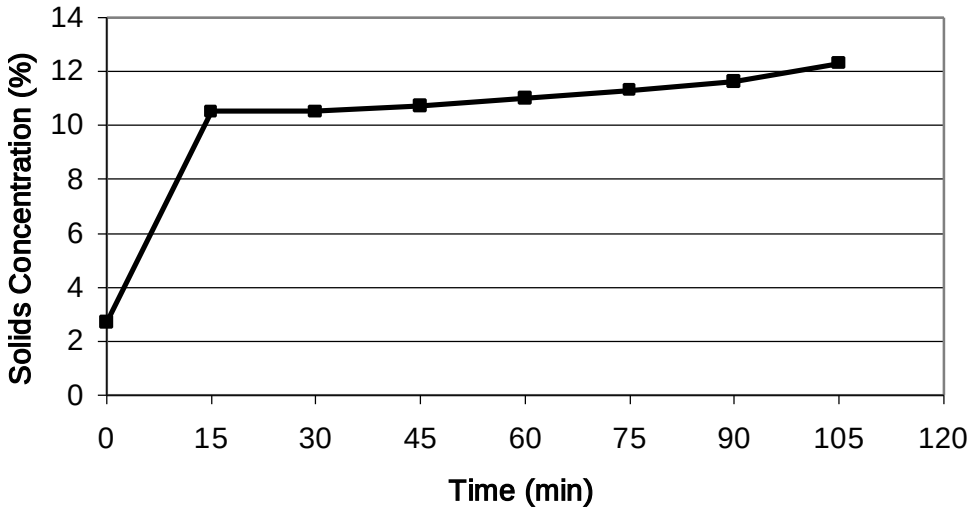

Figure A.29. Chemical Sludge - 200 µm mesh-Batch Type – 84 ml/min

In the Figure A.29, it shown that the flow rate was 84 ml/min. The solids loading was 47.0 kg/m^2.d. At the beginning, solid concentration was 2.7% and the thickened sludge concentration obtained on the mesh was 12.3%. The sludge volume reduction realized as 78%.

As it was seen on the previous experiments of chemical sludge thickening, same trend was occurred. At the 15th minute of the procedure, sludge cake formed and it was not changed during the thickening operation. In the first phase, the sludge cake concentration increased to 11.3% which was 3.2 folds of its initial value and in the second phase, the rise in the solid concentration was 1%. The total increase of concentration investigated as 3.6 folds of initial solids concentration.

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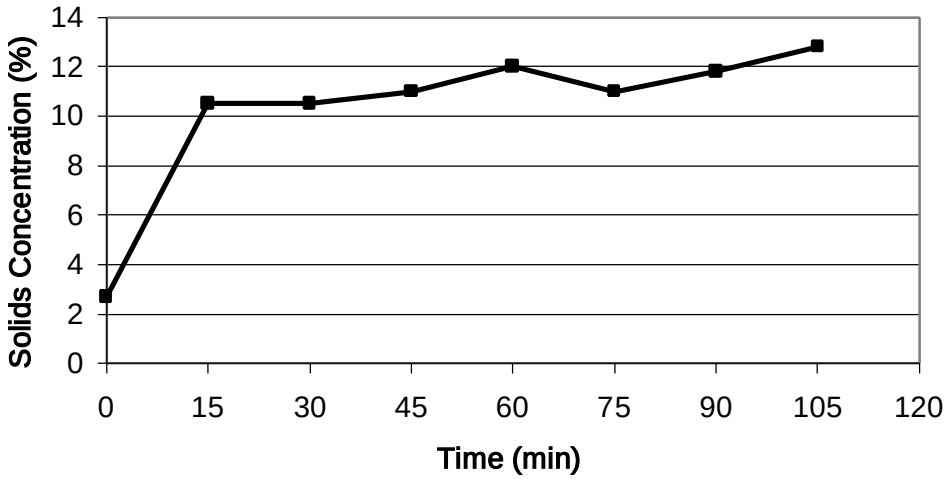

Figure A.30. Chemical Sludge - 200 µm mesh-Batch Type – 100 ml/min

The maximum hydraulic loading which was 100 ml/min was applied to the system. The initial solid concentration was 2.7% and it rose up to 12.8% at the end of procedure. The solids loading was 56.0 kg/m^2.d where the overall sludge volume reduction was 79%.

In the Figure A.30, it can be seen the quick formation of sludge cake at the 15th minute. After that, there was no big difference during the experiment. In the first phase, the sludge increased up to 12.8% concentration and reached 12.4% at the end. The cake sludge concentration compared to the initial value increased 3.6 folds.

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A.2.3. 100 µm Mesh Size Experiments with Polymer

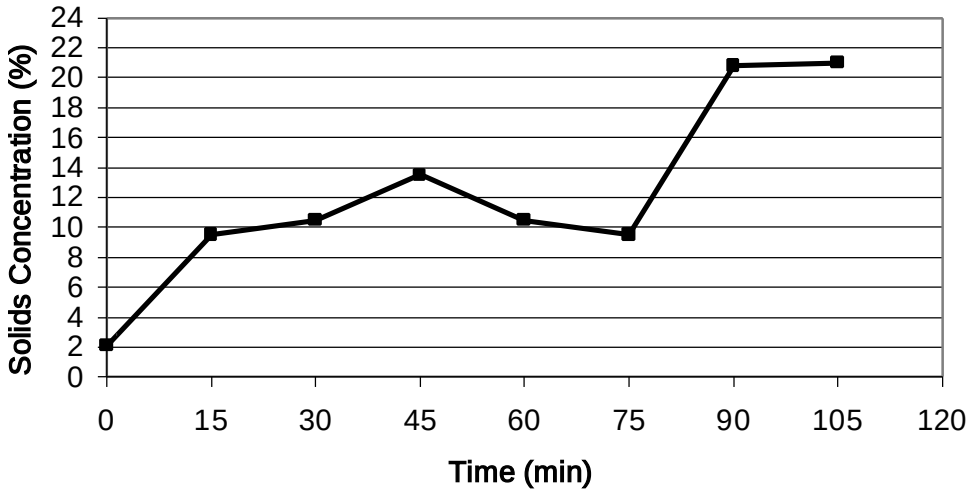

Figure A.31. Chemical Sludge - 100 µm mesh - Batch Type – 20.5 ml/min with 1 mg/l polymer

The starting flow rate of sludge was 20.5 ml/min. the solids loading was calculated as 9.2 kg/m^2.d. Initial solids concentration was 2.1% and at the end, final solids concentration increased to 21.0%. The sludge volume reduction was 90%. This final solids concentration was much bigger than a thickening range and it was fallen to a dewatering range which was considered as 15%.

The pattern of sludge thickening was different from the general pattern of chemical sludge thickening without polymer as it is shown in the Figure A.31. Cake formation was not completed until the 90th minute and it continued to improve. In the first phase, solids concentration raised 5.2 folds (from 2.1% to 13%) of its initial value and at the second phase, reached up to 9 folds of initial solids concentration. Because of the low solids loading and polymer addition, cake formation endured throughout the procedure.

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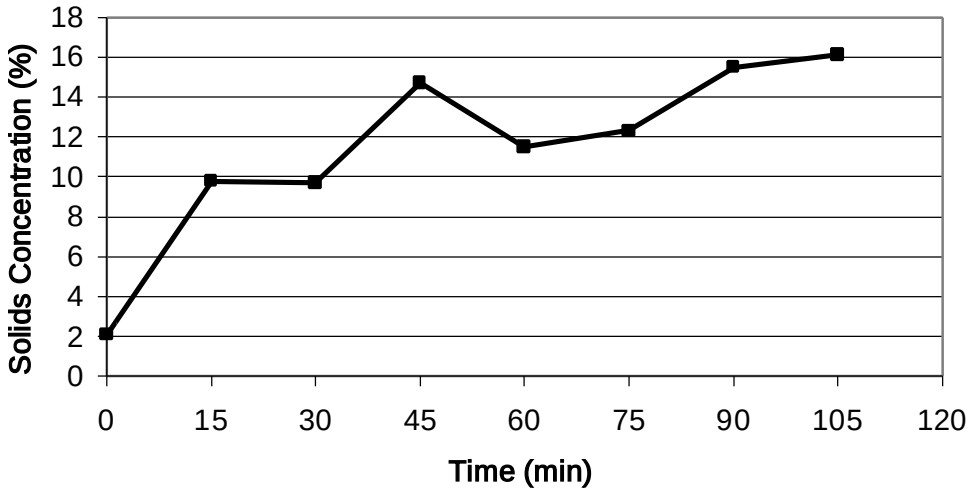

Figure A.32. Chemical Sludge - 100 µm mesh - Batch Type – 41 ml/min with 1 mg/l polymer

The experiment at the 41 ml/min flow rate, with 18.0 kg/m^2.d solids loading, the solids concentration increased from 2.1% to 16.1%. The sludge volume reduction, approximately 87%, was obtained.

As in the Figure A.32, similar to the without polymer added applications, there was no big difference between two phases. Cake formation occurred at the first phase and did not change in the second phase except cake formation time. In this experiment, sludge cake formed later, at 45th minute. In the first phase, the solids concentration on the mesh increased 6.1 folds (from 2.1% to 14.9%) of its initial value and in the second phase, 0.6 folds more. The final solids concentration was 6.7 folds more of the initial concentration.

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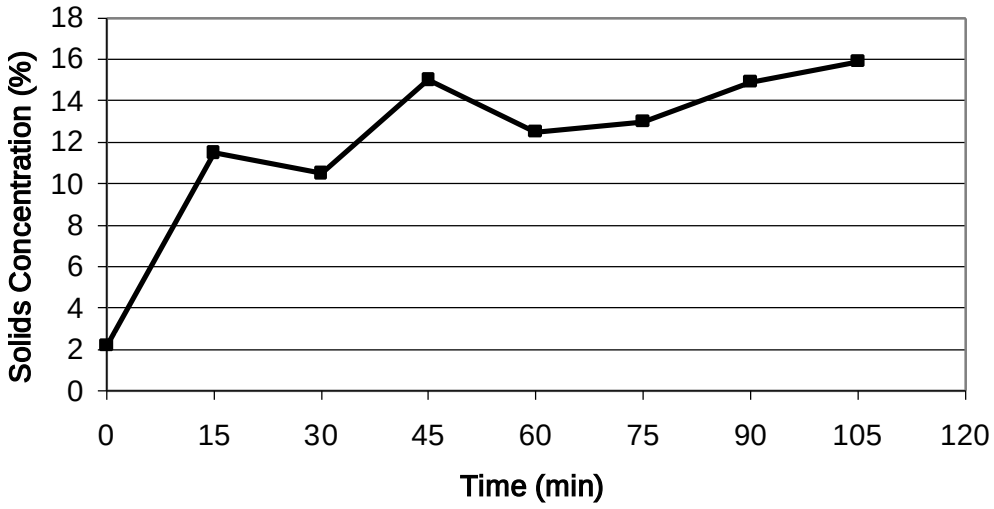

Figure A.33. Chemical Sludge - 100 µm mesh - Batch Type – 61.6 ml/min with 1 mg/l polymer

The sludge feed flow rate was 61.6 ml/min in this experiment. The initial solids concentration was 2.2% and it rose to 15.9% at the end of operation. The overall sludge volume reduction was 86% and this value was obtained by a solids loading of 28.0 kg/m^2.d.

As it is shown in the Figure A.33, the cake formation completed at the same time when compared to the previous experiments. The general pattern was seen. There were no particular differences between two phases of the procedure. In the first phase, 5.8 folds of increase in solids concentration were investigated. In the second phase, this value increased only 0.4 folds and reached to 6.2 folds of its initial value.

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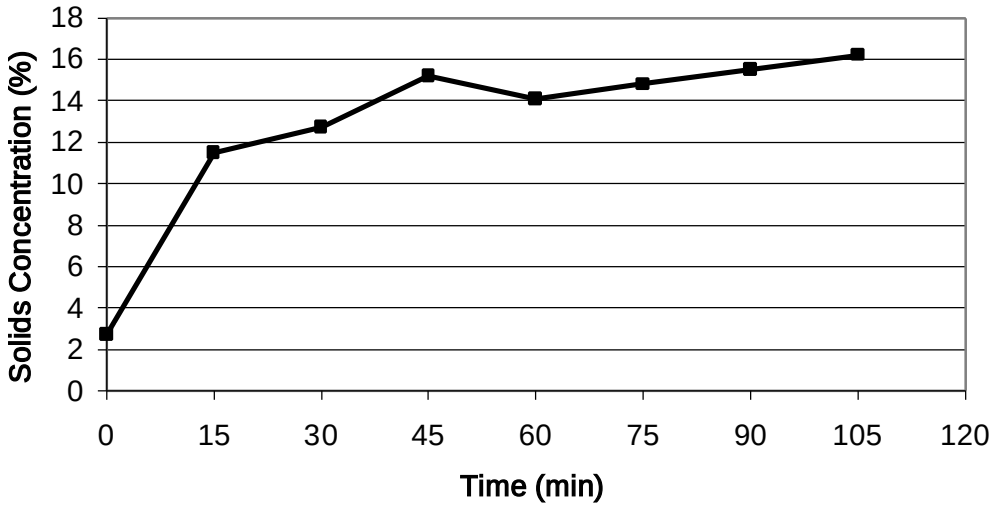

Figure A.34. Chemical Sludge - 100 µm mesh - Batch Type – 84 ml/min with 1 mg/l polymer

The flow rate was 84 ml/min with a solids loading of 43 kg/m^2.d. At the beginning, the solids concentration was 2.7%. Final result of the thickening operation was 16.2%. This gave a sludge volume reduction of 83%.

As seen in the Figure A.34, sludge cake formation completed at the first phase and it was nearly stable. In the first phase, the sludge cake concentration on the mesh was 4.5 folds more of its initial value and in the second phase, it not increased much, it was only 0.5 folds more according to initial concentration.

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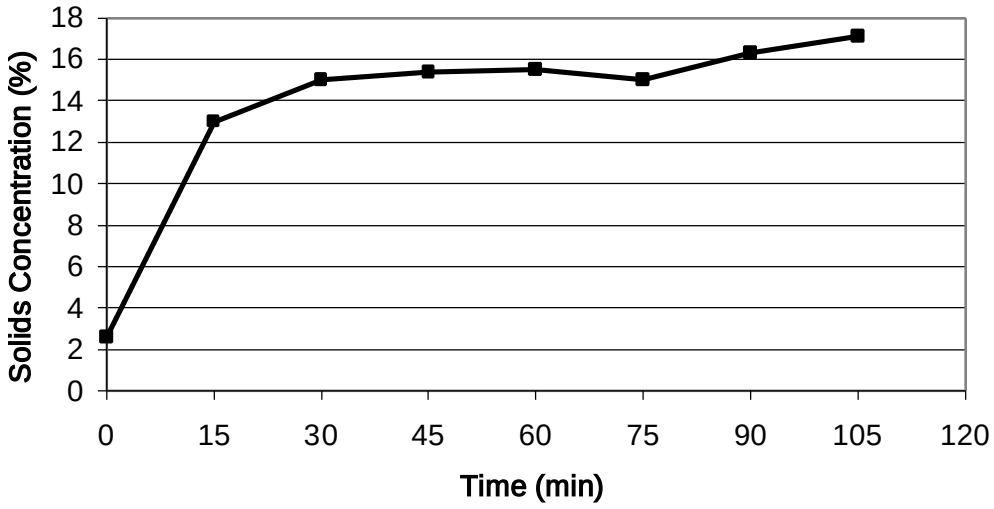

Figure A.35. Chemical Sludge - 100 µm mesh - Batch Type – 100 ml/min with 1 mg/l polymer

The maximum hydraulic loading was used in this experiment. The sludge feed flow rate was 100 ml/min. The solids loading was 54 kg/m^2.d. At the beginning, the solids concentration was 2.6% and it increased to 17.1% at the end. The overall sludge volume reduction was 85%.

In the Figure A.35, it can be seen that the general trend was continued. Sludge cake formed at 45th and endured unchanged throughout the experiment. In the first phase, the solids concentration increase was 4.8 folds of its initial value and in the second phase, it raised up to 5.5 folds compared to initial concentration.

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A.2.4. 200 µm Mesh Size Experiments with Polymer

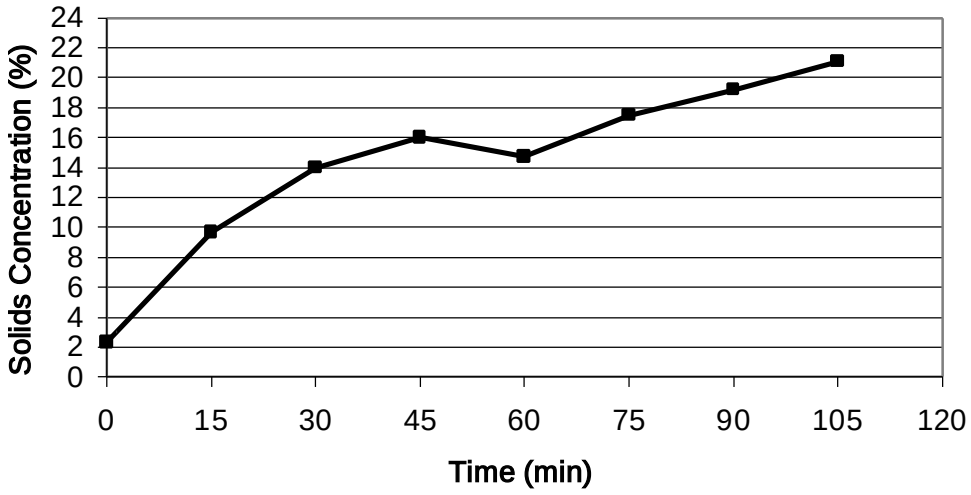

Figure A.36. Chemical Sludge - 200 µm mesh - Batch Type – 20.5 ml/min with 1 mg/l polymer

The starting flow rate of sludge was again 20.5 ml/min. The solids loading was calculated as 10.0 kg/m^2.d. Initial solids concentration was 2.3% and at the end, final solids concentration increased to 21.1%. The sludge volume reduction was 89%. In this case, like in 100 µm mesh size, the final sludge cake concentration passed the limit of dewatering value which was 15%.

The pattern of sludge thickening was different form the general pattern of chemical sludge thickening without polymer as it is shown in the Figure A.36. Cake formation was not completed during the operation and it continued to improve. In the first phase, sludge concentration raised 6.2 folds (from 2.1% to 16%) of its initial value and in the second phase, reached up to 8.2 folds of the initial concentration.

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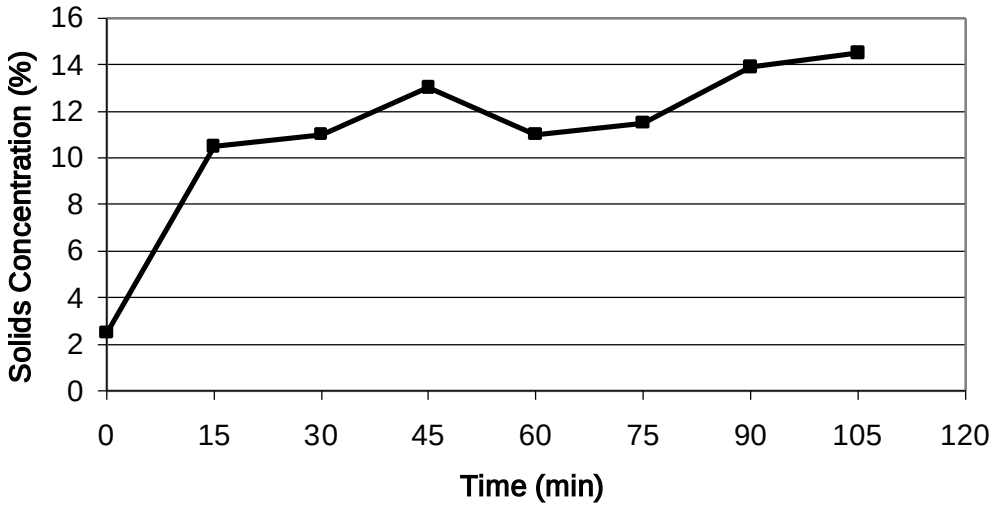

Figure A.37. Chemical Sludge - 200 µm mesh - Batch Type – 41ml/min with 1 mg/l polymer

The experiment at the 41 ml/min flow rate, with 21.0 kg/m^2.d solids loading, the solids concentration increased from 2.5% to 14.5%. The sludge volume reduction, approximately 83%, was obtained.

As in the Figure A.37, similar to the without polymer added applications, there was no big difference of concentration between two phases. Cake formation occurred at the first phase and did not change in the second phase except cake formation time. In this experiment, cake formed later, at 45th minute. In the first part, the sludge concentration on the mesh increased 4.2 folds (from 2.5% to 13%) of its initial value and in the second part, 0.6 folds more. The final solids concentration was 4.8 folds more of the initial concentration.

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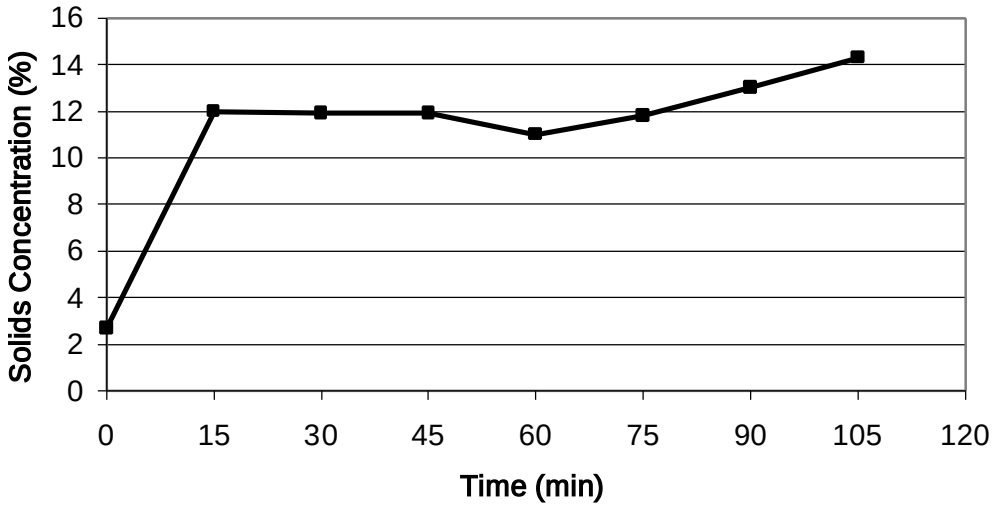

Figure A.38. Chemical Sludge - 200 µm mesh - Batch Type – 61.6 ml/min with 1 mg/l polymer

The sludge flow rate was 61.6 ml/min in this experiment. The initial solids concentration was 2.7% and it rose to 14.3% at the end of operation. The overall sludge volume reduction was 81% and this was obtained by a solids loading of 32.0 kg/m^2.d.

As it is shown in the Figure A.38, the cake formation completed earlier than the previous experiments. This can be due to high solids loading. The general pattern was seen again in this case also. The cake formed at 15th minute and rested approximately stable during the procedure. In the first phase, 3.6 folds of increase in solids concentration were investigated. In the second phase, this value increased to 4.3 folds of its initial value.

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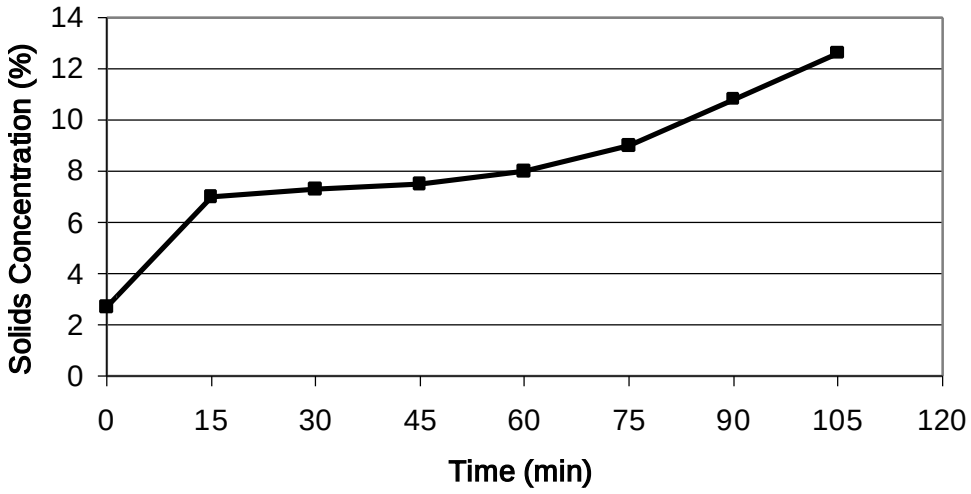

Figure A.39. Chemical Sludge - 200 µm mesh - Batch Type – 84 ml/min with 1 mg/l polymer

The flow rate was 84 ml/min with a solids loading of 46 kg/m^2.d. At the beginning, the solids concentration was 2.7%. Final result of the thickening operation was 12.6% as solids concentration. This gave a sludge volume reduction of 79%.

As seen in the Figure A.39, sludge cake formation endured through all experiment as it was investigated in the 20.5 ml/min application. In the first phase, the sludge concentration on the mesh was 1.8 folds more of its initial value and in the second phase, it increased to3.6 folds compared to initial concentration. In this procedure, it was realized that the effect of polymer was not noticeable. Insufficient dosage was lead to that result with high solids loading.

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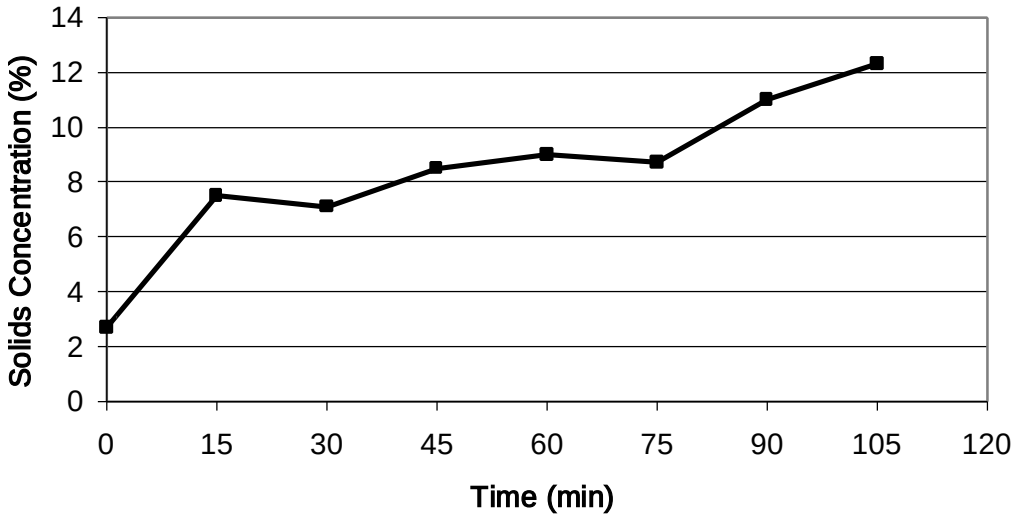

Figure A.40. Chemical Sludge - 200 µm mesh - Batch Type – 100 ml/min with 1 mg/l polymer

The maximum hydraulic loading was used in this experiment. The sludge flow rate was 100 ml/min. The solids loading was 56 kg/m^2.d. At the beginning, the solids concentration was 2.7% and it increased to 12.3% at the end. The overall sludge volume reduction was 78%.

In the Figure A.40, it can be seen that from 15th to 75th minute of the procedure, cake formation did not change much. The drying period which started after 75th minute, increased the sludge concentration more than expected one. In the first phase, the sludge concentration increase was 2.2 folds approximately and in the second phase, it rose up to 3.5 folds of its initial value. Final solids concentration reached to 12.3%.

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A.3. Foam Thickening of Biological Sludges

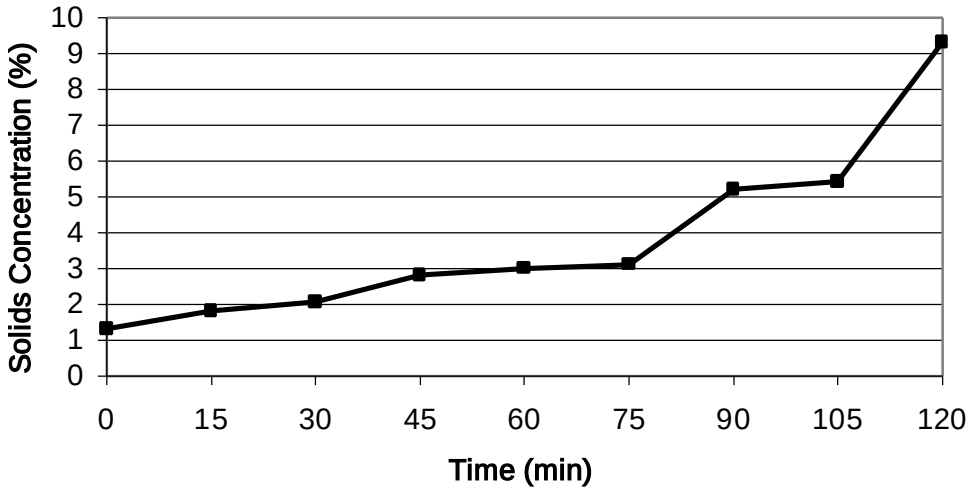

Figure A.41. Foam thickening – Batch type – 40 ml/min

At the lowest flow rate, 40 ml/min, for the polyether foam, with 4.57 kg/m^2.d solids loading, the solids concentration increased from 1.3 to 5.4 and approximately 76% sludge volume reduction was observed. At the end of the experiment, the sludge cake was manually dewatered and very high solids concentration, 9.3%, was observed which was never reached with both meshes. The sludge volume reduction after the manual dewatering reached to 86%.

As in the Figure A.41, the solids concentration over the foam was improved throughout the experiment. The sludge cake formed slowly. This was the general pattern of the foam thickening operation. Except in few experiment, recovery period was not needed. At the end of operation, the sludge thickened 3.2 folds of its initial value. After manual dewatering, this value almost doubled and reached to 6.2 folds of the initial concentration.

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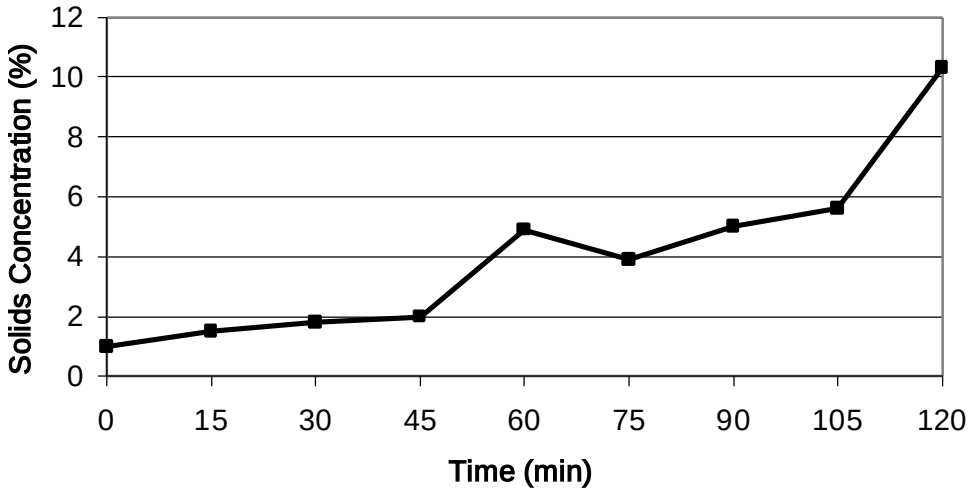

Figure A.42. Foam thickening – Batch type – 61.6 ml/min

The flow rate was increased to 61.6 ml/min and at the beginning solids concentration was 1.0%. With 5.54 kg/m^2.d solids loading, solids concentration increased to 5.6% and very high volume reduction, 80% was observed. After the sludge manually dewatered, sludge cake concentration increased to 10.3% which was nearly 2 times greater than the sludge cake concentration at 105th minute and also the volume reduction was increased to 90%.

The general pattern was very close to the previous experiment as shown in Figure A.42. The cake continued to form throughout the experiment. The solids concentration over the foam increased gradually and reached to 4.6 folds higher value at the end of operation. After manual dewatering, the solid concentration increased up to 9.3 folds according to its initial value. Dewatering the foam after the operation brought 54% improvement of the cake concentration.

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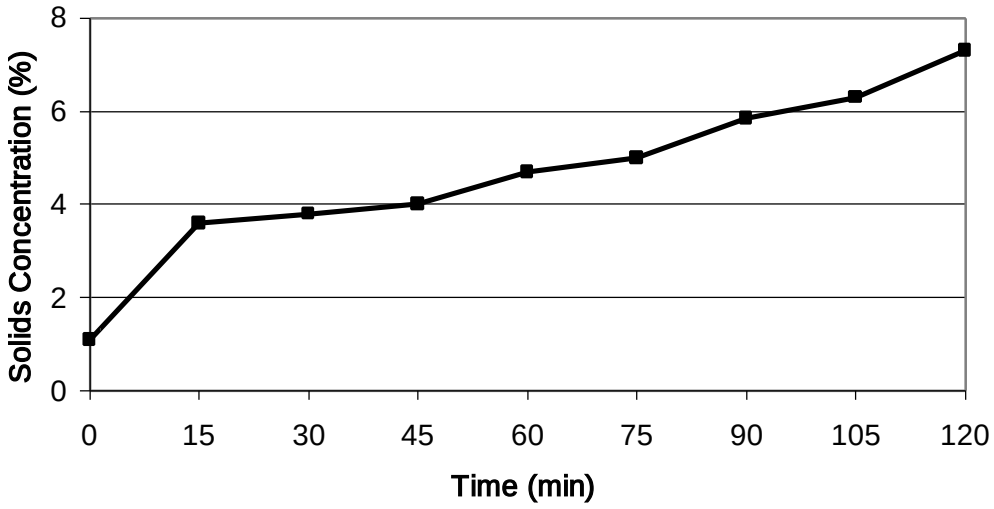

Figure A.43. Foam thickening – Batch type – 84 ml/min

The flow rate was 80 ml/min. The sludge feed had a solids loading of 7.92 kg/m^2.d. The solids concentration increased from 1.1% to 6.3%. The sludge volume reduction was calculated as 82%. After dewatering manually, solids concentration increased to 7.3% which was lower than expected value, although the sludge cake concentration was higher at the 105th minute than previous experiments.

In the Figure A.43, it can be easily seen that the general pattern of foam thickening repeated in that experiment also. The sludge cake concentration increased slowly in every phase. At the end of experiment, the solids concentration reached 4.7 folds of its initial value but dewatering operation was not successful as in the previous trials. It only improved the solids concentration 15%.

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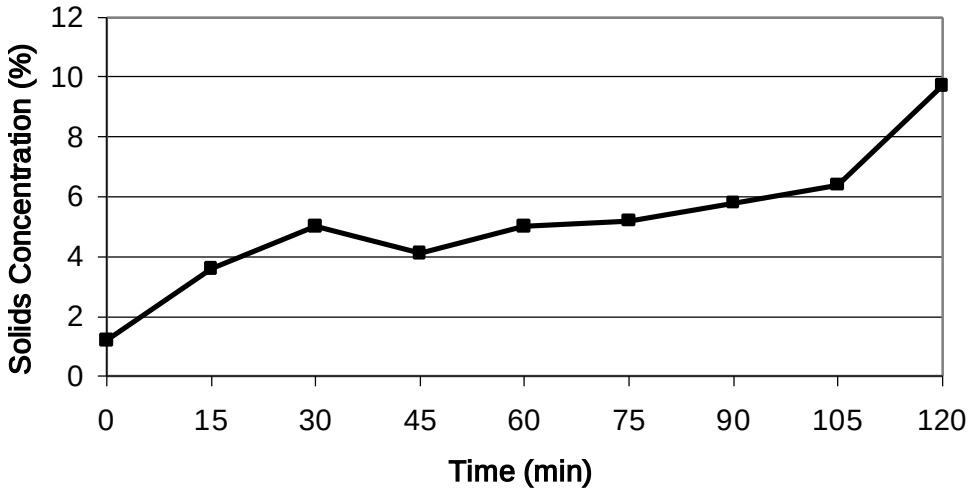

Figure A.44. Foam thickening – Batch type – 100 ml/min

With the flow rate of 100 ml/min and solids loading of 11.07 kg/m^2.d first solids concentration was 1.2%. At the end, final solids concentration was 6.4% and very high volume reduction, approximately 81%, was obtained. After the sludge cake was dewatered manually, thickened solids concentration increased to 9.7% and the volume reduction was increased to 88%. This flow rate was the maximum of the mesh thickening.

As shown in the Figure A.44, the sludge cake concentration rise investigated through all experiment. The general trend was seen again in this operation. The cake concentration increased to 4.3 folds of its initial value. After the manual dewatering operation, the solid concentration further improved to 7.1 folds of the original value. The improvement between final solids concentration of thickening and dewatering was 51%.

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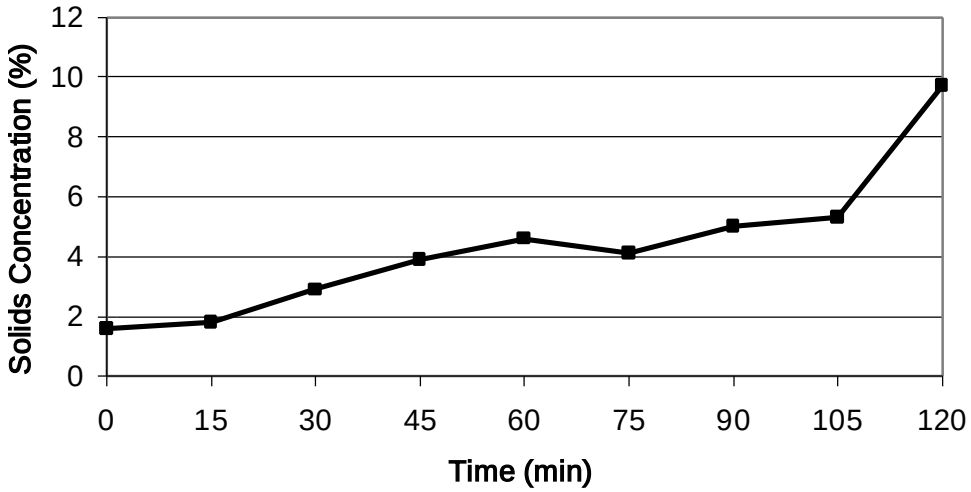

Figure A.45. Foam thickening – Batch type – 120 ml/min

When the flow rate was increased to 120 ml/min, the solids concentration was increased to 5.3% from 1.6% with a solids loading of 16.85 kg/m^2.d. At the end of the experiment, a volume reduction of 70% was observed. After manual dewatering of the sludge, the volume reduction was increased to 84%, where the solids concentration was to 9.7%.

The slow increase in the sludge concentration was investigated according to Figure A.45 which was the general view. After the thickening operation, the foam gathered 2.3 folds more as concentration of sludge. Manual dewatering increased this value to 5.1 folds and that led to 83% improvement in the solids concentration on the foam.

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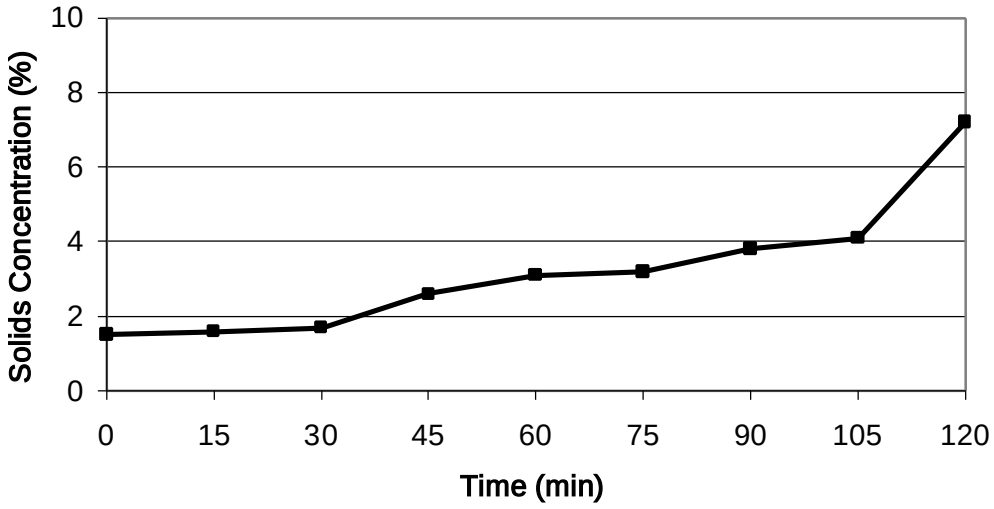

Figure A.46. Foam thickening – Batch type – 140 ml/min

With a flow rate of 140 ml/min and solids loading of 19.4 kg/m^2.d, the solids concentration was increased to 4.1% from 1.5%. The overall sludge volume reduction was 62%. After manually dewatering process, the sludge cake concentration was increased to 7.2% and the volume reduction of sludge became 80%.

The general trend of foam thickening was again shown on this experiment as it is seen in Figure A.46. Although the final sludge concentration was less 5%, it was higher than the usual range of conventional gravity thickener. At the end of experiment, 1.7 folds of increase were calculated. Manual dewatering helped to obtain a 3.8 folds thicker sludge compared to its original value.

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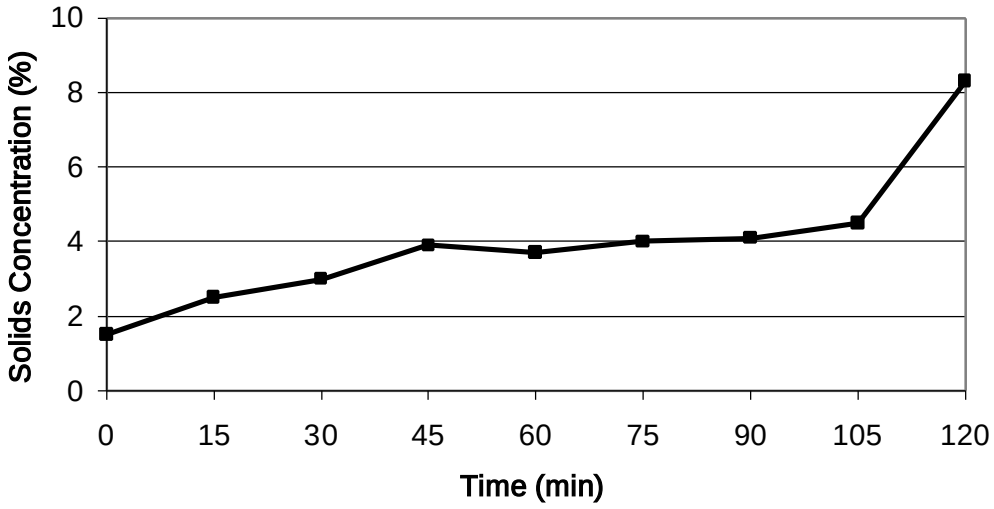

Figure A.47. Foam thickening – Batch type – 160 ml/min

The flow rate was increased to 160 ml/min for the polyether foam and the solids concentration at the beginning was again 1.5% with 22.17 kg/m^2.d solids loading. The solids concentration was increased to 4.8% at the end of the experiment. The volume reduction was 69%. After the manual dewatering of the sludge, the thickened sludge concentration was increased to 8.3% and the volume reduction reached to 82%.

The foam thickening trend was shown in the Figure A.47. Through all experiments, nearly same graphic presented the situation. Slow increase in sludge cake concentration was investigated again. At the end of experiment, the concentration of the sludge cake over the foam raised by 2.2 folds of its initial value and with manual dewatering this value continued to rise up to 4.5 folds of the initial concentration.

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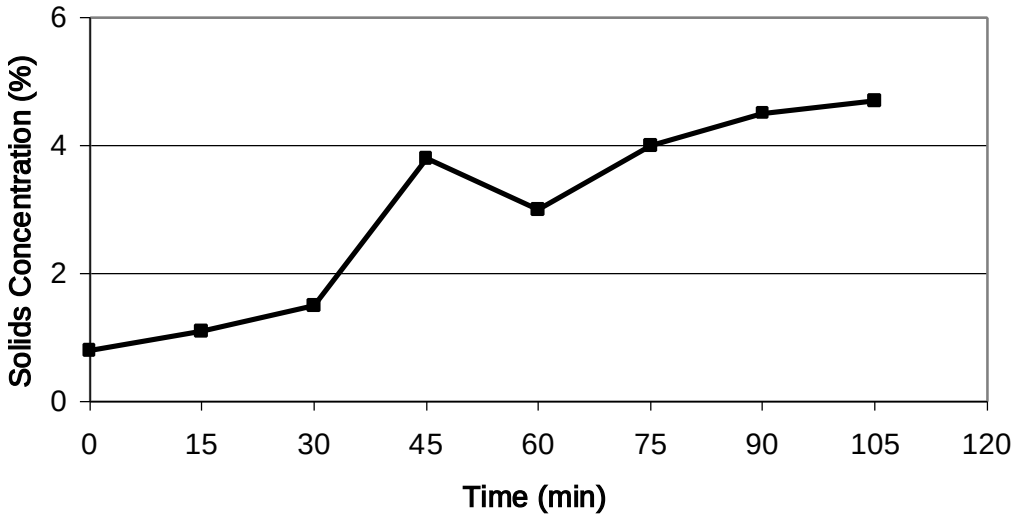

Figure A.48. Foam thickening – Batch type – 180 ml/min

At the highest flow rate for the polyether foam, with 13.28 kg/m^2.d solids loading, the solids concentration increased from 0.8% to 4.7% and very high sludge volume reduction, approximately 83%, was observed.

The general pattern could be investigated in this case also although the flow rate was very high. At the end of procedure, the sludge cake concentration increased 4.9 folds of its initial value.

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