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Solution Tool to Predict Filter Cake Formation for Acid Mine Drainage (AMD) Slurries

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Solution Tool to Predict Filter Cake Formation for Acid Mine Drainage (AMD) Slurries

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Problem Report submitted to the
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Master of Science in
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2020

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ABSTRACT

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Roberto Martinez Ochoa

Acid Mine Drainage (AMD), also known as alkaline mine drainage resulted from abandoned and active coal mining areas has been a major water pollutant in the mid-Atlantic region of the United States affecting aquatic life, recreational areas, tourism, etc. AMD results from during and post mining activities all around the US and the world containing high levels of acidic materials such as sulfate and other heavy metals.

The United States Environmental Protecting Agency (EPA) has recommended the use of different mechanisms for mitigation purposes due to considerable existing and potential damage generated by AMD. This report focuses on the usage of geotextile bags/tubes as a filtration tool in order to retain as much solids from an AMD sample while maximizing its dewatering capacity following methods and assumptions developed by (Weggel and Ward, 2011).

The purpose of this study is to develop a solution tool to predict filter cake formation, and to perform extensive filtration testing of AMD slurries, identifying of a competent geotextile material for filtration purposes for the proposed AMD slurries, and identifying supplemental behavioral data in order to maximize filtration performance

The solution tool is only successful in predicting filter cake thickness comprising materials with high amounts of coarse particles. On the other hand, for materials with high amounts of fines such as the AMD sludges being dewatered in this report, the solution tool is not capable of predicting an accurate filter cake thickness. Optimum results regarding filtration efficiency (retained solids/total solids) by using a non-woven geotextile material produced by Tencate referred to as Mirafi 1100N. Filtration efficiencies ranged between 92% and 100%.

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1 Introduction

Acid Mine Drainage (AMD), also known as alkaline mine drainage resulted from abandoned and active coal mining areas has been a major water pollutant in the mid-Atlantic region of the United States affecting aquatic life, recreational areas, tourism, etc. AMD results from mining activities all around the US and the rest of the world. AMD contains high levels of acidic materials such as sulfate and other heavy metals. AMD is developed by the mixture of these metals and acidic materials with surface weathered rock, and groundwater. Improper disposal of AMD into rivers, groundwater, and lakes can cause for balanced waters to acquire pH levels ranging from 2 to 8. These waters could cause a decrease on agricultural and industrial activities. (Skousen, 2016).

The United States Environmental Protecting Agency (EPA) has recommended the use of different mechanisms for mitigation purposes due to considerable existing and potential damage generated by AMD. Some of the most common practices for the assessment of AMD include the use of chemicals, biological treatment, solvent extraction, reverse osmosis, and filtration (Oyewo et al., 2018).

This report focuses on the development of a solution tool for predicting filter cake formation of AMD sludge.

Optimizing efficiency of geotextile bags as a way to assess dewatering of AMD, chemical waste, dredge material, etc. has caused for scientists to develop different means and methods both considering the texture and form of the geotextile fabrics as well as the type of sludge precipitates being dewatered. Several early methods have focused specifically in the filtration, and dewatering of AMD, and wastewater. Llawson (2008) focused on the capacity of geotextiles to confine material in the hydraulic and environmental field. Geotextile bags capacity to filter wastewater was studied by Aydilek and Edil (2003) and Yaman (2006).

2 Objective

The geotechnical characteristics of the material to be dewatered, the permeability of the system, the permittivity, and the apparent opening size (AOS) of the geotextile are factors to be considered in the performance of the geotextile dewatering process. However, the governing factor in sludge dewatering by the use of geotextile bags is the filter cake accumulated at the inner surface of the bag (Weggel and Dortch, 2011).

The purpose of this study is to develop a solution tool to predict filter cake formation and dewatering performance on surrogate sludges manufactured in the laboratory.

2.1 Scope of work

The following scope of work is broken-down into the following six (6) tasks:

Task I- Perform a literature review on geosynthetics in civil engineering, AMD sludge dewatering (limitations, methods, and pre-treatments), and common wastewater treatments prior to dewatering.

Task II- Develop a solution tool for filter cake formation following Weggel and Ward (2010), and Weggel and Ward (2011) developed numerical model theory and experiments respectively.

Task III- Calibrate the solution tool using published data in Weggel and Dortch (2011).

Task IV- Test the model with experimental geotechnical lab data of West Virginia University of Morgantown, West Virginia

Task V- Compare and contrast the solution tool with experimental data and report observations.

Task VI- Identify and report supplemental behavioral data in order to maximize filtration performance.

3 Literature Review

3.1 Geosynthetics in Filtration

Filtration of soils and sludges comprises a key element in civil engineering water treatment applications and solutions. Some of its main applications are to protect soil from eroding due to groundwater flow, to facilitate road construction by providing proper drainage to protect the road subgrade, to improve dams' performance, and to maximize discharge capacity. Optimum discharge capacity is maximized while attempting to minimize the expulsion of particles that in some cases have a negative effect both from an environmental and an economic point of view. (Fannin, 2006).

Typical filtration systems used in civil engineering applications are usually fabricated out of geotextile materials, specifically the non-woven type. Woven and non-woven geotextiles are mainly differentiated by the methods in which they are fabricated, and their capabilities. Woven geotextiles are fabricated by combining individual polymer threads and fibers in all directions forming one uniform length. Some of their uses include road applications, ground stabilization, and moisture prevention as they are relatively impermeable (Global Synthetics, 2020). For example, woven geofabrics are mainly used as separators between different materials. In pavement applications, when subgrade materials consist of high percentages of cohesive soils, it often leads to deterioration. When such a thing happens, a filter fabric of woven material is typically placed on top of the subgrade for the purposes of separating it from the permeable material. The permeable material is typically used as a subbase layer. This separation prevents the potential deterioration of the existing subgrade generated by the intrusion of moisture along with the existing subbase material. Non-woven geotextiles are fabricated by entangling fibers together, by needle punching through the geotextile, or by thermal fusing of the contact points (Fannin, 2006).

3.2 AMD sludge

As previously mentioned in this report, sludge/slurry developed from active and abandoned mining activities accounts for a major pollutant at the mid-Atlantic region of the United States. AMD takes clean water to an acidic state, causing it to become unsuitable for domestic, agricultural, and industrial use (Skousen et al., 2016). Metal hydroxides, sulfates, gypsum, and

unreacted lime dissolved in AMD account as the foundation of its toxicity (Zinck et al., 1997). Active and abandoned mining activities had been a major source of pollutants in the U.S without any enforcement regulations until 1972. The U.S Federal law then took action by enforcing active mining activities to mitigate AMD prior to its discharge into the environment. However, this regulation only applied for active mining sites, therefore leaving those responsible for the pollution caused by mining prior to 1972 unaccounted for (Skousen et al., 2016). AMD has then become a hot topic in research, as it is a relatively new industry but accounts for a major global pollutant. Scientists, and regulatory agencies have developed systems to alleviate AMD sludge contamination (Skousen et al., 2016). To date, two major mechanisms in AMD sludge treatment are being used: passive and active.

AMD passive treatments refer to relatively simple operations where biology, chemical, and physical operations are used to treat AMD sludge (Skousen et al., 2016). They are mostly effective where the contaminants generated by AMD are not significantly critical, hence they do not require extensive treatment. Some common passive treatment methodologies listed by Skousen et al (2016) are anaerobic wetlands, organic materials, flushing systems for biological treatment, and open limestone channels.

On the other hand, AMD active treatment operations require much more resources and effort, as they are used in sludges with high amounts of pollutants. In the process of these treatments, electric energy and certain chemical reactants such as NH_3 or NaOH are essential. The exposure of human beings and the environment to these reactants can be harmful if not performed under proper precautionary measures (Skousen et al., 2016).

3.2.1 Sludge dewatering

The treated materials generated from chemical, mining, and agriculture impose a big challenge in their disposal. The challenge comes from these materials' significant amounts of moisture, high compressibility, and low shear strength (Liao and Bathia, 2005). To assess high moisture content in sludges, the concept of geotextile bags was introduced in the early 90s and became one of the most effective and attractive solutions to this issue (Krizek, 2000). Geotextile tubes also referred to as geotubes refer to bags constructed of geotextile materials, usually the woven-type. They serve as a dewatering alternative for slurries, as these are placed into these tubes,

where the solid fraction of the material is separated from the liquid fraction (Lawson, 2008). As geotubes became more popular in the assessment of dewatering sludge, many uncertainties and challenges came into place.

Sludge conditions might require pre-treatment operation prior to placement in the geotubes for dewatering purposes. Even post-dewatering process, as per environmental regulations, the dewatered sludge might still need additional treatment (Muthukumaran and Ilamparuthi, 2006) (cited in Apparicio et al., 2020). Similar to common processes in wastewater treatment facilities, for the purposes of improving dewatering capabilities in sludge, the use of coagulants and flocculants are applied.

3.3 Sludge conditions prior to treatment operations

Mining, agricultural, wastewater treatment facilities, industrial, domestic, chemical plant wastes, and paper mills are some of the most common activities and operations that generate complicated sludges with high amounts of moisture that should be dewatered prior to disposal as per environmental regulations (Skousen et al., 2016; Aparicio et al., 2020; Liao and Bathia, 2005; Vaselaire and Cezac, 2004). In most cases, sludges travel through a series of pre-treatment operations and activities that improve their dewater-ability.

Moisture and solids content in sludges account for very challenging characteristics to be determined. Theories and solutions to moisture content of a sludge have been thoroughly discussed in the literature, however difficulties come into place when attempted to be applied as it comprises many parameters such as particle size, extra polymeric substances, cationic salts, filamentous bacteria, and conditioning (Karr and Keinath, 1978; Legrand, 1997; Mikkelsen and Keiding, 2002; Neyens and Baeyends, 2003; Novak et al., 1998; cited in Vaxelaire and Cezac 2004).

3.3.1 Sludge moisture content

Generally, the main components of most sludges contain mostly moisture and various solid particles (Anjum et al., 2016; Mowla et al, 2013). The moisture content present in any sludge accounts for a very important element to consider when attempting to predict how it will react to the design dewatering means and methods. The total water content within sludges highly differ

from sample to sample (Vaxelaire and Cezac, 2004). The treatment performed on sludge prior to entering a dewatering facility, the conditions to which the sludge was exposed to, the location where the sludge comes from, and the duration to which the sludge was exposed to outside factor (if obtained from abandoned former mining operations) are some of the main causes to the water content of different sludges. Wei et al. (2018) performed an extensive review on the moisture content classification in sludges as well as the different testing methods to determine its moisture content to improve the user's understanding of this characteristic and to facilitate a design approach.

A classification of water content in sludge performed by Vesilind (1994), Tsang and Vesilind (1990); Vesilind and Hsu (1997); Smith and Vesilind (1995) has been summarized by Vaxelaire and Cezac (2004). The water content present in a slurry sample that is not affected by the existing solids content in the sludge is referred to as free water content and accounts to up to 70% of the total water content. Free water portion of the sample, the first parameter in moisture content determination, includes water within the sample voids but not the moisture affected by the material capillary. Interstitial water, the water stuck within interstitial spaces was indicated as the second parameter for water classification in a sludge. The third and fourth parameters of water classification were referred to as the surface water and the hydration water also known as internal moisture

The portion known as free water can be accounted for up to 70% of the total water content of the slurry (Chen et al., 2015; Vaxelaire and Cezac, 2004) while the remaining 30% would comprise the content conformed by the interstitial, surface, and hydration water. These put together are denominated bound water (Lee and Hsu, 1995; Lee and Lee, 1995). Initial research indicated that the bound water section of the total moisture content comprised a major element to evaluate the dewatering of the slurry (Erdinçler and Vesilind, 2003; Mowla et al., 2013; Vaxelaire and Cezac, 2004). On the other hand, since the bound water only represents a 30% of the total moisture content in the slurry, Jin et al (2014) stipulated that the free water section was the most dominant element in the dewatering performance of the slurry. Hence, free water could be considered as the governing factor within types of water present in sludge and it should be analyzed as such.

Classification of water within sludge is very challenging to analyze and properly determine. Therefore, an extensive review on moisture content determination performed by Vaxelaire and Cezac (2004) describes in detail advantages and disadvantages of various drying tests means and methods. The tests analyzed by Vaxelaire and Cezac (2004) ranged from conventional mechanical tests to chemical based testing. In general, the free water portion present in a sludge, has a fairly low difficulty level in its determination as it can be achieved by the use of conventional dewatering methods (Erdinçler and Vesilind, 2003). The dilatometric test, a method that refers to a freezing-based method, stipulates that the free water section of the sample is determined by exposing the sample to temperatures of up to -20°C . Since the free water freezes at this temperature, the free water portion of sludge can be determined by observing the expansion of the free water due to freezing. Additionally, the remainder of moisture in the sample (not frozen) is the bound water, that will then be determined by exposing the remaining water content in the sample to 105°C for 24 hours (Vaxelaire and Cezac, 2004).

At present, the challenge of determining the distribution of water within sludge still is yet to be fully understood and solved. A common approach for the determination of water distribution in sludge has been related to the type of drying method used. A dilatometric approach seems to be efficient in the determination of the free water portion. Additionally, the determination of binding energy of the water also shows efficiency in accomplishing water classification. However, identification of the type of energy is still a big challenge (Vaxelaire and Cezac, 2004). Thus, extensive testing and analysis of the water content in sludge is essential for a competent solution to water classification determination.

3.3.2 Solids content in wastewater produced sludge

It is important to understand basic parameters and assumptions taken into account in the determination of the solids content of slurries. Mining, chemical plants, agricultural, and wastewater treatment plants related activities that originate must sludges discussed in this report. Prior to any analysis, it should be noted that they come from several different conditions such as location, previous treatment, and duration of time of exposure. Often times, this results in significant variance within its characteristics, creating high complexity to find a common parameter that will assure how a dewatering process should be designed. Similar to the water

portion of sludge, the solids portion also presents a series of uncertainties that create a challenge in their analysis, especially in sludges resulting from wastewater treatment plants.

Sludges resulting from wastewater treatment activities are known to have been treated successfully by the employment of many biological methods. These methods have been used for decades in sewage treatment as they tend to reduce organic content considerably (Wei et al., 2018). Colin and Gazbar, (1995), and Zhu et al. (2013) concluded that the biological process used to treat wastewater generate considerable amounts of waste activated sludge (WAS) which typically are conformed of at least 95% moisture.

WAS constitutes a major element of wastewater post biological-treatment process and its main components include microorganisms, organic debris, inorganic colloidal particles, and extracellular polymeric substances (EPS) (Christensen et al., 2015). EPS has been considered as the most important factor in the decrease of the dewatering performance in sludge due to its direct effect on the rheological properties of a sludge (Dong et al., 2011). He et al. (2016) indicated that the ability of EPS to retain water due to its negative charge along with its high hydration also plays an important role in the difficulty of sludge dewatering. As such, Wei et al (2018) describe extensive research previously performed regarding EPS effects on sludges resulting as follow:

- Kan et al. (1989) indicate that the remaining material resulting from EPS extraction is not affected, however resistance to filtration is influenced by it,
- The removal of EPS in general decreases flocculants settlement resulting in an increase of dewatering performance (Li and Yang, 2007), however
- Houghton et al. (2001) and Houghton and Stephenson, (2002) found parameters that have EPS as an element that improve the dewatering performance, and
- A study performed by Jun et al. (2004) specifies that as the EPS content decreases, dewatering of a sludge improves.

As discussed above, the solids portion of sludge create many difficulties along with not many straight forward solutions to them. Therefore, extensive testing in sludge characteristics is essential for proper solutions to varying solids content characteristics in sludge dewatering.

3.4 Filtration Performance and General Mechanisms

This study primarily focuses on the filtration processes of Acid Mine Drainage (AMD) sludges by using geotextile materials. These materials are used for the construction of containers that serve as a dewatering tool for materials with high amounts of moisture. For the purposes of understanding how filtration works in geotubes, Fannin's (2006) fundamental parameters should be considered.

Fannin (2006) considers soil retention needs, cross-plane permeability, and geotextile strength as the three main factors in the design criteria of a geotextile filtration system in civil engineering. The first factor, soil retention factor, is governed by the grain size distribution of the soil sample. Soil retention and the second criteria, cross-plane permeability, represent conflicting objectives, as the opening sizes of the geotextiles would need to be minimized in order to improve its soil retention capabilities. On the other hand, permeability of soil is typically maximized with relatively coarser materials with poor gradation characteristics (Fannin, 2006). A balance between soil retention and permeability performances then becomes a challenge in the design of filtration applications using geotextiles. The designer should search for a geotextile with efficient retaining ability that usually leads to larger openings while selecting a material with small enough particle sizes not to seep through the geotextile.

The third main criteria pointed out by Fannin (2006) in geotextiles as filtration tools in civil engineering is their strength. Strength requirement and filtration become somewhat compatible, as woven-geotextiles typically have the ability of resisting loads imposed by the material placed on top of them. Geotextiles obtain this resistance to load from their ability to adapt their shapes, causing them to deform while maintaining their integrity. Fannin (2006) indicates that geotextiles are mostly exposed to failure at the commencement of their installations. Common geotechnical engineering practices using geotextiles include the demand from professional engineers to place geotextiles with an overlap of up to 12-inches between each layer. By doing so, the geotextile will provide assurances in the prevention of unwanted particles seeping through this separation layer. Geotextile installation as a separator in geotechnical engineering practices are shown in Figures 3, and 4. It should be noted that the figures' main objective is to show installation procedures that improve the separating capability of the geotextile and not the filtration capability of the system.

Figure 1. Geotextiles as Separators in Geotechnical Engineering (+/-14-inch overlap length).

Figure 2 Geotextiles as Separators in Geotechnical Engineering

Given the previously described requirements, Palmeira and Fannin, (2002) recommend the need of both index and performance geotechnical properties testing of the soils in question. These will help in the design of the geotextile focused on the soil retention criterion, the hydraulic gradient criterion, and the geotextile strength criterion. Fannin (2006) adapted from Fannin

(2000) discusses typical testing methodology required to assess the design of filtration systems by using geotextiles in civil engineering. Index tests are performed for the soil's design section of strength, hydraulic gradient, and durability. Performance tests assess strength and hydraulic gradient. The common characteristics of geotextiles characteristics obtained prior to the design of a filtration system are permittivity, mass per unit area, UV resistance, burst, puncture, soil-geosynthetic, and interface bond.

3.5 Geotextile bags usage overview

Historically, a very common method used to remediate materials like AMD with very high contents of water has been to place them into dykes and large ponds so that solid particles from AMD can settle and the water content can decrease prior to disposing them (Liao and Bathia, 2005). Gaffney et al. (2001) indicate some alternatives as to how dewatered AMD materials are often used for the purposes of landfill and backfilling operations. Even though for quite some time this method appeared competent, limitations such as the seepage of substances contained in AMD materials to the groundwater, spacing and environmental constraints, and capacity of these dikes have imposed a need to find new alternatives for the dewatering of these materials (Liao and Bathia, 2005). The application of geotextile bags for AMD filtration purposes have become such a competent and feasible method causing scientists and researchers to continuously look into the improvement of testing and application techniques of these. Geotextile bags are made of geosynthetics both in woven and non-woven materials that when put together form an effective tool that assesses limitations that were present when employing dikes as impoundment areas for dredged materials (Moo-Young et al., 2002).

Geotextile bags lead over supplemental dewatering methods such as drains, impervious soil cover or membrane, underground mine sealing, and surface access dry seals. Geotextile bags' main advantage over these techniques include mainly the economic factor as these bags have such a wide range of textures, sizes and characteristics that make them more affordable (Moo-Young et al., 2002). Geotextile bags also require very minimum inspection once they have been properly installed. In addition to the geobags cost, it should also be noted that the assembly of the geobags allow for the designer to maximize the use of the existing area of the project site. The growth of geotextile bags as a filtration system for AMD has also influenced major

producers of geotextile materials such as Tencate Geosynthetics to develop a much wider variety in sizes, textures, and prices of their materials to satisfy their clients' demands.

The Geotextile containers serve as primarily the containment of the solids (AMD, Fly Ash, etc.) in question. The solids will be stored in the geotextile containers and sometimes treated while attempting to maximize the quality of the filtration, which generally takes place, once the solids have completely settled and the liquids have been fully filtrated. The study of filter cake formation which accounts for the main factor in the filtration performance (Weggel et al., 2010). The solids portion of sludge plays a key element of the numerical model developed by Weggel and Ward (2011), as it comprises one of the main factors in filter cake formation. Following one of the objectives in this report (the development of a solution tool to predict filter cake formation as per Weggel and Ward's (2011) numerical model.

The geotextile bags can be split so that the solids can be disposed in a controlled manner. The densified solids can either be disposed at a landfill or they can be incinerated. However, in the case that the materials had been properly treated and pollutants fully removed as per federal regulations, the need of disposal disappears and they can be used for land reclamation, building embankments, and raising levees (Timpson, 2017). On the other hand, in the case of existing contaminants within sludge are not remediated properly, complications in the containment as well as the disposal of the sludges arise. To this issue, some of the most common solutions are:

- enhancing the performance of the geobags,
- additional treatment needed for the disposal of coal-mining activities related materials

3.5.1 Geotextile Bags performance enhancement

In order to perform and maintain an optimum sludge dewatering system a balance between the filtration levels, and the solids containment must be kept throughout the dewatering system. This along with some EPA regulations force the system designer to proceed with caution when developing the system. As mentioned in section 3.1.1, the containment of the solids affects directly the dewatering performance of the system.

For coarse materials as per basic geotechnical properties the filtration process is facilitated due to the larger existing voids from within the sample causing for a steady water flow. For finer

materials (cohesive) dewatering processes turn out to be significantly less effective because of the ability of these particles to retain more moisture and expanding in volume. In consequence, the water flow is reduced as well. For the assessment of the very fine material factor the use of polymer modifiers comes in handy. This chemical process causes the AMD conformed of very fine particles to flocculate; the slurry particles will gain volume increasing the voids in the sample and improving remarkably the drainage in the system by helping the soil particles to stay in the geotextile bag while also causing for the discharge to contain less fines. (Bratby, 2016; Chang, 2011; Lee et al., 2014; Yang et al., 2016) (cited by Wei et al., 2018).

Each AMD slurry is formed with its own characteristics, this makes each of them unique in the sense of selecting the right polymers for an effective flocculation. The American Society of Testing and Materials (ASTM) International has developed extensive research of testing methods and procedures to obtain the polymer type and dosage that will help with the design of the dewatering system for a slurry containing high amounts of fine particles. *Standard test method for determining flow rate of water and suspended solids retention from a close geosynthetic bag ASTM D7880*, is a well-known procedure used contemporarily as it will assist with predicting how much material will be contained in the geotextile bags for dewatering, and how much discharge the system will achieve.

3.6 Sludge filtering methods and limitations

There are two existing processes in sludge dewatering that have significant dominance in its performance: the dewatering itself, and the disposal of the dewatered materials. Typical sewage treatment sludge materials are typically conformed of approximately 92% moisture and only 8% or less solids (Anjum et al., 2016; Nellenschulte and Kayser, 1997) therefore any filtration attempt could result in a quite challenging task. Certain biological stabilization techniques tend to be very common in the treatment of sludges. Their main purpose is to facilitate the sludge's ability to be dewatered in an efficient manner. Anaerobic and aerobic digestion account for some of the most common practices used for these complex materials (Anjum et al., 2016; Nellenschulte and Kayser, 1997). They serve as a tool to separate the moisture content portion from the solids within the sludge, maximizing efficiency of the dewatering and minimizing costs of transportation, treatment, and disposal (Mowla et al., 2013).

Additionally, Ormeci (2016) reviews the literature presented in the 10th Water Conference of the International Water Association on October 10, 2016, and concludes that the sludge management and disposal account for a very popular issue presented in this conference due to its challenges and difficulties in the maximization of their performance. Wei et al., (2018) show an extensive review on contemporary techniques and parameters for the improvement of sludge dewatering and disposal performance most specifically coagulation and flocculation. Literary relevant arguments taken into consideration for the performance of sludge dewatering are capillary suction time (CST), and specific resistance to filtration (SRF) (Pan et al., 2003; Sawalha and Scholz, 2010; Scholz, 2005; Yukseler et al., 2007). Determination procedures for CST tend to be much easier and less financial challenging than SRF which tends to have a bigger complexity. This complexity comes from its scientific approach having a direct connection with its hydrodynamic characteristic (Fitria et al., 2013). CST does not need additional suctioning devices for its determinability (Scholz, 2005). Opposite to SRF, which requires additional planning as its performance depends on an external suctioning device (Sawalha and Scholz 2010; Yukseler et al., 2007). Certain limitations on some common methods, techniques, parameters, and practices regarding sludge filtration are reviewed by Wei et al., (2018):

- While CST, and SRF are empirical methods. SRF departs from the filtration theory developed by Yukseler et al. (2007) as its starting point assumes cake size, porosity, and pore water pressure as constant values. Sawalha and Scholz (2010) later indicated otherwise.
- In the case of CST, it is impossible to predict changes within the test physical properties that must be accounted for in dewatering (Pan et al., 2003; Scholz, 2005)
- Guan et al. (2017) indicate that there is an uncertainty with the sludge moisture content and SRF when it is influenced by dissolving extracellular polymeric substances (EPS). This might cause for a reduction within some of the previously flocculated particles, therefore, to potentially decrease its filtration efficiency.

Wei et al. (2018) also consider dehydration rate as a parameter that influences sludge dewatering specifically referring to a study performed by Zhang et al.(2017). In this study, additional dewatering of urban sludge is performed by using the dehydration rate of the sludge as the main property. Dehydration rate helps determining the sludge's feasibility to dewater by the methods

of being exposed to high pressures, most commonly known as the filtration-compression cell (FCC). FCC consists on placing the sludge in a cell where pressure is applied so it pushes it towards the geotextile walls forming a layer of sediments (cake), and removing the moisture content (Raynaud et al., 2012). While this method has a very interesting initial approach, Wei et al. (2018) find a key element to the test which is the changes in particles sizes, shapes and different components within any sludge. As sludge characteristics change significantly in some sludges, this test initial parameters might be compromised.

3.6.1 Sludge desiccation

In sludge dewatering, much emphasis has been given to the sludge operations and parameters that improve the separation of their solids portion from their moisture portion. However, Wei et al. (2018) indicate that parameters regarding how to properly desiccate sludge are as important. The previous is given by the fact that desiccation phase of dewatering processes will potentially maximize the performance of the sludge dewatering. Desiccation will also minimize the utilization of resources, therefore causing a decrease on financial efforts as well.

Bennamoun (2012) includes centrifugation and filtration as key elements in most mechanical-driven sludge drying processes. Sludge conditions vary considerably from case to case. The weather surrounding the area where a sludge dewatering facility is located at comprises the main factor for the purposes of a naturally-drying approach of a certain sludge. However, due to the inconsistency of this factor, and the extreme levels reached in some areas around the world, mechanical-based sludge drying mechanisms seem to be more popular in sludge desiccation. However, these mechanisms require significant levels of energy for their proper performance, a counterproductive factor for the financial factor (Bennamoun, 2012).

Even though mechanical-drying of sludge is a prominent mechanism, it is not able to achieve sufficient drying effect in sludge as it can only reduce sludge moisture contents to up to 98% (Wang et al., 2010). To the surrounding weathering factor, Wei et al. (2018) added the mixture of solids and liquids within the sludge as another limitation factor. Vaxelaire and Cezac (2004) then considered the water portion of sludge that was partially combined with the geotextile surface as well as the colloidal section of the sludge. In the case of sludge with significant levels of extracellular polymeric substances (EPS), they will potentially connect with water molecules

by the principle of steric force and develop a very stable mixture in suspension (Keiding et al., 2001; Mowla et al., 2013; Neyens et al., 2004; Qi et al., 2011). Thus, causing additional complexity to the filtration approach.

3.6.2 Sludge pre-filtering and pre-treatment methods

The previous section in this report makes emphasis on several factors that comprise the existing difficulties within the sludge dewatering processes, methods, and limitations. As such, the need for researchers to study and perform pre-treatment of the sludges prior to the attempting of a filtering design and methodology has increased enormously. Wei et al. (2018) enumerate some of the most common methodologies of pretreatment in sludge dewatering, Dhar et al., (2012); Liu et al., (2016); Ruiz-Hernando et al., (2014); Zhang et al., (2015); Zhen et al., (2013) present them as the main approach to facilitate and improve the performance of sludge dewatering. These methods were classified according to their ability to enhance the performance of filtration by means of physical, biological, and chemical operations to sludges.

Physical enhancement methodologies include the following:

- Wu et al (2016) mention the use of rice husk flour and (FeCl_3)
- Thermal perspective studied by Neyens and Baeyens (2003)
- Hu et al (2011) sludge freezing methodology
- Cai et al (2017) by means of microwaving
- Ultrasonic methods by Feng et al (2009), and mixtures using ultrasonic methods by Dhar et al (2012); Ruiz-Hernando et al (2014)

Chemical methodologies include the following:

- Li et al (2005) studied the inclusion of alkalis and acids in sludges
- Chen et al (2001); Guan et al (2017) considered the inclusion of surfactants
- Zhang et al (2015) incorporated oxidants
- The use of coagulants and flocculants studied by Mowla et al (2013)

Biological methodologies include the following:

- Heterotrophic bacterial inclusion Guo et al (2015)
- Electrochemical approach by Mahmoud et al (2018); Zhen et al (2013)

From the means and methods exposed by Wei et al (2018), flocculants and coagulants result in a tremendously significant solution for enhancement of sludge dewatering specifically focusing on the profitability of the dewatering operation because of their efficiency in converting minuscule solids into substantial particles maximizing the filtering effectiveness (Chen et al., 2015, 2016a; Novak and O'Brien, 1975).

3.6.3 Coagulants and Flocculants

As several complications and limitations comprising sludge dewatering have been reviewed and discussed, it is the engineer's duty and advocacy to find feasible and competent solutions. To which, in some cases can result quite difficult to achieve given a topic where several limitations have appeared such as sludge filtering operations. To this setback in sludge dewatering, coagulation and flocculation of sludge is among one of the most often used methods to pre-treat sludge to facilitate its dewatering (Bolto and Gregory, 2007; Bratby, 2016; Chang, 2011; Ghernaout and Ghernaout, 2012; Gregory, 2006; Ives, 1977; Jiang, 2015; Khachan et al., 2014; Lee et al., 2014; Lyklema, 1985; Overbeek, 1977; Sillanpaa et al., 2018; Thomas et al., 1999; Verwey and Overbeek, 1948; Yang et al., 2016b).

The starting point of any operation where coagulants and flocculants are used comes from the need of converting solutions (sludge, wastewater, agricultural, and industrial fields) that typically convey very high moisture contents as well as a significant amount of very fine materials into solutions with a higher amount of coarser materials. This will facilitate dewatering, solution cleaning, and sludge particles separation from solids to liquids. In sludge dewatering, detaching existing fine materials from moisture content accounts for the main improvement that coagulation/flocculation has on sludge dewatering.

Typically, coagulation operations consist on adding coagulants to the sludge. These coagulants will provoke the fine particles within the sludge that are suspended in the water to settle down. This occurs because the coagulants' surface charges are opposite to the fine particles' in the

sludge mixed with them, causing fine particles to be undermined and eventually the fine particles will sink (Bratby, 2016; Chang, 2011; Lee et al., 2014; Yang et al., 2016b).

Following coagulants' effects, to further improve dewatering in wastewater treatment operations, polymeric flocculants might also be added to improve this process (Wei et al., 2018). The additional flocculants serve as a connection between the remaining of the particles to stick together and facilitate the removal of them by means of sedimentation (Bratby, 2016; Chang, 2011; Lee et al., 2014; Yang et al., 2016).

Wei et al., (2018) indicated the type of flocculants and coagulants used in sludge as the main factor that affect the efficiency of the coagulation/flocculation process. Bratby (2016); Chang, (2011); Lee et al (2014); Yang et al (2016) list characteristics of coagulants and flocculants such as molecular weight, structural form, charges, and ionic groups as the major factors regarding the efficiency of the coagulation/flocculation operation. Extensive knowledge from the sludge particles attempted to coagulate and flocculate should be performed prior to determining what the most competent coagulants and flocculants are for an efficient operation.

Bratby, (2016); Chang, (2011); Yang et al (2016); Zhang et al.(2010, 2014) note two major methods in coagulation/flocculation: bridging, and charge neutralization. The common denominator in substances dewatered is their negative surface charges, causing difficulties to the dewatering performance. Hence, the Derjaguin, Landau, Verwey, and Overbeek (DLVO) theory along with the diffuse electric double layer model developed by Hubbard (2002); Overbeek, (1977); Verwey and Overbeek (1948) comprises an effective solution. By the addition of typical coagulants (trivalent metal inorganic salts), they manage to control solids' charges in a sludge, and to facilitate dewatering.

To address existing complexity in sludge originated from wastewater treatments, Wei et al., (2018) indicate a solving approach that not only involves using either inorganic coagulants or organic polymeric coagulants, but the mixture of these. Additional to charge stabilization mechanisms for enhancing sludge or wastewater dewatering, bridging flocculation has also become key in sludge or wastewater dewatering operations (Wei et al., 2018). The bridging effect is typically given by the molecular weight of the flocculants used for this process (Anbu Clemensis et al., 2012; Meyn et al., 2012; Zheng et al., 2014). Therefore, Wei et al (2018) state

that the flocculants with more molecular weight, the more efficient will the dewatering performance be.

Sludge dewatering is highly complicated as there are many variables to which not many straight forward approaches are present. The limited time and resources that AMD sludge dewatering has been exposed to regulations and enforcement by federal laws, have caused for very few proper cost-effective solutions to this issue. Former common dewatering methods such as using ponds as containers for AMD slurries, have presented limitations in dewatering capability, causing for scientists and researchers to search innovative solutions. Geotubes comprise one of the most common methods in sludge dewatering as it is cost effective, versatile, and efficient. However, even with improvements achieved in AMD sludge dewatering, there still remain many limitations that should be addressed.

Weggel, and Ward (2011) have developed a numerical model that predicts the formation of filter cake in a falling head experiment as shown in figure 1. This comes in response to a high demand for solutions and approaches in the industry of sludge dewatering given existing limitations and difficulties including sludge characteristics, operations, moisture content, coagulation / flocculation presence, sludge desiccation, and geotextile materials used.

As several studies have focused on the properties of the geotextile used for the dewatering of slurries, this does not represent the dominant factor which is the filter cake formation. The geotextile filtration characteristics in use (permeability = permeability over its thickness) are only dominant at the very commencement of dewatering operations (Weggel and Ward, 2011); (Zofchak, 2001).

4 Filter Cake Solution Tool

4.1 Existing Models

Principal assumptions and factors considered by Weggel and Ward (2011) in the development of their numerical model are the following:

- The experiment is focused on mimicking typical dewatering operations using geotextile bags
- Accumulated filter cake directly limits dewatering performance (Zofchak, 2001)
- The geotextile's primary objective is to retain as many solids while attempting for a "free" water flow
- The model assumes that the geotextile will not allow any particles from the sludge material to seep through

Primary parameters used in Weggel and Ward's (2011) numerical model are:

1. The geotextile's permittivity
2. Accumulated filter cake's permeability
3. The thickness of the filter cake formed
4. The volumetric solids concentration of the slurry (volumes of solids over the volume of the slurry)
5. Settling velocities of particles in the sludge
6. The hydraulic head driving the head flow

4.2 Solution tool following numerical model developed by Weggel and Ward (2011) and Weggel and Dortch (2011).

This tool's main objective is to determine basic parameters that influence the dewater-ability rate within slurries when placed in geotextile bags. By obtaining these parameters and characteristics in question, the user would be able to analyze, identify, and design a proper dewatering system for the sludge of interest. Contrasting with the preliminary thought of considering the index characteristics of the geotextile itself as the most dominant factor in determining the dewatering

performance in a geotextile bag system, the filter cake thickness formation conveys the main factor in dewatering performance (Weggel and Dortch, 2011).

The system allows the user to input certain characteristics previously acquired from the geotextile and the sludge being used for filtration testing purposes. Note that there are several characteristics within the sludge being tested that require extensive laboratory testing prior to the commencement of the filtration test. Although most characteristics for the sludges analyzed in this report have been acquired from experimental laboratory testing, certain additional basic characteristics could also be determined from previously available data in the literature without significant changes to the performed calculations.

4.3 Numerical model by Weggel and Ward (2011)

Initial equations used by Weggel and Ward (2011) are the following:

At the initial phase of this numerical model, Weggel and Ward (2011) assumed that all particles comprised within the slurry are in colloidal stage and they would settle down only by the system flow (typical slurry from wastewater treatment have this characteristic). Preliminary equations for the theoretical behavior of the system parameters are given by:

$$q_0 = \frac{y_0 - z_0}{\left\{ \frac{1}{\psi} + \frac{z_0}{K} \right\}} \quad (1)$$

Where q_0 is the initial discharge rate through the system, y_0 is the initial height of the slurry, z_0 is the filter cake accumulated thickness at the commencement of the test, ψ is the permittivity of the geotextile, and K is the permeability of the system initially assumed constant. (Weggel and Ward, 2011) indicate that when z_0 is zero then the initial head driving the flow, h_0 is simply y_0 , while whenever z_0 is larger than zero, then the initial head is given by $y_0 - z_0$. Predicted heights of the slurry at each time increment is given by

$$y_n = (y_{n-1}) - (q_{n-1})\Delta t \quad (2)$$

Where y_n is the height of the slurry at the current stage of the system, y_{n-1} is the height of the slurry at the previous time increment depending on Δt , and q_{n-1} is the discharge rate of the system at the previous time increment. The thickness of the filter cake at the end of each time increment is

$$z_n = z_{n-1} + q_{n-1} \frac{\alpha_0}{\varepsilon} \Delta t, \quad (3)$$

where z_{n-1} is the filter cake accumulation at the previous time increment. Weggel and Ward (2011) also assumed that slurries are typically conformed of significant amounts of very fine materials they would be in colloidal suspension (particle sizes range between 1-1000nm). Therefore, the acceleration of gravity would not have a significant impact on the settling velocities of the slurry particles so that the rate of settlement is minimized and can be ignored. The parameters considered in the filter cake formation consequently are the volumetric concentration of the solids within the slurry as a whole, α_0 , the porosity of the accumulated filter cake, $n = 1 - \varepsilon$, where ε is the solids fraction of the slurry. The discharge at the end of each time increment is given by

$$q_n = \left[\frac{(h_{n-1} + h_n)/2}{\frac{1}{\psi} + \frac{z_n + z_{n+1}}{2K}} \right] \quad (4)$$

Where $h_{n-1} = y_{n-1} - z_{n-1}$ and $h_n = y_n - z_n$, and the cumulative volumes of liquids lost from the system is expressed as

$$q_{cum(n)} = q_{cum(n-1)} + \frac{q_n + (q_{n-1})}{2} \Delta t \quad (5)$$

The particle sizes within the slurry become a key element due to their ability to completely change approaches within the model. For slurries that have particles that will stay in colloidal suspension, the initial thickness of the filter cake is typically zero. Thus, in cases where the system lacks in accumulated filter cake at its initial stage, a partial or the entire amount of fine particles from within the sludge might be expelled by seeping through the geotextile. On the other hand, for a system with slurries that contain a considerable amount of coarse particles, the initial filter cake thickness will not be zero. Slurries with coarse particles will be influenced by its settling velocities from the start of the dewatering process.

To predict behaviors of AMD sludge under the filtration process by the methods of geotubes a predictive computer solution tool was developed using Microsoft Excel. The slurries considered in this tool are combined with a wide range of geotextiles produced by different manufacturers comprising woven and non-woven materials. Excel was chosen for this developed solution tool because it is friendly to users with basic experience using Microsoft programs. This tool was

created by following the main assumptions and equations used by Weggel and Dortch's (2011) numerical model for filter cake thickness determination.

4.3.1 Solution Tool Inputs and Variables

The solution tool inputs are based on known variables from the model developed by Weggel and Ward (2011), computed soil characteristics values acquired from testing as per ASTM, and from historical data available in the literature. The system performance is based on the filter cake thickness formation, which directly governs the system's filtration efficiency. As the thickness of the filter cake increases, the filtration-rate of the system decreases (Weggel and Ward, 2011). The solution tool is established by three main components of inputs and variables:

1. Soil/Sludge variables,
2. Geotextile Variables, and
3. System Variables

Soil/Sludge variables presented in the solution tool consist first, in the division of the sludge particles in fractions. They would facilitate the prediction of the particles settling velocities within the sludge at each time increment. Given a sludge grain size distribution, the user will identify similar behaviors within the grain size distribution. Consequently, the user can estimate how the particle sizes within the sludge are distributed, as these are needed in the determination of particles settling velocities in the system.

The determination of the fractions present within the sludge is performed by using the identified patterns within the particle sizes to estimate a geometric mean within each selected range in which the particle sizes followed a similar pattern in the sieve curve. The geometric mean is calculated by:

$$\bar{X}_g = (\sum_{i=1}^n x_i)^{\frac{1}{n}} \quad (6)$$

Where, n is the total number of values, and $(x_2, x_1, \dots, x_n)$ are the individual numbers in the data set. The formula is equivalent to:

$$\sqrt[n]{x_1 * x_2 * \dots * x_n} \quad (7)$$

In other words, the geometric mean is the n^{th} root of the product of n values.

With the acquisition of the geometric mean for each component of the slurry, the user is then able to calculate the settling velocities of the particles within the sludge. Settling velocities are crucial when dealing with the dewatering of materials with a high amount of coarse particles. They have the ability to settle down from the start of the test generating some filter cake.

Even though the particles settling velocities do not cause major changes to the filter cake accumulation, when dewatering sludge materials containing high amounts of fines (sludges considered for this report), considering their settling velocities only improves the performance of the system. Settling velocities determination specifically for coarse particles are given by the following equation: Rubey (1933)

$$v = \frac{2}{9} * g * \frac{\rho_p - \rho_f}{\eta} r^2 \quad (8)$$

Where v = settling velocity of particle

r = radius of particle

ρ_p = density of particle

ρ_f = density of fluid

η = coefficient of viscosity of fluid

g = acceleration due to gravity

While for the purposes of obtaining particles settling velocities in materials with a high amount of fines, the following equation is to be used:

$$v = \frac{\sqrt{\frac{4}{3} * g * \rho_f (\rho_p - \rho_f) r^3 + 9\eta^2 - 3\eta}}{\rho_f * r} \quad (9)$$

Table 1 shows the system tool's input variables section in which the user will introduce the values for particle fractions, gravity, and particle diameter sizes. The system will then compute the settling velocities for the sludge of interest.

Table 1. Solution Tool soil/sludge input parameters

Soil/Sludge Variables
Name
USCS Symbol
Particle Fractions (%)
gravity (cm/s^2)
d_i (cm)
ρ_s (g/cm^3)
ρ_{fluid} (g/cm^3)
v_i (cm/s) Weggel
v_i (cm/s) Rubey

A very important factor in filter cake formation at the commencement of the dewatering process of sludge is the material of which the geotube bag is made of. A very wide range of materials exist, therefore different characteristics in geotextiles appear for each material used. Woven and non-woven geotextiles are the most known worldwide however, within these two options there is a great deal of materials with different specifications and characteristics.

Table 2. Solution Tool geotextile input parameters

Geotextile variables	
Name	
Permittivity, ψ (s^{-1})	
Apparent Opening Pore Size (AOS)	
Water flow rate (l/min/m^2)	
q_0 (m/sec)	

Table 2 shows the geotextile inputs and variables that the user can specify so that the solution tool will determine the initial discharge, q_0 of the system. Note that the initial discharge within the system is solely governed by the permittivity, ψ of the geotextile. Note that the permittivity of the geotextiles used in this report has been acquired from the manufacturer's manual specifications.

The system variables and inputs within the solution tool are one of the most important factors in the system as they comprise a mixture of key relationships between values and parameters previously established within the geotextile and the sludge variables.

Table 3. Solution Tool system variables input parameters

System variables
Δt (s)
y_0 (m)
z_0 (m)
K (m/s)
α_i
ε
Testing Cylinder tool I.D (in)
Filter cake thickness (in)
Mass of Moist Filter cake g)
Volume of Filter cake
Density of Filter cake (g/in ³)
Density of Filter cake (g/cm ³)
h_0 (m)

Table 3 shows the input variables regarding the system testing information, and certain parameters acquired prior to and post-testing in which:

Δt is the time interval in which each set of theoretical values are required by the user and can be modified according to what the experiment duration becomes.

K is the permeability of the system measured in cm/s that is obtained at each time interval using the following equation:

$$K_{system} = \left[\frac{z}{\frac{1}{\psi} + \frac{z}{k}} \right] \quad (10)$$

The solution tool uses a mean value of all the permeability values obtained at each time increment.

α_i is the volumetric solids; concentration at each time increment of the system given by the following formula:

$$Cv = \frac{V_s}{V} = \frac{V_s}{V_w + V_s} \quad (11)$$

In which $C_v = \alpha_i$ is the volumetric solids concentration,

V_s is the volume of the solids within the sample

V is the total volume of the sample

V_w is the volume of the water portion in the sample

ε is the solids fraction of the filter cake which can be obtained from

$$\varepsilon = 1 - n \quad (12)$$

In which n is the porosity of the accumulated filter cake given by:

$$n = \frac{V_v}{V} \quad (13)$$

Where V_v is the volume of the voids portion within the accumulated filter cake (for this case), and can be obtained from:

$$V_v = V_w + V_a \quad (14)$$

Where V_a is the volume of the air portion of the filter cake.

Extra care should be taken in this process as, at the end of the test, the geotextile and the filter cake formation adhere to each other. This causes extreme difficulties to remove the accumulated filter cake from the geotextile as it becomes very sensitive to the touch. Human error might become an extremely difficult factor to address. Along with human error, time-consuming factor arises in the determination of each volumetric portions of the accumulated filter cake formation. To improve time efficiency in the testing methodology, it is recommended to seek previously obtained sludge characteristics in the available literature.

A soil phase diagram can easily be determined from the testing apparatus' pipe inside diameter value, which was previously input in the system variables section. Lastly, the accumulated filter cake (z) is obtained from observing the testing apparatus. The mass of the accumulated filter cake at the state in which the test is terminated is also obtained and is used for the determination of the moisture content of the accumulated filter cake.

Table 4. Solution Tool prediction output values

Theoretical						
time (s)	$\alpha i/\varepsilon$	Cumulative drained volume, q_{cum} (m/s)	head, h (m)	Filter cake thickness, z (m)	Water level, y (m)	Discharge rate, q (m/s)

Table 4 shows a screenshot from the solution tool where predicted values are determined from the initial parameters and characteristics from the soil/sludge tested, the geotextile used in the test, and the system characteristics. The system characteristics are also referred to as the combination of sludge and geotextile.

4.3.2 Model Outputs and Estimated Data Collection

The most attractive capability of this solution tool is to predict and graph parameters within the filter cake formation testing. By being able to calculate and plot theoretical values for the filter cake formation, the user would then be able to identify and compare theoretical and experimental values. This will facilitate conclusion determinations from the test. The solution tool plots both individual parameters in separate graphs as well as the combination of related parameters for simplification to the user's eye. However, for specific analysis and evaluation of certain parameters, the solution tool allows the user to be able to observe desired parameters, improving the versatility of the solution tool. Figure 3 shows a theoretical filter cake formation versus time for a certain material. As expected, the filter cake accumulation increases up to a time frame in which the solids section of the sludge has been settled to its fullest and became the accumulated filter cake. Therefore, the filter cake thickness stays constant at that point of the test.

Figure 3. Solution Tool filter cake formation as a function of time

Adding to the filter cake formation behavior description, the discharge rate of the system behavior is shown in figure 4. It shows its peak values at the very beginning of the test where the discharge rate is mostly governed by the permeability of the geotextile itself since no filter cake is formed yet at that point. Note that during this time interval there are typically some particles from the sludge included in the discharge that is expelled from the system but it is mostly negligible, specifically for slurries with high amounts of fines. As the filter cake accumulates in the system, the discharge rate decreases to a point where the filter cake has been formed at its full capacity and the only moisture present in the system is within the accumulated filter cake. The discharge rate can also become very small if the filter cake accumulated at its thickest before the remaining head was expelled from the testing apparatus. At that time interval, it can be concluded that the discharge rate is negligible and that the moisture within the filter cake is expelled by evaporation rather than through discharge.

Figure 4. Solution Tool discharge rate as a function of time

Figure 5 exhibits the plot of the cumulative discharge behavior throughout the system. It can be observed that at the commencement of the test there is no discharge accumulated, however, it continuously increases as the testing time passes by. An important consideration in the cumulative discharge of the system is that the total discharge is reached at or at a very close time increment from where the maximum filter cake formation is reached.

Figure 5. Solution Tool cumulative discharge as a function of time

Total discharge can also occur at the time increment where the discharge rate is very close to zero. Similarly, the water level of the system is at its peak when the test first starts as shown in figure 6. The water level is continuously decreasing mostly governed by the permeability, and

the discharge of the system, reaching the point where it meets the maximum filter cake thickness. At that point the moisture content present in the sample is only within the accumulated filter cake.

Figure 6. Solution Tool water level as a function of time

The solution tool gives the user facilities and solutions for the determination of very important factors required for dewater-ability analysis and design. The versatility and simplicity of the system are within its most important capabilities, as it allows the user to analyze specific desired materials and parameters individually or analyze them as a whole system depending on the required information by the user.

5 Data Analysis

5.1 Testing Methodology

The filtration testing apparatus used in this report follows similar characteristics to the one used by Weggel and Dortch (2011). It consists of a 2 inch inside diameter clear polyvinyl chloride (PVC) pipe that is hung vertically over the side of a tabletop. The tube has 60-centimeters in height and has a ruler in centimeters attached to the outside for the purposes of observing and logging the test behavior throughout the process. The framing system to hold the tube was constructed using lumber and plywood and is secured to the table using a C-clamp. Once the tube is plumbed and leveled, the geotextile fabric is cut and secured to the bottom of the tube using a hose clip. The geotextile used in the tests was the non-woven type Mirafi 1100N produced by Tencate with an apparent opening size (AOS) of 0.15mm, a permittivity of 0.8sec^{-1} , and a flow rate of 3056l/min/m^2

Figure 7. Filtration Testing Apparatus

5.2 Calibration of the Solution Tool

As stated in the previous sections of this report, the basis of the developed solution tool is the filter cake formation numerical model performed by Weggel and Dortch, (2011). The solution tool in this report utilizes the same equations as the ones used by Weggel and Dortch, (2011) and attempts its validity in AMD slurries with high amounts of fines. However, these authors utilize certain parameters and characteristics previously obtained through various testing methodologies. The materials described in Weggel and Dortch (2011) comprise an Ottawa sand, a fine sand, and a plasti-grit. All of which have been extensively analyzed and tested, therefore, a great deal of geotechnical characteristics of these materials are available in the existing literature. The extensive knowledge of these characteristics facilitates the determination of a key element within the solution tool for the prediction of filter cake, settling velocity. However, AMD slurries in this report present geotechnical characteristics opposite to what is shown in Weggel and Dortch (2011), grain size distribution.

A kaolinite material has been used to mimic most existing AMD slurries that lack in pre-treatment processes. Figure 8 shows the grain size distribution of this material. It can be observed that it is mostly comprised of fine particles, hence minimizing the filter cake accumulation rate caused by the minimum settling velocities of the particles. However, creating difficulties in the observation of the filter cake as even though the particles settle down, they do so at a very slow rate so that the accumulated filter cake is very challenging to be seen.

Figure 8. Grain size distribution of Kaolinite

This section comprises an analysis and comparison between both models, refers to what parameters influence the differences between models which refers to and describes how these parameters cause differences in results. The parameters of the sludge in the dewatering system previously described are:

- The settling velocity of the particles, v_i
- Solids fraction of the accumulated filter cake, ε (1-porosity), and
- The volumetric solids concentration of the sludge, α

Settling velocity of particles is used in this model specifically as an additional element for the improvement in the precision of the filter cake thickness. Note that Weggel and Dortch, (2011) had initially only considered the system flow rate to predict the thickness of the filter cake, as they assumed all particles from the material were in colloidal suspension. However, when materials dealt with had coarse particles with high settling velocities, they then included the settling velocity of the material's particles to improve the predicted filter cake formation.

As the consideration of settling velocity of particles improves the system solution tool, it also involves more resource usage and pre-testing operations. Determination of settling velocities accumulation at each time interval as it builds up in a fully dewatered material becomes quite challenging. Equations for the determination of settling velocities include approaches like

Rubey (1933), Stoke's law, Huisman (1973-1995), and Grace (1986). These approaches obtain close results between each other. However, it is critical to perform a preliminary study on the sludge being dewatered to determine what a competent approach should be. The solution tool in this report uses settling velocity equations developed by Rubey, (1933).

Both the solid volumetric concentration at each time increment in which the filter cake has been accumulated as well as the solids fraction of the total accumulated filter cake (1-porosity) are variables determined by the user. They could be acquired from the basic theory of phase soil diagrams and porosity equations previously described in this report. Alternatively, the user could opt to determine these values from what is available in the literature. It should be noted that this option might not be very feasible due to the changing characteristics in sludge as per what kind of treatment it has previously been exposed to, what the origin of the material is, etc. Since these two characteristics of materials used for testing purposes in (Weggel and Dortch, 2011) are not described, a comparison table regarding calibration of the solution tool developed in this report has not been performed.

A comparison between settling velocities obtained in Weggel and Dortch's, (2011) filter cake developed model and the solution tool developed in this report have been created. Percentage differences between both range between 1% and 8%. Material properties used in the comparison are expressed in Table 2 from Weggel and Dortch (2011), specifically for the material labeled as plasti-grit as this material has the more similar characteristics to the slurries used in this report. Results obtained in Table 6 show minimum differences between Weggel and Dortch's (2011) sediment characteristics and the solution tool developed in this report.

Two types of AMD slurries were placed under filtration testing. One of the slurries (T-1) had been previously exposed to flocculation processes. However, it should be noted that between the removal of the slurry from the geotube and transportation to the proper laboratory facilities, the slurry was subjected to high movement. This comprises a counterproductive action for the main purposes of flocculation in sludge and could potentially represent additional complications for filtration. Slurry referred to as T-2 in this report has not been treated with flocculants. Therefore, it is referred to as raw-AMD sludge. The materials used in this report as summarized by:

Table 5. Properties of the slurries comprised in this report

Material	Symbol	Flocculated (Yes/No)	Additional Comments
Kaolinite	CL	No	
AMD Slurry	T-1	Yes	Disturbed during transportation/pH treated
AMD Slurry	T-2	No	pH treated

Figures 17, 18, and 20 (shown in section 6 of this report) show the filter cake thickness behavior for an AMD sludge. Note that this material was previously treated with flocculants, however, it was disturbed at the time of transportation. Therefore, it was considered as a material with minimum to no previous flocculation exposure. Note that the materials' filter cake thickness behaviors consisted of three different scenarios:

1. Filter cake accumulation prior to recirculation
2. Filter cake accumulation post-initial recirculation
3. Filter cake accumulation post-secondary circulation

The previous scenarios implemented in this report, different from the conventional falling head test in sludge dewatering were in response to addressing the case in which sludge filtration is not fully accomplished by the initial run in the geotube. In slurries comprised of high amounts of fines without previous flocculation treatment, a partial portion of the sludge's solid content is expelled through the geotube, requiring extra treatment prior to being released into the environment. Scenario 1 refers to the typical falling head test procedure previously described in this report. Scenario 2 comprises a recirculation cycle through the falling head test. Lastly, scenario 3 refers to a secondary circulation process. Note that scenario 3 not only assesses the decrease in filter cake thickness but the permeability of the filter cake. These scenarios were

performed as per recommendations by Aparicio et al., (2020) to mimic typical recirculation processes at sludge treatment facilities. Testing procedures followed in this report are shown in the table below:

Table 6. American Society of Testing and Materials (ASTM) test procedures used in this report

Test Procedure	ASTM Standard
Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis	D6913/ D6913M - 17

6 Results and Discussion

A solution tool has been developed for the purposes of predicting filter cake thickness of sludge dewatering. The solution tool was developed as per equations and assumptions shown in Weggel and Ward's (2011) numeral model on filter cake formation and Weggel and Dortch's (2011) filter cake formation experiments.

Table 6 also shows different particle size diameters within the same material. This assumption comes from the particle size distribution graphs from each material in which Weggel and Dortch (2011) observed a close to a linear relationship between a certain range of particles and then determined that all particles within this range will have the same diameter sizes.

Table 7. Comparison between settling velocities obtained from Weggel and Dortch (2011) and the Solution Tool developed

Soil Variables					
Name				Kaolinite	
USCS				CL	
Particle Fractions (%)	44.09	4.47	6.71	8.95	35.78
gravity (cm/s²)	980.67	980.67	980.67	980.67	980.67
Particle Diameter d_i (cm)	0.0206	0.0095	0.0068	0.0041	0.0019
Density of Solid ,ρ_s (g/cm³)	1.59	1.59	1.59	1.59	1.59
Density of Fluid ρ_{fluid} (g/cm³)	1	1	1	1	1
Settling Velocity (cm/s) (Solution Tool)	0.0104	0.0029	0.0015	0.0005	0.00001
Settling Velocity (cm/s) (Weggel and Ward, 2011)	0.0103	0.0029	0.0015	0.0005	0.00001
Difference (%)	1%	0%	0%	0%	0%

Figures 9, 10, and 11 show filter cake thicknesses behaviors for three experiments performed using kaolinite. Experiments 1 and 2 (K-1 and K-2) both comprised a slurry formed with clean water and 50 grams of kaolinite. While the slurry in experiment 3 was formed with water and 10 grams of kaolinite. Comparison between experiments K-1 and K-2 show that their theoretical predicted filter cake behavior would rapidly settle at the commencement of the experiment. Causing a filter cake formation to create at its fullest and remain constant for the rest of the experiment. However, experimental values show that it took a considerable amount of time for a

minimum filter cake thickness to develop. Additionally, while the solution tool projected an immediate increase in filter cake to its thickest, the experiment showed that it took 1160 seconds for a filter cake of 2.54 centimeters to form. Note that even though this was the first time that a filter cake reading could be observed, this does not suggest a sudden increase in the filter cake during that time. It is deduced that the filter cake continuously increased as projected by the dotted lines shown in Figures 9 and 10, however, a filter cake thickness was not observable prior to that time frame.

Figure 9. Kaolinite's (50grams) K-1 filter cake formation as a function of time

Figure 10. Kaolinite's (50 grams) K-2 filter cake thickness as a function of time

Figure 11 which refers to the experiment using the slurry formed of clean water and 10 grams of kaolinite, shows a similar theoretical behavior that the ones shown in figures 9 and 10. On the other hand, the experimental filter cake thickness remains unseen throughout the majority of the experiment until a clear thickness could be observed. This behavior does not necessarily suggest that the filter cake suddenly accumulated but the fines remained on colloidal suspension and settled very slowly preventing a clear view of the accumulated filter cake.

Figure 11. Kaolinite's (10 grams) filter cake thickness as a function of time

Figures 12, 13, 14, and 15 show the water level and hydraulic conductivity behaviors for experiments referred to as K-1 and K-2 respectively. It can be observed in both experiments that the hydraulic conductivity increases, decreases, or remains constant contingent with the behavior of the discharge throughout the system. A rapid decrease in water level correlates to the increase in the hydraulic conductivity of the system, and vice versa.

Figure 12. Experimental kaolinite's (K-1) hydraulic conductivity as a function of time

Figure 13. Experimental kaolinite's (K-1) water level as a function of time

Figure 14. Experimental kaolinite (K-2) water level as a function of time

Figure 15. Experimental kaolinite K-2 hydraulic conductivity as a function of time

In figures 16, 17, and 18, it can be observed a rapid formation of filter cake during scenario 1, caused by the effects of flocculation in this sludge. Note that the filter cake formation decreases. Preliminary observations suggest that this decrease in filter cake is caused by the means of settlement. The experiment represented in figure 16 was placed under scenarios 1 and 2, while the experiments displayed in Figures 17, and 18 was placed under scenarios 1, 2, and 3.

Figure 16. Experimental AMD slurry (T-1) filter cake thickness as a function of time

Figure 17. Experimental AMD slurry (T-1) filter cake thickness as a function of time

Hydraulic conductivity behavior for T-1 material is shown in Figure 18 during scenarios 1-3. As expected, at the commencement of the experiment, hydraulic conductivity reached its peak value and it continuously decreased as time passed by in scenario 1. However, at the start of scenario 2, hydraulic conductivity suddenly increased at the very moment that recirculation started. This is caused by the disturbance in the filter cake that occurs by the partially dewatered AMD being poured back into the testing apparatus. During scenario 3, the same reacting occurs within the hydraulic conductivity of the system. There is a minor increase at the very commencement of scenario 3. However, it is very minimum at this point.

Figure 18. Experimental AMD slurry (T-1) hydraulic conductivity as a function of time

Figure 19 displays the filter cake behavior for the material referred to as T-2. Experiments 1 and 2 were performed following scenarios 1-3, while experiment 3 was performed under scenarios 1-2. Note that the initial cake observed during the test occurred rapidly post-recirculation. No filter cake was observed prior to that point. This was caused by the lack of flocculants present in this sample as previously discussed. Filter cake thickness in experiment 3 continuously decreased. At the time of the experiment termination, the filter cake thickness had not reached a constant thickness. This comprises a much smaller initial thickness in filter cake than in experiments 1 and 2.

Figure 19. Experimental AMD slurry (T-2) filter cake formation as a function of time

Figure 20 refers to the hydraulic conductivity behavior using AMD sludges without previous flocculation treatment (T-2). At the commencement of the experiment, an inconsistent path for hydraulic conductivity can be observed. This inconsistency was caused by the disturbance previously generated from the effect of pouring the wee-mixed sample into the testing apparatus. The absence of flocculants in the slurry causes the effects of disturbance in the sample to be maximized. Therefore, a high increase in hydraulic conductivity is observed at the commencement of post-secondary circulation effects. It should be noted that hydraulic conductivity goes back to constant post- secondary circulation as the filter cake had already been at a constant rate at that moment.

Figure 20. Experimental AMD slurry (T-2) filter cake thickness as a function of time

Table 8 comprises a summary of results from five experiments utilizing sheared and raw PC also referred to in this report as T-1 and T-2 respectively. In this table, filtration performance characteristics can also be observed. Filtration efficiency values are given by,

$$\text{Filtration efficiency (\%)} = \frac{\text{total mass of dry solids} - \text{mass of dry solids retained}}{\text{total mas of dry solids}} * 100\% \quad (16)$$

Table 8. AMD slurries summarized results

Material	Geotextile	Retained filter cake in geotextile (%)	Passing Solids (%)	Filtration Efficiency (%)	Solids Lost (%)	Moisture Content average (%)
Sheared PC	Tencate 1100N-W	96.1%	2.2	97.8	1.7	96.8
Sheared PC	Tencate 1100N-W	98.0%	0	100	2	96.7
Raw PC	Tencate 1100N-W	91.9%	6	94	2.1	94.8
Raw PC	Tencate 1100N-W	88.9%	8	92	3.1	94.8
Raw PC	Tencate 1100N-W	96.9%	0	100	3.1	94.8

7 Conclusions

This report's findings are summarized below:

A solution tool to predict filter cake formation for AMD sludge following Weggel and Ward's (2011) numerical model and Weggel and Dortch (2011) has been developed. The solution tool is only successful in predicting filter cake thickness comprising materials with high amounts of coarse particles. On the other hand, for materials with high amounts of fines such as the AMD sludges being dewatered in this report, the solution tool is not capable of predicting an accurate filter cake thickness. This limitation within the solution tool suggests that the settling velocities of the particles within slurries studies in this report are very low. Resulting in the impediment to observe filter cake accumulation. A kaolinite material's behavior under filtration testing was analyzed using the solution tool. Specifically, predicted filter cake thickness was compared with experimental data observed. While the solution tool projected a theoretical immediate increase in filter cake to its thickest, the experiment showed that it took 1160 seconds for a filter cake of 2.54 centimeters to form. Note that even though this was the first time that a filter cake reading could be observed, this does not suggest a sudden increase in the filter cake during that time. It is deduced that the filter cake continuously increased, however, a filter cake thickness was not observable prior to that time frame.

Filtration experiments were conducted for various AMD slurries. Optimum results regarding filtration efficiency by using a non-woven geotextile material produced by Tencate referred to as Mirafi 1100N. Filtration efficiencies ranged between 92% and 100%. The accumulated filter cake within these slurries rapidly formed at the start of the filtration experiment and proceeded to decrease by the apparent means of settlement.

Hydraulic conductivity behavior observed in experiments using slurries in this report suggest that at the commencement of filtration, these values are at its highest due to the absence of filter cake formation. Additionally, as the time passes by, the hydraulic conductivity decreases as the filter cake thickness increases. However, the duration in which filter cake is formed for slurries with high amounts of fines tends to be much higher. Especially in slurries without extensive pre-filtering treatments.

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