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Dewatering of Golden Horn sludge with geotextile tube and determination of optimum operating conditions: A novel approach

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ABSTRACT
Environmental concerns about Golden Horn's polluted sediments have led to 320,000 m^3 of sea dredging, generated annually by bucket dredgers to be stored in landfills without dewatering. This study presents an efficient dewatering methodology and a beneficial alternative to store the sludge. In this scenario, the sludge of a suction-cutter dredger is transported to a pond. The beneficial use of geotextile tubes filled with the sludge at circumferential embankments of pond is evaluated. An anionic polyacrylamide (APAM) is used for conditioning the high plastic silt sludge with 10% solid content. APAM dosage is optimized by Rapid Dewatering Test (RDT) for geotextile material. Microscale SEM-EDS analyzes depicted the flocculated form of the sludge. Laboratory-scale Geotextile Dewatering Test (GDT) shows improvements in the turbidity of filtrate, the quantity of solid particles retained in the tube, and the filtration efficiency, determined to be 92 NTU, 18.5% and 90.5% respectively. In accordance with the ICP-OES analysis, the discharge of the filtrate to the aquatic media is admissible. Undrained shear strength of the dewatered sludge is assessed as low, by Vane and undrained unconsolidated triaxial compression tests. Further improvements of the dewatered sludge with vacuum preloading method were projected by completion of the consolidation tests.

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Dredged sludge; dewatering; geotextile tube; polyacrylamide

1. Introduction

Dredging deep sediments on a regular basis is critical for maintaining water depth in harbors, marinas, and water channels, as well as for ecological reasons (Bates et al. 2015). Environmental management costs of deep dredged materials can increase considerably with large high-water content and pollution potential. When planning the phases of a dredging activity, it is critical to create a decision tree based on the physical properties and the chemical characterization of the material to be dredged (Başar et al. 2017). These materials are disposed of in one of three ways: to the sea, on land, or for beneficial purposes (OSPAR 2009). Uncontrolled disposal to the sea in a particular area will not only disrupt the area's ecological structure, but will also cause various stability issues on the seabed (Sheehan and Harrington 2012). Because of the high cost, large area, and need for long-term monitoring, land disposal of dredged materials is usually not preferred unless they are classified as hazardous waste in controlled landfills (Agostini, Skoczylas, and Lafhaj 2007; LIFE 2002). The alternative, the use of dredging for beneficial purposes, is a sustainable solution that attracts the attention of many researchers. The productions of the lightweight concrete (Wang 2009; Tang et al. 2011), the daily or intermediate covers and impermeable layers in landfill sites (Riordan, Murphy, and Harrington 2008; Çevikbilen et al. 2020), and the engineering structures such as coastal protection structures with prefabricated vertical drains (Cai et al. 2017) are some examples of these studies based on this alternative usage.

Different dredging methods, such as a suction-cutter dredges, clamshell dredges or bucket dredgers, are used during dredging. The water content of the dredged sludges varies according to the dredging technique; the water content of the dredged sludges remains high in dredging activities conducted with excavations and suction tips. When the volume of dredged materials decreases through dewatering using vacuum filters, centrifuges, band filters, press filters and sludge drying beds, it is stored in sludge lagoons. The selection of the dewatering method shall determine the assessment of the mechanical behavior of the dredged material and its alternative beneficial uses. The use of geotextile tubes and polyacrylamide (PAM) is increasingly becoming widespread (Satyamurthy and Bhatia 2009; Chu, Guo, and Yan 2011; Berilgen and Bulut 2016; Cetin et al. 2017; Jia et al. 2017; Ardila et al. 2020). Figure 1 shows a schematic diagram of the dewatering application using geotextile and PAM. The tubes made of geotextile materials have high tensile strength and permeability and act as filters between the solid and liquid parts in this application. A standard geotextile tube is made of woven geotextiles

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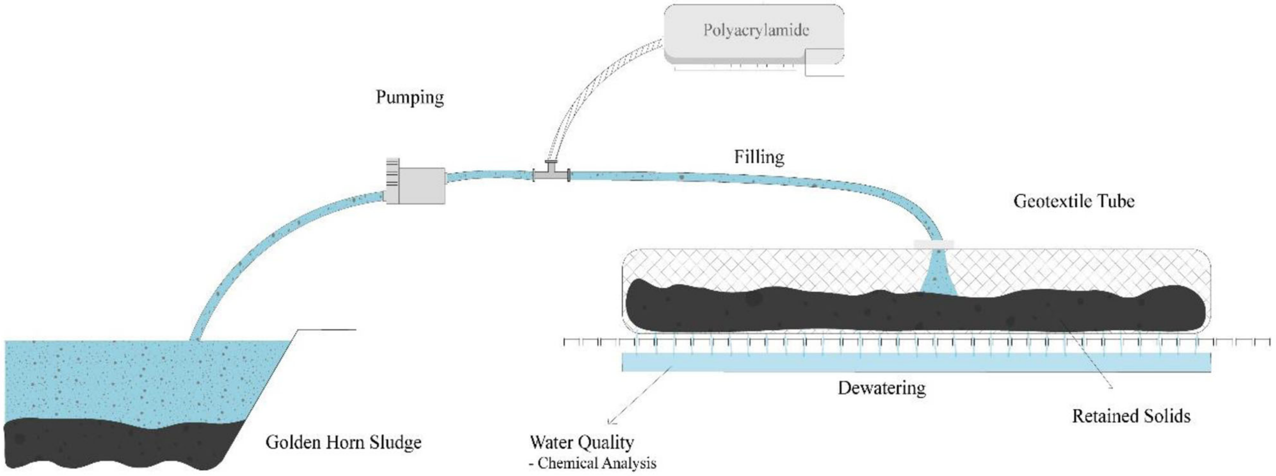

Figure 1. Geotextile tube filling chart.

composed of polypropylene or polyester (Bezuijen and Vastenburg 2013), when using different types of geotextiles, the apparent opening size (AOS) is important (Maurer et al. 2012; Khachan et al. 2012). The amount of solid substances that can pass into the leachate is limited because the grain size diameter of the material to be dewatered is too large to pass through the geotextile pores. PAMs are an indispensable ingredient in sludge dewatering applications. In the suspension, polyacrylamides aggregate the fine-grained particles into larger flocculated particles. After flocculation, the supernatant water is easily filtered to accelerate the dewatering process. PAMs are used by bridging or charging neutralization mechanisms. Although soils are generally negatively charged, the organic content is another important measure of the mechanism. The bridging mechanism dominated by anionic polyacrylamides (APAM) or nonionic polyacrylamides (NPAM) is effective on inorganic soils, while the cationic polyacrylamide CPAM) neutralization mechanism is effective for organic soils (Elimelech et al. 1995; Gregory 2005). PAMs have a wide range of molecular structures and ion charges, and their activities vary depending on the pH and zeta potential of the environment they join. Researchers have developed various designs for their laboratory scaled model experiments in geotextile and PAM dewatering activities (Satyamurthy and Bhatia 2009; Yee and Lawson 2012; Maurer et al. 2012; TenCate 2015; Driscoll et al. 2016; Cetin et al. 2017; Fatema, Bahatia, and Grady 2018; Ardila et al. 2020). Researchers have observed that dewatering efficiency increases with the effective use of a PAM (Moo-Young, Douglas, and Mo 2002; Maurer et al. 2012). Satyamurthy, Liao, and Bhatia (2011) have shown that the use of PAM in dredging materials reduces the dewatering time in the geotextile tube by approximately 85%. Studies are also conducted on limiting the different chemical contents of dredged sludge. Worley et al. (2008) achieved successful results in the removal of phosphorus content from organic lagoon sludge.

The importance of assessing the beneficial use alternatives for dredging materials has been highlighted in this study. Several publications on the dewatering of the Istanbul Golden Horn's dredged sludge have been published in recent years. In a study using 4 different anionic and cationic PAMs, Berilgen and Bulut (2016) showed that PAM can be effectively used in the dewatering of Golden Horn sludge, with the geotextile tube, if the water content of the dredged sludge suspension is above 800 or the solid material content is 10% or higher. In a study on Golden Horn dredged sludge, containing a 10% solid content, Karadoğan et al. (2020) evaluated the polymer activity of 13 different anionic and cationic PAMs during the flocculation process. In the study, it was shown that APAMs produce better results for the Golden Horn dredged sludge suspensions than CPAMs in terms of turbidity and precipitation rate. It can therefore be seen that the choice of an appropriate geotextile tube and an efficient PAM can provide economic and environmental benefits in the dewatering of dredged sludge. Studies on dewatering dredging sludge with geotextile tubes and PAMs are available in the literature. However, there are very few studies of the engineering parameters for filter cake formed in the tube after dewatering, and the use of dewatered dredge sludge in the geotechnical field (Maurer 2011; Berilgen and Bulut 2016; Kim et al. 2021). The recovery of dewatered dredged material will bring significant economic benefits and reduce environmental pollution.

The aim of this study was to optimize the dewatering performance of the sludge suspension resulting from potential dredging in the Golden Horn with a suction cutter tip. For this purpose, the combined use of the geotextile tube (Berilgen and Bulut 2016) chosen for the dewatering process and the APAM (Karadoğan et al. 2020) were evaluated, the efficacy of which were determined in terms of flocculation, sedimentation rate and turbidity. The dewatering performance was modeled on a one and three-dimensional scale of the laboratory. The quality of the leachate that would have formed during dewatering has been chemically examined and the results obtained have been interpreted in an environmentally sound manner. In addition, a variety of mechanical and hydraulic experiments have been conducted to project the usability of the geotextile tube filled with dredged sludge at circumferential berms of a waste pond to increase the filling capacity.

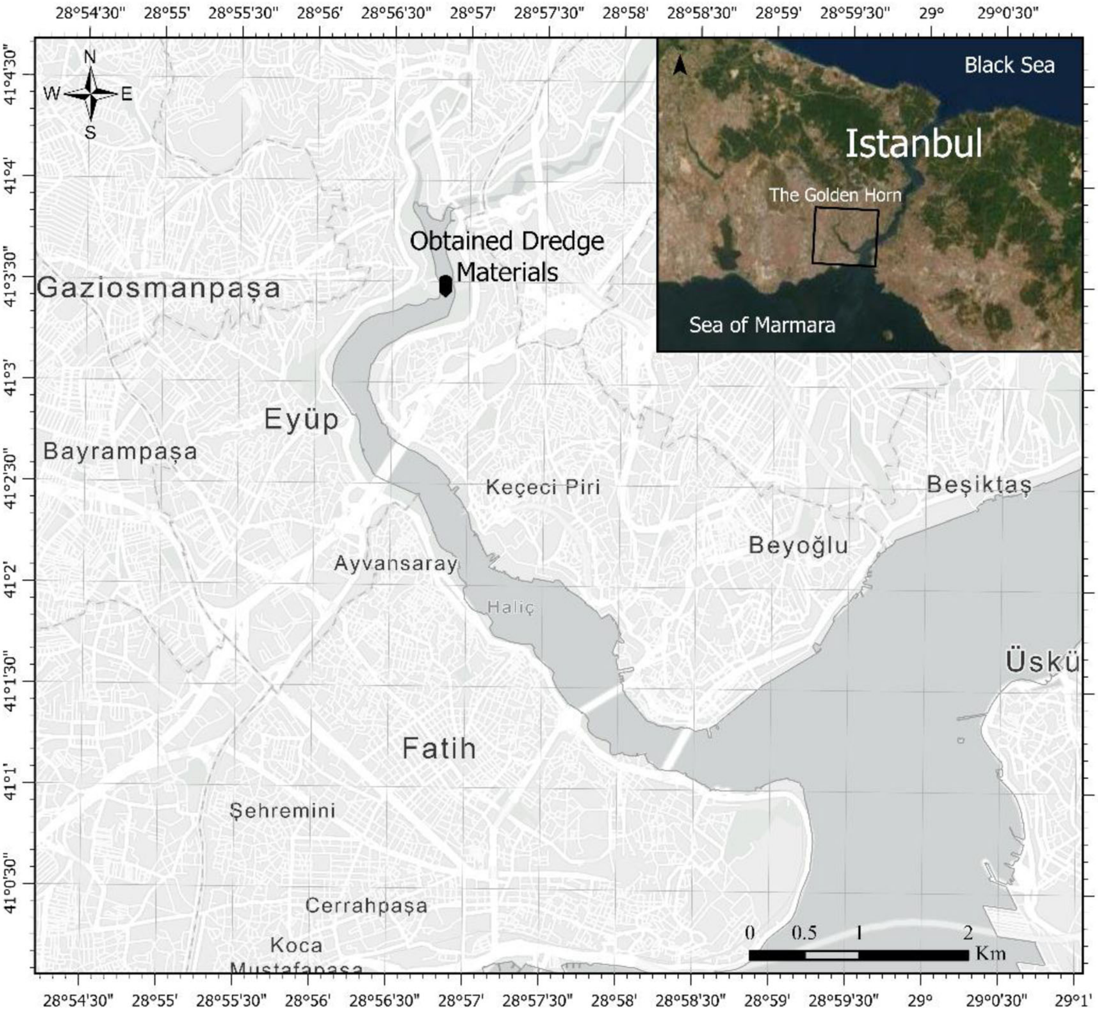

Figure 2. The study area with dredging location for sampling.

2. Test materials

2.1. Golden horn sludge

This study was conducted on soil-based dredging material taken from Golden Horn by a backhoe dredger (Karadoğan et al. 2020). The area of study is shown in Figure 2. The particle size distribution curve of the material is shown in Figure 3 and the index properties are summarized in Table 1.

2.2. Polyacrylamide

A commercially available solid form of AA4 polyacrylamide-was used in the scope of this study, which was determined to be effective at the dose of 30 ppm for Golden Horn dredged sludge by Karadoğan et al. (2020). This moderately high molecular weight (12–14 million daltons) polyacrylamide was anionic.

Readily mixed APAM solutions (0.1 g/100 ml) were prepared by mixing with a magnetic stirrer until homogeneity was obtained. Conditioning was carried out just before the dewatering tests were initiated by adding the desired amount of APAM solution to the sludge suspension, to verify the dose of APAM in total. The mixture was stirred for an additional 2 minutes more to activate the flocculation progress after the APAM had been added.

2.3. Geotextile

A monofilament fibrillated polypropylene woven geotextile with high tensile strength was used in dewatering studies (G1). The mechanical and filtration properties of the geotextile are summarized in Table 2. Geotextile samples, pre-cut in circular shape, were used in one-way filtration experiments. Three-dimensional filtration behavior was tested with the geotextile pillow supplied by the manufacturer.

3. Methods

First, the laboratory-scale test methods to control the geotextiles and polyacrylamide to be used in dewatering applications, were determined based on filtration efficiency. Filtration efficiency is used as a measure of the sediment holding ability of geotextile tubes. Then, chemical analyzes were carried out on the suspension and the leachate was examined in order to consider the environmental aspects. Finally, the geotechnical issues of the dewatered material

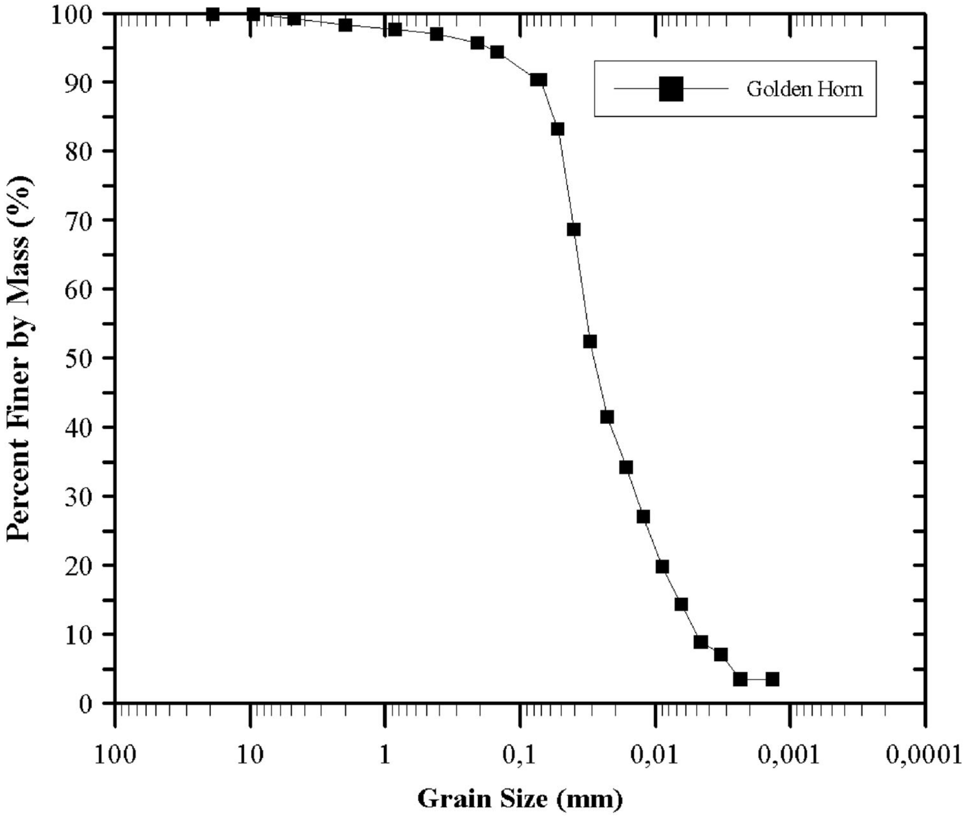

Figure 3. Particle size distribution of Golden Horn sea dredging.

Table 1. Index properties of Golden Horn sludge (Karadoğan et al. 2020).

Description	Value	Method
Organic content (%)	1.2	SM 2540 C
Liquid limit (%)	59	ASTM D4318-17e
Plastic limit (%)	45	ASTM D4318-17e
Plasticity index (%)	14	ASTM D4318-17e
Specific gravity (Gs)	2.46	ASTM D854-14
Percent passing No. 200 sieve	90	ASTM D2487-17
USCS classification	MH	ASTM D2487-17

Table 2. Geotextile properties.

Properties	Description	Unit	Value	Test method
Physical	Mass/unit area	g/m^2	585	ASTM D5261
	Thickness	mm	1.8	ASTM D5199
	Apparent opening size (AOS)	mm	0.425	ASTM D4751
Mechanical	Minimum tensile strength	kN/m	78	ASTM D4595
	Minimum seam strength	kN/m	70	ASTM D4884
Filtration	Water flow rate	l/min/m^2	813	ASTM D4491
	Pore size distribution (O_{50})	micron	80	ASTM D6767
	Pore size distribution (O_{95})	micron	195	ASTM D6767

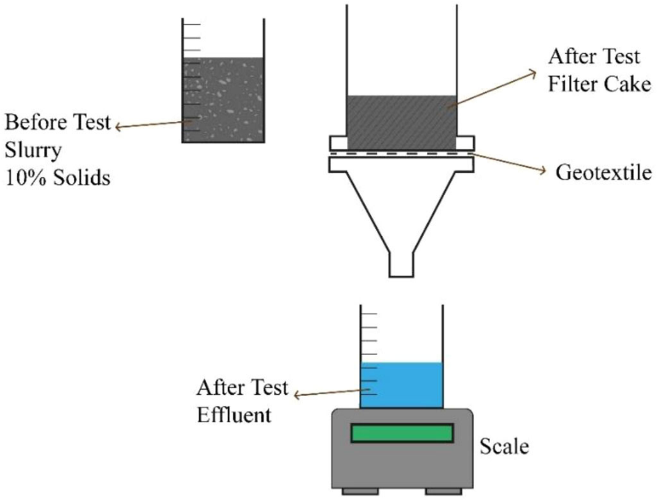

Figure 4. Schematic representation of the filter test setup.

retained in the tube were addressed by means of loading capacity, compressibility and hydraulic conductivity tests.

3.1. Laboratory scale dewatering tests

The use of geotextiles in dewatering applications of PAM-free or APAM-conditioned sludge requires the control of dewatering efficiency by 1-D filtration models in bench scale such as falling head or pressure filtration tests. In this study, a falling head type filtration system was used, which is a modified version of the rapid dewatering test (RDT) (TenCate 2015). It consists of a filling chamber with a stand over a beaker placed on a balance sheet (Figure 4). 500 ml suspension containing 10% solid weight was prepared with dredged sludge and water. The homogenized suspension, which was easily mixed on a magnetic mixer for 2 minutes, was poured onto the geotextile material inside the filling chamber. Throughout the test, the amount of leachate was collected in a lower beaker placed on a balance that recorded the weight up to 4 decimal points per second. After the test, the weight of the filter cake and leachate was compared before and after being kept at 105 °C in an oven overnight. The test was repeated on PAM-free and 10, 20, 30, 40 and 50 ppm APAM-conditioned sludge. Through

Figure 5. Oedometer cell specialized for falling head permeability test.

these tests, the use of the APAM dosage was selected, in which the minimum water content of the filter cake and the amount of solid material in the leachate were determined to be optimal.

A Geotextile Dewatering Test (GDT) is an active method for the mid-scale modeling of dewatering processes in hanging bags or shaped pillows of geotextile containers (ASTM 2013 D7880/D7880M). This study used a 53 cm × 53 cm pillow type container with a capacity of 28,000 cm^3 of sludge from the geotextile tube supplier company. It was filled with suspensions of 10% solid content of Golden Horn dredged sludge through a PVC pipe with a height of 68.5 cm connected to a 10 cm diameter port above it (TenCate 2007). In the GDT, the pillow was placed on the frame covered with a geogrid that allowed three-way water outflow. The stand was placed in a large container to observe the leachate volume during the test. After 2 trials, the filling of the easily mixed suspension in the pillow was concluded within 24-hour intervals. Filtrate turbidity was measured by HACH 2100 P Turbidimeter from a sample taken 1 minute after filling (ASTM D7725-17). The test for PAM-free and APAM-conditioned sludge was repeated for comparison.

3.2. Chemical and morphological analysis

The chemical analysis of the leachate was carried out on the GDT-conditioned suspension of the APAM. Ion exchange chromatography (IC) (Dionex ICS-3000) was used for ion determination, while heavy metal and other elemental analyzes were performed by inductively coupled plasma optical emission spectroscopy (ICP-OES) (Perkin Elmer). The leachate's water quality has been classified in accordance with the National Inland Water Quality Criteria (SKKY, Water Pollution Control Regulation in Turkey).

The comparison of structure in micro scale due to the APAM-conditioning was presented by Scanning Electron Microscopy Energy Dispersive X-Ray Spectroscopy (SEM-EDS) (FEI Quanta FEG 200) on Golden Horn dredged sludge samples after dewatering. The distribution of the elements by mass and atoms was also detected by elemental analysis of both PAM-free and APAM-conditioned samples.

3.3. Laboratory testing on the dewatered sludge

The workability of the APAM-conditioned dredged sludge in earthworks was evaluated after geotextile dewatering by means of shear strength. The final stabilized height of the geotextile tube after GDT was approximately 10 cm in the middle. Samples recovered after the GDT were used for testing. Unconsolidated triaxial compression (UU) and Vane tests were performed on undisturbed samples to determine the undrained shear strength of the sludge in the tube. Vane tests were carried out with ELE and Pilcon Brands vane shear devices (ASTM D8121, 2019, BS1377-9) at different points and depths of the dredged material stored in the GDT container after cutting the top of the pillow. In addition, UU tests (ASTM D2850-15) were performed on undisturbed samples within a diameter of 38 mm diameter and 76 mm height at 50 kN/m^2, 100 kN/m^2 and 150 kN/m^2 cell pressures.

Sludge compressibility in the tube was evaluated by a consolidation test (ASTM D2435). The undisturbed sample recovered after GDT was placed in a 7.5-cm-diameter and 2-cm-high stainless ring. For testing, a special ELE brand oedometer cell, placed in a front-loading consolidation type frame, was used (Figure 5). Drainage was allowed through the filter paper and porous stone placed at the upper and bottom bounds of the sample. Assuming the unit load increment ratio LIR = 1, the loading program used was 12.5, 25, 50, 100, 200, 400, 800, 400, 200, 100, 50, 25 and 12.5 kN/m^2. Time-dependent compression was recorded for a period of time when the load increment duration was LID > 24 hours, taking into account the completion of primary consolidation (EOP).

Hydraulic conductivity of the sludge retained in the tube was assessed in light of additional loadings. As a result, the falling head permeability test was also performed during the consolidation test at each loading step after the EOP. Before the test, the load yoke was locked to prevent further compression or swelling. The ELE modified oedometer cell in which the O-ring surrounding the stainless ring to separate the water housing at the bottom from the top to be pressurized was used for the falling head type permeability test. As a result, the initial head difference was provided by raising the water level in the burette connected to the bottom end while the water level at the top end remained constant. Each test lasted at least two days. After the test, the water levels at the top and bottom ends were balanced and the lock was released for further loadings.

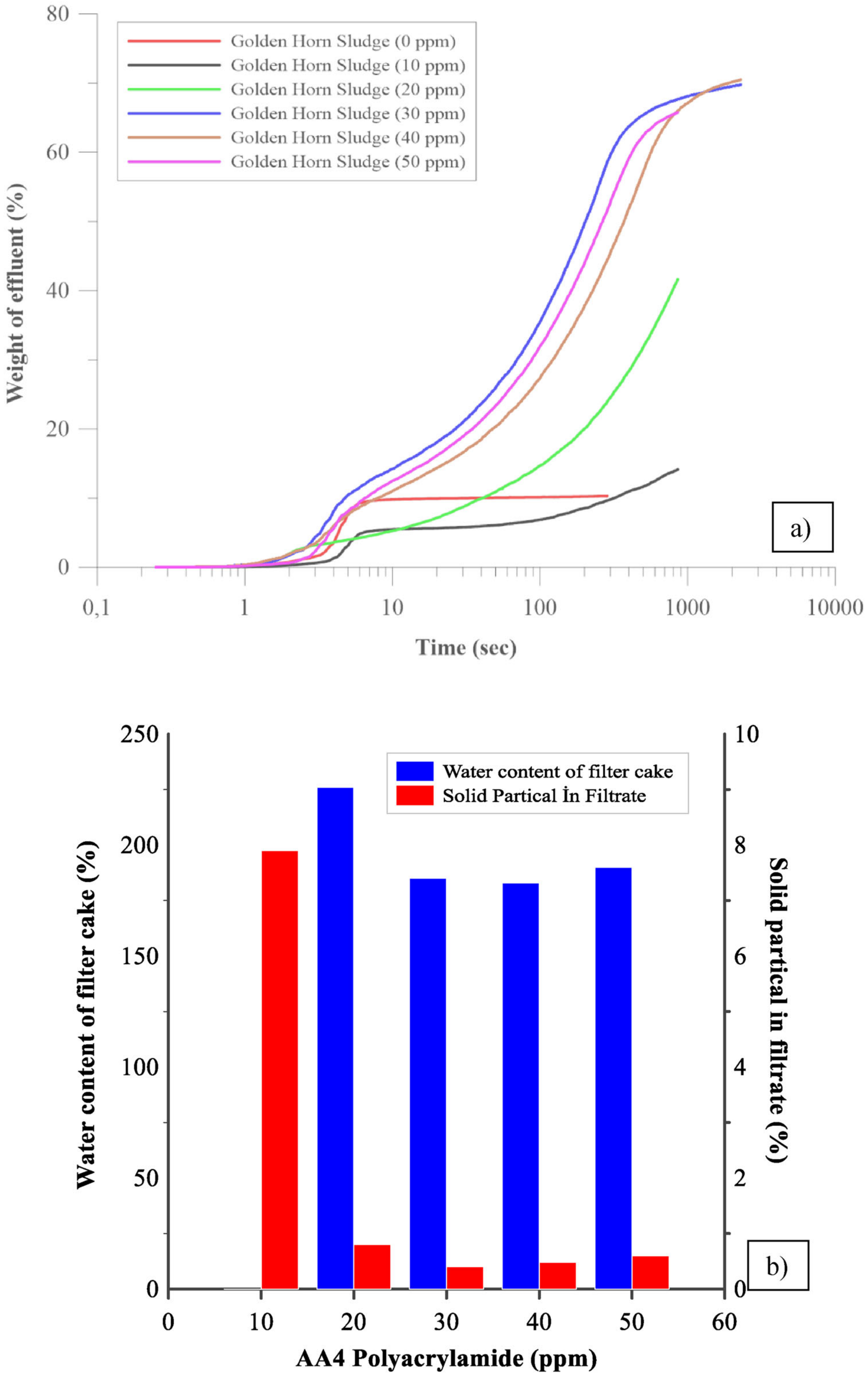

Figure 6. (a) Time-varying changes in the percentage of filtrate, (b) water content of filter cake(%)-solid particle in filtrate(%).

4. Results

4.1. Dewatering test results

All dewatering experiments were carried out in 3 repetitions. The results are given by taking the average of the experimental results.

Initially, the dewatering process of the Golden Horn dredging sludge was evaluated by RDT testing of the PAM-free and AA4 APAM-conditioned suspensions. Figure 6(a) shows the ratio of filtrate to initial suspension weight versus time plots for PAM-free suspensions and 5 different doses of APAM-conditioned suspensions. The ratio, which was limited to 12% in the PAM-free suspension, increased by up to 70% through conditioning. The increase is in direct proportion with a dosage of up to 40 ppm, it decreases slightly thereafter. The fastest filtration occurred in the 30 ppm

Table 3. Geotextile tube dewatering (GDT) results.

GDT results for	PAM-free	PAM conditioned
Total amount of sludge filled ($\times 10^{-3}$ m^3)	60	150
Total amount of filtrate ($\times 10^{-3}$ m^3)	46.9	116.4
Solid percent in the filtrate by initial weight (%)	51	0.8
Turbidity (NTU)	32,800	92
Solid content after GDT (%)	12	54
Filtration efficiency (%)	18.5	90.5

APAM conditioned suspension during the experiment. After the test, the water content of the filter cake and the solid content of the filtrate were determined (Figure 6b). While the solid content in the influent was limited to 8% by 10 ppm APAM conditioning, higher doses reduced it more efficiently; less than 0.5% by 30 ppm was observed. Similarly, APAM conditioning reduced the final water content of the filter cake, where the minimum value at 40 ppm is 160%. RDT and GDT experiment results were found to be similar (Berilgen and Bulut, 2016). Considering the results of the GDT, the effectiveness of geotextile dewatering on PAM-free and 30 ppm AA4 APAM-conditioned suspensions prepared with a 10% solid content of dredging sludge was discussed. The geotextile pillow bag used in the test was filled with a one-day interval in two trials. For both suspensions, the capacity of the bag on the second day was half of the first day. Thus, the total number of PAM-free and APAM-conditioned suspensions filled in the container was 60×10^{-3} m^3 and 150×10^{-3} m^3 respectively (Table 3). This enormous difference is caused by the clogging of the pores of the geotextile for PAM-free sludge, consequently, no further filling trial was applicable after the first trial. However, a second filling could be achieved with APAM conditioned sludge. Although 77% of these volumes were filtered through the geotextile for both suspensions, the solid percentage of the initial filtrate decreased from 51% to 0.8% with PAM-conditioning causing the turbidity value to decreased dramatically from 32,800 to 92 NTU (Figure 7). The solid content value, defined as the ratio of the solid weight to the total weight of the dewatered material retained in the tube, increased from 12 to 54% with APAM conditioning. In addition, the filtration efficiency value, as defined by Moo-Young, Douglas, and Mo (2002), was increased from 18.5 to 90.5 percent using APAM conditioning in the initial suspension to the retention in the geotextile tube after dewatering.

4.2. Chemical analysis results

The study focused on the anthropogenic contamination of heavy metals due to industrial activities around the Golden Horn. Table 4 presents a total of 25 chemical compounds tested on inflow and outflow samples during GDT of APAM-conditioned suspension. The dominant elements in both of the samples were observed to be sodium (Na^+) and chloride (Cl^-) which are the ionic compounds of salt. Bolt nitrite (NO_2^-) and phosphate (PO_4^{3-}) were below the limit values, while copper (Cu), molybdenum (Mo) and nickel (Ni) were not detected in the samples. In addition, to evaluate the chemical compound retention performance of geotextile tubes after APAM conditioning the retention rate of a compound was defined as

$$RR = \frac{C_i - C_e}{C_i} \times 100 \ (\%) \tag{1}$$

where C_i is the concentration in influent (mg/L), C_e is the concentration in effluent (mg/L). Retention rates were above 68% with the exception of fluoride (F^-), which has a value of 10%. The pH value of the influent which was 7.2 and did not change significantly with APAM conditioning. The pH value of effluent was measured as 6.8.

The SEM images taken to compare post-GDT PAM-free microstructures and APAM conditioned dredged sludge are shown in Figure 8. The 1000× magnification SEM images show that the plaque shaped PAM-free sludge microstructures in Figure 8(a) have been transformed into flocculated particles by APAM conditioning in Figure 8(c). In addition, the SEM images shown in Figure 8(b) and 8(d) at a magnification rate of 2,000x present an increase in the total volume of the dark areas, which represent APAM conditioning voids. Table 5 shows the percentage of the mass of the elements observed by the EDX elemental analysis performed on the PAM-free and APAM-conditioned suspension samples after the GDT. In this study of sea dredging, whether or not APAM-conditioned was implemented, the dominant elements were observed to be oxygen and silicon, in which silica (SiO_2) is the most common sand constituent. Due to the charge neutralization mechanism of polyacrylamide, a higher quantity of positively charged magnesium, aluminum, potassium and iron were present in APAM-conditioned sludge.

4.3. Dewatered sludge's engineering properties

The engineering properties of the APAM-conditioned sludge after Geotextile Tube Dewatering were evaluated in light of the tests performed on samples after GDT. Pocket Vane tests performed on dewatered sludge retained in the geotextile bag showed an average undrained shear strength equivalent to 42 kN/m^2. The unconsolidated undrained triaxial test (UU Test), conducted on undisturbed samples recovered from the bag, resulted in an undrained shear strength of 38 kN/m^2. Obviously, both methods had similar test results with only a slight difference.

Figure 9(a) shows the compression ratio versus consolidation pressure, σ_c graph of one-dimensional consolidation test, performed on the undisturbed sample. The compression index C_c and swelling index C_s were determined as 0.769 and 0.0585 respectively. Figure 9(b) presents the calculated values of the consolidation coefficient c_v considering the logarithm of time method versus σ_c.

The hydraulic conductivity of the dewatered sludge was assessed by the falling head type of permeability tests performed under the applied consolidation pressures, σ_c. The values of permeability coefficients, k versus σ_c were plotted in Figure 9(c). As expected, k was inversely proportional to σ_c that it exhibited ten-thousand-fold decrease from 12.5 kN/m^2 to 800 kN/m^2.

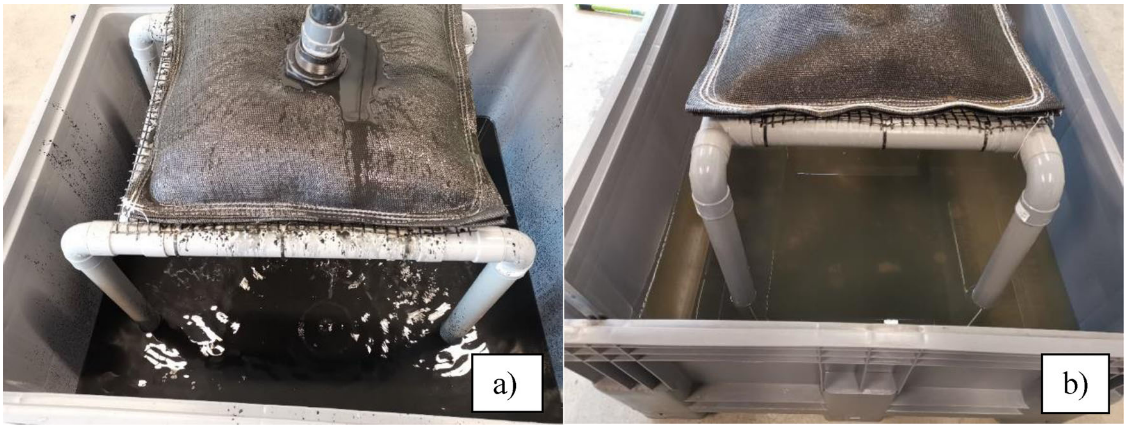

Figure 7. GDT of (a) PAM-free, (b) PAM-conditioned sludge.

Table 4. Chemical analysis of GDT sample after PAM-conditioning.

Parameter	Influent (mg/L)	Effluent (mg/L)	Retention (%)
Antimon (Sb)	0.027	0.008	70.4
Arsenic (As)	0.023	0.001	95.7
Bromide (Br^-)	85.03	4.440	94.8
Cadmium (Cd)	0.033	0.003	90.9
Chloride (Cl^{2-})	12,548	1603	87.2
Chromium (Cr)	0.146	0.012	91.8
Cobalt (Co)	0.149	0.014	90.6
Copper (Cu)	n.a.	n.a.	–
Floride (F^-)	0.470	0.420	10.6
Lead (Pb)	0.062	0.005	91.9
Magnesium (Mg^{2+})	730.5	71.08	90.3
Manganese (Mn)	0.225	0.027	88
Molybdenum (Mo)	n.a.	n.a.	–
Nickel (Ni)	n.a.	n.a.	–
Nitrate (NO_3^-)	242.25	<0.200	$\sim$100
Nitrite (NO_2^-)	<0.200	<0.200	–
Phosphate (PO_4^{3-})	<0.400	<0.400	–
Potassium (K^+)	210.95	57.5	72.7
Selenium (Se)	0.094	0.010	89.4
Sodium (Na^+)	5150.78	876.45	83
Strontium (Sr)	1.140	0.322	71.8
Sulphate (SO_4^{2-})	219.79	70.08	68.1
Tin (Sn)	0.179	0.016	91.1
Vanadium (V)	0.056	0.009	83.9
Zinc (Zn)	0.020	0.001	95

5. Discussion

5.1. Dewatering performance

The Jar type flocculation tests are critical for the selection of the type of PAM to be used, which may have a complete effect on the dewatering process for fine grained sediments. Misuse of PAM will result in inefficient dewatering, thus, there is a need to study dosage optimization for PAM-conditioning sludge. Geotextile tube type dewatering applications, however, require additional filtration tests to be carried out in order to control the consistency between the geotextile material and the conditioned sludge.

This study involves 1D filtration examined by falling head type RDT on 5 different doses of AA4 APAM-conditioned sludge (Figure 6a). The filtration process was very limited in the PAM-free suspension, due to fine particles blocking the pores of the geotextile, whereas in the APAM-conditioned pores, filtration was able to continue. The APAM dosage in use was not sufficient for the flocculation of the target fine content of up to 30 ppm, where the filtration efficiency was optimized and the highest dewatering rate was observed. In addition, the 30 ppm APAM-conditioned suspension shows the minimum value in the final water content of filter cakes and the solid content of filters (Figure 6b). These findings support the study by Karadoğan et al. (2020) on the dredging sedimentation of the Golden Horn in which the rate of sedimentation and polymer efficiency was maximized at 30 ppm of AA4 APAM-conditioning with minimal turbidity. AA4 APAM conditioning therefore reduces the solid content of the filtrate at an optimum dose of 30 ppm and accelerates the filtration process.

Subsequently, the 3D filtration process is modeled in a mid-scale GDT using a pillow type container, which is one of the most standard and commonly preferred method (ASTM 2013 D7880/D7880M). Comparing the PAM-free and APAM-conditioned sludge test results, it is clear that APAM conditioning increased the volume of suspension dewatered in the pillow bag by 250% and decreased the solid percent and turbidity values in the filtrate by 50% and 99.7% respectively. The effect of APAM-conditioning on geotextile dewatering was evident as the turbidity decreased to 92 NTU, the filtration efficiency was as high as 90.5% and the solid content of the dewatered sludge was 54%. The filtration efficiency determined in the GDT of the PAM-free suspension was quite limited due to the grain-shaped structure of the plaque, blocking the pores of the geotextile and forming a low-permeability filter cake in a short time. However, it was observed to be 5 times higher when the optimum dose of APAM determined by RDT was used. The success of APAM conditioning is illustrated with SEM images by the flocculated fine particles and the more localized form of the empty volumes around them. Similar to this study, He et al. (2017) take SEM images of soil samples without APAM and add 3 g/kg PAM. The PAM-free suspension particles interacted with the repulsive face-to-face and shifted stray. After the addition of APAM, an end-to-face contact was established due to flocculation mechanisms (He et al. 2017). Thus, the more dispersed structure due to flocs with less rough surfaces and the more interconnected voids between them, allocate drainage paths. However, the fact that very little solid material passed through these drainage pathways to the filtrate in the APAM conditioned suspension is proof of the effectiveness of flocculation. Although

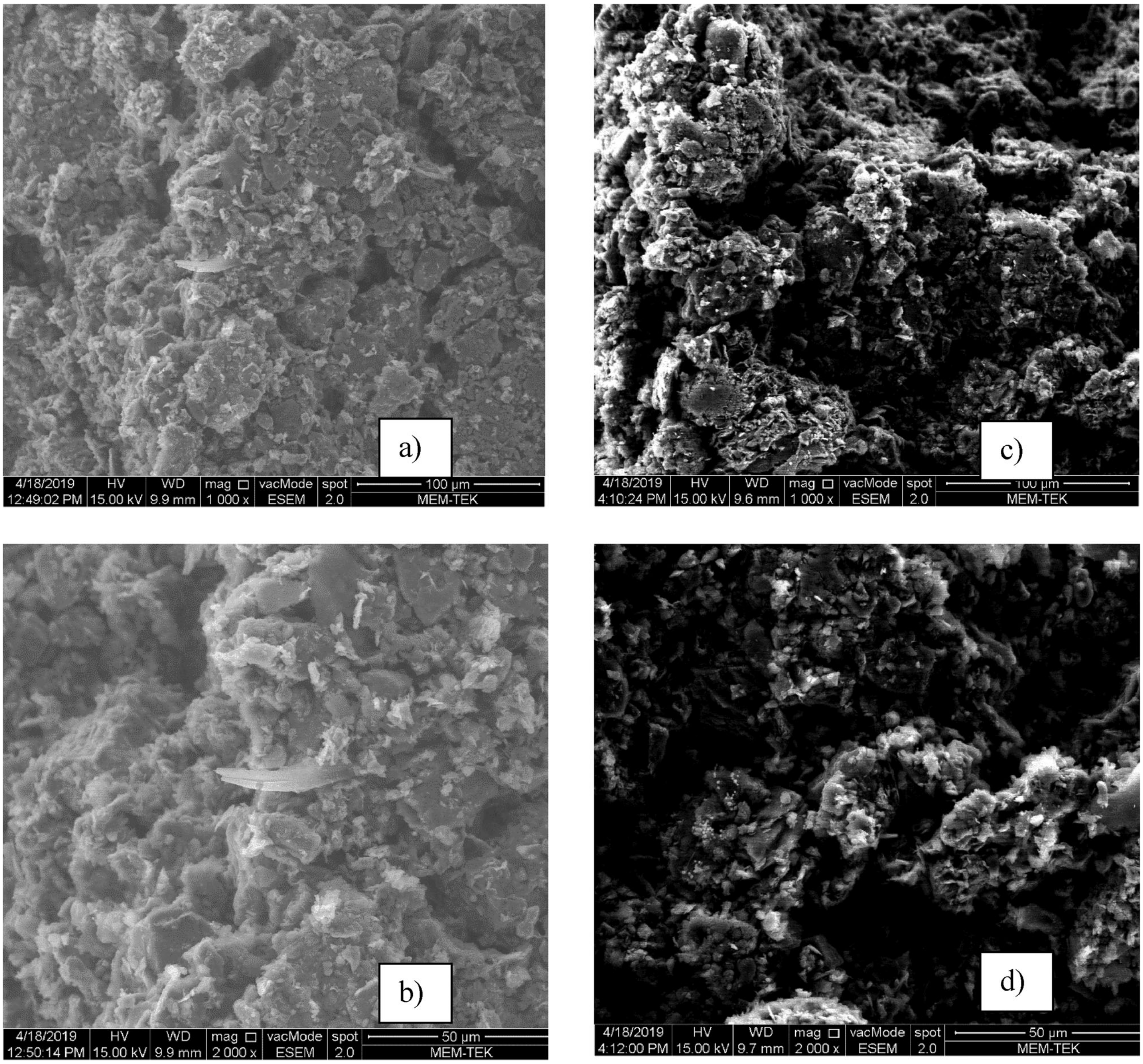

Figure 8. SEM images of (a) 1000×, (b) 2000× PAM-free and (c) 1000×, (d) 2000×, PAM-conditioned sludge.

Table 5. Elemental analysis result of the Golden Horn dredged sludge.

Element	Without PAM W_T (%)	With PAM W_T (%)
C	7.01	6.21
O	45.34	43.45
F	1.37	1.31
Na	1.43	0.84
Mg	1.81	1.81
Al	10.57	10.83
Si	25.24	24.88
S	0.71	1.33
Cl	0.62	5.80
K	1.17	4.86
Ca	1.46	0.84
Fe	3.27	1.81

PAMs can provide the same efficiencies, for the beneficial use of alternatives to dewatered sludge, the substance requiring less usage should be preferred, given the long-term environmental concerns about the life cycle of alternative sludge. Since organic matter can anchor inorganic components, such as soil flocs, and increase the electrostatic repulsion between surfaces of particles and PAM molecules, high organic matter content reduces PAM sorption, likely due to a decrease in active sorptive sites (Lu, Wu, and Letey 2002). On the other hand, since the volume of organic matter in the Golden Horn sludge is just 1%, PAM sorption is a viable option for retaining ions. When EDX elemental analysis findings are examined (Table 5), it is seen that S, K and Cl increase in APAM-conditioned sludge. These elements are thought to be adsorbed by APAM through ion-binding and/or electrostatic interaction mechanisms (Rabiee 2010). As this finding is compared to the effluent chemical analysis, it is clear that the removal rates for K and Cl are almost identical. In this context, this study shows better results than Berilgen and Bulut (2016) in terms of solid content and filtration efficiency for the dewatering of the Golden Horn dredged sludge geotextile tube by using the same low PAM dosage geotextile brand.5.2. Environmental Assessments.

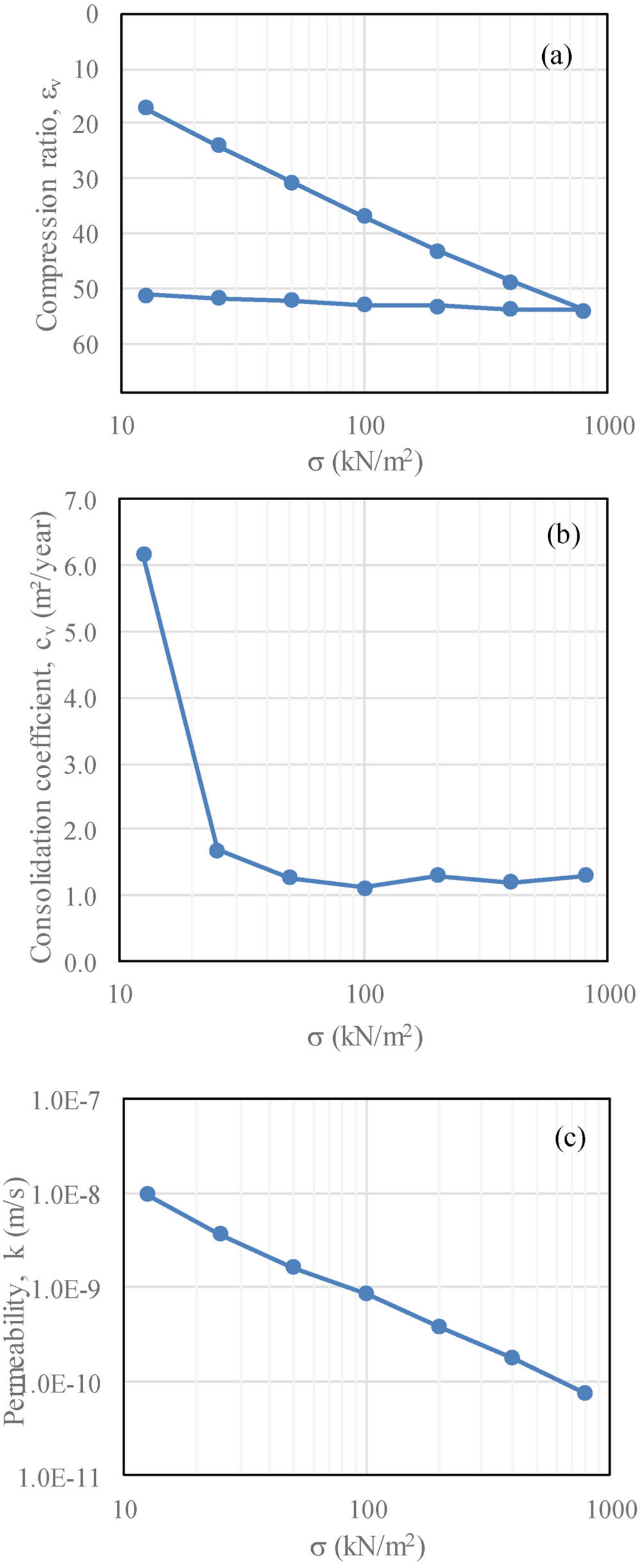

Figure 9. Consolidation test result of PAM conditioned Golden Horn sludge after GDT test.

5.2. Environmental assessments

Success in the retention of contaminants in the dewatering of dredged material with a geotextile tube depends largely on the retention of particles less than 60 μm (Berg and Oliveira 2019). Figure 10(a) presents the results of a solid particle size analysis performed on PAM-free, APAM-conditioned suspensions and GDT filtrate. As a result, the cumulative distribution of particle sizes and flocs was reproduced for better comprehension as shown in Figure 10(b). It is clear that the PAM-free suspension curve shifted to the left by APAM conditioning, where the volume of particles with a fineness of less than 60 μm were reduced to 19%, equal to 50%. Although the filtrate curve, shown to the right most, had 72% fine particles, the percentage of solids in the filtrate was only 0.8% as a result of successful APAM conditioning (Table 3). Accordingly, the chemical analysis of the filtrate showed that the pollutants could largely be retained in the tube during the dewatering of the suspensions with the geotextile tube after APAM conditioning (Table 4).

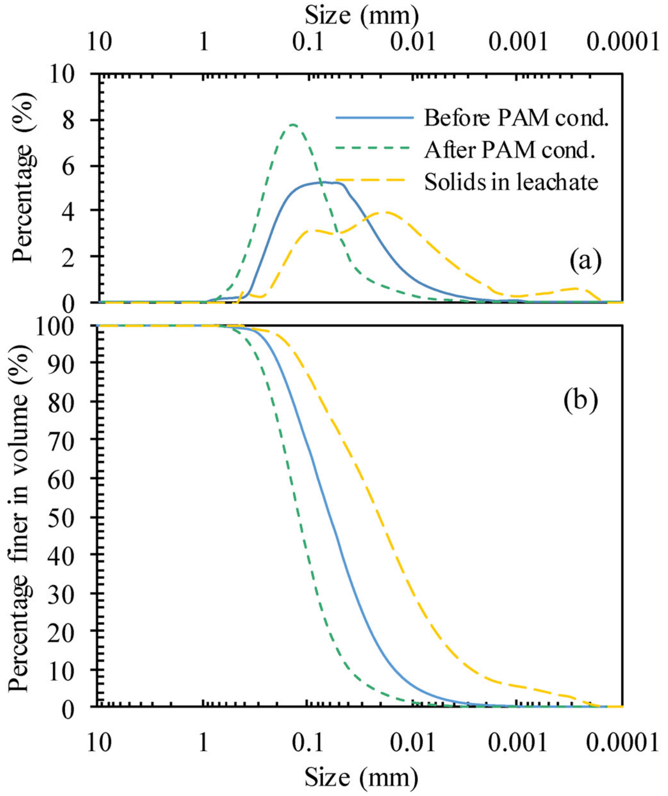

Figure 10. Variation of grain size diameter distribution by volume in geotextile tube dewatering.

In the chemical analysis, the two ions with the highest proportions in the APAM-conditioned suspension and the filtrate, sodium and chloride, are also the two predominant ions in seawater and the main causes of salinity (Sengul 2016). Depending on regional conditions, such as precipitation and active currents, salinity may vary from time to time. The salinity of the study area may show variability over time under the influence of currents from the less salty Black Sea to the relatively saltier Marmara Sea (Kılıç et al. 2019). For all these reasons, sodium and chloride are considered to be high in both inflows and outflows. Copper, molybdenum and nickel were not present in both the influent and the effluent. Effluent concentrations of antimony, arsenic, cadmium, lead, selenium, vanadium and zinc were less than 10 ppb. The migration of heavy metals Cu, Cd and Pb was investigated in a study of rapid dewatering with anionic PAM in river dredged sludge (Liu et al. 2020). As in

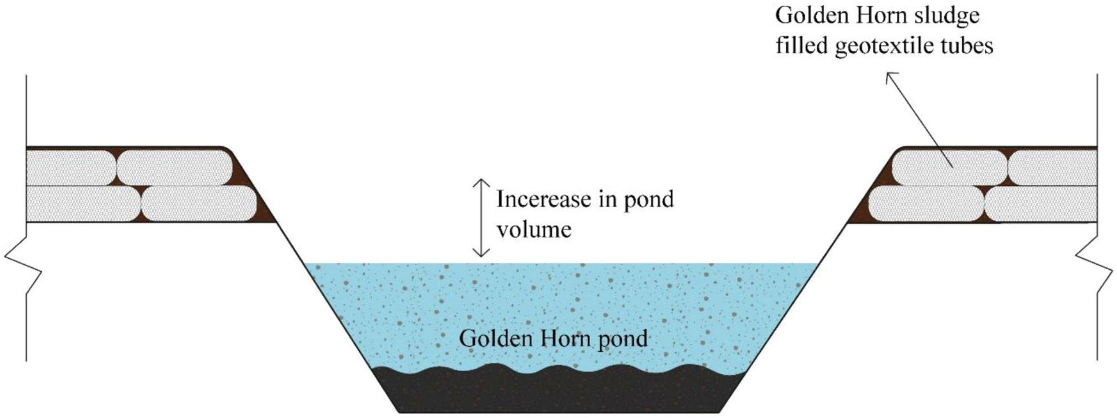

Figure 11. The capacity increment of existing waste ponds by the use of Geotextile Tubes.

our work, it has been observed that the retention rate of heavy metals is more than 80 per cent due to the fact that APAM reduces adsorption and thickens the adsorption layer.

No conventional dewatering studies were carried out for dewatering the Golden Horn dredging sludge. Currently, dredging is done using dredgers and the resulting sludge is taken to a sludge dump site by closed box trucks. The solid rate of transported sludge is around 20% (Ozturk 2016). Transfer by closed box trucks is more expensive than using regular trucks. With the geotextile tube dewatering method, the solid rate of the filter cake increases to around 50%. Thus, it provides serious economic gains compared to the current situation. Dewatering with geotextile tubes provides economic advantages, as there is no initial investment cost and the resulting dewatered sludge is easier to transport. Furthermore, geotextile tubes are a good alternative to conventional methods (Lee et al. 2014), as they can be used for various field applications in desired sizes. The flexibility of geotextiles also provides additional advantages. Despite the advantages mentioned, geotextile tubes have a few drawbacks, they can be damaged by sharp objects during filling. Thus, the filling material in the tube may leak and harm marine creatures and the environment. At the same time, some sludge may settle in the tube over time after dewatering, and can create stability problems. These issues need to be addressed for long term performance and for use as beneficial alternatives to other substances.

5.3. Evaluation of beneficial use alternatives in embankments

In this study, the final water content of 30 ppm APAM-conditioned sludge was 180% in RDT after 5 minutes of 1D filtration and 100% in GDT after a 7 days of 3D filtration waiting period to stabilize the shape of the tube and negligible amount of water outlet. Considering the liquid limit value of the PAM-free dredging which was equal to 56%, 100% is still quite high in order to have enough stability to work with. However, due to the bridging capability of APAM, which flocculates and stabilizes fine particles, a low shear strength was achieved in the Vane and UU APAM conditioned sludge tests. Even if land disposal is applied, the efficient dewatering of the geotextile tube resulting in a lower final water content and a higher shear strength of the sludge during the specified time will have a positive impact on the transport volume and type that dominate the cost. Figure 9 proposes a reduction in the water content of the sludge retained in the tube in the event of preloading.

The lack of new areas for waste ponds in the near-field areas may require an increase in capacity of existing ones. Figure 11 presents a way of increasing the capacity by constructing a circumferential bank in the contours of the previous one, which requires the stability control of the existing pond under the new loading conditions. Although stability varies with the geometry of the design and the local conditions of the site, such as soil stratigraphy, topography and groundwater, the internal stability and water retention performance of the structure will mainly be dominated by the properties of compressibility and permeability of the sludge in the geotextile tube. No quasi-pre-consolidation pressure was determined by APAM conditioning, such as the cementing effect on the consolidation curve shown in Figure 9, so that the curve could be assumed to be the virgin compression line of the APAM conditioned sludge under pressure of interest. Moreover, Figure 9(c) exhibits that the k value of the sludge will be 10^{-8}m/s after a minimum preloading σ_c=12.5 kN/m^2, while $k < 10^{-9}$m/s, which is mostly requested for clay liners of the landfills, will be achieved when $\sigma_c \geq 90$ kN/m^2., which may be efficient, as mentioned by Liu et al. (2020) for a vacuum preloading application of the river dredged sludge after APAM conditioning. As the slope stability of the circumferential bank requires the tension forces of the tubes to be taken into account, preserving the durability of geotextile tube from any environmental effects is essential with a proper final cover. It may involve using a geotextile clay liner, geomembrane and a top soil layer to prevent negative impacts of infiltration of acid rain and UV, for example. The drainage systems composed of the prefabricated horizontal drains which are enhanced by vacuum suction system, are located within the voids between the tubes, which will accelerate the dewatering process and satisfy lower water content, void ratio and higher shear strength (Shin and Oh 2007; Liu et al. 2020).

6. Conclusion

This study shows that the use of APAM during dewatering with a geotextile tube increases the filtration rate in the Golden Horn dredged sludge suspension and reduces the solid content, turbidity in the leachate and ensures that the pollutants remain in the tube to a large extent. It is proposed that the soil improvement method adapted during the geotextile tube dewatering of fine-grained sea dredging will have a positive impact on the dewatering efficiency, compressibility and permeability of the sludge. In regards to the beneficial use of alternatives to sludge in embankments or water retention structures, a loading pattern should be determined. As a result, the use of the geotextile tube to condition the dragging to be used in embankments or as part of the water retention structure will make a significant contribution to the economy. Project-based numerical analysis will be carried out on the basis of the findings of this study, which may be supported by in-situ test outputs.

The dewatering of Golden Horn deep sludge after APAM conditioning in a geotextile tube and the quality of the leachate was examined in this study. RDT was performed to use APAM at the correct concentration and, as a result, the use of 30 ppm AA4 was determined. After the GDT was carried out both with and without additives, analyzes were carried out in the filter cake and the leachate.

- The turbidity value of the leachate after GDT with APAM conditioning decreased to 92 NTU (99.7% efficiency). The solid rate of the filter cake in the tube increased from 12% to 54%. The filtration efficiency value also increased from 18.5% to 90.5%.
- The undrained shear strength obtained as a result of the triaxial test was calculated to be approximately 38 kPa.
- When the chemical analysis of the output water was examined after GDT, it was determined that the pollution from anthropogenic sources had decreased.
- SEM-EDS analysis showed that smoother and more combined flocs were formed after GDT.
- Laboratory tests on the sludge lead to predict compressibility behavior when it is capsulated in geotextile tubes.
- It is thought that the dewatering of organic sediments through PAM conditioned geotextile dewatering method will become more important. Preloading improvement techniques are promising to accelerate the dewatering process of the APAM conditioned dredged sludge to satisfy the required level of permeability and shear strength values for the further beneficial use alternatives.

Disclosure statement

No potential conflict of interest was reported by the authors.

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