INTEGRATED AND UNIVERSAL INTELLIGENT SYSTEM AND METHOD FOR TRANSFORMING MULTIPLE STREAMS OF INDUSTRIAL SOLID WASTES INTO LIGHTWEIGHT AGGREGATE

Description

Technical field

The present invention relates to an integrated and universal intelligent system and production method for treating and transforming multiple streams of industrial solid waste into lightweight aggregate (LWA) by microwave sintering. The system and method disclosed herein reduce leachable portion of heavy metals, organic pollutants, and soluble salts in the different streams of hazardous wastes and transform them into useful and quality LWA products that are suitable for reuse in multiple applications, diverting them from the landfill and helping mankind achieve resource efficiency.

Background of the invention

As a result of rapid economic and industrial growth, the amount of solid wastes generated according to such development is continuously increasing. At present, about 2,100 tons of solid waste are being landfilled daily in Singapore. This comprises 600 tons of various non-incinerable waste (NIW), mostly ash, slag, and sludge, and 1,500 tons of ash, consisting of both incineration bottom ash (IBA) and incineration fly ash (IFA). The vast generation of these solid wastes presents serious consequences, including rapid exhaustion of waste storage space in landfill and environmental pollution. Therefore, it is imperative to find solutions to divert these solid wastes from landfill by utilizing them as value-added secondary resources in order to achieve the goal of Zero Waste. In addition, in many countries, Singapore included, there are no known naturally occurring reserves of commercially exploitable LWA. The high costs of imported LWA make the valorization of the solid wastes for the production of LWA for use in lightweight concrete (LWC) and in gardening as good alternatives to landfill disposal. The processes to produce LWA from solid wastes involve a sintering process which is conventionally accomplished in a rotary kiln. Such production relies on heat conduction and has a low energy efficiency. Moreover, the quality of LWA may be inconsistent due to non-uniform heating. Considering the restriction of the conventional rotary kiln, the use of alternative energy sources to produce LWA has also begun to be studied. In recent years, microwave radiation with characteristics of a more rapid and uniform heating has been proposed as a viable alternative means for LWA production from various solid wastes.

Wastewater treatment sludge (WS)

WS is a byproduct of industrial wastewater treatment process. It may contain coagulants, heavy metals, and organic compounds. WS is currently directly landfilled in Singapore, potentially producing secondary environmental pollution owing to the leaching of heavy metals.

Sewage sludge (SS)

SS refers to waste generated from biological treatment (i.e., activated sludge system, trickling filters, and other attached growth systems which utilize microbes to remove organic matter from wastewater) of industrial or municipal wastewater. The characteristics of SS vary depending upon the stage of treatment from which it is drawn. A common characteristic of SS is that it contains high organic content, considerably high heavy metal concentrations and pathogens. Typical SS disposal practices include landfilling or by incineration followed by landfilling.

Coal fly ash (CFA)

Coal burning power plants typically produce very large quantities of coal ash that must be disposed of in an environmentally acceptable manner. Depending on the characteristics, coal ash can be divided into two categories, fly ash and bottom ash, and CFA, which accounts for 70 – 85% of the total coal ash, is actively recycled as a raw material for concrete admixture and cement.

Coal bottom ash (CBA)

In comparison to CFA, there is a limitation in recycling for the CBA due to quality problems resulting from the workability, which is due to the interlocking phenomenon and management of water content by surface pore.

Spent catalyst

Spent catalysts are the byproduct generated from the oil refining process in the petrochemical industry. The spent catalysts are microporous crystalline aluminosilicate materials which are contaminated with varying amounts of heavy metals from crude oil.

Environmental standards

It is crucial to ensure that the final products made from the solid wastes are safe to be used for humans and for the environment. The assessment of the long-term environmental impacts can be achieved by performing leaching tests on the final LWA products. The leaching tests measure the amount of leachable pollutants that can be extracted from the waste and be carried away by the groundwater or rainwater. Hence, it provides a good representation of the risk when the LWA is used in non-structural concrete or in gardening media. Depending on the particular environmental standards that are set by the local authority, the criteria could be very stringent and meeting such criteria for solid waste reuse remains a challenge. As currently there is no local standard available in Singapore for solid waste utilization, reference was made to the Danish Waste-to-Resource (WtR) standard for category 3 from Statutory Order No. 1662 of 2010 in this patent.

Proprietary algorithm expert system

The complexity of waste types, waste sources, and waste treatment technologies results in variations in the solid waste treatment system. These uncertainties further result in fluctuations in product quality and operation costs. Intelligent digitalization by the proprietary algorithm expert system used in this patent helps simplify processes in solid waste treatment, providing operators with actionable insights to adjust treatment processes to stay in compliance and achieve improved efficiencies and reduced operation costs.

Lightweight aggregates (LWAs)

LWAs are characterized by a granular and porous structure with loose bulk density and particle density no higher than 1.20 g/cm^3 and 2.0 g/cm^3, respectively. These characteristics are promoted by high-temperature sintering treatment, where the matrix melts to a viscous, pyro-plastic mass and forming a hard vitrified surface layer, thus preventing the run out of gases derived from the sintering of the matrix material. The entrapped gases in the viscous mass cause bloating of the mass and subsequently a porous structure with low density is obtained upon cooling. LWA products have a variety of applications including replacement of aggregates in non-structural concrete or as water filtration media; moreover, they are also commonly used as hydroponic growth media or are mixed with other growing media such as soil and peat to improve drainage in gardening applications. The LWAs suitable for gardening and agricultural use would have specific characteristics such as 24-hours water absorption > 20 %, single aggregate crushing strength > 1 MPa, pH value in the range of 6.5 – 7.5, and electrical conductivity (E.C.) in the range of 0.2 – 2 mS/cm. The LWAs suitable for non-structural concrete applications would have specific characteristics such as 24-hours water absorption < 20% and single aggregate crushing

strength > 1.8 MPa. The LWAs suitable for geotechnical applications would have specific characteristics such as single aggregate crushing strength > 1.8 MPa. LWAs can be classified in two groups: natural and synthetic. Natural LWAs are produced from materials of volcanic origin such as pumice, scoria, and tuff while synthetic LWAs are conventionally produced from materials such as shale and expansive clay. Due to the criticality of conserving natural resources, the production of LWAs by sintering green pellets, i.e., pellets made of waste materials, would be gradually becoming the mainstream. In relation to existing commercial LWA produced from wastes, it is known that fly ash can be pelletized with small amounts of water and/or coal and sintered to form granules (UK registered trade name LYTAG). LYTAG has been used principally for structural grades of concrete because strengths in excess of 70 N/mm^2 can be obtained at 28 days.

Microwave sintering

In recent years, a technique for sintering solid waste by microwave sintering has been developed and proposed. Microwave technology has been widely used in many applications such as the treatment of persistent organic pollutants (POPs) and heavy metals in municipal solid wastes incineration fly ash (MSWIFA). Huge productivity gains can be expected as the unique microwave process has a more rapid and uniform heating, shorter processing time than conventional sintering using a rotary kiln, resulting in significant energy savings and production costs. Moreover, unlike conventional sintering process which relies on heat conduction and causes a temperature gradient from the shell to the core of the LWA, microwave sintering provides a better control over the sintering process and produces consistent LWA product due to uniform heating. Therefore, high-quality LWA can be produced.

Patent literature

Patent CN103601526B, filed by Liu et al in 2013, describes a method to produce porous ceramsite through microwave sintering of medical waste. The method is not a universal treatment method for all types of solid wastes, and there is no intelligent component that can automatically adjust treatment parameters.

Patent US6104015, filed by Jayan et al in 2000, discloses a microwave sintering process for raw alumina particles. However, the method is only for raw alumina and not for industrial wastes.

Summary of the invention

Summary of invention

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 treating and transforming multiple streams of solid waste, such as river sediment, WS, SS, CFA, CBA, and spent catalysts into LWA for safe reuse applications. To achieve these and similar objectives of the present invention, the system for treating solid wastes for LWA production comprises:

a) A preconditioning chamber housing preconditioning processor unit that stores a comprehensive database of waste profile and executes appropriate precondition treatment steps; drying unit; milling unit; and sieving unit;
b) A batching chamber consisting of a sensor network and algorithm system that classify the preconditioned wastes according to their chemical composition based on the solid waste profile stored in the preconditioning processor unit; dosing and mixing unit; and dosing processor unit that processes formulations and executes instructions for selection of suitable LWA formulation based on intended end applications and compositions of the preconditioned wastes;

c) A granulation chamber consisting of pelletization-1 unit, pelletization-2 unit, and pulverization unit;
d) A furnace chamber housing loading device; drying and preheating unit; microwave sintering unit consisting of a plurality of microwave sources disposed in an array to introduce uniform electromagnetic radiation to heat up the pellets, furnace processor unit that executes instructions for the selection of treatment parameters such as number of crucible boats in operation, vertical movement of the tube device and insulation lids, sintering profiles, lateral movement of the crucible boats, rotation of the flat circular tray within the crucible boats, and power of the microwave sources, wireless sensor network system consisting of infrared sensors and camera sensors for monitoring temperatures, foaming process, and pore structure formation of the LWA and feeds the information to the furnace processor unit for treatment decision making, and a tube device for placement of insulation lids; cooling unit consisting of induced blower; transmission device consisting of a moving track configured in a circular fashion, and a chain of material carriers in the form of crucible boats which traverse in the furnace chamber using roller mechanism controlled by the furnace processor; unloading device consisting of a vacuum system; and gas scrubber treatment unit; and
e) An LWA product screening and grading system that classifies LWA products according to different end applications.

Problem solved by the invention

The continuous growth of the economy has made the disposal of solid wastes a serious challenge globally. Conventional management practice of solid wastes is to landfill them. However, this is an unsustainable approach due to environmental concerns and space constraint. Current technologies that target solid waste reutilization applications include washing, thermal stabilization by sintering, and chemical encapsulation through the addition of various additives. These technologies have a low percentage incorporation of waste materials, and few can universally treat multiple streams of solid wastes to meet the stringent reuse standards at a reasonable cost. Converting the solid wastes into LWA can address the low dosage issue and it can incorporate multiple streams of solid waste. However, the conventional process to produce LWA from solid wastes involve a sintering process in a rotary kiln which relies on heat conduction and has a low energy efficiency. Moreover, the quality of LWA may be inconsistent due to non-uniform heating.

Means for solving the problems

The system described in the present invention provides an integrated universal intelligent WtR solution for solid wastes, including, but not limited to, river sediment, WS, SS, CFA, CBA, and spent catalyst.

The treatment system comprises a preconditioning chamber with a preconditioning processor unit equipped with waste profile archiving functions by a proprietary algorithm expert system. Waste information stored includes but are not limited to, particle size distribution, moisture content, and chemical composition derived from quantitative phase analysis (X-ray diffraction (XRD) plus Rietveld refinement). By keying in the waste types into the preconditioning processor unit, the different components of the preconditioning chamber including drying unit, milling unit, and sieving unit can be automatically switched on and off depending on the type of wastes received.

The treatment system also comprises a batching chamber with sensor network and algorithm system that classify the preconditioned waste according to their chemical composition based on the waste profile stored in the preconditioning processor. The dosing processor unit in the batching chamber stores archive of various LWA formulations for different intended end applications and waste types and adopts proprietary algorithm technology to generate an optimized formulation such that the chemical composition of the final mix contains 50 % to 80 % SiO_2, 10 % to 25 % Al_2O_3, and 5 % to 30 % flux, where flux is defined as sum of mass percentages of Fe_2O_3,

K_2O, Na_2O, CaO, and MgO to satisfy viscosity requirements for LWA production. The mixture will be homogenized in the dosing and mixing unit within the batching chamber before being pelletized into particulate spheres of 1 – 15mm size in diameter in the pelletization units and pulverization unit within the granulation chamber.

Further, the treatment system consists of a furnace chamber. The different components of the furnace chamber include loading device, drying and preheating unit, microwave sintering unit, cooling unit, and unloading device. The furnace chamber also includes a furnace processor unit that stores archive of waste sintering treatment information and adopts proprietary algorithm technology to determine the best course of treatment and to execute instructions for the selection of sintering profile based on the information about the solid wastes and the end use application guidelines. This archive of information can be used to optimize the current treatment process and improve future treatment process for the incorporation of new streams of solid wastes. The furnace chamber uses a wireless sensor network system of infrared sensors and camera sensors disposed throughout the furnace chamber to measure real-time treatment process parameters such as temperature of sample, pore size development, and foaming behavior of LWA, and sends this information to the furnace processor unit to control and finetune treatment parameters, such as number of crucible boats in operation, temperature ramp up rate and temperature dwell time, lateral movement of the crucible boats, rotation of the flat circular tray within the crucible boats, and power of the microwave source, in order for the final LWA products to meet desired reuse criteria. With historical and real-time data, the proprietary algorithm expert system platform can create what-if scenarios and make automatic operational control. The furnace chamber further comprises a transmission device consisting of a moving track configured in a circular fashion and a chain of material carriers in the form of crucible boats that transport samples within the furnace chamber using roller mechanism controlled by the furnace processor unit. Lastly, a gas scrubber treatment unit is provided to remove particles and any toxic chemicals from the flue gas generated during sintering in the microwave sintering unit before the gas is released to the atmosphere.

Advantages of the invention

Other solid waste treatment systems can only treat one type of waste, or they may consist of different systems, each of which can treat one type of waste. The present invention is a universal treatment system that treats all types of solid wastes in one system, as it adopts different formulations and process conditions depending on the types of waste received and the intended end applications. In addition, typical systems treat solid wastes for landfill. The system and method described in the present invention divert the solid wastes from the landfill and enable the treated waste materials to be transformed into safe and quality LWA product that can be used in different applications including but not limited to materials for aggregates in non-structural LWC and gardening.

In addition, the integrated treatment system leverages on the intrinsic properties of solid wastes and takes advantage of the synergy of different waste material for LWA production. The dosing processor unit is programmed with database of LWA formulations and is used to formulate the mixture in such a way that the waste mixture contains the primary chemical composition necessary to produce LWA and the system requires minimal addition of chemicals and raw virgin material.

Moreover, the integrated system is a zero-waste discharge system whereby no waste or wastewater is generated, even the small quantities of LWA in the form of reject (i.e., LWA that does not comply with the specification) are returned to the preconditioning chamber as a raw material for LWA production.

The system is also very robust and fluctuations in the generation rate or characteristics of incoming feed will not compromise the product quality as the treatment system utilizes a sensor network with feedback loop to ensure compliance with set criteria. For example, the wireless sensor network system in the furnace chamber of the present invention measures treatment process parameters, such as pore formation, foaming behavior, and temperature of the sample and sends the information to the furnace processor unit to control and finetune treatment system parameters such as temperature dwell time and ramp up rate, lateral movement of the crucible boats, rotation of the flat circular tray within the crucible boats, and power of the microwave sources, to ensure that the final LWA achieves sufficient pore development and vitrification and meet applicable reuse standards.

Further, with the accumulated information and experience, the proprietary algorithm expert system of the present invention builds an LWA production library from multiple streams of solid wastes that can guide and instruct future treatments and new wastes can always be incorporated into the database of the processor unit.

With historical and real-time data, the proprietary algorithm expert system platform can create what-if scenarios, and devise optimal treatment system and process parameters to make automatic operational control. This offers multiple advantages including reduced time required for formulation and process optimization, reduced treatment operating costs (by reducing unnecessary chemical usage, excessively high sintering temperature, and unnecessarily long sintering duration, etc.), and enables non-experts to operate the treatment system.

Another novel feature of the present invention is that the furnace chamber is configured in a circular fashion such that the furnace chamber can be operated continuously as the crucible boat traverses continuously within the furnace chamber following completion of a heating cycle. Further, the remaining heat of the crucible boats can be reutilized as they traverse from the cooling unit back to the drying and preheating unit to load in a new batch of pellets. The exhaust heat from the cooling unit can also be reclaimed by the induced blower installed within the cooling unit for drying and preheating of green pellets in the drying and preheating unit of the furnace chamber and updraft drying of raw group II waste material in the drying unit of the preconditioning chamber. In addition, the moving track consists of three parallel major tracks to process three different formulations at the same time. Maximum productivity and energy efficiency can therefore be achieved in this manner.

Moreover, the chain of material carriers used in the system has a unique characteristic wherein it consists of an automatic coupler that uses a hook-and-clamp mechanism to attach and detach each crucible boat to each other easily, thereby, the coupled crucible boats are able resist horizontal bends and rotational movements in the circular configuration tracks, further, the automatic coupling allows malfunctional crucible boat to be detached from the chain independently and exit the major tracks via the minor tracks for maintenance work with minimum disruption to the system operation. Similarly, additional crucible boat can be joined easily to the chain by the automatic coupler mechanism via the minor tracks to increase the throughput of the system.

Lastly, the flue gas generated during sintering in the microwave sintering unit will be extracted and channeled to a gas scrubber treatment unit to remove particles and any toxic chemicals before it is released to the atmosphere.

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.

Figure 1 is an overview of the solid waste treatment scheme.

Figure 2 is top view showing a general configuration of the furnace chamber according to an embodiment of the invention.

Figure 3 is a sectional view showing a general configuration of the transmission device of the furnace chamber according to another embodiment of the invention.

Figure 4 is a top view showing a general configuration of the transmission device of the furnace chamber according to another embodiment of the invention.

Figure 5 is a perspective view of the transmission device of the furnace chamber according to another embodiment of the invention.

Figure 6 is a sectional view of the unloading device of the furnace chamber according to another embodiment of the invention.

Detailed description of the embodiments

Best mode for carrying out the invention

It is the main objective of the present invention to treat solid wastes including, but not limited to river sediment, WS, SS, CFA, CBA, and spent catalyst to produce LWA for reuse applications. The integrated and universal intelligent system of the present invention allows the hazardous solid wastes to be transformed into safe and high-quality LWA product as the organic pollutants are thermally decomposed by the high temperature sintering treatment while the heavy metals are safely encapsulated within the solid matrix of the LWA. The heavy metals that are immobilized by the present invention include, but are not limited to, arsenic, barium, cadmium, chromium (total), copper, nickel, lead, selenium, and zinc. Further, the LWAs possess superior characteristics such as low particle density and high crushing strength making them suitable as aggregates for multiple applications in non-structural concrete, geotechnical fill, and gardening medium.

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

a) A preconditioning chamber housing preconditioning processor unit that stores a comprehensive database of waste profile and executes appropriate precondition treatment steps; drying unit; milling unit; and sieving unit;
b) A batching chamber consisting of a sensor network and algorithm system that classify the preconditioned wastes according to their chemical composition based on the solid waste profile stored in the preconditioning processor unit; dosing and mixing unit; and dosing processor unit that processes formulations and executes instructions for selection of suitable LWA formulation based on intended end applications and compositions of the preconditioned wastes;

c) A granulation chamber consisting of pelletization-1 unit, pelletization-2 unit, and pulverization unit;
d) A furnace chamber housing loading device; drying and preheating unit; microwave sintering unit consisting of a plurality of microwave sources disposed in an array to introduce uniform electromagnetic radiation to heat up the pellets, furnace processor unit that executes instructions for the selection of treatment parameters such as number of crucible boats in operation, vertical movement of the tube device and insulation lids, sintering profiles, lateral movement of the crucible boats, rotation of the flat circular tray within the crucible boats, and power of the microwave sources, wireless sensor network system consisting of infrared sensors and camera sensors for monitoring temperatures, foaming process, and pore structure formation of the LWA and feeds the information to the furnace processor unit for treatment decision making, and a tube device for placement of insulation lids; cooling unit consisting of induced blower; transmission device consisting of a moving track configured in a circular fashion, and a chain of material carriers in the form of crucible boats which traverse in the furnace chamber using roller mechanism controlled by the furnace processor unit; unloading device consisting of a vacuum system; and gas scrubber treatment unit; and
e) An LWA product screening and grading system that classifies LWA products according to different end applications.

In the preconditioning chamber **1**, the preconditioning processor unit **2** stores a comprehensive database of waste information. The information stored include, but are not limited to particle size distribution, moisture content, and chemical composition derived from quantitative phase analysis (XRD plus Rietveld refinement). The solid waste being introduced into the preconditioning chamber **1** is classified into types I to III by the preconditioning processor unit **2** such that I is ash with moisture content <5 % and particle size <550 µm, II is sludge with moisture content 30 % to 90 % and particle size <550 µm, and III is spent catalyst with crushing strength >10 MPa and particle size distribution 10 mm to 15 mm.

Solid wastes that are too wet for optimal treatment are dried in drying unit **3**. For example, type II materials are dried to have maximum moisture content of 10 %. Type I and III materials do not require drying for the process disclosed herein.

Milling of the solid particles is done in milling unit **4** for wastes with large particle size. For example, type III materials are milled to have maximum particle size of 550 µm. As hard lumps could be formed during the drying process, type II materials also require size reduction by milling to reduce particle agglomeration after drying. Type I material does not require milling for the process disclosed herein.

Sieving of the wastes in sieving unit **5** serves to ensure that the wastes are sufficiently fine for uniform dispersal in the mixing step. Besides ensuring a homogenous mix, particle size reduction can also serve in favor of bloating through higher sintering efficiencies and better gas entrapments; it also improves compactness and compressive strength of the product. For example, type II and III materials are sieved to particle size of <550 µm. Type I material does not require sieving for the process disclosed herein.

After preconditioning, the solid wastes are sufficiently dry and fine to be mixed homogeneously for pellet preparation.

In the batching chamber **6**, the sensor network and algorithm system **7** classify the preconditioned wastes according to their chemical composition based on the solid waste profile information stored in the preconditioning processor unit **2**. The dosing processor unit **8** also stores an archive of various LWA formulations for different usage scenarios and waste types and adopts proprietary algorithm expert system technology to generate optimized formulation such that the chemical composition of the final mix contains 50 %

to 80 % SiO_2, 10 % to 25 % Al_2O_3, and 5 % to 30 % flux, where flux is defined as sum of mass percentages of Fe_2O_3, K_2O, Na_2O, CaO, and MgO to satisfy viscosity requirements for LWA production.

The sensor network and algorithm system **7** connects the dosing and mixing unit **9** to the dosing processor unit **8**. This helps the dosing processor unit **8** to automatically adjust the proportion of each waste, percentage addition of chemicals, and other process parameters. The dosing and mixing unit **9** mixes solid wastes particles homogenously with water, binder, and foaming agent in proportions of about 20 wt. % to 40 wt. %, 2 wt.% to 10 wt. %, and 5 wt.% to 20 wt. %, respectively at 150 rpm for 10 minutes, and the binders are selected from the group consisting of sodium silicate, glycerol, sodium lignosulfonate, bentonite, or combinations thereof, and foaming agents are selected from the group consisting of calcium carbonate, potassium carbonate, carbon, silicon carbide, organic solid wastes, or combinations thereof.

After the mixture is homogenized in the dosing and mixing unit **9**, the mixture will proceed to the granulation chamber **10**. The blended mixture is first fed to pelletization-1 unit **11** which agglomerates the mixture into small pellets in the range of 1 – 15 mm in diameter. The screened out undersize and oversize pellets are pulverized in the pulverization unit **13** and sent back to pelletization-1 unit **11** whereas the on-specification green pellets produced in pelletization-1 unit **11** are fed to pelletization-2 unit **12** in which the pellets are coated with a layer of aluminum oxide powder to prevent the green pellets from sticking to each other or to the crucible boat surfaces during sintering treatment in the furnace chamber **14**. The coating may or may not be necessary, depending upon the sticking tendency of the pellets, and pelletization-2 unit **12** is bypassed for formulations that do not require the surface coating. For example, in case of waste mixture of group B containing <15% Al_2O_3, the on-specification pellets are coated with a thin layer of aluminum oxide powder in pelletization-2 unit **12** and transported to the furnace chamber **14** and in case of waste mixture of group B containing >15% Al_2O_3, the pelletization-2 unit **12** is bypassed and the on-specification LWA pellets are transported directly to the furnace chamber **14**.

The on-specification pellets with or without surface coating are transported to the furnace chamber **14**. The furnace chamber **14** comprises drying and preheating unit **15**, microwave sintering unit **16**, and cooling unit **17**, separated by electromagnetic sealing doors **24**.

The green pellets are injected into the drying and preheating unit **15** of the furnace chamber **14** by a loading device **18** comprising a storage silo of green pellets, wherein a funnel from the silo extends downward with its outlet discharge ends positioned into the drying and preheating unit **15**. The silo further includes a sensor gate to control the discharge rate of pellets into the empty crucible boats **25** within the drying and preheating unit **15**.

A transmission device **21** is provided whereby a moving track **26** that extends through the furnace chamber **14** is used for conveying material from drying and preheating unit **15** to microwave sintering unit **16** and then to cooling unit **17**. The moving track **26** of the furnace chamber **14** is configured in a circular fashion such that the furnace chamber **14** can be operated continuously as the crucible boats **25** traverse continuously within the furnace chamber **14** following completion of a heating cycle. Thereby, the remaining heat of the crucible boat **25** can be reutilized as it traverses from the cooling unit **17** back to the drying and preheating unit **15** to load in a new batch of green pellets. The exhaust heat from the cooling unit **17** can also be reutilized for drying and preheating of green pellets in the drying and preheating unit **15** of the furnace chamber **14** and updraft drying of raw waste material of group II in the drying unit **3** of the preconditioning chamber **1**.

In addition, the moving track **26** consists of three parallel major tracks to process three different formulations at the same time. Each track will be set such that it produces one type of product (e.g., for gardening, for non-structural LWC, or for geotechnical fill). Maximum productivity and energy efficiency can therefore be achieved

in this manner. Further, the moving track **26** consists of minor maintenance tracks to allow malfunctioned crucible boats to exit the major tracks for maintenance work with minimum disruption to the system operation and additional crucible boats to be joined to the major tracks to improve the throughputs of the system. Each track has a series of ceramic rollers **27** mounted on a roller mechanism so that they rotate and drive the movement of the crucible boats **25**. The transmission device **21** further comprises a chain of material carriers in the form of crucible boats **25** and the movement of the crucible boat **25** through the furnace chamber **14** is achieved using roller mechanism, wherein the furnace processor unit **19** provides control signals to the ceramic rollers **27** to drive and control the lateral movement of the crucible boats **25**, and each crucible boat **25** is connected to other crucible boat **25** in series by an automatic coupler **28**, wherein the number of crucible boats **25** in operation in the furnace chamber **14** can be adjusted based on the amount of feed material and design throughput.

Each crucible boat **25** consists of a flat circular tray **29** installed within and is rotated by drive mechanism by a rotating shaft **30**. The flat circular tray **29** revolves continuously about the normal axis driven by the rotating shaft **30** which is rotated at a desired rate controlled by the furnace processor unit **19** as the crucible boat **25** traverses within the microwave sintering unit **16** to achieve homogenous sintering of the pellets.

The crucible boat **25** contains susceptors **31**, wherein said susceptor **31** has high dielectric loss at low temperatures and can absorb and transform microwave energy into heat from room temperature to its maximum use temperature, and the susceptors **31** are made of material that is selected from the group consisting of coarse grain polycrystalline beta alumina, gamma alumina oxide, silicon carbide, tantalum carbide, tungsten carbide or combinations thereof. The outside dimension of the susceptor **31** is separated from the inside dimension of the crucible boat **25**, by loose insulation **32**, in the form of alumina bubbles, zirconia bubbles, microwave transparent fiber board made of alumina fibers or combinations thereof. The loose insulation **32** remains microwave transparent throughout its useful temperature range.

The microwave sintering unit **16** of the furnace chamber **14** comprises a tunnel-shaped furnace with thermal insulation material as internal liner. Within the microwave sintering unit **16** are two elongated ceramic tubes mounted on a mechanism such that the tube device can be raised and lowered with a series of insulation lids **33** disposed on top, such that as the chain of crucible boats **25** enters the microwave sintering unit **16**, the tube device is lowered slightly for the insulation lids **33** to cover the tops of crucible boats **25** for containing and thermally insulating the LWA pellets inside. The insulation lid **33** is constructed in a manner to allow for temperature and pore structure formation monitoring of the sample within the crucible boat **25** by the wireless sensor network system **20**. Both the crucible boat **25** and insulation lid **33** are made of material selected from the group consisting of alumina, calcium oxide, zirconia, or combinations thereof, and are able to withstand high temperatures in excess of 1500^{o}C and maintain microwave transparent up to that temperature such that the cavity microwave energy is freely transmitted uniformly into the pellets through the insulating material while surface heat loss from the pellets is minimized.

At the microwave sintering unit **16**, is also a microwave power source for generating microwave radiation to activate the susceptor **31** so that the susceptor **31** can be heated by the radiation at room temperature and in turn heats the pellet until desired pore development and vitrification is achieved.

The furnace processor unit **19** is programmed with database of expansion behavior profile of different waste materials. The is done through a simulation of industrial processing so as to characterize thermal behavior and assessment of aggregate expansion. Parameters simulated includes bulk density, bloating index by means of hot-stage microscope (HSM), chemical composition of the vitreous phase inferred from quantitative phase analysis (XRD plus Rietveld refinement), and viscosity of the vitreous phase.

Wireless sensor network system **20** consisting of infrared sensors and camera sensors is provided within the microwave sintering unit **16**. The infrared sensors measure radiation from the sample and provide temperature related data and signal to the furnace processor unit **19**. Besides temperature, the wireless sensor network system **20** also consists of camera sensors that continuously monitor foaming process and pore structure formation of the LWA and feeds the information to the furnace processor unit **19**. The furnace processor unit **19** then executes instruction for the selection of treatment parameters, such as number of crucible boats **25** in operation, vertical movement of the tube device and insulation lids **33**, sintering profile, lateral movement of the crucible boats **25**, rotation of the flat circular tray **29** within the crucible boats **25**, and power of the microwave sources.

At the ceiling of the cooling unit **17** is an induced blower. Hot LWAs are cooled through a heat exchange with the air aspirated by the aspirating force of the induced blower, and the heat aspirated by the induced blower is recycled to the drying and preheating unit **15** and drying unit **3**. In this way, heat in the furnace chamber **14** is utilized effectively through recirculation.

At the ceiling of the outlet end of the cooling unit **17** is also an unloading device **22** consisting of vacuum system **34** with suction pipe **35** and a round suction nozzle **36**. The suction nozzle **36** having corresponding diameter as the flat circular tray **29** within the crucible boat **25** covers the flat circular tray **29** fully to suck and draw off the sintered and cooled LWA out of the crucible boat **25** and pumps them into a conveying line.

Downstream of the cooling unit **17** is a vibrating sieve for separating the LWA products into different particle sizes. LWA with particle size smaller than 1mm will be rejected and be sent back to the milling unit **4** of the preconditioning chamber **1** as raw materials for LWA production. An LWA product screening and grading system **23** classifies the LWA according to different end applications. The classified LWA products are stored in their respective storage silo and are discharged to a transport means such as truck whenever necessary and are transported outside the system.

Lastly, a gas scrubber treatment unit removes particles and any toxic chemicals from the flue gas generated during sintering in the microwave sintering unit **16** before the gas is released to the atmosphere.

Examples

Example 1: Transformation of river sediment and coal fly ash into LWA

Representative contaminated sediment sample and CFA sample were collected from a rural river and a coal power plant respectively. The preconditioning processor unit was switched on for keying in the waste type. According to the guidelines from the proprietary algorithm expert system, the drying unit, milling unit, and sieving unit were automatically switched on for river sediment. For CFA, preconditioning steps were bypassed. For drying of river sediment, the temperature was 55ºC and the drying duration was 24 hours. For crushing of river sediment, the rotating speed was 250 rpm, and the crushing duration was 3 minutes. In the batching chamber, the sensor network and algorithm system classified the wastes according to their chemical composition and feedback to the dosing processor unit. As the operator wished to use the LWA in non-structural concrete application, the dosing processor unit chose the formulation based on the requirement and according to the proprietary algorithm expert system platform, 15 w.% river sediment and 85 wt.% CFA were mixed homogenously together with an amount of 8 wt.% water and 5 wt. % sodium silicate based on the total dry weight of river sediment and CFA for 15 minutes at 150 rpm. After which, the mixtures were pelletized in the pelletization-1 unit in the granulation chamber for 20 minutes at 30 rpm, during which 25 wt.% of water was added as a fine spray. The on-specification pellets with particle size between 1 – 15 mm were then transported

to pelletization-2 unit to coat with a thin layer of aluminum oxide powder before being conveyed to the furnace chamber. The green pellets are injected onto the crucible boats for drying and preheating at 200ºC for 20 minutes. The oven-dried pellets are then conveyed to the microwave sintering unit by roller mechanism and are covered with insulation lids. As the operator wished to use the LWA in non-structural concrete application, the furnace processor unit chose the sintering profile based on the requirement and the dried pellets undergo microwave sintering treatment at 30ºC/min ramp up rate to 1100ºC. The flat circular trays within the crucible boats revolve continuously for homogenous heating of the pellets by the microwave source. The temperature, pore structure formation, and foaming process were continuously monitored by the wireless sensor network system and the dwell time of the sintering treatment was extended from 10 to 15 minutes. At the end, LWA products with porous structure and low density were obtained upon cooling.

The untreated river sediment and CFA, and LWA product were subjected to leaching and analytical tests to verify the treatment efficiency. The employed leaching test method was a batch leaching method that is specified in British Standard EN12457-1:2022 (British Standards Institution). The leachates were analyzed, as described in Standard Methods for the Examination of Water and Wastewater that is published by the American Public Health Association (APHA), by inductively coupled plasma-optical emission spectrometry (ICP-OES) for metals and metalloids including arsenic, barium, cadmium, chromium (total), copper, nickel, lead, selenium, and zinc. pH and specific electrical conductivity (E.C.) measures of the LWA were also performed following the APHA standards. Further, the LWA products were subjected to single aggregate crushing strength using a universal testing machine wherein each individual granule was crushed to failure using a press. In addition, the 24-hour water absorption and oven-dried particle density of the LWA products were determined based on the established procedure described in British Standard EN 1097- 6: 2013 (Annex C) standards (British Standards Institution). Moreover, diameters of the LWAs before and after sintering expressed in terms of bloating index were recorded. Mean values of the results of the experiments conducted on a plurality of LWA products were used as the data for the 24-hour water absorption, single aggregate crushing strength, oven-dried particle density and bloating index. All testing results were inputted to the processing unit.

As shown in Table 1, concentrations of all contaminants decreased after treatment with the system and process described herein and the concentrations could meet the Danish WtR standard. The 24-hours water absorption, single aggregate crushing strength, oven-dried particle density, bloating index, and E.C. were 1.08 %, 5.51 MPa, 0.98 g/cm^3, 1.4, and 1.6 mS/cm respectively. The LWA product was classified to be suitable for non-structural concrete application and was sent to a precast concrete company for manufacturing of LWC prototypes.

Table 1: Leaching outcome of river sediment and coal fly ash

Contaminants	**Test method**	**Danish WtR Standard (Cat3) (mg/kg)**	**River sediment (mg/kg)**	**CFA (mg/kg)**	**LWA (mg/kg)**
Arsenic	APHA 3120B	0.45	0.0645	ND	ND
Barium		24	3.9799	0.4949	0.28
Cadmium		0.13	0.0546	0.0059	ND
Chromium (total)		2.8	ND	1.1593	ND
Copper		9	0.0846	0.0357	ND
Nickel		0.3	0.0066	ND	ND
Lead		0.45	ND	0.2547	0.03
Selenium		0.11	ND	0.1255	ND
Zinc		6.6	ND	0.0319	ND

Abbreviations – ND, non-detectable.

Example 2: Transformation of wastewater treatment sludge and sewage sludge into LWA

Representative WS sample and SS sample were collected from a semiconductor plant and a petrochemical wastewater treatment plant respectively. The preconditioning processor unit was switched on for keying in the waste type. According to the guidelines from the proprietary algorithm expert system, the drying unit, milling unit, and sieving unit were automatically switched on for WS and SS. For drying of WS and SS, the temperature was 55^{o}C and the drying duration was 24 hours. For crushing of WS and SS, the rotating speed was 250 rpm, and the crushing duration was 3 minutes. In the batching chamber, the sensor network and algorithm system classified the wastes according to their chemical composition and feedback to the dosing processor unit. As the operator wished to use the LWA in gardening application, the dosing processor unit chose the formulation based on the requirement and according to the proprietary algorithm expert system platform, 65 wt.% WS and 35 wt.% SS were mixed homogenously together with an amount of 10 wt.% water and 7 wt.% sodium lignosulfonate based on the total dry weight of WS and SS for 15 minutes at 150 rpm. The mixtures were then pelletized in the pelletization-1 unit in the granulation chamber for 15 minutes, during which 27 wt.% of water was added as a fine spray. The on-specification pellets with particle size between 1 – 15 mm were transported to the furnace chamber for drying and preheating at 200^{o}C for 20 minutes. As the operator wished to use the LWA in gardening application, the furnace processor unit chose the sintering profile based on the requirement and the dried pellets undergo microwave sintering treatment at 30^{o}C/min ramp up rate to 1000^{o}C. The temperature, pore structure formation, and foaming process were continuously monitored by the wireless sensor network system and the dwell time of the sintering treatment was reduced from 15 to 10 minutes. LWAs with porous structure and low density were obtained on cooling.

The untreated WS and SS, and LWA product were subjected to leaching and analytical tests to verify the treatment efficiency. The leaching characterization method was BS EN12457-1:2022. The leachates were analyzed by ICP-OES for metals and metalloids including arsenic, barium, cadmium, chromium (total), copper, nickel, lead, selenium, and zinc. The LWA products were also tested for pH and E.C. following APHA standards and subjected to single aggregate crushing strength using a universal testing machine. In addition, the 24-hours water absorption and oven-dried particle density of the LWA products were determined based on the BS EN 1097- 6: 2013 (Annex C). Moreover, diameters of the LWAs before and after sintering expressed in terms of bloating index were recorded. All testing results were inputted to the processing unit.

As shown in Table 2, concentrations of all contaminants decreased after treatment with the system and process described herein and the concentrations could meet the Danish WtR standard. The 24-hours water absorption, single aggregate crushing strength, oven-dried particle density, bloating index, and E.C. were 27.4 %, 1.03 MPa, 1.21g/cm^{3}, 1.1, and 1 mS/cm respectively. The LWA product was classified to be suitable for gardening applications.

The LWA produced was used as gardening media to grow potted *Epipremnum aureum* sp., and the chlorophyll contents of the leaves were measured weekly over a span of 6 weeks using a SPAD- 502 Plus portable chlorophyll meter for fast on-site non-destructive diagnosis. The 6 weeks monitoring showed promising results where positive percentage growth (5.22 %) expressed in terms of the increase in chlorophyll concentration was observed. Although the result was less significant than the percentage growth observed in the plant grown in soil (11.6 %) and Leca (9.2 %), the result was still encouraging, and it highlights the potential of the LWA as a partial or even full replacement for traditional medium used in the gardening industry.

Table 2: Leaching outcome of wastewater treatment sludge and sewage sludge

Contaminants	Test method	Danish WtR Standard (Cat3) (mg/kg)	WS (mg/kg)	SS (mg/kg)	LWA (mg/kg)
Arsenic	APHA 3120B	0.45	0.0727	1.398	ND
Barium		24	0.0401	0.0636	0.039
Cadmium		0.13	0.0054	ND	ND
Chromium (total)		2.8	0.0319	ND	0.01
Copper		9	0.0173	0.4844	ND
Nickel		0.3	ND	ND	ND
Lead		0.45	ND	ND	ND
Selenium		0.11	0.1865	ND	ND
Zinc		6.6	0.0170	ND	ND

Abbreviations – ND, non-detectable.

Example 3: Transformation of coal bottom ash and spent catalyst into LWA

Representative CBA sample and spent catalyst sample were collected from a coal burning power plant and a petrochemical plant, respectively. The preconditioning processor unit was switched on for keying in the waste type. According to the guidelines from the proprietary algorithm expert system, the milling unit and sieving unit were automatically switched on for spent catalyst. For CBA, preconditioning steps were bypassed. For crushing of spent catalyst, the rotating speed was 450 rpm, and the crushing duration was 5 minutes. In the batching chamber, the sensor network and algorithm system classified the wastes according to their chemical composition and feedback to the dosing processor unit. As the operator wished to use the LWA in non-structural concrete application, the dosing processor unit chose the formulation based on the requirement and according to the proprietary algorithm expert system platform, 80 wt. % CBA and 20 wt.% spent catalyst were mixed homogenously together with an amount of 8 wt.% water, 6 wt.% glycerol, and 10 wt.% carbon based on the total dry weight of CBA and spent catalyst for 15 minutes at 150 rpm. The mixtures were then pelletized in the pelletization-1 unit in the granulation chamber for 15 minutes, during which 35 wt. % of water was added as a fine spray. The on-specification pellets with particle size between 1 – 15 mm were transported to the furnace chamber for drying and preheating at 250^{o}C for 15 minutes. As the operator wished to use the LWA in non-structural concrete application, the furnace processor unit chose the sintering profile based on the requirement and the dried pellets underwent microwave sintering treatment at 35^{o}C/min ramp up rate to 1100^{o}C. The temperature, pore structure formation, and foaming process were continuously monitored by the wireless sensor network system and the dwell time of the sintering treatment was set at 15 minutes. LWAs with porous structure and low density were obtained on cooling.

The untreated CBA and spent catalyst, and LWA product were subjected to leaching and analytical tests based on BS EN12457-1:2022 to verify the treatment efficiency. The leachates were analyzed by ICP-OES for metals and metalloids including arsenic, barium, cadmium, chromium (total), copper, nickel, lead, selenium, and zinc. The LWA products were also tested for pH and E.C. following APHA standards and subjected to single aggregate crushing strength using a universal testing machine. In addition, the 24-hours water absorption and oven-dried particle density of the LWA products were determined based on the BS EN 1097- 6: 2013 (Annex C). Moreover, diameters of the LWAs before and after sintering expressed in terms of bloating index were recorded. All testing results were inputted to the processing unit.

As shown in Table 3, concentrations of all contaminants decreased after treatment with the system and process described herein and the concentrations could meet the Danish WtR standard. The 24-hours water absorption, single aggregate crushing strength, oven-dried particle density, bloating index, and E.C. were 5.6 %, 2.4 MPa, 0.96 g/cm^3, 1.05, and 1.72 mS/cm respectively. The LWA product was classified to be suitable for non-structural concrete applications.

Table 3: Leaching outcome of coal bottom ash and spent catalyst

Contaminants	**Test method**	**Danish WtR Standard (Cat3) (mg/kg)**	**CBA (mg/kg)**	**Spent catalyst (mg/kg)**	**LWA by microwave sintering (mg/kg)**	**LWA by electric muffle furnace sintering (mg/kg)**
Arsenic	APHA 3120B	0.45	0.0731	0.2170	ND	ND
Barium		24	0.6636	0.0146	0.39	0.55
Cadmium		0.13	0.0053	0.0074	ND	0.22
Chromium (total)		2.8	0.0427	0.0270	0.08	0.10
Copper		9	0.0176	0.1457	ND	ND
Nickel		0.3	ND	ND	0.03	0.05
Lead		0.45	ND	ND	0.06	0.10
Selenium		0.11	0.0141	ND	ND	ND
Zinc		6.6	0.0257	0.0435	ND	ND

Abbreviations – ND, non-detectable.

The pellets produced using CBA and spent catalyst were also sintered using an electric muffle furnace to compare the treatment efficiency with the microwave sintering design of this patent. As shown in Table 3, concentrations of all contaminants decreased after treatment with the system and process described in this patent and the concentrations could meet the Danish WtR standard. However, when using the conventional electric muffle furnace, the concentration of cadmium could not meet the Danish WtR standard. In addition, when sintered at the same temperature, the sintering duration of the electric muffle furnace was extended from 1 hour to 2 hours as the LWA was sintered at a slower heating rate of 10^{o}C/min in order to achieve full vitrification. As such, it can be seen how microwave sintering has a faster sintering rate which enhances the overall energy efficiency of the system.

Example 4: Transformation of coal fly ash and wastewater treatment sludge into LWA

Representative CFA sample and WS sample were collected from a coal burning power plant and a semiconductor plant respectively. The preconditioning processor unit was switched on for keying in the waste type. According to the guidelines from the proprietary algorithm expert system, the drying unit, milling unit, and sieving unit were automatically switched on for WS. For CFA, preconditioning steps were bypassed. For drying of WS, the temperature was 55^{o}C and the drying duration was 24 hours. For crushing of WS, the rotating speed was 250 rpm, and the crushing duration was 3 minutes. In the batching chamber, the sensor network and algorithm system classified the wastes according to their chemical composition and feedback to the dosing processor unit. As the operator wished to use the LWA in geotechnical application, the dosing processor unit chose the formulation based on the requirement and according to the proprietary algorithm expert system platform, 30 wt.% CFA and 70 wt.% WS were mixed homogenously together with an amount of 9 wt.% water, 6 wt.% sodium silicate, and 10 wt.% calcium carbonate based on the total dry weight of CFA and WS for 15 minutes at 150 rpm. The mixtures were then pelletized in the pelletization-1 unit in the granulation chamber for 15 minutes, during which

30 wt.% of water was added as a fine spray. The on-specification pellets with particle size between 1 – 15 mm were transported to the furnace chamber for drying and preheating at 200^{o}C at 20 minutes. As the operator wished to use the LWA in geotechnical application, the furnace processor unit chose the sintering profile based on the requirement and the dried pellets undergo microwave sintering treatment at 30^{o}C/min ramp up rate to 1000^{o}C. The temperature, pore structure formation and foaming process were continuously monitored by the wireless sensor network system and the dwell time of the sintering treatment was set at 10 minutes. LWA with porous structure and low density were obtained on cooling.

The untreated CFA, WS, and LWA product were subjected to leaching and analytical tests to verify the treatment efficiency. The leaching characterization method was BS EN12457-1:2022. The leachates were analyzed by ICP-OES for metals and metalloids including arsenic, barium, cadmium, chromium (total), copper, nickel, lead, selenium, and zinc. The LWA products were also tested for pH and E.C. following APHA standards and subjected to single aggregate crushing strength using a universal testing machine. In addition, the 24-hours water absorption and oven-dried particle density of the LWA products were determined based on the BS EN 1097- 6: 2013 (Annex C). Moreover, diameters of the LWAs before and after sintering expressed in terms of bloating index were recorded. All testing results were inputted to the processing unit.

As shown in Table 4, concentrations of all contaminants decreased after treatment with the system and process described herein and the concentrations could meet the Danish WtR standard. The 24-hours water absorption, single aggregate crushing strength, oven-dried particle density, bloating index and E.C. of the LWA were 11.7 %, 2.4 MPa, and 1.24 g/cm^3, 1.1, and 1.6 mS/cm respectively. The LWA product was classified to be suitable for geotechnical applications.

Table 4: Leaching outcome of coal fly ash and wastewater treatment sludge

Contaminants	**Test method**	**Danish WtR Standard (Cat3) (mg/kg)**	**CFA (mg/kg)**	**WS (mg/kg)**	**LWA with rotation of tray (mg/kg)**	**LWA without rotation of tray (mg/kg)**
Arsenic	APHA 3120B	0.45	ND	0.0727	ND	ND
Barium		24	0.4949	0.0401	ND	ND
Cadmium		0.13	0.0059	0.0054	0.0038	0.1700
Chromium(total)		2.8	1.1593	0.0319	0.0401	0.0700
Copper		9	0.0357	0.0173	ND	ND
Nickel		0.3	ND	ND	ND	0.1
Lead		0.45	0.2547	ND	ND	ND
Selenium		0.11	0.1255	0.1865	ND	ND
Zinc		6.6	0.0319	0.0170	ND	ND

Abbreviations – ND, non-detectable.

Sintering treatment was also performed without rotating the flat circular tray within the crucible boat. Without the revolution of the tray, treatment efficiency decreased compared to when the tray was revolved continuously, and concentration of cadmium could not meet the Danish WtR standard. This was due to inhomogeneous sintering of the LWA by the microwave radiation, therefore, it highlights the importance of the flat circular tray feature in this patent.

Example 5: Transformation of coal bottom ash and river sediment into LWA

Representative contaminated sediment sample and CBA sample were collected from a rural river and a coal burning power plant respectively. The preconditioning processor unit was switched on for keying in the waste type. According to the guidelines from the proprietary algorithm expert system, the drying unit, milling unit, and sieving unit were automatically switched on for river sediment. For CBA, preconditioning steps were bypassed. For drying of river sediment, the temperature was 55^{o}C and the drying duration was 24 hours. For crushing of river sediment, the rotating speed was 250 rpm, and the crushing duration was 3 minutes. In the batching chamber, the sensor network and algorithm system classified the wastes according to their chemical composition and feedback to the dosing processor unit. As the operator wished to use the LWA in gardening application, the dosing processor unit chose the formulation based on the requirement and according to the proprietary algorithm expert system platform, 20 w.% river sediment and 80 wt.% CBA were mixed homogenously together with an amount of 12 wt.% water and 5 wt.% sodium silicate based on the total dry weight of river sediment and CBA for 15 minutes at 150 rpm. After which, the mixtures were pelletized in the pelletization-1 unit in the granulation chamber for 20 minutes at 30 rpm, during which 25 wt.% of water was added as a fine spray. The on-specification pellets with particle size between 1 – 15 mm were then transported to the furnace chamber. Due to increase in feed material supply, five additional crucible boats were attached to the chain of material carriers to increase the throughputs of the furnace chamber. The green pellets were dried and preheated at 200^{o}C for 20 minutes. As the operator wished to use the LWA in gardening application, the furnace processor unit chose the sintering profile based on the requirement and the dried pellets undergo microwave sintering treatment at 30^{o}C/min ramp up rate to 1000^{o}C. The temperature, pore structure formation, and foaming process were continuously monitored by the wireless sensor network system and the dwell time of the sintering treatment was set at 12 minutes. At the end, LWA products with porous structure and low density were obtained upon cooling.

The untreated CBA and river sediment, and LWA product were subjected to leaching and analytical tests to verify the treatment efficiency. The leaching characterization method was BS EN12457-1:2022. The leachates were analyzed by ICP-OES for metals and metalloids including arsenic, barium, cadmium, chromium (total), copper, nickel, lead, selenium, and zinc. The LWA products were also tested for pH and E.C. following APHA standards and subjected to single aggregate crushing strength using a universal testing machine. In addition, the 24-hours water absorption and oven-dried particle density of the LWA products were determined based on the BS EN 1097- 6: 2013 (Annex C). Moreover, diameters of the LWAs before and after sintering expressed in terms of bloating index were recorded. All testing results were inputted to the processing unit.

As shown in Table 5, concentrations of all contaminants decreased after treatment with the system and process described herein and the concentrations could meet the Danish WtR standard. The 24-hours water absorption, single aggregate crushing strength, oven-dried particle density, bloating index and E.C. were 25.2 %, 2.87 MPa, 1.36 g/cm^3, 1.1, and 1.34 mS/cm respectively. The LWA product was classified to be suitable for gardening applications.

Table 5: Leaching outcome of coal bottom ash and river sediment

Contaminants	Test method	Danish WtR Standard (Cat3) (mg/kg)	CBA (mg/kg)	River sediment (mg/kg)	LWA (mg/kg)
Arsenic	APHA 3120B	0.45	0.0731	0.0645	ND
Barium		24	0.6636	3.9799	ND
Cadmium		0.13	0.0053	0.0546	0.008
Chromium(total)		2.8	0.0427	ND	ND
Copper		9	0.0176	0.0846	ND
Nickel		0.3	ND	0.0066	0.01
Lead		0.45	ND	ND	ND
Selenium		0.11	0.0141	ND	ND
Zinc		6.6	0.0257	ND	ND

Abbreviations – ND, non-detectable.

Example 6: Transformation of sewage sludge and spent catalyst into LWA

Representative SS sample and spent catalyst sample were collected from a petrochemical plant. The preconditioning processor unit was switched on for keying in the waste type. According to the guidelines from the proprietary algorithm expert system, the drying unit, milling unit, and sieving unit were automatically switched on for SS. For spent catalyst, the milling unit and sieving unit were automatically switched on while the drying unit was bypassed. For drying of SS, the temperature was 55ºC and the drying duration was 24 hours. For crushing of SS, the rotating speed was 250 rpm, and the crushing duration was 3 minutes. For crushing of spent catalyst, the rotating speed was 450rpm and the crushing duration was 5 minutes. In the batching chamber, the sensor network and algorithm system classified the wastes according to their chemical composition and feedback to the dosing processor unit. As the operator wished to use the LWA in geotechnical application, the dosing processor unit choose the formulation based on the requirement and according to the proprietary algorithm expert system platform, 35 wt.% spent catalyst and 65 wt.% SS was mixed homogenously together with an amount of 9 wt.% water and 8 wt.% sodium silicate based on the total dry weight of WS and spent catalyst for 15 minutes at 150 rpm. The mixtures were then pelletized in the pelletization-1 unit in the granulation chamber for 15 minutes, during which 35 wt.% of water was added as a fine spray. The on-specification pellets with particle size between 1 – 15 mm were transported to the furnace chamber for drying and preheating at 200ºC at 20 minutes. As the operator wished to use the LWA in geotechnical application, the furnace processor unit choose the sintering profile based on the requirement and the pellets undergo microwave sintering treatment at 35ºC/min ramp up rate to 1025ºC. The temperature, pore structure formation, and foaming process were continuously monitored by the wireless sensor network system and the dwell time of the sintering treatment was set at 10 minutes. LWAs with porous structure and low density were obtained on cooling.

The untreated SS and spent catalyst, and LWA product were subjected to leaching and analytical tests to verify the treatment efficiency. The leaching characterization method was BS EN12457-1:2022. The leachates were analyzed by ICP-OES for metals and metalloids including arsenic, barium, cadmium, chromium (total), copper, nickel, lead, selenium, and zinc. The LWA products were also tested for pH and E.C. following APHA standards and subjected to single aggregate crushing strength using a universal testing machine. In addition, the 24-hours water absorption and oven-dried particle density of the LWA products were determined based on the BS EN 1097- 6: 2013 (Annex C). Moreover, diameters of the LWAs before and after sintering expressed in terms of bloating index were recorded. All testing results were inputted to the processing unit.

As shown in Table 6, concentrations of all contaminants could meet the Danish WtR standard. The 24-hours water absorption, single aggregate crushing strength, oven-dried particle density, bloating index and E.C. of the LWA were 9.4 %, 3.02 MPa, and 1.32 g/cm^3, 1.01, and 1.5 mS/cm respectively. The testing results were inputted into the product screening and grading system. The LWA product was classified to be suitable for geotechnical applications.

Table 6: Leaching outcome of sewage sludge and spent catalyst

Contaminants	**Test method**	**Danish WtR Standard (Cat3) (mg/kg)**	**SS (mg/kg)**	**Spent catalyst (mg/kg)**	**LWA (mg/kg)**
Arsenic	APHA 3120B	0.45	1.398	0.2170	ND
Barium		24	0.0636	0.0146	ND
Cadmium		0.13	ND	0.0074	0.0015
Chromium (total)		2.8	ND	0.0270	ND
Copper		9	0.4844	0.1457	ND
Nickel		0.3	ND	ND	ND
Lead		0.45	ND	ND	ND
Selenium		0.11	ND	ND	ND
Zinc		6.6	ND	0.0435	0.08

Abbreviations – ND, non-detectable.

Claims

The claims of system and method for lightweight aggregate produced from multiple streams of industrial solid wastes are as follows.

1. An integrated and universal intelligent system that uses industrial solid wastes to produce lightweight aggregate comprising the following components:

(a) A preconditioning chamber consisting of:

A preconditioning processor unit that stores a comprehensive database of waste profile archiving waste information such as waste generation rate, particle size distribution, moisture content, and chemical composition, and built-in computing capabilities to store and execute instructions for selection of suitable pretreatment steps based on information about solid wastes to precondition the wastes before their incorporation into formulation for lightweight aggregate production;

A drying unit;

A milling unit; and

A sieving unit;

(b) A batching chamber consisting of:

A sensor network and algorithm system that classify the preconditioned wastes according to their chemical compositions, waste database of which is stored in the preconditioning processor unit;

A dosing and mixing unit; and

A dosing processor unit with built-in computing capabilities to store formulations and execute instructions for selection of suitable lightweight aggregate formulation based on intended end applications and compositions of the preconditioned wastes to ensure that chemical composition of the waste mixture adheres to a predetermined criterion to satisfy mineralogical requirements for lightweight aggregate production;

(c) A granulation chamber consisting of a pelletization-1 unit, a pelletization-2 unit, and a pulverization unit;

(d) A furnace chamber consisting of:

A drying and preheating unit;

A loading device comprising a storage silo of green pellets that has a funnel from a silo extending downward with outlet discharge ends positioned into the drying and preheating unit and a sensor gate;

A microwave sintering unit consisting of:

A tunnel-shaped furnace with thermal insulation material as internal liner;

A plurality of microwave sources disposed in an array within cavity body of the microwave sintering unit to introduce uniform electromagnetic radiation to heat up lightweight aggregate pellets;

A furnace processor unit that executes instructions for selection of treatment parameters, such as number of crucible boats in operation, vertical movement of tube device and insulation lids, sintering profiles, lateral movement of the crucible boats through the furnace chamber, rotation of flat circular tray within crucible boats, and microwave power;

A wireless sensor network system consisting of infrared sensors and camera sensors that monitor temperatures of lightweight aggregate samples, foaming process, and pore structure formation of the lightweight aggregate, and feeds such information to the furnace processor unit for treatment decision making; and

A tube device consisting of two elongated ceramic tubes with a series of insulation lids disposed on top, wherein the tube device is mounted on a mechanism such that it can be raised and lowered and controlled by the furnace processor unit, such that the insulation lids cover tops of crucible boats for containing and thermally insulating lightweight aggregate pellets inside, wherein the insulation lids are constructed in a manner to allow for temperature, foaming and pore structure formation monitoring of the lightweight aggregate pellets by the wireless sensor network system, and the insulation lid material is transparent to microwaves such that cavity microwave energy is freely transmitted uniformly into lightweight aggregate pellets through insulating material while surface heat loss from the lightweight aggregate pellets is minimized, and the insulation lids are made of material that is selected from the group consisting of alumina, calcium oxide, zirconia, or combinations thereof;

A cooling unit consisting of an induced blower located at the ceiling, wherein hot lightweight aggregates are cooled through a heat exchange with air aspirated by aspirating force of the induced blower, and the heat aspirated by the induced blower is recycled to the drying and preheating unit of the furnace chamber and drying unit of the preconditioning chamber such that waste heat in the furnace chamber is utilized efficiently through recirculation;

A transmission device extending through the furnace chamber consisting of:

A moving track that:

Transports lightweight aggregate within the furnace chamber, wherein the moving track is configured in circular shape in cross section perpendicular to its longitudinal direction,

Has a series of ceramic rollers mounted on a mechanism so that they can rotate and drive movement of crucible boats,

Has three parallel major tracks to process three different lightweight aggregate products at the same time, wherein the three major tracks operate independently of one another and adopt different treatment conditions, and

Has three horizontal minor tracks to allow crucible boats to exit the major tracks for maintenance work with minimum disruption to furnace operation and additional crucible boat to join the major tracks to improve system throughput;

A chain of material carriers wherein:

Material carriers are crucible boats that have dimensions approximately 1000 mm in length, 1000 mm in width, and 300 mm in height, and wherein movement of the crucible boats is controlled by the furnace processor unit through a roller mechanism;

The chain has each crucible boat connected to one another in series by an automatic coupler controlled by the furnace processor unit, wherein treatment capacity of the furnace chamber can be adjusted by controlling number of functioning crucible boats;

The chain has each crucible boat made of material selected from the group consisting of alumina, calcium oxide, zirconia, or combinations thereof;

The chain has each crucible boat with a flat circular tray installed within that revolves continuously about normal axis driven by a rotating shaft for homogenous sintering of the lightweight aggregate pellets, wherein rate of revolution of the flat circular tray is controlled by the furnace processor unit; and

The chain has each crucible boat containing susceptors, wherein each said susceptor has high dielectric loss at low temperatures and can absorb and transform microwave energy into heat from room temperature to its maximum use temperature, and the susceptors are made of material that is selected from the group consisting of coarse grain polycrystalline beta alumina, gamma alumina oxide, silicon carbide, tantalum carbide, tungsten carbide or combinations thereof, wherein outside dimension of the susceptor is separated from the inside dimension of the crucible boat, by a loose insulation, in the

form of alumina bubbles, zirconia bubbles, or microwave-transparent fiber board made of alumina fibers;

Electromagnetic sealing doors as microwave barriers that are made of heat-resistant stainless steel, titanium carbide, and lanthanum chromate at inlet and at outlet ends of the microwave sintering unit to minimize leakage of microwave energy, wherein the electromagnetic sealing doors for the three major tracks operate independently of one another as the three major tracks adopt different treatment conditions and have different residence time in the microwave sintering unit;

An unloading device consisting of a vacuum system with suction pipes to suck and draw off air-cooled lightweight aggregate pellets out of the crucible boats and pump them into a conveying line of discharge hopper;

A gas scrubber treatment unit to remove particles and any toxic chemicals from flue gas generated during sintering in the microwave sintering unit before gas is released to the atmosphere; and

A vibrating sieve at downstream of the cooling unit to separate lightweight aggregates into different particle sizes; and

(e) A lightweight aggregate product screening and grading system that classifies lightweight aggregate products according to different end applications based on lightweight aggregate products' chemical and physical properties.

2. An integrated and universal intelligent lightweight aggregate production method using the system of claim 1 comprising the following steps:

(a) Preconditioning of waste;

(b) Mixing of waste;

(c) Pelletizing of waste mixture;

(d) Sintering of pellets further consisting of the steps of:

Green pellets are injected onto crucible boats by the loading device;

The green pellets gradually advance within the drying and preheating unit of claim 1 (d) along the moving track for drying and preheating at a temperature between 200°C to 250°C for 15 to 20 minutes;

Movement of crucible boat and pellet sample contained within is achieved by the roller mechanism of claim 1 (d);

When lightweight aggregate pellets travel from the drying and preheating unit into the microwave sintering unit, the tube device of claim 1 (d) is lowered such that the insulation lids disposed on top of the tube device can enclose the pellets and the crucible boats;

After closing the electromagnetic sealing doors of claim 1 (d), the microwave sources are turned on;

Lightweight aggregate pellets are sintered at sintering profile selected from database stored in the furnace processor unit;

Flat circular trays within the crucible boats revolve for homogenous heating of the pellets by the microwave sources by controlling rotation speed of the rotating shaft of claim 1 (d);

Foaming process and pore structure formation of the lightweight aggregate and the temperatures of the samples are continuously monitored by the wireless sensor network system of claim 1 (d) and provide signal feedback to the furnace processor unit such that treatment parameters such as sintering profiles, rotation of the flat circular trays within the crucible boats, and power of the microwave sources of claim 1 (d) are automatically adjusted;

After sintering run is completed, the microwave sources are turned off, the flat circular trays within the crucible boats stop revolving, and the tube device is raised to uncover the crucible boats;

The electromagnetic sealing doors of claim 1 (d) is activated and the crucible boats holding the sintered lightweight aggregates traverse out of the microwave sintering unit;

The resulting lightweight aggregates follow the moving track to the horizontally adjoining, but functionally separate, cooling unit of claim 1 (d) to cool the lightweight aggregate down to room temperature via the induced blower located at the ceiling of the cooling unit of claim 1 (d); and

The lightweight aggregates are vacuumed by the vacuum system;

(e) Screening and grading of lightweight aggregate.

3. The method of integrated and universal intelligent lightweight aggregate production of claims 2 wherein for the preconditioning step of claim 2 (a):

Moisture content and particle size of solid waste are determined, and solid waste is classified using the preconditioning processor unit of claim 1 (a) into groups I, II, and III such that:

I is ash such as incineration fly ash, coal fly ash or coal bottom ash with moisture content <5% and particle size <550 μm;

II is sludge or sediment such as sewage sludge, river sediment, biological sludge, wastewater treatment sludge with moisture content 30% to 90% and particle size <550 μm; and

III is spent catalyst with crushing strength >10MPa and particle size distribution 10 mm to 15 mm.

4. The method of integrated and universal intelligent lightweight aggregate production of claim 3 wherein for the preconditioning step of claim 2 (a) the drying unit of claim 1 (a) of the preconditioning chamber dries solid waste material by warm exhaust gas from the cooling unit of claim 1 (d) of the furnace chamber for group II and that is switched off for groups I and III.

5. The method of integrated and universal intelligent lightweight aggregate production of claims 3 to 4 wherein for the preconditioning step of claim 2 (a) the milling unit of claim 1 (a) mills solid wastes to particle size <550 µm and rotating speed of the milling unit is 450 rpm for group III, and 250 rpm for group II, and the milling unit is switched off for group I.

6. The method of integrated and universal intelligent lightweight aggregate production of claims 3 to 5 wherein for the preconditioning step of claim 2 (a) the sieving unit of claim 1 (a) sieves solid waste particles of group II and III to particle size <550 µm and the sieving unit is bypassed for group I.

7. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 6 wherein for the mixing step of claim 2 (b) the dosing processor unit of claim 1 (b) stores an archive of various lightweight aggregate formulations for different usage scenarios and waste types and adopts proprietary algorithm technology to generate optimized formulations and uses the sensor network and algorithm system of claim 1 (b) to adjust chemical composition of fine particles passing through the sieving unit of claim 1 (a) such that chemical composition of final mix with particle size <550 µm contains 50 % to 80 % SiO_2, 10 % to 25 % Al_2O_3, and 5 % to 30 % flux, where flux is defined as sum of mass percentages of Fe_2O_3, K_2O, Na_2O, CaO, and MgO.

8. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 7 wherein for the mixing step of claim 2 (b) the dosing processor unit of claim 1 (b) automatically adjusts proportion of each waste, percentage addition of chemicals, mixing speed, and mixing duration such that wastes are mixed and homogenized with water, binder, and foaming agent inside the dosing and mixing unit of claim 1 (b) at 150 rpm for 10 minutes wherein water, binder, and foaming agent are mixed in the proportions of about 20 wt.% to 40 wt.%, 2 wt.% to 10 wt.%, and 5 wt.% to 20 wt. % , respectively, and the binder is selected from the group consisting of sodium silicate, glycerol, sodium lignosulfonate, bentonite, or combinations thereof and foaming agent is selected from the group consisting of calcium carbonate, potassium carbonate, carbon, silicon carbide, organic solid wastes, or combinations thereof.

9. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 8 wherein for the pelletizing step of claim 2 (c) mixture from the dosing and mixing unit of claim 1 (b) is shaped into particulate spheres using the pelletization-1 unit of claim 1 (c) and lightweight aggregate pellets so formed from mixed material on pelletizing disc are discharged over rim of disc into the vibrating sieve via a self-classifying effect into groups of A, B, and C such that:

A is undersize pellets that have particle size <1 mm;

B is on-specification pellets that have particle size 1 to 15 mm; and

C is oversize pellets that have particle size >15 mm.

10. The method of integrated and universal intelligent lightweight aggregate production of claim 9 wherein for the pelletizing step of claim 2 (c),

For groups A and C, the screened out undersize and oversize pellets are pulverized in the pulverization unit of claim 1 (c) and sent back to the pelletization-1 unit of claim 1 (c);

In case of waste mixture of group B containing <15% Al_2O_3, the on-specification lightweight aggregate pellets are coated with a thin layer of aluminum oxide powder in the pelletization-2 unit of claim 1 (c) to prevent the pellets from sticking to each other or to the crucible boat surface during subsequent sintering treatment and are transported to the furnace chamber of claim 1 (d); and

In case of waste mixture of group B containing >15% Al_2O_3, the pelletization-2 unit is bypassed and the on-specification lightweight aggregate pellets are transported to the furnace chamber of claim 1 (d) directly.

11. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 10 wherein for the sintering step of claim 2 (d) the sensor gate of claim 1 (d) controls discharge rate of green pellets into empty crucible boats within the drying and preheating unit of claim 1 (d) such that crucible boats do not overflow, and designed throughput of process instructed by the furnace processor unit can be achieved.

12. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 11 wherein for the sintering step of claim 2 (d) the plurality of microwave sources of claim 1 (d):

Are disposed in an array in multiple groups of three on both sides within the furnace cavity body for generating and introducing uniform electromagnetic radiation, and avoiding phase interference between different microwave sources; and

Have adjustable power levels from 0 - 5 kilowatts and a total rated power of 200 kilowatts, wherein the microwave power of each microwave source is controlled independently by the furnace processor unit, and microwave radiation generated is used to activate the susceptors within each crucible boat of the chain of material carriers of claim 1 (d) so that the susceptors can be heated by the radiation at room temperature and thereby allowing controlled heating rates of lightweight aggregate pellets of up to 50^{o}C/min until desired pore development and vitrification are achieved.

13. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 12 wherein for the sintering step of claim 2 (d) the furnace processor unit as set forth in claim 1:

Is programmed with a database of expansion behavior profile of different waste materials, such as viscosity of the vitreous phase and bloating index, various operator-defined temperature ramp-up rates, temperature hold stages, temperature hold times, and built-in computing capabilities for temperature programming and control in the range of 200°C to 1500^{o}C, wherein the said furnace processor unit executes instructions for automatic operation of lightweight aggregate production using various programmed operator-defined sintering profiles based on formulations and the intended end application, further, the furnace processor unit controls process conditions including but not limited to number of

crucible boats in operation in the three major tracks by attaching or detaching crucible boats to the material carriers using the automatic coupler, position of the insulation lids for the crucible boats by controlling vertical movement of the tube device, push-through rate of the crucible boats by controlling rotation speed of ceramic rollers installed on the moving track, revolution of the flat circular tray within the crucible boats for homogenous heating of the pellet samples by the microwave sources by controlling the rotation speed of the rotating shaft, and sintering temperature by controlling each microwave source independently for closed loop control of temperature in the furnace chamber such that the lightweight aggregates achieve sufficient pore development and complete vitrification; and

Is programmed with predetermined stages of preheating, sintering, and cooling from past treatments to inform future thermal processing regimes and profiles to various unknown feed materials and to produce lightweight aggregate for different intended applications.

14. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 13 wherein for the sintering step of claim 2 (d) the wireless sensor network system consisting of a plurality of infrared sensors and camera sensors of claim 1 (d) installed at 1m intervals within the microwave sintering unit for continuous monitoring of the radiation and temperature of the samples, foaming process, and pore structure formation of lightweight aggregate, and signals from these sensors are provided to the furnace processor unit of claim 1 (d) to automatically adjust sintering method in the microwave sintering unit for selection of treatment parameters, such as number of crucible boats in operation, vertical movement of the tube device and the insulation lids, sintering profile, lateral movement of the crucible boats, rotation of the flat circular trays within the crucible boats and power of the microwave sources for quality control and energy efficiency such that total porosity of the lightweight aggregate is > 40 % and intended pore structure of whether open porosity or closed porosity is developed.

15. The method of integrated and universal intelligent lightweight aggregate production of claims 3 to 14 wherein for the sintering step of claim 2 (d) the moving track is configured in a circular fashion such that the furnace chamber can be operated continuously as the crucible boats traverse continuously within the furnace chamber following completion of a heating cycle, thereby, remaining heat of the crucible boat can be reutilized as the crucible boat traverses from the cooling unit back to the drying and preheating unit to load in a new batch of lightweight aggregate pellets, further, exhaust heat from the cooling unit is also utilized for drying and preheating of green pellets in the drying and preheating unit of the furnace chamber and updraft drying of raw water material of group II in the drying unit of the preconditioning chamber of claim 1 (a).

16. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 15 wherein for the sintering step of claim 2 (d) the chain of material carriers consists of the automatic coupler that uses a hook-and-clamp mechanism to attach and detach each crucible boat to one another, so that coupled crucible boats are able to resist horizontal bends and rotational movements in the moving track, further, automatic coupling allows malfunctioned crucible boats to be detached from the material carriers and to exit the major tracks through the minor tracks for maintenance without affecting system operation, and allows additional crucible boats to join the material carriers to increase system throughput.

17. The method of integrated and universal intelligent lightweight aggregate production of claims 2 to 16 wherein for the sintering step of claim 2 (d) the vacuum system at outlet end of the ceiling of the cooling unit consisting of a vacuum blower that is made of heat-resistant stainless steel with suction pipes and a round suction nozzle, wherein the suction nozzle having same diameter as the flat circular tray of the crucible boat covers the flat

circular tray fully to suck and draw off the lightweight aggregate out of the crucible boats and pumps lightweight aggregate into conveying line and stores lightweight aggregate in corresponding storage silo.