Use of Pulp and Paper Sludge to Improve Performance of Topsoil Layer in a Landfill Capping System

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Thesis Submitted in Partial Fulfillment of

the Requirements for the Degree of

Master of Science

in

Mathematical, Computer, and Physical Sciences

(Chemistry)

The University of Northern British Columbia

July 2006

Your file Votre référence
ISBN: 978-0-494-28401-8
Our file Notre référence
ISBN: 978-0-494-28401-8

APPROVAL

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Degree: Master of Science

Thesis Title: Use of Pulp And Paper Sludge To Improve Performance Of Topsoil Layer In A Landfill Capping System

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ABSTRACT

Sludge is one of the major solid waste products in the pulping process. It consists of wood fibers, fines, some inorganic fillers, and water. Prince George mills produce approximately 11,000 wet tons of sludge annually. Presently, the sludge is either landfilled or incinerated causing potential environmental problems. Pulp mill sludge may be used as soil amendment in the topsoil layer of a landfill cap to enhance plant growth and minimize the formation of cracks, hence reduce erosion and infiltration problems.

The objective of this research was to chemically and physically characterize sludge from two different pulping processes and to investigate their suitability as soil amendment in the topsoil layer of a landfill cap.

Chemical analysis of both sludge samples revealed that metal concentrations were below maximum allowable concentrations for municipal sewage biosolids. Both sludges have a high C:N ratio and a neutral to alkaline pH. The N immobilization and pH adjustment could be addressed with appropriate fertilization. The type of sludge under consideration will determine the fertilizer composition to enhance plant growth.

The high organic content and fibrous structure of the sludges decreased the bulk density of the soil and increased its water holding capacity. Water holding capacity (WHC) was determined by gravity and moisture retention curves were established for sludge and soil samples, various sludge-soil mixtures and sludge-soil layer systems. BCTMP sludge samples had a higher WHC than the soil, resulting in higher water retention and higher amount of plant available water.

Kraft mill sludge samples showed the opposite effect on WHC, water retention and plant available water. Soil amended with increasing amounts of sludge resulted in increasing water retention. Layering systems showed that the soil layers exhibited attributes of constant WHC, while the sludge layers varied depending on their position within the layer system.

These attributes of the sludge used in this research would improve the performance of the topsoil layer with less environmental impact than current disposal options. The results and conclusions are not necessarily applicable to any sludge in the pulp and paper industry.

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Acknowledgements

The author would like to sincerely thank all the people who gave her their encouragement and assistance to conduct this research. In particular, the author would like to recognize:

Dr. R. W. Thring, my supervisor, for giving me this opportunity to realize this research and support and guide me through this time.

The members of my committee: Dr. J. Arocena, Dr. M. Mandy, L. Gardner, and J. Spankie for their input and guidance.

The environmental science, chemistry and central equipment laboratories for lending me equipment and assisting me with sample analysis.

The Science Council of British Columbia and its GREAT scholarship for providing the financial support required to complete this thesis.

Michele, Eric, Alida, Dave, Svetlana, and Geoffrey for their friendship and boosting me up by telling me “that everything would work out”.

My husband for being so patient and encouraging while I completed my degree, for rescuing my data and fixing all the little computer problems.

Finally, to my high school chemistry teacher, who not only inspired my interest in chemistry but also helped me to set my career path.

I would like to dedicate this project to my friend, Sheri Merchant, whose excitement and passion for the sludge project lifted me over some course work hurdles († July 2002).

Chapter 1 Introduction

Municipal solid waste landfills are capped when they reach their disposal capacities. The primary purposes of this cap are to minimize the infiltration of precipitation and to limit the release of landfill gases. Landfill caps combine layers of clay, sand, vegetated topsoil, and, sometimes, synthetic liners. To restore the local environment, it is desirable that the top layer of the cap supports vegetation. Therefore, additional material needs to be blended with the capping material to improve vegetation growth.

The objective of this project was to chemically and physically characterize sludge from two different pulping processes and investigate their suitability for use as landfill capping material. Presently, the vast majority of sludge is either landfilled or incinerated. Due to high waste-related disposal costs, increased difficulty and expense of permitting new landfills, and the growing environmental concerns, the pulp and paper industry is searching for technologies that are capable of reusing or recycling this sludge, one of the most difficult wastes to handle or deal with.

1.1 *Landfill capping*

The safe and reliable disposal of municipal and industrial solid waste is an important component of integrated waste management. Landfill is the term used to describe the physical facilities used for the disposal of solid wastes in the surface soils of the earth. Landfill refers to an engineered facility for disposal of municipal solid waste (MSW) designed and operated to minimize public and environmental impacts. Since the turn of the century, the use of landfills, in one form or another, has been the most economical and environmentally acceptable method for disposal of solid wastes throughout the world. Although many landfills have been constructed in the past with little or no thought for the long-term protection of public health and the environment, in the last 20 years, practices have changed substantially (Kreith, 1994).

Municipal solid waste landfills are capped with a final cover when they reach capacity. The landfill final cover system is designed to control fire, water infiltration, gas, dust, blowing litter, and erosion, and to enhance site appearance. One main function of the final cover system is to minimize infiltration of rainwater into the underlying waste and therefore reduce the amount of leachate generated in the landfill. Most covers incorporate a layered arrangement to minimize the quantity of water entering the landfill. The configuration of the final cover system depends on the site, waste characteristics, regulatory requirements, and future use of the site (GeoSyntec Consultants, 1995).

When water percolates through solid wastes that are undergoing decomposition, both biological materials and chemical constituents are leached into solution (Tchobanoglous et al., 1993). As leachate percolates through the underlying strata, many of the chemical and biological constituents originally contained in it will be removed by the filtering and adsorptive action of the material composing the strata. In general, the extent of this action depends on the characteristics of the soil, especially the clay content. Because of the potential risk involved in allowing leachate to percolate to the groundwater, best practice calls for its elimination or containment (Tchobanoglous et al., 1993).

The purpose in the design of a final landfill cover system is to minimize the infiltration of leachate into the subsurface soils below the landfill thus reducing the potential for groundwater contamination. A number of cover system designs have been developed to minimize the movement of leachate into the subsurface below the landfill. In general, the final cover system is a combination of different layer types: surface layer, protection layer, drainage layer, barrier layer, gas collection layer, and foundation layer.

Each of the layers has one or more functions and the material typically used to construct them are listed in table 1.

Table 1: Typical materials that comprise a final landfill cover system (GeoSyntec Consultants, 1995)

Component	Typical materials	Purpose	Thickness
Surface layer	topsoil; cobbles, paving material	support vegetation growth, promote rainwater run-off	min. 6"
Protection layer	soil; cobbles	promote rainwater run-off, prevent penetration by roots	min. 24"
Drainage layer	sand, gravel; geonet, geotextile	limit buildup of hydraulic head on top of barrier layer, reduce infiltration	40 – 60 mil
Barrier layer	clay, geomembrane	minimize leachate generation	min. 18"
Gas collection layer	sand, gravel, geotextile, geonet	collect and transmit generated landfill gas	min. 12"
Foundation layer	soil, selected waste	provide subgrade for overlying layers of final cover	min. 12"

To meet the above mentioned purposes, the final landfill cover system must:

a) be able to withstand climatic extremes (e.g., hot/cold, wet/dry, and freeze/thaw cycles),

b) be able to resist water and wind erosion,

c) have stability against slumping, cracking and slope failure, and downslope slippage or creep,

d) resist the effects of differential landfill settlements caused by the release of landfill gas and the compression of the waste and the foundation soil,

e) resist failure due to surcharge loads resulting from the stockpiling of cover material and the travel of collection vehicles across completed portions of the landfill,

f) resist deformation caused by earthquakes,

g) withstand alterations to cover materials caused by constituents in the landfill gas,

h) resist the disruptions caused by plants, burrowing animals, worms, and insects (Kreith, 1994).

A 1988 study by the U.S. Environmental Protection Agency (EPA) of randomly selected landfills revealed that the vast majority of final landfill cover systems are leaking, and many have caused severe contamination of the groundwater and surrounding ecosystems (Dwyer, 1998). Examining the factors that affect cap performance, it is apparent that hydrologic and erosional processes account for most of the performance-related problems (Duguid, 1977; Jacobs et al., 1980; Hakonson et al., 1982). For example, erosion associated with runoff can breach the cap and expose waste to the biosphere (Nyhan and Lane, 1982; Nyhan et al., 1984). The drastic outcomes motivated a new research area in waste management.

The instability of existing cover systems and increasing costs for recommended cover materials required by regulatory authorities suggest a broad variety of research projects on suitable alternative cover materials.

The British Columbia Landfill Criteria (MoELP, 1993) set minimum standards for landfill covers, specifying permeability and construction materials. The cover must be configured such that it can be maintained efficiently and be amenable to relatively easy repair. Components of this conventional closure system may be modified if the proposed alternative performs to an equivalent standard.

The final vegetative cover is the only mechanism that almost completely controls infiltration independent of site location. The majority of precipitation is unable to infiltrate the landfill because of surface slopes and runoff control. Slope and permeability are two parameters that are largely variable and controllable by various engineering methods. These parameters determine the quantity of water that affect the landfill, a large portion of which is captured by a surface collection system and is diverted away from the landfill. If a dense vegetative cover is present on the landfill, the evapotranspiration of these plants can be considerable. Depending on the local climate and annual precipitation, up to 60% of the water may evaporate and, depending on the slope grades, another 5 to 20% can be diverted on the surface (Bilitewski et al., 1994).

The function of the surface layer is to cover and protect the barrier layer from water and wind erosion, desiccation, freeze-thaw, and penetration by equipment or burrowing animals, and to support the growth of vegetation. Soils capable of supporting vegetation growth are used in the surface layer. Other materials may also be used in the surface layer such as cobbles and paving materials, although these applications are rare (GeoSyntec Consultants, 1995).

The surface layer of the final cover system will be exposed to environmental conditions over the design life of the landfill. During this time period, erosion and sediment control measurements are implemented to minimize soil loss due to rain, runoff, and wind, prevent the development of rills or gullies, protect the underlying layers of the cover system including the barrier layer, and minimize sediment impact to the surrounding environment (GeoSyntec Consultants, 1995).

According to the universal soil loss equation (Hillel, 1998), soil loss is related to rainfall intensity, soil type, length and inclination of slope, vegetation, and land management practices. To reduce soil loss, certain criteria for construction material, construction of the surface, plant selection, and maintenance of the surface layer have to be implemented. Soils or other materials used in the surface layer are selected to be of appropriate texture, organic content, salt content, acidity, and nutrient content for plant growth depending on the plant species and climatic conditions at the site.

The failures of existing cover systems (from 163 landfills, 146 have groundwater contamination, EPA 1988) and results of several research projects support the need for finding an adequate capping system with regards to ecological and economical aspects based on site specific parameters (e.g. climate, geology, hydrogeology, leachate and landfill gas management, end use) (Dwyer, 1998; Siuru, 1996; Hakonson, 1997). EPA recommends a soil tolerance level of 4.4 tons ha^{-1} yr^{-1} to prevent deflation of the cover surface over the lifetime of the site. Cover design features that are used to prevent erosion include the establishment of vegetation, the use of mulching techniques, synthetic mats, controlling slope and slope length, and the construction of terraces or benches (Hakonson, 1997).

Depending on the capping system, costs range from \$400,000 to \$500,000 per hectare (Dwyer, 1997). Hence, the landfill is operated on a 'user pay' basis; wherein tipping fees are set to recover these future costs. Late implementation of these costs would end in a drastic increase of the tipping fees.

1.2 *Pulp and paper sludge*

Pulp mill sludge, hereafter referred to as sludge, is a by-product of the pulp and paper industry. The pulp and paper industry in the United States generates 5.3 million metric tons of sludge annually (dry weight) (National Council for Air and Stream Improvement (NCASI), 2000). Quebec and Ontario mills produce an estimated 720,000 metric tons per year (Chong et al., 1988), while a Kraft mill in Prince George produces approximately 10,950 wet tons of sludge per year (Sigfusson, 1999). Presently, the sludge is treated as an industrial waste and either landfilled or incinerated. Sludge disposal poses significant environmental liabilities, logistical problems, and economic burdens. Paper mills spend between \$50 and \$100 per ton to dispose of the sludge at a typical landfill. Pressured by high waste-related disposal costs, increased difficulty and expense of permitting new landfills, accompanied by growing environmental concerns, the pulp and paper industry is searching for beneficial alternatives to dispose of sludge.

Paper making is a three step process. First, the source of cellulose fiber has to be identified. The source can be wood, recovered paper or non-woody plants. In the second step, usable cellulose fibers are produced (pulping). In the final step, paper is made after formatting sheets of pulp, pressing and drying. The main processes used in the pulp and paper industry to make pulp are mechanical pulping, semi-mechanical pulping, and chemical pulping.

Mechanical (groundwood or refiner) pulping uses physical forces to separate wood fibers, resulting in a high yield pulp that is characterized by shorter fibers and relatively low strength (Mabee, 2001). However, it is a lower cost method compared to producing pulps for other useful applications than from chemical pulping. Also, compared to chemical pulping which only produces about 50% yield of pulp from the starting wood feedstock, mechanical pulping operations typically attain about 100% yields. Groundwood pulps are made by forcing a log against the face of a cylindrical abrasive stone which rotates at high speed. Refiner pulps are made by passing wood chips in water through a set of disc refiners (one or both rotating at high speed) (Walker, 1993).

Semi-mechanical pulping techniques include the addition of heat and/or chemicals. Thermomechanical pulps (TMP), chemi-thermomechanical pulps (CTMP), and bleached chemi-thermomechanical pulps (BCTMP) can be produced after the initial mechanical process. Mechanical and semi-mechanical pulps account for only 15% of North America's total pulp output (Mabee, 2001). The current trend in the industry has been an increase in semi-mechanical and less investment in purely mechanical pulping.

Chemical pulping also includes CTMP and BCTMP, as well as alkaline pulping, and sulphite pulping. Alkaline or acidic chemicals are used to dissolve lignin and release individual fibers. This method of pulping can work in both high and low pH ranges, has an increased chemical to wood ratio, uses more severe cooking, and the pulp is readily bleached (Roberts, 1996). The CTMP process produces pulps with short average fiber length, resulting in low paper strength (Mabee, 2001). A CTMP mill generally uses less power than the BCTMP process and has pulp yields of 85-90% (MacDonald et al., 1969). Alkaline pulping, also known as Kraft or sulphate process, is the most common method used in the pulp and paper industry, and is responsible for approximately 80% of North American pulp production (Mabee, 2001). Kraft pulping produces pulp in good yields and is consistent with the highest pulp quality and strength (Biermann, 1993).

Paper is generally made out of a blend of hardwood and softwood to meet the strength and printing surface demands of the customer. Wood is mostly composed of cellulose, hemicellulose, lignin, and extractives. Cellulose is a highly suitable raw material with wide applications and shows small morphological differences among species of trees (Schuerch, 1989). It consists of long, straight chains of glucose monomers. It forms the skeleton of the plant cell wall and has the most desired properties for making paper. These fibers are long, strong and translucent (Blum, 1996).

Hemicelluloses are short, branched polysaccharides from a variety of sugars. This results in a polymer with a lower molecular weight than cellulose. Hemicelluloses fill in space in the plant cell wall and make up 20% of the total wood mass, although this fraction can change between soft and hardwood species. They are more soluble in water and thus are often removed during the pulping process.

Lignin is the most complicated wood macro polymer. Unlike cellulose and hemicellulose, lignin is not fibrous, and is composed mostly of aromatics (Glasser et al., 1996). It is an amalgamation of two (or three) principal phenylpropane groups and their derivatives, which combine in countless numbers of ways to produce a very large, amorphous molecule. This three dimensional cross-linked polymer of heterogeneous structure generally acts as an interfiber bonding agent, imparting strength and cohesiveness to the physical structure of the tree (Zakis, 1994). The presence of lignin is considered undesirable by the pulp and paper industry, as it hampers the production of quality paper and imparts color to the nearly white tone of cellulosic matter. Lignin usually makes up 20% of the total wood mass (Mabee, 2001).

Extractives is a collective term referring to extractable components and trace elements found in wood. Some of these substances include fatty acids, resins, tannins, sugars, resenes, turpenes (appendix A), gums, and waxes (Roberts, 1996). These components serve no structural function, and normally form the smallest portion of the total wood mass at approximately 3-8% (Mabee, 2001).

Pulp mill sludge represents the waste portion of the pulping process. It contains knotted and separated wood fibers, dirt, and any other materials introduced through the pulping or recycling process. The principle component of sludge is water, which makes up more than half of the total mass of sludge even after dewatering (Mabee, 2001). Sludge is mainly composed of unused cellulose and is produced in various stages of the pulping process (Figure 1). As the wood input, the wood processing and the subsequent effluent treatment varies greatly, so does the composition of the sludge. The physical and chemical characteristics of the sludge of a single mill changes over time, and the sludges from different mills using similar processes will exhibit different properties. A better understanding of the characteristics of sludge is needed to come up with more effective and economically viable means of disposal and/or recycling.

As governmental regulations require that at least 10% of manufactured paper must be recycled, more and more paper mills are using recycled paper in the manufacture of paper. Production of paper from recycled materials increases the amount of sludge produced at paper mills (Coburn and Dolan, 1995). Because of recycling, more unusable, short, odd-shaped fibers (cellulose) are generated from post-consumer fibers than from virgin pulp.

Sludge or wastewater treatment plant solid residuals are those solid materials, collected in the process of treating water used in the mill prior to release into the environment. Typically, these materials consist of solids collected in primary treatment (separation of solids from raw wastewater) and secondary treatment (biological treatment followed by clarification to separate biosolids) (NCASI, 2000). Primary sludge is produced through the physical cleaning of the wastewater stream. It is collected in screens and filters and is fairly clean, consisting of wood fibers, fines, some inorganic fillers, and water (Mabee, 2001). Primary sludge is usually easy to dewater because of the relatively high fiber to fines ratio of the organics and because of the high proportion of woody-organic material in the sludge (Kennedy et al., 1989). The moisture content varies from 30 to 70% depending on the drying process employed. As there is ten times more primary then secondary residual they are combined to facilitate handling.

Primary sludge is derived from primary clarification treatment and is comprised predominantly of wood fibers. Because of the high wood fiber content, primary sludge has low nitrogen (N) concentration, ranging from 0.05 to 0.9%, with C:N ratios often ranging from 100:1 to 300:1. Secondary sludge is derived from biological treatment of effluent during which N and P are commonly added. This sludge consist largely of microbial biomass and has higher concentrations of N and P and lower C:N ratios ranging from 5:1 to 20:1. Both primary and secondary sludge can provide significant sources of other macro- and micronutrients, although concentrations of these constituents vary widely (NCASI, 2000). The vast majority of sludge is combined primary and secondary sludge representing 54% of the total residual production (NCASI, 1999b). A simplified layout of sludge generation paths is shown in Figure 1.

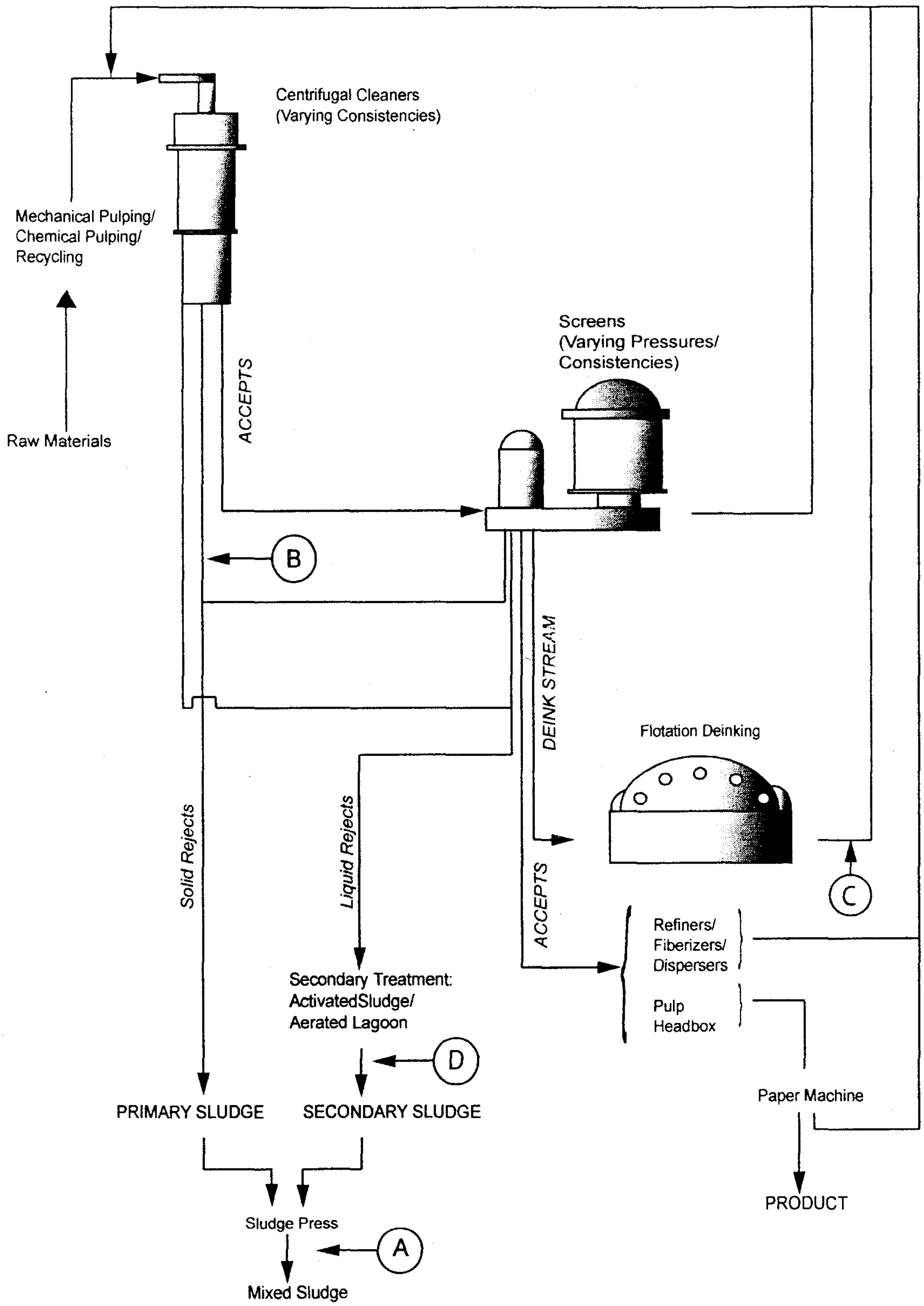


Figure 1: Simplified layout of sludge generation paths after Mabee, 2001
A to D : Recovered sludge sources

The sludge is also generally low in potential environmental contaminants. In recent years the reduction of metal concentrations in ink, analysis of raw materials and processing chemicals led to lower metal concentrations in the sludge. Nevertheless, chemical characterization is important as the metal concentrations in sludge wood fibers are largely derived from the manufacturing process.

1.3 *Environmental considerations*

The high organic matter content of sludge represents a valuable resource as soil amendment (Bellamy et al., 1995; Bowen et al., 1996; Edwards, 1997; Carpenter and Fernandez, 2000) when soils are depleted or subject to erosion. Sludge is also rich in macro- and micronutrients. The organic matter and nutrients are the two main elements that make the use of this kind of waste on agricultural land as fertilizer and organic soil amendment suitable.

Although attractive for use as soil amendment, there can be potentially harmful effects from the sludge depending on its constituents. The most significant environmental concerns associated with the land application of sludge are the potential for constituent movement – either down and out of the soil profile potentially entering surface or groundwater, or the assimilation into plants and associated food chain effects. This is largely dependent on the volume of material applied, concentrations of trace elements, mobility and toxicity of elements from the materials, and incorporation of the elements into living organisms (Barker et al., 2000; Mullen, 2002). Sludge properties such as percent organic matter, pH, cation exchange capacity, texture, and timelines for microbial modification are expected to influence short and long term metal and nutrient mobility. In terms of soil quality, the British Columbian Landscape Association (BCLA, 2001) has set quality criteria for boron (B), total nitrogen (N), phosphorus (P), potassium

(K), calcium (Ca), and magnesium (Mg) besides C:N ratio, organic matter concentration and pH. These standards are listed in Table 2.

Table 2: Quality standards for productive soils (BCLNA, 2001).

Constituent	Units	Range
C:N	ratio	< 40
Organic matter	%	3-5
Acidity	pH	6-7
Boron	ppm	< 1
Total N	%	0.2-0.6
Phosphorus	ppm	20-100
Potassium	ppm	50-250
Calcium	ppm	1500-2000
Magnesium	ppm	175-250

Nitrogen (N) content often limits the effectiveness of sludge as a soil amendment (Edwards, 1997; O'Brien, 2001). Only secondary sludge contains significant quantities of N. Because of their low N concentrations and high C:N ratios, primary sludge can induce N deficiencies in vegetation when land applied. As with most organic material, soil microorganisms utilize both C and N during decomposition of sludge applied to soil. Since the C:N ratio of the sludge is much higher than that of microbial cells (roughly 7:1), soil microorganisms must utilize inorganic N (i.e., NH_4^+ and NO_3^-) from the surrounding soil matrix during sludge decomposition. The immobilized N is not lost from the system, but is synthesized into organic forms that are unavailable for plant uptake until the microbes die and decompose themselves. This process can reduce N leaching when high N sludges are applied, but is also the cause of potential N deficiencies in vegetation when low N sludges are used. Depending on the N concentration in the surrounding soil, primary sludge may have to be applied in limited quantities or external sources of N added to prevent such deficiencies in the soil sludge system.

As secondary sludge contains mainly microbial biomass and nutrients (primarily N and P) the properties of the combined sludges depend on the proportion of primary and secondary sludge in the mix, and the type of products being produced by the mill. Secondary sludge can thus provide a valuable source of N for vegetation, but there is also more potential for N leaching and runoff if high application rates are used (NCASI, 2000).

Organic matter, such as sludge, has a direct effect on water retention because of its hydrophilic nature, and an indirect effect because of the modification of the soil structure that may be affected due to the presence of the organic matter. Porous media like soil consist of solid material and void or pore space. Air and water and possibly non-aqueous phase liquids occupy the pore space. The spatial arrangement of the soil particles relate to both the size and shape of the components and their arrangement in aggregates. There are two broad categories of aggregates. Microaggregates are less than 250 μm in diameter and macroaggregates more than 250 μm. Pore diameters in microaggregates mainly range from 0.2 to 6 μm; in macroaggregates from 25 to 100 μm. Pore size determines the hierarchy at which pores remain water-filled at differing soil water potentials (Paul et al. 1996).

The relation between the soil water content and the soil water suction (matric potential) is a fundamental part of the characterization of the hydraulic properties of a soil. The water retention function relates a capacity factor, the water content, to an intensity factor, the energy state of the soil water. The term soil water is used for the solution or liquid phase of the soil (Klute, 1986). A soil is composed of 25% water, 25% air, 47% minerals and 3% organics (Klocke et al., 1996). The amount of water in the soil influences many processes, including gas exchange with the atmosphere, diffusion of nutrients to plant roots, soil temperature, and the speed with which solutes move through the root zone during irrigation or rainfall. The force with which water is retained by the soil matrix also affects the amount of drainage occurring under gravity, and the extent of upward movement of water and solutes against gravity (Gardner et al., 1991). The soil water characteristic curve (also called moisture characteristic, matric potential, or water retention curve) shows the relationship between water content and soil suction in the vadose zone (Burckhard et al., 2000). The terms matric potential, matric suction, and soil water suction are used interchangeably. Soil suction is defined as the negative gauge pressure, relative to the external gas pressure on soil water. It describes the soil's ability to store and release water. If the soil water retention curve is known then it is possible to estimate the amount of water available to plant roots. The upper soil moisture limit for plant available water is considered to be at field capacity. The micropores are still filled with water and can supply plants with needed water. The matric potential will vary from soil to soil but is generally in the range of -10 to -30 kPa (Brady et al., 1999). The lower soil moisture limit for plant available water is the permanent wilting point (PWP). There is only some water remaining in the smallest of the micropores as a thin film. By convention the permanent wilting point is the amount of water retained by the soil when the water potential is -1500 kPa. Moisture retention curves of soil samples are determined in the laboratory by using a pressure plate apparatus. This equipment allows the application of successive suction values and repeated measurement of the equilibrium soil wetness at each suction.

Sludge as an organic amendment affects soil structure by increasing soil aggregation and stability. In well-aggregated soil, the interaggregate macropores drain very quickly, while the intra-aggregate micropores tend to retain their moisture against gravity. On the other hand, a dispersed or compacted soil has few macroaggregates and drains very slowly. Air entry and oxygen diffusion are thereby affected. Depending on the amount of organic matter present, soil organic matter can contribute to the retention of soil moisture. The moisture retention or water holding capacity represents the temporary internal drainage or redistribution of water in the soil, responsible for maintaining an amount of moisture for plants to survive during periods between rains or irrigations.

Organic matter increases soil aggregation and stability, reduces bulk density, and increases water-holding capacity and retention (Khaleel et al., 1981; Metzger and Yaron, 1987; Tester, 1990; Hill and James, 1995). The increased soil aggregation is also due to increased microbial activity, which increases soil porosity (Hill and James, 1995). Over time microorganisms incorporate carbon into soil organic matter (Camberato et al., 1997). As sludge decomposes, carbon is lost to the atmosphere as carbon dioxide, which gradually decreases the C:N ratio and increases the availability of nitrogen for plant growth.

The concentration of organic matter in soil is mainly responsible for water and ion retention and supplying both to plants. High and low concentrations of organic matter limit soil productivity.

Metal and nutrient availability in part depend on the soil acidity. Soil acidity is affected by low pH as well as the effects the pH has on metal and micronutrient availability. The U.S. EPA has established metal loading limits for land-applied municipal sewage sludge, which generally have high metal concentrations compared to paper mill sludge (Table 3). In British Columbia the metal contents in soils used for specific sites such as agricultural, urban park, residential, commercial and industrial lands are regulated under the Contaminated Sites Regulation.

Table 3: Comparison of macro- and micronutrient concentrations in pulp and paper sludge [a] and municipal sewage biosolids [d] (NASCI, 2000).

	NCASI 54 Mill Survey [b,c]		Municipal sewage biosolids[d]	
	range	median	range	median
Macronutrients (g/kg)				
N	0.51 - 87.5	8.98	<1.0 - 210	32.0
P	0.01 - 25.4	2.35	<1.0 - 150	14.0
K	0.12 - 10	2.2	0.2 - 650	2.3
Ca	0.28 - 210	14	1.0 - 250	27.0
Mg	0.2 - 19.0	1.55	0.3 - 25.0	4.0
S	0.2 - 20.0	4.68	6.0 - 15	11.0
Micronutrients/Metals (mg/kg)				
Ag	<0.1 - <11	0.55	NA	NA
Al	590 - 59000	13400	1000 - 13500	4000.0
As	<0.07 - 8.3	1.2	0.3 - 315.6	6
B	<1 - 491	25.0	4 - 1000	33
Ba	17.9 - 1800	160.0	<0.01 - 9000	200
Cd	<0.09 - 56	1.2	0.7 - 8220	7
Cl	<0.06 - 8500	383	NA	NA
Co	0 - 9.7	NA	1 - 260	10
Cr	3.0 - 2250	42.0	2.0 - 3750	40
Cu	3.9 - 1590	52.0	6.8 - 3120	463
Fe	97.1 - 10800	1540	1000 - 15400	1700
Hg	0.0009 - 3.52	0.35	0.2 - 47.0	4
Mn	13 - 2200	155.0	32 - 9870	260
Mo	<2.5 - 14.0	NA	2.0 - 67.9	11
Na	300 - 66700	2200	100 - 30700	2400
Ni	1.3 - 133	18.3	2.0 - 976	29
Pb	<0.05 - 880	28	9.4 - 1670	106
Se	<0.01 - <31	0.21	0.5 - 70.0	5
Sn	<70.6	NA	40 - 700	150
Ti	3100 - 76000	NA	NA	NA
Zn	13 - 3780	188.0	38 - 68000	725

[a] Concentrations of some metals in sludge have declined in recent years due to reductions in metal concentrations in inks and more careful scrutiny of raw materials and processing chemicals. For this reason, metal concentrations in samples collected prior to 1990, particularly maximum values, may be higher than those in present day sludges and should be interpret with a high degree of caution.

[b] An assortment of primary, secondary & combined sludge.

[c] NCASI 1984 NA = not available [d] McGovern et al. 1983

The total trace element content of a soil may not relate to the plant growth; as only a portion of the total metal is available to the plant through absorption from the soil solution (Pais and Jones, 1997). As different plant species have different elemental needs, this would be another consideration in the suitability of using sludge. Table 4 lists typical ranges of the plant macro- and micronutrients required for plant growth and their primary function in plants.

Table 4: Plant macro- and micronutrients and their functions (Whitehead, 2000).

Constituent	Typical Range	Primary Function
Macronutrients		
N	2.0-3.5%	required for protein synthesis
P	0.2-0.5%	transfer of energy through ADP to ATP for energy storage
S	0.15-0.60%	form amino acids which are incorporated into proteins
Ca	0.6-0.8%	cell wall stabilization and osmotic regulation
Mg	0.25-0.30%	photosynthesis and protein synthesis
K	1.0-3.5%	open/close stomata and transport photosynthate
Micronutrients		
B	8-15 ppm	cell wall synthesis and membrane function
Cu	10-15 ppm	photosynthesis and nitrogen fixation
Fe	150-175 ppm	Constituent of proteins involved in redox reactions
Mn	70-100 ppm	electron transfer and detoxification of free radicals
Mo	0.1-4.0 ppm	N metabolism (conversion of ammonium to nitrate)
Zn	35-40 ppm	enzyme catalyst

Since the late 1980s, dioxins have been an environmental concern with sludge derived from chlorine-based bleaching processes. Over the last decade; however, new technologies have reduced dioxin concentrations in bleaching mill effluents and residuals (sludge) (NCASI, 2000). Although concentrations of metals and potential organic contaminants in sludge are generally low, elevated concentrations can occur in some situations and should be determined prior to establishing a recycling path.

1.4 *Project objectives*

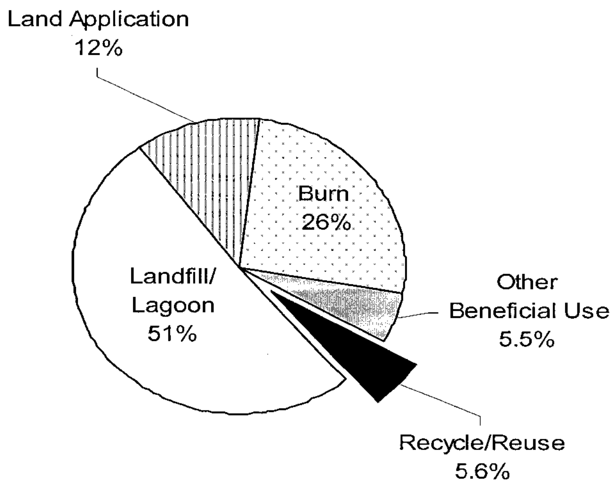
The focus of this research was to evaluate the moisture retention properties of sludge amended soil in a laboratory set up in order to determine the usefulness of sludge as landfill cover. The moisture retention influences the available amount of water for plants. Organic matter increases water holding capacity. As the water holding capacity affects the water uptake by plants, it is important for the final layer of a landfill capping system. The final layer is also exposed to water related damage resulting in soil loss and further infiltration. Sludge amendment could result in higher absorption of water, thus reducing infiltration to the barrier layer.

Chapter 2 Literature Review

Currently, 67% of sludge produced in North America is landfilled or incinerated, neither of which utilizes the potentially valuable properties of this paper mill by-product (Carpenter and Fernandez, 2000). Only 13% of the sludge is reused or recycled. The pulp and paper industry has sought alternatives to sludge disposal since the early 80's. At the same time, individual pulp companies privately owned over 50% of landfills used in the pulp and paper industry. This figure is declining, due to increasingly stringent requirements for siting and construction (Glowacki, 1994).

2.1 Sludge disposal alternatives

Since sludge is mainly composed of organic fibers other disposal options are incineration, land application, and recycling/reusing the fiber-rich material. The sludge disposal practices are shown in Figure 2. Figure 2 summarizes a survey conducted by NCASI representing 98% of the sludge generated by 204 mills in the U.S. in 1995.



3.9 Million Tons – Total Sludge Production

Figure 2: Final sludge disposal practices (NCASI, 1999).

In 1995, according to NCASI, the pulp and paper industry produced a total of 3.9 million dry tons of sludge. Of this, 51% were landfilled, 26% incinerated, and 23% were beneficially used. These numbers are slightly different from Carpenter and Fernandez (2000) publication as they come from different sources and years.

Incineration of sludge serves the purpose of disposing the material to recover energy for the paper making process. Unfortunately, the high moisture and ash content of sludge make total combustion difficult. Modification of traditional incinerator technology and mixing sludge with high amounts of bark is necessary in order to totally incinerate the organic material. Before combustion, the moisture content of the material needs to be reduced. A great deal of heat is necessary to burn sludge when it has high moisture content (Mabee, 2001). Other, but less economical alternatives to incineration include ethanol production by indirect combustion and pelletizing sludge as an alternative fuel source.

Recycling options are based on the chemical or physical characteristics of the sludge. Because sludge is a significant source of organic matter and nutrients, early research focused on land application for enhancing growth of trees and crops. Land application of sludge is the most popular disposal alternative for the pulp and paper industry in countries such as the United States, Sweden, Finland, India, Brazil and Canada (Alberta, British Columbia, Ontario, Quebec). The main problem identified in the earliest trials was the low fertilization value associated with the sludge (NCASI, 1984a). This problem was addressed by numerous pilot projects using discrete materials mixed with sludge to be of beneficial use as soil amendment.

Another option to increase the fertilization value was composting mixed sludges, most utilizing the aerated static pile method (Biofine Inc., 1998). Composting lowers the

C content, which combined with high N feedstock decreases the C:N ratio. Several composting facilities include wood ash in their feedstock mixture to decrease the moisture content and increase the mineral content of the mix (Kunzler, 2001). However, composting can be quite expensive (upwards of $30/ton) and thus economic success is dependent upon market conditions (Pickell and Wunderlich, 1995).

Further recycling technologies are based on the physical characteristics of sludge. The fibrous material can be used in the manufacture of ceramic and building materials, such as cement, bricks and concrete. If sludge is used as filler or aggregate in cement or concrete, the tensile strength increases. Sludge-amended material will not crack as easily under freezing and thawing conditions. It could be used to construct highways, buildings and bridges, providing a longer lifespan (Canning, 1999). Sludge has been used beneficially as absorbent materials for industrial cleanups, hydromulch, and animal beddings.

Land-applied sludge is a source of organic matter affecting physical properties of the soil like aggregation, stability, bulk density, water holding capacity, and water retention. Organic matter plays a fundamental role in the stabilization of soil and the formation of pores (Khaleel et al. 1981; Metzger and Yaron, 1987; Tester, 1990; Hill and James, 1995). These attributes are of importance in land reclamation and construction projects.

Sludge has been used beneficially in several land reclamation projects in the UK and U.S. Recovery of unusable land is enhanced by sludge application to areas where plant growth is non-existent or limited, often due to previous industrial activities that have introduced or brought to the surface substances which are unfavorable to plant growth. In the UK and U.S., sludge has been applied to spoil mounds from abandoned coalmines. Such locations tend to generate acidic run-off (as low as pH 3-4 in some cases) due to oxidation of pyrites in the colliery spoil (Webb, 2000). That means that the absorptive activity and the buffering capacity of any calcium carbonate in the sludge is particularly valuable. Sludge also has a much higher affinity to adsorb heavy metals than typical kaolinite clay because of its high organic content. This characteristic is used in another research project in the U.S. where sludge was utilized to build a slurry wall around an old processing plant where zinc and lead contamination endangered groundwater (Canning, 1999; Brown et al., 2003).

The clay like behavior of sludge is also of interest for landfill capping. The NCASI has investigated the use of sludge as cover material on a daily, intermediate, and final cover of varying thickness on industrial, municipal, and industrial/municipal waste landfills. The most important physical property affecting the suitability of sludge as material for the barrier layer is hydraulic conductivity. It describes the ratio of the flux to the potential gradient of water (volume per time) (Hillel, 1998). Field hydraulic conductivity studies were conducted at barrier layer test plots over eight years. At the effective stress of approximately 5 kPa existing during the service life of the test plots, sludge had a hydraulic conductivity of 4×10^{-8} cm/sec. The clay test plots had a hydraulic conductivity of 1×10^{-6} cm/sec. The test results also showed that the barrier layers made with paper mill sludge underwent no deterioration in performance during their service life. After the eight year study sludge in the test plots appeared identical to fresh sludge, which also suggests that the sludge had not degraded. In addition to the hydraulic conductivity measurements, a dye tracer study was conducted. The study showed that only one preferential flow pattern existed in the sludge barriers, and this flow path appeared to be in a construction defect. In contrast, the clay barrier layers were riddled with preferential flow paths, and thus had much higher hydraulic conductivity than the paper mill sludge (NASCI, 1997). Some of the earth normally used to cap the daily inputs can be replaced by sludge. The observation that sludge has properties similar to some clay soils has created particular interest in using sludge as landfill liner material and as the hydraulic barrier layer in landfill covers. Results from previous studies are summarized in Table 5.

Table 5: Residuals index properties and hydraulic conductivity of sludge used as barrier layer from previous studies (NCASI, 2002).

Source	Water Content[1] (%)	Ash Content (%)	Organic Content	Solids Content (%)	Specific Gravity	Hydraulic Conductivity[3] (cm/s)	Residuals Type
Andersland and Laza (1972)	-	49-84	28-50	-	2.2-2.36	8.1×10^{-5} – 8.1×10^{-6}	Sorted Organic Residual
Kraus et al. (1997)	150-260	44-56	-	-	-	1.4×10^{-3} - 2.8×10^{-8}	Primary and combined
Zimmie and Moo Young (1993-1997)	150-268	-	35-60	29-40	1.8-2.0	7.4×10^{-7} – 1.1×10^{-8}	Primary and combined
NCASI (1989)	121-409	10-62	-	20-45	1.6-2.4	4.2×10^{-4} – 5.8×10^{-8}	Primary and combined
Benson and Wang (1996)	-	-	-	-	-	8.3×10^{-7} – 9.9×10^{-9}	Primary and combined[2]

[1]water content = (wet mass-dry mass)/dry mass
[2]tests conducted at effective stresses ranging from 5 kPa to 60 kPa
[3]sludge compacted similar to compacted clay

2.2 *Case studies of various applications*

Sludge from paper manufacturing has been applied to agricultural and forestry land to increase net primary productivity for decades. Numerous studies throughout North America and Europe have highlighted the benefits associated with utilization of sludge as soil amendment.

Intensive agriculture and nursery culture in the Niagara area of Ontario have resulted in a high demand for organic soil amendments. Besides manures and peat moss, organic-rich paper sludge and sludge-based composts could serve as substitute soil amendments. In several studies, crop yield was investigated in relation to sludge application (Bellamy et al., 1995). Tomatoes, cucumbers, and peppers were grown with separate and mixed primary, secondary and deinking sludge components. All growth responses were related to N content in the sludges. Inhibited growth was observed with primary and deinking sludge, which are low in N content. Secondary sludge, which is rich in N, produced excessive growth. A blend of primary and secondary sludge enriched with N fertilizer had a beneficial effect on vegetable growth in the greenhouse. In a second greenhouse experiment with shrubs and an additional field experiment with corn the growth of the species was correlated to the percent of N in the sludge soil mixture. In conclusion, sludge utilization is constrained by N immobilization in sludge-treated growing media or field soils, resulting in N deficiencies in plants. This could be overcome by adding appropriate quantities of N fertilizer (Bellamy et al., 1995).

In Spain, three organic residues (olive mill sludge, municipal solid waste compost, paper mill sludge) were used in a 3-year field experiment involving orange production (Madejón et al., 2003). The application of compost and paper mill sludge increased orange yield. Moreover, total carbon and humic substances significantly increased in soils treated with all the organic amendments. Positive correlations between enzymatic activities and total organic carbon were found for all treatments. However, a clear inhibition of phosphatase activity was observed in soils treated with sludge. This result indicates that repeated application of moderate amounts of organic amendments has positive effects on the chemical and biochemical properties of the soil, as well as on the orange yield (Madejón et al., 2003; Gagnon et al., 2001). Sludge amendment promotes microbial growth and activity in the soil by improving carbon and water availability. A measurable indicator for bacterial growth is the enzyme phosphatase, which accelerates the hydrolysis and synthesis of organic esters of phosphoric acid and the transfer of phosphate groups to other compounds. Phosphatase activates the mineralization of organic phosphorous, releasing phosphate, which would otherwise not be available.

In Atlantic Canada, the amendment of sludge to organic-matter-depleted potato-producing soils was investigated. One year after incorporating sludge at rates equivalent to 0.5, 1.0, 2.0, and 4% organic matter in the plow layer of a gravelly loam soil, bulk density had decreased with increasing rates of organic matter addition, while saturated hydraulic conductivity and specific moisture content increased. The beneficial effects of the organic matter treatment include 2.1 times delay in runoff initiation, and 23 and 71% reduction in runoff and soil loss. Although the beneficial effects in soil and water conservation are apparent, a minor drawback appears to be lower field soil moisture content, which could be controlled by sludge application rates (Chow et al., 2003).

Forest land application is a particularly attractive use for this material because many companies own forest lands that are in close proximity to mill sites where the sludge is generated and would be consistent with the concepts of sustainable forestry (NCASI, 2000). In one study, growth and yield of lodgepole pine and white spruce grown on sludge-treated soil were measured. Primary and secondary sludge mixed in the ratio of 1:2 was applied to marginal forestland at a rate of 80 t/ha per year. The resulting seedling growth showed significant increases of up to 250% in both height and diameter compared to control sites (Macyk, 1999; Mabee, 2001).

Effects of land-applied sludges on forest productivity have been shown to depend to a great extent on their N content and availability. A study on productivity of cottonwood, Douglas fir, Noble fir, and white pine seedlings grown in nursery beds showed direct dependency on the C:N ratio (Henry, 1986). Growth responses to sludge were positive with C:N ratios up to 20:1. Positive tree growth responses have been reported for sludges having C:N ratios of 100:1 to 150:1 (Henry, 1991).

While the contribution of organic matter from sludge is often confounded by effects on N availability, the importance of sludge as a source of organic matter has been demonstrated on some sites. One study showed that land application of primary sludge (C:N 213) on a fertile alluvial site in Oregon increased initial cottonwood height growth 41% above fertilized, control plots (Shields et al., 1986). Although greater initial growth increases (68%) were obtained with a higher nutrient, primary:secondary sludge mixture, respective increases in height growth after three years were 31% and 38% for primary and mixed sludge treatments. This suggests that site factors related to organic matter were more limiting than nutrients. Surface-applied sludge can also enhance soil moisture retention and alter soil temperature due to its mulching effect. Positive effects of surface-applied sludge increased tree growth were attributed to improved moisture retention on a site in the Pacific Northwest (Henry, 1991). A study in Maine showed reduced growth of red pine, Japanese larch, and black spruce seedlings due to lower soil temperature brought about by surface-applied sludge (Kraske, 1992; NCASI, 2000).

2.3 *Landfill applications*

In numerous laboratory and field studies, some paper mill sludges have been shown to possess engineering properties similar to clays. The use of paper mill sludge in landfill construction was initially investigated by Stoffel and Ham (1979) and Pepin (1984). Based on these promising studies, significant research has been done by NCASI and others using sludges for construction of barrier layers in landfill final covers (NCASI, 1989; Genthe, 1993; Floess et al., 1995; Moo-young and Zimmie, 1996; NCASI, 1997). These studies indicate that the hydraulic performance of barrier layers constructed with sludge will be as good as, or better than, the performance of barriers with clay. The earliest reported date for a sludge incorporated into a landfill cover was 1990. This disposal alternative has the potential to use large quantities of sludge, and may be particularly advantageous to landfill operators in regions where paper mills exist and clay sources are scarce or costly (NCASI, 1997).

Hydraulic conductivity tests were conducted on 15 paper mill sludges of various origins (NCASI, 1989). After compaction of the specimens at their as-received water contents (120-409%) using standard Proctor procedures (ASTM D 698), rigid-wall compaction-mold permeaters were used for hydraulic conductivity testing. The resulting hydraulic conductivities ranged from 4.2×10^{-6} to 5.8×10^{-10} m/s. The low hydraulic conductivity obtained for some of the paper mill sludges suggested that some sludges may be viable for use in constructing barrier layers, which generally are required to have hydraulic conductivities less than 1×10^{-9} m/s (Kraus et al., 1997).

Since 1990, more then 14 landfills in the U.S. have been closed with sludge as the hydraulic barrier material. Landfill size ranges from 1.21 ha municipal landfill to a 12.1 ha industrial landfill. The combined sludges contained approximately 5% to 15% secondary sludge. Barrier layer thickness ranged from 0.6 to 1.2 meter. In some cases, the sludge was placed 25% thicker than the target thickness to account for consolidation. Hydraulic conductivity ranges from 10^{-5} to 10^{-9} cm/sec. Overburden thickness ranged from 0.08 to 0.6 meter. In several cases synthetic soil was used as overburden material. This manufactured soil was made from low-quality local soil as the base material. Sludge added to the soil improved desired soil characteristics such as water retention and the ability to support vegetative growth (NCASI, 1997).

In Massachusetts, the Hubbardston municipal sanitary landfill used sludge as a substitute low-permeability material for the final cap. The sludge applied to the landfill originated from a small mill processing 100% waste paper, typically pre- and post consumer ground-free ledger and book paper. The annual 12,000 dry tons of sludge contain a high percentage of clay resulting in hydraulic conductivity of 6×10^{-7} cm/s. Based on the results of the pilot study the design of the final cap was approved and a 0.76 meter layer of sludge was substituted for the normal 0.46 meter low-permeability soil layer in the cap (Floess et al., 1995).

In Michigan, MEAD Publishing Paper Division operates an integrated pulp and paper mill producing approximately 400 t/day of dewatered combined sludge. Instead of disposing the sludge at the company-owned industrial landfill, it was utilized as hydraulic barrier material for the closure of Mead's 3.64-ha Phase 2 landfill (Malmstead et al., 1999).

Recent studies focus on geotechnical, biochemical and microbiological properties of soil organic matter as sludge seems to have applications beyond landfill barrier layers. It has been used as a topsoil amendment in the municipal landfill caps for the towns of Wilton and Hadley (N.Y.). These projects indicate that the sludge amended topsoil readily absorbs large quantities of rainfall, reducing infiltration to the barrier layer and also holding water for vegetation growth during dry periods (Floess et al., 1995).

Being at the surface, cover systems exhibit the greatest change in temperature, moisture and atmospheric pressure. On the other hand, the stability of the soil pore system is one of the important properties that affect the ability of the soil to store and transmit air, water, and solutes. Sudden wetting is an important factor that can modify the number, shape, continuity, and size distribution of the soil (Gregorich et al., 1993). Rapid wetting of a structurally unstable soil results in filling of the interaggregate pores by microaggregates, reduced porosity, changes in the pore-size distribution, and a decreased infiltration rate (Nemati et al. 2000). Organic matter plays a fundamental role in the stabilization of soil and the formation of pores (Bolt et al., 1986; Chow, 2003) and bulk density (Martens, 1992). When subjected to sudden wetting, sludge application can improve the resistance of the amended soil to the destructive action of rapid wetting. On comparatively smooth soil surfaces, the beating action of raindrops causes most of the detachment. Where water is concentrated into channels, the cutting action of turbulent flowing water detaches soil particles. As dispersed material dries, it may develop hard crusts, which will prevent the emergence of seedlings and will encourage runoff from subsequent precipitation (Brady and Weil, 1999). These steps are the mechanics of water erosion resulting in soil loss. Sludge has the potential to protect the soil during critical periods of vegetation establishment and to prevent erosion on steep side slopes.

The processes of depletion and replenishment of soil moisture have received considerable attention from agricultural scientists because of the dependence of plant growth on soil moisture supply. The maximum amount of moisture that can be stored in soil in the field and the degree of dryness to which plants can reduce the moisture content of soil are the limits that determine the range of moisture available to plants (Richards and Weaver, 1944). The effect of organic matter on soil moisture retention became more and more an issue as soil and water quality and quantity became a growing environmental concern. The consequences of soil amended with organic matter were mainly studied in long term field experiments over the last decade. As the case studies show, the research focus was on determining optimum application rates of various organic amendments, including sludge, to improve soil conditions for plant growth. There is no literature available on the effect of organic matter on soil moisture retention investigated in laboratory experiments.

Laboratory experiments allow research of various parameters under defined conditions. They can be performed on a small scale, in less time, and in a controlled environment. This environment provides more flexible and cost efficient research without negatively impacting the actual application site. The influence of each parameter on the outcome can be adjusted in the lab and the consequences can be determined which has the advantage of optimizing procedures for field conditions. The result can then be applied to those field conditions and eventually lead to field applications.

Chapter 3 Chemical and Physical Characterization

The chemical and physical characteristics of sludge vary with the manufacturing process, and the type of effluent treatment employed. This research was designed to evaluate the feasibility of utilizing two different sludges as soil amendments on a clay topsoil layer in a landfill capping system, amendments designed to support vegetation without causing an adverse environmental impact.

The first step in conducting the experimental part was to obtain a clay sample, representative of the Prince George area. Two sludge samples have been obtained: One from a Kraft pulping process and one from a bleaching chemo-thermo-mechanical process (BCTMP). Sludge and soil samples have been distributed in smaller portions and stored in a walk-in-freezer to prevent alterations. The structural composition of the sludge samples was determined visually and with the scanning electron microscope. To chemically characterize the sludge, pH, moisture content, ash content, C:N ratio, cation exchange capacity, electrical conductivity, and salinity were determined. Selected elements were quantitatively determined after closed vessel microwave acid digestion by ICP-AES. Carbon and nitrogen were determined by total combustion. For physical characterization bulk density, porosity, and water holding capacity were determined. Water holding capacity was determined by gravity for three different treatments: original sludge and soil samples, sludge-soil mixtures for BCTMP and Kraft mill sludge samples (10:40, 20:30, 25:25, 30:20, 40:10), and sludge-soil layer systems for BCTMP and Kraft mill sludge samples (1,2,3 layer systems). All samples were utilized as received. Moisture retention curves were established for all three treatments using the pressure plate experiment. Statistical analysis has been performed on all obtained data.

Because sludge is composed mainly of organic fibers, standard procedures for chemical analysis and methods for organic soils were applied. Methods and procedures are outlined in this chapter. Results are summarized and discussed in chapter 4.

3.1 Materials and methods

3.1.1 Sample collection

A clay type soil sample, representative of the Prince George area, was taken in June 2002 at Tyner Boulevard/Ospika. The soil is similar to the Aleza Lake 1 – Orthic Luvic Gleysol (Arocena and Sanborn, 1999). After removing the dried top layer from a soil stockpile samples were taken from three different spots in the pile. The soil sample was collected in a 20-liter bucket with lid and stored in the walk-in cooler (4°C) at UNBC. Before usage the soil was mixed well in the bucket.

The two sludge samples are solid wastes from two different pulp and paper mills. One sludge is from a Kraft pulping process and one from a bleaching chemo-thermo-mechanical pulping process (BCTMP). Both sludge samples were taken directly from the filter press output. The sludge samples are representative samples from a pile of sludge that was produced at that time. As pulping process conditions change the chemical and physical sludge composition will vary.

The pulp mill sludge from the BCTMP was obtained on December 19, 2001. This sludge sample was collected in two 20-liter buckets. Each of the buckets was half filled. The sludge sample from these two buckets was then evenly distributed among four buckets. After closing and labeling, the four buckets were placed in the –20° C walk-in freezer at the University of Northern British Columbia (UNBC).

The pulp mill sludge from the Kraft process was obtained on January 23, 2002. This sludge sample was also collected in two 20-liter buckets. Each bucket was half filled with sludge and the material evenly distributed among four buckets. After closing and labeling, the four buckets were placed in the –20° C walk-in freezer at UNBC together with the BCTMP samples (Merchant, 2001).

3.1.2 Sample storage

For further experiments, smaller amounts of the original sludge samples are needed. Thus, 10 samples of each sludge of approximately 10 g were placed into Zip-Lock sandwich bags. The 20 bags were put together in a labeled box and stored in the –20° C walk-in freezer at UNBC alongside with the sludge samples in the buckets until needed.

3.2 Sludge characterization

3.2.1 pH Determination

For pH determination with a pH-meter, a 1:4 sludge-to-liquid (wet weight/volume) mixture was used. The liquid was distilled water. In a 250 ml beaker 5 grams of each sludge sample was weighed and 20 ml of distilled water added. The sludge-water mixtures were left for 30 minutes to equilibrate. After vacuum filtration the pH of the milky, beige filtrate was measured with a pH-meter, ORION, model 420 A (Kalra and Maynard, 1994).

3.2.2 Moisture content

The moisture content of both sludge samples was determined by weighing the original sample in an aluminum dish, followed by drying the sludge in an oven and then reweighing. The loss in weight (water) is expressed as a percentage of ovendried weight (Kalra and Maynard, 1994). Drying of the wet sludge samples was conducted at three different temperatures: 55 °C, 80 °C, 105 °C overnight, for a period of no less than 24 hours. At higher temperatures, some components of organic matter may be volatilized. If the sludge samples contain significant amounts of volatile compounds, the drying temperature would be a source of variation in the results. For the BCTMP and Kraft mill sludge the water content was conducted on 8 trials for the three temperatures. Data obtained from the moisture content determination are listed in appendix B.

Calculations:

(1) $W_d = W_t - W_{Al}$

where W_d is the weight of the dry sludge sample in g, W_t represents the weight of the dry sludge sample and the weighing dish in g, and W_{Al} represents the weight of the weighing dish in g.

(2) $$\Theta = \frac{\text{weight of sample wet (Ww) - weight of sample dry (Wd)}}{\text{weight of sample dry (Wd)}} \times 100\%$$

where θ is the moisture content in percent, W_w represents the mass of the wet sample and W_d represents the mass of the dry sample. The mass wetness (W_w), also called gravimetric wetness, is the ratio of the weight loss in drying to the dry weight of the sample (mass and weight being proportional) (Hillel, 1998).

3.2.3 Bulk density

The bulk density was determined for each treatment in the water holding capacity and pressure plate experiment. The bulk density for each sample is obtained by dividing the total dry mass over the total volume. The results for the original sludge and soil samples are listed in Table 8.

Calculation:

(3) $$D_b = \frac{W_d}{V_s} = \frac{\text{weight of oven - dried sludge [g]}}{\text{volume of sludge [cm}^3\text{]}} = \text{bulk density [g/cm}^3\text{]}$$

where D_b is the bulk density in g/cm^3, W_d represents the weight of the oven-dried sludge in g and V_s represents the volume of the sludge in cm^3 (Brady and Weil, 1999).

This calculation was applied to all experimental parts where bulk density was determined.

3.2.4 Porosity

With the bulk density, the porosity can be calculated. Knowing the porosity permits interpretation of the sludge behavior in terms of infiltration.

Calculation:

(4) $$P = 1 - \frac{D_b}{D_p} = 1 - \frac{\text{bulk density [Mg/m}^3\text{]}}{\text{particle density [Mg/m}^3\text{]}} = \text{porosity [ ]}$$

Where, P is porosity; D_b represents bulk density and D_p represents soil particle density.

Assumption: D_p = 1.51 Mg/m^3; particle density for organic soil (McGill, 2002)

3.2.5 Scanning Electron Microscopy and Energy Dispersive X-ray System

The scanning electron microscope (SEM) uses a beam of highly energetic electrons to examine objects on a very fine scale. This examination can yield to information as to structure and composition of the sludge samples.

Each of the two oven-dried sludge samples (105 °C) was fixed to an aluminum peg with silver epoxy glue and sputter coated with a thin layer of gold (McGill, 2002).

The sludge samples were observed under different enlargements to describe the sludge appearance and compare the structure of the two samples. Semi-quantitative elemental analysis was also provided on both sludge samples by using the energy dispersive X-ray system (EDX) of the SEM (Philips Electron Optics, Philips XL 30). The results of the elemental analysis depend on the spot in the sample analyzed.

3.2.6 Total Carbon and total Nitrogen (%C and %N)

For the determination of total carbon and nitrogen in the Kraft mill sludge and the BCTMP sludge the oven-dried (105 °C) and ground samples (100 mesh) were used.

The method used to determine the carbon to nitrogen ratio is total combustion (Brooks et al., 1989). It is based on the principle of oxidation of the carbon and nitrogen in the sample to carbon dioxide, water, and nitrogen. The analysis has been carried out with an elemental analyzer (Fisons Instruments, Fisons NA1500 NC) by A. Esler, UNBC. The weight of the samples used was 2-3 mg.

3.2.7 Ash content

The ash content of the original sludge and soil samples was determined by combustion at 525 °C (TAPPI standard test method T 211 om-93). Three replicates of each sludge sample and the soil samples were weighed in crucibles and ignited in a muffle furnace until the weight of the ash was constant.

Calculation:

(5) ash % = (mass of ash [g] / mass of dry sample [g]) x 100%

3.2.8 Elemental Analysis of selected inorganic components

The inorganic composition of BCTMP sludge and Kraft mill sludge was characterized by using inductively coupled plasma atomic emission spectroscopy (ICP-AES; Leeman, Labs PS1000-UV spectrometer). For the ICP analysis of BCTMP and Kraft mill sludge, oven-dried (105°C) samples of each of the sludges were used. Three replicates of each sludge sample were analyzed for macro- and micronutrients.

Sludge is mainly composed of organic matter. The sludge fibers are digested by acid oxidation. Digestion of the sludge samples weighing approximately 0.2 g each was accomplished by microwave acid digestion with 6 ml of HNO_3 (approximately 68% concentration) and 1.5 ml H_2O_2 (approximately 37% concentration). This procedure for organic matter digestion was developed at UNBC. The procedure gives a homogeneous solution which is transferred to a 50 ml volumetric flask. The total volume of 50 ml was made up with nanopure water. The samples were stored in Nalgene containers at 4°C.

Inductively coupled plasma – atomic emission spectroscopy (ICP-AES) was used for elemental analysis of aluminum, boron, calcium, cadmium, cobalt, chromium, copper, iron, lead, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, sodium, and zinc in the digested sludge samples.

ICP-AES is a multi-element analysis technique that will dissociate a sample into its constituent atoms and ions and cause them to emit light at a characteristic wavelength by exciting them to a higher energy level. This is accomplished by the use of an inductively coupled plasma source, usually argon. A monochromator can separate specific wavelengths of interest, and a detector is used to measure the intensity of the emitted light. This information can be used to calculate the concentration of that particular element in the sample.

As there were no elemental analysis data available for the Kraft mill and BCTMP sludge, the data from NCASI Sludge analysis (NCASI, 2002) was the basis for estimating the concentration ranges for the standard calibration curves. Determination of the concentration of each element in the sludge sample relies on the standard calibration curve. Knowledge of possible concentration ranges of the element in the sludge sample helps to determine appropriate standard concentrations.

For each element three different concentrations of calibration standards were made up in 5% nitric acid (HNO_3). Samples of 5% nitric acid were used as blanks to perform background corrections (appendix G).

3.2.9 Electrical conductivity and salinity

The 1:5 soil-to-water extraction method was used to determine electrical conductivity and salinity of the BCTMP sludge, Kraft mill sludge, and soil sample (Kalrad and Maynard, 1994). Fifteen grams of air-dried sludge and soil was transferred to a 250 ml Erlenmeyer flask and 75 ml of de-ionized water added. The stoppered flasks were put on a reciprocating shaker, (Eberbach Corporation, Ann Arbor, Michigan) and the mixtures shaken for 1 hour. The filtrates obtained after vacuum filtration were centrifuged for 5 minutes at 10,000 rpm/16,000 g (centrifuge model: Hermle, Z382K). Electrical conductivity and salinity was determined from the clear, pale yellow decanted filtrates of the sludge samples and the clear, colorless decanted filtrate of the soil samples. The pale yellow color of the sludge filtrates is induced by lignin. The conductivity instrument, YSI Model 3100, was calibrated with 0.01 M KCl solution at 25 °C. The cell constant was set to 1 at a measuring range of 0 – 49.99 mS/cm. For the conductivity measurements the mode temperature compensated was chosen.

Conductivity and salinity were determined for three replicates of each sludge sample and the soil sample.

3.2.10 Effective cation exchange capacity (CECe), exchangeable cations

The barium chloride method was used to determine the exchangeable cations and the effective cation exchange capacity for the BCTMP sludge, Kraft mill sludge, and soil samples (Gillman and Sumpter, 1986). The soil sample was analyzed directly, but the 2 sludge samples were milled using a Cyclotec mill and homogenized before analysis to enable representative sampling. The soil sample was extracted at a ratio of 1.5 g to 15 ml extracting solution as per mineral soils. The BCTMP sludge was extracted at 0.6 g to 15 ml as per high organic soils. The Kraft mill sludge sample had to be extracted at 0.6 g to 30 ml extractant due to its very fibrous and absorbent nature (Clive R. Dawson, 2003). The analysis was performed by the British Columbia Ministry of Forests Research Branch Laboratory, Analytical Chemistry Section. Triplicate analysis was conducted (appendix F).

3.2.11 Water holding capacity

The water-holding capacity (WHC) of sludge and soil samples can be determined by a “soak and drain” method where water in saturated samples is extracted by gravity. Water can also be extracted from saturated samples over a water potential range of 0 to –10 kPa using a pressure plate (Tempe cells) or a tension table apparatus (Carter, 1993).

3.2.11.1 Gravity or European Method

To determine the water-holding capacity plastic columns of 7.0 centimeters height with a diameter of 6.9 centimeters were used. One end of the column was covered with 2-3 layers of cheese cloth. The column was filled ¾ with sample and tapped gently to compact the sample. The prepared columns were weighed empty and when filled with sample. The height of the sample was also determined. The column enclosing the sample was placed in a vessel containing enough water to saturate the sample. When the sample was saturated (24 hours), the vessel was removed and the sample allowed to drain for 24 hours. The top of the column was covered loosely with parafilm to minimize evaporation and a couple of small holes (needle) permit airflow. When drainage was complete, duplicate samples were removed from the central portion of each column for moisture content determination. These samples were dried in an oven at 105 °C for 24 hours. This moisture content is approximately equal to water-holding capacity (Gomez et al., 1997; Harding et al., 1964).

The above described set up was used for three different treatments:

a) original sludge and soil samples

b) sludge-soil mixtures for the BCTMP and Kraft mill sludge samples

c) sludge-soil layer systems for the BCTMP and Kraft mill sludge samples.

The number of replicates varied depending on the experiment. The columns were filled with original samples and various sludge-soil mixtures to a height of approximately 4 centimeters.

For the sludge-soil layer systems, a total height of 6 cm was maintained for the 1, 2, and 3 layer system. The height of each sludge and soil layer was selected to maintain the same total height within the various sludge-soil layer systems.

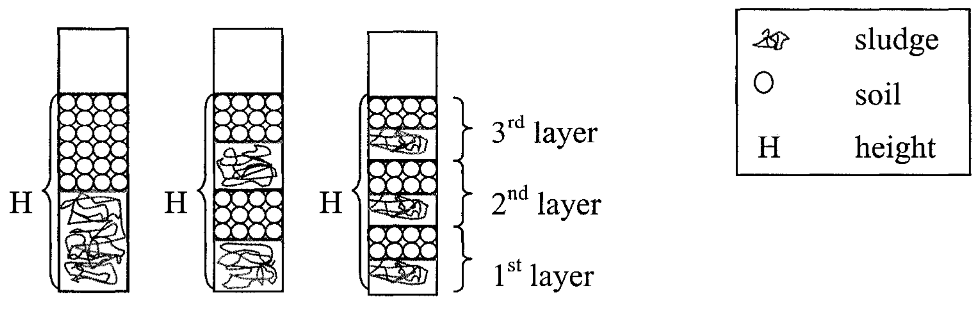


Figure 3: Outline for the sludge-soil layer systems.

First, the bulk density and the water-holding capacity of the original sludge and soil samples were examined. The original data are used for comparison. The same procedure was applied to various mixtures of sludge and soil (10:40, 20:30, 25:25, 30:20, 40:10). The sludge was mixed with soil in a blender, Proctor Silex, 7 Blend Master, on pulsation. The control sludge samples were treated in the same manner.

This procedure was also applied to sludge-soil layer systems, where each sludge and soil layer has a different height, but the total height of the sample in the column stays the same.

Calculations:

(6) Sample volume: $V = (\pi/4) \times d^2 \times h$

where d is the diameter of the column, 6.9 cm, and h is the height of the entire sample in cm in the column. The sample volume is given in cm^3.

(3) Bulk density: $D_b = \frac{W_d}{V_s}$ [g/cm^3]

where D_b is the bulk density in g/cm^3, W_d represents the weight of the oven-dried sludge in g and V_s represents the volume of the sludge in cm^3 (Brady and Weil, 1999).

(7) Gravimetric water-holding capacity at equilibrium (Gomez et al., 1997):

$$WHC_g = \frac{\text{weight of sample wet - weight of sample dry}}{\text{weight of sample dry}} \times 100\%$$

3.2.11.2 Pressure Plate Experiment

Through the application of pressure plate extractors the characteristic moisture retention curve can be developed for each soil type. The curves relate the soil suction, at which moisture is held by the soil, to its moisture content. This relationship is important in studies of soil moisture movement and of quantity and availability of soil moisture for plant growth (Soilmoisture Equipment Corp., 2001).

To determine the moisture retention curves, the sample preparation described under 3.2.11.1 was used. The column was filled with sample to a height of 1 cm. The sample was gently compacted with the bottom of a beaker and the height remeasured. The prepared columns were weighed empty and when filled with sample. The column enclosing the sample was placed directly on the ceramic plate and placed in a vessel containing enough water for 24 hours to saturate sample and ceramic plate. Saturated ceramic plate and sample are placed in the pressure plate extractor and left until equilibrated at the desired pressure. Gravimetric moisture content was determined after drying the sample in an oven at 105 °C for 24 hours.

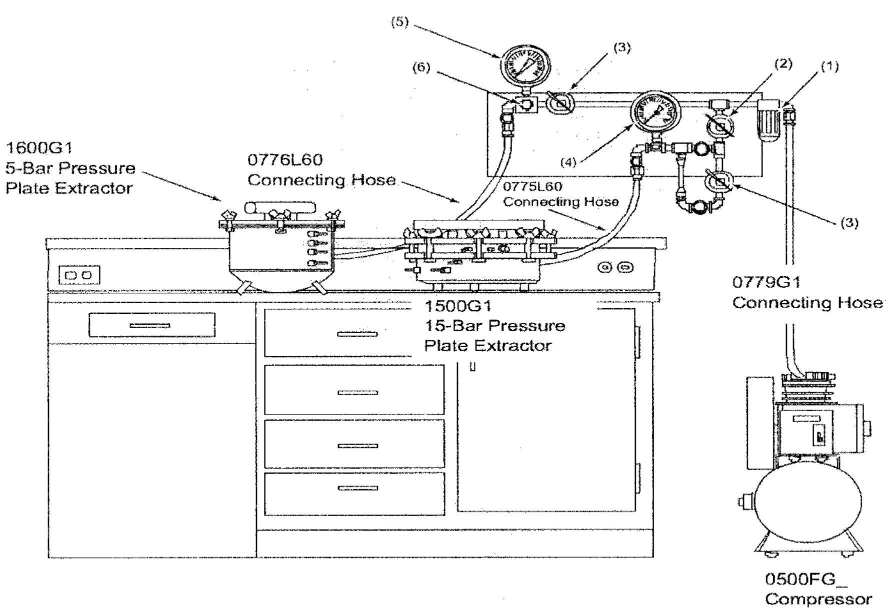


Figure 4: Pressure plate extractor set up (Soilmoisture Equipment Corp., 2001).

For the moisture retention curves of the original sludge and soil samples, the moisture content of 11 pressure points was determined (0.1;0.2;0.3 ;0.4;0.5;0.7;1.0;2.0;

5.0; 10.0;15.0 bar). For each run, one Kraft mill, BCTMP sludge and soil sample was placed on the pressure plate. A 1 bar ceramic plate was used for pressures up to 1 bar. For the pressures 1.0 and 2.0 bar a 3 bar ceramic plate was used. A 15 bar ceramic plate was used for 5.0, 10.0, and 15 bar pressure.

Moisture content was determined from the entire sample when equilibrium was reached.

Calculations:

(8) Volumetric water-holding capacity at equilibrium (Brady and Weil, 1999):

$$WHC_v = \frac{\text{weight of sample wet - weight of sample dry}}{\text{weight of sample dry}} \times D_b \times 100\%$$

(9) Available water (Brady and Weil, 1999):

field capacity water content (0.3 bar)
- wilting point water content (15.0 bar)

= available water

The above described set up was also used for sludge-soil mixtures using BCTMP and Kraft mill sludge samples. The mixtures were prepared as described in 3.2.11.1. For the moisture retention curves of the sludge-soil mixtures the moisture content of 9 pressure points was determined (0.1;0.3;0.5;0.7;1.0;5.0;10.0;15.0 bar). At 0.3 and 15 bar, three replicates of each of the mixtures were measured, and from the average the available water was calculated. Two trials for each mixture were performed at 1.0 bar.

Using the same set up as before, the moisture retention curves for sludge-soil layer systems for the BCTMP and Kraft mill sludge samples were determined. The same layer systems as described in 3.2.1.1 were prepared. The pressure points analyzed were 0.5, 1.0, and 5.0 bar. When equilibrium was reached each layer was split in half for moisture content determination.

3.2.12 Statistical Analysis

Statistical analyses were performed on all data except the semi-quantitative results from the energy dispersive x-ray analysis. Microsoft Excel was used to determine average, standard error, and standard deviation. Error analysis was carried out by using the method of propagation of random errors for the gravimetric and volumetric water holding capacity data.

Random or statistical errors are unpredictable errors resulting from limited precision of the measuring instrument and minor uncontrollable variations in the operation of the equipment (Δm, Δd, Δh). However, random error is not correctable and the degree of uncertainty in measurements is indicated by derivations of the experimental results. The errors expressed as $\pm$ ΔDb, $\pm$ ΔWHC_g and $\pm$ ΔWHC_v represent the uncertainty in the quantity of interest in terms of confidence limits. Random error is reduced by good tools and a large sample size.

Calculation:

(10) For F = axyz (or axy/z or ax/yz or a/xyz),

$$\frac{\Delta^2(F)}{F^2} = \frac{\Delta^2(x)}{x^2} + \frac{\Delta^2(y)}{y^2} + \frac{\Delta^2(z)}{z^2}$$

where a,x,y,z are actual values and F represents the uncertainty in the final result (Shoemaker et al., 1996).

Chapter 4 Results and Discussion

The two major aspects for reusing sludge are its chemical and physical characteristics. Sludge samples from BCTMP and Kraft mill processing were compared and their water holding effect on a clay type of soil examined. Analysis was conducted following the methods described in chapter 3.

4.1 Baseline characteristics

The BCTMP sludge sample in Figure 5 appeared as soft pellets and clumps of fibers of medium to dark brown color. The sludge pellets contained smaller pieces of white-yellowish wood fibers (0.5-1 cm length). The Kraft mill sludge in Figure 6 appeared in lumps of fibers in a brown-beige color and contained fewer but larger pieces of darker brown wood fibers (2-3 cm length).

The micrographs in Figure 7 and 8 show the sludge samples on an enlarged scale. The Kraft mill sludge sample appears to be more homogeneous in its fiber structure. The BCTMP sludge sample is composed of a broader variety of fibers and wood pieces.

The difference in structure and aggregation of the sludge and soil samples were visually inspected. The soil sample had a finer texture than the sludge samples. The Kraft mill sludge sample has the coarsest texture. This is reflected in the bulk density and porosity results (Table 8). Both sludge samples have a lower bulk density than the soil. Bulk density indicates how easily a soil will till, how easily water will infiltrate, how it will hold water, and its suitability for growing plants. There is more pore space available to be filled with water in the sludge samples than in the soil.

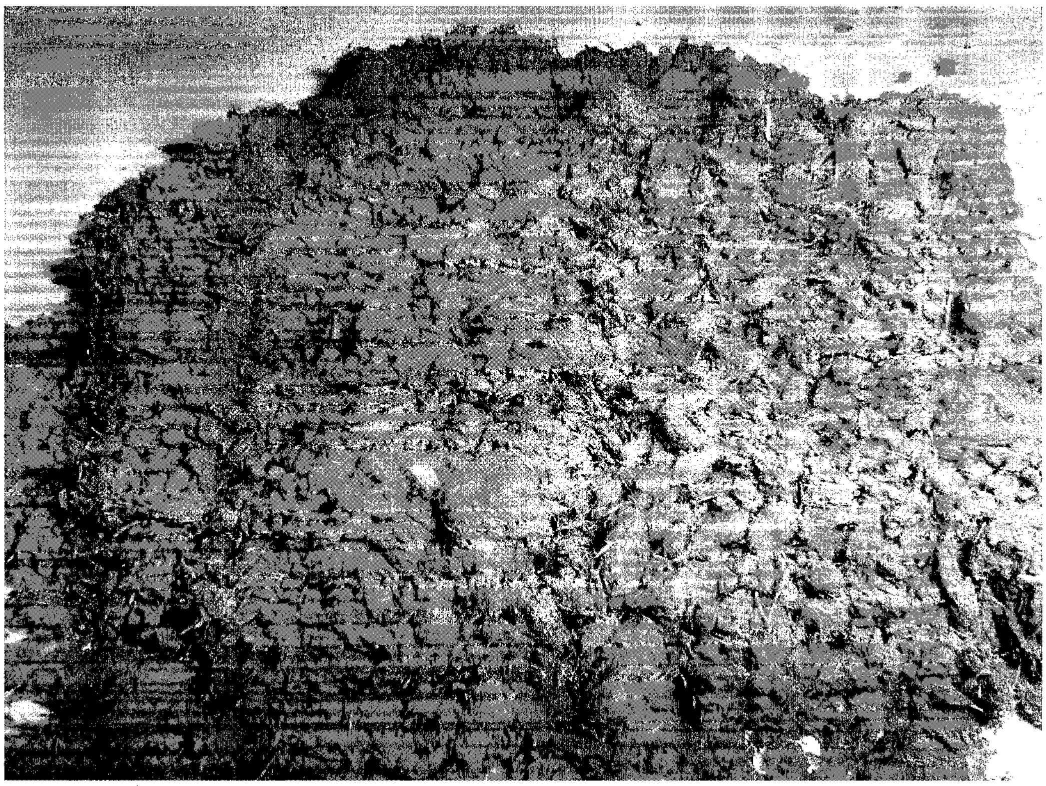


FIGURE 5: BCTMP sludge (1:1)

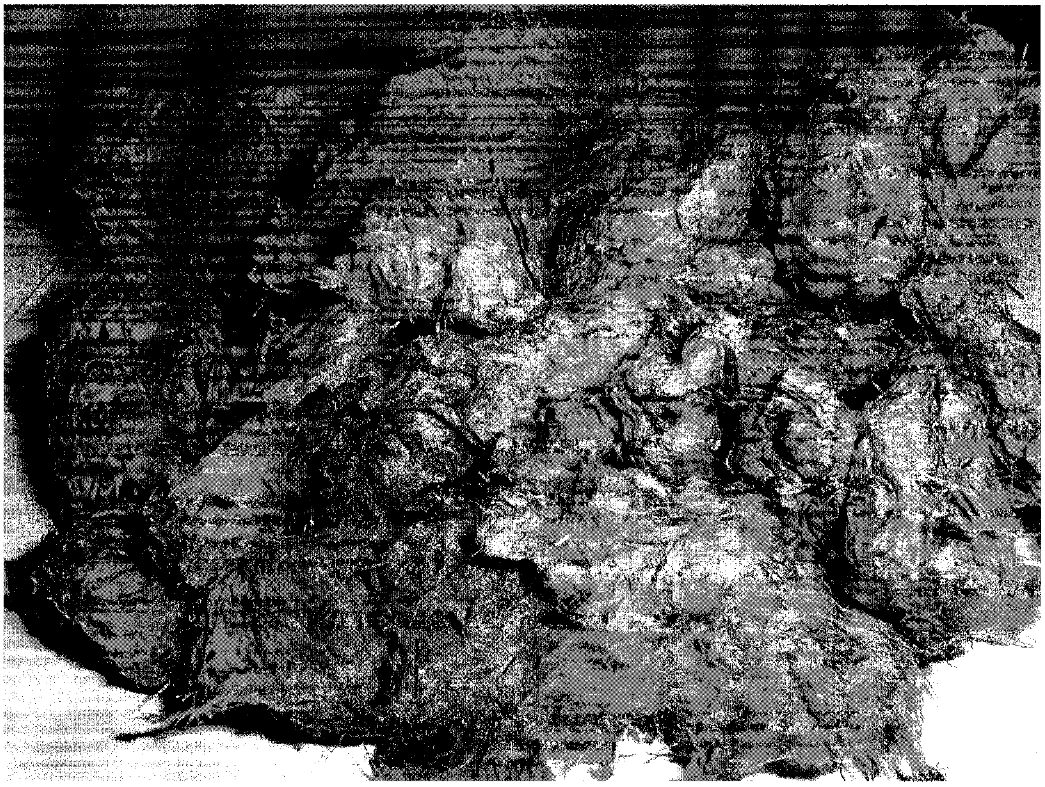


FIGURE 6: Kraft mill sludge (1:1)

FIGURE 7: SEM micrograph of BCTMP sludge (15x).

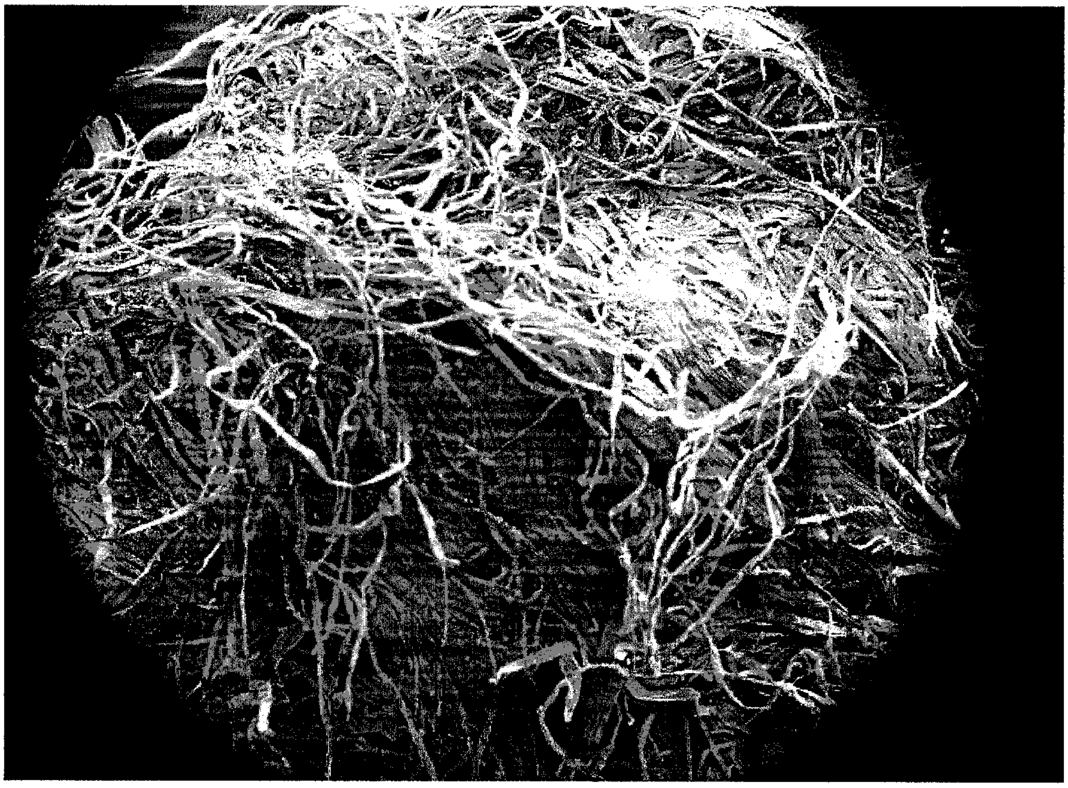


FIGURE 8: SEM micrograph of Kraft mill sludge (15x).

When preparing the sludge soil mixtures, the original sludge and soil structure was changed by using a blender. The sludge and soil particles were separated into more individual aggregates. The arrangement of aggregates gives the soil its structure. However; soil particles filled the void space in the sludge samples. This is partially due to the original sludge moisture content and the blending. After soaking and draining the soil sludge layer samples, it was observed that the soil particles on the interface filled the void pore space of the sludge. This change in aggregates increased the degree of stability. When the sludge soil layer samples were taken out of the plastic columns, they resisted sliding and crumbled less than the original soil sample. Increasing stability of the topsoil layer is especially desirable at the site slopes.

4.2 Chemical characterization

4.2.1 General properties

A variety of properties are used to characterize sludge, including pH, moisture content, ash content, C:N ratio, cation exchange capacity, electrical conductivity, and salinity. The results are summarized in Table 6 and compared to previous studies.

Table 6: Properties of BCTMP and Kraft mill sludge compared with previous data.

component	n	unit	BCTMP	Kraft mill	literature
pH	2	-	6.95	8.25	6.43 [a]
moisture content	8	%	164 ± 1.78	165 ± 3.41	121 – 409 [b]
ash content	3	%	4.40 ± 0.15	4.40 ± 0.23	10 – 62 [b]
C:N	4	-	52:1	43:0	100:1; 300:1 [c]
CEC	3	cmol+/kg	35.25 ± 0.12	19.70 ± 0.04	NA [d]
electrical conductivity	3	μS/cm	1466	241	1120 [a]
salinity	3	ppt	0.8	0.1	NA [d]

[a]The data were indirectly calculated based on a 3:1 primary to secondary sludge ratio (Clear Lake Ltd., 1993).

[b]NCASI, 2002; [c]NCASI, 2000; [d]NA = not available

With a pH of 6.95 the BCTMP sludge is neutral. The Kraft mill sludge with a pH of 8.25 is basic. The calculated literature value is slightly acidic with a pH of 6.43 (Clear Lake Ltd., 1993).

The moisture content represents the average of 8 samples, oven-dried at 55°C, 80°C, and 105° C for 24 h until constant weight (± 0.2 g). The BCTMP sludge sample at 80° C represents the average of 6 samples. Raw data, standard deviation and standard error are presented in Table (21-23) for Kraft mill and Table (24-26) for BCTMP sludge (appendix B). The difference in moisture content determination at three different temperatures for both sludge samples was small, which indicates the low presence of volatile compounds. The larger standard errors for the Kraft mill sludge sample (± 3.41 at 105° C) compared to the BCTMP sludge sample (± 1.78 at 105° C) indicates a broader variance around the average. This is a result of a less homogeneous sample. The moisture content of both samples is alike and falls into the lower range of the literature value.

The ash content for both sludge samples is 4.40% and represents the average of three samples. The standard error for the BCTMP sludge is ± 0.15%, and ± 0.23% for the Kraft mill sludge (Table (28), appendix D). Compared to the soil with 95.5% ash content the sludge samples are high in organic matter expressed in the low percentage of ash content. The reference range of the ash content is 10 to 62%. The sludge samples are under the minimum value, which means, they are higher in organic matter. Raw data are presented in Table (28), appendix D.

The C:N ratio for BCTMP sludge is 52:1 by mass. For Kraft mill sludge it is 43:0.1 by mass. Raw data are presented in Table (27), appendix C. The actual nitrogen content in the BCTMP sludge could enhance vegetation growth on the final cover layer of a landfill. However, because of the very small amounts of nitrogen present in the sludge, the soil-type of sludge mixture is important at as well as additional fertilization possibilities to promote plant growth in landfill cover amended with sludge.

The cation exchange capacity for BCTMP sludge is 35.35 cmol+/kg and 19.70 cmol+/kg for Kraft mill sludge (Table 6). There is almost double the amount of exchangeable cations available in BCTMP sludge. In the soil sample the CEC is 15.25 cmol+/kg. Raw data are presented in Table (31), appendix F. Normal CEC ranges in soils would be from < 3 cmol+/kg to > 25 cmol+/kg (Ross, 2003). Cations retained electrostatically are easily exchangeable with other cations in the sludge/soil solution and are thus easily available for plant uptake. The CEC is pH dependent. Addition of sludge material will likely increase the soil's CEC.

The electrical conductivity of BCTMP sludge (1466 μS/cm) is 31% higher than the literature value with 1120 μS/cm (Table 6). The conductivity of the Kraft mill sludge is 78% lower than the literature value. The electrical conductivity is a measurement of a solution's ability to conduct electric current. As the ability of a solution to conduct electric current depends upon ions, there are more ions in the BCTMP than in the Kraft mill solution. Conductivity is also an indirect measurement of salt content. The measured salinity of BCTMP is 0.8 ppt and of Kraft mill sludge 0.1 ppt. These results are consistent with the conductivity measurements.

4.2.2 Elemental analysis

The main elements found in both sludge samples by energy dispersive x-ray analysis (Table 29 and 30, appendix E) are carbon and oxygen as they are the skeleton of the cellulose fibers. The carbon to oxygen ratio of Kraft mill sludge is 2.65:1, and 1.53:1 for the BCTMP sludge. The section of the BCTMP sludge analyzed under the microscope showed that it contains sodium, silicon, sulfur, potassium, and calcium. The section of the Kraft mill sludge analyzed under the microscope showed that it contains neither sulfur nor potassium. Kraft mill sludge contains double the amount of sodium than BCTMP sludge. BCTMP sludge contains approximately four times more calcium than Kraft mill sludge. These results are semi-quantitative and represent only a section of the sludge sample on the peg.

In both sludge samples, the levels of macro- and micronutrients were established. In each sludge sample, 17 elements were quantitatively determined after closed vessel microwave acid digestion by ICP-AES. These elements include the macronutrients K, Ca, Mg, and P. The other macronutrients S and N were not determined by ICP-AES. All of the micronutrients were determined except chloride. Results are summarized in Table 7 (Table 32, appendix G). The resulting concentrations for all elements are in the lower range of the concentrations determined by NCASI (NACSI, 2000). These results support the findings from NCASI that pulp and paper mill sludge is in general low in potential environmental contaminants.

Both types of sludge can provide the nutrients for plant growth. The Kraft mill sludge has lower concentrations of B, K, Mg, Mo, and P than required for plant growth (Barak, 1999). The concentrations for Ca, Co, Fe, Mn, Ni, and Zn are higher than the typical requirements for plant growth. BCTMP sludge differs from Kraft mill sludge. The concentrations of B, K, Na, Ni, P, and Pb are higher in BCTMP sludge while concentrations of Cu, Mg, and Mn are lower in BCTMP sludge (Table 7).

Micronutrients are as important for plant growth as macronutrients but in lower concentrations. Whether a macronutrient or micronutrient, the most growth-limiting nutrient will limit growth, no matter how favorable the nutrient supply of other elements is. All essential elements are absorbed by the plants from soil solutions, as either cations or anions, thus soil pH is an important factor to determine, as the ionic charge of the elements depends on the surrounding pH.

Table 7: Summary of results for the elemental analysis in oven-dried (105°C) Kraft mill and BCTMP sludge samples determined by ICP-AES and literature data.

Element	Symbol	Kraft Mill [mg/kg]	BCTMP [mg/kg]		NCASI [1] [mg/kg]	Nutrients [2] [mg/kg]
Aluminum	Al	702	295		590 - 59,000	n/a
Boron	B	0.672	62.0		<1 - 491	20
Calcium	Ca	5931	7936		280 - 210,000	5,000
Cadmium	Cd	0.088	0.232		<0.09 - 56	n/a
Cobalt	Co	0.582	1.491		0 - 9.7	n/a
Chromium	Cr	4.97	13.52		3.0 - 2,250	n/a
Copper	Co	14.51	7.87		3.9 - 1,590	6
Iron	Fe	587	312		97.1 - 10,800	100
Potassium	K	72.8	277		120 - 10,000	10,000
Magnesium	Mg	1795	478		200 - 19,000	2,000
Manganese	Mn	89.0	28.6		13 - 2,200	50
Molybdenum	Mo	*BDL	*BDL		<2.5 - 14.0	0.1
Sodium	Na	162	904		300 - 66,700	n/a
Nickel	Ni	1.819	8.088		1.3 - 133	0.1
Phosphorus	P	41.2	932		10 - 25,400	2,000
Lead	Pb	4.09	*BDL		<0.05 - 880	n/a
Zinc	Zn	30.5	28.4		13 - 3,780	20

[1] NCASI 54 Mill survey (NACSI, 2000)

[2] Typical concentrations sufficient for plant growth (Barak, 1999)

* Below detection limit n/a = not applicable

The limiting growth factor of sludge is the low level of nitrogen. The nitrogen concentrations in pulp mill sludge are ranging from 1.1 g/kg to 59 g/kg (NCASI, 2000). Extensive research has been conducted in the past to overcome this disadvantage of the sludge amendment. Compounds rich in organic nitrogen like manure, compost, and biosolids were mixed with sludge and applied to agricultural land. Some of these studies are mentioned in chapter II. Most landfills use compost produced onsite as fertilizer for vegetation growth. The growth and appearance of plants varies considerably from one species to another and even within species, depending on the environment. Alfalfa utilizes 272 kg of nitrogen and yields 25.4 t/ha. Clover-grass utilizes only 136 kg of nitrogen and yields 15.3 t/ha (Tisdale et al., 1985). In accordance with the vegetation applicable to landfill restoration plans and site climate, nitrogen sources need to be added in quantities that will meet the requirements of the plants.

4.3 Physical characterization

4.3.1 Bulk density and porosity

BCTMP sludge has a higher bulk density with 0.094 Mg/m^3 than Kraft mill sludge with 0.054 Mg/m^3. The different aggregation of the two sludge samples causes different results in porosity. Kraft mill sludge has a coarser texture than BCTMP sludge. This results in lower bulk density and higher porosity. The clay type soil has the highest bulk density with 0.827 Mg/m^3 and the lowest porosity. Data are summarized in Table 8.

Table 8: Bulk density and porosity of BCTMP and Kraft mill sludge.
Assumption: Dp = 1.51 Mg/m^3; particle density for organic soil (McGill, 2002).

sample	Bulk density [Mg/m^3]	Porosity
Kraft mill	0.054	0.964
BCTMP	0.094	0.937
Soil	0.827	0.452

These results support the observations under 4.1.

4.3.2 Water holding capacity by gravity

Data obtained from the bulk density and water holding capacity determination for Kraft mill and BCTMP sludge and soil are listed in appendix H. In Table 9, the average of the moisture content determination (=WHC_g) of the duplicates of all dried samples is summarized.

The Kraft mill and BCTMP sludge samples have a bulk density approximately one order of magnitude lower than the clay type soil sample. The bulk density determined for the blended sludge samples is lower than for the original samples.

Table 9: Bulk density and gravimetric water holding capacity obtained from original and blended Kraft mill and BCTMP sludge and soil sample.

sample	**bulk density** $[g/cm^3]$	**± se** (n=5)	$\mathbf{WHC_g}$ **[%]**	**± se** (n=5)
Kraft mill, blend	0.033	0.006	710	9.64
BCTMP, blend	0.063	0.002	520	4.10
Kraft mill	0.054	0.001	509	6.68
BCTMP	0.095	0.002	393	6.90
Soil	0.827	0.005	32	0.61

The gravimetric water holding capacity is lowest for the soil sample and highest for the blended Kraft mill sludge sample. The BCTMP sludge sample has approximately 12 times and the Kraft mill sludge sample approximately 16 times more water holding capacity than the soil sample. The data obtained in this part of the experiment demonstrate that different structures and pore size distributions result in very different water holding capacity.

In Table 10 and 11 the bulk density and moisture content on a weight basis (=WHC_g) average of dried samples of various sludge-soil mixtures is summarized. Data obtained from the bulk density and water holding capacity determination for Kraft mill and BCTMP sludge-soil mixtures are listed in appendix H. The original sludge sample was mixed with 10, 20, 25, 30, and 40 mass percent of soil using a blender (Table 10 and 11). The original sludge was blended and used as reference. For both sludge samples, the bulk density increased with higher percentage of soil in the sludge-soil mixtures. The water holding capacity decreased with higher amounts of soil in the mixture. The BCTMP sludge-soil mixture 10:40 has the highest bulk density and the lowest water holding capacity. By comparing the sludge-soil mixtures the 25:25 mixture doubles in water holding capacity compared to the 10:40 mixtures. Comparing the sludge-soil mixtures with the lowest amount of sludge added (10:40) and the water holding capacity of the clay type soil, the water holding capacity doubles with Kraft mill sludge and increases by two thirds with BCTMP sludge.

Table 10: Bulk density and gravimetric water holding capacity obtained from various Kraft Mill sludge-soil mixtures.

sample	**bulk density [g/cm^3]**	**± se** (n=3)	**WHC_g [%]**	**± se** (n=6)
Kraft mill/soil 10:40	0.343	0.005	65	4.74
Kraft mill/soil 20:30	0.157	0.015	139	11.95
Kraft mill/soil 25:25	0.145	0.006	145	11.73
Kraft mill/soil 30:20	0.098	0.004	251	17.31
Kraft mill/soil 40:10	0.055	0.001	447	19.44
Kraft mill blend	0.033	0.001	710	9.64

Table 11: Bulk density and gravimetric water holding capacity obtained from various BCTMP sludge-soil mixtures

sample	**bulk density [g/cm^3]**	**± se** (n=3)	**WHC_g [%]**	**± se** (n=6)
BCTMP/soil 10:40	0.499	0.008	52	1.19
BCTMP/soil 20:30	0.311	0.016	87	5.48
BCTMP/soil 25:25	0.256	0.011	107	3.67
BCTMP/soil 30:20	0.181	0.006	178	6.03
BCTMP/soil 40:10	0.117	0.003	294	7.77
BCTMP blend	0.063	0.002	521	4.10

Data obtained in this part of the experiment demonstrate the effect of the sludge amendment. Adding higher amounts of sludge results in decreasing bulk densities and increasing water holding capacities. The same effects were found when sludge at different rates was amended to gravelly loam soil in a field study (Chow et al., 2003). In this study, results on water-stable aggregates revealed that the organic matter in the pulp fiber combined smaller aggregates to form larger aggregates, resulting in a larger proportion of macropores as compared to micropores. The original sludge samples (Table 8) have a higher bulk density and a lower water holding capacity compared to the blended samples. Blending the sludge affects the fiber structure, resulting in different bulk density and water holding capacity.

Another alternative to examining sludge-soil mixtures was to look at packing sludge and soil in layers (Figure 4). By keeping the total height of the sample the same, the height of each sludge and soil layer varied between the 1, 2 and 3 layer systems. In Table 12 and 13, the average of the gravimetric moisture content determination (=WHC_g) of dried samples of sludge-soil layer systems are summarized. Data obtained from the bulk density and water holding capacity determination for Kraft mill and BCTMP sludge-soil layer systems are listed in appendix H.

The water holding capacity of the bottom layer of sludge increased for the 2 and 3 layer system compared to the 1 layer system. For the 1 layer system, the water holding capacity for the sludge is approximately 10 times higher than in the soil. The same effect can be observed for the soil layer in the 2 and 3 layer systems. This is consistent with reduced water transmission being induced by surrounding sludge layers. The water holding capacity of the soil layer stays between 36 and 39% in all three systems.

Table 12: Bulk density and gravimetric water holding capacity of 1, 2, and 3 layer systems of Kraft mill sludge.

	sample	**Bulk density [g/cm^3]**	**± se** (n=3)	**WHC_g [%]**	**± se** (n=6)
Kraft mill 1 layer	Sludge 1	0.084	0.014	332	42.0
	Soil 1	0.916	0.016	39	0.60
	weighted average			**185**	
Kraft mill 2 layer	Sludge 1	0.061	0.002	487	16.5
	Soil 1	0.840	0.050	38	0.59
	Sludge 2	0.073	0.004	494	11.4
	Soil 2	0.941	0.059	39	0.23
	weighted average			**264**	
Kraft mill 3 layer	Sludge 1	0.077	0.006	486	8.60
	Soil 1	0.677	0.009	36	0.65
	Sludge 2	0.114	0.012	380	15.9
	Soil 2	0.810	0.024	38	0.67
	Sludge 3	0.095	0.003	431	26.9
	Soil 3	1.019	0.099	38	0.36
	weighted average			**235**	

Table 13: Bulk density and gravimetric water holding capacity of 1, 2, and 3 layer systems of BCTMP sludge.

	sample	Bulk density [g/cm^3]	± se (n=3)	WHC_g [%]	± se (n=6)
BCTMP 1 layer	Sludge 1	0.094	0.001	378	3.69
	Soil 1	0.897	0.011	40	0.46
	weighted average			**209**	
BCTMP 2 layer	Sludge 1	0.097	0.006	476	44.9
	Soil 1	0.681	0.009	41	0.53
	Sludge 2	0.126	0.005	434	14.6
	Soil 2	0.795	0.010	40	0.55
	weighted average			**248**	
BCTMP 3 layer	Sludge 1	0.121	0.001	394	7.23
	Soil 1	0.850	0.034	42	0.62
	Sludge 2	0.121	0.013	356	13.2
	Soil 2	0.790	0.009	42	0.51
	Sludge 3	0.134	0.009	424	17.6
	Soil 3	0.742	0.007	41	0.63
	weighted average			**217**	

Comparing the total water holding capacity calculated by weighted average, the 2 layer system has the highest water holding capacity with 264 % for Kraft mill sludge and 248 % for BCTMP sludge. The 3 layer system has a total water holding capacity of 235 % for Kraft mill sludge and 217 % for CTMP sludge, and the 1 layer system is lowest with 185 % for Kraft mill sludge and 209 % for BCTMP sludge. Adding a third layer of sludge and soil resulted in a lower total water holding capacity than in the 2 layer system. This could be due to each layer decreasing in layer thickness to maintain the same total height. The increase in water holding capacity in the sludge layer in all three layer systems refers to the sludges capability to retain water. In the three layer system the second sludge layer has a lower water holding capacity than the first and third layer. This second sludge layer is enclosed by soil layers. The soil particles filled some of the voids in the sludge reducing water holding capacity of the sludge.

The water holding capacity in the layer systems is similar to the 30:20 sludge-soil mixtures and lower than the original sludge samples. The slightly higher bulk density in the second sludge layer of the 2 and 3 layer system are due to soil particle attached to the sludge fibers.

4.3.3 Pressure plate experiment

When equilibrium was reached water holding capacity or moisture content was determined for the sludge and soil samples at different pressures. Data obtained for bulk density, moisture content and error analysis are listed in appendix I. The water holding capacity is expressed on a volume basis using equation (8). For 11 samples of BCTMP sludge and for 11 samples of Kraft mill sludge the average bulk density is 0.14 g/cm^3. The average bulk density for 10 samples of soil is 1.37 g/cm^3. Compared to the original samples (Table 8) bulk densities determined in the pressure plate experiment are higher. A summary of the volumetric moisture content data with random errors is presented in Table 14.

BCTMP sludge can hold the highest amount of water. It includes the available, unavailable, and gravitational water. The soil holds the lowest amount of water. The observed water holding capacity is similar to the general literature value of 52% for clay loams (Klocke, 1996). At field capacity, BCTMP sludge has moisture retention of 53.7%, Kraft mill sludge has 36.7%, and soil has 39.2%. The water held between field capacity and wilting point available water is most important for vegetation. Plants can use approximately 50 percent of the available water without stress, as the water is retained by capillary forces. The total amount of available water in BCTMP sludge is 4 times higher than in soil and Kraft mill sludge is 7 times lower than in soil. This water storage capacity of BCTMP sludge can be used beneficially to increase the water holding capacity in soils.

The moisture retention curves obtained for the sludge and soil samples are shown in Figure 9 and 10.

Table 14: Volumetric moisture retention curve data with random errors for BCTMP sludge, Kraft mill sludge, and soil (n=1).

	pressure	moisture % vol.					
	[bar] x (-1)	**BCTMP**	± *Δ* WHC_v	**Kraft mill**	± *Δ* WHC_v	**Soil**	± *Δ* WHC_v
	0.1	49.6	*1.01*	58.8	*1.20*	52.2	*1.07*
	0.2	52.8	*1.08*	42.3	*0.86*	45.1	*0.92*
Field capacity	0.3	53.7	*1.10*	36.7	*0.75*	39.2	*0.80*
	0.4	49.5	*1.01*	38.5	*0.79*	44.9	*0.92*
	0.5	46.1	*0.94*	33.5	*0.68*	31.8	*0.65*
	0.7	45.5	*0.93*	33.4	*0.68*	35.3	*0.72*
	1	45.4	*0.93*	32.1	*0.66*	38.0	*0.78*
	2	46.5	*0.95*	30.4	*0.62*	36.3	*0.74*
	5	48.9	*1.00*	38.1	*0.78*	40.3	*0.82*
	10	40.2	*0.82*	35.6	*0.73*	35.0	*0.72*
Wilting point	15	37.2	*0.76*	36.1	*0.74*	34.7	*0.71*
Available water		16.5		0.6		4.5	

The pressure plate experiment was used to determine moisture retention curves for soil samples. The soil is different in structure from the two sludge samples. The sludge samples are less homogeneous and a broader variety of pore sizes is involved. The various pores are distributed unevenly. This affects the sample preparation and is expressed in the random errors. As the experimental process to obtain a data set for one pressure takes 4 days, no replicates have been conducted. The above information is used for comparison with sludge-soil mixtures and sludge-soil layer systems.

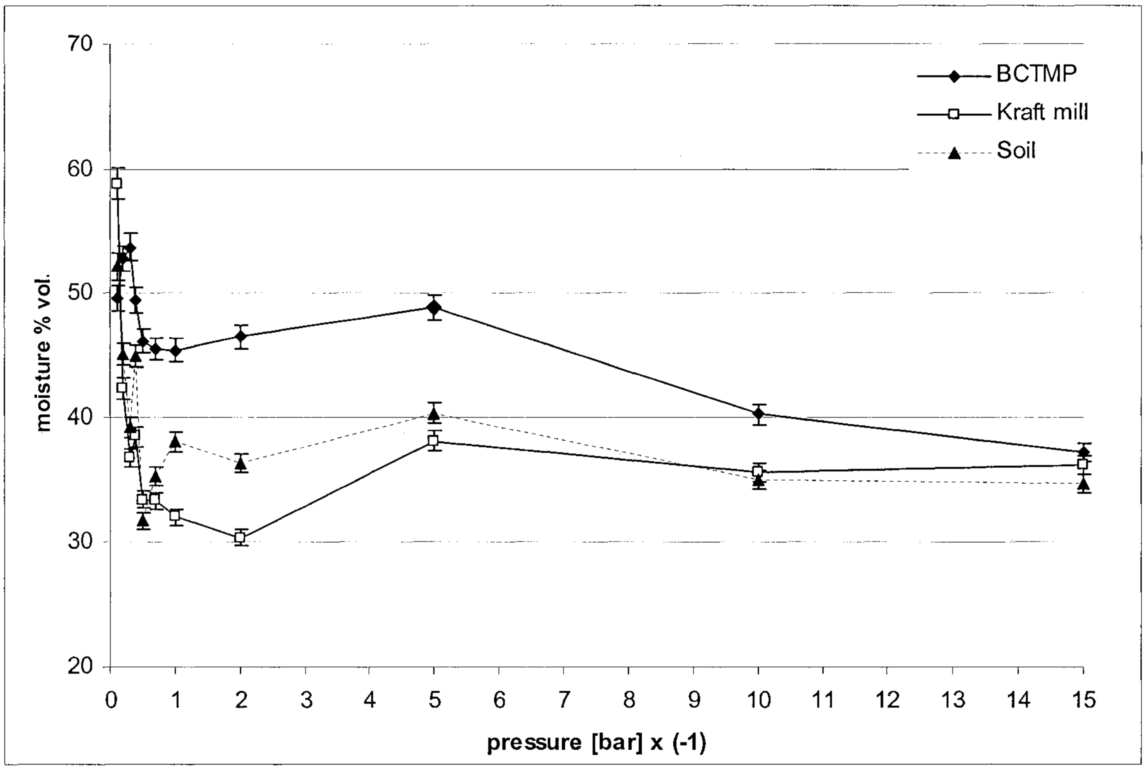


Figure 9: Moisture retention curves for BCTMP sludge, Kraft mill sludge and soil from 0.1 to 15 bar x (-1) with random errors.

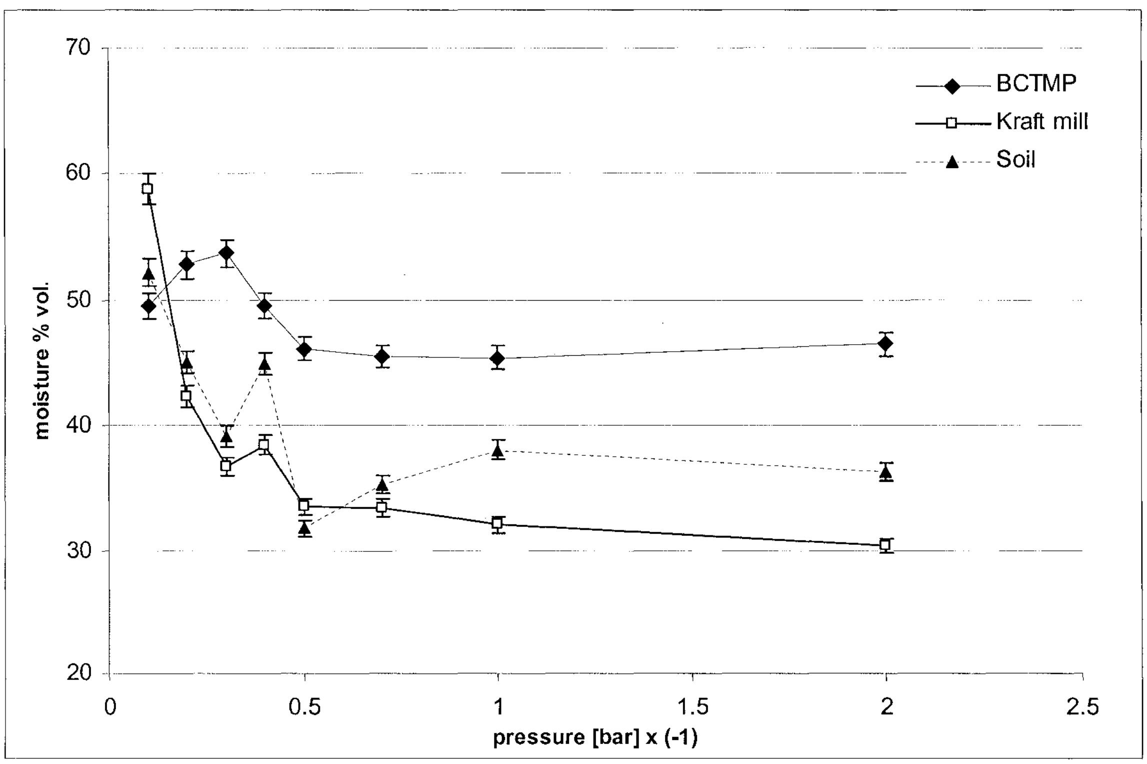


Figure 10: Moisture retention curves for BCTMP sludge, Kraft mill sludge and soil from 0.1 to 2.5 bar x (-1) with random errors.

Examination of the moisture retention curves of the sludge-soil mixtures support the findings from several field experiments, that organic matter increases the water retention in soil (Foley and Cooperband, 2002). BCTMP sludge-soil mixture 25:25 and Kraft mill sludge-soil mixture 30:20 have the highest volumetric moisture retention at -0.1 bar. The sludge-soil mixture 20:30 for BCTMP sludge, and the original Kraft mill sludge have the lowest volumetric moisture retention at -0.1 bar (Figures 11 to 14). Compared to the soil sample at field capacity (39%) and permanent wilting point (35%) Kraft mill sludge-soil mixtures increased volumetric moisture retention more than BCTMP sludge-soil mixtures. Wei et al. (1985) showed that biosolids additions increased water retention at low tensions in a silty clay loam soil, suggesting an increase in larger pores. Recently, Zibilske et al. (2000) showed that multiple applications of paper mill residuals significantly increased soil moisture holding capacity. Municipal solid waste compost addition to sandy soil increased water retention, but did not change plant available water (Turner et al., 1994).

Volumetric moisture content and random errors are summarized in Table 15 for BCTMP sludge-soil mixtures and in Table 16 for Kraft mill sludge-soil mixtures. Data for bulk density, moisture content, and error analysis are provided in appendix I. Bulk density of soil decreases with increasing amounts of sludge added. Overall the BCTMP and Kraft mill sludge-soil mixture bulk densities are similar (Tables 54 to 67, appendix I).

Both sludge samples have through all sludge-soil mixtures an outlier at 0.5 or 0.7 bar. The original sludge and soil samples show an outlier at 0.4 bar (Figure 9 and 10). This is not referring to a change of pressure plates as the experiment was conducted with a 1 bar ceramic plate up to and including 1 bar. At this point data collected are not sufficient to provide an explanation for the outliers. Further experiments with smaller pressure increments are necessary to explain the outliers.

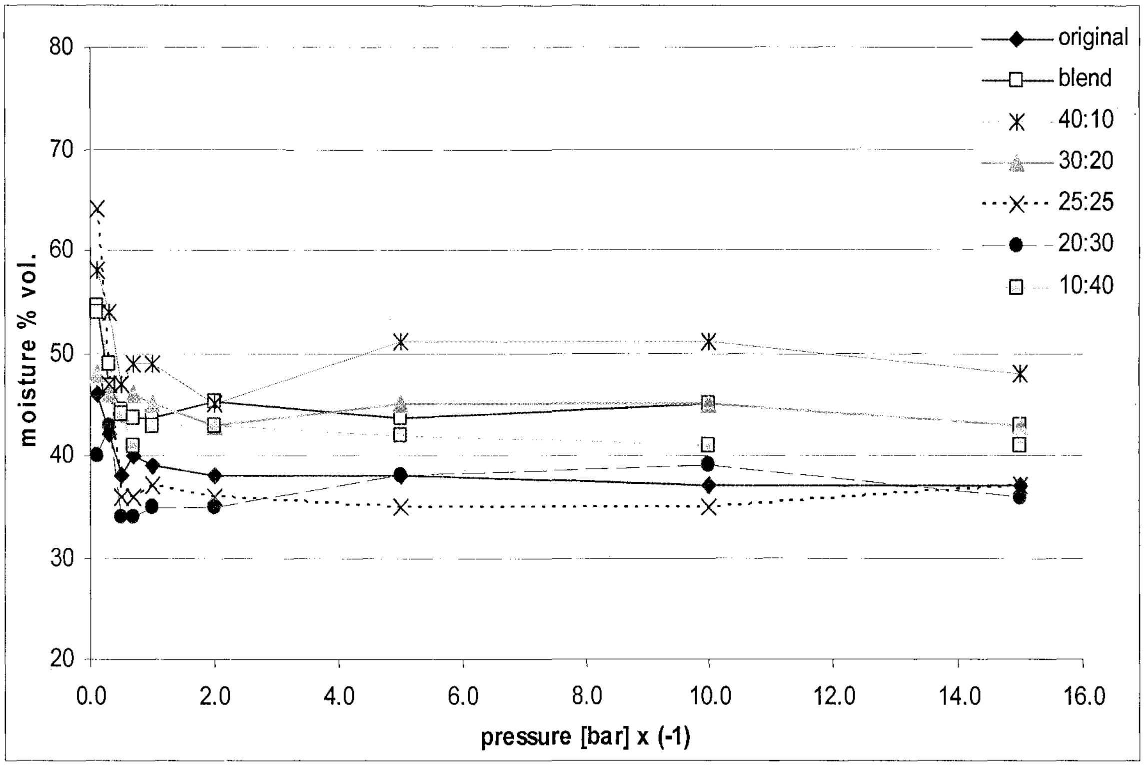


FIGURE 11: Moisture retention curves for BCTMP sludge-soil mixtures from 0.1 to 15 bar x (-1).

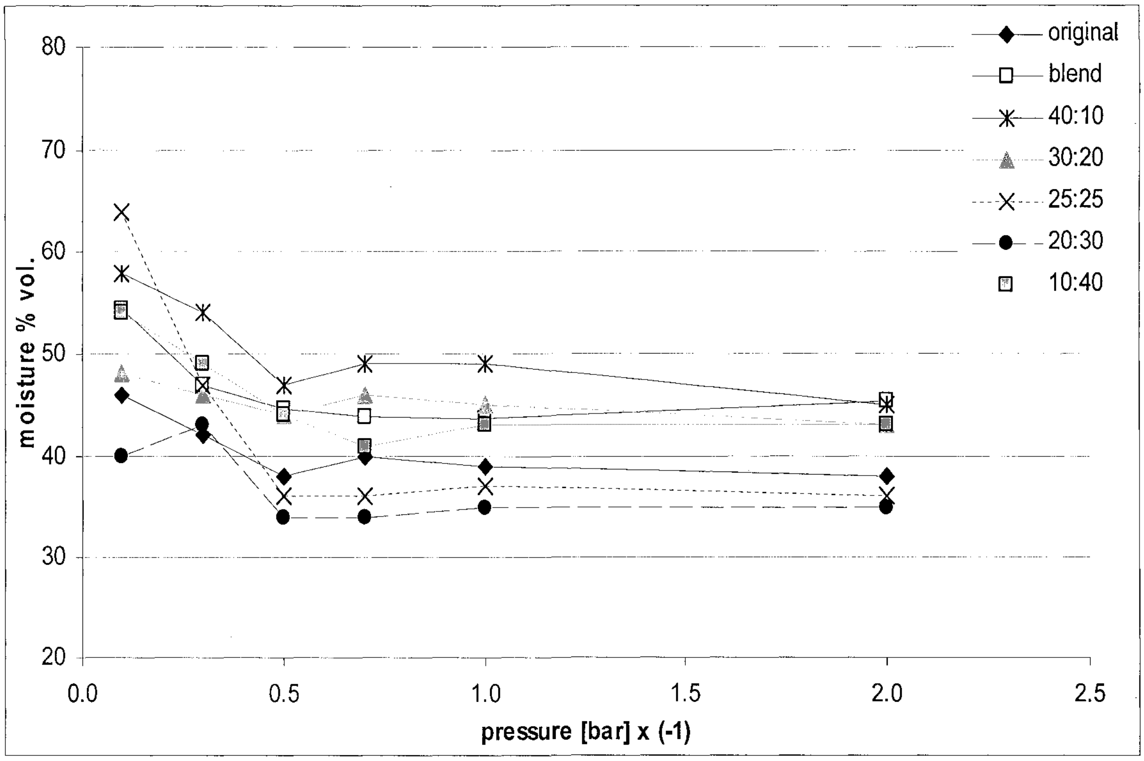


FIGURE 12: Moisture retention curves for BCTMP sludge-soil mixtures from 0.1 to 2.5 bar x (-1). (Enlarged graphs with error bars see appendix I, Figure 27 – 30)

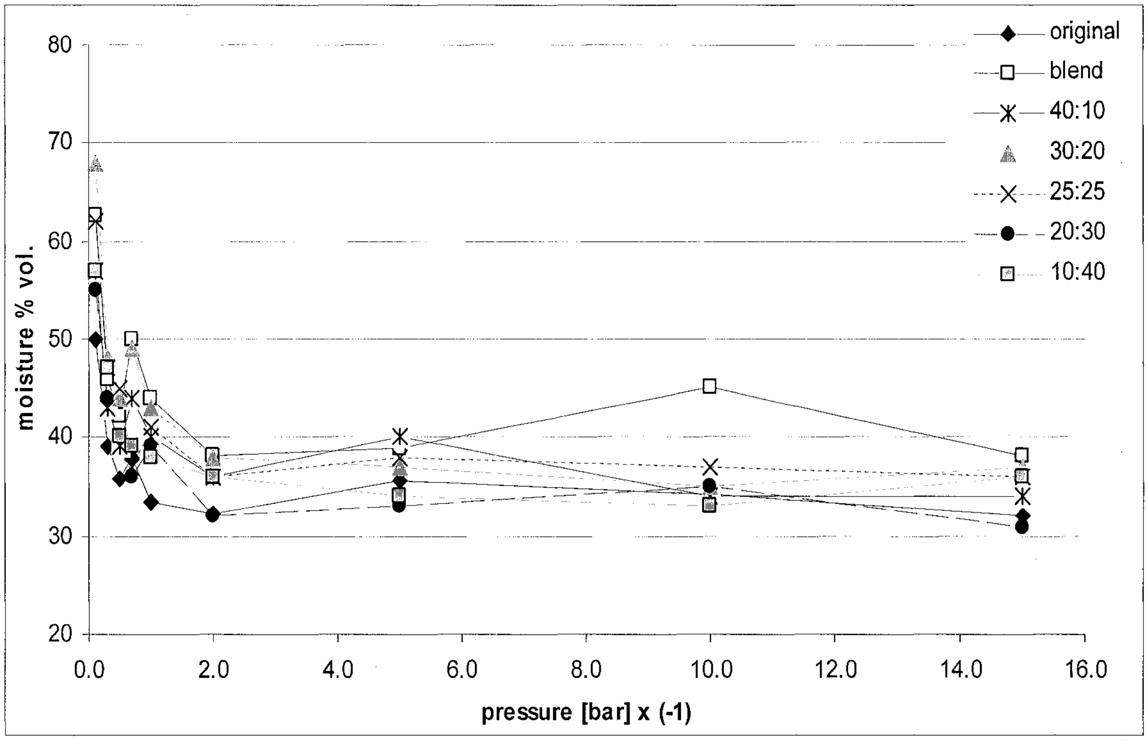


FIGURE 13: Moisture retention curves for Kraft mill sludge-soil mixtures from 0.1 to 15 bar x (-1).

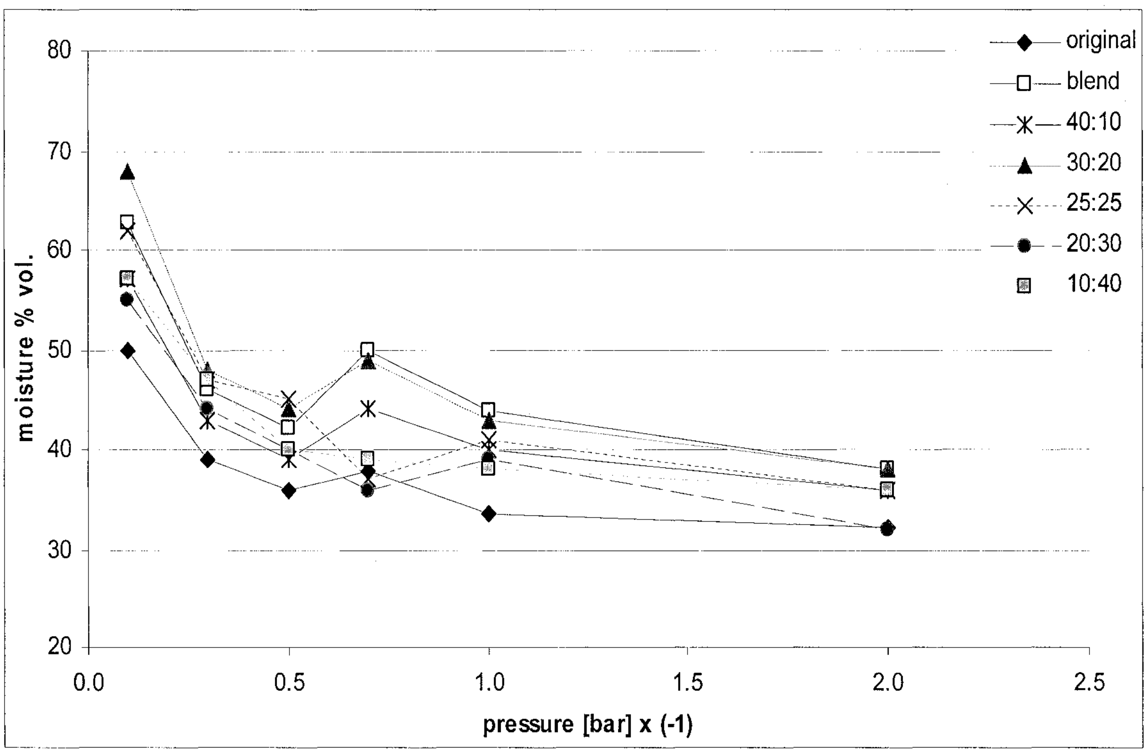


FIGURE 14: Moisture retention curves for Kraft mill sludge-soil mixtures from 0.1 to 2.5 bar x (-1). (Enlarged graphs with error bars see appendix I, Figure 19 – 22)

Moisture-retention-curves for BCTMP sludge-soil-mixtures

Table 15: Volumetric moisture retention curve data with random errors for BCTMP sludge-soil mixtures.

	pressure	moisture % vol.													
	[bar]	original	± *Δ WHC*$_v$	blend	± *Δ WHC*$_v$	40:10	± *Δ WHC*$_v$	30:20	± *Δ WHC*$_v$	25:25	± *Δ WHC*$_v$	20:30	± *Δ WHC*$_v$	10:40	± *Δ WHC*$_v$
	0.1	46	*0.94*	55	*1.11*	58	*1.18*	48	*0.99*	64	*1.31*	40	*0.81*	54	*1.10*
FC	0.3	42	*0.86*	47	*0.96*	54	*1.10*	46	*0.93*	47	*0.97*	43	*0.88*	49	*0.99*
	0.5	38	*0.78*	45	*0.91*	47	*0.96*	44	*0.90*	36	*0.73*	34	*0.69*	44	*0.90*
	0.7	40	*0.82*	44	*0.89*	49	*0.99*	46	*0.94*	36	*0.73*	34	*0.69*	41	*0.84*
	1.0	39	*0.79*	44	*0.89*	49	*0.99*	45	*0.90*	37	*0.75*	35	*0.71*	43	*0.87*
	2.0	38	*0.78*	45	*0.92*	45	*0.92*	43	*0.88*	36	*0.74*	35	*0.71*	43	*0.88*
	5.0	38	*0.74*	44	*0.89*	51	*1.05*	45	*0.91*	35	*0.72*	38	*0.77*	42	*0.85*
	10.0	37	*0.75*	45	*0.92*	51	*1.04*	45	*0.91*	35	*0.71*	39	*0.80*	41	*0.83*
PWP	15.0	37	*0.75*	43	*0.88*	48	*0.98*	43	*0.88*	37	*0.74*	36	*0.74*	41	*0.85*
AW		5	*0.80*	4	*0.93*	6	*1.02*	3	*0.92*	10	*0.82*	7	*0.75*	8	*0.90*

FC = Field Capacity; PWP = Permanent Wilting Point; AW = Available Water

Moisture-retention-curves for Kraft mill sludge-soil-mixtures

Table 16: Volumetric moisture retention curve data with random errors for Kraft mill sludge-soil mixtures.

	pressure	moisture % vol.													
	[bar]	original	± *Δ* WHC_v	blend	± *Δ* WHC_v	40:10	± *Δ* WHC_v	30:20	± *Δ* WHC_v	25:25	± *Δ* WHC_v	20:30	± *Δ* WHC_v	10:40	± *Δ* WHC_v
	0.1	50	*1.02*	63	*1.28*	57	*1.17*	68	*1.38*	62	*1.26*	55	*1.13*	57	*1.16*
FC	0.3	39	*0.80*	46	*0.94*	43	*0.89*	48	*0.98*	47	*0.95*	44	*0.90*	47	*0.97*
	0.5	36	*0.73*	42	*0.86*	39	*0.80*	44	*0.89*	45	*0.92*	40	*0.82*	40	*0.81*
	0.7	38	*0.77*	50	*1.02*	44	*0.89*	49	*1.01*	37	*0.75*	36	*0.73*	39	*0.97*
	1.0	33	*0.68*	44	*0.90*	40	*0.81*	43	*0.88*	41	*0.83*	39	*0.80*	38	*0.78*
	2.0	32	*0.66*	38	*0.78*	36	*0.73*	38	*0.77*	36	*0.74*	32	*0.65*	36	*0.73*
	5.0	36	*0.73*	39	*0.80*	40	*0.81*	37	*0.75*	38	*0.77*	33	*0.67*	34	*0.70*
	10.0	34	*0.70*	45	*0.92*	34	*0.69*	35	*0.71*	37	*0.75*	35	*0.71*	33	*0.67*
PWP	15.0	32	*0.66*	38	*0.78*	34	*0.69*	37	*0.76*	36	*0.74*	31	*0.63*	36	*0.73*
AW		7	*0.75*	8	*0.92*	9	*0.83*	11	*0.90*	11	*0.86*	13	*0.78*	11	*0.81*

FC = Field Capacity; PWP = Permanent Wilting Point; AW = Available Water

Bulk density decrease with addition of organic matter was reported in other studies (Chow et al., 2003; Foley and Cooperband, 2002; Nemati, 2000). With increasing organic matter, the bulk densities decreased and the porosity increased, thus the water retention at field capacity was greater. At the wilting point, the water retained is slightly lower, but exhibit similar trend. Foley and Cooperband (2002) reported a similar relationship between bulk density and water retention in soil from field experiments. The increase in water held at 0.3 bar is related to increased soil porosity, which allows the soil to hold more water. However, the increase in small pores improved the soil's ability to retain water at 15 bar (Foley and Cooperband, 2002).

Plant available water slightly increased for BCTMP sludge-soil mixtures 25:25, 20:30, and 40:10 compared to the original sludge sample (Table 15). Plant available water increased for all Kraft mill sludge-soil mixtures compared to the original sludge sample (Table 16). Evidence of greater pore-size distribution and a shift toward smaller pores is given by experimental findings from Bauer and Black (1992), suggesting that greater moisture retention at field capacity might be offset by greater moisture retention at the wilting point. These findings would support the plant available water results determined in the laboratory.

Table 17: Volumetric moisture content in % and bulk density in g/cm^3 of BCTMP sludge-soil mixtures.

	0.3 [bar] = FC		15.0 [bar] = PWP	
BCTMP	moisture % vol.	D_b [g/cm^3]	moisture % vol.	D_b [g/cm^3]
original	42	0.16	37	0.15
blend	47	0.18	43	0.18
40:10	54	0.33	48	0.33
30:20	46	0.42	43	0.45
25:25	47	0.55	37	0.48
20:30	43	0.57	36	0.58
10:40	49	0.95	41	0.97

Table 18: Volumetric moisture content in % and bulk density in g/cm^3 of Kraft mill sludge-soil mixtures.

	0.3 [bar] = FC		15.0 [bar] = PWP	
Kraft	moisture % vol.	D_b [g/cm^3]	moisture % vol.	D_b [g/cm^3]
original	39	0.13	32	0.14
blend	46	0.17	38	0.16
40:10	43	0.26	34	0.26
30:20	48	0.41	37	0.42
25:25	47	0.52	36	0.50
20:30	44	0.58	31	0.58
10:40	47	0.92	36	0.93

In this part of the experiment, the moisture content at 0.1 bar is an average of two replicates, and 0.3 and 15 bar are averages of three replicates. The available water is slightly higher for Kraft mill sludge and sludge-soil mixtures than for BCTMP sludge and sludge-soil mixtures. For Kraft mill sludge plant available water is highest (13%) with a sludge-soil mixture of 20:30. For BCTMP sludge it is highest (9%) with a 25:25 sludge-soil mixture.

The volumetric moisture content of the original sludge and soil samples measured first (Table 14) are slightly higher for both sludge samples than when measured with the sludge-soil mixtures (Table 15 and 16). BCTMP and Kraft mill sludge are similar in their overall ability to hold water. Nevertheless, BCTMP sludge has higher moisture content at field capacity for most sludge-soil mixtures except the mixtures 30:20 and 20:30. Volumetric moisture content decreases most over the entire pressure range compared to Kraft mill sludge. Preparing the samples in the column is the most crucial part of the experiment due to the different textures of the samples. This is probably reflected in the different results of the two trials.

The pressure plate experiment was also applied to sludge-soil layer systems. The samples were prepared following the description in 3.2.11.1 (Figure 3). As the overall height of the sample for the layer treatment was 6 cm instead of 1 cm used for original samples and sludge-soil mixtures. As the time required to reach equilibrium varies according to the square of the sample height, the layer systems never reached equilibrium. Gravimetric moisture content was determined after 14 days for 0.5, 1.0, and 5.0 bar. Results for the moisture content are summarized in Table 19 for BCTMP sludge-soil layer systems and in Table 20 for Kraft mill sludge-soil layer systems. Data for bulk density, moisture content, and error analysis are provided in appendix I (Table 82 to 85).

Layers of BCTMP sludge or layers of Kraft mill sludge have higher volumetric moisture content than the soil layer. In the layer systems, the BCTMP sludge layer has double the water holding capacity of soil. The Kraft mill sludge layer has a slightly higher or same water holding capacity compared to the soil layer. In the layer systems BCTMP sludge layer has more water holding capacity than Kraft mill sludge. Increasing the amount of layers is not affecting the overall moisture content. For both sludge samples volumetric moisture content remains similar throughout the sludge-soil layer systems. The soil layer surrounded by sludge layers in the 2 and 3 layer systems has similar moisture content as the first layer. This leads to the conclusion that water transmission was induced by surrounding sludge and soil layers. There is less change in moisture content of the soil layers than in the sludge layers.

As the equilibrium moisture content was not determined the data represent only a trend. The volumetric moisture content in the BCTMP sludge-soil layer systems is higher in the sludge layers at -0.5 bar compared to various sludge-soil mixtures and the original sludge samples. It is higher in the BCTMP sludge-soil layer systems than in the Kraft mill sludge-soil layer systems.

Table 19: Total volumetric moisture content of 1, 2, and 3 BCTMP sludge-soil layer systems at 0.5, 1.0, and 5.0 bar pressure.

pressure		**0.5 bar**			**1.0 bar**			**5.0 bar**	
		WHC_v [%]	**total WHC_v [%]**		**WHC_v [%]**	**total WHC_v [%]**		**WHC_v [%]**	**total WHC_v [%]**
BCTMP 1 layer	sludge	48			51			46	
	soil	30	39.2		24	37.5		29	37.2
BCTMP 2 layers	sludge 1	51			48			46	
	sludge 2	47			46			51	
	soil 1	25			24			24	
	soil 2	33	38.9		24	35.5		29	37.4
BCTMP 3 layers	sludge 1	42			53			40	
	sludge 2	39			43			36	
	sludge 3	38			40			40	
	soil 1	30			29			26	
	soil 2	36			33			33	
	soil 3	32	36.2		25	37.3		28	34.0

Table 20: Total volumetric moisture content of 1, 2, and 3 Kraft mill sludge-soil layer systems at 0.5, 1.0, and 5.0 bar pressure.

pressure		**0.5 bar**			**1.0 bar**			**5.0 bar**	
		WHC_v [%]	**total WHC_v [%]**		**WHCv [%]**	**total WHC_v [%]**		**WHCv [%]**	**total WHC_v [%]**
Kraft mill 1 layer	sludge	35			27			26	
	soil	28	31.8		30	28.4		28	26.7
Kraft mill 2 layers	sludge 1	38			35			31	
	sludge 2	34			31			26	
	soil 1	21			23			24	
	soil 2	28	30.3		29	29.4		29	26.8
Kraft mill 3 layers	sludge 1	35			33			28	
	sludge 2	36			38			28	
	sludge 3	25			29			24	
	soil 1	27			26			25	
	soil 2	27			31			24	
	soil 3	30	30.1		27	30.6		26	26.0

Water holding capacity determined by two different methods (i.e., soak and drain method and pressure plate experiment) show the same trends for all 3 sludge-soil treatments. The plain sludge samples have properties such as much lower bulk density and higher porosity than the soil sample. This results in higher water holding capacity in the sludge samples. For the sludge-soil mixtures either method showed, that with increasing organic matter, bulk density decreased and moisture retention increased. The experimental set-up of the pressure plate equipment has its limitations in the sample height. To analyze sludge-soil layer systems using the soak and drain method allows keeping the sample height the same throughout the entire experiment. Water holding capacity results can be compared. The pressure plate experiment is difficult and requires runs of more than one week duration with samples greater than 1 cm in height. The soak and drain method is less time consuming and replicates can be added more easily. More specific information, such as percent of plant available water, can be determined with the pressure plate experiment. The most crucial part of the experiment is the packing of the columns. Soil and sludge are very different in structure. Soil being composed of smaller and more uniform particles than sludge can be packed in the column evenly. Sludge being composed of different types of fibers is more difficult to pack without defined compaction. This is reflected in the error analysis for bulk density determination.

The topsoil or vegetative layer is part of a landfill capping system. The main purpose of this system is to prevent infiltration and build the basis for environmental restoration of the landfill area. The vegetative layer is exposed to heavy rainfalls, desiccation, and freeze/thaw cycles. These events can cause severe damage to the cover. The top layer is most vulnerable during germination and seedling growth time. Sludge amended to soil could improve the performance of the topsoil layer. The experimental findings show, that organic matter decreases bulk density and increases porosity. The sludge amendment changes the soil structure by increasing the amount of macropores, resulting in higher water retention capacity (Foley and Cooperband, 2002). The changes in pore-size distribution increase the soil stability and resistance to environmental impacts, especially heavy rainfalls (Nemati, 2000). Erosion and soil loss problems caused by heavy rainfalls and stormwater runoff could be reduced as the sludge amended soil increases the water storage. Under simulated rainfall the beneficial effects of a 4% organic matter treatment with a gravelly loam soil include 2.1 times delay in runoff initiation, and 23 and 71% reduction in runoff and soil loss (Chow et al., 2003). The most concentrated location of erosive forces on landfills occurs in the structures that convey water from the top of the cap to the base of the side slopes (Cabalka, 1996). Desiccation cracking and deterioration due to freeze/thaw cycles could also be minimized by the change in the aggregation of the soil. Sludge could replace the hydraulic mulch typically applied that offers a short-term (four- to eight-week) service life to assist germination and seedling growth. Despite the advantages of the physical properties of sludge amended soils, other amendments like compost, biosolids, or manure need to be considered to provide nitrogen.

Ecological and economical evaluation of sludge amendment depends on regional conditions. Costs for implementing the topsoil layer in general includes topsoil mixing and placing, hydroseeding, and erosion control matting are approximately CAD 10.00/m^2. One quarter of this price is spent on erosion control matting. The Prince George Regional District Landfill has a surface cover area of 49,886 m^2. The top layer has a minimum thickness of 60 cm. The construction, maintenance and after closure costs of a landfill can be minimized, by using adequate alternative materials, which are locally available.

Reduction of the deposition of organic wastes is one of the main goals of a municipal solid waste landfill. Organic wastes account for most of the landfill gas and leachate problems as well as settlement problems. After the closure of a landfill, the settlement problems affect the cover system including the top layer. Beyond financial concerns, the reuse of sludge would reduce the input of organic matter to the landfill, and save ever-shrinking landfill space. Sludge requires only basic equipment like a manure spreader and bulldozer for placement. The high moisture content is ideal for placing and spreading. Cap construction with sludge can proceed under a broader range of weather conditions. Sludge amended soils readily absorb large quantities of rainfall reducing infiltration to the protective layer and storing water for vegetation growth during dry periods.

All field studies were long-term experiments persisting between 1 and 7 years. Even though more parameters like depth of water penetration and percolation time can be determined in field experiments, the laboratory results of the moisture retention determination are a concise alternative to predict amending effects in soil. A number of functional forms were considered to describe the relationship between water content and matric potential. None of the current functions adequately describe the data. An acceptable function should provide minimum order of polynomial with a maximum accuracy.

Chapter 5 Summary

The objective of this study was to chemically and physically characterize sludge from two different pulping processes to investigate their suitability as a substitute or amendment in the topsoil layer of a landfill capping system. The purposes of the topsoil layer are to enhance plant vegetation, moisture retention, and minimize infiltration and chances of cracks followed by erosion and associated with infiltration problems.

Pulp mill sludge represents the waste portion of the pulping process. As the wood input, the wood processing and the subsequent effluent treatment varies greatly, so does the composition of the sludge. To identify potential environmental impacts, elemental analysis was performed and the results compared to literature data from a mill survey (NACSI, 2000) and typical nutrient concentrations sufficient for plant growth (Barak, 1999). The BCTMP and Kraft mill sludge samples analyzed are low in potential environmental contaminants. These results support previous findings.

Both sludge samples have high C:N ratios. The low nitrogen content often limits the effectiveness of sludge as soil amendment. The N limitation could be alleviated with appropriate fertilization and application rates. The type of sludge under consideration will determine the fertilizer composition to enhance plant growth.

As the pH controls more or less nutrient availability, the neutral pH of BCTMP sludge and alkaline pH of Kraft mill sludge could cause a deficiency for micronutrients, eg. Fe, Zn that are important for plant growth. The pH could be altered by mixing sludge with other material or determining appropriate loading rates. Mixtures of compost, or biosolids, or boiler ash with sludge have been used successfully as forestry soil amendment (NACSI, 2000).

Sludge is composed mainly of organic matter. Various studies found that organic amendments increase soil aggregation and stability, reduce bulk density, and increase water holding capacity. This contribution of organic matter was investigated.

Soil has the highest bulk density, followed by BCTMP and Kraft mill sludge. The original sludge samples have a higher bulk density than the blended samples. Blending the sludge affects the fibre structure, resulting in lower bulk density.

Water holding capacity was determined by gravity and moisture retention curves were established for original sludge and soil samples, various sludge-soil mixtures and sludge-soil layer systems. In both experiments the blended sludge samples had the highest water holding capacity and soil had the lowest. The sludge-soil mixtures demonstrated increasing water holding capacity with increasing amounts of sludge added to soil. The water holding capacity in the sludge-soil layer systems is lower in the sludge layers than in the sludge-soil mixtures and the original sludge samples.

The moisture retention curves of BCTMP and Kraft mill sludge are similar in their overall ability to hold water. BCTMP sludge, however, has higher moisture content at field capacity and its moisture content decreases most over the entire pressure range compared to Kraft mill sludge. The BCTMP sludge has the most plant available water. The pressure plate experiment could not be applied successfully to the sludge-soil layer system as with increasing sample height, the time to reach equilibrium increases exponentially.

Laboratory experiments are a short-time, concise alternative to field studies and the results can assist predicting the effect of sludge amendment to soil. The laboratory findings should be validated by field studies to determine their application to real world conditions. Kraft mill sludge and soil have similar water holding capacities. Compared to Kraft mill sludge BCTMP sludge has a higher water holding capacity, resulting in high water retention and higher amount of plant available water. Increasing organic matter amendment reduces soil bulk density and increases soil microbial activity, which increases soil porosity. This alteration in soil physical properties is a consequence of the pore size distribution of sludge and soil particles. These attributes of the sludge are improving the performance of the topsoil layer with less environmental impact than the current disposal options. Sludge could provide coverage for landfill cap erosion control and vegetation needs. Another advantage for construction is the nature of the sludge, no further treatment or special equipment is needed. Such use would reduce expenses on mill and landfill budgets while conserving significant amount of valuable landfill space.

The results and conclusions from this study are not necessarily applicable to any sludge in the pulp and paper industry. Based on this work it is recommended that any end user contemplating using sludge in a landfill capping system should consider chemical and physical characteristics of the sludge under consideration. The most important parameter is the economic feasibility.

Chapter 6 Recommendations for future work

Sludge amendments have the potential to protect the soil during critical periods of vegetation establishment, thus reducing on-site damages and costs as well as reducing off-site impacts on water quality.

1. Samples should be collected over a longer period of time, and mixed to have a more representative sample for the experiments of interest.

2. Organic matter plays a fundamental role in the stabilization of soil structure and the formation of pores. Other physical properties of interest to further realize the potential of sludge as soil amendment are the effects of freezing and thawing cycles and shear strength of the samples.

3. Field experiments should be implemented to confirm laboratory results on water holding capacity (WHC) including important parameters like time and depth of water infiltration after a wetting event.

4. Different treatments of sludge (mixtures and layer systems) should be investigated in field studies to determine the most effective application of sludge. Future studies should include various sludge application rates, as well as other amendments to increase plant available N. The process in a pulp mill can change daily to effect the properties of sludge produced. The type of sludge determines the fertilizer composition.

5. Investigations on sludge decomposition and changes in C:N ratios over time should be conducted to assess consequences of sludge amendments.

6. Mathematical retention functions could be applied to express the relationship of moisture content and matric potential and predict retention characteristics of sludge.
7. The time to reach equilibrium is a crucial factor for the sludge-soil layer systems. Future laboratory experiments should investigate whether different physical set ups for the samples could reduce the time for equilibrium. Factors such as using plastic columns with smaller diameter and compacting the sample under defined conditions could be explored.
8. To get a better understanding of the pore-size distribution in sludge-soil mixtures, samples of the mixtures should be observed under different magnifications under the scanning electron microscope (SEM). Aggregation size could be determined and compared to original sludge and soil samples.
9. The success of plant growth in the topsoil layer depends on various factors such as soil quality, climate, and plant species. Research on various plant species should be conducted to determine adequate species for successful long-term revegetation.

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Appendix A: Glossary

BCTMP: bleached chemi-thermomechanical pulping uses physical forces with some additional heat and/or chemicals to separate wood fibers.

Capping system: a combination of several layers of diverse material for the final closure of a landfill.

Dioxins: any of a group of chemical compounds that is an undesirable by-product in the manufacture of herbicides, disinfectants, and other agents. In popular terminology, dioxin has become a synonym for one specific dioxin 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD) *from Encyclopaedia Britannica*.

EPA: United States Environmental Protection Agency, responsible for protecting human health and safeguarding the natural environment.

ICP-AES: Inductively coupled plasma-atomic emission spectroscopy is a quantitative analytical technique for the determination of trace elements in samples.

Kraft pulping: chemical pulping process, also known as alkaline or sulphate process. It is the most common method used in the pulp and paper industry.

MoELP: Ministry of Environment, Lands and Parks committed to protecting and enhancing the quality of British Columbia's environment; *now* Ministry of Water, Land and Air Pollution and Ministry of Sustainable Resource Management.

NCASI: National Council for Air and Stream Improvement; Research Triangle Park in North Carolina serving the forest industry

Original sludge: sludge sample as received from the mill without any treatment.

SEM: scanning electron microscope

Appendix A: Glossary

Sludge: wastewater treatment plant solid residuals are those solid materials collected in the process of treating water used in the mill prior to release into the environment. Typically, these materials consist of solids collected in primary treatment (separation of solids from raw wastewater) and secondary treatment (biological treatment followed by clarification to separate biosolids). Often these primary and secondary residuals are combined to facilitate handling (NCASI, 1999).

TAPPI: Technical Association of the Pulp and Paper Industry

Turpenes: By-product from the Kraft pulping process; a mixture of turpenes consists of monoterpenes and pinenes. The basic structural unit is isoprene (C_5H_8).

UNBC: University of Northern British Columbia

WHC: Water holding capacity or water retention or field capacity or soil wetness characteristics are all expressions for the soils ability to store water.

Appendix B: Determination of moisture content in sludge samples

TABLE 21: Kraft mill sludge dried at 55 °C (n=8); *uncertainty ± 0.0001*

#	W_{Al} Al dish [g]	W + sludge wet [g]	W_t + sludge dry [g]	W_w sludge wet [g]	W_d sludge dry [g]	θ moisture content [%]
1	3.1473	9.7137	5.7337	6.5664	2.5864	154
2	3.1389	9.9190	5.7402	6.7801	2.6013	161
3	3.1339	10.1768	5.7500	7.0429	2.6161	169
4	3.1354	9.8010	5.6838	6.6656	2.5484	162
5	3.1462	9.9072	5.7202	6.7610	2.5740	163
6	3.1463	10.1450	5.7366	6.9987	2.5903	170
7	3.1646	10.0738	6.0092	6.9092	2.8446	143
8	3.1458	10.0532	5.7814	6.9074	2.6356	162
average						*160*
stdev						*8.72*
se						*± 3.08*

TABLE 22: Kraft mill sludge dried at 80 °C (n=8); *uncertainty ± 0.0001*

#	W_{Al} Al dish [g]	W + sludge wet [g]	W_t + sludge dry [g]	W_w sludge wet [g]	W_d sludge dry [g]	θ moisture content [%]
1	3.1232	10.6888	5.8524	7.5656	2.7292	177
2	3.1358	10.6486	5.8102	7.5128	2.6744	181
3	3.1456	10.3413	5.5443	7.1957	2.3987	200
4	3.1397	11.0038	5.9415	7.8641	2.8018	181
5	3.1541	11.1413	5.9925	7.9872	2.8384	181
6	3.1466	10.5190	5.7488	7.3724	2.6022	183
7	3.1377	10.5869	5.8402	7.4492	2.7025	176
8	3.1554	11.1696	5.9508	8.0142	2.7954	187
average						*183*
stdev						*7.58*
se						*± 2.68*

TABLE 23: Kraft mill sludge dried at 105 °C (n=8); *uncertainty ± 0.0001*

#	W_{Al} Al dish [g]	W + sludge wet [g]	W_t + sludge dry [g]	W_w sludge wet [g]	W_d sludge dry [g]	θ moisture content [%]
1	3.1200	9.9696	5.8332	6.8496	2.7132	152
2	3.1300	9.5982	5.7059	6.4682	2.5759	151
3	3.1405	10.0065	5.7522	6.8660	2.6117	163
4	3.1354	10.0875	5.6582	6.9521	2.5228	176
5	3.1497	10.2195	5.7845	7.0698	2.6348	168
6	3.1423	10.1312	5.7506	6.9889	2.6083	168
7	3.1317	10.7912	5.8949	7.6595	2.7632	177
8	3.1524	9.9102	5.7439	6.7578	2.5915	161
average						*165*
stdev						*9.65*
se						*± 3.41*

Appendix B: Determination of moisture content in sludge samples

TABLE 24: BCTMP sludge dried at 55 °C (n=8); *uncertainty ± 0.0001*

#	W_{Al} Al dish [g]	W + sludge wet [g]	W_t + sludge dry [g]	W_w sludge wet [g]	W_d sludge dry [g]	θ moisture content [%]
1	3.1356	10.0053	5.8749	6.8697	2.7393	151
2	3.1738	10.1558	5.9669	6.9820	2.7931	150
3	3.1574	10.1315	5.9270	6.9741	2.7696	152
4	3.1677	10.1080	5.8984	6.9403	2.7307	154
5	3.1583	10.4646	6.0204	7.3063	2.8621	155
6	3.1492	10.4175	5.9833	7.2683	2.8341	156
7	3.1516	10.0293	5.8311	6.8777	2.6795	157
8	3.1429	10.0700	5.8303	6.9271	2.6874	158
average						*154*
stdev						*2.93*
se						*± 1.04*

TABLE 25: BCTMP sludge dried at 80 °C (n=6); W* =porcelain dish; *uncertainty ± 0.0001*

#	W* dish [g]	W + sludge wet [g]	W_t + sludge dry [g]	W_w sludge wet [g]	W_d sludge dry [g]	θ moisture content [%]
1	55.5007	60.8127	56.9204	5.3120	1.4197	274
2	55.0895	60.2873	56.4515	5.1978	1.3620	282
3	56.2052	61.4097	57.5833	5.2045	1.3781	278
4	54.9497	60.1029	56.3158	5.1532	1.3661	277
5	55.9984	61.2109	57.3514	5.2125	1.3530	285
6	57.1587	62.1692	58.4543	5.0105	1.2956	287
average						*280*
stdev						*4.93*
se						*± 2.01*

TABLE 26: BCTMP sludge dried at 105 °C (n=8); *uncertainty ± 0.0001*

#	W_{Al} Al dish [g]	W + sludge wet [g]	W_t + sludge dry [g]	W_w sludge wet [g]	W_d sludge dry [g]	θ moisture content [%]
1	3.1345	9.8600	5.6825	6.7255	2.5480	164
2	3.1721	10.8150	6.0112	7.6429	2.8391	169
3	3.1554	9.9368	5.7962	6.7814	2.6408	157
4	3.1645	10.0964	5.8488	6.9319	2.6843	158
5	3.1565	10.3138	5.8411	7.1573	2.6846	167
6	3.1469	10.0852	5.7983	6.9383	2.6514	162
7	3.1496	10.9675	6.0881	7.8179	2.9385	166
8	3.1408	10.0391	5.6857	6.8983	2.5449	171
average						*164*
stdev						*5.04*
se						*± 1.78*

Appendix C: Determination of total C and total N

TABLE 27: Total carbon and nitrogen raw data (*n=4*)

	sample	total N %	total C %			sample	total N %	total C %
trial 1	Kraft mill sludge (1)	0.00	44.01		trial 1	BCTMP sludge (1)	1.18	53.59
trial 1	Kraft mill sludge (2)	0.00	44.56		trial 1	BCTMP sludge (2)	1.16	53.73
trial 2	Kraft mill sludge (1)	0.14	39.66		trial 2	BCTMP sludge (1)	1.47	50.06
trial 2	Kraft mill sludge (2)	0.12	43.65		trial 2	BCTMP sludge (2)	1.32	51.62
	average	*0.07*	*42.97*			*average*	*1.28*	*52.25*
	stdev	*0.08*	*2.24*			*stdev*	*0.14*	*1.75*
	± se	*0.04*	*1.12*			*± se*	*0.07*	*0.87*

Appendix D: Determination of ash content in sludge and soil samples

TABLE 28: Ash content of sludge and soil samples
(BCTMP and Kraft mill ash samples were weighed with lid. Soil ash samples were weighed without lid.)

			n=3			*n=3*			*n=3*
sample	BCTMP (1)	BCTMP (2)	BCTMP (3)	Kraft mill (1)	Kraft mill (2)	Kraft mill (3)	soil (1)	soil (2)	soil (3)
crucible + lid [g]	85.1951	87.3807	90.6643	85.9560	85.8533	85.8868	85.9571	85.8522	85.8868
crucible [g]	54.9472	55.9816	57.1441	55.4978	55.0871	56.1963	55.4977	55.0868	56.1967
crucible+sample[g]	56.5230	57.5132	58.6368	56.6113	56.5255	57.5989	56.8018	56.5075	57.5212
sample wet [g]	1.5758	1.5316	1.4927	1.1135	1.4384	1.4026	1.3041	1.4207	1.3245
dried at 105° C	55.3414	56.3607	57.5114	55.7878	55.4718	56.5761	56.6137	56.3030	57.3372
sample dry [g]	0.3942	0.3791	0.3673	0.2900	0.3847	0.3798	1.1160	1.2162	1.1405
ash after 4h [g]	85.2124	87.3989	90.6799	85.9670	85.8703	85.9068	56.5917	56.2796	57.3151
ash after 6h [g]	85.2109	87.3969	90.6781	85.9657	85.8682	85.9036	56.5932	56.2812	57.3170
ash after 8h [g]	85.2123	87.3984	90.6796	85.9678	85.8698	85.9052	56.5915	56.1850	57.3153
ash [g]	0.0172	0.0177	0.0153	0.0118	0.0165	0.0184	1.0938	1.0982	1.1186
ash content %	4.36	4.67	4.17	4.07	4.29	4.84	98.01	90.30	98.08
average %			*4.40*			*4.40*			*95.5*
stdev			*0.254*			*0.400*			*4.47*
se			*± 0.146*			*± 0.231*			*± 2.58*

Appendix E: Energy Dispersive X-ray Analysis

TABLE 29: Elemental analysis of Kraft mill sludge; elements are expressed in relative percentage.

A:\Kraft Mill.SPC

Acquisition Time : 08:54:34 Date : 15-Mar- 2

kV:20.00 Tilt: 0.00 Take-off:20.0(Tc:40

Detector Type :SUTW Resolution :151.58 Lsec :183

EDAX ZAF Quantification Standardless
Element Normalized

Element	Wt %	At %	K-Ratio	Z	A	F
C K	68.89	75.72	0.3817	1.008	0.5495	1.0002
O K	26.27	21.68	0.0395	0.9912	0.1518	1.0001
NaK	3.69	2.12	0.012	0.928	0.3499	1.0001
SiK	0.77	0.36	0.0056	0.9508	0.7714	1.0001
S K	0	0	0	0.9292	0.9486	1.0003
K K	0	0	0	0.8981	1.0462	1.0014
CaK	0.38	0.13	0.0037	0.9198	1.0541	1
Total	100	100				

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
C K	7.87	0.64	2.74	12.24
O K	1.28	1.99	10.43	0.64
NaK	0.93	3.6	16.86	0.26
SiK	0.5	2.45	25.56	0.2
S K	0	2.1	0	0
K K	0	1.57	0	0
CaK	0.22	1.3	41.76	0.17

K-Ratio - constant
Z, A, F - correction factors: Z= atomic number
A= absorption factor
F= fluorescence

Appendix E: Energy Dispersive X-ray Analysis

TABLE 30: Elemental analysis of BCTMP sludge; elements are expressed in relative percentage.

A:\BCTMP.spc

Acquisition Time : 09:09:03 Date : 15-Mar- 2

kV:20.00 Tilt: 0.00 Take-off:20.00 Tc:40
Detector Type :SUTW Resolution :151.58 Lsec :37

EDAX ZAF Quantification Standardless
Element Normalized

Element	Wt %	At %	K-Ratio	Z	A	F
C K	58.2	65.95	0.3105	1.0092	0.5284	1.0003
O K	38.02	32.34	0.064	0.9925	0.1696	1
NaK	1.42	0.84	0.0041	0.9292	0.3112	1.0001
SiK	0.33	0.16	0.0023	0.952	0.7503	1.0005
S K	0.25	0.11	0.0022	0.9307	0.942	1.0012
K K	0.55	0.19	0.0052	0.8994	1.0419	1.0042
CaK	1.23	0.42	0.0118	0.9212	1.046	1
Total	100	100				

Element	Net Inte.	Bkgd Inte.	Inte. Error	P/B
C K	108.15	2.32	1.58	46.58
O K	35.01	8.39	3.06	4.17
NaK	5.38	14.59	13.49	0.37
SiK	3.48	20.13	22.66	0.17
S K	2.69	14.8	25.24	0.18
K K	5.54	10.05	11.58	0.55
CaK	11.69	9.82	6.44	1.19

K-Ratio - constant
Z, A, F - correction factors: Z= atomic number
A= absorption factor
F= fluorescence

Appendix F: Cation exchange capacity

TABLE 31: Effective cation exchange capacity and exchangable Al, Fe, K, Mg, Mn, and Na for BCTMP and Kraft mill sludge and soil samples.

(Analysis was conducted by British Columbia Ministry of Forests Research Laboratory, Analytical Chemistry Section)

Sample	Exch Al cmol+/kg	Exch Ca cmol+/kg	Exch Fe cmol+/kg	Exch K cmol+/kg	Exch Mg cmol+/kg	Exch Mn cmol+/kg	Exch Na cmol+/kg	CEC (Ba) cmol+/kg Effective
soil 1	0.002	9.474	< 0.001	0.300	5.231	0.04	0.196	15.24
soil 2	0.009	9.328	0.003	0.294	5.142	0.04	0.195	15.01
soil 3	0.009	9.629	0.001	0.302	5.318	0.04	0.212	15.51
average	*0.007*	*9.477*	*0.001*	*0.299*	*5.230*	*0.040*	*0.201*	*15.25*
stdev	*0.004*	*0.151*	*0.001*	*0.004*	*0.088*	*0.001*	*0.010*	*0.250*
se	*± 0.0013*	*± 0.0503*	*± 0.0003*	*± 0.0013*	*± 0.0293*	*± 0.0003*	*± 0.0033*	*± 0.0833*
BCTMP 1	0.036	26.793	0.006	0.755	3.456	0.06	4.124	35.23
BCTMP 2	0.037	27.082	0.006	0.761	3.492	0.06	4.163	35.60
BCTMP 3	0.037	26.585	0.005	0.743	3.422	0.06	4.058	34.91
average	*0.037*	*26.820*	*0.006*	*0.753*	*3.457*	*0.061*	*4.115*	*35.25*
stdev	*0.001*	*0.250*	*0.001*	*0.009*	*0.035*	*0.001*	*0.053*	*0.345*
se	± 0.0003	± 0.0833	± 0.0003	± 0.0030	± 0.0117	± 0.0003	± 0.0177	± 0.1150
Kraft mill 1	< 0.001	13.015	< 0.001	0.474	5.428	0.07	0.686	19.66
Kraft mill 2	< 0.001	13.174	< 0.001	0.474	5.413	0.07	0.721	19.84
Kraft mill 3	< 0.001	12.996	< 0.001	0.435	5.385	0.07	0.729	19.61
average	*< 0.001*	*13.062*	*< 0.001*	*0.461*	*5.409*	*0.070*	*0.712*	*19.70*
stdev	*< 0.001*	*0.098*	*< 0.001*	*0.023*	*0.022*	*0.001*	*0.023*	*0.121*
se	*± 0.0003*	*± 0.0327*	*± 0.0003*	*± 0.0077*	*± 0.0073*	*± 0.0003*	*± 0.0077*	*± 0.0403*

Appendix G: Elememtal analysis

TABLE 32: Elemental analysis of oven-dried BCTMP and Kraft mill sludge by ICP-AES. (Aluminium, Boron, Calcium, Cadmium, Cobalt, Chromium, Copper, Iron, Potassium, Magnesium, Manganese, Molybdenium, Sodium, Nickel, Phosphorus, Lead, Zinc).

[1]BDL = below detection limit

Element	Detection Limit [ppm]	Kraft mill [μg/g]	stdev (*n=4*)	± se	BCTMP [μg/g]	stdev	± se (*n=4*)
Aluminum	0.068	702	46.4	23.2	295	23.7	11.9
Boron	0.01	0.672	0.604	0.302	62.0	1.28	0.642
Calcium	0.009	5931	238	119	7936	86.6	43.3
Cadmium	0.008	0.088	0.106	0.053	0.232	0.241	0.121
Cobalt	0.05	0.582	0.416	0.208	1.491	1.171	0.585
Chromium	0.025	4.97	1.63	0.816	13.52	4.59	2.30
Copper	0.006	14.51	3.58	1.79	7.87	1.80	0.90
Iron	0.007	587	35.0	17.5	312	37.4	18.7
Potassium	0.5	72.8	54.6	27.3	277	56.4	28.3
Magnesium	0.003	1795	36.4	18.2	478	21.4	10.7
Manganese	0.001	89.0	9.99	4.99	28.6	1.06	0.529
Molybdenium	0.062	[1]BDL	–	–	[1]BDL	–	–
Sodium	0.05	162	30.7	15.36	904	49.8	24.9
Nickel	0.019	1.819	1.488	0.752	8.088	13.75	6.961
Phosphorus	0.35	41.2	54.4	27.2	932	123	61.4
Lead	0.125	4.09	2.75	1.38	[1]BDL	–	–
Zinc	0.012	30.5	10.1	5.08	28.4	1.84	0.910

Appendix H: Determination of gravimetric water holding capacity

Part A: Bulk density

TABLE 33: Raw data for sludge and soil samples; (n=5)

sample	column empty [g]	column&sludge [g]	mass wet [g]	height [cm]	volume [cm^3]
Kraft mill sludge 1	63.372	112.052	48.680	4.1	153.23
Kraft mill sludge 2	63.778	114.602	50.824	4.0	149.50
Kraft mill sludge 3	63.170	111.812	48.642	4.0	149.50
Kraft mill sludge 4	63.502	111.844	48.342	3.9	145.76
Kraft mill sludge 5	63.842	112.176	48.334	4.0	149.50
BCTMP sludge 1	63.504	129.685	66.181	3.9	145.76
BCTMP sludge 2	63.360	130.935	67.575	3.8	142.02
BCTMP sludge 3	63.600	132.065	68.465	4.0	149.50
BCTMP sludge 4	65.150	133.835	68.685	3.9	145.76
BCTMP sludge 5	65.578	134.275	68.697	3.8	142.02
Soil 1	63.566	220.510	156.944	3.8	142.02
Soil 2	64.194	213.270	149.076	3.7	138.28
Soil 3	63.272	215.632	152.360	3.7	138.28
Soil 4	63.494	213.062	149.568	3.7	138.28
Soil 5	63.850	214.690	150.840	3.7	138.28

TABLE 34: Raw data for Kraft mill sludge-soil mixtures; (n=3)

sample	column empty [g]	column&sludge [g]	mass wet [g]	height [cm]	volume [cm^3]
Kraft mill/soil 10:40; 1	63.918	142.585	78.667	3.7	138.28
Kraft mill/soil 10:40; 2	63.586	135.540	71.954	3.5	130.81
Kraft mill/soil 10:40; 3	63.446	138.380	74.934	3.5	130.81
Kraft mill/soil 20:30; 1	63.282	113.336	50.054	3.7	138.28
Kraft mill/soil 20:30; 2	63.728	114.504	50.776	3.7	138.28
Kraft mill/soil 20:30; 3	63.156	113.050	49.894	3.5	130.81
Kraft mill/soil 25:25: 1	63.392	113.322	49.930	3.9	145.76
Kraft mill/soil 25:25: 2	63.812	114.260	50.448	3.9	145.76
Kraft mill/soil 25:25: 3	63.346	113.900	50.554	3.8	142.02
Kraft mill/soil 30:20; 1	64.342	114.702	50.360	4.0	149.50
Kraft mill/soil 30:20; 2	63.234	112.806	49.572	3.9	145.76
Kraft mill/soil 30:20; 3	63.370	113.458	50.088	4.0	149.50
Kraft mill/soil 40:10; 1	63.798	107.488	43.690	3.9	145.76
Kraft mill/soil 40:10; 2	63.210	109.148	45.938	4.0	149.50
Kraft mill/soil 40:10; 3	63.324	107.194	43.870	4.0	149.50
Kraft mill orig. blend 1	64.918	104.416	39.498	4.0	149.50
Kraft mill orig. blend 2	64.788	105.374	40.586	4.0	149.50
Kraft mill orig. blend 3	63.712	105.808	42.096	4.2	156.97

Appendix H: Determination of gravimetric water holding capacity

TABLE 35: Raw data for BCTMP sludge-soil mixtures; (n=3)

sample	column empty [g]	column&sludge [g]	mass wet [g]	height [cm]	volume [cm^3]
BCTMP/soil 10:40; 1	63.328	166.365	103.037	3.8	142.02
BCTMP/soil 10:40; 2	63.938	165.980	102.042	3.5	130.81
BCTMP/soil 10:40; 3	62.900	163.510	100.610	3.5	130.81
BCTMP/soil 20:30; 1	63.682	138.655	74.973	3.5	130.81
BCTMP/soil 20:30; 2	63.786	139.030	75.244	3.5	130.81
BCTMP/soil 20:30; 3	63.854	138.620	74.766	3.4	127.07
BCTMP/soil 25:25; 1	64.598	135.750	71.152	3.8	142.02
BCTMP/soil 25:25; 2	65.464	145.355	79.891	3.9	145.76
BCTMP/soil 25:25; 3	63.556	133.525	69.969	3.5	130.81
BCTMP/soil 30:20; 1	65.934	135.920	69.986	4.0	149.50
BCTMP/soil 30:20; 2	64.078	144.625	80.547	4.1	153.23
BCTMP/soil 30:20; 3	63.802	139.425	75.623	3.9	145.76
BCTMP/soil 40:10; 1	63.920	130.700	66.780	3.9	145.76
BCTMP/soil 40:10; 2	63.558	130.330	66.772	3.9	145.76
BCTMP/soil 40:10; 3	63.398	131.435	68.037	3.9	145.76
BCTMP orig. blend 1	63.378	116.058	52.680	3.9	145.76
BCTMP orig. blend 2	63.774	122.815	59.041	4.0	149.50
BCTMP orig. blend 3	63.192	127.46	64.268	4.1	153.23

Appendix H: Determination of gravimetric moisture content

TABLE 36: Total dry sample mass and Db for sludge and soil samples
(Volume for Db calculation as determined in table 33)

sample	sludge wet [g]	sum wet [g]	sludge dry [g]	sum dry [g]	total mass dry [g]	Db [g/cm^3]	average (n=5)	stdev	± se
Kraft mill 1a	12.231		2.122						
Kraft mill 1b	15.277	27.508	2.490	4.612	8.162	0.053			
Kraft mill 2a	15.977		2.666						
Kraft mill 2b	18.522	34.499	3.087	5.753	8.475	0.057			
Kraft mill 3a	15.840		2.610						
Kraft mill 3b	19.057	34.897	3.189	5.799	8.083	0.054			
Kraft mill 4a	19.384		2.999						
Kraft mill 4b	17.033	36.417	2.873	5.872	7.795	0.053			
Kraft mill 5a	20.634		3.280						
Kraft mill 5b	20.293	40.927	3.207	6.487	7.661	0.051	0.054	0.002	0.001
BCTMP 1a	10.204		2.096						
BCTMP 1b	9.250	19.454	1.929	4.025	13.69	0.094			
BCTMP 2a	9.501		2.046						
BCTMP 2b	10.073	19.574	2.152	4.198	14.49	0.102			
BCTMP 3a	12.813		2.618						
BCTMP 3b	11.749	24.562	2.390	5.008	13.96	0.093			
BCTMP 4a	12.570		2.533						
BCTMP 4b	12.004	24.574	2.412	4.945	13.82	0.095			
BCTMP 5a	13.339		2.525						
BCTMP 5b	12.026	25.365	2.271	4.796	12.99	0.091	0.095	0.004	0.002
Soil 1a	28.893		21.630						
Soil 1b	25.484	54.377	19.219	40.849	117.90	0.830			
Soil 2a	25.206		19.302						
Soil 2b	27.750	52.956	21.493	40.795	114.84	0.830			
Soil 3a	26.399		19.876						
Soil 3b	25.082	51.481	18.782	38.658	114.41	0.827			
Soil 4a	31.167		23.398						
Soil 4b	28.342	59.509	21.023	44.421	111.65	0.807			
Soil 5a	24.417		18.660						
Soil 5b	25.018	49.435	19.324	37.984	115.90	0.838	0.827	0.012	0.005

Appendix H: Determination of gravimetric moisture content

TABLE 37: Total sample mass dry and Db for Kraft mill sludge-soil mixtures
(Volume for Db calculation as determined in table 34)

sample	sludge wet [g]	sum wet [g]	sludge dry [g]	sum dry [g]	total mass dry [g]	Db [g/cm^3]	average (n=3)	stdev	± se
Kraft mill/soil 10:40; 1a	14.646		9.024						
Kraft mill/soil 10:40; 1b	13.169	27.815	7.908	16.932	47.89	0.346			
Kraft mill/soil 10:40; 2a	11.711		7.063						
Kraft mill/soil 10:40; 2b	11.748	23.459	7.152	14.215	43.60	0.333			
Kraft mill/soil 10:40; 3a	9.704		5.262						
Kraft mill/soil 10:40; 3b	10.173	19.877	6.871	12.133	45.74	0.350	0.343	0.009	0.005
Kraft mill/soil 20:30; 1a	10.303		3.735						
Kraft mill/soil 20:30; 1b	10.388	20.691	4.099	7.834	18.95	0.137			
Kraft mill/soil 20:30; 2a	9.534		3.900						
Kraft mill/soil 20:30; 2b	9.287	18.821	3.684	7.584	20.46	0.148			
Kraft mill/soil 20:30; 3a	9.785		4.986						
Kraft mill/soil 20:30; 3b	12.003	21.788	5.643	10.629	24.34	0.186	0.157	0.026	0.015
Kraft mill/soil 25:25; 1a	7.882		3.319						
Kraft mill/soil 25:25; 1b	7.268	15.150	2.518	5.837	19.24	0.132			
Kraft mill/soil 25:25; 2a	10.499		4.972						
Kraft mill/soil 25:25; 2b	7.744	18.243	2.856	7.828	21.65	0.149			
Kraft mill/soil 25:25; 3a	9.116		3.970						
Kraft mill/soil 25:25; 3b	8.362	17.478	3.561	7.531	21.78	0.153	0.145	0.011	0.006
Kraft mill/soil 30:20; 1a	9.119		2.763						
Kraft mill/soil 30:20; 1b	9.167	18.286	2.715	5.478	15.09	0.101			
Kraft mill/soil 30:20; 2a	11.718		4.067						
Kraft mill/soil 30:20; 2b	11.099	22.817	2.795	6.862	14.91	0.102			
Kraft mill/soil 30:20; 3a	13.756		3.853						
Kraft mill/soil 30:20; 3b	10.054	23.810	2.523	6.376	13.41	0.090	0.098	0.007	0.004
Kraft mill/soil 40:10; 1a	11.513		2.395						
Kraft mill/soil 40:10; 1b	11.177	22.690	1.901	4.296	8.27	0.057			
Kraft mill/soil 40:10; 2a	13.983		2.427						
Kraft mill/soil 40:10; 2b	14.085	28.068	2.374	4.801	7.86	0.053			
Kraft mill/soil 40:10; 3a	10.143		2.031						
Kraft mill/soil 40:10; 3b	9.684	19.827	1.778	3.809	8.43	0.056	0.055	0.002	0.001

Appendix H: Determination of gravimetric moisture content

sample	sludge wet [g]	sum wet [g]	sludge dry [g]	sum dry [g]	total mass dry [g]	Db [g/cm^3]	average (n=3)	stdev	± se
Kraft mil orig.blend 1a	10.182		1.262						
Kraft mill orig.blend 1b	12.963	23.145	1.541	2.803	4.78	0.032			
Kraft mill orig.blend 2a	11.025		1.352						
Kraft mill orig.blend 2b	10.993	22.018	1.324	2.676	4.93	0.033			
Kraft mill orig.blend 3a	13.830		1.753						
Kraft mill orig.blend 3b	12.810	26.640	1.643	3.396	5.37	0.034	0.033	0.001	0.001

TABLE 38: Total sample mass dry and Db for BCTMP sludge-soil mixtures
(Volume for Db calculation as determined in table 35)

sample	sludge wet [g]	sum wet [g]	sludge dry [g]	sum dry [g]	total mass dry [g]	Db [g/cm^3]	average (n=3)	stdev	± se
BCTMP/soil 10:40; 1a	9.947		6.779						
BCTMP/soil 10:40; 1b	10.240	20.187	6.658	13.437	68.58	0.483			
BCTMP/soil 10:40; 2a	11.705		7.620						
BCTMP/soil 10:40; 2b	11.871	23.576	7.675	15.295	66.20	0.506			
BCTMP/soil 10:40; 3a	11.513		7.636						
BCTMP/soil 10:40; 3b	10.754	22.267	7.082	14.718	66.50	0.508	0.499	0.014	0.008
BCTMP/soil 20:30; 1a	12.047		6.165						
BCTMP/soil 20:30; 1b	11.693	23.740	5.788	11.953	37.75	0.289			
BCTMP/soil 20:30; 2a	10.084		5.512						
BCTMP/soil 20:30; 2b	9.368	19.452	4.743	10.255	39.67	0.303			
BCTMP/soil 20:30; 3a	12.696		7.640						
BCTMP/soil 20:30; 3b	11.169	23.865	6.191	13.831	43.33	0.341	0.311	0.027	0.016
BCTMP/soil 25:25; 1a	10.508		5.015						
BCTMP/soil 25:25; 1b	8.815	19.323	4.010	9.025	33.23	0.234			
BCTMP/soil 25:25; 2a	10.658		5.212						
BCTMP/soil 25:25; 2b	9.835	20.493	4.719	9.931	38.72	0.266			
BCTMP/soil 25:25; 3a	9.845		5.120						
BCTMP/soil 25:25; 3b	7.904	17.749	3.762	8.882	35.01	0.268	0.256	0.019	0.011

Appendix H: Determination of gravimetric moisture content

sample	sludge wet [g]	sum wet [g]	sludge dry [g]	sum dry [g]	total mass dry [g]	Db [g/cm^3]	average (n=3)	stdev	± se
BCTMP/soil 30:20; 1a	12.080		4.464						
BCTMP/soil 30:20; 1b	12.124	24.204	4.300	8.764	25.34	0.170			
BCTMP/soil 30:20; 2a	9.499		3.236						
BCTMP/soil 30:20; 2b	9.469	18.968	3.318	6.554	27.83	0.182			
BCTMP/soil 30:20; 3a	6.927		2.754						
BCTMP/soil 30:20; 3b	11.770	18.697	4.159	6.913	27.96	0.192	0.181	0.011	0.006
BCTMP/soil 40:10; 1a	7.221		1.907						
BCTMP/soil 40:10; 1b	8.829	16.050	2.284	4.191	17.44	0.120			
BCTMP/soil 40:10; 2a	8.658		2.121						
BCTMP/soil 40:10; 2b	7.903	16.561	1.894	4.015	16.19	0.111			
BCTMP/soil 40:10; 3a	8.435		2.290						
BCTMP/soil 40:10; 3b	7.621	16.056	1.882	4.172	17.68	0.121	0.117	0.005	0.003
BCTMP orig. blend 1a	7.686		1.260						
BCTMP orig. blend 1b	8.224	15.910	1.353	2.613	8.65	0.059			
BCTMP orig. blend 2a	8.376		1.329						
BCTMP orig. blend 2b	7.954	16.330	1.263	2.592	9.37	0.063			
BCTMP orig. blend 3a	7.322		1.167						
BCTMP orig. blend 3b	8.484	15.806	1.372	2.539	10.32	0.067	0.063	0.004	0.002

Appendix H: Determination of gravimetric water holding capacity

TABLE 39: Raw data for Kraft mill sludge-soil layer systems and Db; 1, 2, and 3 layer systems (n=3)

	sample	column empty [g]	column&sample [g]	mass wet [g]	layer [g]	height [cm]	volume [cm³]	mass dry [g]	Db [g/cm³]
1 layer	sludge (1/1)	64.100	99.690	35.590	35.590	3.0	112.12	8.31	0.0741
	soil (1/1)	64.100	228.850	164.750	129.160	2.7	100.91	93.72	0.9287
	sludge (2/1)	63.818	102.658	38.840	38.840	3.0	112.12	12.51	0.1116
	soil (2/1)	63.818	228.140	164.322	125.482	2.7	100.91	89.24	0.8844
	sludge (3/1)	63.298	103.004	39.706	39.706	3.1	115.86	7.51	0.0648
	soil (3/1)	63.298	239.435	176.137	136.431	2.8	104.65	97.75	0.9341
2 layer	sludge (1/1)	64.474	83.232	18.758	18.758	1.5	56.06	3.31	0.0591
	soil (1/1)	64.474	159.620	95.146	76.388	1.6	59.80	56.03	0.9371
	sludge (1/2)	64.474	178.785	114.311	19.165	1.4	52.32	3.43	0.0655
	soil (1/2)	64.474	253.340	188.866	74.555	1.4	52.32	53.83	1.0289
	sludge (2/1)	63.604	82.754	19.150	19.150	1.4	52.32	3.38	0.0646
	soil (2/1)	63.604	147.160	83.556	64.406	1.6	59.80	46.31	0.7745
	sludge (2/2)	63.604	172.730	109.126	25.570	1.4	52.32	4.13	0.0789
	soil (2/2)	63.604	241.905	178.301	69.175	1.6	59.80	49.60	0.8295
	sludge (3/1)	63.582	84.778	21.196	21.196	1.5	56.06	3.40	0.0606
	soil (3/1)	63.582	146.990	83.408	62.212	1.5	56.06	45.31	0.8082
	sludge (3/2)	63.582	172.075	108.493	25.085	1.5	56.06	4.16	0.0743
	soil (3/2)	63.582	247.480	183.898	75.405	1.5	56.06	54.13	0.9656
3 layer	sludge (1/1)	63.148	82.412	19.264	19.264	1.3	48.59	3.40	0.0700
	soil (1/1)	63.148	109.482	46.334	27.070	0.8	29.90	19.68	0.6582
	sludge (1/2)	63.148	132.000	68.852	22.518	1.0	37.37	5.18	0.1386
	soil (1/2)	63.148	173.985	110.837	41.985	1.0	37.37	30.86	0.8256
	sludge (1/3)	63.148	193.450	130.302	19.465	1.0	37.37	3.72	0.0995
	soil (1/3)	63.148	254.035	190.887	60.585	1.0	37.37	44.07	1.1793
	sludge (2/1)	64.366	85.452	21.086	21.086	1.1	41.11	3.61	0.0878
	soil (2/1)	64.366	120.225	55.859	34.773	1.0	37.37	25.67	0.6868
	sludge (2/2)	64.366	140.040	75.674	19.815	1.0	37.37	3.87	0.1035
	soil (2/2)	64.366	183.650	119.284	43.610	1.1	41.11	31.38	0.7632
	sludge (2/3)	64.366	200.825	136.459	17.175	0.9	33.64	3.28	0.0976
	soil (2/3)	64.366	255.020	190.654	54.195	1.0	37.37	38.91	1.0410
	sludge (3/1)	62.876	82.608	19.732	19.732	1.2	44.85	3.24	0.0723
	soil (3/1)	62.876	113.670	50.794	31.062	0.9	33.64	23.07	0.6859
	sludge (3/2)	62.876	132.055	69.179	18.385	1.0	37.37	3.74	0.1001
	soil (3/2)	62.876	175.875	112.999	43.820	1.0	37.37	31.48	0.8423
	sludge (3/3)	62.876	191.500	128.624	15.625	0.9	33.64	2.98	0.0887
	soil (3/3)	62.876	239.195	176.319	47.695	1.1	41.11	34.46	0.8382

Appendix H: Determination of gravimetric water holding capacity

TABLE 40: Raw data for BCTMP sludge-soil layer systems and Db; 1, 2, and 3 layer systems (n=3)

	sample	column empty [g]	column&sample [g]	mass wet [g]	layer [g]	height [cm]	volume [cm^3]	mass dry [g]	Db [g/cm^3]
1 layer	sludge (1/1)	64.114	117.084	52.970	52.970	3.1	115.86	10.94	0.0944
	soil (1/1)	64.114	242.620	178.506	125.536	2.7	100.91	88.81	0.8800
	sludge (2/1)	63.998	115.350	51.352	51.352	3.0	112.12	10.78	0.0961
	soil (2/1)	63.998	250.960	186.962	135.610	2.9	108.38	96.68	0.8920
	sludge (3/1)	63.140	112.048	48.908	48.908	3.0	112.12	10.36	0.0924
	soil (3/1)	63.140	255.955	192.815	143.907	3.0	112.12	102.92	0.9180
2 layer	sludge (1/1)	63.192	92.962	29.770	29.770	1.5	56.06	4.73	0.0844
	soil (1/1)	63.192	147.850	84.658	54.888	1.5	56.06	38.81	0.6923
	sludge (1/2)	63.192	189.470	126.278	41.620	1.7	63.54	7.60	0.1197
	soil (1/2)	63.192	242.250	179.058	52.780	1.3	48.59	37.68	0.7756
	sludge (2/1)	63.870	93.750	29.880	29.880	1.5	56.06	5.59	0.0998
	soil (2/1)	63.870	147.685	83.815	53.935	1.5	56.06	38.43	0.6855
	sludge (2/2)	63.870	189.360	125.490	41.675	1.5	56.06	7.59	0.1354
	soil (2/2)	63.870	252.450	188.580	63.090	1.5	56.06	45.13	0.8051
	sludge (3/1)	63.122	94.596	31.474	31.474	1.5	56.06	5.95	0.1061
	soil (3/1)	63.122	147.395	84.273	52.799	1.5	56.06	37.22	0.6638
	sludge (3/2)	63.122	182.170	119.048	34.775	1.5	56.06	6.96	0.1242
	soil (3/2)	63.122	245.495	182.373	63.325	1.5	56.06	45.07	0.8039
3 layer	sludge (1/1)	63.138	88.202	25.064	25.064	1.1	41.11	5.05	0.1230
	soil (1/1)	63.138	134.420	71.282	46.218	1.0	37.37	32.74	0.8761
	sludge (1/2)	63.138	152.660	89.522	18.240	1.0	37.37	4.00	0.1071
	soil (1/2)	63.138	193.680	130.542	41.020	1.0	37.37	28.87	0.7725
	sludge (1/3)	63.138	220.640	157.502	26.960	1.0	37.37	5.67	0.1518
	soil (1/3)	63.138	260.345	197.207	39.705	1.0	37.37	27.76	0.7429
	sludge (2/1)	63.752	85.024	21.272	21.272	1.0	37.37	4.48	0.1200
	soil (2/1)	63.752	132.365	68.613	47.341	1.0	37.37	33.29	0.8908
	sludge (2/2)	63.752	151.545	87.793	19.180	1.0	37.37	4.10	0.1096
	soil (2/2)	63.752	193.555	129.803	42.010	1.0	37.37	29.58	0.7916
	sludge (2/3)	63.752	220.39	156.638	26.835	1.0	37.37	4.69	0.1256
	soil (2/3)	63.752	258.470	194.718	38.080	1.0	37.37	27.22	0.7282
	sludge (3/1)	63.150	90.876	27.726	27.726	1.2	44.85	5.42	0.1207
	soil (3/1)	63.150	133.010	69.860	42.134	1.0	37.37	29.26	0.7829
	sludge (3/2)	63.150	154.745	91.595	21.735	0.9	33.64	4.92	0.1463
	soil (3/2)	63.150	197.285	134.135	42.540	1.0	37.37	30.08	0.8048
	sludge (3/3)	63.150	224.110	160.960	26.825	1.1	41.11	5.12	0.1245
	soil (3/3)	63.150	263.690	200.540	39.580	1.0	37.37	28.18	0.7540

Appendix H: Determination of gravimetric water holding capacity

TABLE 41: Db and statistics for Kraft mill sludge-soil layer systems; 1, 2, and 3 layer systems (n=3)

	sample	Db [g/cm3]	average (n=3)	stdev	± se
1 layer	sludge (1/1)	0.0741			
	sludge (2/1)	0.1116			
	sludge (3/1)	0.0648	0.084	0.025	0.014
	soil (1/1)	0.9287			
	soil (2/1)	0.8844			
	soil (3/1)	0.9341	0.916	0.027	0.016
2 layer	sludge (1/1)	0.0591			
	sludge (2/1)	0.0646			
	sludge (3/1)	0.0606	0.061	0.003	0.002
	soil (1/1)	0.9371			
	soil (2/1)	0.7745			
	soil (3/1)	0.8082	0.840	0.086	0.050
	sludge (1/2)	0.0655			
	sludge (2/2)	0.0789			
	sludge (3/2)	0.0743	0.073	0.007	0.004
	soil (1/2)	1.0289			
	soil (2/2)	0.8295			
	soil (3/2)	0.9656	0.941	0.102	0.059
3 layer	sludge (1/1)	0.0700			
	sludge (2/1)	0.0878			
	sludge (3/1)	0.0723	0.077	0.010	0.006
	soil (1/1)	0.6582			
	soil (2/1)	0.6868			
	soil (3/1)	0.6859	0.677	0.016	0.009
	sludge (1/2)	0.1386			
	sludge (2/2)	0.1035			
	sludge (3/2)	0.1001	0.114	0.021	0.012
	soil (1/2)	0.8256			
	soil (2/2)	0.7632			
	soil (3/2)	0.8423	0.810	0.042	0.024
	sludge (1/3)	0.0995			
	sludge (2/3)	0.0976			
	sludge (3/3)	0.0887	0.095	0.006	0.003
	soil (1/3)	1.1793			
	soil (2/3)	1.0410			
	soil (3/3)	0.8382	1.019	0.172	0.099

TABLE 42: Db and statistics for BCTMP sludge-soil layer systems; 1, 2, and 3 layer systems (n=3)

	sample	Db [g/cm3]	average (n=3)	stdev	± se
1 layer	sludge (1/1)	0.0944			
	sludge (2/1)	0.0961			
	sludge (3/1)	0.0924	0.094	0.002	0.001
	soil (1/1)	0.8800			
	soil (2/1)	0.8920			
	soil (3/1)	0.9180	0.897	0.019	0.011
2 layer	sludge (1/1)	0.0844			
	sludge (2/1)	0.0998			
	sludge (3/1)	0.1061	0.097	0.011	0.006
	soil (1/1)	0.6923			
	soil (2/1)	0.6855			
	soil (3/1)	0.6638	0.681	0.015	0.009
	sludge (1/2)	0.1197			
	sludge (2/2)	0.1354			
	sludge (3/2)	0.1242	0.126	0.008	0.005
	soil (1/2)	0.7756			
	soil (2/2)	0.8051			
	soil (3/2)	0.8039	0.795	0.017	0.010
3 layer	sludge (1/1)	0.1230			
	sludge (2/1)	0.1200			
	sludge (3/1)	0.1207	0.121	0.002	0.001
	soil (1/1)	0.8761			
	soil (2/1)	0.8908			
	soil (3/1)	0.7829	0.850	0.059	0.034
	sludge (1/2)	0.1071			
	sludge (2/2)	0.1096			
	sludge (3/2)	0.1463	0.121	0.022	0.013
	soil (1/2)	0.7725			
	soil (2/2)	0.7916			
	soil (3/2)	0.8048	0.790	0.016	0.009
	sludge (1/3)	0.1518			
	sludge (2/3)	0.1256			
	sludge (3/3)	0.1245	0.134	0.015	0.009
	soil (1/3)	0.7429			
	soil (2/3)	0.7282			
	soil (3/3)	0.7540	0.742	0.013	0.007

Appendix H: Determination of gravimetric water holding capacity

Part B: Gravimetric moisture content after soaking and draining = WHC_g

TABLE 43: WHC_g of sludge and soil samples; (n = 10)

sample	container [g]	cont. & sludge wet [g]	sludge wet [g]	cont. & sludge dry [g]	sludge dry [g]	WHC_g [%]	average [%]	stdev	± se
Kraft mill 1a	3.142	15.373	12.231	5.264	2.122	476			
Kraft mill 1b	3.162	18.439	15.277	5.652	2.490	514			
Kraft mill 2a	3.152	19.129	15.977	5.818	2.666	499			
Kraft mill 2b	3.128	21.650	18.522	6.215	3.087	500			
Kraft mill 3a	3.132	18.972	15.840	5.742	2.610	507			
Kraft mill 3b	3.147	22.204	19.057	6.336	3.189	498			
Kraft mill 4a	3.130	22.514	19.384	6.129	2.999	546			
Kraft mill 4b	3.161	20.194	17.033	6.034	2.873	493			
Kraft mill 5a	3.759	24.393	20.634	7.039	3.280	529			
Kraft mill 5b	3.148	23.441	20.293	6.355	3.207	533	509	21.12	6.68
BCTMP 1a	3.146	13.350	10.204	5.242	2.096	387			
BCTMP 1b	3.166	12.416	9.250	5.095	1.929	380			
BCTMP 2a	3.154	12.655	9.501	5.200	2.046	364			
BCTMP 2b	3.130	13.203	10.073	5.282	2.152	368			
BCTMP 3a	3.133	15.946	12.813	5.751	2.618	389			
BCTMP 3b	3.148	14.897	11.749	5.538	2.390	392			
BCTMP 4a	3.132	15.702	12.570	5.665	2.533	396			
BCTMP 4b	3.164	15.168	12.004	5.576	2.412	398			
BCTMP 5a	3.761	17.100	13.339	6.286	2.525	428			
BCTMP 5b	3.151	15.177	12.026	5.422	2.271	430	393	21.83	6.90
Soil 1a	3.121	32.014	28.893	24.751	21.630	34			
Soil 1b	3.152	28.636	25.484	22.371	19.219	33			
Soil 2a	3.148	28.354	25.206	22.450	19.302	31			
Soil 2b	3.142	30.892	27.750	24.635	21.493	29			
Soil 3a	3.170	29.569	26.399	23.046	19.876	33			
Soil 3b	3.144	28.226	25.082	21.926	18.782	34			
Soil 4a	3.136	34.303	31.167	26.534	23.398	33			
Soil 4b	3.132	31.474	28.342	24.155	21.023	35			
Soil 5a	3.143	27.560	24.417	21.803	18.660	31			
Soil 5b	3.144	28.162	25.018	22.468	19.324	29	32	1.92	0.61

Appendix H: Determination of gravimetric water holding capacity

TABLE 44: WHC_g of Kraft mill sludge-soil mixtures; (n = 6)

sample	container [g]	cont. & sludge wet [g]	sludge wet [g]	cont. & sludge dry [g]	sludge dry [g]	WHC_g [%]	average [%]	stdev	± se
Kraft mill/soil 10:40; 1a	3.130	17.776	14.646	12.154	9.024	62			
Kraft mill/soil 10:40; 1b	3.161	16.330	13.169	11.069	7.908	67			
Kraft mill/soil 10:40; 2a	3.759	15.470	11.711	10.822	7.063	66			
Kraft mill/soil 10:40; 2b	3.147	14.895	11.748	10.299	7.152	64			
Kraft mill/soil 10:40; 3a	3.121	12.825	9.704	8.383	5.262	84			
Kraft mill/soil 10:40; 3b	3.155	13.328	10.173	10.026	6.871	48	65	11.62	4.74
Kraft mill/soil 20:30; 1a	3.142	13.445	10.303	6.877	3.735	176			
Kraft mill/soil 20:30; 1b	3.161	13.549	10.388	7.260	4.099	153			
Kraft mill/soil 20:30; 2a	3.152	12.686	9.534	7.052	3.900	144			
Kraft mill/soil 20:30; 2b	3.127	12.414	9.287	6.811	3.684	152			
Kraft mill/soil 20:30; 3a	3.132	12.917	9.785	8.118	4.986	96			
Kraft mill/soil 20:30; 3b	3.147	15.150	12.003	8.790	5.643	113	139	29.28	11.95
Kraft mill/soil 25:25; 1a	3.141	11.023	7.882	6.460	3.319	137			
Kraft mill/soil 25:25; 1b	3.161	10.429	7.268	5.679	2.518	189			
Kraft mill/soil 25:25; 2a	3.152	13.651	10.499	8.124	4.972	111			
Kraft mill/soil 25:25; 2b	3.128	10.872	7.744	5.984	2.856	171			
Kraft mill/soil 25:25; 3a	3.132	12.248	9.116	7.102	3.970	130			
Kraft mill/soil 25:25; 3b	3.144	11.506	8.362	6.705	3.561	135	145	28.74	11.73
Kraft mill/soil 30:20; 1a	3.169	12.288	9.119	5.932	2.763	230			
Kraft mill/soil 30:20; 1b	3.170	12.337	9.167	5.885	2.715	238			
Kraft mill/soil 30:20; 2a	3.220	14.938	11.718	7.287	4.067	188			
Kraft mill/soil 30:20; 2b	3.171	14.270	11.099	5.966	2.795	297			
Kraft mill/soil 30:20; 3a	3.222	16.978	13.756	7.075	3.853	257			
Kraft mill/soil 30:20; 3b	3.186	13.240	10.054	5.709	2.523	298	251	42.40	17.31
Kraft mill/soil 40:10; 1a	3.133	14.646	11.513	5.528	2.395	381			
Kraft mill/soil 40:10; 1b	3.166	14.343	11.177	5.067	1.901	488			
Kraft mill/soil 40:10; 2a	3.772	17.755	13.983	6.199	2.427	476			
Kraft mill/soil 40:10; 2b	3.156	17.241	14.085	5.530	2.374	493			
Kraft mill/soil 40:10; 3a	3.212	13.355	10.143	5.243	2.031	399			
Kraft mill/soil 40:10; 3b	3.177	12.861	9.684	4.955	1.778	445	447	47.61	19.44
Kraft mil orig.blend 1a	3.133	13.315	10.182	4.395	1.262	707			
Kraft mill orig.blend 1b	3.148	16.111	12.963	4.689	1.541	741			
Kraft mill orig.blend 2a	3.154	14.179	11.025	4.506	1.352	715			
Kraft mill orig.blend 2b	3.160	14.153	10.993	4.484	1.324	730			
Kraft mill orig.blend 3a	3.145	16.975	13.830	4.898	1.753	689			
Kraft mill orig.blend 3b	3.165	15.975	12.810	4.808	1.643	680	710	23.61	9.64

Appendix H: Determination of gravimetric water holding capacity

TABLE 45: WHC_g of BCTMP sludge-soil mixtures; (n = 6)

sample	container [g]	cont. & sludge wet [g]	sludge wet [g]	cont. & sludge dry [g]	sludge dry [g]	WHC_g [%]	average [%]	stdev	± se
BCTMP/soil 10:40; 1a	3.142	13.089	9.947	9.921	6.779	47			
BCTMP/soil 10:40; 1b	3.162	13.402	10.240	9.820	6.658	54			
BCTMP/soil 10:40; 2a	3.151	14.856	11.705	10.771	7.620	54			
BCTMP/soil 10:40; 2b	3.128	14.999	11.871	10.803	7.675	55			
BCTMP/soil 10:40; 3a	3.132	14.645	11.513	10.768	7.636	51			
BCTMP/soil 10:40; 3b	3.144	13.898	10.754	10.226	7.082	52	52	2.90	1.19
BCTMP/soil 20:30; 1a	3.131	15.178	12.047	9.296	6.165	95			
BCTMP/soil 20:30; 1b	3.162	14.855	11.693	8.950	5.788	102			
BCTMP/soil 20:30; 2a	3.757	13.841	10.084	9.269	5.512	83			
BCTMP/soil 20:30; 2b	3.147	12.515	9.368	7.890	4.743	98			
BCTMP/soil 20:30; 3a	3.120	15.816	12.696	10.760	7.640	66			
BCTMP/soil 20:30; 3b	3.154	14.323	11.169	9.345	6.191	80	87	13.41	5.48
BCTMP/soil 25:25; 1a	3.131	13.639	10.508	8.146	5.015	110			
BCTMP/soil 25:25; 1b	3.162	11.977	8.815	7.172	4.010	120			
BCTMP/soil 25:25; 2a	3.757	14.415	10.658	8.969	5.212	104			
BCTMP/soil 25:25; 2b	3.147	12.982	9.835	7.866	4.719	108			
BCTMP/soil 25:25; 3a	3.120	12.965	9.845	8.240	5.120	92			
BCTMP/soil 25:25; 3b	3.153	11.057	7.904	6.915	3.762	110	107	8.99	3.67
BCTMP/soil 30:20; 1a	3.145	15.225	12.080	7.609	4.464	171			
BCTMP/soil 30:20; 1b	3.144	15.268	12.124	7.444	4.300	182			
BCTMP/soil 30:20; 2a	3.171	12.670	9.499	6.407	3.236	194			
BCTMP/soil 30:20; 2b	3.145	12.614	9.469	6.463	3.318	185			
BCTMP/soil 30:20; 3a	3.136	10.063	6.927	5.890	2.754	152			
BCTMP/soil 30:20; 3b	3.131	14.901	11.770	7.290	4.159	183	178	14.78	6.03
BCTMP/soil 40:10; 1a	3.141	10.362	7.221	5.048	1.907	279			
BCTMP/soil 40:10; 1b	3.162	11.991	8.829	5.446	2.284	287			
BCTMP/soil 40:10; 2a	3.757	12.415	8.658	5.878	2.121	308			
BCTMP/soil 40:10; 2b	3.147	11.050	7.903	5.041	1.894	317			
BCTMP/soil 40:10; 3a	3.121	11.556	8.435	5.411	2.290	268			
BCTMP/soil 40:10; 3b	3.154	10.775	7.621	5.036	1.882	305	294	19.04	7.77
BCTMP orig. blend 1a	3.142	10.828	7.686	4.402	1.260	510			
BCTMP orig. blend 1b	3.163	11.387	8.224	4.516	1.353	508			
BCTMP orig. blend 2a	3.152	11.528	8.376	4.481	1.329	530			
BCTMP orig. blend 2b	3.128	11.082	7.954	4.391	1.263	530			
BCTMP orig. blend 3a	3.133	10.455	7.322	4.300	1.167	527			
BCTMP orig. blend 3b	3.144	11.628	8.484	4.516	1.372	518	521	10.04	4.10

Appendix H: Determination of gravimetric water holding capacityy

TABLE 46: WHC_g of Kraft mill sludge-soil layer systems; 1,2, and 3 layer systems (n = 6)

	sample	container [g]	cont. & sludge wet [g]	sludge wet [g]	cont. & sludge dry [g]	sludge dry [g]	WHC_g [%]	average [%]	stdev	± se
Kraft mill 1 layer	sludge (1/1/a)	3.154	10.202	7.048	4.744	1.590	343			
	sludge (1/1/b)	3.129	10.095	6.966	4.811	1.682	314			
	sludge (2/1/a)	3.132	10.977	7.845	6.285	3.153	149			
	sludge (2/1/b)	3.162	10.31	7.148	4.839	1.677	326			
	sludge (3/1/a)	3.120	10.161	7.041	4.477	1.357	419			
	sludge (3/1/b)	3.153	10.17	7.017	4.456	1.303	439	332	103	42.0
	soil (1/1/a)	3.143	18.901	15.758	14.469	11.326	39			
	soil (1/1/b)	3.164	20.149	16.985	15.596	12.432	37			
	soil (2/1/a)	3.132	19.198	16.066	14.571	11.439	40			
	soil (2/1/b)	3.144	20.225	17.081	15.279	12.135	41			
	soil (3/1/a)	3.756	20.762	17.006	15.969	12.213	39			
	soil (3/1/b)	3.146	24.427	21.281	18.364	15.218	40	39	1.48	0.60
Kraft mill 2 layers	sludge (1/1/a)	3.133	8.266	5.133	4.080	0.947	442			
	sludge (1/1/b)	3.161	7.626	4.465	3.908	0.747	498			
	sludge (2/1/a)	3.759	8.079	4.320	4.533	0.774	458			
	sludge (2/1/b)	3.164	7.832	4.668	3.977	0.813	474			
	sludge (3/1/a)	3.146	7.592	4.446	3.822	0.676	558			
	sludge (3/1/b)	3.134	7.835	4.701	3.924	0.790	495	487	40.5	16.5
	sludge (1/2/a)	3.133	6.783	3.650	3.781	0.648	463			
	sludge (1/2/b)	3.124	7.012	3.888	3.824	0.700	455			
	sludge (2/2/a)	3.140	7.69	4.550	3.871	0.731	522			
	sludge (2/2/b)	3.133	8.13	4.997	3.944	0.811	516			
	sludge (3/2/a)	3.146	8.151	5.005	3.975	0.829	504			
	sludge (3/2/b)	3.145	8.223	5.078	3.99	0.845	501	494	27.8	11.4
	soil (1/1/a)	3.142	12.962	9.820	10.381	7.239	36			
	soil (1/1/b)	3.180	13.825	10.645	10.953	7.773	37			
	soil (2/1/a)	3.155	11.404	8.249	9.082	5.927	39			
	soil (2/1/b)	3.158	10.555	7.397	8.482	5.324	39			
	soil (3/1/a)	3.147	13.087	9.940	10.333	7.186	38			
	soil (3/1/b)	3.155	13.852	10.697	10.999	7.844	36	38	1.45	0.59
	soil (1/2/a)	3.164	13.689	10.525	10.736	7.572	39			
	soil (1/2/b)	3.175	13.447	10.272	10.620	7.445	38			
	soil (2/2/a)	3.146	12.054	8.908	9.532	6.386	39			
	soil (2/2/b)	3.158	12.216	9.058	9.655	6.497	39			
	soil (3/2/a)	3.186	13.398	10.212	10.513	7.327	39			
	soil (3/2/b)	3.153	13.468	10.315	10.562	7.409	39	39	0.57	0.23

Appendix H: Determination of gravimetric water holding capacityy

	sample	container [g]	cont. & sludge wet [g]	sludge wet [g]	cont. & sludge dry [g]	sludge dry [g]	WHC_g [%]	average [%]	stdev	± se
Kraft mill 3 layers	sludge (1/1/a)	3.133	6.452	3.319	3.730	0.597	456			
	sludge (1/1/b)	3.163	6.617	3.454	3.762	0.599	477			
	sludge (2/1/a)	3.139	8.747	5.608	4.108	0.969	479			
	sludge (2/1/b)	3.133	8.566	5.433	4.053	0.920	491			
	sludge (3/1/a)	3.165	11.057	7.892	4.444	1.279	517			
	sludge (3/1/b)	3.152	10.783	7.631	4.424	1.272	500	486	21.1	8.60
	sludge (1/2/a)	3.129	8.558	5.429	4.406	1.277	325			
	sludge (1/2/b)	3.120	8.538	5.418	4.339	1.219	344			
	sludge (2/2/a)	3.142	9.568	6.426	4.404	1.262	409			
	sludge (2/2/b)	3.130	8.998	5.868	4.269	1.139	415			
	sludge (3/2/a)	3.148	7.642	4.494	4.024	0.876	413			
	sludge (3/2/b)	3.150	7.334	4.184	4.040	0.890	370	380	38.9	15.9
	sludge (1/3/a)	3.757	7.433	3.676	4.324	0.567	548			
	sludge (1/3/b)	3.163	7.258	4.095	4.080	0.917	347			
	sludge (2/3/a)	3.141	8.485	5.344	4.175	1.034	417			
	sludge (2/3/b)	3.142	8.483	5.341	4.150	1.008	430			
	sludge (3/3/a)	3.108	7.738	4.630	4.018	0.910	409			
	sludge (3/3/b)	3.146	8.193	5.047	4.084	0.938	438	431	65.8	26.9
	soil (1/1/a)	3.132	9.768	6.636	7.945	4.813	38			
	soil (1/1/b)	3.147	7.819	4.672	6.555	3.408	37			
	soil (2/1/a)	3.136	11.632	8.496	9.363	6.227	36			
	soil (2/1/b)	3.150	10.567	7.417	8.669	5.519	34			
	soil (3/1/a)	3.145	8.649	5.504	7.201	4.056	36			
	soil (3/1/b)	3.128	9.431	6.303	7.842	4.714	34	36	1.60	0.65
	soil (1/2/a)	3.151	9.436	6.285	7.790	4.639	35			
	soil (1/2/b)	3.153	9.737	6.584	7.972	4.819	37			
	soil (2/2/a)	3.134	13.604	10.470	10.667	7.533	39			
	soil (2/2/b)	3.142	12.730	9.588	10.041	6.899	39			
	soil (3/2/a)	3.148	9.181	6.033	7.470	4.322	40			
	soil (3/2/b)	3.142	9.349	6.207	7.613	4.471	39	38	1.63	0.67
	soil (1/3/a)	3.141	10.447	7.306	8.448	5.307	38			
	soil (1/3/b)	3.142	10.587	7.445	8.566	5.424	37			
	soil (2/3/a)	3.170	11.880	8.710	9.404	6.234	40			
	soil (2/3/b)	3.144	12.040	8.896	9.549	6.405	39			
	soil (3/3/a)	3.150	9.098	5.948	7.444	4.294	39			
	soil (3/3/b)	3.137	9.182	6.045	7.508	4.371	38	38	0.88	0.36

Appendix H: Determination of gravimetric water holding capacityy

TABLE 47: WHC_g of BCTMP sludge-soil layer systems; 1, 2, and 3 layer systems (n = 6)

	sample	container [g]	cont. & sludge wet [g]	sludge wet [g]	cont. & sludge dry [g]	sludge dry [g]	WHC_g [%]	average [%]	stdev	± se
BCTMP 1 layer	sludge (1/1/a)	3.152	10.210	7.058	4.646	1.494	372			
	sludge (1/1/b)	3.127	10.111	6.984	4.533	1.406	397			
	sludge (2/1/a)	3.129	10.174	7.045	4.603	1.474	378			
	sludge (2/1/b)	3.161	10.571	7.410	4.721	1.560	375			
	sludge (3/1/a)	3.120	10.068	6.948	4.594	1.474	371			
	sludge (3/1/b)	3.153	10.265	7.112	4.658	1.505	373	378	9.63	3.93
	soil (1/1/a)	3.143	18.085	14.942	13.630	10.487	42			
	soil (1/1/b)	3.163	19.77	16.607	14.994	11.831	40			
	soil (2/1/a)	3.131	21.906	18.775	16.449	13.318	41			
	soil (2/1/b)	3.143	19.758	16.615	15.055	11.912	39			
	soil (3/1/a)	3.756	22.243	18.487	16.954	13.198	40			
	soil (3/1/b)	3.146	20.976	17.830	15.922	12.776	40	40	1.12	0.46
BCTMP 2 layers	sludge (1/1/a)	3.131	7.340	4.209	3.929	0.798	427			
	sludge (1/1/b)	3.161	6.976	3.815	3.638	0.477	700			
	sludge (2/1/a)	3.758	8.359	4.601	4.615	0.857	437			
	sludge (2/1/b)	3.164	8.501	5.337	4.167	1.003	432			
	sludge (3/1/a)	3.141	8.240	5.099	4.109	0.968	427			
	sludge (3/1/b)	3.131	8.616	5.485	4.164	1.033	431	476	110	44.9
	sludge (1/2/a)	3.127	10.892	7.765	4.488	1.361	471			
	sludge (1/2/b)	3.120	11.821	8.701	4.767	1.647	428			
	sludge (2/2/a)	3.139	9.421	6.282	4.216	1.077	483			
	sludge (2/2/b)	3.131	10.932	7.801	4.619	1.488	424			
	sludge (3/2/a)	3.143	9.814	6.671	4.498	1.355	392			
	sludge (3/2/b)	3.144	10.084	6.940	4.515	1.371	406	434	35.8	14.6
	soil (1/1/a)	3.130	9.771	6.641	7.808	4.678	42			
	soil (1/1/b)	3.147	9.83	6.683	7.890	4.743	41			
	soil (2/1/a)	3.142	10.137	6.995	8.147	5.005	40			
	soil (2/1/b)	3.144	9.388	6.244	7.572	4.428	41			
	soil (3/1/a)	3.135	10.891	7.756	8.662	5.527	40			
	soil (3/1/b)	3.145	11.256	8.111	8.802	5.657	43	41	1.29	0.53
	soil (1/2/a)	3.155	9.939	6.784	7.972	4.817	41			
	soil (1/2/b)	3.153	9.855	6.702	7.964	4.811	39			
	soil (2/2/a)	3.135	10.178	7.043	8.177	5.042	40			
	soil (2/2/b)	3.150	9.717	6.567	7.844	4.694	40			
	soil (3/2/a)	3.170	10.601	7.431	8.529	5.359	39			
	soil (3/2/b)	3.144	10.299	7.155	8.166	5.022	42	40	1.35	0.55

Appendix H: Determination of gravimetric water holding capacityy

	sample	container [g]	cont. & sludge wet [g]	sludge wet [g]	cont. & sludge dry [g]	sludge dry [g]	WHC_g [%]	average [%]	stdev	± se
BCTMP 3 layers	sludge (1/1/a)	3.131	7.162	4.031	3.947	0.816	394			
	sludge (1/1/b)	3.161	7.346	4.185	4.002	0.841	398			
	sludge (2/1/a)	3.140	7.105	3.965	3.981	0.841	371			
	sludge (2/1/b)	3.141	7.628	4.487	4.082	0.941	377			
	sludge (3/1/a)	3.169	9.678	6.509	4.422	1.253	419			
	sludge (3/1/b)	3.155	9.175	6.020	4.349	1.194	404	394	17.7	7.23
	sludge (1/2/a)	3.128	7.306	4.178	4.044	0.916	356			
	sludge (1/2/b)	3.119	6.861	3.742	3.941	0.822	355			
	sludge (2/2/a)	3.140	8.554	5.414	4.416	1.276	324			
	sludge (2/2/b)	3.131	9.004	5.873	4.266	1.135	417			
	sludge (3/2/a)	3.153	9.746	6.593	4.619	1.466	350			
	sludge (3/2/b)	3.155	10.748	7.593	4.901	1.746	335	356	32.5	13.2
	sludge (1/3/a)	3.757	8.650	4.893	4.790	1.033	374			
	sludge (1/3/b)	3.164	7.057	3.893	3.980	0.816	377			
	sludge (2/3/a)	3.143	8.346	5.203	4.051	0.908	473			
	sludge (2/3/b)	3.143	8.312	5.169	4.049	0.906	471			
	sludge (3/3/a)	3.115	9.184	6.069	4.281	1.166	420			
	sludge (3/3/b)	3.140	8.618	5.478	4.178	1.038	428	424	43.19	17.6
	soil (1/1/a)	3.133	7.516	4.383	6.221	3.088	42			
	soil (1/1/b)	3.148	7.250	4.102	6.071	2.923	40			
	soil (2/1/a)	3.135	9.039	5.904	7.291	4.156	42			
	soil (2/1/b)	3.152	9.630	6.478	7.704	4.552	42			
	soil (3/1/a)	3.151	6.614	3.463	5.577	2.426	43			
	soil (3/1/b)	3.132	7.533	4.401	6.167	3.035	45	42	1.52	0.62
	soil (1/2/a)	3.154	6.831	3.677	5.763	2.609	41			
	soil (1/2/b)	3.154	6.494	3.340	5.484	2.330	43			
	soil (2/2/a)	3.135	7.697	4.562	6.321	3.186	43			
	soil (2/2/b)	3.145	8.743	5.598	7.114	3.969	41			
	soil (3/2/a)	3.155	7.608	4.453	6.281	3.126	42			
	soil (3/2/b)	3.147	7.818	4.671	6.472	3.325	40	42	1.24	0.51
	soil (1/3/a)	3.143	7.008	3.865	5.856	2.713	42			
	soil (1/3/b)	3.144	7.306	4.162	6.044	2.900	44			
	soil (2/3/a)	3.170	8.021	4.851	6.652	3.482	39			
	soil (2/3/b)	3.143	7.924	4.781	6.545	3.402	41			
	soil (3/3/a)	3.154	7.416	4.262	6.186	3.032	41			
	soil (3/3/b)	3.153	8.390	5.237	6.884	3.731	40	41	1.55	0.63

Appendix I: Pressure Plate Experiment

Part A: Moisture retention curves for sludge and soil samples

sample height:	1.0 cm	Δh	0.02 cm
sample diameter:	6.9 cm	Δd	0.02 cm
sample volume:	37.37 cm^3	Δm	0.001 g

TABLE 48: Raw data for moisture retention curve of Kraft mill sludge (n=1)

pressure [bar]	container [g]	cont.&sludge wet [g]	sludge wet [g]	cont.&sludge dry [g]	sludge dry [g]	WHC_g [%]	bulk density [g/cm^3]	WHC_v [%]
0.1	3.815	30.600	26.785	8.615	4.800	458	0.128	58.8
0.2	3.816	24.877	21.061	9.060	5.244	302	0.140	42.3
0.3	3.818	22.025	18.207	8.294	4.476	307	0.120	36.7
0.4	3.815	23.176	19.361	8.798	4.983	289	0.133	38.5
0.5	3.815	20.825	17.010	8.314	4.499	278	0.120	33.5
0.7	3.815	20.616	16.801	8.142	4.327	288	0.116	33.4
1.0	3.818	20.614	16.796	8.622	4.804	250	0.129	32.1
2.0	3.818	19.824	16.006	8.468	4.650	244	0.124	30.4
5.0	3.818	23.734	19.916	9.490	5.672	251	0.152	38.1
10.0	3.815	23.112	19.297	9.819	6.004	221	0.161	35.6
15.0	3.816	23.237	19.421	9.739	5.923	228	0.158	36.1
						average	*0.1347*	
						stdev	*0.0159*	
						se	*± 0.0048*	

Appendix I: Pressure Plate Experiment

TABLE 49: Raw data for moisture retention curve of BCTMP sludge (n=1)

pressure [bar]	container [g]	cont.&sludge wet [g]	sludge wet [g]	cont.&sludge dry [g]	sludge dry [g]	WHC_g [%]	bulk density [g/cm^3]	WHC_v [%]
0.1	3.828	26.992	23.164	8.439	4.611	402	0.123	49.6
0.2	3.830	28.638	24.808	8.893	5.063	390	0.135	52.8
0.3	3.826	29.360	25.534	9.293	5.467	367	0.146	53.7
0.4	3.829	27.433	23.604	8.922	5.093	363	0.136	49.5
0.5	3.828	25.878	22.050	8.633	4.805	359	0.129	46.1
0.7	3.828	25.501	21.673	8.494	4.666	364	0.125	45.5
1.0	3.827	25.467	21.640	8.510	4.683	362	0.125	45.4
2.0	3.828	26.015	22.187	8.649	4.821	360	0.129	46.5
5.0	3.830	27.232	23.402	8.969	5.139	355	0.138	48.9
10.0	3.829	25.041	21.212	10.012	6.183	243	0.165	40.2
15.0	3.829	23.578	19.749	9.689	5.860	237	0.157	37.2
						average	*0.1372*	
						stdev	*0.0138*	
						se	*± 0.0041*	

TABLE 50: Raw data for moisture retention curve of soil (n=1)

pressure [bar]	container [g]	cont.& soil wet [g]	soil wet [g]	cont.& soil dry [g]	soil dry [g]	WHC_g [%]	bulk density [g/cm^3]	WHC_v [%]
0.1	3.783	73.136	69.353	53.635	49.852	39	1.334	52.2
0.2	3.807	73.758	69.951	56.920	53.113	32	1.421	45.1
0.3	3.785	65.080	61.295	50.442	46.657	31	1.249	39.2
0.4	3.805	74.858	71.053	58.069	54.264	31	1.452	44.9
0.5	3.785	58.519	54.734	46.652	42.867	28	1.147	31.8
0.7	3.783	63.518	59.735	50.334	46.551	28	1.246	35.3
1.0	3.785	70.530	66.745	56.315	52.530	27	1.406	38.0
2.0	3.785	71.218	67.433	57.660	53.875	25	1.442	36.3
5.0	3.815	73.182	69.367	58.114	54.299	28	1.453	40.3
10.0	3.812	71.224	67.412	58.126	54.314	24	1.453	35.0
15.0	3.823	70.398	66.575	57.414	53.591	24	1.434	34.7
						average	*1.3670*	
						stdev	*0.1072*	
						se	± 0.0323	

Appendix I: Pressure Plate Experiment

TABLE 51: Determination of random errors of bulk density, gravimetric (WHC_g) and volumetric moisture content (WHC_v) for Kraft mill sludge.

pressure [bar]	mass wet [g]	mass dry [g]	WHC_g [%]	± ΔWHC_g	Db [g/cm^3]	± ΔDb	WHC_v [%]	± ΔWHC_v
0.1	26.785	4.800	458	0.141	0.128	0.0026	58.8	1.201
0.2	21.061	5.244	302	0.090	0.140	0.0029	42.3	0.864
0.3	18.207	4.476	307	0.107	0.120	0.0024	36.7	0.750
0.4	19.361	4.983	289	0.091	0.133	0.0027	38.5	0.786
0.5	17.010	4.499	278	0.098	0.120	0.0025	33.5	0.684
0.7	16.801	4.327	288	0.105	0.116	0.0024	33.4	0.682
1.0	16.796	4.804	250	0.084	0.129	0.0026	32.1	0.655
2.0	16.006	4.650	244	0.086	0.124	0.0025	30.4	0.621
5.0	19.916	5.672	251	0.072	0.152	0.0031	38.1	0.778
10.0	19.297	6.004	221	0.062	0.161	0.0033	35.6	0.726
15.0	19.421	5.923	228	0.064	0.158	0.0032	36.1	0.737

TABLE 52: Determination of random errors of bulk density, gravimetric (WHC_g) and volumetric moisture content (WHC_v) for BCTMP sludge.

pressure [bar]	mass wet [g]	mass dry [g]	WHC_g [%]	± ΔWHC_g	Db [g/cm^3]	± ΔDb	WHC_v [%]	± ΔWHC_v
0.1	23.164	4.611	402	0.131	0.123	0.0025	49.6	1.014
0.2	24.808	5.063	390	0.116	0.135	0.0028	52.8	1.079
0.3	25.534	5.467	367	0.102	0.146	0.0030	53.7	1.096
0.4	23.604	5.093	363	0.108	0.136	0.0028	49.5	1.011
0.5	22.050	4.805	359	0.114	0.129	0.0026	46.1	0.942
0.7	21.673	4.666	364	0.118	0.125	0.0025	45.5	0.929
1.0	21.640	4.683	362	0.117	0.125	0.0026	45.4	0.927
2.0	22.187	4.821	360	0.114	0.129	0.0026	46.5	0.949
5.0	23.402	5.139	355	0.105	0.138	0.0028	48.9	0.998
10.0	21.212	6.183	243	0.064	0.165	0.0034	40.2	0.821
15.0	19.749	5.860	237	0.067	0.157	0.0032	37.2	0.759

TABLE 53: Determination of random errors of bulk density, gravimetric (WHC_g) and volumetric moisture content (WHC_v) for soil.

pressure [bar]	mass wet [g]	mass dry [g]	WHC_g [%]	± ΔWHC_g	Db [g/cm^3]	± ΔDb	WHC_v [%]	± ΔWHC_v
0.1	69.353	49.85	39.1	0.0042	1.334	0.0272	52.2	1.065
0.2	69.951	53.11	31.7	0.0039	1.421	0.0290	45.1	0.920
0.3	61.295	46.66	31.4	0.0044	1.249	0.0255	39.2	0.800
0.4	71.053	54.26	30.9	0.0038	1.452	0.0296	44.9	0.917
0.5	54.734	42.87	27.7	0.0048	1.147	0.0234	31.8	0.648
0.7	59.735	46.55	28.3	0.0044	1.246	0.0254	35.3	0.720
1.0	66.745	52.53	27.1	0.0039	1.406	0.0287	38.0	0.777
2.0	67.433	53.88	25.2	0.0038	1.442	0.0294	36.3	0.741
5.0	69.367	54.30	27.8	0.0038	1.453	0.0297	40.3	0.823
10.0	67.412	54.31	24.1	0.0037	1.453	0.0297	35.0	0.716
15.0	66.575	53.59	24.2	0.0038	1.434	0.0293	34.7	0.709

Appendix I: Pressure Plate Experiment

Part B: Moisture retention curves for sludge-soil mixtures

Table 54: Raw data for moisture retention curve of Kraft mill sludge

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.840	27.303	23.463	8.591	4.751	0.127
0.3	1	3.840	24.055	20.215	8.925	5.085	0.136
0.3	2	3.838	23.094	19.256	8.816	4.978	0.133
0.3	3	3.839	23.316	19.477	8.756	4.917	0.132
0.5	1	3.651	22.122	18.471	8.719	5.068	0.136
0.7	1	3.838	23.242	19.404	9.071	5.233	0.140
1.0	1	3.838	21.791	17.953	8.881	5.043	0.135
1.0	2	3.650	20.380	16.730	8.255	4.605	0.123
2.0	1	3.837	20.833	16.996	8.769	4.932	0.132
5.0	1	3.839	22.463	18.624	9.146	5.307	0.142
10.0	1	3.650	21.673	18.023	8.859	5.209	0.139
15.0	1	3.651	20.899	17.248	8.629	4.978	0.133
15.0	2	3.651	20.953	17.302	8.880	5.229	0.140
15.0	3	3.651	20.686	17.035	8.573	4.922	0.132
						average	*0.134*
						stdev	*0.005*
						± se	*0.001*

TABLE 55: Raw data for moisture retention curve of blended Kraft mill sludge

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.818	33.607	29.789	10.165	6.347	0.170
0.3	1	3.819	27.716	23.897	9.802	5.983	0.160
0.3	2	3.817	27.050	23.233	10.293	6.476	0.173
0.3	3	3.818	26.848	23.030	9.978	6.160	0.165
0.5	1	3.582	25.263	21.681	9.505	5.923	0.158
0.7	1	3.818	29.801	25.983	11.124	7.306	0.196
1.0	1	3.819	28.311	24.492	10.699	6.880	0.184
1.0	2	3.582	24.965	21.383	9.714	6.132	0.164
2.0	1	3.817	23.853	20.036	9.611	5.794	0.155
5.0	1	3.817	24.024	20.207	9.459	5.642	0.151
10.0	1	3.582	27.963	24.381	11.065	7.483	0.200
15.0	1	3.582	24.121	20.539	9.971	6.389	0.171
15.0	2	3.583	23.302	19.719	9.346	5.763	0.154
15.0	3	3.582	24.359	20.777	9.728	6.146	0.164
						average	*0.169*
						stdev	*0.015*
						± se	*0.004*

Appendix I: Pressure Plate Experiment

Table 56: Raw data for moisture retention curve of Kraft mill sludge-soil mixture 40:10

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.699	34.877	31.178	13.435	9.736	0.261
0.3	1	3.700	30.793	27.093	13.798	10.098	0.270
0.3	2	3.699	28.473	24.774	12.546	8.847	0.237
0.3	3	3.701	29.515	25.814	13.731	10.030	0.268
0.5	1	3.625	27.321	23.696	12.751	9.126	0.244
0.7	1	3.698	28.921	25.223	12.639	8.941	0.239
1.0	1	3.700	28.668	24.968	13.928	10.228	0.274
1.0	2	3.623	27.561	23.938	12.510	8.887	0.238
2.0	1	3.697	26.46	22.763	13.023	9.326	0.250
5.0	1	3.701	28.343	24.642	13.494	9.793	0.262
10.0	1	3.625	26.025	22.400	13.358	9.733	0.260
15.0	1	3.624	25.851	22.227	12.872	9.248	0.247
15.0	2	3.625	26.071	22.446	13.804	10.179	0.272
15.0	3	3.627	26.107	22.480	13.433	9.806	0.262
						average	*0.256*
						stdev	*0.013*
						± se	*0.004*

Table 57: Raw data for moisture retention curve of Kraft mill sludge-soil mixture 30:20

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.791	44.371	40.580	19.024	15.233	0.408
0.3	1	3.794	37.728	33.934	18.455	14.661	0.392
0.3	2	3.795	36.299	32.504	19.325	15.530	0.416
0.3	3	3.795	36.784	32.989	19.269	15.474	0.414
0.5	1	3.651	35.066	31.415	18.691	15.040	0.402
0.7	1	3.794	37.261	33.467	18.834	15.040	0.402
1.0	1	3.794	36.479	32.685	20.018	16.224	0.434
1.0	2	3.650	35.582	31.932	19.906	16.256	0.435
2.0	1	3.794	34.056	30.262	19.929	16.135	0.432
5.0	1	3.796	35.014	31.218	21.299	17.503	0.468
10.0	1	3.650	33.701	30.051	20.650	17.000	0.455
15.0	1	3.649	33.353	29.704	19.408	15.759	0.422
15.0	2	3.650	33.162	29.512	19.266	15.616	0.418
15.0	3	3.652	33.170	29.518	19.420	15.768	0.422
						average	*0.423*
						stdev	*0.021*
						± se	*0.006*

Appendix I: Pressure Plate Experiment

Table 58: Raw data for moisture retention curve of Kraft mill sludge-soil mixture 25:25

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.822	46.694	42.872	23.586	19.764	0.529
0.3	1	3.827	40.435	36.608	22.469	18.642	0.499
0.3	2	3.826	40.975	37.149	24.499	20.673	0.553
0.3	3	3.828	40.682	36.854	22.749	18.921	0.506
0.5	1	3.667	39.294	35.627	22.460	18.793	0.503
0.7	1	3.827	36.435	32.608	22.657	18.830	0.504
1.0	1	3.827	37.500	33.673	22.726	18.899	0.506
1.0	2	3.668	36.682	33.014	21.166	17.498	0.468
2.0	1	3.825	36.565	32.740	23.025	19.200	0.514
5.0	1	3.828	37.565	33.737	23.471	19.643	0.526
10.0	1	3.668	36.317	32.649	22.594	18.926	0.506
15.0	1	3.668	34.720	31.052	21.402	17.734	0.475
15.0	2	3.669	37.142	33.473	23.272	19.603	0.525
15.0	3	3.671	36.035	32.364	22.488	18.817	0.504
						average	*0.508*
						stdev	*0.021*
						± se	*0.006*

Table 59: Raw data for moisture retention curve of Kraft mill sludge-soil mixture 20:30

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.830	45.428	41.598	24.743	20.913	0.560
0.3	1	3.834	43.016	39.182	25.589	21.755	0.582
0.3	2	3.835	41.378	37.543	25.898	22.063	0.590
0.3	3	3.836	41.698	37.862	25.306	21.470	0.575
0.5	1	3.681	40.549	36.868	25.568	21.887	0.586
0.7	1	3.835	40.022	36.187	26.667	22.832	0.611
1.0	1	3.835	40.115	36.280	25.876	22.041	0.590
1.0	2	3.681	38.986	35.305	23.899	20.218	0.541
2.0	1	3.834	38.082	34.248	26.270	22.436	0.600
5.0	1	3.835	38.705	34.870	26.437	22.602	0.605
10.0	1	3.682	38.180	34.498	25.097	21.415	0.573
15.0	1	3.682	36.438	32.756	25.072	21.390	0.572
15.0	2	3.682	37.211	33.529	25.836	22.154	0.593
15.0	3	3.683	37.069	33.386	24.949	21.266	0.569
						average	*0.582*
						stdev	*0.019*
						± se	*0.005*

Appendix I: Pressure Plate Experiment

Table 60: Raw data for moisture retention curve of Kraft mill sludge-soil mixture 10:40

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.819	59.523	55.704	38.295	34.476	0.923
0.3	1	3.822	55.832	52.010	38.114	34.292	0.918
0.3	2	3.821	56.310	52.489	38.685	34.864	0.933
0.3	3	3.821	55.869	52.048	38.099	34.278	0.917
0.5	1	3.700	52.806	49.106	38.006	34.306	0.918
0.7	1	3.819	53.448	49.629	38.994	35.175	0.941
1.0	1	3.820	52.823	49.003	38.100	34.280	0.917
1.0	2	3.699	52.143	48.444	38.353	34.654	0.927
2.0	1	3.819	52.253	48.434	38.953	35.134	0.940
5.0	1	3.822	50.887	47.065	38.045	34.223	0.916
10.0	1	3.700	49.894	46.194	37.697	33.997	0.910
15.0	1	3.701	51.174	47.473	37.863	34.162	0.914
15.0	2	3.700	52.313	48.613	38.738	35.038	0.938
15.0	3	3.701	51.748	48.047	38.668	34.967	0.936
						average	*0.925*
						stdev	*0.011*
						± se	*0.003*

Appendix I: Pressure Plate Experiment

TABLE 61: Raw data for moisture retention curve of BCTMP sludge

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.829	27.017	23.188	9.777	5.948	0.159
0.3	1	3.829	24.760	20.931	9.745	5.916	0.158
0.3	2	3.830	26.152	22.322	9.774	5.944	0.159
0.3	3	3.837	25.179	21.342	9.416	5.579	0.149
0.5	1	3.830	23.794	19.964	9.578	5.748	0.154
0.7	1	3.830	24.605	20.775	9.658	5.828	0.156
1.0	1	3.830	24.184	20.354	9.555	5.725	0.153
1.0	2	3.840	23.796	19.956	9.488	5.648	0.151
2.0	1	3.841	23.822	19.981	9.572	5.731	0.153
5.0	1	3.652	22.823	19.171	9.241	5.589	0.150
10.0	1	3.650	23.067	19.417	9.333	5.683	0.152
15.0	1	3.651	22.638	18.987	9.276	5.625	0.151
15.0	2	3.840	22.700	18.860	9.421	5.581	0.149
15.0	3	3.651	23.615	19.964	9.299	5.648	0.151
						average	*0.153*
						stdev	*0.004*
						± se	*0.001*

TABLE 62: Raw data for moisture retention curve of blended BCTMP sludge

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.816	30.809	26.993	10.427	6.611	0.177
0.3	1	3.816	25.677	21.861	10.270	6.454	0.173
0.3	2	3.817	29.486	25.669	10.687	6.870	0.184
0.3	3	3.815	28.427	24.612	10.157	6.342	0.170
0.5	1	3.816	27.203	23.387	10.551	6.735	0.180
0.7	1	3.818	26.684	22.866	10.347	6.529	0.175
1.0	1	3.817	26.957	23.140	10.442	6.625	0.177
1.0	2	3.817	26.406	22.589	10.281	6.464	0.173
2.0	1	3.818	27.354	23.536	10.424	6.606	0.177
5.0	1	3.583	26.822	23.239	10.462	6.879	0.184
10.0	1	3.581	27.043	23.462	10.212	6.631	0.177
15.0	1	3.580	26.645	23.065	10.363	6.783	0.182
15.0	2	3.817	25.405	21.588	10.348	6.531	0.175
15.0	3	3.581	26.893	23.312	10.134	6.553	0.175
						average	*0.177*
						stdev	*0.004*
						± se	*0.001*

Appendix I: Pressure Plate Experiment

TABLE 63: Raw data for moisture retention curve of BCTMP sludge-soil mixture 40:10

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.162	36.213	33.051	14.629	11.467	0.307
0.3	1	3.158	34.812	31.654	15.513	12.355	0.331
0.3	2	3.158	35.651	32.493	14.650	11.492	0.308
0.3	3	3.695	36.308	32.613	16.261	12.566	0.336
0.5	1	3.159	33.499	30.340	15.902	12.743	0.341
0.7	1	3.157	33.894	30.737	15.751	12.594	0.337
1.0	1	3.157	34.046	30.889	15.635	12.478	0.334
1.0	2	3.155	33.479	30.324	15.599	12.444	0.333
2.0	1	3.704	32.731	29.027	15.808	12.104	0.324
5.0	1	3.624	36.822	33.198	17.596	13.972	0.374
10.0	1	3.626	36.060	32.434	17.091	13.465	0.360
15.0	1	3.624	35.591	31.967	16.623	12.999	0.348
15.0	2	3.700	32.547	28.847	15.807	12.107	0.324
15.0	3	3.624	33.429	29.805	15.332	11.708	0.313
						average	*0.334*
						stdev	*0.019*
						± se	*0.005*

TABLE 64: Raw data for moisture retention curve of BCTMP sludge-soil mixture 30:20

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.784	38.088	34.304	19.975	16.191	0.433
0.3	1	3.797	36.125	32.328	19.873	16.076	0.430
0.3	2	3.796	36.530	32.734	19.716	15.920	0.426
0.3	3	3.787	37.621	33.834	19.413	15.626	0.418
0.5	1	3.794	36.382	32.588	19.904	16.110	0.431
0.7	1	3.792	37.351	33.559	20.151	16.359	0.438
1.0	1	3.792	37.827	34.035	21.187	17.395	0.465
1.0	2	3.792	37.335	33.543	20.888	17.096	0.457
2.0	1	3.803	36.717	32.914	20.608	16.805	0.450
5.0	1	3.650	38.094	34.444	21.462	17.812	0.477
10.0	1	3.652	37.945	34.293	21.255	17.603	0.471
15.0	1	3.650	37.436	33.786	21.027	17.377	0.465
15.0	2	3.792	35.703	31.911	20.617	16.825	0.450
15.0	3	3.651	35.908	32.257	19.312	15.661	0.419
						average	*0.445*
						stdev	*0.020*
						± se	*0.005*

Appendix I: Pressure Plate Experiment

TABLE 65: Raw data for moisture retention curve of BCTMP sludge-soil mixture 25:25

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.818	52.304	48.486	28.409	24.591	0.658
0.3	1	3.821	42.510	38.689	25.091	21.270	0.569
0.3	2	3.822	41.830	38.008	24.130	20.308	0.543
0.3	3	3.818	42.386	38.568	24.331	20.513	0.549
0.5	1	3.828	34.589	30.761	21.268	17.440	0.467
0.7	1	3.822	34.772	30.950	21.392	17.570	0.470
1.0	1	3.821	35.029	31.208	21.425	17.604	0.471
1.0	2	3.820	35.116	31.296	21.383	17.563	0.470
2.0	1	3.821	35.219	31.398	21.652	17.831	0.477
5.0	1	3.668	36.344	32.676	23.252	19.584	0.524
10.0	1	3.668	36.704	33.036	23.702	20.034	0.536
15.0	1	3.668	36.224	32.556	22.153	18.485	0.495
15.0	2	3.823	34.075	30.252	20.710	16.887	0.452
15.0	3	3.668	35.020	31.352	21.579	17.911	0.479
						average	*0.511*
						stdev	*0.056*
						± se	*0.015*

TABLE 66: Raw data for moisture retention curve of BCTMP sludge-soil mixture 20:30

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.827	37.420	33.593	22.644	18.817	0.504
0.3	1	3.829	39.065	35.236	25.425	21.596	0.578
0.3	2	3.830	42.759	38.929	25.066	21.236	0.568
0.3	3	3.826	41.559	37.733	24.716	20.890	0.559
0.5	1	3.830	36.996	33.166	24.360	20.530	0.549
0.7	1	3.829	37.907	34.078	25.210	21.381	0.572
1.0	1	3.828	37.563	33.735	24.669	20.841	0.558
1.0	2	3.828	38.083	34.255	25.092	21.264	0.569
2.0	1	3.830	37.859	34.029	24.832	21.002	0.562
5.0	1	3.679	40.949	37.27	26.863	23.184	0.620
10.0	1	3.680	40.900	37.220	26.250	22.570	0.604
15.0	1	3.679	39.950	36.271	26.798	23.119	0.619
15.0	2	3.831	36.795	32.964	24.071	20.240	0.542
15.0	3	3.679	39.411	35.732	24.804	21.125	0.565
						average	*0.569*
						stdev	*0.031*
						± se	*0.008*

Appendix I: Pressure Plate Experiment

TABLE 67: Raw data for moisture retention curve of BCTMP sludge-soil mixture 10:40

pressure [bar]	trial #	alu empty [g]	& sample wet [g]	mass wet [g]	&sample dry [g]	mass dry [g]	Db [g/cm^3]
0.1	1	3.786	60.560	56.774	40.473	36.687	0.982
0.3	1	3.814	56.166	52.352	39.666	35.852	0.959
0.3	2	3.816	58.258	54.442	39.323	35.507	0.950
0.3	3	3.816	58.645	54.829	39.455	35.639	0.954
0.5	1	3.818	55.981	52.163	39.559	35.741	0.956
0.7	1	3.824	54.870	51.046	39.520	35.696	0.955
1.0	1	3.824	55.863	52.039	39.868	36.044	0.965
1.0	2	3.822	55.167	51.345	39.171	35.349	0.946
2.0	1	3.822	55.697	51.875	39.538	35.716	0.956
5.0	1	3.699	55.094	51.395	39.569	35.870	0.960
10.0	1	3.699	55.879	52.180	40.725	37.026	0.991
15.0	1	3.698	54.862	51.164	39.854	36.156	0.968
15.0	2	3.821	56.023	52.202	40.666	36.845	0.986
15.0	3	3.700	56.148	52.448	39.901	36.201	0.969
						average	*0.964*
						stdev	*0.014*
						± se	*0.004*

Appendix I: Pressure Plate Experiment

Part B: Moisture retention curves for sludge-soil mixtures

TABLE 68: WHC_g, Db, WHC_v, and random errors of original Kraft mill sludge.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm^3]	± Δ Db [g/cm^3]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	23.463	4.751	394	0.125	0.127	0.0026	50	1.022
0.3	1	20.215	5.085	298	0.092	0.136	0.0028	40	0.827
0.3	2	19.256	4.978	287	0.091	0.133	0.0027	38	0.780
0.3	3	19.477	4.917	296	0.094	0.132	0.0027	39	0.796
0.5	1	18.471	5.068	264	0.084	0.136	0.0028	36	0.732
0.7	1	19.404	5.233	271	0.083	0.140	0.0029	38	0.774
1.0	1	17.953	5.043	256	0.082	0.135	0.0028	35	0.705
1.0	2	16.730	4.605	263	0.092	0.123	0.0025	32	0.663
2.0	1	16.996	4.932	245	0.081	0.132	0.0027	32	0.659
5.0	1	18.624	5.307	251	0.077	0.142	0.0029	36	0.728
10.0	1	18.023	5.209	246	0.077	0.139	0.0028	34	0.700
15.0	1	17.248	4.978	246	0.081	0.133	0.0027	33	0.670
15.0	2	17.302	5.229	231	0.073	0.140	0.0029	32	0.660
15.0	3	17.035	4.922	246	0.082	0.132	0.0027	32	0.662

TABLE 69: WHC_g, Db, WHC_v, and random errors of blended Kraft mill sludge.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm^3]	± Δ Db [g/cm^3]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	29.789	6.347	369	0.088	0.170	0.0035	63	1.281
0.3	1	23.897	5.983	299	0.078	0.160	0.0033	48	0.979
0.3	2	23.233	6.476	259	0.064	0.173	0.0035	45	0.916
0.3	3	23.030	6.160	274	0.071	0.165	0.0034	45	0.922
0.5	1	21.681	5.923	266	0.072	0.158	0.0032	42	0.861
0.7	1	25.983	7.306	256	0.057	0.196	0.0040	50	1.020
1.0	1	24.492	6.880	256	0.060	0.184	0.0038	47	0.962
1.0	2	21.383	6.132	249	0.066	0.164	0.0034	41	0.833
2.0	1	20.036	5.794	246	0.069	0.155	0.0032	38	0.778
5.0	1	20.207	5.642	258	0.074	0.151	0.0031	39	0.796
10.0	1	24.381	7.483	226	0.050	0.200	0.0041	45	0.923
15.0	1	20.539	6.389	221	0.058	0.171	0.0035	38	0.773
15.0	2	19.719	5.763	242	0.069	0.154	0.0031	37	0.763
15.0	3	20.777	6.146	238	0.064	0.164	0.0034	39	0.799

TABLE 70: WHC_g, Db, WHC_v, and random errors of Kraft mill sludge-soil mixture 40:10.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm^3]	± Δ Db [g/cm^3]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	31.178	9.736	220	0.038	0.261	0.0053	57	1.171
0.3	1	27.093	10.098	168	0.031	0.270	0.0055	45	0.928
0.3	2	24.774	8.847	180	0.037	0.237	0.0048	43	0.870
0.3	3	25.814	10.030	157	0.030	0.268	0.0055	42	0.862
0.5	1	23.696	9.126	160	0.033	0.244	0.0050	39	0.796
0.7	1	25.223	8.941	182	0.036	0.239	0.0049	44	0.890
1.0	1	24.968	10.228	144	0.028	0.274	0.0056	39	0.805
1.0	2	23.938	8.887	169	0.035	0.238	0.0049	40	0.822
2.0	1	22.763	9.326	144	0.031	0.250	0.0051	36	0.734
5.0	1	24.642	9.793	152	0.030	0.262	0.0053	40	0.811
10.0	1	22.400	9.733	130	0.028	0.260	0.0053	34	0.692
15.0	1	22.227	9.248	140	0.030	0.247	0.0051	35	0.709
15.0	2	22.446	10.179	121	0.026	0.272	0.0056	33	0.670
15.0	3	22.480	9.806	129	0.028	0.262	0.0054	34	0.692

Appendix I: Pressure Plate Experiment

TABLE 71: WHC_g, Db, WHC_v, and random errors of Kraft mill sludge-soil mixture 30:20.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	40.580	15.233	166	0.020	0.408	0.0083	68	1.385
0.3	1	33.934	14.661	131	0.019	0.392	0.0080	52	1.053
0.3	2	32.504	15.530	109	0.016	0.416	0.0085	45	0.927
0.3	3	32.989	15.474	113	0.017	0.414	0.0085	47	0.957
0.5	1	31.415	15.040	109	0.017	0.402	0.0082	44	0.895
0.7	1	33.467	15.040	123	0.018	0.402	0.0082	49	1.007
1.0	1	32.685	16.224	101	0.015	0.434	0.0089	44	0.899
1.0	2	31.932	16.256	96	0.015	0.435	0.0089	42	0.856
2.0	1	30.262	16.135	88	0.015	0.432	0.0088	38	0.772
5.0	1	31.218	17.503	78	0.013	0.468	0.0096	37	0.749
10.0	1	30.051	17.000	77	0.013	0.455	0.0093	35	0.713
15.0	1	29.704	15.759	88	0.015	0.422	0.0086	37	0.762
15.0	2	29.512	15.616	89	0.015	0.418	0.0085	37	0.759
15.0	3	29.518	15.768	87	0.015	0.422	0.0086	37	0.751

TABLE 72: WHC_g, Db, WHC_v, and random errors of Kraft mill sludge-soil mixture 25:25.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	42.872	19.764	117	0.013	0.529	0.0108	62	1.262
0.3	1	36.608	18.642	96	0.013	0.499	0.0102	48	0.981
0.3	2	37.149	20.673	80	0.011	0.553	0.0113	44	0.900
0.3	3	36.854	18.921	95	0.013	0.506	0.0103	48	0.980
0.5	1	35.627	18.793	90	0.013	0.503	0.0103	45	0.920
0.7	1	32.608	18.830	73	0.012	0.504	0.0103	37	0.753
1.0	1	33.673	18.899	78	0.012	0.506	0.0103	40	0.807
1.0	2	33.014	17.498	89	0.013	0.468	0.0096	42	0.848
2.0	1	32.740	19.200	71	0.012	0.514	0.0105	36	0.740
5.0	1	33.737	19.643	72	0.011	0.526	0.0107	38	0.770
10.0	1	32.649	18.926	73	0.012	0.506	0.0103	37	0.750
15.0	1	31.052	17.734	75	0.013	0.475	0.0097	36	0.728
15.0	2	33.473	19.603	71	0.011	0.525	0.0107	37	0.758
15.0	3	32.364	18.817	72	0.012	0.504	0.0103	36	0.740

TABLE 73: WHC_g, Db, WHC_v, and random errors of Kraft mill sludge-soil mixture 20:30.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	41.598	20.913	99	0.012	0.560	0.0114	55	1.130
0.3	1	39.182	21.755	80	0.011	0.582	0.0119	47	0.952
0.3	2	37.543	22.063	70	0.010	0.590	0.0121	41	0.846
0.3	3	37.862	21.470	76	0.011	0.575	0.0117	44	0.896
0.5	1	36.868	21.887	68	0.010	0.586	0.0120	40	0.818
0.7	1	36.187	22.832	58	0.009	0.611	0.0125	36	0.730
1.0	1	36.280	22.041	65	0.010	0.590	0.0120	38	0.778
1.0	2	35.305	20.218	75	0.011	0.541	0.0110	40	0.824
2.0	1	34.248	22.436	53	0.010	0.600	0.0123	32	0.645
5.0	1	34.870	22.602	54	0.009	0.605	0.0123	33	0.670
10.0	1	34.498	21.415	61	0.010	0.573	0.0117	35	0.715
15.0	1	32.756	21.390	53	0.010	0.572	0.0117	30	0.621
15.0	2	33.529	22.154	51	0.010	0.593	0.0121	30	0.621
15.0	3	33.386	21.266	57	0.010	0.569	0.0116	32	0.662

Appendix I: Pressure Plate Experiment

TABLE 74: WHC_g, Db, WHC_v, and random errors of Kraft mill sludge-soil mixture 10:40.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	$\pm \Delta WHC_g$ [%]	Db [g/cm^3]	$\pm \Delta$ Db [g/cm^3]	WHC_v [%]	$\pm \Delta WHC_v$ [%]
0.1	1	55.704	34.476	62	0.006	0.923	0.0188	57	1.160
0.3	1	52.010	34.292	52	0.006	0.918	0.0187	47	0.968
0.3	2	52.489	34.864	51	0.006	0.933	0.0190	47	0.963
0.3	3	52.048	34.278	52	0.006	0.917	0.0187	48	0.971
0.5	1	49.106	34.306	43	0.006	0.918	0.0187	40	0.809
0.7	1	49.629	35.175	41	0.006	0.941	0.0192	39	0.790
1.0	1	49.003	34.280	43	0.006	0.917	0.0187	39	0.804
1.0	2	48.444	34.654	40	0.006	0.927	0.0189	37	0.753
2.0	1	48.434	35.134	38	0.006	0.940	0.0192	36	0.727
5.0	1	47.065	34.223	38	0.006	0.916	0.0187	34	0.702
10.0	1	46.194	33.997	36	0.006	0.910	0.0186	33	0.666
15.0	1	47.473	34.162	39	0.006	0.914	0.0187	36	0.727
15.0	2	48.613	35.038	39	0.006	0.938	0.0191	36	0.742
15.0	3	48.047	34.967	37	0.006	0.936	0.0191	35	0.715

Appendix I: Pressure Plate Experiment

TABLE 75: WHC_g, Db, WHC_v, and random errors of original BCTMP sludge.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	23.188	5.948	290	0.077	0.159	0.0032	46	0.942
0.3	1	20.931	5.916	254	0.069	0.158	0.0032	40	0.820
0.3	2	22.322	5.944	276	0.074	0.159	0.0032	44	0.895
0.3	3	21.342	5.579	283	0.080	0.149	0.0030	42	0.861
0.5	1	19.964	5.748	247	0.070	0.154	0.0031	38	0.777
0.7	1	20.775	5.828	256	0.071	0.156	0.0032	40	0.817
1.0	1	20.354	5.725	256	0.072	0.153	0.0031	39	0.799
1.0	2	19.956	5.648	253	0.073	0.151	0.0031	38	0.782
2.0	1	19.981	5.731	249	0.071	0.153	0.0031	38	0.779
5.0	1	19.171	5.589	243	0.071	0.150	0.0031	36	0.742
10.0	1	19.417	5.683	242	0.070	0.152	0.0031	37	0.750
15.0	1	18.987	5.625	238	0.070	0.151	0.0031	36	0.730
15.0	2	18.860	5.581	238	0.070	0.149	0.0030	36	0.726
15.0	3	19.964	5.648	253	0.073	0.151	0.0031	38	0.782

TABLE 76: WHC_g, Db, WHC_v, and random errors of blended BCTMP sludge.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	26.993	6.611	308	0.073	0.177	0.0036	55	1.114
0.3	1	21.861	6.454	239	0.061	0.173	0.0035	41	0.842
0.3	2	25.669	6.870	274	0.063	0.184	0.0038	50	1.027
0.3	3	24.612	6.342	288	0.072	0.170	0.0035	49	0.998
0.5	1	23.387	6.735	247	0.060	0.180	0.0037	45	0.910
0.7	1	22.866	6.529	250	0.062	0.175	0.0036	44	0.893
1.0	1	23.140	6.625	249	0.061	0.177	0.0036	44	0.902
1.0	2	22.589	6.464	249	0.063	0.173	0.0035	43	0.881
2.0	1	23.536	6.606	256	0.063	0.177	0.0036	45	0.925
5.0	1	23.239	6.879	238	0.057	0.184	0.0038	44	0.894
10.0	1	23.462	6.631	254	0.062	0.177	0.0036	45	0.920
15.0	1	23.065	6.783	240	0.058	0.182	0.0037	44	0.890
15.0	2	21.588	6.531	231	0.059	0.175	0.0036	40	0.823
15.0	3	23.312	6.553	256	0.063	0.175	0.0036	45	0.916

TABLE 77: WHC_g, Db, WHC_v, and random errors of BCTMP sludge-soil mixture 40:10.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	33.051	11.467	188	0.029	0.307	0.0063	58	1.179
0.3	1	31.654	12.355	156	0.024	0.331	0.0067	52	1.054
0.3	2	32.493	11.492	183	0.028	0.308	0.0063	56	1.147
0.3	3	32.613	12.566	160	0.024	0.336	0.0069	54	1.095
0.5	1	30.340	12.743	138	0.022	0.341	0.0070	47	0.961
0.7	1	30.737	12.594	144	0.023	0.337	0.0069	49	0.991
1.0	1	30.889	12.478	148	0.023	0.334	0.0068	49	1.006
1.0	2	30.324	12.444	144	0.023	0.333	0.0068	48	0.977
2.0	1	29.027	12.104	140	0.023	0.324	0.0066	45	0.925
5.0	1	33.198	13.972	138	0.020	0.374	0.0076	51	1.050
10.0	1	32.434	13.465	141	0.021	0.360	0.0074	51	1.036
15.0	1	31.967	12.999	146	0.022	0.348	0.0071	51	1.036
15.0	2	28.847	12.107	138	0.023	0.324	0.0066	45	0.915
15.0	3	29.805	11.708	155	0.025	0.313	0.0064	48	0.989

Appendix I: Pressure Plate Experiment

TABLE 78: WHC_g, Db, WHC_v, and random errors of BCTMP sludge-soil mixture 30:20.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	34.304	16.191	112	0.016	0.433	0.0088	48	0.990
0.3	1	32.328	16.076	101	0.015	0.430	0.0088	43	0.888
0.3	2	32.734	15.920	106	0.016	0.426	0.0087	45	0.919
0.3	3	33.834	15.626	117	0.017	0.418	0.0085	49	0.995
0.5	1	32.588	16.110	102	0.015	0.431	0.0088	44	0.900
0.7	1	33.559	16.359	105	0.015	0.438	0.0089	46	0.940
1.0	1	34.035	17.395	96	0.014	0.465	0.0095	45	0.909
1.0	2	33.543	17.096	96	0.014	0.457	0.0093	44	0.899
2.0	1	32.914	16.805	96	0.014	0.450	0.0092	43	0.880
5.0	1	34.444	17.812	93	0.013	0.477	0.0097	45	0.909
10.0	1	34.293	17.603	95	0.014	0.471	0.0096	45	0.912
15.0	1	33.786	17.377	94	0.014	0.465	0.0095	44	0.896
15.0	2	31.911	16.825	90	0.014	0.450	0.0092	40	0.824
15.0	3	32.257	15.661	106	0.016	0.419	0.0086	44	0.907

TABLE 79: WHC_g, Db, WHC_v, and random errors of BCTMP sludge-soil mixture 25:25.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	48.486	24.591	97	0.010	0.658	0.0134	64	1.305
0.3	1	38.689	21.270	82	0.011	0.569	0.0116	47	0.952
0.3	2	38.008	20.308	87	0.012	0.543	0.0111	47	0.967
0.3	3	38.568	20.513	88	0.011	0.549	0.0112	48	0.986
0.5	1	30.761	17.440	76	0.013	0.467	0.0095	36	0.728
0.7	1	30.950	17.570	76	0.013	0.470	0.0096	36	0.731
1.0	1	31.208	17.604	77	0.013	0.471	0.0096	36	0.743
1.0	2	31.296	17.563	78	0.013	0.470	0.0096	37	0.750
2.0	1	31.398	17.831	76	0.013	0.477	0.0097	36	0.741
5.0	1	32.676	19.584	67	0.011	0.524	0.0107	35	0.715
10.0	1	33.036	20.034	65	0.011	0.536	0.0109	35	0.710
15.0	1	32.556	18.485	76	0.012	0.495	0.0101	38	0.769
15.0	2	30.252	16.887	79	0.014	0.452	0.0092	36	0.730
15.0	3	31.352	17.911	75	0.013	0.479	0.0098	36	0.734

TABLE 80: WHC_g, Db, WHC_v, and random errors of BCTMP sludge-soil mixture 20:30.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	33.593	18.817	79	0.012	0.504	0.0103	40	0.807
0.3	1	35.236	21.596	63	0.010	0.578	0.0118	36	0.745
0.3	2	38.929	21.236	83	0.011	0.568	0.0116	47	0.967
0.3	3	37.733	20.890	81	0.011	0.559	0.0114	45	0.920
0.5	1	33.166	20.530	62	0.011	0.549	0.0112	34	0.690
0.7	1	34.078	21.381	59	0.010	0.572	0.0117	34	0.694
1.0	1	33.735	20.841	62	0.010	0.558	0.0114	35	0.704
1.0	2	34.255	21.264	61	0.010	0.569	0.0116	35	0.710
2.0	1	34.029	21.002	62	0.010	0.562	0.0115	35	0.712
5.0	1	37.270	23.184	61	0.009	0.620	0.0127	38	0.770
10.0	1	37.220	22.570	65	0.010	0.604	0.0123	39	0.800
15.0	1	36.271	23.119	57	0.009	0.619	0.0126	35	0.719
15.0	2	32.964	20.240	63	0.011	0.542	0.0111	34	0.695
15.0	3	35.732	21.125	69	0.011	0.565	0.0115	39	0.798

Appendix I: Pressure Plate Experiment

TABLE 81: WHC_g, Db, WHC_v, and random errors of BCTMP sludge-soil mixture 10:40.

pressure [bar]	trial #	mass wet [g]	mass dry [g]	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm³]	± Δ Db [g/cm³]	WHC_v [%]	± Δ WHC_v [%]
0.1	1	56.774	36.687	55	0.006	0.982	0.0200	54	1.097
0.3	1	52.352	35.852	46	0.006	0.959	0.0196	44	0.901
0.3	2	54.442	35.507	53	0.006	0.950	0.0194	51	1.034
0.3	3	54.829	35.639	54	0.006	0.954	0.0195	51	1.048
0.5	1	52.163	35.741	46	0.006	0.956	0.0195	44	0.897
0.7	1	51.046	35.696	43	0.006	0.955	0.0195	41	0.839
1.0	1	52.039	36.044	44	0.006	0.965	0.0197	43	0.874
1.0	2	51.345	35.349	45	0.006	0.946	0.0193	43	0.874
2.0	1	51.875	35.716	45	0.006	0.956	0.0195	43	0.883
5.0	1	51.395	35.870	43	0.006	0.960	0.0196	42	0.848
10.0	1	52.180	37.026	41	0.006	0.991	0.0202	41	0.828
15.0	1	51.164	36.156	42	0.006	0.968	0.0198	40	0.820
15.0	2	52.202	36.845	42	0.006	0.986	0.0201	41	0.839
15.0	3	52.448	36.201	45	0.006	0.969	0.0198	43	0.888

Appendix I: Pressure Plate Experiment

Moisture retention curves for Kraft mill sludge-soil mixtures

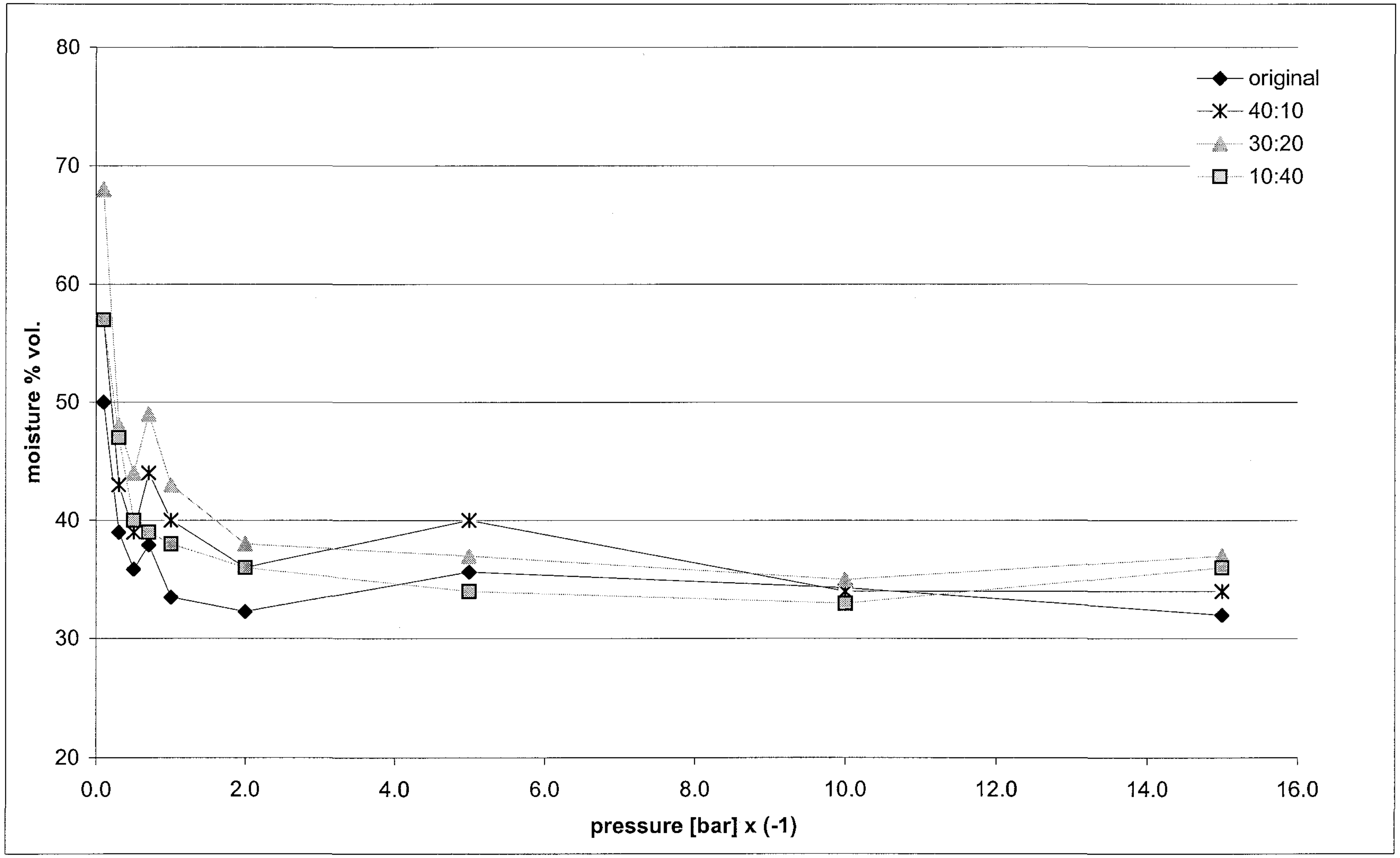

FIGURE 15: Moisture retention curves for Kraft mill sludge, Kraft mill sludge-soil mixtures 40:10, 30:20 and 10:40 from 0.1 to 15 bar x (-1).

Appendix I: Pressure Plate Experiment

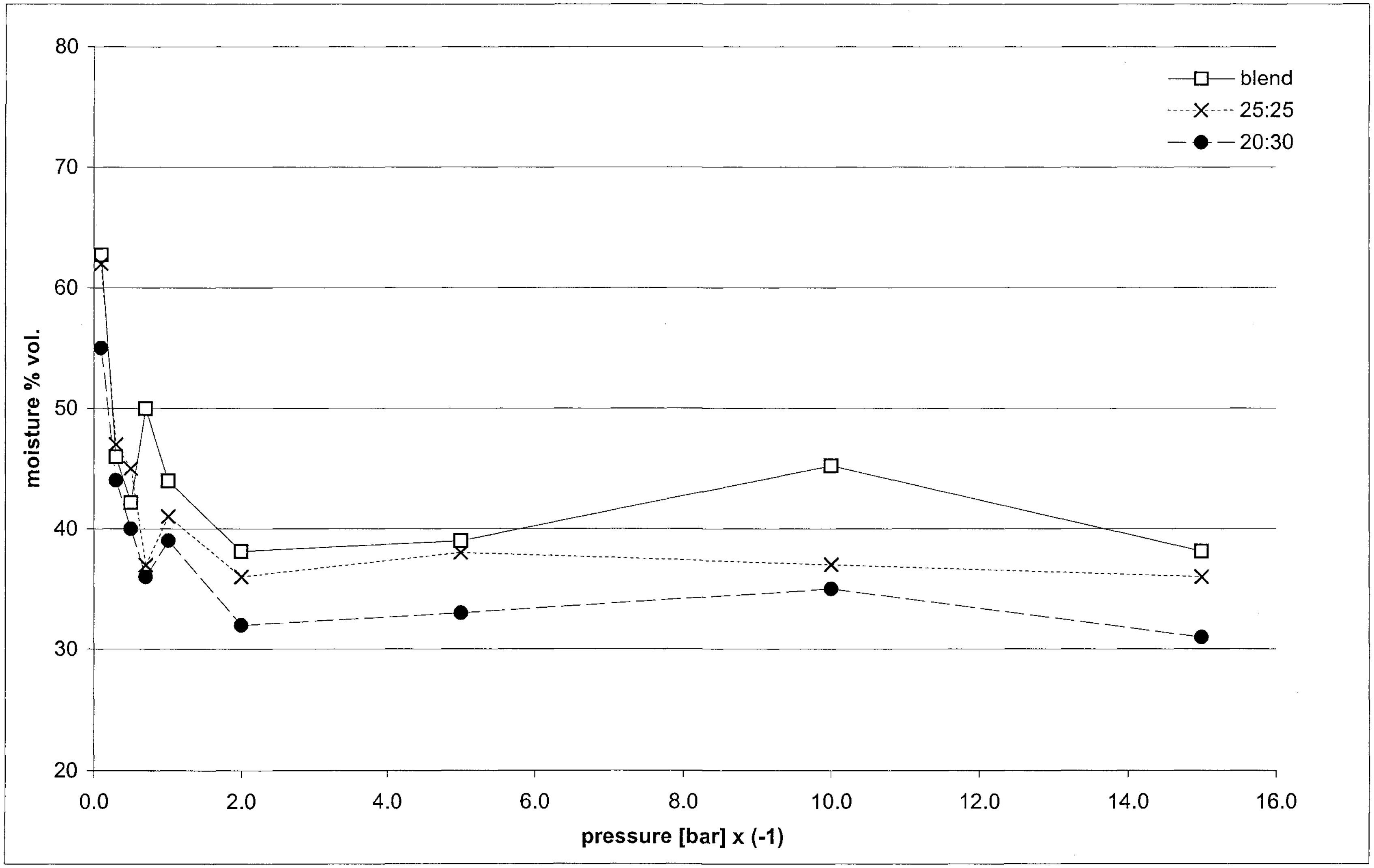

FIGURE 16: Moisture retention curves for blended Kraft mill sludge, Kraft mill sludge-soil mixtures 25:25 and 20:30 from 0.1 to 15 bar x (-1).

Appendix I: Pressure Plate Experiment

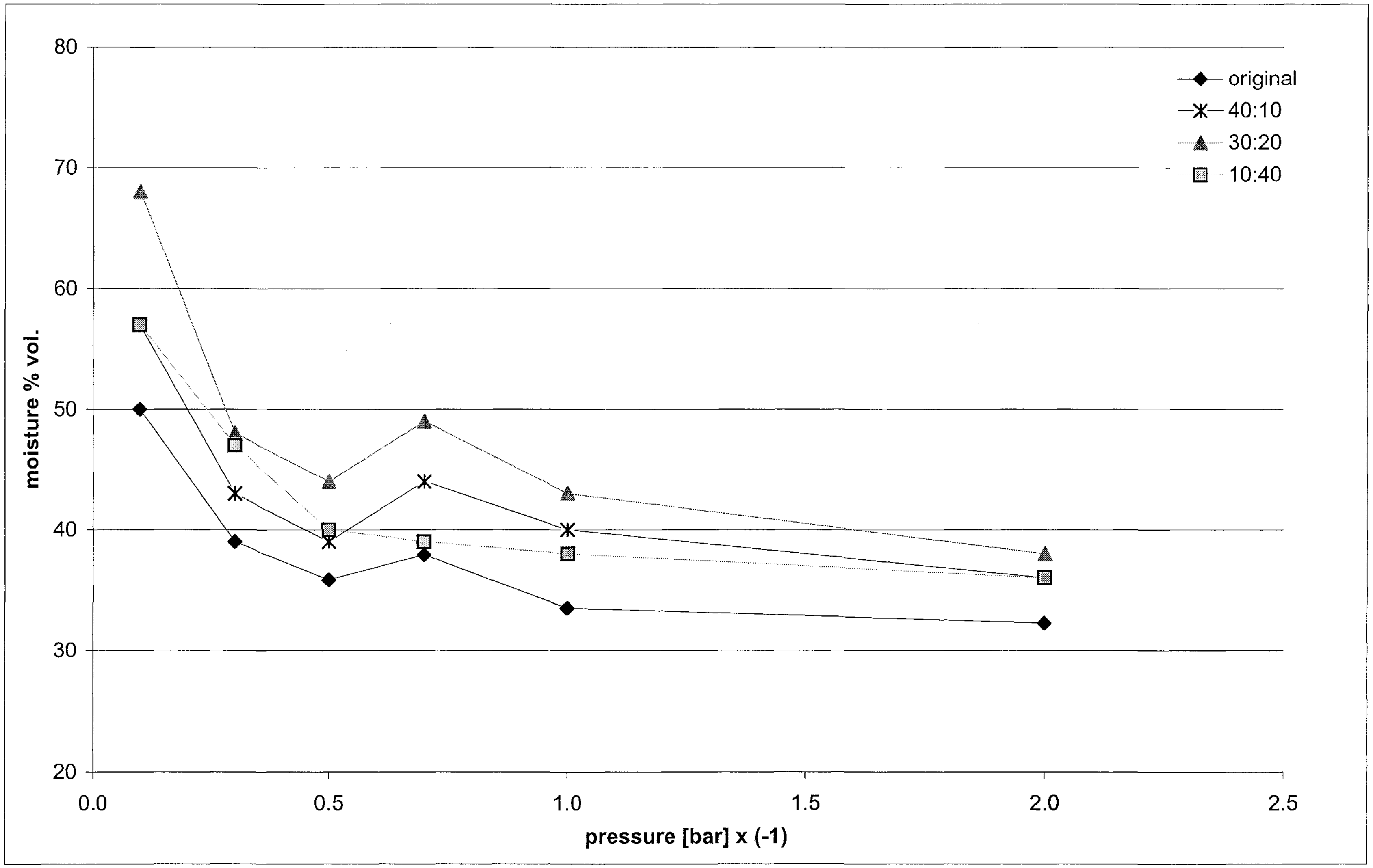

FIGURE 17: Moisture retention curves for Kraft mill sludge, Kraft mill sludge-soil mixtures 40:10, 30:20 and 10:40 from 0.1 to 2.5 bar x (-1).

Appendix I: Pressure Plate Experiment

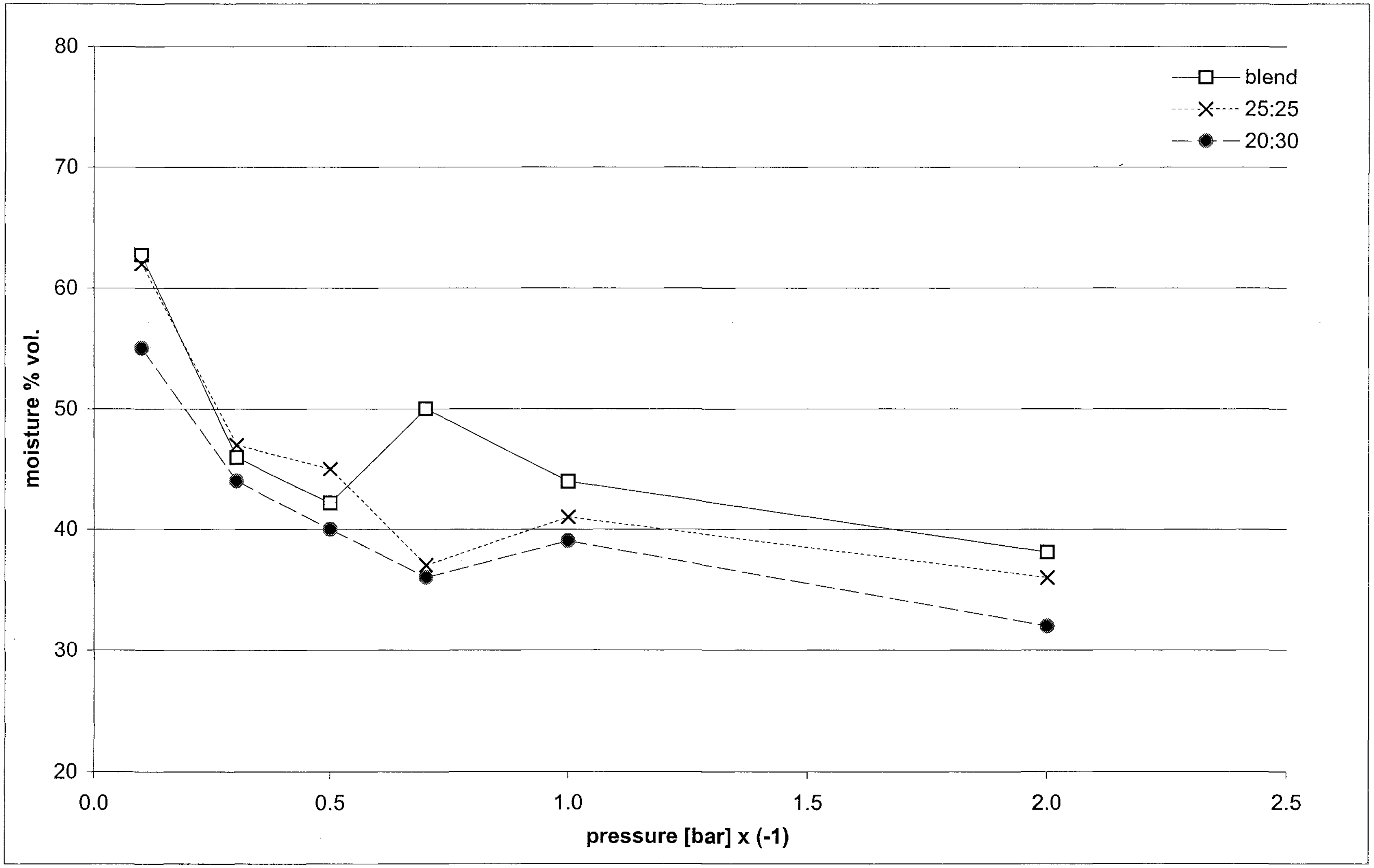

FIGURE 18: Moisture retention curves for blended Kraft mill sludge, Kraft mill sludge-soil mixtures 25:25 and 20:30 from 0.1 to 2.5 bar x (-1).

Appendix I: Pressure Plate Experiment

Moisture retention curves for Kraft mill sludge-soil mixtures with random errors

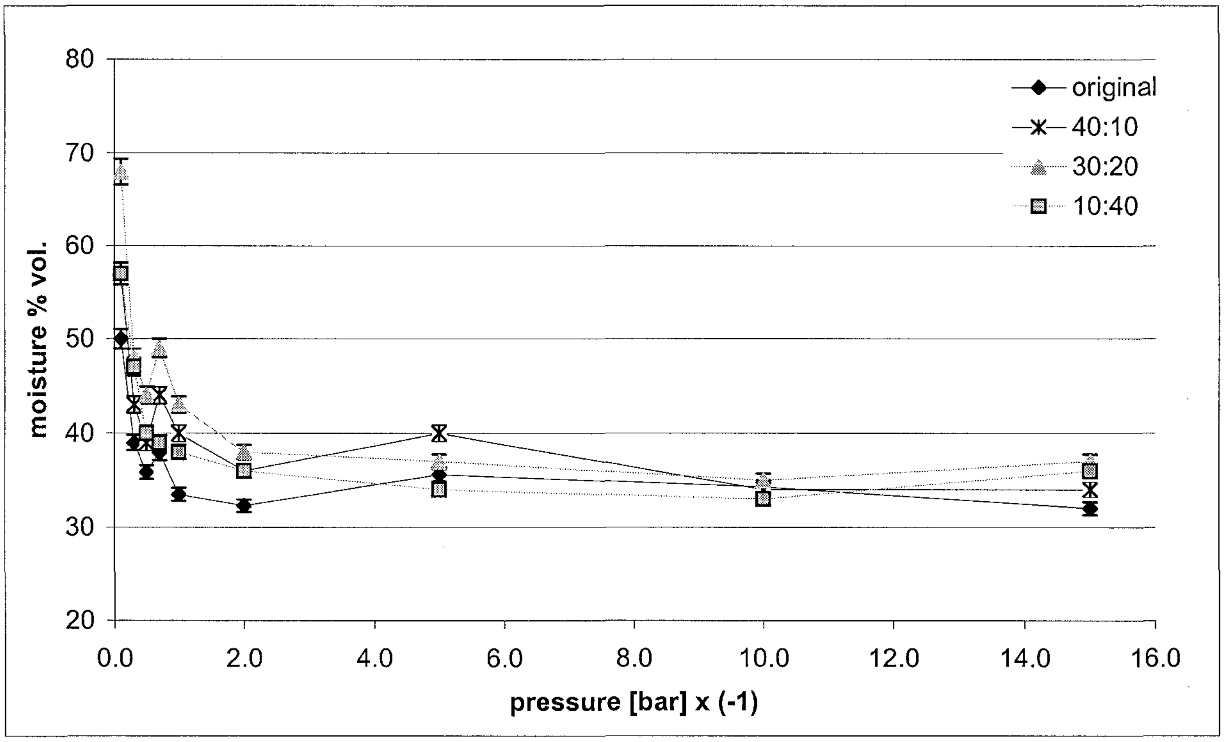

FIGURE 19: Moisture retention curves for original Kraft mill sludge, Kraft mill sludge-soil mixtures 40:10, 30:20 and 10:40 with random errors from 0.1 to 15 bar x (-1).

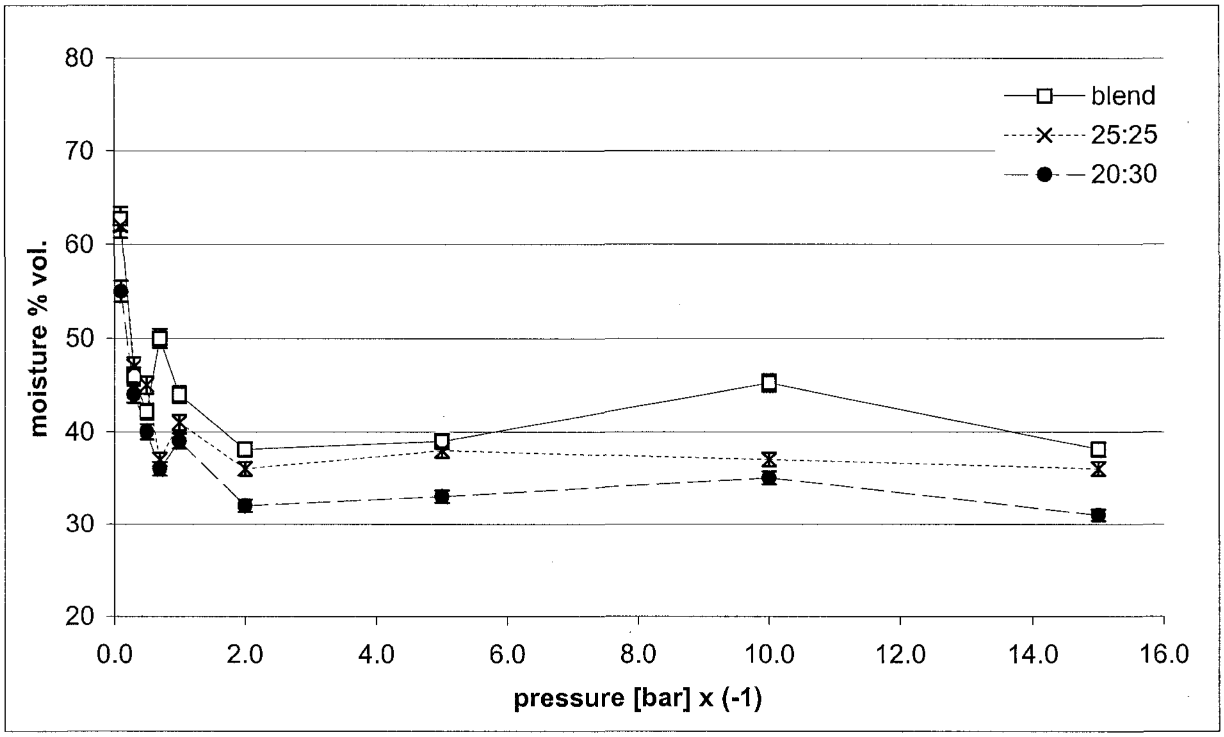

FIGURE 20: Moisture retention curves for blended Kraft mill sludge, Kraft mill sludge-soil mixtures 25:25 and 20:30 with random errors from 0.1 to 15 bar x (-1).

Appendix I: Pressure Plate Experiment

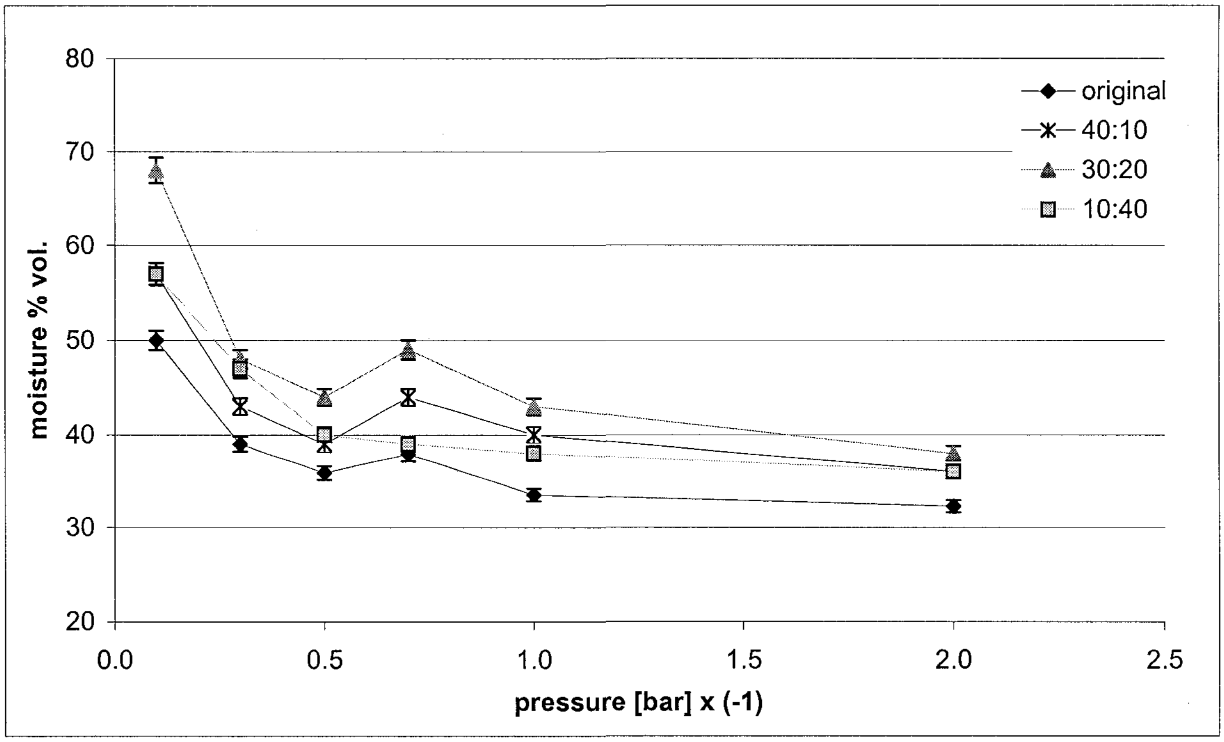

FIGURE 21 : Moisture retention curves for original Kraft mill sludge, Kraft mill sludge-soil mixtures 40:10, 30:20 and 10:40 with random errors from 0.1 to 2.5 bar x (-1).

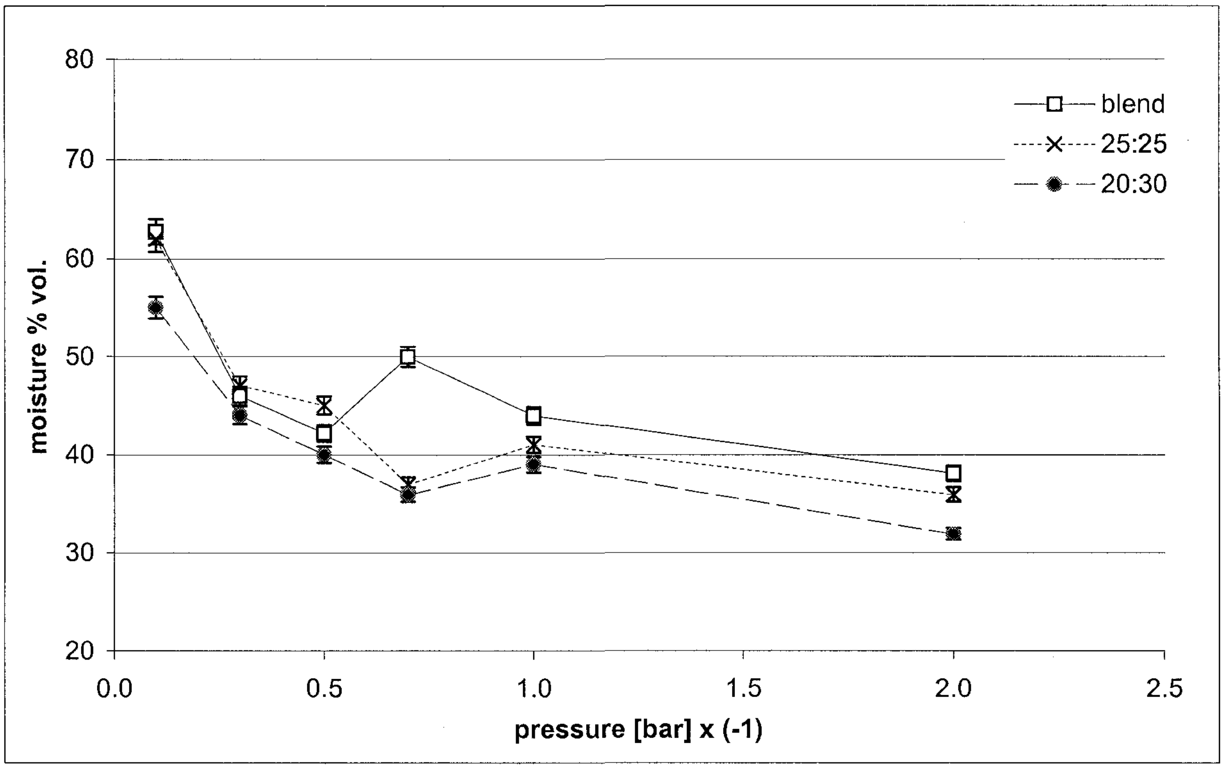

FIGURE 22: Moisture retention curves for blended Kraft mill sludge, Kraft mill sludge-soil mixtures 25:25 and 20:30 with random errors from 0.1 to 2.5 bar x (-1).

Appendix I: Pressure Plate Experiment

Moisture retention curves for BCTMP sludge-soil mixtures

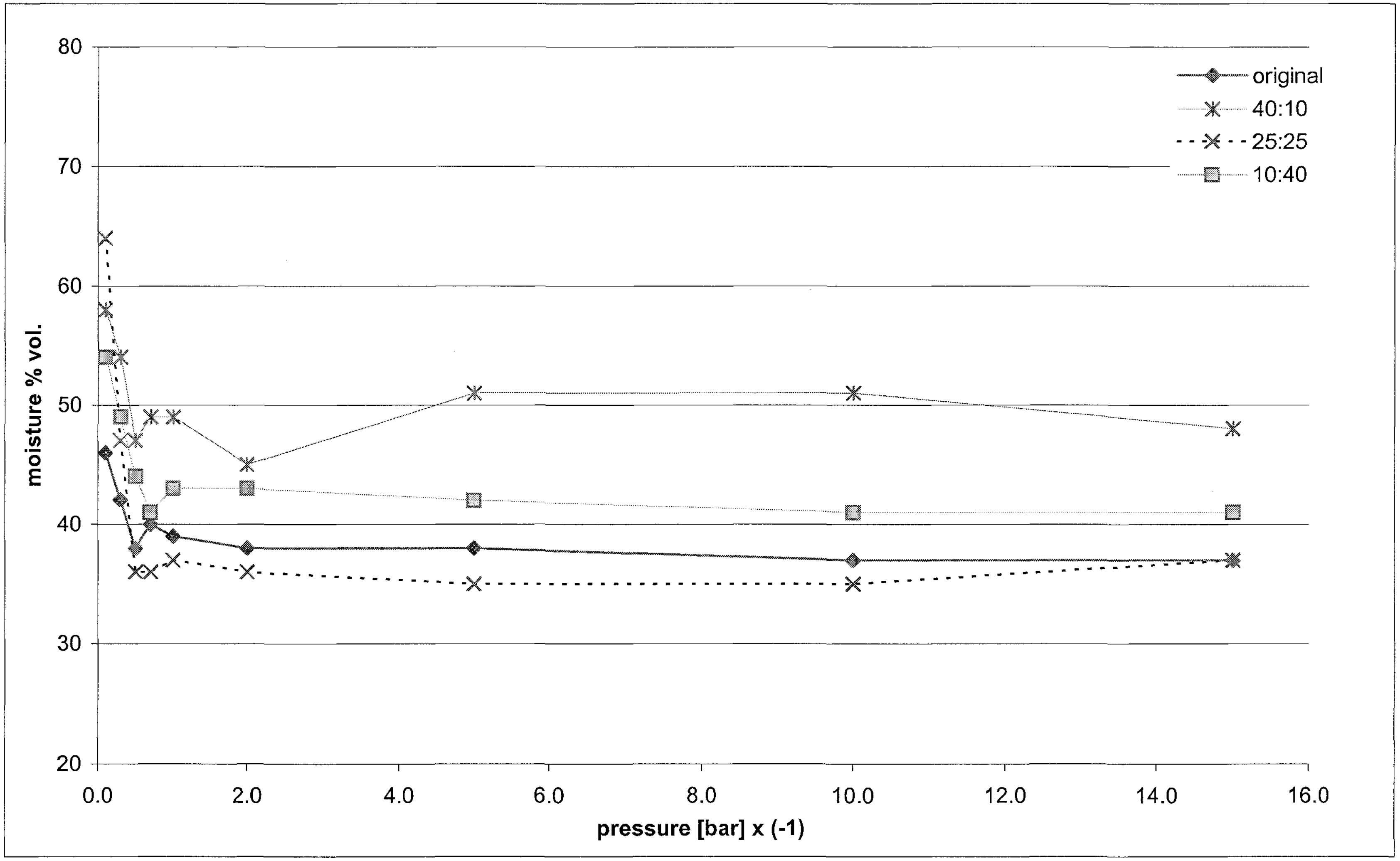

FIGURE 23: Moisture retention curves for BCTMP sludge, BCTMP sludge-soil mixtures 40:10, 25:25 and 10:40 from 0.1 to 15 bar x (-1).

Appendix I: Pressure Plate Experiment

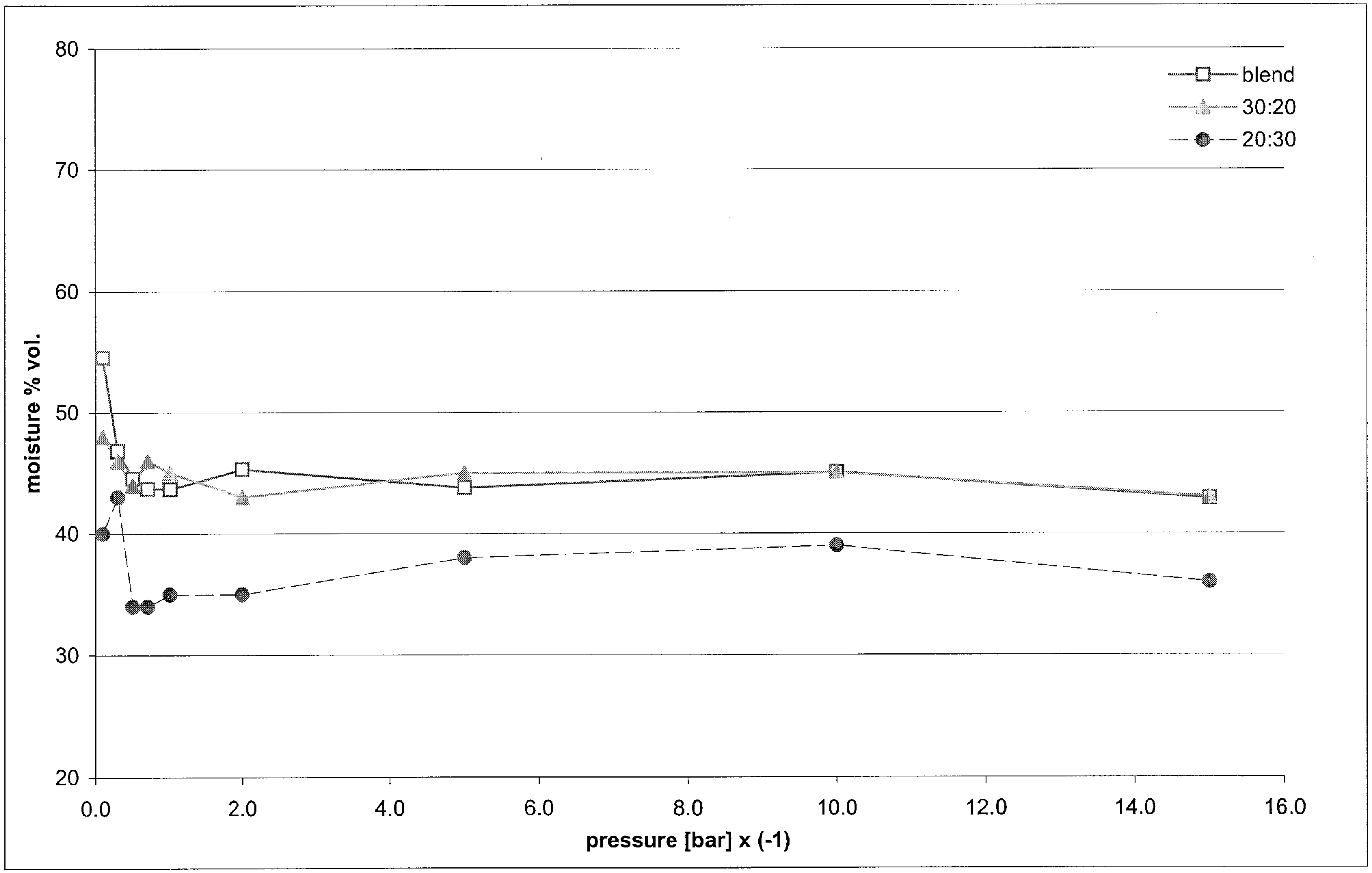

FIGURE 24: Moisture retention curves for blended BCTMP sludge, BCTMP sludge-soil mixtures 20:30 and 30:20 from 0.1 to 15 bar x (-1).

Appendix I: Pressure Plate Experiment

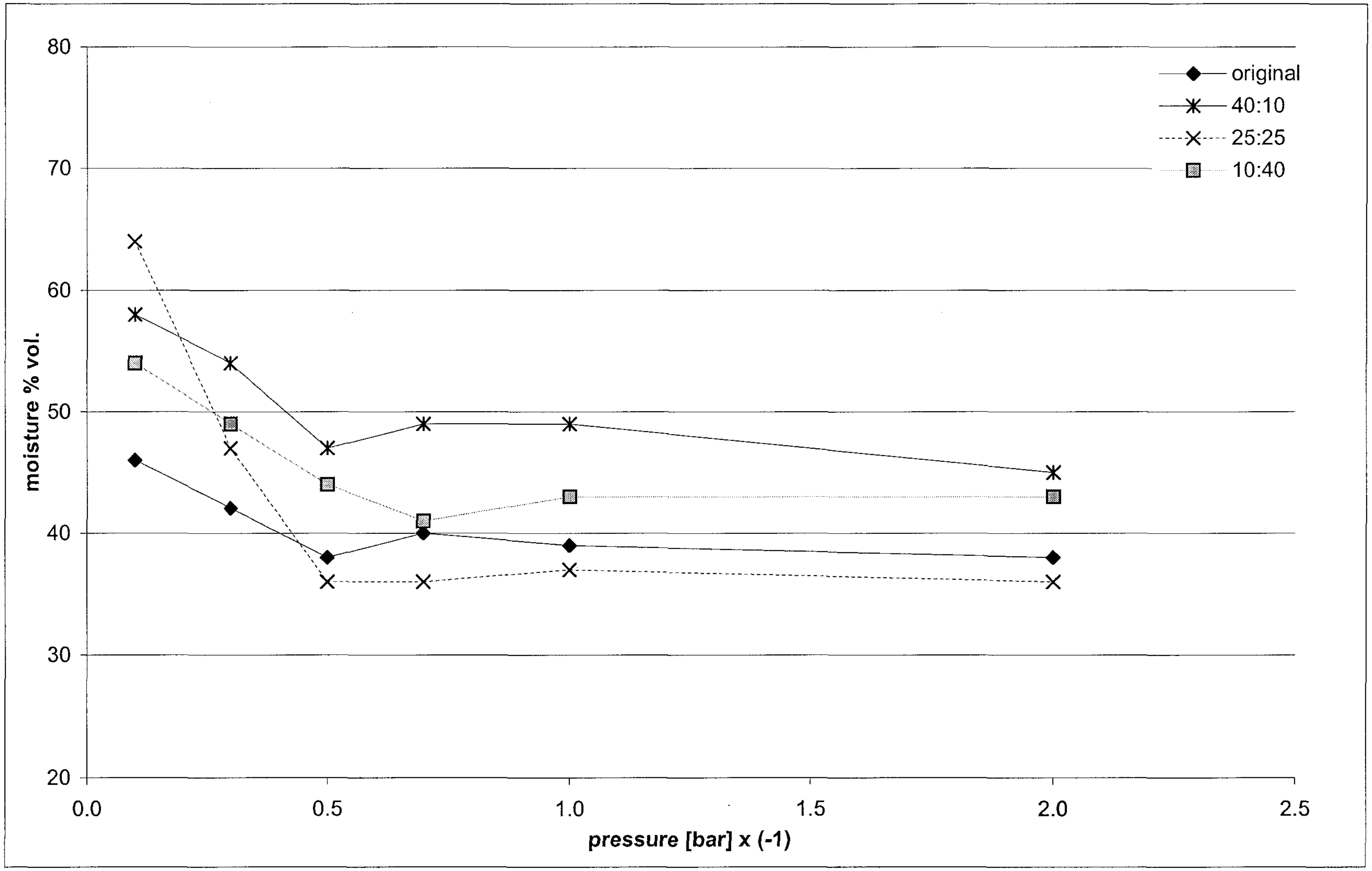

FIGURE 25: Moisture retention curves for BCTMP sludge, BCTMP sludge-soil mixtures 40:10, 25:25 and 10:40 from 0.1 to 2.5 bar x (-1).

Appendix I: Pressure Plate Experiment

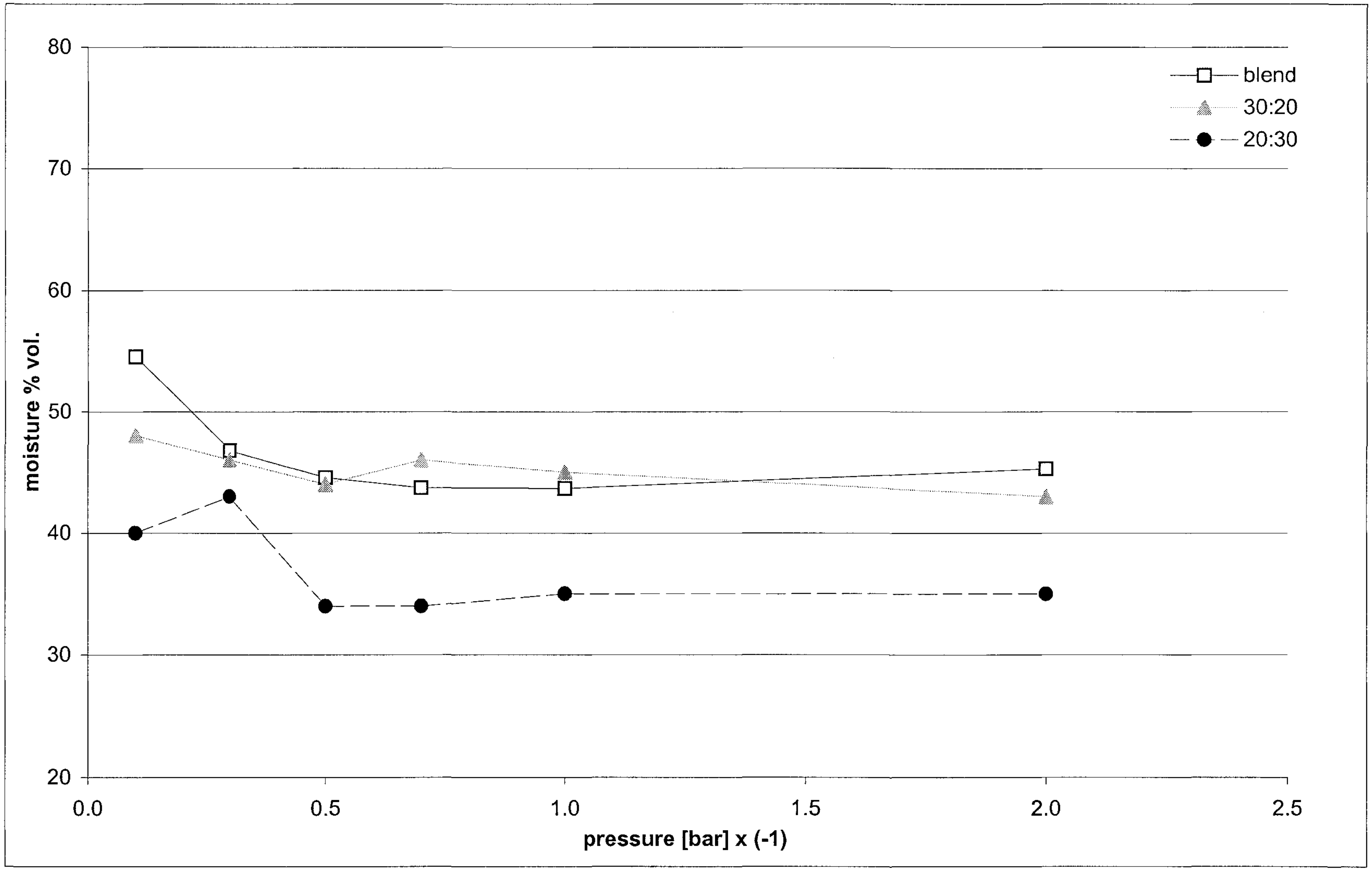

FIGURE 26: Moisture retention curves for blended BCTMP sludge, BCTMP sludge-soil mixtures 20:30 and 30:20 from 0.1 to 2.5 bar x (-1).

Appendix I: Pressure Plate Experiment

Moisture retention curves for BCTMP sludge-soil mixtures with random errors

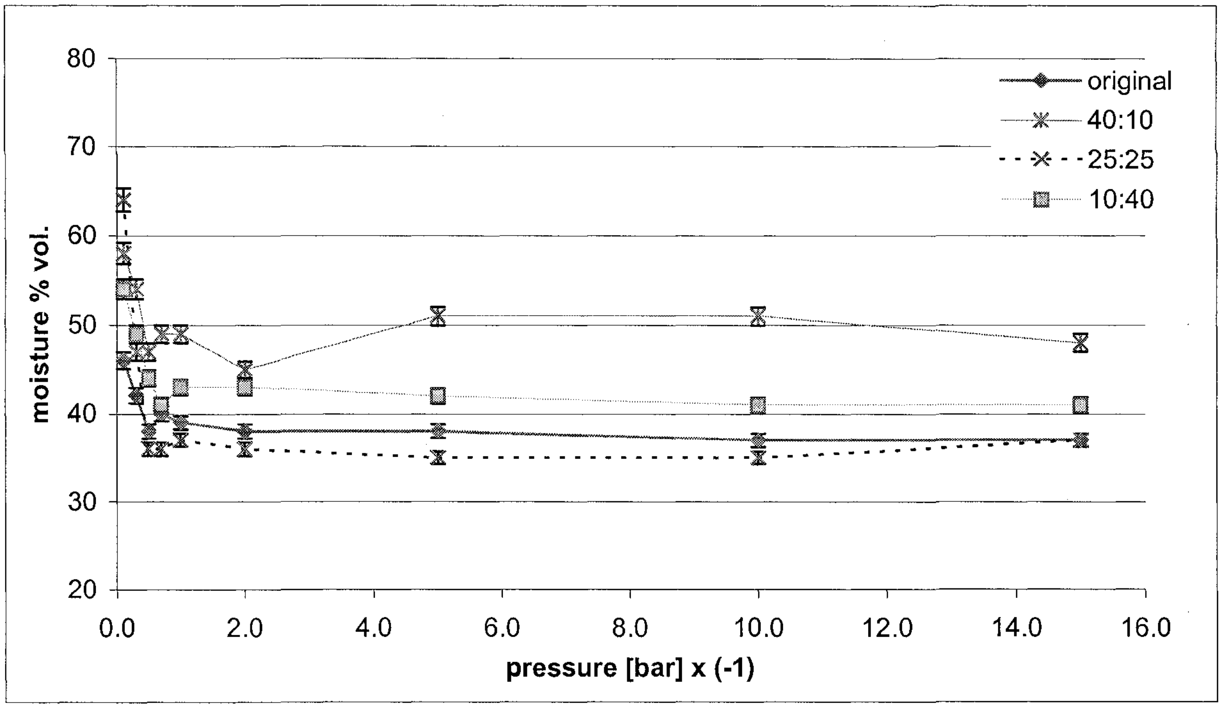

FIGURE 27: Moisture retention curves for BCTMP sludge, BCTMP sludge-soil mixtures 40:10, 25:25 and 10:40 with random errors from 0.1 to 15 bar x (-1).

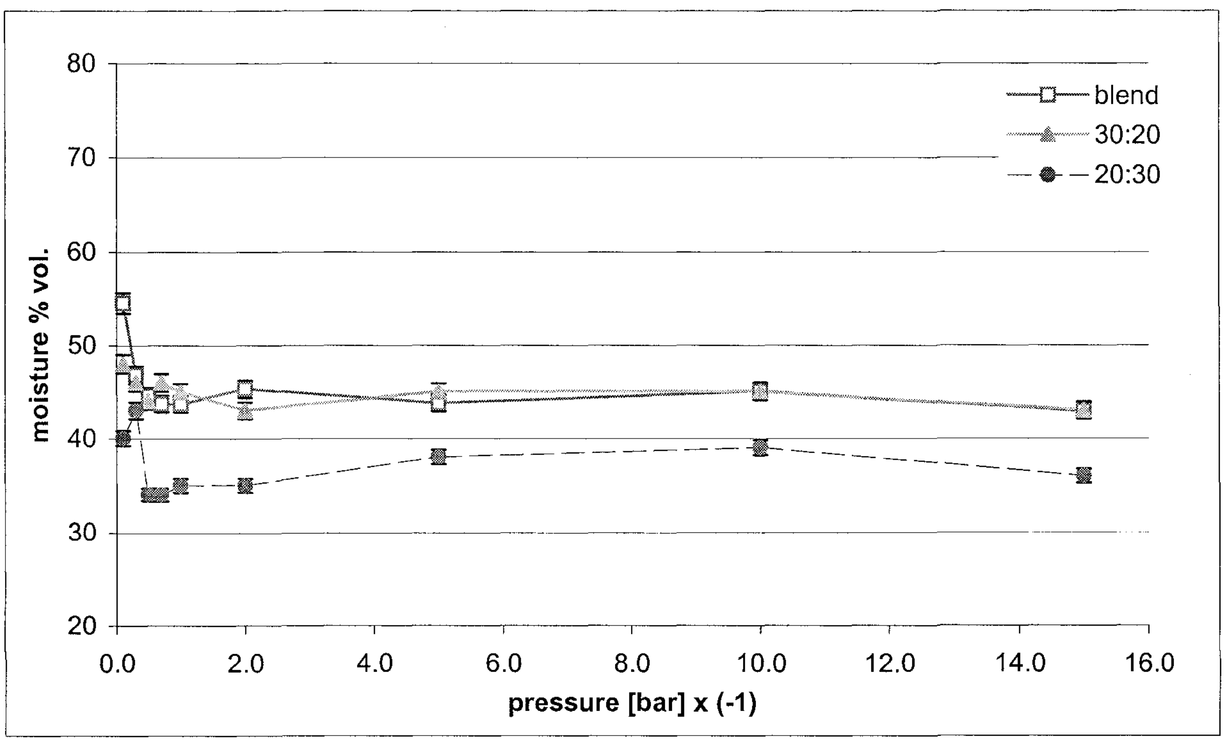

FIGURE 28: Moisture retention curves for blended BCTMP sludge, BCTMP sludge-soil mixtures 30:20 and 20:30 with random errors from 0.1 to 15 bar x (-1).

Appendix I: Pressure Plate Experiment

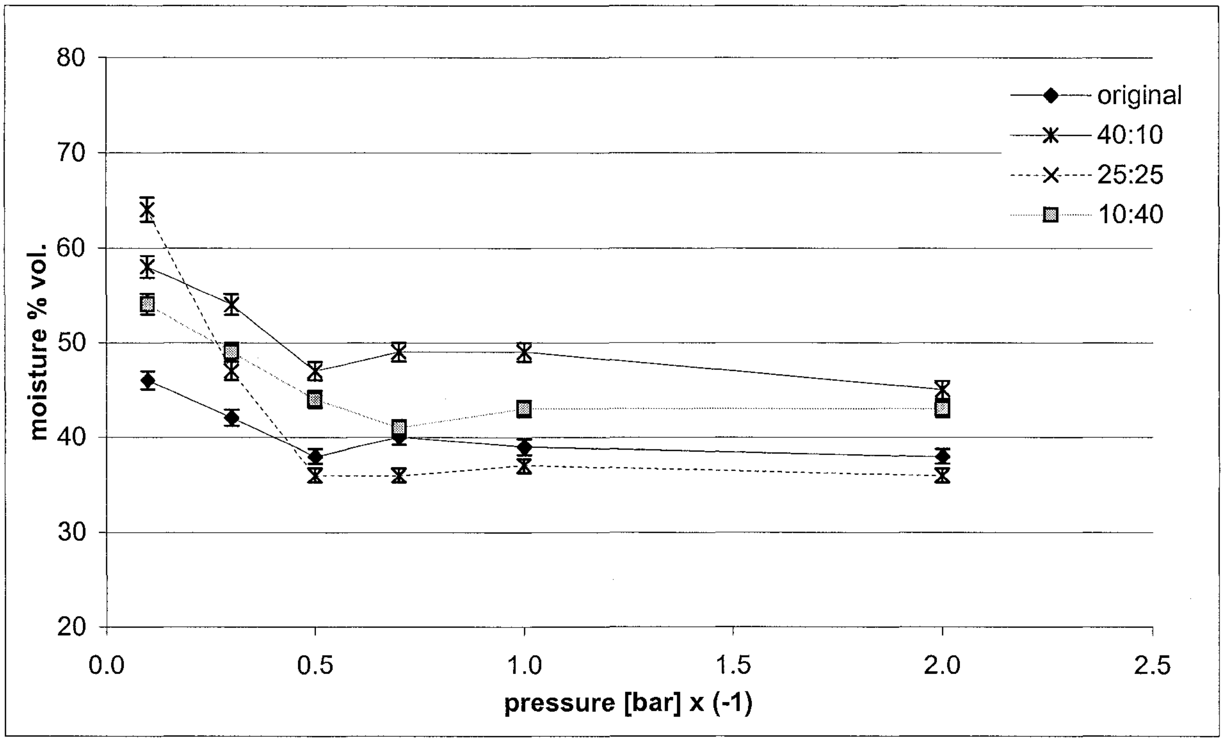

FIGURE 29: Moisture retention curves for BCTMP sludge, BCTMP sludge-soil mixtures 40:10, 25:25 and 10:40 with random errors from 0.1 to 2.5 bar x (-1).

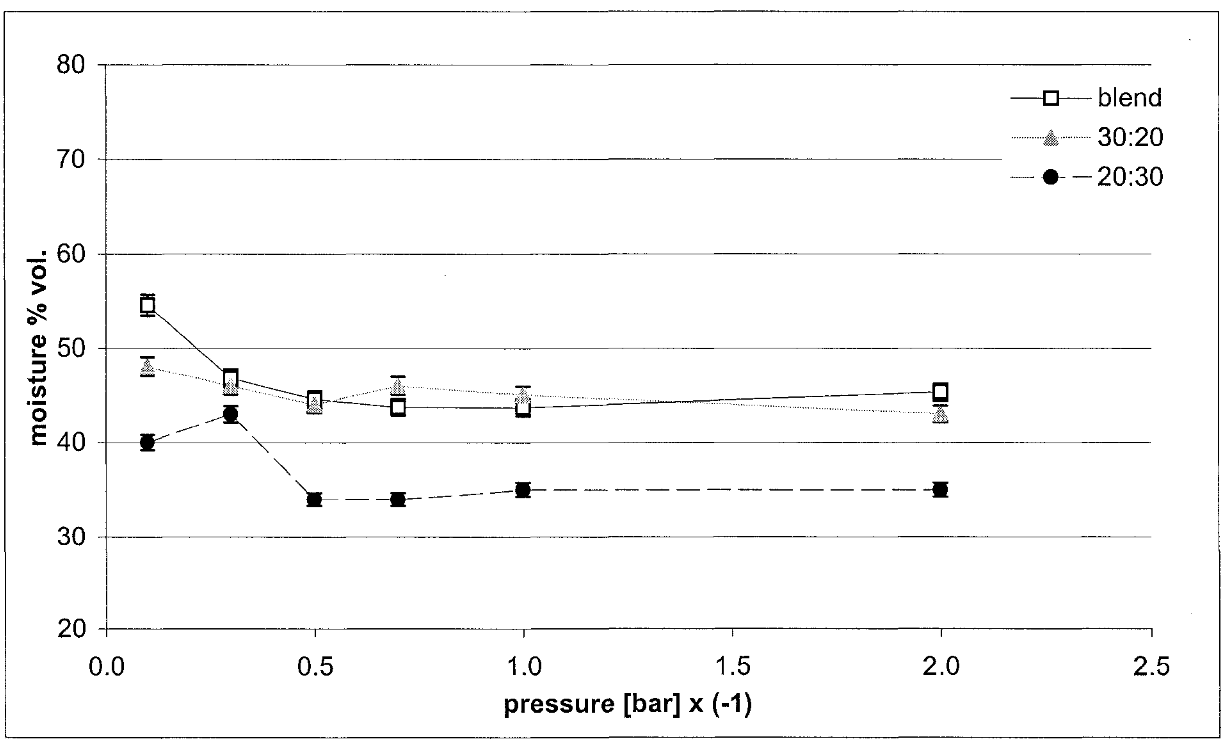

FIGURE 30: Moisture retention curves for blended BCTMP sludge, BCTMP sludge-soil mixtures 30:20 and 20:30 with random errors from 0.1 to 2.5 bar x (-1).

Appendix I: Pressure Plate Experiment

Part C : Moisture retention curves for sludge-soil layer systems

TABLE 82: Raw data for bulk density, WHC_g and WHC_v determination of each sludge and soil layer for Kraft mill sludge.

pressure [bar]		sample	column empty [g]	column&sample [g]	mass wet [g]	height [cm]	volume [cm^3]	mass dry [g]	Db [g/cm^3]	WHC_g [%]	WHC_v [%]
0.5	1 layer	sludge (1/1)	63.636	105.876	42.240	2.5	93.435	9.281	0.099	355	35
		soil (1/1)	63.636	233.100	127.224	3.2	119.596	93.857	0.785	36	28
	2 layer	sludge (1/1)	63.184	90.656	27.472	1.5	56.061	6.028	0.108	356	38
		soil (1/1)	63.184	138.430	47.774	1.5	56.061	35.819	0.639	33	21
		sludge (1/2)	63.184	163.370	24.940	1.5	56.061	5.741	0.102	334	34
		soil (1/2)	63.184	221.905	58.535	1.5	56.061	43.036	0.768	36	28
	3 layer	sludge (1/1)	63.956	80.854	16.898	1.0	37.374	3.871	0.104	337	35
		soil (1/1)	63.956	121.990	41.136	1.0	37.374	30.95998	0.828	33	27
		sludge (1/2)	63.956	139.910	17.920	1.0	37.374	4.347611	0.116	312	36
		soil (1/2)	63.956	179.120	39.210	1.0	37.374	29.17028	0.780	34	27
		sludge (1/3)	63.956	191.845	12.725	1.0	37.374	3.34202	0.089	281	25
		soil (1/3)	63.956	234.665	42.820	1.0	37.374	31.72521	0.849	35	30
1.0	1 layer	sludge (1/1)	63.670	106.402	42.732	3.0	112.122	12.39111	0.111	245	27
		soil (1/1)	63.670	240.765	134.363	3.0	112.122	101.0059	0.901	33	30
	2 layer	sludge (1/1)	63.112	90.836	27.724	1.5	56.061	8.21771	0.147	237	35
		soil (1/1)	63.112	145.445	54.609	1.5	56.061	41.82798	0.746	31	23
		sludge (1/2)	63.112	170.240	24.795	1.5	56.061	7.562232	0.135	228	31
		soil (1/2)	63.112	235.855	65.615	1.5	56.061	49.3774	0.881	33	29
	3 layer	sludge (1/1)	63.760	81.566	17.806	1.0	37.374	5.499461	0.147	224	33
		soil (1/1)	63.760	122.045	40.479	1.0	37.374	30.79523	0.824	31	26
		sludge (1/2)	63.760	142.875	20.830	1.0	37.374	6.488033	0.174	221	38
		soil (1/2)	63.760	182.695	39.820	1.0	37.374	28.56459	0.764	40	31
		sludge (1/3)	63.760	198.170	15.475	1.0	37.374	4.805622	0.129	222	29
		soil (1/3)	63.760	239.965	41.795	1.0	37.374	31.65859	0.847	32	27

Appendix I: Pressure Plate Experiment

pressure [bar]		sample	column empty [g]	column&sample [g]	mass [g]	height [cm]	volume [cm^3]	mass dry [g]	Db [g/cm^3]	WHC$_g$ [%]	WHC$_v$ [%]
5.0	1 layer	sludge (1/1)	63.504	106.128	42.624	2.9	108.384	14.5458	0.134	193	26
		soil (1/1)	63.504	233.500	127.372	3.0	112.122	96.47162	0.860	32	28
	2 layer	sludge (1/1)	63.958	91.160	27.202	1.6	59.798	8.942058	0.150	204	31
		soil (1/1)	63.958	146.480	55.320	1.5	56.061	41.85136	0.747	32	24
		sludge (1/2)	63.958	167.945	21.465	1.5	56.061	6.860678	0.122	213	26
		soil (1/2)	63.958	236.305	68.360	1.5	56.061	51.64439	0.921	32	29
	3 layer	sludge (1/1)	63.934	81.026	17.092	1.0	37.374	6.731907	0.180	154	28
		soil (1/1)	63.934	122.190	41.164	1.0	37.374	31.59084	0.845	30	25
		sludge (1/2)	63.934	140.660	18.470	1.1	41.111	6.914675	0.168	167	28
		soil (1/2)	63.934	180.260	39.600	1.0	37.374	30.29019	0.810	30	24
		sludge (1/3)	63.934	193.210	12.950	0.9	33.636	4.810314	0.143	169	24
		soil (1/3)	63.934	235.190	41.980	1.0	37.374	32.34456	0.865	30	26

Appendix I: Pressure Plate Experiment

TABLE 83: Raw data for bulk density, WHC_g and WHC_v determination of each sludge and soil layer for BCTMP sludge.

pressure [bar]		sample	column empty [g]	column&sample [g]	mass wet [g]	height [cm]	volume [cm^3]	mass dry [g]	Db [g/cm^3]	WHC_g [%]	WHC_v [%]
0.5	1 layer	sludge (1/1)	61.758	133.890	72.132	3.0	112.122	18.257	0.163	295	48
		soil (1/1)	61.758	260.180	126.290	3.0	112.122	92.116	0.822	37	30
	2 layer	sludge (1/1)	62.266	100.600	38.334	1.5	56.061	9.951	0.178	285	51
		soil (1/1)	62.266	153.630	53.030	1.5	56.061	38.920	0.694	36	25
		sludge (1/2)	62.266	194.095	40.465	1.7	63.536	10.389	0.164	289	47
		soil (1/2)	62.266	258.420	64.325	1.5	56.061	45.888	0.819	40	33
	3 layer	sludge (1/1)	61.862	83.036	21.174	1.0	37.374	5.592	0.150	279	42
		soil (1/1)	61.862	123.930	40.894	1.0	37.374	29.689	0.794	38	30
		sludge (1/2)	61.862	143.200	19.270	1.0	37.374	5.277	0.141	277	39
		soil (1/2)	61.862	193.535	50.335	1.0	37.374	36.948	0.989	36	36
		sludge (1/3)	61.862	215.145	21.610	1.1	41.111	5.918	0.144	266	38
		soil (1/3)	61.862	258.200	43.055	1.0	37.374	31.228	0.836	38	32
1.0	1 layer	sludge (1/1)	61.670	139.925	78.255	3.0	112.122	21.634	0.193	262	51
		soil (1/1)	61.670	245.480	105.555	3.0	112.122	78.350	0.699	35	24
	2 layer	sludge (1/1)	62.184	99.570	37.386	1.5	56.061	10.607	0.189	253	48
		soil (1/1)	62.184	152.285	52.715	1.5	56.061	39.037	0.696	35	24
		sludge (1/2)	62.184	188.010	35.725	1.5	56.061	10.207	0.182	250	46
		soil (1/2)	62.184	239.860	51.850	1.5	56.061	38.540	0.687	35	24
	3 layer	sludge (1/1)	61.832	89.590	27.758	1.0	37.374	8.031	0.215	246	53
		soil (1/1)	61.832	130.210	40.620	1.0	37.374	29.971	0.802	36	29
		sludge (1/2)	61.832	152.750	22.540	1.0	37.374	6.560	0.176	244	43
		soil (1/2)	61.832	199.990	47.240	1.0	37.374	34.766	0.930	36	33
		sludge (1/3)	61.832	220.950	20.960	1.0	37.374	6.097	0.163	244	40
		soil (1/3)	61.832	258.185	37.235	1.0	37.374	27.713	0.742	34	25

Appendix I: Pressure Plate Experiment

pressure [bar]		sample	column empty [g]	column&sample [g]	mass wet [g]	height [cm]	volume [cm^3]	mass dry [g]	Db [g/cm^3]	WHC_g [%]	WHC_v [%]
5.0	1 layer	sludge (1/1)	64.270	136.550	72.280	3.0	112.122	21.204	0.189	241	46
		soil (1/1)	64.270	260.810	124.260	3.0	112.122	92.100	0.821	35	29
	2 layer	sludge (1/1)	63.998	101.120	37.122	1.5	56.061	11.542	0.206	222	46
		soil (1/1)	63.998	154.380	53.260	1.5	56.061	39.823	0.710	34	24
		sludge (1/2)	63.998	195.040	40.660	1.5	56.061	11.999	0.214	239	51
		soil (1/2)	63.998	259.625	64.585	1.5	56.061	48.718	0.869	33	29
	3 layer	sludge (1/1)	64.812	86.754	21.942	1.0	37.374	6.973	0.187	215	40
		soil (1/1)	64.812	126.575	39.821	1.0	37.374	29.960	0.802	33	26
		sludge (1/2)	64.812	146.305	19.730	1.0	37.374	6.272	0.168	215	36
		soil (1/2)	64.812	196.490	50.185	1.0	37.374	37.705	1.009	33	33
		sludge (1/3)	64.812	218.715	22.225	1.0	37.374	6.698	0.179	221	40
		soil (1/3)	64.812	261.520	42.805	1.0	37.374	32.323	0.865	32	28

Appendix I: Pressure Plate Experiment

TABLE 84: Determination of bulk density, gravimetric and volumetric moisture content with random errors of each layer and the total WHC_v of the sludge-soil layers for Kraft mill sludge.

pressure [bar]	sample	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm^3]	± Δ Db [g/cm^3]	WHC_v [%]	± Δ WHC_v [%]	total WHC_v [%]	± Δ WHC_v [%]
0.5	sludge (1/1)	355	0.058	0.099	0.0008	35	0.283		
	soil (1/1)	36	0.002	0.785	0.0049	28	0.177	31.76	0.167
	sludge (1/1)	356	0.090	0.108	0.0014	38	0.511		
	sludge (1/2)	334	0.089	0.102	0.0014	34	0.466		
	soil (1/1)	33	0.006	0.639	0.0085	21	0.281		
	soil (1/2)	36	0.005	0.768	0.0102	28	0.369	30.30	0.208
	sludge (1/1)	337	0.134	0.104	0.0021	35	0.699		
	sludge (1/2)	312	0.111	0.116	0.0023	36	0.727		
	sludge (1/3)	281	0.133	0.089	0.0018	25	0.512		
	soil (1/1)	33	0.007	0.828	0.0166	27	0.547		
	soil (1/2)	34	0.007	0.780	0.0156	27	0.531		
	soil (1/3)	35	0.006	0.849	0.0170	30	0.595	30.05	0.248
1.0	sludge (1/1)	245	0.032	0.111	0.0007	27	0.181		
	soil (1/1)	33	0.002	0.901	0.0060	30	0.199	28.40	0.134
	sludge (1/1)	237	0.047	0.147	0.0020	35	0.464		
	sludge (1/2)	228	0.050	0.135	0.0018	31	0.414		
	soil (1/1)	31	0.005	0.746	0.0100	23	0.309		
	soil (1/2)	33	0.004	0.881	0.0118	29	0.388	29.42	0.199
	sludge (1/1)	224	0.068	0.147	0.0029	33	0.660		
	sludge (1/2)	221	0.057	0.174	0.0035	38	0.768		
	sludge (1/3)	222	0.077	0.129	0.0026	29	0.574		
	soil (1/1)	31	0.007	0.824	0.0165	26	0.511		
	soil (1/2)	40	0.007	0.764	0.0153	31	0.612		
	soil (1/3)	32	0.006	0.847	0.0170	27	0.543	30.58	0.252
5.0	sludge (1/1)	193	0.023	0.134	0.0009	26	0.179		
	soil (1/1)	32	0.002	0.860	0.0058	28	0.184	26.72	0.128
	sludge (1/1)	204	0.039	0.150	0.0019	31	0.382		
	sludge (1/2)	213	0.053	0.122	0.0016	26	0.351		
	soil (1/1)	32	0.005	0.747	0.0100	24	0.319		
	soil (1/2)	32	0.004	0.921	0.0123	29	0.394	26.79	0.181
	sludge (1/1)	154	0.044	0.180	0.0036	28	0.555		
	sludge (1/2)	167	0.045	0.168	0.0031	28	0.511		
	sludge (1/3)	169	0.065	0.143	0.0032	24	0.540		
	soil (1/1)	30	0.006	0.845	0.0169	25	0.508		
	soil (1/2)	31	0.007	0.810	0.0162	24	0.487		
	soil (1/3)	30	0.006	0.865	0.0173	26	0.520	25.99	0.213

Appendix I: Pressure Plate Experiment

TABLE 85: Determination of bulk density, gravimetric and volumetric moisture content with random errors of each layer and the total WHC_v of the sludge-soil layers for BCTMP sludge.

pressure [bar]	sample	WHC_g [%]	± Δ WHC_g [%]	Db [g/cm^3]	± Δ Db [g/cm^3]	WHC_v [%]	± Δ WHC_v [%]	total WHC_v [%]	± Δ WHC_v [%]
0.5	sludge (1/1)	295	0.025	0.163	0.0011	48	0.321		
	soil (1/1)	37	0.002	0.822	0.0055	30	0.203	39.22	0.190
	sludge (1/1)	285	0.045	0.178	0.0024	51	0.675		
	sludge (1/2)	289	0.044	0.164	0.0019	47	0.560		
	soil (1/1)	36	0.005	0.694	0.0093	25	0.334		
	soil (1/2)	40	0.005	0.819	0.0109	33	0.437	38.90	0.259
	sludge (1/1)	279	0.079	0.150	0.0030	42	0.836		
	sludge (1/2)	277	0.084	0.141	0.0028	39	0.783		
	sludge (1/3)	266	0.072	0.144	0.0026	38	0.712		
	soil (1/1)	38	0.007	0.794	0.0159	30	0.604		
	soil (1/2)	36	0.006	0.989	0.0198	36	0.701		
	soil (1/3)	38	0.007	0.836	0.0167	32	0.636	36.18	0.292
1.0	sludge (1/1)	262	0.019	0.193	0.0013	51	0.338		
	soil (1/1)	35	0.003	0.699	0.0047	24	0.163	37.51	0.188
	sludge (1/1)	253	0.039	0.189	0.0025	48	0.639		
	sludge (1/2)	250	0.040	0.182	0.0024	46	0.610		
	soil (1/1)	35	0.005	0.696	0.0093	24	0.325		
	soil (1/2)	35	0.005	0.687	0.0092	24	0.321	35.45	0.249
	sludge (1/1)	246	0.050	0.215	0.0043	53	1.058		
	sludge (1/2)	244	0.061	0.176	0.0035	43	0.857		
	sludge (1/3)	244	0.065	0.163	0.0033	40	0.800		
	soil (1/1)	36	0.007	0.802	0.0161	29	0.578		
	soil (1/2)	36	0.006	0.930	0.0186	33	0.670		
	soil (1/3)	34	0.007	0.742	0.0148	25	0.505	37.25	0.313
5.0	sludge (1/1)	241	0.019	0.189	0.0013	46	0.305		
	soil (1/1)	35	0.002	0.821	0.0055	29	0.192	37.16	0.180
	sludge (1/1)	222	0.032	0.206	0.0027	46	0.610		
	sludge (1/2)	239	0.033	0.214	0.0029	51	0.685		
	soil (1/1)	34	0.005	0.710	0.0095	24	0.322		
	soil (1/2)	33	0.004	0.869	0.0116	29	0.383	37.42	0.261
	sludge (1/1)	215	0.052	0.187	0.0037	40	0.803		
	sludge (1/2)	215	0.058	0.168	0.0034	36	0.722		
	sludge (1/3)	221	0.082	0.179	0.0036	40	0.792		
	soil (1/1)	33	0.007	0.802	0.0160	26	0.530		
	soil (1/2)	33	0.005	1.009	0.0202	33	0.666		
	soil (1/3)	32	0.006	0.865	0.0173	28	0.554	34.00	0.280

Appendix I: Pressure Plate Experiment

<u>Summary:</u> Volumetric moisture content determination for Kraft mill sludge-soil layers

TABLE 86: Total volumetric moisture content of 1, 2, and 3 Kraft mill sludge-soil layer systems at 0.5, 1.0, and 5.0 bar pressure with random errors.

pressure		0.5 bar				1.0 bar				5.0 bar			
		WHC_v [%]	$\pm \Delta WHC_v$ [%]	total WHC_v [%]	$\pm \Delta WHC_v$ [%]	WHC_v [%]	$\pm \Delta WHC_v$ [%]	total WHC_v [%]	$\pm \Delta WHC_v$ [%]	WHC_v [%]	$\pm \Delta WHC_v$ [%]	total WHC_v [%]	$\pm \Delta WHC_v$ [%]
Kraft mill 1 layer	sludge	35	*0.283*			27	*0.181*			26	*0.179*		
	soil	28	*0.177*	31.8	*0.167*	30	*0.199*	28.4	*0.134*	28	*0.184*	26.7	*0.128*
Kraft mill 2 layers	sludge 1	38	*0.511*			35	*0.464*			31	*0.382*		
	sludge 2	34	*0.466*			31	*0.414*			26	*0.351*		
	soil 1	21	*0.281*			23	*0.309*			24	*0.319*		
	soil 2	28	*0.369*	30.3	*0.208*	29	*0.388*	29.4	*0.199*	29	*0.394*	26.8	*0.181*
Kraft mill 3 layers	sludge 1	35	*0.699*			33	*0.660*			28	*0.555*		
	sludge 2	36	*0.727*			38	*0.768*			28	*0.511*		
	sludge 3	25	*0.512*			29	*0.574*			24	*0.540*		
	soil 1	27	*0.547*			26	*0.511*			25	*0.508*		
	soil 2	27	*0.531*			31	*0.612*			24	*0.487*		
	soil 3	30	*0.595*	30.1	*0.248*	27	*0.543*	30.6	*0.252*	26	*0.520*	26.0	*0.213*

<u>Summary:</u> Volumetric moisture content determination for BCTMP sludge-soil layers

TABLE 87: Total volumetric moisture content of 1, 2, and 3 BCTMP sludge-soil layer systems at 0.5, 1.0, and 5.0 bar pressure with random errors.

pressure		0.5 bar				1.0 bar				5.0 bar			
		WHC_v [%]	$\pm \Delta WHC_v$ [%]	total WHC_v [%]	$\pm \Delta WHC_v$ [%]	WHC_v [%]	$\pm \Delta WHC_v$ [%]	total WHC_v [%]	$\pm \Delta WHC_v$ [%]	WHC_v [%]	$\pm \Delta WHC_v$ [%]	total WHC_v [%]	$\pm \Delta WHC_v$ [%]
BCTMP 1 layer	sludge	48	*0.321*			51	*0.338*			46	*0.305*		
	soil	30	*0.203*	39.2	*0.190*	24	*0.163*	37.5	*0.188*	29	*0.192*	37.2	*0.180*
BCTMP 2 layers	sludge 1	51	*0.675*			48	*0.639*			46	*0.610*		
	sludge 2	47	*0.560*			46	*0.610*			51	*0.685*		
	soil 1	25	*0.334*			24	*0.325*			24	*0.322*		
	soil 2	33	*0.437*	38.9	*0.259*	24	*0.321*	35.5	*0.249*	29	*0.383*	37.4	*0.261*
BCTMP 3 layers	sludge 1	42	*0.836*			53	*1.058*			40	*0.803*		
	sludge 2	39	*0.783*			43	*0.857*			36	*0.722*		
	sludge 3	38	*0.712*			40	*0.800*			40	*0.792*		
	soil 1	30	*0.604*			29	*0.578*			26	*0.530*		
	soil 2	36	*0.701*			33	*0.670*			33	*0.666*		
	soil 3	32	*0.636*	36.2	*0.292*	25	*0.505*	37.3	*0.313*	28	*0.554*	34.0	*0.282*