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SLUDGE CHARACTERISTICS AND DISPOSAL ALTERNATIVES FOR THE PULP AND PAPER INDUSTRY[1]

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ABSTRACT

Waste handling is a concern in all pulp and paper mills. It is especially important in mills where secondary fiber is used. Sludge composition, separation, treatment, and disposal methods need to be addressed. This paper explores the composition of sludge resulting from the pulp and papermaking process and compares secondary-fiber and virgin-fiber operations. The residue from separate operations is characterized, indicating the composition of various waste streams. Alternative disposal methods are discussed in reference to these characteristics. Thus, the final sludge use can be based on its characterization, resulting in more efficient use of the residue.

INTRODUCTION

On the average, 35% of the material entering pulp and paper mills becomes residue in forms of rejects (1). This waste includes such material as wastewater sludge, woodyard waste, causticizing wastes (from Kraft mills), mill trash, such as shipping materials, demolition debris, and ash from boilers (2). Currently, some of these residues provide 56% of the energy needs of the industry (1). The disposal of the remainder of this material has put a great burden on the pulp and paper industry, which must handle this material in a ecological and economical manner.

Currently, the residue from pulp and paper mills is handled by the waste handling components of the mill and is discharged to the air in the form of stack gases, to the water in the form of treated effluent, and to the land in the form of solid waste and sludge (Fig. 1). Part of this system may also involve recovery of materials and energy from the waste. In the last two decades, air and water quality have significantly improved. In many cases, the water being discharged is cleaner than the water taken in by the mill. As these components are removed from the air and water discharge streams, however, there is usually a greater amount of solid waste that must be disposed of.

Additionally, the increase in the amount of recycling in the last decade has also increased the amount of material that needs to be disposed of. Currently, this residue is commonly sent to landfills. In the United States, an estimated 4.1 million dry tons of sludge are produced each year by pulp and paper mills (3,4).

Recently, concern has risen over the amount and quality of future landfill space. Landfills are becoming difficult to site and costly to construct and operate because of more stringent regulations, diminishing land availability, and public opposition (5). In 1978, the United States had about 14,000 landfills, in 1988 there were 5,500, and by the year 2000, the number of landfills is expected to drop to 2,200 (6). Although alternatives, such as land application, seem to be working, many mills worry about future problems. With the detectable limits of toxins decreasing, some mills fear that current sites will have to be cleaned up at high cost due to water contamination. Traditional burning shifts some of the residue back to the air discharge stream with its resulting costs and problems. Some alternative processes, such as fluidized bed systems, seem to be more environmentally friendly. Microbiological treatment is still relatively new and is yet to be used on a large scale. Alternative uses for sludge ash, such as bricks and cement, are an excellent option if a user can be found near the mill and if long term contracts can be acquired. New products developed from pulp and paper mill sludge, however, need to have a market to make them economically feasible. It does not make sense to develop and create products for which there is no market.

This paper explores the options available for disposal of the solid waste stream from pulp and paper mill operations. The largest portion of this stream is the primary and secondary sludge produced from wastewater treatment plants. Recyclers produce two to four times as much sludge as virgin mills. Also, deinking mills produce additional waste for disposal when the raw

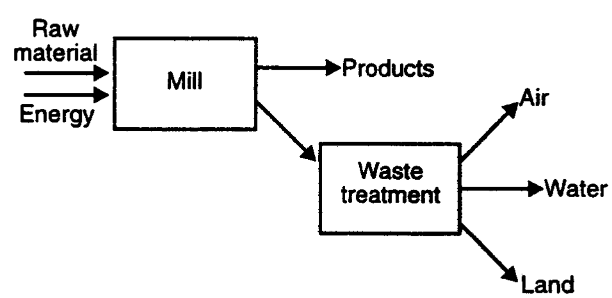

Fig. 1. Material flow in the pulp and paper industry.

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Table I. Amount of Solid Waste Produced by Different Types of Pulp Mills(7)

Mill type	Sludge (kg/ton)	Additional waste (kg/ton)
Kraft mill	58	
Sulfite mill	102	
Deinking mill	234	
Bale wrappers		23
Sorting rejects		9
Baling wires and metal		4
Other waste		2

material is received in bales (Table I). As the amount of recycling increases, the amount of material needing to be disposed of will also increase. This paper focuses on the disposal of pulp and paper-mill sludge, especially that from recycled mills.

CHARACTERIZATION OF SLUDGE

"Sludge" is a generic term for the residue that results from pulp and papermaking. To better understand its properties, it is necessary to review how it is formed. Generally, it is the solid residue recovered from the wastewater stream of the pulping and papermaking process (Fig. 2). Sludge is produced at two steps in the process of treating the effluent. Primary sludge is recovered by the first stage of the processing at the primary clarifier. Primary clarification is usually carried out by sedimentation, but can also be performed by dissolved air flotation. In sedimentation, the wastewater to be treated is pumped into large settling tanks, with the solids being removed from the tank bottom. These solids can range from 1.5% to 6.5% depending on the characteristics of the material. The overflow, or clarified water, is passed on to the secondary treatment.

Secondary treatment is usually a biological process in which micro-organisms convert the waste to carbon dioxide and water while consuming oxygen. The resulting solids are then removed through clarification as in the primary treatment. The resulting sludge is then mixed with the primary sludge prior to dewatering and disposal. In general, primary sludges are easier to dewater than the biological sludges resulting from the second stage.

Mill Level Characterization

Mills produce different amounts of sludge depending on their raw material, process, and final product (Table I). The amount of residue produced for each grade of paper depends, in part, on the source of the raw material (Table II) (8). Additional information can be found in (3) and (4). These surveys result in some of the same conclusions. Mills that use recycled fiber for raw material have more waste to dispose of than mills that **use wood as** raw material. This is partly due to fillers in the paper which,

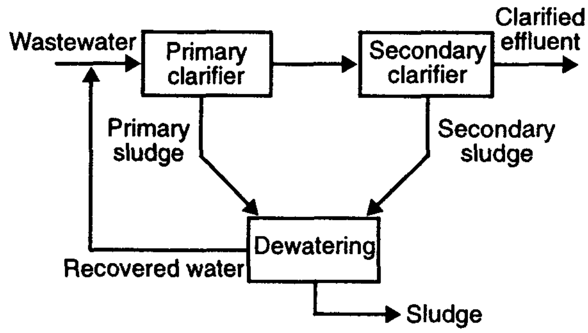

Fig. 2. Wastewater treatment.

Table II. Amount of Residue Produced by Different Paper Grades When Virgin and Recycled Raw Materials Are Used (8)

Paper grade	Residue amount (kg/ton) Wood only	Recycled paper	Both
Unbleached	(a)	(a)	(a)
Newsprint	57	164	69
Tissue	33	406	382
Printing & writing	62	187	165
Speciality	45	12	11

[a]Average 4.3%.

for the most part, are not recovered. This is especially true for the tissue grades, a low-filler content grade that can **use office** waste, a more highly filled grade, for a fiber source. This discrepancy between the characteristics of the product and those of the raw material means that more residue must be disposed of. This is also the case in printing and writing grades, which also use office waste as a raw material. Here both the product and the raw material are highly filled, but the filler material (clay or calcium carbonate) may be difficult to recover, contaminated, or its characteristics may have changed making it unusable in the recycled sheet. Not only do mills produce varying amounts of sludge, the sludges they produce are distinctly different in composition. They differ between virgin and recycled mills; however, there is also significant variation within the same categories (Table III). For example, Table III shows that two deinking mill sludges have different ash values. The high-ash sludge has only 60% of the heating value of the low-ash sludge. The analyses for bark and wood chips (which virgin mills commonly bum in a "hog" boiler) and wastepaper (which can be used as an energy source) are also given for comparison. Bark, except for its high solids content, is similar to the low-ash recycled mill sludge, suggesting that this sludge may be suitable for incineration. In general, kraft pulp mill sludge tends to have a higher sulfur content, while deinking mill sludge has a greater ash content. Between pulp mill and paper mill sludges, the former tends to be higher in sulfur compounds (15). High ash is detrimental to the heating **value** of sludge. This significantly effects its suitability for incineration. Further comparisons

Table III. Analysis of Sludge Produced From Different Sources. (Values for Bark and Wastepaper are Given for Comparison)

Source	Analysis (%)							Heating value (MJ/kg)
	Solids	Ash	C	H	S	O	N	
Bleached pulp mill (9)	33.4	1.9	48.7	6.6	0.2	42.4	0.2	20.1
Pulp mill (10)	42.0	4.9	51.6	5.7	0.9	29.3	0.9	21.5
Kraft mill (11)	37.6	7.1	55.2	6.4	1.0	26.0	4.4	24.1
Kraft mill (12)	40.0	8.0	48.0	5.7	0.8	36.3	1.2	19.8
Deinking m (10)	42.0	20.2	28.8	3.5	0.2	18.8	0.5	12.0
Deinking mill (10)	42.0	14.0	31.1	4.4	0.2	30.1	0.9	12.2
Recycle mill (13)	45.0	3.0	48.4	6.6	0.2	41.3	0.5	20.8
Recycled paper mill (11)	50.5	2.8	48.6	6.4	0.3	41.6	0.4	20.6
Bark (12)	54.0	3.5	48.0	6.0	0.1	42.1	0.3	20.3
Baric(10)	50.0	0.4	50.3	6.2	0.0	43.1	0.0	20.8
Wood chips (11)	79.5	0.2	49.2	6.7	0.2	43.6	0.1	19.4
Wastepaper (14)	92.0	7.0	48.7	7.0	0.1	37.1	0.1	25.0

Table IV. Type and Amount of Waste Produced From Different Processing Steps in a Recycling Mill (18)

Equipment	Waste	Flow (kg/ton)	
		Deinking plant	Linerboard mill
Pulper	Large contaminants	5	20
High density cleaning	Metal, glass	10	
Prescreening	Plastics	60	20
Flotation	Inks, fillers		
Forward cleaning	Sand, shives	15	20
Fine screening	Plastics, hot melts		
Reverse cleaning	Light weight contaminants, plastics		
Whitewater claritication	Clay, tillers, inks, small particles	40	10

between pulp mill sludges, municipal sludge, retail and commercial fertilizer, and soil are discussed in by Phenicie and Maher (16).

Process Level Characterization

Sludge from waste treatment plants is combination of waste streams from many different processing steps within the mill. The water used in the process, which can include effluent that is mixed from both pulp and paper mills in an integrated operation, has often passed through several of these steps before being sent to the treatment plant. In general, paper mill sludge is highly fibrous (17). while kraft pulp mill sludge tends to be higher in sulfur compounds. Deinking mill sludge tends to have high ash levels, depending on the type of recycled paper used. Newspapers tend to be around 5% to 10% ash by weight, but magazines and office waste can be up to 30% ash. Additionally, in a deinking pulp mill, rejects from the screens, cleaners, and flotation cells are typically mixed before treatment.

Table IV summarizes the types of rejects that are removed at each processing step (18). Typically, the rejects from the pulper and the high density cleaner are easily dewatered and not mixed with the remaining rejects. They are usually disposed of in the mill solid-waste stream. The rejects from the other process operations (and the water removed from the rejects just mentioned, if not recycled back to the process) are generally combined and sent to effluent treatment where some components may be recovered in, for example, a whitewater clarification system. Whenever possible, the clarified or filtered water is reused in the process. It may be possible to recover some useful material from certain rejects before they are combined. This is especially true if a large portion of a single component comes out in a certain processing step, and it is suitable for recovery and reuse. Reject composition depends on the equipment that is used for cleaning and deinking the pulp. Even with the same type of equipment, there is wide variation between equipment configurations. Furthermore, efficiency can never be 100%. That is, some good fiber is rejected. The ultimate goal, however, must be to reduce this amount, which can reach as high as 50-80% in some cases (19).

CURRENT DISPOSAL METHODS

The paper industry uses several methods to dispose of the sludge that pulp and paper production generates (Table V) (8). (Some mills may use multiple methods, hence the total is greater than 100%. A mill may landspread in the summer when the fields are accessible and incinerate for steam production during the winter when steam demand is greater (20)). Currently, most sludge produced by pulp and paper mills is dewatered and landfilled. These landfills can be industrial landfills that are constructed and operated by the mills or they can be independently owned, requiring the mills to pay a "tipping fee" for sludge disposal. Current landfills are reaching capacity and new ones are difficult to site and construct because of more stringent environmental requirements. Although tipping fees averaged around $34 per ton in the United States in April 1993, they ranged from a low of $7 per ton in North Dakota to nearly $100 per ton in New Jersey (13). These fees will increase in the future.

Although landfilling is the most common solution, other uses and disposal methods are being investigated. The final section of this paper discusses some of the more common methods. Incineration, in its various forms, is the most common alternative disposal method (Table V). It decreases the volume of material that needs to be landfilled (the ash) and recovers some energy from the sludge, thus reducing the need for other fuels. Large capital investments and the stringent pollution controls that are necessary are the major drawbacks to incineration. The air quality standards are an obstacle since the pollution cannot be shifted from land (landfills) to air. Incineration can emit gaseous NO_x and SO_2 (acid rain), as well as cause problems due to the chlorinated compounds found in plastics that contaminate the paper (13).

Other questions involving incineration need to be addressed as more mills turn to this disposal option. As mentioned before, we must not shift the problem from the land to the air. Also, the economics of the process must be considered to justify the large capital expenditure. Issues regarding the need for supplementary fuel to sustain combustion, ash handling and disposal, sludge dewatering capacity, and the efficiency of existing boilers all need to be considered (12, 21, 22).

Another increasingly common method is landspreading, which is discussed at length below. Other options include the use of sludge in construction material such as cement, asphalt, aggregates, and composites; in fertilizers; and in lower grades of paper such as boxboard used for nonfood purposes. The high clay content of some sludges make it suitable for use in capping

Table V. Distribution of Current Disposal Practices (8)

Disposal method	Mills using method (%)
Landfill	69
Incineration	21
Landspreading	8
Other methods	8

landfills. High-fiber-content sludges could be used as animal bedding or for ethanol production (8). In smaller mills that produce low amounts of waste, the effluent may be sent to the municipal treatment plant to be combined with the municipal effluent. The two waste streams have been found to be highly compatible in two cases (23, 24).

Many of these methods require some form of preprocessing prior to disposal. Sludge removed from the primary and secondary clarifiers requires a significant amount of dewatering, especially before landfilling or incineration. Since most landfills charge by weight or volume, it is not economical to pay for water disposal. Several different types of equipment are available for dewatering. These include belt presses, screw presses, V-belt presses, and centrifuges (3, 4, 7, 25), with the most common being belt presses. Also, dewatering technology has significantly changed over the past 15 to 20 years from lagoon and land treatment methods to the mechanical methods listed above. An overview of the operations involved in dewatering sludges is given in (25).

ALTERNATIVE TECHNOLOGY

Two different objectives may be looked at for the use of secondary-fiber sludge: the entire fraction can be used as a whole or the components can be separated and used. In the first case, no special separation processing is needed, but the composition of the sludge must be suitable to the product. Additionally, the product must be insensitive to changes in sludge composition. The second objective, separation (filler recovery, for example), requires additional effort to achieve the separation, but a more homogeneous product is possible. The recovery of clay from sludge is the subject of two U.S. patents (26, 27). Wet air oxidation has successfully recovered clay from paper mill sludge (28).

Alternatives to landfilling are needed to address the problem of sludge disposal. The problem can be approached in two ways: by reducing the amount of effluent that needs to be treated or by addressing the disposal of the resulting sludge. The first solution needs to be addressed where the solid waste portion of the effluent is generated. For example, switching from wet debarking to dry debarking can reduce the amount of solid materials to be disposed of (29). Closing the water loop can also reduce the amount of effluent that needs to be treated. This method, however, can cause dissolved solids to accumulate in the water, which can lead to increased chemical consumption (29). Increasing the efficiency or the number of stages of screening or cleaning can reduce the amount of solid residue produced by recovering a greater amount of the fiber. This comes, however, at the expense of more, presumably lower grade material exiting with the product, as well as increased capital and operating costs.

The second alternative is treating the residue after it is produced. The objective of these techniques is to reduce the volume of material that is landfilled, to recover material, such as fibers and fillers, from the waste stream for reuse, and to recover usable energy from the sludge. Some alternatives discussed below satisfy both of these objectives (30).

Combustion Technology

Energy recovery covers a wide range of technologies from simple incineration to more advanced methods such as destructive distillation and wet air oxidation. The use of combustion technology reduces the amount of solid material that needs to be disposed of and produces energy. Incineration is normally not cost effective due to low fuel values (15). Experts predict air pollution regulations will cause burning facilities to close, thus fewer mills will use incineration (6). The chlorinated organics in sludge make using high temperatures beneficial. Following is a discussion of some combustion technologies available and the difficulties involved in using them for sludge disposal.

Traveling gate combustion process.

A common method for burning sludge is to co-fire sludge with bark using an existing power boiler. Problems arise because sludge is more difficult to burn than bark due to differences in the ash and oxygen content. The moisture content (MC) of sludge is higher than that of bark. This increases moisture in the boiler, which lowers the combustion temperature. Like moisture, the high ash and low oxygen content in sludge further reduce the combustion zone temperature. To compensate for the higher ash and lower oxygen content, the MC of the sludge-must be lowered to produce the same combustion zone temperatures that exist for bark alone. Kraft and Orender discuss the process changes necessary to compensate for the different MC levels (10). For example, a 10°C increase in the combustion air temperature compensates for the MC being 1% higher. Other options to compensate for moisture include raising the combustion air temperature by removing economizer surface area and adding air heater surface, increasing the capacity of the over-fire-air system, covering the lower furnace walls with refractory material (only if continuous feed), dewatering the sludge to a higher original MC, or making the sludge more uniform throughout the bark mixture when co-fired (10).

Several difftculties exist with this combustion process. Uniformity of feed is important to maintain boiler temperature. As mentioned above, this temperature is sensitive to the MC mainly because the primary heat transfer mechanism is radiation. The high ash content can also increase the heating load of the boiler and reduce its efficiency, especially in the case of deinking mills (10). Advantages of this system include the simplicity of this established technology and the ability to use existing incinerators. The amount of sludge that can be co-fired may be limited, however, due to moisture and other operating considerations.

Fluidized bed.

When the MC of the material is high, the traditional incineration techniques described above are inadequate due to the detrimental effect this moisture has on the combustion temperature. In a fluidized bed reactor, the furnace bottom is filled with an inert bed material, such as sand or limestone, to a depth of 0.6 to 1.2 m (2 to 4 ft). Air flows through this material and it expands to a height of 0.9 to 1.5 m (3 to 5 ft). As air flows through this bed, kinetic energy is transferred between bed particles. As sludge drops to the bed, the moisture evaporates, the sludge absorbs heat from the bed, and the fuel ignites. The bed temperature is between 760°C and 900°C (1400 and 1600°F), which is lower than a normal boiler due to conduction with the bed particles that facilitate heat transfer (10). If sludge can be dewatered to a point where no in-bed heat transfer surface is required, sludge can be burned alone. An in-bed surface removes excess heat from the bed material. Without heat removal, the bed temperature would increase above the desired point. No in-bed surface is required up to bark/sludge combinations or sludge only MC levels of approximately 58% to 62% because at this point, the heat produced by incineration balances the heat needed for evaporation and heating (10). Exact values depend on the heating value of the material. One mill found the fluidized bed system to be “efficient, reliable, and economical.” It was adaptable where secondary sludge, peat, miscellaneous paper and board wastes, and groundwood wastes had been used as feed (9). In the fluidized bed system, supplemental fuel may be needed if the MC is too high. Also, fouling of the bed material can occur if incineration products deposit on the bed material causing the bed material to drop to the bottom of the reaction. This may require periodic cleaning and replacement of the inert bed material. On the other hand, fluidized bed reactors are less sensitive to changes in fuel conditions, which is a problem with traditional incineration.

Circulating fluid bed.

When burning sludge with high amounts of bark, coal, or other higher Btu solid fuel, more heat is produced than is needed for evaporation and heating. To maintain the bed temperature, heat must be removed either by in-bed heat transfer surface or other means. A circulating fluid bed avoids the use of in-bed surface by removing some of the hot bed material. Bed material is blown into the furnace where it contacts the furnace walls, giving up heat and lowering the temperature. The cooled particles either fall through the combustion zone back into the bed, or are sent there via hot particulate collection devices (10). Eventually, an equilibrium is reached in which the temperature of the bed material and the furnace are approximately equal.

Bubbling bed gasifier.

Operation of a bubbling bed as a gasifier is another way to control the bed temperature without the use of in-bed heat transfer area. By using only a portion of the combustion air, a smaller amount of the fuel's heat is released to the bed. The remaining fuel leaves the bed as a mixture of carbon monoxide, methane, and other gaseous hydrocarbons and enters the furnace where combustion is completed and the remaining heat is released. As the heating value of the fuel increases, the heat to the furnace must increase so bed temperature does not rise. For bark, typically 50% of the combustion occurs in the bed.

Table VI summarizes the fluidized bed technologies in relation to the heating value of the fuel. For bubbling beds, fuels greater than 10,500 KJ/kg may cause the furnace temperature to increase above 1371°C (2500°F), which can cause operational problems. Extremely low heating value fuels in the fluidized bed may require supplemental fuel to maintain the proper bed temperature. With all bed technologies, ash can sometimes be a problem. Alkalis in the ash can cause the formation of eutectics, which will coat the bed material and remain in the bed leading to agglomeration and defluidization. To control this, the amount of alkali fed to the bed can be limited , or a portion of the bed material can be drained, thereby increasing the fresh bed makeup (10). Emissions from burning sludge can be a problem in all incineration technologies. Sludge tends to be high in nitrogen, sulfur, and ash. The higher nitrogen in the deinking sludge leads to proportionately larger increases in the NO_x emissions. Deinking sludge releases sulfur, but not all of it is released in the form of sulfur dioxide. Pulp mill sludge is also high in sulfur, and due to the low ash content, most of it will be released. When considering burning sludge, it is important to consider how close you are to the emission limits. It may not necessarily be the boiler equipment that cannot handle the sludge, but the emission requirements (18).

Indirect steam gasifier.

Recycling operations have wastes with high MC levels and large amounts of plastics. Thus, it is difficulty to maintain the combustion temperature because it is lowered by evaporation and toxic gas production from plastic combustion. A pulse-enhanced, indirectly-heated fluidized bed gasifier system uses a fluidized bed reactor with in-bed heater tubes, which are part of a pulse combustor, and the gas produced as fuel. The pulse combustor allows for high heat transfer rates that heat the bed and bring

Table VI. Fluidized Bed Technology for Fuels of Various Heating Values (10)

Bed configuration	Typical fuel heating values (KJ/kg)
Fluidized	<7,000
Bubbling	7,000 - 10,500
Circulating	>10,500

about gasification reactions. These reactions produce a medium Btu gas and a char material consisting mainly of carbon. Higher char yields were found for the mill sludges due to high rates of entrainment by the fiber. Also, due to high MC levels, vaporization of the feed moisture resulted in gas superficial velocities within the fluid bed that were generally higher than those for other feeds tested. A large amount of the biological oxygen demand (BOD) from the condensed steam (contains tar/oil and particulate products) is in the form of carbon particulate, which can be clarified or filtered out.

An advantage of this system is a net destruction of dioxin and the prevention of its formation. In one case, the gasitier gave a net dioxin destruction efficiency of approximately 97.5%. The dioxin level in the gas product was not measured, but the gas condensate showed low levels of dioxin. Also, any dioxin present in the gas phase is likely to be destroyed with high efficiency upon subsequent combustion. The high dioxin destruction efftciency is thought to be attributed to the use of calcium material within the fluid bed, which absorbs HCl released during gasification, and the absence of oxygen in the reducing environment of the reactor. Thus, gasification of chlorinated waste material may avoid the dioxin-forming reaction that contributes to dioxin emissions from incineration processes. The cyclone char and ash disposal should present no problem for disposal since both have low toxicity. The gasifier does not require special handling such as pelletization for feedstock and can handle high MC, low ash fusion temperature, and high plastic contents (11).

Supercritical water oxidation.

Supercritical water oxidation (SCWO) oxidizes organics effectively at moderate temperatures (400°C to 600°C) and high pressures (25.5 MPa) using water as a reaction medium. The products of oxidation are carbon dioxide and inorganic acids. On a bench scale, it was found to reduce total organic carbon and total organic halides by 99% to 99.9%, and dioxin by 95% to 99.9% (30, 31).

Sludge and oxygen is pressurized to 25.5 MPa and heated **to** room temperature in a concentration of 94% waste and 6% oxygen. In the reactor the sludge and oxygen are heated to 300°C to 400°C, depending on the concentration of oxidizable material in the waste. After reaching approximately 360°C. everything is in the vapor phase where the mixing of oxygen and organics is thorough. After reaching the insulated reactor, the remaining organics are oxidized. The peak temperature of 600°C is desirable to reach high destruction efficiencies. The mixture is cooled back to room temperature in a heat exchanger. The liquid phase contains all of the particulate, all of the acid gases, and some of the carbon dioxide. The effluent is separated by phase and the oxygen, once separated from the carbon dioxide, is recycled back to the process. (31).

The recovery of carbon dioxide and steam make the process cost effective. Using a 10 weight percent feed concentration (of either primary, secondary, or mixed sludge), sludge can be oxidized and over 45% of the heating value can be recovered as steam. Steam recovered is a combination of 8272, 4136, and 1034 KPa steam. Residence time is approximately 5 to 10 min (31). Although no commercial units were put in at the time of the paper, the economic analysis (done in 1991) showed the SCWO process to be more economical than dewatering plus incineration for 40 weight percent solids sludge. The wet oxidation process allows for a chemical oxygen demand (COD) reduction of between 80% and 85% (15). The advantages to using wet oxidation are several: dewatering is not required, reusable filler is recovered, the process is exothermic (self-sustaining except for startup), the process uses both deinked and nondeinked sludge, no environmental odor problems exist, and is the process ecologically acceptable.

Destructive distillation.

Destructive distillation is "the breakdown of organic matter through the application of indirect heat in an oxygen free atmosphere capturing the volatiles" (32). The distillation process uses indirect heat with no air or oxygen present during decomposition. Thus, combustion does not occur. Destructive distillation decreases air and water pollution, odors, toxins, and reduces sludge to gases and a usable char, while reducing volume about 90% (32). The economics depend on the heat value of sludge and the initial dewatering. The char is approximately 50% carbon and has useful absorbent properties. Activation of carbon with one additional step would make removal of lower level contaminants from water possible. This could remove organic contaminants from water that other processes do not, thereby making it more attractive to industry.

Microbiological Degradation

Composting is a naturally occurring biological activity that can be used as a "low tech" method of handling sludge from pulp and paper mills (30). The decomposition rate depends on the oxygen content in the sludge. Sludge for use in composting should be dewatered primary or secondary sludge or a combination of the two. Volatile solids should range from 40% to 60%, ash content should fall between 35% and 50%, and pH should be between 5.5 and 9.5. The heavy metal content of the sludge will not affect decomposition, but may limit the sludge to nonagricultural uses. Also, if the sludge contains toxins, composting would degrade the sludge to a safe product (33).

Another study found that secondary sludge from a pulp and paper mill was easily composted, resulting in material with excellent chemical and physical properties suitable for plant growth. The study, which contains an extensive amount of background on this technology, concluded that the compost properties of cation-exchange capacity and total humus content were well correlated with composting time and plant biomass. This allows these values to be used as predictors of the compost maturity (34).

Forced aeration, or the "Beltsville" method, uses air mechanically drawn through the composting pile to decrease the time used in composting. In addition to the forced air, a bulking agent is used to achieve uniform porosity and increase the solids content. Some bulking agents used would be bark and wood chips. These can later be screened out and reused. The actual time needed to compost depends on the degree of stabilization required and the type of sludge used. It normally varies between 2 and 6 weeks (33). The major disadvantages of composting are the long reaction time necessary and the large land area needed. The capital investment requirements, however, are minimal.

Other biological treatments are also effective for treating mill waste streams. Ligninolytic fungi reduce the color of bleach plant effluent. In this system, mill sludge is inoculated with fungal spores that are allowed to grow for two to four days in the reactor. At this point, the bleach plant effluent is treated by this "activated reactor" for color removal. In this system, the ligninolotyic fungi degrade the chromophoric material in the effluent, which is a chlorine-containing oxidized lignin fragment (35). Alternatively, inoculation of the sludge with a cellulolytic thermophilic bacteria reduces the volume of the sludge while producing a high-value protein that can be used to produce animal feeds. The bacteria grows well on low-lignin pulps and pulp mill fines (36).

Landspreading

Landspreading is applying sludge to forest or agricultural lands. This technique is appealing since it represents a natural reuse and recycling of the material. It can be cost effective and reduce the dependence on landfilling while maintaining a clean environment (37). Landspreading can be accomplished with either dewatered or nondewatered sludge. When the sludge is not dewatered, it is fluid enough to allow spray application. Transportation costs can become prohibitive, however, if the undewatered sludge needs to be transported a great distance from the mill. With dewatered sludge, the application areas can be farther from the mill. While spray application can also be used by rediluting the sludge, other application methods can also be used (38).

A problem with landspreading is locating enough land on which to spread the sludge (15). If the mill owns forest lands nearby, this may be the ideal situation. Difftculties arise when the land needs to be leased or other arrangements need to be made for spreading. With maximum application rates per year being approximately 12 t/.405 ha, even a moderately sized mill will need a large area on which to spread its sludge (39). Additionally, the odor of the applied sludge can sometimes be a problem. Odor is strongest for the first few days, but diminishes due to stabilization after about 30 days.

A primary concern for landspreading is the composition of the sludge in both an organic and inorganic sense. Contrary to what is commonly believed, mill sludge is generally not hazardous due to heavy metals. On the other hand, sludge from deink and wastepaper mills may be relatively high in heavy metals due to the formulation used in the removed inks. Semichemical pulp mills produce sludges that are high in sodium, and mills that use clays in papermaking produce higher levels of aluminum (5).

Compounds that have been found in mill sludges at concentrations above 10 mg/dry kg include naphthalene, some phthalates, chloroform, PCBs, and wood extractives or derivatives (abietic acid, dehydroabietic acid, norabietetriene, tetrahydroretene, and retene). Deink and other wastepaper mills may have PCBs in the sludge resulting from older carbonless copy paper. Detectable total organic halogen levels of 600 mg per dry kg and 1,900 mg per dry kg have been measured in two of four sludges examined. The presence of bleach plants tends to increase this component of the sludge. Chlorinated lignin derivatives of large molecular weight are surmised to be responsible for the high toxicity readings from mills using chlorine bleaching (5). Primary and combined sludges from kraft mills generally have high calcium concentrations. Secondary sludges are normally higher in nitrogen and phosphorus than primary ones because these compounds are added to wastewater prior to biological treatment. As mentioned above, heavy metals are also a concern. For example, cadmium will bioaccumulate in plant tissues if it is found in sludge.

Advantages to landspreading include the nourishing, conditioning, and buffering of the soil and the breaking down of pesticides. The release of nitrogen occurs by natural mineralization and nitrification, which depends on temperature, pH, and bacterial activity. If pH can be controlled, the nitrogen released can be controlled and optimized. If high carbon to nitrogen (C:N) ratios exist, ammoniacal nitrogen is immobilized, resulting in the need for supplemental nitrogen. Organic matter has good moisture retention properties and nutrient value, but care must be taken not to overload a system. This is accomplished through crop selection and degradation rates that do not allow a buildup of organic matter.

Table VII. C:N Ratios of Sludges (5,41)

Sludge type	C:N ratio
Primary mill	32-930:1
Secondary mill	9-81:1
Combined mill	6-115:1
Muncipal sludge	18:1
Soil	75:1

A great deal of work has been done in respect to landspreading of both industrial and municipal sludge. Much of this is summarized in (5). Most of the studies concluded that sludge could be landspread, benefitting plants. The main factors that determined how sludge assisted plant growth were the C:N ratio and nitrogen loading. In general, primary sludge has a higher C:N ratio than soil, while secondary and municipal sludge have lower C:N ratios (Table VII). Primary-treated paper mill sludges (from several sources) can cause nitrogen-limited growth responses. Secondary treatment sludges with C:N ratios of 20:1 or less had positive effects on plant growth (37).

Primary sludge, when applied to cottonwood plots, increased height 41% over fertilized control plots. Mixed sludge, a combination of primary and secondary sludge, resulted in a 68% increase in height over the control plots. Spray application could be used because dipping the plant in sludge did not cause different results (39). Secondary application caused prolonged increase in soil total nitrogen concentration. Available phosphorus did not increase. An increase in exchangeable calcium levels was found in primary sludge applications (39). Monitoring wells that were located near the mixing lagoon showed high conductivity, indicating seepage. A slight and short-lived increase in tannin, sodium, and iron occurred. The nitrate concentrations in the wells were low (39). Depending on plantation age, the annual application rates were a maximum of 27 dry Mg/ha (12 tons/acre). The limiting factor in the application rates was the nitrogen loading (39). The importance of the amount of nitrogen was also shown in a study of the sludges from three Wisconsin mills (40). In this study, the biomass production was found to fall off dramatically when the C:N ratio was greater than 20:30. Problems with the high C:N ratio were alleviated with the use of supplemental nitrogen. Additional phosphorus and potassium were beneficial since mill sludges are generally low in these nutrients. One mill indicated that the high ash content of their sludge improved the water retention characteristics of the sandy soil it was applied on (7). The four species tested were hybrid cottonwood, Douglas-fir, noble fir, and white pine. The sludges used were a municipal sludge, two pulp and paper mill primary sludges, and a pulp and paper mill secondary sludge. The growth rate was found to be inversely proportional to the C:N ratio. That is, as the C:N ratio increased (the primary sludges), the growth rate decreased. The secondary sludge exhibited the highest growth rates. The primary sludges showed low or negative growth when compared to the control (41). The negative growth rate was thought to be caused by the available nitrogen being immobilized by the low-nitrogen sludge. With decomposition, the immobilized nitrogen may be released. This difficulty with sludge may be handled through crop selection as well as the timing and magnitude of the application. Forest lands should be more tolerant of these periods of immobilization than agricultural lands (5).

By species, the noble fir was the most sensitive to the C:N ratio of the applied sludge. Higher mortality was found in treatments with high growth response, which included the secondary sludge alone and municipal sludge alone. Mortality was not due to water stress because plots were watered regularly. It may have been due to the readily degradable high organic loading that resulted in anaerobic conditions after irrigation (41). Problems can also occur when the sludges have a high salt content, which may have toxic results (5). Care must be taken to prevent groundwater contamination through the leaching of salts, nitrates, and heavy metals from the sludge.

Particular sludges can also be landspread to achieve a particular purpose. High ash sludges, especially those from deinking operations, can benefit sandy soils. The ash, which is mainly kaolin clay, can aid in water retention in fast-draining soils. This can increase the water that is available for plants, as well as increase the organic matter content and ion exchange capability. Additional examples of landspreading can also be found in (5).

For an average sized mill, landspreading needs to be done on a relatively high volume basis to use the amount of sludge that is produced. The most feasible method is a direct agreement between the mill and the landowner (if not the same). It will be some time before “sludge brokers” are available to collect and redistribute sludge as wastepaper is now handled.

Pulp mill sludge is also useful in the reclamation of strip mine sites. At these sites, the sludge is used as a soil replacement to promote the regrowth of vegetation. Concern over dioxin contamination put a temporary halt to spreading, but extensive environmental testing showed that the dioxin produced no deletorious effects (42).

Other Uses of Sludge

Various alternatives for the use of sludge have been proposed or tried. Many of these are low-volume uses, that is, they will not be able to handle a large amount of sludge but they may be useful for smaller applications.,

More than half of the recycled paperboard mills in the United States reuse primary sludges directly in the production process as filler material (7). A problem with this reuse is an increase in ash content in the paperboard, resulting in higher density sheets. In certain systems, it may also be necessary to increase retention aid (43, 44). Sludge in board grades can improve stability and strength of the resulting product. Clay-containing sludge may alter the pressing conditions on the machine (15). The reincorporation of the sludge may also affect the recyclability of the product in the future.

The use of sludge in fodder was found to have a digestibility of organic matter of about 84%. With such fodder, a nitrogen component would have to be added as a supplement due to the fact that protein digestion is reduced (15). Elsewhere it was reported that sludge had a low feeding value, causing the test animals to lose weight in comparison to the control (45, 46). As can be expected, this use is only feasible with organic content sludges. Deinking sludges, which are high in ash, would probably be less suitable for this use.

Using sludge in cement tiles increases plasticity and workability of the cement. Tiles containing 13% high-ash sludge have the required strength and weatherproofness needed for commercial use. Similarly, sludge with a 20% to 30% ash content may be used to produce a facing brick for commercial use (30). The advantages of the bricks are better compression rates and water permeabilities.

Sludge can be used as an asbestos substitute to produce fire resistant products for internal and external use (15). Another possibility is the use of sludge as a landfill cover (8, 7, 30). Its suitability for this depends on its density, specific gravity, hydraulic conductivity, particle size distribution, and porosity. Kitty litter may also be a commercial option especially for high-ash content sludges (17, 30). Dried sludge could be used as bedding material for cattle (8, 30, 46). An experimental process to hydrolyze the carbohydrates to monosaccharides for fermentation to ethanol is also being investigated (30, 45, 46). Other miscellaneous uses are listed with references in (30).

CONCLUSIONS

Better use of the solid residue from the pulp and paper manufacturing process will become more of a concern in the next several years. This is especially true with the increase in recycling, when greater amounts of material will need to be landfilled. Landfilling will become less of a viable alternative for sludge disposal. Two methods are available to address this concern. First is recovery of the material in the process itself. That is, reduce the amount of material that is being sent for treatment. This can be done through process improvements or additional processing stages that recover more of the material to be used in the final product. It must be considered, however, that the additional recovered material will be lower grade. In this way, the quality of the final product will need to tolerate inclusion of this material. The second strategy is the recovery of material from the sludge after it has been processed. Here recovered material can be used in any grade of material and not necessarily in the grade being produced at the mill. Energy recovery is also an option for extracting value from the sludge.

In the case of recycling mills, matching the characteristics of the wastepaper used to the paper produced may help reduce the amount of material that needs to be landfilled. Recycling old corrugated containers into new corrugated containers should minimize the residue produced. Likewise, recycling old newsprint into new newsprint should produce a minimum of waste. However, recycling mixed office waste (MOW) into tissue has some difficulties since MOW is a relatively high-ash fiber source while tissue is a low-ash product. Recycling MOW into printing and writing paper has similar difficulties if the ash is not also recycled into the new product.

There are several research needs that should be considered. First, the various waste streams, both from a mill-wide perspective as well as a process perspective, need to be well characterized. This should indicate the relative value of the various waste streams and point to their most appropriate use. It may be discovered that some streams are easier to recover and should be separated from other streams. For the material that can not be recovered, the "best use" depending on the characteristics of the material needs to be found. For example, high-organic, low-moisture sludges are good candidates for incineration while high-ash (clay) sludges could possibly be used for a landfill cap. Low-contamination sludges should be considered for landspreading. It must be remembered that due to degradation, some material will always have to be rejected. System design and product use, however, must make sure that the maximum value has been achieved: we must recycle at the highest level possible.

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