Automatic System and Method for Resource Recovery from Freshwater Sludge and Similar Solid Wastes

Technical field

The present invention relates to an automatic system and method for resource recovery from freshwater sludge and other similar solid wastes. The system and method disclosed herein reduce organic content and recover metallic salt coagulant in freshwater sludge and other similar solid wastes, and transform leftover materials into lightweight aggregate.

Background of the invention

The rapid growth of population and urbanization have exerted the potable water demand around the world, especially in major cities. As a result of increasing demand for clean water, large volumes of freshwater sludge, also known as water treatment residuals, are generated. In many countries, freshwater sludge is considered as a non-hazardous waste and, therefore, landfilling has been the most widely applied method for freshwater sludge management. To address the problems of rising sludge generation, and escalating landfill costs and reduction in available land space, industries are exploring waste conversion into materials and useful products in order to substantially reduce final waste volume.

Freshwater sludge

Freshwater sludge, or drinking water sludge, or water treatment sludge or residuals, is a waste byproduct from the purification process of surface water for potable supply, which typically involves coagulation, flocculation, sedimentation, and filtration for removing colloidal and suspended solids, such as sand, silt, clay, and humic particles. Besides landfilling, current management practice of freshwater sludge also includes disposal into existing sewage system. Since freshwater sludge has relatively low levels of pollutants and high amount of coagulant metals, the recovery and utilization of freshwater sludge has been investigated in different fields, for example in construction material, adsorbent for phosphorus removal, and coagulant recovery for treating wastewater.

Industrial wastewater treatment sludge

Wastewater treatment sludge is a byproduct of wastewater treatment process. It may contain coagulants used during the wastewater treatment process, heavy metals, and organic compounds. Current common management practice is to dispose of wastewater treatment sludge in landfills. This is due to the high concentrations of heavy metals in the wastewater treatment sludge that make other management options less appealing.

Buried sludge

Buried sludge refers to sludge that is buried underground for a long period of time, perhaps as part of sludge disposal in the past. The origin of such sludge may not be identified. The sludge composition may also change over the time due to reaction with other substances present in the soil. Some substances that may be present in the sludge are organic pollutants, heavy metals, and chemical pollutants. Usually, such sludge is excavated during construction or excavation works of the land, and it needs to be treated properly to avoid contamination or disposed safely.

Coagulants in water and wastewater treatment processes

Coagulation and flocculation are the important processes in water and wastewater treatment. During the treatment process, coagulant is added to facilitate the aggregation of small colloidal particles into larger flocs. Common coagulants applied in water and wastewater treatment processes include aluminum sulfate, aluminum hydroxide chloride, sodium aluminate, ferric aluminum sulfate, etc. After the water and wastewater treatment process, most coagulants are bound with flocs in sludge, and can be potentially recovered to reduce both sludge quantities and handling cost, by regenerating and reuse coagulants.

Coagulant recovery

There are several methods that can be used to recover coagulant, including alkalization, acidification, ion exchange, and membrane processes. Aluminum and iron ions that are recovered from sludge can be used again as a coagulant. Since the quality requirement for drinking water is stringent, the recovered coagulant is usually not used in drinking water treatment.

Biological digestion

Benefits of aerobic treatment involving thermophilic microorganisms include high rate of biodegradation and inactivation of pathogens. Most commonly isolated organisms in thermophilic aerobic process for wastewater treatment belong to bacteria from the genus *Bacillus*. Thermophilic aerobic digestion process relies on the heat-stable enzyme produced by thermophilic microorganism to dissolve insoluble organic substances.

Lightweight aggregates

Lightweight aggregates are an essential component of lightweight concrete with superior thermal insulation and soundproof property. Some other uses of lightweight aggregates include lightweight masonry, stone veneer products, filtration media, gardening media, and coastal protection. Most lightweight aggregates are produced from materials such as clay, shale, or slate. In order to reduce production cost and reuse waste materials instead of landfilling, a wide range of waste materials, such as municipal solid waste incineration ash, wastewater treatment sludge, coal fly ash and slag, and waste glass, have been investigated as partial or total replacement of conventional raw materials for lightweight aggregates.

Artificial intelligence

Artificial intelligence technology uses computer systems and programs that can mimic human capabilities, such as problem solving, learning, perception, understanding, reasoning, and awareness of surroundings. Advanced computer models have been used to study climate patterns to forecast weather and predict air pollution levels. In recent years, artificial intelligence has also been used in monitoring characteristics of water contamination, waste sorting, determining waste collection truck routes, etc. Therefore, the technology holds potential to improve efficiency, and perhaps effectiveness or accuracy, of solid waste treatment, environmental management, and risk assessment.

Use of waste acid

Waste acid is acid spent in industrial process of industry. It is reused to substitutes expensive concentrated acid to lower the pH of solution that can accept certain pollutant level, such as coagulant solution that is used in wastewater treatment. However, purification may be required to remove contaminants for higher quality requirements.

Crusher/shredder design

Industrial crushers/shredders are used for size diminution of solids. For more efficient biological digestion of freshwater sludge, the sludge needs to be pulverized to reduce its particle or lump size. Pulverization of freshwater sludge to small particle size is also necessary because any large sludge particles that remain intact during coagulant recovery lowers the coagulant recovery rate. Pulverization of sludge sometimes can be a challenge because soft sludge sticks to the mixing blades and axle, impeding proper mixing. Therefore, crusher/shredder design is of critical importance in sludge treatment.

Synergy

Freshwater sludge or other types of sludge contain organic and inorganic portions. The organic portion can be reduced by biological digestion and the spent coagulant, part of the inorganic portion, can be recovered, leaving behind the majority of the original inorganic portion and some small amount of the organic portion. In lightweight aggregate production, excessive organics can lower the mechanical strength of the lightweight aggregates. However, having a small amount of organics can help in the formation of lightweight aggregates. Therefore, synergies among different components of freshwater sludge treatment can be maintained to optimize lightweight aggregate production from freshwater sludge. At a grand level, the synergies help divert waste from landfill and approach zero waste.

Combined use of fungi and bacteria

Large organic molecules or polymers such as cellulose and lignin cannot be easily digested by bacteria alone, so the mass and volume reduction efficiencies are limited. Fungi are efficient in breaking down those complex organic polymers into smaller molecules which can be easily digested and utilized for driving microorganism activities. Therefore, the combined use of fungi and bacteria can substantially increase the overall efficiency in biological digestion and achieve greater mass and volume reductions.

Patent literature

Patent US3959133A, filed by Metcalf and Eddy Inc in 1974, describes a method of recovering alum from water treatment sludge by acidulating the sludge with sulfuric acid.

Patent US5674402A, filed by Kemira Kemi AB in 1994, describes a method for the treatment of water treatment sludge containing aluminum or iron chemical coagulant, wherein acidification, separation of acidic solution, and separate precipitation of alunite and jarosite compound.

Patent EP1985590A1, filed by Jihoceska Universita V Ceskych Budejovicich in 2008, describes a method of treatment of iron-containing waterworks sludge from drinking water treatment plants, by producing pelleted fuel with sawdust addition, and recovering iron chloride from ash.

However, the abovementioned methods do not employ more than one method to recover resources from freshwater sludge.

Summary of the invention

Summary of invention

Throughout this specification and beyond, unless the context requires otherwise, “comprise,” or variations such as “comprises” or “comprising,” shall be understood to imply the inclusion of a stated component or components or integrated components but not the exclusion of any other components. In addition, as they appear in the specification and claims, the singular forms “a,” “an,” and “the” include the plural referents unless otherwise stated.

The present invention has been accomplished under a context described in previous sections. It is, therefore, the main objective of the present invention to provide a system and method for coagulant recovery from freshwater sludge and similar solid wastes and transform leftover materials into lightweight aggregate. To achieve these and similar objectives of the present invention, the system for treating solid waste comprises:

a) A central processor with artificial intelligence technology that analyzes current process information and executes appropriate operational decisions;
b) A pulverization component;
c) A bioreactor that performs aerobic digestion;
d) A coagulant recovery unit with mixing, foam removal, and filtration functions;
e) A purification unit with filtration device and adjacent wastewater treatment unit; and
f) A lightweight aggregate fabrication unit with dryer, ball mill, mixer, pelletizer, and sintering device.

Problems solved by the invention

The amount of freshwater sludge generated in the world is increasing with population growth and stringent water quality control measures. Due to the relatively high inorganic contents, which typically include high metallic salt content from coagulant dosed, conventional management practice of freshwater sludge is landfilling. The high content of metals in freshwater sludge limits the suitability for its disposal to landfill. In addition, resources in freshwater sludge that hold potential to be utilized are directed into landfill and occupying precious landfill space. The manufacture of lightweight artificial aggregates can also lessen the exploitation of natural resources.

Means for solving the problems

The system described in the present invention provides an automatic system and method for resource recovery from freshwater sludge and other similar solid wastes. The system comprises different components that can reduce organic content and recover metallic salt coagulant and transform leftover materials into lightweight aggregate. The different components include pulverization device, bioreactor, coagulant recovery unit, purification unit, and lightweight aggregate fabrication unit. The process uses aerobic digestion by thermophilic fungi and bacteria to reduce organic content in freshwater sludge and other similar wastes, at the same time reduce waste volume. Next, the present invention includes a process of coagulant recovery, which can recover metallic salt coagulant through acidification. The recovered coagulant, mainly aluminum salt and ferric salt, can be reused directly in wastewater treatment process. A purification unit is also included to remove impurities or unwanted ions for production of high-quality coagulant. The process also includes a lightweight aggregates fabrication

unit with pelletization device and sintering device, converting inorganic residues into lightweight aggregates.

Advantages of the invention

Freshwater sludge is generated from the treatment process of water from reservoir, river, lakes, and other surface water source. Characteristics of freshwater sludge vary with water treatment method and incoming water quality depending on water source, weather, pollutant from nearby activities, aquatic environment, and more, which are seasonal and regional factors. The unstable characteristics of freshwater sludge and other similar solid wastes could result in unstable operating parameters for each type and batch of wastes feeding into the system. The central processor of the present invention that features artificial intelligence technology, automatically adjusts operational parameters, and executes appropriate process depending on monitoring data from the sensor network. This ensures accurate operating parameters and minimizes process interruption for optimal process condition and product quality.

The bioreactor included in the invention can reduce organic matter and thus total amount of waste. Reducing waste amount brings advantages of lowering reagents and chemicals required in subsequent resource utilization process (in particular, acid that is used for recovering coagulant), assisting material handling, and reducing treatment cost.

The freshwater sludge and other similar solid wastes after biological digestion and coagulant recovery consist of primarily inorganic portion, and it is suitable to be part of the matrix of lightweight aggregates. Small amount of organic matter that can remain in waste is also beneficial to lightweight aggregates for porous structure formation. As the material is heated, it liquefies and carbonaceous compounds in the material form gas bubbles, which expand the material. Sometimes, in cases of fabricating lightweight aggregates with different types of wastes, carbon source is added for gas bubbles formation. Waste after biological digestion and coagulant recovery can produce lightweight aggregates with other types of waste without additional organic source.

The texture of freshwater sludge from different source can vary. To handle this variation, the present invention features a dual-pulverization component that crushes/shreds on the one hand hard freshwater sludge that is more brittle and requires higher crushing power, and on the other hand soft freshwater sludge that is of muddy or clay texture and the lump size needs to be reduced. Furthermore, the pulverization component that shreds soft freshwater sludge features mixing paddles that are free-rotating about the paddle attachment to the central axle and the degree of rotation of the paddles is determined by the softness of the waste material.

Commercial acids such as sulfuric acid are expensive. To help reduce the cost of dissolving freshwater sludge, the system and method of the present invention accommodates use of waste acid from industry. Waste acid may contain impurities from industrial processes, and to overcome this, a purification step is introduced to precipitate coagulant metal hydroxide, e.g., $Al(OH)_3$, which can be further processed to produce coagulant for reuse. In addition, a wastewater treatment unit is included to remove impurities to meet discharge requirements.

The system and method of the present invention is adaptable for dedicated centralized freshwater sludge treatment or for co-location within an existing industrial wastewater treatment facility or on-site treatment of sludge that is buried in the ground. In the case of co-location within an existing industrial wastewater treatment facility, after coagulant recovery, the filtrate containing the dissolved coagulant

is transferred to a holding tank for coagulant dosage in wastewater treatment. In the case of on-site treatment of sludge that is buried in the ground, the system of the present invention fits inside a commercial container for deployment.

Large organic molecules or polymers such as cellulose and lignin cannot be easily digested by bacteria alone, so the mass and volume reduction efficiencies are limited. Fungi are efficient in breaking down complex organic polymers into smaller molecules which can be easily digested and utilized for driving microorganism activities. Therefore, the combined use of fungi and bacteria can substantially increase the overall efficiency in biological digestion and achieve greater mass and volume reductions.

Brief description of the drawings

The invention as described graphically in an exemplary manner, without restricting the general intent of the invention including but not limited to the particular configuration, shape, and scale of any of the elements in the drawing, based on exemplary embodiments in reference to the drawing, whereby the schematic drawing is expressly referred to for the disclosure of all details according to the invention that are not explained in greater detail in the text.

FIG. 1 is an overview of the resource recovery system.

FIG. 2 shows the pulverization component.

FIG. 3 shows the bioreactor.

FIG. 4 shows the coagulant recovery unit.

FIG. 5 shows the purification unit.

FIG. 6 shows the lightweight aggregate fabrication unit.

Detailed description of the preferred embodiments

Best mode for carrying out the invention

The object of the present invention is an automatic system and method for resource recovery from freshwater sludge and other similar solid wastes. It is the main objective of the present invention to recover metallic coagulant from freshwater sludge and other similar solid wastes and convert leftover material into lightweight aggregate. The microorganisms that digest organic matter in freshwater sludge include fungi species that is selected from group comprising *Aspergillus Terreus, Aspergillus Fumigatus, Fusarium verticillioides, and Eurotium rubrum*, and bacteria species that is selected from group comprising *Bacillus stearothermophilus, Bacillus brevis, Bacillus licheniformis, Bacillus coagulans*. The metallic coagulants that are recovered by the method of the present invention include, but not limited to, aluminum sulfate, aluminum hydroxide chloride, sodium aluminate, and ferric aluminum sulfate. The recovered coagulant solution is directly reused in wastewater treatment process. Alternatively, a precipitant that is selected from the group comprising {ammonium hydroxide, calcium hydroxide, magnesium hydroxide, sodium carbonate, sodium hydroxide} is added to obtain precursor material in coagulant synthesis in the forms of aluminum hydroxide or iron (III) hydroxide. The leftover material is dried, milled, and fabricated into lightweight aggregates by sintering method with another

solid matrix, foaming agent, and binding agent. Lightweight aggregates fabricated by the present invention may be used for applications of lightweight concrete, gardening media, filtration media etc.

The preferred embodiment of the treatment system of the present invention comprises the following components that function together in synergy:

a) A central processor with artificial intelligence technology
b) A pulverization component;
c) A bioreactor that performs aerobic digestion;
d) A coagulant recovery unit with mixing, foam removal, and filtration functions;
e) A purification unit with filtration device and adjacent wastewater treatment unit; and
f) A lightweight aggregate fabrication unit with dryer, ball mill, mixer, pelletizer, and sintering device.

The central processor utilizes artificial intelligence technology to collect and analyze information and predict outcomes to inform operational paraments in future resource recovery from freshwater sludge and other wastes.

The pulverization component consists of a double-rotating-shaft crusher with teeth and a paddle shredder. Both hard and soft wastes can be pulverized and mixed homogeneously.

The bioreactor is a cylindrical reactor with thermal jacket that minimizes the heat loss and double ribbon mixing element that facilitates thermophilic aerobic digestion to take place.

The coagulant recovery unit is the component that carries out acidification with a mixer, a defoaming skimmer that removes foam generated during coagulant recovery, and a filter that obtains recovered coagulant solution.

The purification unit with a filtration device produces solid coagulant by precipitation and treats filtrate after purification in a wastewater treatment unit.

The lightweight aggregate fabrication unit consists of a drying and milling chamber that produces dry waste powder, a mixing device that produces mixed materials based on formulation, a pelletization unit that produces aggregate particles, and a sintering unit that heats aggregate particles.

FIG. 1 shows the overview of a system for resource recovery from freshwater sludge and other similar solid wastes.

The system comprises the following steps: i) pulverization of solid wastes, ii) autothermal thermophilic aerobic digestion, iii) coagulant recovery process, iv) coagulant purification process, and v) lightweight aggregate fabrication.

The freshwater sludge or other similar solid wastes enters the system and is pulverized to lump size of below 1 mm in order to enhance mixing and reaction efficiency in the following steps. The organic matter in pulverized waste is digested by thermophilic aerobic fungi and bacteria. The inorganic matter including coagulant, and small portion of microorganisms and undigested organic matter that remain are fed to coagulant recovery process. The waste particles are dissolved by acid and the coagulant metallic ions are released into acid solution. The recovered coagulant can be reused directly in solution form. The purification unit serves as an optional unit to precipitate coagulant as solid form. The

remaining materials after coagulant recovery are dried, milled, and mixed with other ingredients, then sintered to fabricate lightweight aggregates.

FIG. 2 shows the schematic of a pulverization component.

The freshwater sludge or other similar solid wastes being introduced into the system is classifies into types. The solid wastes can be classified into H, S, and T such that H is hard sludge that is brittle and consists of greater than 50% by volumetric basis slabs that are of dimensions 10 cm to 12.5 cm in length, 5 cm to 7.5 cm in width, and 0.5 cm to 1 cm in thickness, S is soft sludge that is of muddy or clay texture and consists of less than 20% by volumetric basis slabs that are of dimensions 10 cm to 12.5 cm in length, 5 cm to 7.5 cm in width, and 0.5 cm to 1 cm in thickness, and T is thickened sludge that contains >95% moisture content. Type H waste is fed into double rotating shaft crusher **1**, while type S waste enters paddle shredder **4**. Type T waste is fed directly into bioreactor **8** in FIG. 2 without pulverization.

The paddle shredder has mixing paddles **6** distributed in spiraling manner about the central mixing axle **5** such that the degree of rotation is adjustable to suit the feeding waste. Each mixing paddle is of length 10 cm to 14 cm, width 8 cm to 12 cm, and thickness 5 mm to 8 mm. Length of paddle attachment to central axle is 1 cm to 2 cm. The degree of rotation is automatically adjusted to 60° to 80° from line of central axle, by central processor that analyses waste information controlling paddle attachment **7**. The pulverization component ensures a final product that is homogeneously mixed and has lump size of below 1 mm. This increases the surface area that contacts with microorganisms and allows a more efficient digestion process.

FIG. 3 shows the schematic of a bioreactor.

The bioreactor **8** allows mixing of pulverized waste and thermophilic aerobic fungi and bacteria. Bioreactor outlet **13** opens at the end of digestion to allow internal contents to empty out by movement of double ribbon of bioreactor.

Thermophilic aerobic digestion microorganism dosage is 0.5% to 2.5% by mass for fresh batch of digestion. For continuing batch of digestion of same type of sludge, 5% by mass previously digested material is used as recycling sludge, such that the activated microorganisms in digested sludge are returned to the bioreactor, instead of adding new microorganisms. The ratio of fungi to bacteria added is 0.5 to 1. Fungi produce enzymes that can digest large organic molecule, such as cellulose, into smaller organic molecule that can more easily digested by bacteria. Co-digestion by fungi and bacteria ensures a better digestion efficiency. The microorganisms can be substituted with enzymes extracted from the microorganisms.

Operating temperature and moisture content of the mixture are automatically maintained at 40°C to 60°C and 60% to 80%, respectively, for optimum bacterial activity and thus maximum digestion efficiency. Thermal jacket **14** which is the insulation material covered on the bioreactor prevents the heat generated by microorganism activities from releasing to the surroundings and greatly improves energy efficiency. Moisture content is adjusted by water spray **10**. The central processor receives information from thermometer **12** and automatically adjusts the temperature.

Most organic matter is digested by microorganisms and metabolized into carbon dioxide and water vapor, while small amount of organic matter and microorganisms are remained in waste matrix and contribute to porous structure formation in lightweight aggregate fabrication. Weighing sensor **11**

measures and monitors mass of waste during digestion process and sends the data to the central processor for analysis and determination of system parameters for sludge treatment in the future. The digestion is stopped when overall mass loss is greater than 30% and the pre-set target is achieved.

FIG. 4 shows the schematic of a coagulant recovery unit.

The biologically digested waste is mixed with acidic solution that is selected from the group comprising {sulfuric acid, hydrochloric acid, nitric acid, hydrobromic acid, hydroiodic acid, perchloric acid, chloric acid} or with aqueous non-organic waste acid that has acid concentration 1% to 30% by volume**,** in the coagulant recovery reactor **15**, at a liquid:solid ratio of 2:1 to 5:1 to facilitate mixing. Waste particles are dissolved by acid and metallic ions from coagulant, for example, aluminum ion and iron (II) ion, are released into acid solution. pH is monitored through pH meter **19** and is automatically maintained at 1.5 to 3, for optimum ion recovery rate.

Waste acid is stored in waste acid storage tank **16**. Information of waste acid received including acid type, factory source, and pH is recorded by the central processor.

Metallic ion concentration sensor **20** monitors concentration of coagulant ions in solution and sends the data to central processor. The coagulant recovery reaction is stopped when metallic ion concentration reaches a pre-set recovery rate, for example, 50% to 90% based on average past metallic content in untreated freshwater sludge or other industrial solid wastes.

Defoaming skimmer **17** removes foam generated during coagulant recovery, sends collected foam to neutralization tank **18** with mixing device where 0.5% by mass lime is used to break the foams. Foam removal substantially enhances mixing and improves recovery efficiency.

Filter press **21** separates undissolved solid residual and acid solution, where undissolved solid residual is directed into lightweight aggregate fabrication unit while acid solution can be reused directly as coagulant in wastewater treatment process, or alternatively enters purification unit.

If concentrated acid is used in coagulant recovery, liquid obtained from filter press is used as liquid coagulant in wastewater treatment at dosage of 0.1% to 5% on wastewater volumetric basis. If waste acid is used in coagulant recovery, liquid obtained from filter press is sent to purification unit to remove pollutants from waste acid.

FIG. 5 shows the schematic of a purification unit.

Purification reactor **22** with scraper **23** receives acid solution from coagulant recovery unit if waste acid is used in coagulant recovery. A precipitant that is selected from the group comprising {ammonium hydroxide, calcium hydroxide, magnesium hydroxide, sodium carbonate, sodium hydroxide} is added in the purification reactor to a pH of 7 to 7.5. Metallic hydroxide is formed and filtered out by filter press **24** to be used as precursor material in coagulant synthesis where precipitants thus formed are dissolved by sulfuric acid to be reused as coagulant. The filtrate resulted from the filter press is sent to wastewater treatment unit **2**5.

The wastewater is treated with a flocculating or coagulating step using a chemical that is selected from group consisting of aluminum sulfate, ferric chloride, ferric sulfate, ferrous sulfate, polyacrylamide, polyaluminum chloride, polyaluminum chlorosulfate, polyaluminum silicatesulfate, sodium alginates, polyelectrolytes, and combinations thereof.

FIG. 6 shows the schematic of a lightweight aggregate fabrication unit.

The solid residual from filter press **21** in coagulant recovery unit is dried by rotary dryer **26** at a temperature of 90°C to 105°C until the moisture content is <1%, then milled by horizontal ball mill **27** to a particle size of <75μm . The solid residual so dried and milled is mixed with formulation consisting of 2% to 5% sludge residual so dried and milled, 10% to 12% binding agent that is selected from group comprising {sodium silicate, potassium silicate}, 60% to 70% SiO_2, 20% to 25% Al_2O_3, and 3% to 5% flux, where flux is defined as sum of mass percentages of Fe_2O_3, K_2O, Na_2O, CaO, and MgO in formulation mixing unit **28**.

Mass weighing sensor **29** measures and controls the mass of each ingredient added, according to instruction from central processor. Ratio of each ingredient can be adjusted based on the target characteristics of final lightweight aggregate product and its intended use.

The mix from formulation mixing unit is fed into pan pelletizer **30**, a circular pan rotating at a speed of 30 rpm to 60 rpm at an angle of 34.5° to 55.5° from vertical position, to produce aggregate particles of diameter 10 mm to 20 mm. Mass of water sprayed is controlled by water spraying apparatus based on mass information of mix, such that moisture content of mix is 15% to 20%, based on mass information from mass sensor.

After pelletization, sintering unit **31** heats particles produced from pelletizer to a temperature of 1,100 °C to 1,200 °C. After sintering, fabrication of lightweight aggregates is completed. Produced lightweight aggregates that have simultaneously particle density <2 g/cm^3 and loose bulk density 0.65 – 2 g/cm^3 are incorporated into 1% to 75% by volume of coarse aggregates in concrete formulation, and lightweight aggregates that have loose bulk density 0.75 g/cm^3 to 1.2 g/cm^3 are used for growth medium in gardening.

Examples

Example 1: Treatment of hard freshwater sludge

A representative hard freshwater sludge sample was collected at a drinking water treatment plant that used aluminum sulfate as coagulant. The hard freshwater sludge with mass 4,000 kg was to be treated. The central processor had determined that the freshwater sludge to be of H type, and following this, the sludge went into the double-rotating shaft crusher with teeth to be crushed to below 1 mm in particle size. Next, the crushed sludge went into the bioreactor. According to analysis by the central processor, the recommended biological digestion temperature was 60°C and the target mass reduction was set to be 48%. For this biological digestion, 1% microorganism with fungi species *Aspergillus Terreus,* and bacteria species *Bacillus stearothermophilus* at mass ratio of 0.55was used. Moisture content was monitored by the central processor and maintained at 70% by intermittent use of the water spray. The reactor automatically stopped after the target mass reduction was achieved and the digestion period was 118 hours. At the end of the digestion, the digested freshwater sludge went into the coagulant recovery unit, and 8,800 liters of water and 800 liters of 98% (v/v) sulfuric acid, as determined by the central processor, were added to maintain the pH of coagulant recovery at 2.7. During coagulant recovery, a lot of foams were generated, and the foams were removed by the defoaming skimmer and transferred to the neutralization tank where 0.5% by mass lime was used to break the foams. After the foams were broken up, remaining solid residues were disposed of. The target coagulant recovery rate was set to be 80% and the process took place for 1.5 hours. After coagulant recovery, the acidic mixture went into the filter press to separate the liquid and solid portions. The liquid portion separated by the filter press could be used directly as coagulant in wastewater treatment in a dosage of 2% by mass of the wastewater. The solid portion from the filter press, in this example the mass of which is 780 kg, went into the LWA fabrication unit. In the LWA fabrication unit, the solid portion from the filter press was dried and ball milled, and the solid so dried and ball milled was mixed with formulation containing 3900 kg sodium silicate, 25,350 kg SiO_2, 7,800 kg Al_2O_3, and 1,170 kg Fe_2O_3. The LWA formulation was mixed for 20 minutes and the whole formulation was sent to the pan pelletizer, where the rotation speed of the pan pelletizer was 30 rpm and the operating angle was 34.5° from the vertical position. The moisture content of the whole LWA formulation was monitored and maintained at 35% by use of the mass sensor and water spraying device. After the pellets were formed, they were sent to the sintering unit, where they were sintered at 1,000°C. After sintering, the LWA had particle density of 1.21 g/cm^3 and loose bulk density of 0.95 g/cm^3 which met the standard of EN 13055:2016 and were incorporated into 10% by volume of coarse aggregates in concrete formulate for lightweight concrete applications.

The leaching results of sintered LWA are shown below and all the values meet the Danish WtR Category 3 Standard.

Table 1A: Leaching results of LWA

Pollutant	**Concentration (mg/kg)**	**Danish WtR Cat. 3 Standard (mg/kg)**
Cadmium	<0.005	0.13
Chromium	<0.05	2.8
Lead	<0.05	0.45
Mercury	<0.0005	0.0083

The coagulant properties are shown in the table below and the EN878 Standard Type 1 requirements of coagulant concentration and pollutants levels can be fully met.

Table 1B: Coagulant Properties

S/N	Parameters			EN 878 Standard
1	Coagulant Concentration (g/kg product)	33.2		32-44
2	Pollutants Concentrations (mg/kg Al)	Antimony	0.0197	20
		Arsenic	0.510	14
		Cadmium	ND	3
		Chromium	0.00372	30
		Lead	ND	40
		Mercury	ND	4
		Nickel	0.0113	20
		Selenium	0.0000467	20

ND is "not detected" in this and following tables.

Example 2: Treatment of soft freshwater sludge

A representative soft freshwater sludge sample was collected at a drinking water treatment plant that used ferric sulfate as coagulant. The soft freshwater sludge with mass 3,000 kg was to be treated. The central processor had determined that the freshwater sludge to be of S type, and following this, the sludge went into the paddle shredder to be crushed to below 1 mm in lump size. The degree of rotation of each paddle was 60° from the line of central axle. Next, the shredded sludge went into the bioreactor. According to analysis by the central processor, the recommended biological digestion temperature was 50°C and the target mass reduction was set to be 54%. For this biological digestion, 1% microorganisms with fungi species *Aspergillus Fumigatus* and bacteria species *Bacillus brevis* at mass ratio of 0.85 was used. Moisture content was monitored by the central processor and maintained at 75% by intermittent use of the water spray. The reactor automatically stopped after the target mass reduction was achieved and the digestion period was 96 hours. At the end of the digestion, the digested freshwater sludge went into the coagulant recovery unit, and 6,600 liters of water and 600 liters of 98% (v/v) sulfuric acid, as determined by the central processor, were added to maintain the pH of coagulant recovery at 2.5. During coagulant recovery, a lot of foams were generated, and the foams were removed by the defoaming skimmer and transferred to the neutralization tank where 0.5% by mass lime was used to break the foams. After the foams were broken up, remaining solid residues were disposed of. The coagulant recovery rate was set to be 80% and the process took place for 2.1 hours and after coagulant recovery the acidic mixture went into the filter press to separate the liquid and solid portions. The liquid portion separated by the filter press could be used directly as coagulant in wastewater treatment in a dosage of 3% by mass of the wastewater. The solid portion from the filter press, in this example the mass of which is 580 kg, went into the LWA fabrication unit. In the LWA fabrication unit, the solid portion from the filter press was dried and ball milled, and the solid so dried and ball milled was mixed with formulation containing 2,900 kg potassium silicate, 18,850 kg SiO_2, 5,800 kg Al_2O_3, and 870 kg K_2O. The LWA formulation was mixed for 20 minutes and the whole formulation was sent to the pan pelletizer, where the rotation speed of the pan pelletizer was 40 rpm and the operating angle was 40° from the vertical position. The moisture content of the whole LWA formulation was monitored and maintained at 30% by use of the mass sensor and water spraying device. After the pellets were formed, they were sent to the sintering unit, where they were sintered at 1,100°C. After sintering, the LWA had particle density of 1.13 g/cm^3 and loose bulk density of 0.87 g/cm^3 which met the EN 13055:2016 standard and were incorporated into 10% by volume of coarse aggregates in concrete formulate for lightweight concrete applications.

The leaching results of sintered LWA are shown below and all the values meet the Danish WtR Category 3 Standard.

Table 2A: Leaching results of LWA

Pollutant	**Concentration (mg/kg)**	**Danish WtR Cat. 3 Standard (mg/kg)**
Cadmium	<0.005	0.13
Chromium	<0.05	2.8
Lead	<0.05	0.45
Mercury	<0.0005	0.0083

The coagulant properties are shown in the table below and the EN890 Standard Type 2 requirements of pollutants levels are met. Although the coagulant concentration in the product cannot meet Class C standard for commercial products, the recovered coagulant was tested by using nickel plating wastewater containing 10 ppm Ni and after coagulation and filtration, the concentration of Ni in the wastewater was reduced to 0.03 ppm.

Table 2B: Coagulant characteristics

S/N	**Parameters**			**EN 878 Standard Type 1**
1	Coagulant Concentration (Mass Fraction in %)	2.05		8.40-8.80 (Class C)
2	Pollutants Concentrations (mg/kg Fe)	Antimony	0.0135	10
		Arsenic	0.251	1
		Cadmium	ND	1
		Chromium	0.00603	100
		Lead	ND	10
		Mercury	ND	0.1
		Nickel	0.0269	300
		Selenium	ND	1

Example 3: Treatment of thickened freshwater sludge

A representative thickened freshwater sludge sample was collected from treatment tank before filter press at a drinking water treatment plant that used aluminum chloride as coagulant. The thickened freshwater sludge with mass 4,500 kg was to be treated. The central processor had determined that the freshwater sludge to be of T type, and following this, the sludge went into the went into the bioreactor directly without being crushed. According to analysis by the central processor, the recommended biological digestion temperature was 65°C and the target mass reduction was set to be 50%. For this biological digestion, 1% microorganisms with fungi species *Fusarium verticillioides* and bacteria species *Bacillus licheniformis* at mass ratio of 0.60 was used. Moisture content was monitored by the central processor and maintained at 77% by intermittent use of the water spray. The reactor automatically stopped after the target mass reduction was achieved and the digestion period was 98 hours. At the end of the digestion, the digested freshwater sludge went into the coagulant recovery unit, and 9,900 liters of water and 900 liters of 98% (v/v) sulfuric acid, as determined by the central processor, were added to maintain the pH of coagulant recovery at 2.6. During coagulant recovery, a lot of foams were generated, and the foams were removed by the defoaming skimmer and transferred to the neutralization tank where 0.5% by mass lime was used to break the foams. After the foams were broken up, remaining solid residues were disposed of. The coagulant recovery was set to be 80% and the process took place for 2.5 hours. After coagulant recovery the acidic mixture went into the filter press to separate the liquid and solid portions. The liquid portion separated by the filter press could be used directly as coagulant in wastewater treatment in a dosage of 3% by mass of the wastewater. The solid

portion from the filter press, in this example the mass of which is 875 kg, went into the LWA fabrication unit. In the LWA fabrication unit, the solid portion from the filter press was dried and ball milled, and the solid so dried and ball milled was mixed with formulation containing 4,375 g sodium silicate, 28,437.5 g SiO_2, 8,750 g Al_2O_3, and 1312.5 g Na_2O. The LWA formulation was mixed for 20 minutes and the whole formulation was sent to the pan pelletizer, where the rotation speed of the pan pelletizer was 45 rpm and the operating angle was 45° from the vertical position. The moisture content of the whole LWA formulation was monitored and maintained at 35% by use of the mass sensor and water spraying device. After the pellets were formed, they were sent to the sintering unit, where they were sintered at 1,200°C. After sintering, the LWA pellets had particle density of 1.17 g/cm^3 and loose bulk density of 0.93 g/cm^3 which met EN 13055:2016 standard and were incorporated into 10% by volume of coarse aggregates in concrete formulate for lightweight concrete applications.

The leaching results of sintered LWA are shown below and all the values meet the Danish WtR Category 3 Standard.

Table 3A: Leaching results of LWA

Pollutant	**Concentration (mg/kg)**	**Danish WtR Cat. 3 Standard (mg/kg)**
Cadmium	<0.005	0.13
Chromium	<0.05	2.8
Lead	<0.05	0.45
Mercury	<0.0005	0.0083

The coagulant properties are shown in the table below and the EN878 Standard Type 1 requirements of coagulant concentration and pollutants levels can be fully met.

Table 3B: Coagulant Properties

S/N	**Parameters**			**EN 878 Standard**
1	Coagulant Concentration (g/kg product)	36.3		32-44
2	Pollutants Concentrations (mg/kg Al)	Antimony	0.0125	20
		Arsenic	0.626	14
		Cadmium	ND	3
		Chromium	0.00827	30
		Lead	ND	40
		Mercury	ND	4
		Nickel	0.00652	20
		Selenium	0.000361	20

Example 4: Treatment of hard freshwater sludge using waste acid

A representative hard freshwater sludge sample was collected at a drinking water treatment plant that used aluminum sulfate as coagulant. The hard freshwater sludge with mass 3,000 kg was to be treated. The central processor had determined that the freshwater sludge to be of H type, and following this, the sludge went into the double-rotating shaft crusher with teeth to be crushed to below 1 mm in particle size. Next, the crushed sludge went into the bioreactor. According to analysis by the central processor, the recommended biological digestion temperature was 45°C and the target mass reduction was set to be 52%. For this biological digestion, 1% microorganisms with fungi species *Eurotium rubrum* and bacteria species *Bacillus stearothermophilus* at mass ratio of 0.85 was used. Moisture content was

monitored by the central processor and maintained at 70% by intermittent use of the water spray. The reactor automatically stopped after the target mass reduction was achieved and the digestion period was 107 hours. At the end of the digestion, the digested freshwater sludge went into the coagulant recovery unit, and 4,725 liters of water and 2,475 liters of waste acid from copper refining industry with pH of -0.47, as determined by the central processor, were added to maintain the pH of coagulant recovery at 2.7. During coagulant recovery, foams were generated, and the foams were removed by the defoaming skimmer and transferred to the neutralization tank where 0.5% by mass lime was used to break the foams. After the foams were broken up, remaining solid residues were disposed of. The target coagulant recovery rate was set to be 75% and the process took place for 2.6 hours. After coagulant recovery, the acidic mixture went into the filter press to separate the liquid and solid portions.

The liquid portion separated by the filter press carried heavy metal pollutants in the waste acid and was sent to the purification unit. In the purification process, 1,100 liters of 12M sodium hydroxide solution was added to the unit to raise the pH to 7. The purification process was stopped automatically when there was no more precipitation formed and the process period was 15 minutes. The supernatant solution in the purification unit went to the wastewater tank and the precipitation was pumped out and filtered by filter press to separate the liquid and solid portions. The liquid portion separated went to the wastewater tank while the solid portions was dissolved in sulfuric acid to form liquid coagulants.

The solid portion from the filter press, in this example the mass of which is 590 kg, went into the LWA fabrication unit. In the LWA fabrication unit, the solid portion from the filter press was dried and ball milled, and the solid so dried and ball milled was mixed with formulation containing 2,950 kg sodium silicate, 19,175 kg SiO_2, 5,900 kg Al_2O_3, and 885 kg Fe_2O_3. The LWA formulation was mixed for 20 minutes and the whole formulation was sent to the pan pelletizer, where the rotation speed of the pan pelletizer was 30 rpm and the operating angle was 35° from the vertical position. The moisture content of the whole LWA formulation was monitored and maintained at 35% by use of the mass sensor and water spraying device. After the pellets were formed, they were sent to the sintering unit, where they were sintered at 1,100°C. After sintering, the LWA had particle density of 0.95 g/cm^3 and loose bulk density of 0.83 g/cm^3 which met the standard of EN 13055:2016 and were incorporated into 10% by volume of coarse aggregates in concrete formulate for lightweight concrete applications.

The leaching results of sintered LWA are shown below and all the values meet the Danish WtR Category 3 Standard.

Table 4A: Leaching results of LWA

Pollutant	**Concentration (mg/kg)**	**Danish WtR Cat. 3 Standard (mg/kg)**
Cadmium	<0.005	0.13
Chromium	<0.05	2.8
Lead	<0.05	0.45
Mercury	<0.0005	0.0083

The coagulant properties are shown in the table below and the EN878 Standard Type 1 requirements of coagulant concentration and pollutants levels can be fully met.

Table 4B: Coagulant Properties

S/N	**Parameters**			**EN 878 Standard**
1	Coagulant Concentration (g/kg product)	33.2		32-44
2	Pollutants Concentrations (mg/kg Al)	Antimony	0.0079	20
		Arsenic	ND	14

		Cadmium	ND	3
		Chromium	0.00032	30
		Lead	ND	40
		Mercury	ND	4
		Nickel	0.0013	20
		Selenium	ND	20

Example 5: Treatment of freshwater sludge on site of wastewater treatment plant

A representative hard freshwater sludge sample was collected at a drinking water treatment plant that used aluminum sulfate as coagulant. The hard freshwater sludge with mass 3,600 kg was to be treated on site. The central processor had determined that the freshwater sludge to be of H type, and following this, the sludge went into the double-rotating shaft crusher with teeth to be crushed to below 1 mm in particle size. Next, the crushed sludge went into the bioreactor. According to analysis by the central processor, the recommended biological digestion temperature was 55°C and the target mass reduction was set to be 45%. For this biological digestion, 1% microorganism with fungi species *Aspergillus Terreus* and bacteria species *Bacillus stearothermophilus* at mass ratio of 0.95 was used. Moisture content was monitored by the central processor and maintained at 70% by intermittent use of the water spray. The reactor automatically stopped after the target mass reduction was achieved and the digestion period was 99 hours. At the end of the digestion, the digested freshwater sludge went into the coagulant recovery unit, and 7,920 liters of water and 720 liters of 98% (v/v) sulfuric acid, as determined by the central processor, were added to maintain the pH of coagulant recovery at 2.6. During coagulant recovery, a lot of foams were generated, and the foams were removed by the defoaming skimmer and transferred to the neutralization tank where 0.5% by mass lime was used to break the foams. After the foams were broken up, remaining solid residues were disposed of. The target coagulant recovery rate was set to be 80% and the process took place for 1.5 hours. After coagulant recovery, the acidic mixture went into the filter press to separate the liquid and solid portions. The liquid portion separated by the filter press could be used directly as coagulant in wastewater treatment in a dosage of 2% by mass of the wastewater and was transported through corrosion-resistant pipeline to a coagulant storage tank on site. The solid portion from the filter press, in this example the mass of which is 710 kg, went into the LWA fabrication unit. In the LWA fabrication unit, the solid portion from the filter press was dried and ball milled, and the solid so dried and ball milled was mixed with formulation containing 3,550 kg sodium silicate, 23,075 kg SiO_2, 7,100 kg Al_2O_3, and 1,065 kg Fe_2O_3. The LWA formulation was mixed for 20 minutes and the whole formulation was sent to the pan pelletizer, where the rotation speed of the pan pelletizer was 45 rpm and the operating angle was 35.5° from the vertical position. The moisture content of the whole LWA formulation was monitored and maintained at 30% by use of the mass sensor and water spraying device. After the pellets were formed, they were sent to the sintering unit, where they were sintered at 1,200°C. After sintering, the LWA had particle density of 1.3 g/cm^3 and loose bulk density of 1.1 g/cm^3 which met the standard of EN 13055:2016 and were incorporated into 10% by volume of coarse aggregates in concrete formulate for lightweight concrete applications.

The leaching results of sintered LWA are shown below and all the values meet the Danish WtR Category 3 Standard.

Table 5A: Leaching results of LWA

Pollutant	**Concentration (mg/kg)**	**Danish WtR Cat. 3 Standard (mg/kg)**
Cadmium	<0.005	0.13
Chromium	<0.05	2.8
Lead	<0.05	0.45

Mercury	<0.0005	0.0083

The coagulant properties are shown in the table below and the EN878 Standard Type 1 requirements of coagulant concentration and pollutants levels can be fully met.

Table 5B: Coagulant Properties

S/N	Parameters			EN 878 Standard
1	Coagulant Concentration (g/kg product)	34.8		32-44
2	Pollutants Concentrations (mg/kg Al)	Antimony	0.0184	20
		Arsenic	0.603	14
		Cadmium	0.0006	3
		Chromium	ND	30
		Lead	ND	40
		Mercury	ND	4
		Nickel	0.0254	20
		Selenium	ND	20

Example 6: Treatment of food processing wastewater treatment sludge

A representative food processing sludge sample was collected at a food factory that used aluminum sulfate as coagulant. The soft freshwater sludge with mass 2,800 kg was to be treated. The central processor had determined that the food processing sludge to be of S type, and following this, the sludge went into the paddle crusher to be crushed to below 1 mm in lump size. The degree of rotation of each paddle was 65° from the line of central axle. Next, the crushed sludge went into the bioreactor. According to analysis by the central processor, the recommended biological digestion temperature was 60°C and the target mass reduction was set to be 60%. For this biological digestion, 1% microorganisms with fungi species *Aspergillus Terreus* and bacteria species *Bacillus stearothermophilus* at mass ratio of 0.70 was used. Moisture content was monitored by the central processor and maintained at 70% by intermittent use of the water spray. The reactor automatically stopped after the target mass reduction was achieved and the digestion period was 68 hours. At the end of the digestion, the digested freshwater sludge went into the coagulant recovery unit, and 4,950 liters of water and 450 liters of 98% (v/v) sulfuric acid, as determined by the central processor, were added to maintain the pH of coagulant recovery at 2.7. During coagulant recovery, a lot of foams were generated, and the foams were removed by the defoaming skimmer and transferred to the neutralization tank where 0.5% by mass lime was used to break the foams. After the foams were broken up, remaining solid residues were disposed of. The target coagulant recovery rate was set to be 80% and the process took place for 1.8 hours. After coagulant recovery, the acidic mixture went into the filter press to separate the liquid and solid portions. The liquid portion separated by the filter press could be used directly as coagulant in wastewater treatment in a dosage of 2% by mass of the wastewater. The solid portion from the filter press, in this example the mass of which is 180 kg, went into the LWA fabrication unit. In the LWA fabrication unit, the solid portion from the filter press was dried and ball milled, and the solid so dried and ball milled was mixed with formulation containing 900 kg sodium silicate, 5,850 kg SiO_2, 1,800 kg Al_2O_3, and 270 kg Fe_2O_3. The LWA formulation was mixed for 20 minutes and the whole formulation was sent to the pan pelletizer, where the rotation speed of the pan pelletizer was 30 rpm and the operating angle was 37° from the vertical position. The moisture content of the whole LWA formulation was monitored and maintained at 35% by use of the mass sensor and water spraying device. After the pellets were formed, they were sent to the sintering unit, where they were sintered at 1,200°C. After sintering, the LWA had particle density of 1.01 g/cm^3 and loose bulk density of 0.76 g/cm^3 which met the standard of EN

13055:2016 and were incorporated into 10% by volume of coarse aggregates in concrete formulate for lightweight concrete applications.

The leaching results of sintered LWA are shown below and all the values meet the Danish WtR Category 3 Standard.

Table 6A: Leaching results of LWA

Pollutant	**Concentration (mg/kg)**	**Danish WtR Cat. 3 Standard (mg/kg)**
Cadmium	<0.005	0.13
Chromium	<0.05	2.8
Lead	<0.05	0.45
Mercury	<0.0005	0.0083

The coagulant properties are shown in the table below and the EN878 Standard Type 1 requirements of pollutants levels can be fully met. The coagulant concentration was lower than the standard requirement due to the relatively low concentration of coagulant in the food process sludge.

Table 6B: Coagulant Properties

S/N	**Parameters**			**EN 878 Standard**
1	Coagulant Concentration (g/kg product)	26.8		32-44
2	Pollutants Concentrations (mg/kg Al)	Antimony	ND	20
		Arsenic	0.00213	14
		Cadmium	ND	3
		Chromium	ND	30
		Lead	ND	40
		Mercury	ND	4
		Nickel	0.0045	20
		Selenium	ND	20

Example 7: Treatment of mixture of freshwater sludge and sewage sludge

A representative mixture of soft freshwater sludge and sewage sludge sample was collected at a municipal wastewater treatment plant and the freshwater sludge contained ferric sulfate coagulant. The sludge mixture with mass 3,500 kg was to be treated. The central processor had determined that the freshwater sludge to be of S type, and following this, the sludge went into the paddle crusher to be crushed to below 1 mm in lump size. The degree of rotation of each paddle was 70° from the line of central axle. Next, the crushed sludge went into the bioreactor. According to analysis by the central processor, the recommended biological digestion temperature was 60°C and the target mass reduction was set to be 57%. For this biological digestion, 1% microorganisms with fungi species *Aspergillus Terreus* and bacteria species *Bacillus brevis* at mass ratio of 0.80 was used. Moisture content was monitored by the central processor and maintained at 75% by intermittent use of the water spray. The reactor automatically stopped after the target mass reduction was achieved and the digestion period was 110 hours. At the end of the digestion, the digested freshwater sludge went into the coagulant recovery unit, and 7,700 liters of water and 700 liters of 98% (v/v) sulfuric acid, as determined by the central processor, were added to maintain the pH of coagulant recovery at 2.5. During coagulant recovery, a lot of foams were generated, and the foams were removed by the defoaming skimmer and transferred to the neutralization tank where 0.5% by mass lime was used to break the foams. After the foams were broken up, remaining solid residues were disposed of. The coagulant recovery rate was set to be 80%

and the process took place for 2.7 hours and after coagulant recovery the acidic mixture went into the filter press to separate the liquid and solid portions. The liquid portion separated by the filter press could be used directly as coagulant in wastewater treatment in a dosage of 5% by mass of the wastewater. The solid portion from the filter press, in this example the mass of which is 650 kg, went into the LWA fabrication unit. In the LWA fabrication unit, the solid portion from the filter press was dried and ball milled, and the solid so dried and ball milled was mixed with formulation containing 3,250 kg potassium silicate, 21,125 kg SiO_2, 6,500 kg Al_2O_3, and 975 kg K_2O. The LWA formulation was mixed for 20 minutes and the whole formulation was sent to the pan pelletizer, where the rotation speed of the pan pelletizer was 40 rpm and the operating angle was 40° from the vertical position. The moisture content of the whole LWA formulation was monitored and maintained at 35% by use of the mass sensor and water spraying device. After the pellets were formed, they were sent to the sintering unit, where they were sintered at 1,100°C. After sintering, the LWA had particle density of 0.97 g/cm^3 and loose bulk density of 0.81 g/cm^3 which met the EN 13055:2016 standard and were incorporated into 10% by volume of coarse aggregates in concrete formulate for lightweight concrete applications.

The leaching results of sintered LWA are shown below and all the values meet the Danish WtR Category 3 Standard.

Table 7A: Leaching results of LWA

Pollutant	**Concentration (mg/kg)**	**Danish WtR Cat. 3 Standard (mg/kg)**
Cadmium	<0.005	0.13
Chromium	<0.05	2.8
Lead	<0.05	0.45
Mercury	<0.0005	0.0083

The coagulant properties are shown in the table below and the EN890 Standard Type 2 requirements of pollutants levels are met. The coagulant concentration is low because the low concentration of coagulants in the mixture of sludges.

Table 7B: Coagulant properties

S/N	**Parameters**			**EN 878 Standard Type 1**
1	Coagulant Concentration (Mass Fraction in %)	1.96		8.40-8.80 (Class C)
2	Pollutants Concentrations (mg/kg Fe)	Antimony	0.0283	10
		Arsenic	0.683	1
		Cadmium	ND	1
		Chromium	0.0219	100
		Lead	0.0672	10
		Mercury	ND	0.1
		Nickel	0.835	300
		Selenium	ND	1

Example 8: Treatment of buried sludge with containerized system

A representative unknown excavated sludge sample was collected at a construction site. The unknown sludge was buried under ground initially and was excavated out during the piling process. According to the lab analysis results, 32,500 mg/kg of aluminum sulfate was found in the sludge. The unknown sludge with mass 100 kg was to be treated in a containerized system for feasibility study.

The central processor had determined that the freshwater sludge to be of S type, and following this, the sludge went into the paddle crusher to be crushed to below 1 mm in lump size. The degree of rotation of each paddle was 80° from the line of central axle. Next, the crushed sludge went into the bioreactor. According to analysis by the central processor, the recommended biological digestion temperature was 60°C and the target mass reduction was set to be 30%. For this biological digestion, 1% microorganisms with fungi species *Aspergillus Terreus* and bacteria species *Bacillus stearothermophilus* at mass ratio of 0.55 was used. Moisture content was monitored by the central processor and maintained at 70% by intermittent use of the water spray. The reactor automatically stopped after the target mass reduction was achieved and the digestion period was 230 hours. At the end of the digestion, the digested freshwater sludge went into the coagulant recovery unit, and 220 liters of water and 20 liters of 98% (v/v) sulfuric acid, as determined by the central processor, were added to maintain the pH of coagulant recovery at 2.5. During coagulant recovery, a lot of foams were generated, and the foams were removed by the defoaming skimmer and transferred to the neutralization tank where 0.5% by mass lime was used to break the foams. After the foams were broken up, remaining solid residues were disposed of. The target coagulant recovery rate was set to be 85% and the process took place for 3 hours. After coagulant recovery, the acidic mixture went into the filter press to separate the liquid and solid portions. The liquid portion separated by the filter press was sent for lab analysis and the results are shown in the table below.

The solid portion from the filter press, in this example the mass of which is 23 kg, went into the LWA fabrication unit. In the LWA fabrication unit, the solid portion from the filter press was dried and ball milled, and the solid so dried and ball milled was mixed with formulation containing 115 kg sodium silicate, 747.5 kg SiO_2, 230 kg Al_2O_3, and 34.5 kg Fe_2O_3. The LWA formulation was mixed for 20 minutes and the whole formulation was sent to the pan pelletizer, where the rotation speed of the pan pelletizer was 40 rpm and the operating angle was 34.5° from the vertical position. The moisture content of the whole LWA formulation was monitored and maintained at 30% by use of the mass sensor and water spraying device. After the pellets were formed, they were sent to the sintering unit, where they were sintered at 1,000°C. After sintering, the LWA had particle density of 1.05 g/cm^3 and loose bulk density of 0.93 g/cm^3 which met the standard of EN 13055:2016.

The leaching results of sintered LWA are shown below and all the values meet the Danish WtR Category 3 Standard.

Table 8A: Leaching results of LWA

Pollutant	**Concentration (mg/kg)**	**Danish WtR Cat. 3 Standard (mg/kg)**
Cadmium	<0.005	0.13
Chromium	<0.05	2.8
Lead	<0.05	0.45
Mercury	<0.0005	0.0083

The coagulant properties are shown in the table below and the EN878 Standard Type 1 requirements of pollutants levels can be fully met but the coagulant concentration is too low to be directly used due to low initial concentration in the unknown sludge.

Table 8B: Coagulant Properties

S/N	**Parameters**	**EN 878 Standard**

1	Coagulant Concentration (g/kg product)	11.6		32-44
2	Pollutants Concentrations (mg/kg Al)	Antimony	0.0197	20
		Arsenic	0.510	14
		Cadmium	ND	3
		Chromium	0.00372	30
		Lead	ND	40
		Mercury	ND	4
		Nickel	0.0113	20
		Selenium	0.0000467	20

The results showed that it is not economical to recover the coagulants in the unknown sludge.

Claims

1. A system for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge comprising the following components that function in synergy:

(a) A central processor with artificial intelligence technology to continuously optimize system and method parameters with inbuilt algorithms based on various types of information on waste type and treatment parameters, and the processor analyzes information of freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge to classify the freshwater sludge into groups H, S, and T such that:

H is hard sludge that is brittle and comprises greater than 50% by volumetric basis slabs that are of dimensions 10 cm to 12.5 cm in length, 5 cm to 7.5 cm in width, and 0.5 cm to 1 cm in thickness;

S is soft sludge that is of muddy or clay texture and comprises less than 20% by volumetric basis slabs that are of dimensions 10 cm to 12.5 cm in length, 5 cm to 7.5 cm in width, and 0.5 cm to 1 cm in thickness; and

T is thickened sludge that contains >95% moisture content;

(b) A pulverization component that comprises:

A double-rotating shaft crusher with teeth; and

A paddle shredder that has mixing paddles distributed in spiraling manner about a central mixing axle; each mixing paddle is of length 10 cm to 14 cm, width 8 cm to 12 cm, and thickness 5 mm to 8 mm; length of paddle attachment to the central mixing axle is 1 cm to 2 cm; each paddle is free-rotating about its attachment to the central mixing axle, and degree of rotation is 60° to 80° from line of the central mixing axle;

(c) A bioreactor that is cylindrical in design with a thermal insulation jacket, a double ribbon mixing element, a mass sensor, a moisture meter, a temperature sensor, a water spraying device, and an outlet of 20 cm to 30 cm in diameter at bottom of the bioreactor;

(d) A coagulant recovery unit with a defoaming skimmer, a mixing device, a filtration device, a pH probe, a neutralization tank, a waste acid storage tank, and a metallic ion concentration sensor;

(e) A purification unit with a filtration device and an adjacent wastewater treatment unit; and

(f) A lightweight aggregate fabrication unit with a drying device, a horizontal ball mill, a mixing device that is a single ribbon mixer with a mass weighing sensor, a pan pelletizer, a water spraying apparatus, a moisture meter, and a sintering device.

2. Method for resource recovery from freshwater sludge and similar solid wastes using the system of claim 1 wherein

Solid waste of group H enters the double-rotating shaft crusher of claim 1 (b), and solid waste of group S enters the paddle shredder of claim 1 (b), and in both cases of H and S waste material solid waste is crushed to lump size that is below 1 mm;

For solid waste of group S, lump size reduction to below 1 mm is aided by the free-rotating paddles in the paddle shredder of claim 1 (b) such that degree of rotation from the central mixing axle reduces from 80° to 60° until lump size is below 1 mm; and

For solid waste of group T the step of crushing using the double-rotating shaft crusher or the paddle shredder is bypassed.

3. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claim 2 wherein digestion inside the bioreactor of claim 1 (c) incorporates use of thermophilic aerobic digestion microorganisms consisting of fungal species that is selected from the group consisting of: *Aspergillus Terreus, Aspergillus Fumigatus, Fusarium verticillioides,* and *Eurotium rubrum* and bacteria species that is selected from the group consisting of: *Bacillus stearothermophilus*, *Bacillus brevis*, *Bacillus licheniformis*, and *Bacillus coagulans* and the bioreactor outlet opens at the end of digestion to allow internal contents to empty out by movement of the double ribbon mixing element of the bioreactor; the mass ratio of fungi to bacteria is 0.5 to 1.

4. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 3 wherein

For fresh batch of digestion, thermophilic aerobic digestion microorganism dosage is 0.5% to 2.5% by mass, digestion duration is 48 to 120 hours, operating temperature of digestion is controlled to be 40°C to 70°C by use of the temperature sensor of claim 1 (c), and moisture content is automatically maintained at 60% to 80% by use of the moisture meter of claim 1 (c) and the water spraying device of claim 1 (c); or

For continuing batch of digestion, 5% by mass previously digested sludge mixture material is used as recycling sludge for next round of digestion, digestion duration is 48 to 120 hours, operating temperature of digestion is controlled to be 40°C to 70°C by use of the temperature sensor of claim 1 (c), and moisture content is automatically maintained at 60% to 80% by use of the moisture meter of claim 1 (c) and the water spraying device of claim 1 (c).

5. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 4 wherein coagulant recovery is performed on material that has gone through the bioreactor of claim 1 (c) and concentrated acid that is selected from the group consisting of sulfuric acid, hydrochloric acid, nitric acid, hydrobromic acid, hydroiodic acid, perchloric acid, and chloric acid or with aqueous non-organic waste acid that has acid concentration 1% to 30% by volume from the waste acid storage tank of claim 1 (d), pH of coagulant recovery is automatically maintained at 1.5 to 3 using the pH probe, water is introduced into the mixture at a liquid:total solid waste ratio of 2:1 to 5:1 to facilitate mixing of solid waste and acid.

6. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 5 wherein the defoaming skimmer of claim 1 (d) removes

foam generated during coagulant recovery, sends collected foam to the neutralization tank with a mixing device where 0.5% by mass lime is used to break the foams.

7. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 6 wherein the metallic ion concentration sensor of claim 1 (d) monitors concentration of coagulant ions such as aluminum or iron (III) ions and stops coagulant recovery reaction if theoretical recovery rate based on past average metallic content in untreated freshwater sludge or other industrial solid wastes is 50% to 90%.

8. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 7 wherein:

If concentrated acid is used to adjust pH to 1.5 to 3 in coagulant recovery, liquid portion of coagulant recovery unit is separated by the filtration device of claim 1 (d) and 0.1% to 5% on wastewater volumetric basis of the liquid so obtained is used as liquid coagulant in wastewater treatment; or

If waste acid is used to adjust the pH to 1.5 to 3 in coagulant recovery, liquid portion of coagulant recovery unit that is separated by the filtration device of claim 1 (d) is sent to the purification unit of claim 1 (e) and a precipitant that is selected from the group consisting of ammonium hydroxide, calcium hydroxide, magnesium hydroxide, sodium carbonate, and sodium hydroxide is added in the purification unit to a pH of 7 to 7.5 and, furthermore:

Supernatant of purification reaction is sent to the wastewater treatment unit of claim 1 (e);

All precipitants thus formed are filtered out by the filtration device of claim 1 (e) to be used as precursor material in coagulant synthesis where precipitants thus formed are dissolved by sulfuric acid to be reused as coagulant; and

Filtrate from the filtration device of claim 1 (e) is sent to the wastewater treatment unit of claim 1 (e).

9. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 8 wherein the wastewater treatment unit of claim 1 (e) comprises a flocculating or coagulating step using a chemical that is selected from group consisting of aluminum sulfate, ferric chloride, ferric sulfate, ferrous sulfate, polyacrylamide, polyaluminum chloride, polyaluminum chlorosulfate, polyaluminum silicatesulfate, sodium alginates, polyelectrolytes, and combinations thereof.

10. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 9 wherein:

Remaining residual solid portion of freshwater sludge or other wastes after the coagulant recovery unit of claim 1 (d) is dried by rotary dryer at a temperature of 90°C to 105°C until moisture content is <1% and so dried sludge residual is milled by the horizontal ball mill to a particle size of <75μm;

Sludge residual so dried and milled is mixed with formulation consisting of 2% to 5% sludge residual so dried and milled, 10% to 12% binding agent that is selected from group consisting of sodium silicate and potassium silicate, 60% to 70% SiO_2, 20% to 25% Al_2O_3, and 3% to 5% flux, where flux is defined as sum of mass percentages of Fe_2O_3, K_2O, Na_2O, CaO, and MgO; and

The mass weighing sensor of claim 1 (f) measures and records the mass of mix.

11. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 10 wherein the pan pelletizer produces aggregate particles of diameter 10 mm to 20 mm, and the mass weighing sensor of claim 1 (f) and the moisture meter of claim 1 (f) send mass information of mix and moisture content information of mix, respectively, to the water spraying apparatus of claim 1 (f) to control mass of water sprayed such that moisture content of resulting mix is 30% to 35%.

12. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 11 wherein the pan pelletizer that is a rotating circular pan rotates at a speed that is 30 rpm to 60 rpm and operates at an angle that is 34.5° to 55.5° from vertical position.

13. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 12 wherein the sintering device heats particles produced from the pan pelletizer to a temperature of 1,000 °C to 1,200 °C.

14. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 13 wherein produced lightweight aggregates that have simultaneously particle density <2 g/cm^3 and loose bulk density 0.65 g/cm^3 to 2 g/cm^3 are incorporated into 1% to 75% by volume of coarse aggregates in concrete formulation, and lightweight aggregates that have loose bulk density 0.75 g/cm^3 to 1.2 g/cm^3 are used for growth medium in gardening.

15. The method for resource recovery from freshwater sludge and similar solid wastes such as industrial wastewater treatment sludge of claims 2 to 14 wherein the central processor of claim 1 (a) utilizes artificial intelligence technology to collect and analyze information and optimize operational parameters in future resource recovery and minimize prediction error through feedback loop, and furthermore:

Analyzes waste information and automatically adjusts angle of rotation of the mixing paddles of the paddle shredder of claim 1 (b);

Monitors mass information from the mass sensor of claim 1 (c) on digestion sludge mass and stops digestion when overall mass loss is >30%;

Collects information from the moisture meter of claim 1 (c) on digestion sludge moisture content and automatically adjusts digestion sludge moisture content to 60% to 80% by controlling the water spraying device of claim 1 (c), saves all treatment and waste type information, and determines future system parameters based on waste type;

Accumulates information of waste acid received in the waste acid storage tank on acid type, factory source of waste acid, and waste acid pH, and automatically adjusts dosage of waste acid used inside the coagulant recovery unit of claim 1 (d) such that pH is 1.5 to 3;

Monitors information from the metallic ion concentration sensor of claim 1 (d) and automatically controls coagulant recovery duration such that 70% to 90% of coagulant metal ions such as aluminum or iron (III) ions based on average past metallic content in untreated freshwater sludge or other industrial solid wastes are dissolved by acid inside the coagulant recovery unit; and

Collects information from the mass weighing sensor of claim 1 (f) and automatically controls the water spraying apparatus of claim 1 (f) to produce mix moisture content of 30% to 35% at the pan pelletizer of claim 1 (f).