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Technical, Environmental, and Economic Analysis of Required Pretreatments for Recycling Different Wastes to be Utilized as Raw Material for Producing Geocomposite

Examiners: Professor Timo Kärki
D.Sc. (Tech). Anna Keskisaari

ABSTRACT

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High consumption of raw materials producing vast amount of wastes has become a major concern in the world. Recycling is one of the discussed solutions for this problem. Different recycled waste materials are nowadays substituted virgin ones in various applications. This study aims to detect the required pretreatments for recycling five different wastes to be used as raw material for producing geocomposites. Moreover, the needed annual investment for initiating and running such a project as well as the environmental effects of the selected processes in terms of energy consumption are investigated. This study develops the earlier researches regarding this scope which are presented as literature review. Results indicate considerable differences regarding investment cost and environmental effects for diverse waste materials owing to their required pretreatments in which the flotation sand from the mining industry contributes to the least risks for the environment with the lowest required investment.

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Finally, I would like to thank God for helping me and taking care of me in all stages of my life.

In Lappeenranta, 10.10.2019

Sanaz Afshariantorghabeh

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LIST OF SYMBOLS AND ABBREVIATIONS

€	Euro
°C	Degree Celsius
3D	Three Dimensional
µm	Micrometer
Al	Aluminum
As	Arsenic
Cacl2	Calcium Chloride
Cd	Cadmium
CO2	Carbon dioxide
Cr	Chromium
Cu	Copper
Fe	Iron
Gs	Gauss
Hg	Mercury
KCl	Potassium chloride
kg	Kilogram
kgoe	Kilogram of oil equivalent
kV	Kilovolt
kW	Kilowatt
kWh	Kilowatt hour
m^2	Square meter

m^3	Cubic meter
m^3/h	Cubic meter per hour
mg	Milligram
mm	Millimeter
MPa	Megapascal
Mtph	Metric ton per hour
NaCl	Sodium chloride
Ni	Nickel
Pb	Lead
R3	Reuse, Recycle, and Recover
r/min	Revolutions per minute
t/h	Ton per hour
tph	Ton per hour
Zn	Zinc
CC	Conventional Concrete
C&D W	Construction and Demolition Waste
CMYK	Cyan, Magenta, Yellow, and Black sensors
FRAAC	Fiber Reinforced Alkali-Activated Concrete
HSI	Horizontal-Shaft Impactor
HVAC	Heating, Ventilation, Air conditioning
IRM	Induced Roll Magnetic
LCA	Life Cycle Assessment
LIMS	Wet Low-Intensity Electromagnetic Separator

LSP	Light Spectrophotometry
MIR	Mid Infrared
MSWI	Municipal Solid Waste Incineration
NIR	Near Infrared
OPC	Ordinary Portland Cement
PAHs	Polycyclic Aromatic Hydrocyclones
PVC	Polyvinyl Chloride
RED	Rare-Earth Roll
RGB	Red, Green, and Blue sensor
RPM	Reclaimed Pavement Materials
SFRCC	Steel Fiber Reinforced Conventional Concrete
VIS	Visual Imaging Sensor
VSI	Vertical-shaft Impactor
WHIMS	Wet High-Intensity Electromagnetic Separator

1. INTRODUCTION

Nowadays, there is an increasing concern around the globe about the growing use of raw materials. Population growth, urbanization, and industrialization are the most significant factors which affect producing more and more products resulting in a considerable amount of waste. These growing waste materials cause various difficulties like negative impacts on the environment such as groundwater contamination, releasing of toxic elements, some kinds of odor problems as well as decreasing the landfill for disposal of these materials. (Mohajerani et al., 2019.)

Those aforementioned obstacles became key drivers for the global community to create the concept of sustainable development. The purpose of sustainable development is to provide the requirements of the present generation besides conserves the resources efficiently so that the future generation can meet their requirements as well. Also, Sustainable development makes a balance between social, economic and environmental requirements (Klarin, 2018).

One of the important activities to reach the sustainable development is to develop recycling. Alongside reducing the environmental pollutions and cutting down the amount of waste in landfills, recycling can recover different valuable materials that are discarded. Also, it can conserve natural resources as the need for virgin raw materials will be decreased in this way. Although a lot of efforts and researches have been performed for increasing the recycling rates, still some issues restrict it. For instance, sometimes the quality of the products which are made from recycled waste materials are not as good as the virgin material. Moreover, the whole procedure, from sorting and separation to the recycling process, for some products can be energy and labor-intensive also expensive that cause the market to continue using virgin raw materials. (Grosso et al., 2017.)

All over the world, the scientific community is searching for discovering efficient methods to recycle waste materials for use in various applications. One of the recent developments is to make use of some waste materials to produce geocomposites to substitute the non-environmentally friendly cement. There are various industrial, mining and construction wastes which can be suitable for making geocomposites. Some significant researches have been implemented in this regard but still, this process requires closer inspection in its different aspects in order to have the most productive result.

1.1 Legislations

The most important targets for waste legislation are to conserve the natural resources as efficient as possible and to decline the possible damages to the environment and humans. Moreover, these legislations are helpful to conduct societies into more sustainable manners.

According to the European directive 2008/98/EC, waste is defined as any material that is discarded, to be discarded or is needed to be discarded. Based on the definition in this directive, the waste is not anymore a waste, which is named end-of-waste, if it is utilized for a particular application; a specific market or requisition is available for that material or object; its utilization is legal and also its use does not have any impairments for the environment and human health.

Moreover, it is important to note the difference between waste and by-products. Most of the processes have some by-products. The definition of by-product in the European directive 2008/98/EC is that it should have another use; it can be utilized in the form it is produced without performing any special processes rather than the common industrial procedures; it has to completely come from the production process and also it must not pose any threat in the regard of the environment and human health.

All over the world, authorities and organizations have made a lot of efforts to decrease the waste generation through defining legislations and responsibilities for different sectors. One example of this regard relates to the producer’s responsibilities. Legislations determine that the responsibility of the waste products at the end of their life span is with the producers and they should provide facilities for collecting their discarded products. The main principle behind this legislation is to make the producers be aware of the end life of their products (Piippo, 2013). Another action to control producing waste is by applying taxes and fees for wastes. Waste generators should pay for their landfilled waste. Tax payment is prevented in the case of using waste in the landfill structure or any other application (Keskisaari and Kärki, 2018).

Furthermore, the other notable action for mitigating waste production is related to defining the waste management hierarchy by the European commission (figure 1). Disposing rate must be declined by accomplishing some activities before that. The first step in the waste management hierarchy is to reduce waste production. Thereupon, reusing the products should be taken into account and if reusing is not possible then recycling is required to be performed. Recovering is the next step for some materials and products in which recycling may cause some harmful effects and it is not practically feasible. (Piippo, 2013.)

Figure 1. Waste management hierarchy (European Union, 2010).

It is noteworthy that, European directives have ascertained different recycling rates for various waste materials which are required to be achieved by European members. One of the significant wastes in this regard is construction and demolition waste. There is specific legislation for the construction and demolition wastes founded on the European directives. This legislation determines that 70 % of the non-hazardous construction and demolition wastes are needed to be recycled by 2020 and the incineration or the landfilling should be prevented as much as possible. Although some of the European countries like Germany and Austria have already achieved this 70%, in Finland this rate is still 58%. (Keskisaari and Kärki, 2018; Liikanen et al., 2019.)

1.2 Waste volumes

According to the Eurostat statics, more than 2500 million tons of waste was generated in Europe in 2016 from economic and household activities. The following pie chart shows the share of different sectors in the total produced waste. This chart shows that the greatest shares of wastes in Europe were related to construction and mining waste with more than 36 % and 25 %, respectively.

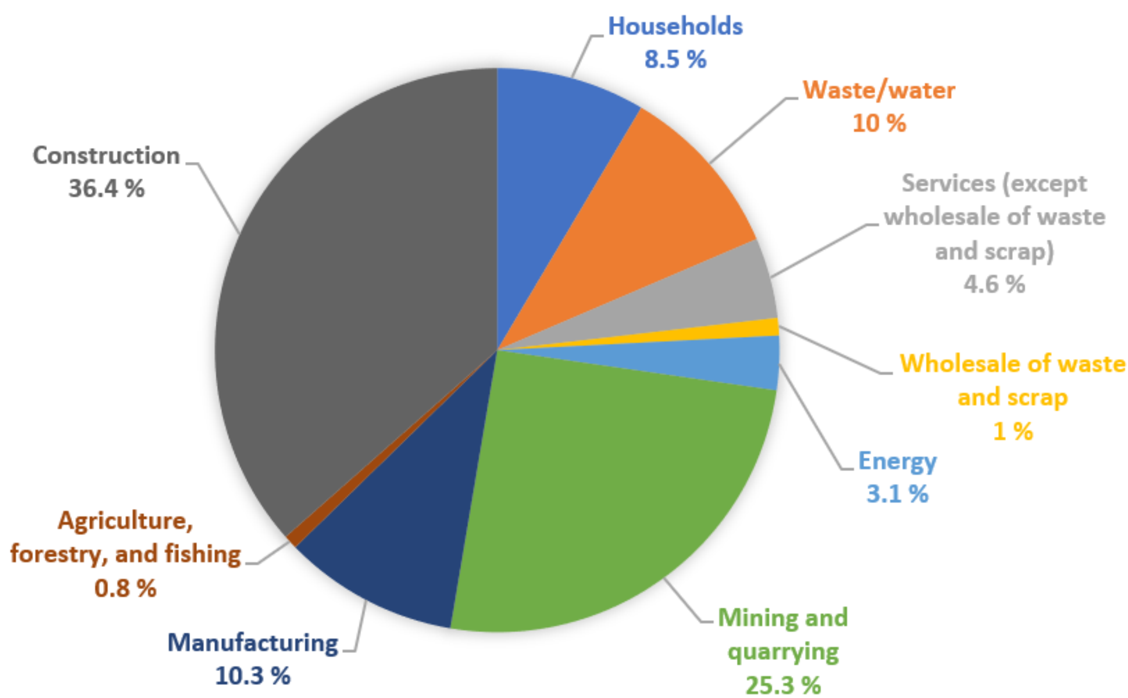

Figure 2. Share of different sectors in total waste generated in Europe in 2016 (Eurostat, 2019).

Likewise, the total amount of waste generated in Finland in 2016 is more than 122 million tones. The contribution of different activities in waste generation in Finland is stated in figure 3 established upon the Eurostat statics. The greatest share of wastes in Finland belonged to the mining and quarrying sector. Wastes from the construction industry contributed to the second biggest rank.

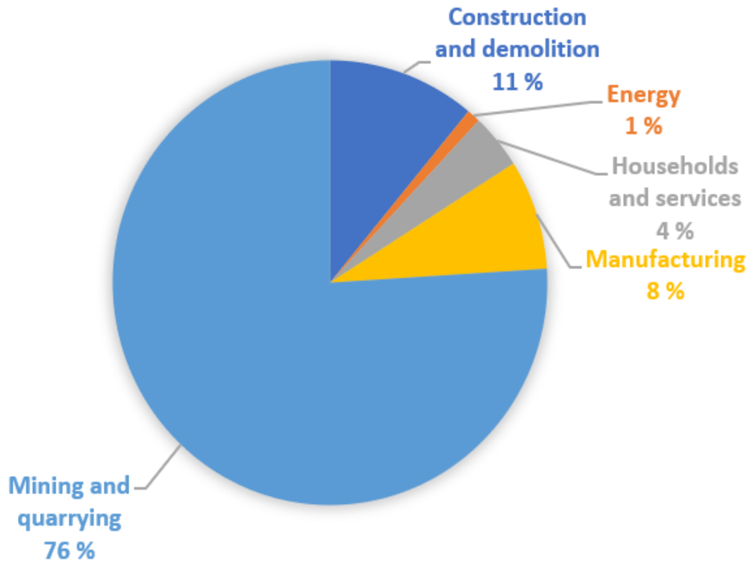

Figure 3. Share of different sectors in total waste generated in Finland in 2016 (Eurostat, 2019).

The previous pie chart is almost equivalent to the following table which is the amount of waste generated in different sectors in 2016 provided by Statistics Finland.

Table 1. Waste generation in Finland (Statistics Finland, 2018).

Category	**Amount (1000 tones)**
Mining and quarrying	93 661
Construction	13 825
Manufacturing	9 350
Households and services	2 909
Electricity, gas, steam and air conditioning supply	1 098

1.3 Previous studies

A lot of researches have been carried out about required treatments for recycling of mining, industrial, construction and demolition wastes. In this section, some of the significant researches are reviewed regarding certain materials of these categories which are the target of this research including green liquor sludge, ash, fiber reject, flotation sand, and construction and demolition wastes. In addition, the hazardous substances that can be existed in those materials are introduced and the defined thresholds for their usage in different applications are presented. Eventually, in the last section of this part, the results of some available researches about the environmental effects of recycling these materials are mentioned.

1.3.1 Green liquor sludge

Generally, Pulp and paper mill produces a broad range of organic and inorganic material streams. Wood is transformed into the cellulose through different pulping processes. Green liquor sludge is one of the materials which results in the chemical circulation of the pulp mill (figure 4). The total amount of produced green liquor sludge in Finland in 2012 was 90 000 metric tons based on the Kinnarinen et al. (2016). In addition, in the mentioned research, they stated an approximation of about 0.5 to 1.3 million tons of green liquor sludge per year in the world. Up to the present time, they are not promising applications for recycled green liquor sludge and it is mainly be treated to then goes to the landfill

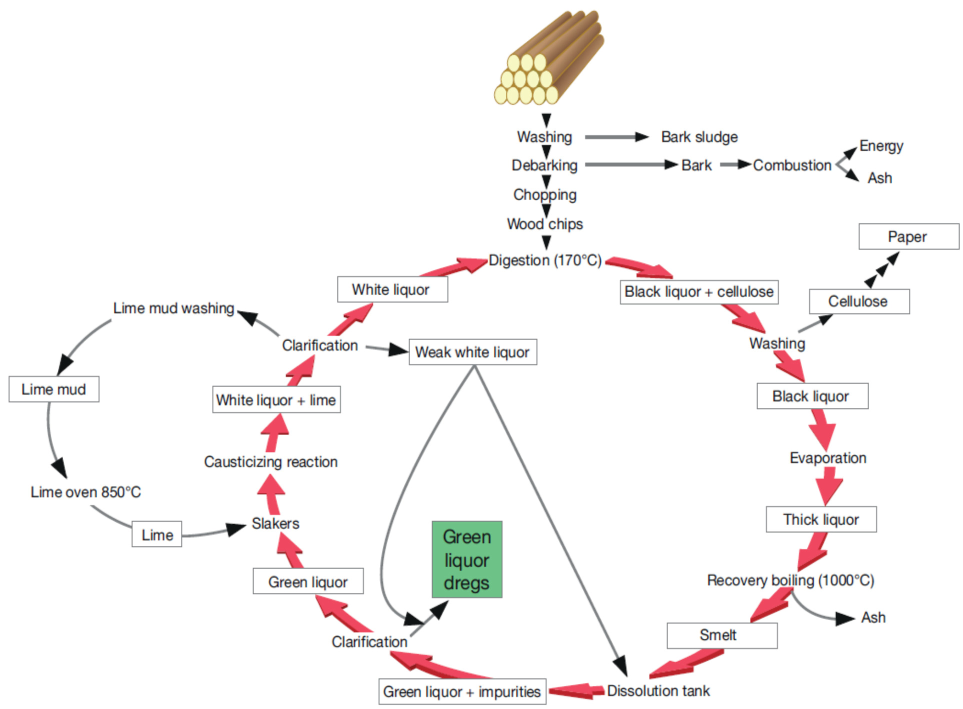

Figure 4. The kraft production process which produces green liquor sludge (Mäkitalo et al., 2014).

Usually, by performing some treatments, the sludge is removed from the green liquor which thereafter those green liquor is recessed to the process (Mäkelä et al., 2016). There are three major targets for the treatment of the green liquor which are separating the dreg from the green liquor, obtaining the suitable quality for dreg to being disposed of or recycled by performing treatments, and finally reduction of the green liquor temperature for recausticizing (Kinnarinen et al., 2016).

Regarding the suitable separation and treatment methods, Kinnarinen et al. (2016) and Golmaei (2018) proposed to separate the sludge from green liquor through using sedimentation or filtration processes. However, it is indicated that the filtration method is more effective and more flexible upon the changes in the process compared to the sedimentation. Thereafter, the washing and dewatering step is implemented to decrease the negative effects of the sludge in case of disposal and for recovering the precious alkaline materials. On the other hand, in another research Mäkelä et al. (2016) suggested using cyclone treatment for green liquor sludge in order to decline the heavy metal amount of the green liquor sludge.

According to Golmaei (2018), if some toxic elements like cadmium (Cd) exist in the green liquor sludge, then more treatment steps are required to eliminate that material. The reason is that the cadmium is not dissolved in water. The proposed methods for this purpose are removing them by chelating agents or using hydrocyclones in which filtration characteristics of the green liquor can be enhanced.

1.3.2 Ash

Ash is one of the noticeable waste materials in the recycling industry since it has the potential for utilizing in multi applications. One promising application of recycled ash is in the construction sector as a binder in concrete, cement, and mortar because it improves their workability and strength properties. Using as a fertilizer is another popular utilization of recycled ash in forestry. Table 2 shows some of the applications of fly ash in various sectors. In this current research, the aim is to use the ash as a raw material for producing geopolymers.

Table 2. Possible applications of fly ash (Mod. Vilamová and Piecha, 2016).

Branch	**Area of utilization**
Metallurgy	Production of steel, making dusting and thermal insulation layers, dusting core material, shaping material throughout steel casting
Mining	To the basis of robbed mining areas
Agriculture	Upgrading of heavy oils, making bio-organic mineral fertilizers, seed coating, in the role of micro and macro particles
Construction	Production of cement and aggregates, fabrication of artificial stones, concrete, brick, and ceramics as well as road construction

In Finland, the combustion of different fuels mainly woods, and barks produces fly and bottom ash. The bottom and fly ash differs from each other in the regard that the bottom ash drops from the bottom of the boiler because of its heavier weight and the fly ash gets mixed with the hot air which comes out of the boiler. It worth mentioning that, the smaller ashes have a greater surface area, greater reactivity and as a result, they are more valuable (Dong et al., 2013).

Depended on the target application, diverse types of treatments are needed for ashes. According to Joseph et al. (2018), one of the early stages for beneficiation of ashes in order to use in the constructing materials is firstly separation of ferrous metals. Various ferrous metals, mainly iron (Fe) can be separated through magnetic separation.

Furthermore, ashes can contain significant amounts of unburned carbons. Mohebbi et al. (2015) indicated that in the condition of using fly ash for making concrete, the existence of unburned carbon can negatively affect the rheological characteristics of the concrete. In addition, these unburned carbons can be extracted and returned to the processes as the fuel so that their separation from the ashes becomes significant (Zhang et al., 2018). Basically, there are two methods for separating unburned carbons from the ashes; wet and dry techniques. In the wet method, the unburned carbon is separated through froth flotation and in the dry method, the triboelectrostatic separation is applied. Generally, the efficiency of froth flotation is higher than that of the electrostatic method (Zou, 2008).

Zhang et al. (2018) mentioned that the most significant characteristics of the ashes for triboelectrostatic technique are charge-to-mass ratio and charge polarity. The latter property is depended on the humidity, temperature and friction material but the charge-to-mass ratio can be changed by the work function, friction area, and frequency. It should be noticed that the different dispensation of the particles can affect the density and the polarity so that affects the separation process.

On the other hand, Liu et al. (2013) evaluated separation of carbon from the ashes of hospital solid waste incinerator by the wet method, column flotation. They mentioned that this method successfully removed the unburned carbon and it is an inexpensive method which makes it popular for the treatment of the ashes.

One notable point about the ashes is that they might contain a great amount of heavy metals, dioxins, and some other contaminants and that is the reason for some countries to classify ashes as hazardous materials. Some of the heavy metals include lead (Pb), mercury (Hg), arsenic (As), cadmium (Cd), chromium (Cr), Copper (Cu), and zinc (Zn). Usually, fly ash contains more heavy metals so that it is considered as more dangerous material compared to bottom ash. Consequently, another treatment for the ashes with heavy metals should be carried out to remove them as well as to eliminate salts to make ashes non-hazardous for recycling or landfilling. (Sun et al., 2016.)

Joseph et al. (2018) and Sun et al. (2016) stated that water washing is the simplest way to eliminate the salts from the ashes. However, the disadvantage of this method is the considerable use of water which is polluted with heavy metals and salts. For instance, Day and Dinovo (2013) indicated that for conditioning 50000 tons fly ash with water at 16% moisture which is the typical range of moisture, 8000 tons of water is needed. According to Chen et al. (2016), different sorts of chlorides like NaCl, KCl, and CaCl2 can be eliminated by the washing process.

Afterward, for efficient separating of heavy metals solidification, stabilization or thermal treatments are applied. In the case of solidification, cement solidification is the most popular method because of its simplicity, inexpensiveness, and efficiency. The main disadvantage of this method is that the ash volume will be raised after treatment. In this method, a mixture of cement, ash, and water is created with the specific proportion of each of them. In one research Fan et al. (2018) mentioned the pros and cons of using various cement for cement solidification that it is presented in the next table. They used these materials for immobilization of municipal solid waste incineration (MSWI) fly ash.

Table 3. Advantages and disadvantages of using different types of cement in cement solidification of MSWI fly ash (Mod. Fan et al., 2018).

Cement	**Advantages**	**Disadvantages**
Portland cement	Simple operation, Low cost, Moderate compressive strength	High throughput and rate of weight raising, weak longstanding security and durability
Phosphate cement	High compressive strength, good dry shrinkage, low cost	High throughput and rate of weight raising, weak longstanding security and durability
Aluminate cement	easy operation, low cost	High throughput and rate of weight raising, weak durability, poor dry shrinkage
Alkali activated cement	High compressive strength, low cost, good long-term security, and durability	High throughput and rate of weight raising, weak dry shrinkage

For stabilization, various stabilizers like phosphate, sulfide, and gypsum can be used like in one research, Vavva et al. (2017) stated that washing and phosphate stabilization are the most effective methods after examining various possible treatments. Finally, the thermal treatment methods are categorized in vitrification, sintering, and fusion. Generally, thermal treatment is not suggested because of its high energy consumption (Sun et al., 2016).

It is important to notice that in the case of using triboelectrostatic separation for separating the carbon, water washing, and solidification/stabilization are followed for separating salts and heavy metals. On the other hand, in another research, H. Q. Liu et al. (2017) proposed a two-step froth flotation in which the first step is decarbonization and the second step is for removal of heavy metals and toxic elements by acid leaching, sulphidation, and precipitation from the hospital solid waste incinerator fly ash. A flow chart of this two-step process is as follows.

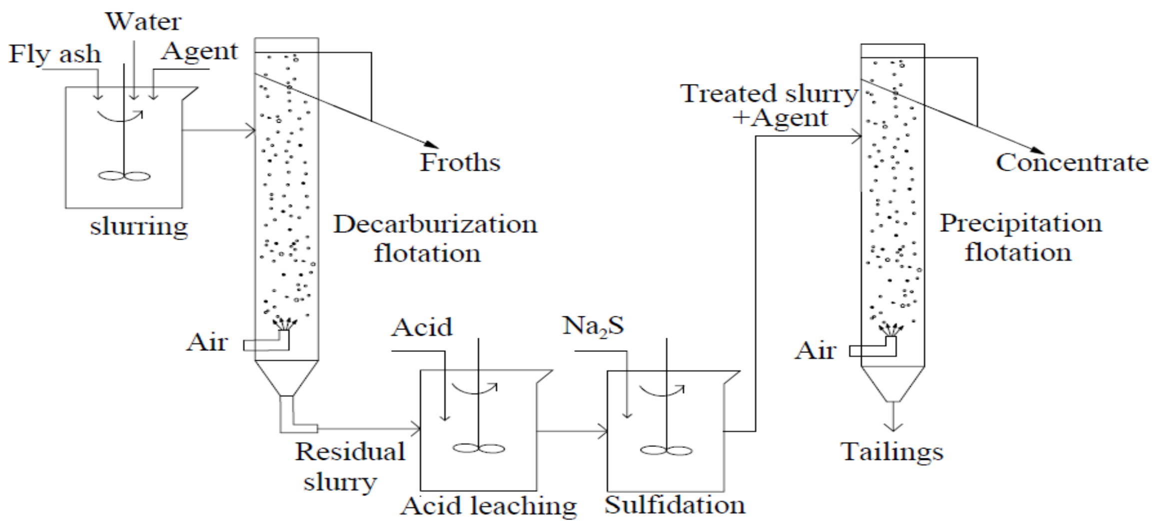

Figure 5. Two-step froth flotation process (H. Q. Liu et al., 2017).

Regarding bottom ashes, instead of wet treatment methods including washing and stabilization/solidification, a dry method which is the ageing process can be implemented for removing heavy metals. For this purpose, bottom ash should be exposed to the open air to reduce the PH as well as to decline the leaching properties. However, this method is not efficient for removing salts. (Nordic Council of Ministers, 2009.)

Another recent development about eliminating the leaching problem of the heavy metals in the ashes is adding silica nanoparticles to the ashes so that the heavy metals are entangled, and they cannot be leached. This method is investigated by a research group in Singapore and it is mentioned that its efficiency is almost 20-30 % higher than the common industrial methods. However, this treatment is evaluated only in the lab-scale and its feasibility should be studied for high capacities. (Tang, 2017.)

Furthermore, one thing that should be considered about the ashes is that there is a possibility that some kinds of impurities will be present among the ashes. As a result, performing a screening stage in their treatment process might be needed to remove those impurities. Screening can be implemented at the first of the process before magnetic separation.

1.3.3 Fiber reject

Fiber rejects are wood branches from the pulping process. Two main classifications of the rejects are coarse and fine rejects. Generally, the pulping process like de-trashing produces coarse rejects and the fine rejects mainly come from the cleaning and screening processes. According to the Andritz (no date), the next figure states the main processes for the treatment of various rejects from the pulping process.

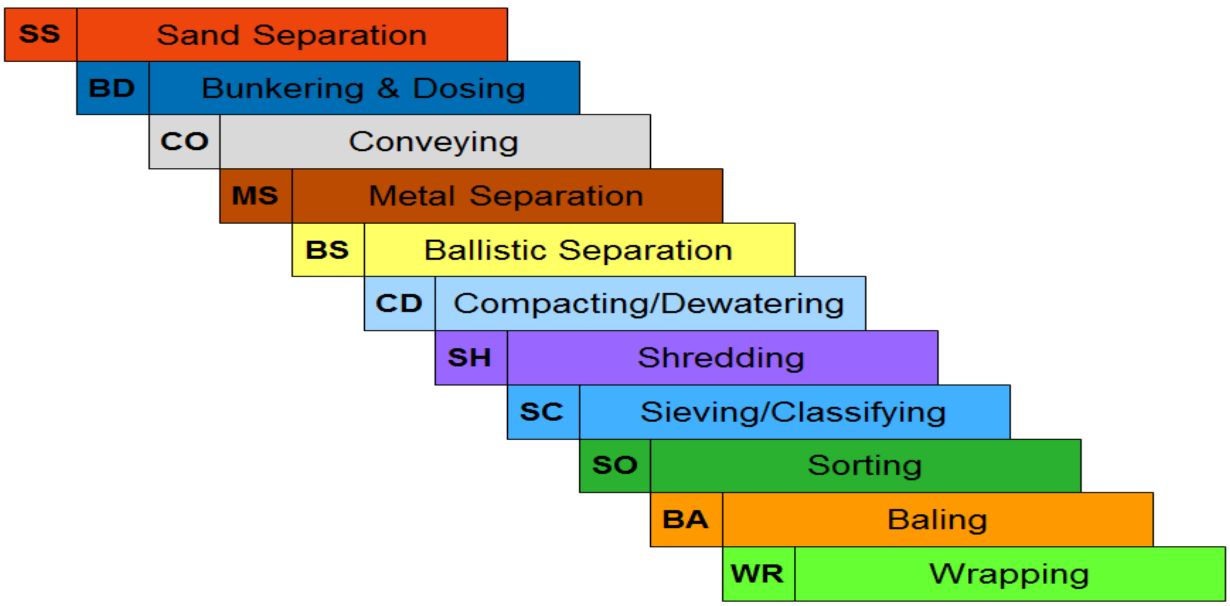

Figure 6. Main processes for treatment of pulping process' rejects (Andritz, no date).

In the case of fiber reject, the required treatment stages are drying, shredding, and screening. Right after the pulping process, particles are completely wet, and they contain a significant amount of water and that is the reason for fiber rejects to be dried before further use in some applications.

Before implementing the shredding stage one thing should be carefully considered. Based on the intended application, the fiber length can have a significant effect. In this research, the target is to use the fiber reject as reinforcing fiber and according to various studies like Amuthakkannan et al. (2013), there is not a linear relation between fiber length and strength properties of the final product. Consequently, another research is needed to find the optimum length of fibers and afterward if needed the fibers should be cut down to reach their optimum length.

Although fine shredding produces uniform particles, there are some tiny fiber fragments. These small particles can make dust problems and difficulties for measurement. Due to these reasons, performing the screening stage becomes significant. (Andritz, no date.)

1.3.4 Flotation sand

Flotation sand is a by-product of the production of calcite and wollastonite. Flotation sand is made up of all the minerals and residues that are not possible to be used in the flotation procedure. The mixture of the flotation sand and the water is commonly named tailing. (Keskisaari and Kärki, 2018.) Great amounts of tailings are produced in the mining industry in the world. Usually, these tailings are considered waste material and they are disposed of, although they consist of precious materials that can be further used for various products.

In Nordkalk Lappeenranta, there are three dams in which tailing is transferred. In these dams, by natural sedimentation process, flotation sand settles. Firstly, the bigger sands settle which is called the coarse flotation sand and afterward the minute sands settle named fine flotation sand. Additionally, through this process, water is again clarified. The privilege of this step is that this recovered water is then recessed to the process so that it helps to increase the cost efficiency of the whole process and can considerably conserve the natural resources by decreasing the water usage. (Keskisaari and Kärki, 2018.)

Canadian Natural Resources - Disclaimer (no date) mentioned that if before reaching the dam, the CO2 is added to the tailing, it can help to reduce the required pond area as well as to adjust the PH of the water to be like the river water. Another advantage of adding CO2 is that it speeds up the sedimentation process in the pond so that sands are settled more quickly. Finally, like the ashes, after collecting the settled flotation sands as they might contain some impurities, implementing the screening process is required.

1.3.5 Construction and demolition waste

Construction and demolition waste (C&DW) are the wastes which are produced from construction, maintenance, and demolition activities. Commonly, C&DW has two major sorts including inert materials like sand, bricks, and concrete as well as non-inert ones like plastic, glass, and wood (Ulubeyli et al., 2017). Based on the provided statics by Eurostat 2017, the total amount of construction and demolition waste in Europe per year is 820 million tones. This amount is almost about 30% of the whole produced waste. Statics show that more than 80% of this construction and demolition waste comes from concrete, ceramics, and masonry. (Gálvez-Martos et al., 2018; Liikanen et al., 2019.)

Recycled construction and demolition wastes are usually used in road and building construction like for new concrete. However, still the share of recycled material in these applications is low, and the whole parts come from virgin materials. One important reason is the cost of recycled materials which is usually higher than virgin ones. (Giorgi et al., 2018.)

According to the researches of the Gálvez-Martos et al. (2018), Huang et al. (2002), and Broere (2003), as can be seen in figure 7, separation process of C&DW is started with sorting the large wastes like wood, metals, and rocks via utilizing a vibrating screen. Afterward, for those tiny particles which cannot be separated by vibrating screen due to the size of meshes, the horizontal trommel screen and disk screen are performed. These materials can be sand, soil, gravel, grain, or pebbles. Magnetic separation is carried out for separating the ferrous metal applying an overhead magnetic separator. Wood, ceramics, and plastics are detached by an air classifier and then they are transferred to the next step which is manual separation for further separation. In the end, the residues of concrete and masonry are sent to a crusher. Conditional upon the end required product, screening and secondary crushing might be implemented. Also, it should be mentioned that nowadays in the industry the crushing process is mainly done at first to provide homogenous materials in order to increase the efficiency of the other separation processes (Keskisaari and Kärki, 2018).

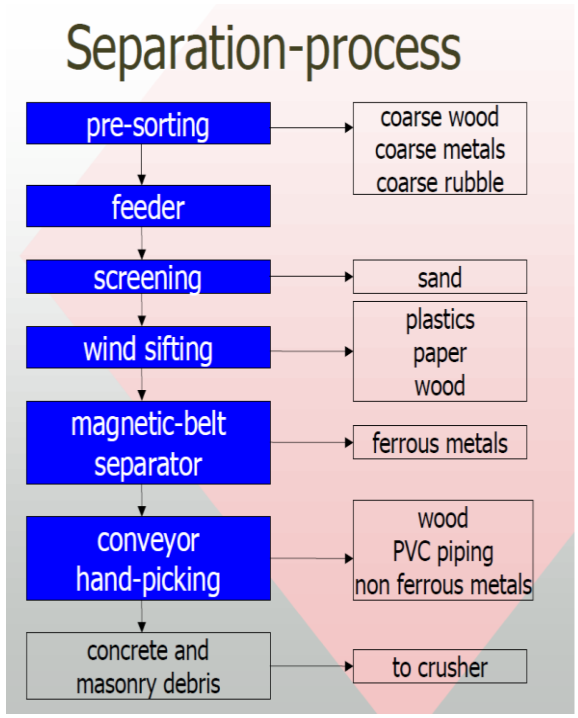

Figure 7. C&D W separation and crushing processes (Broere, 2003).

C&D waste recycling sites are divided into mobile and stationary sites. Generally, Mobile sites have one or two crushers, screens, and some separation devices like magnetic separators. These plants are called mobile plants as they are carried to the demolition location. The main privileges of this kind of plant are that it is a proper option for big C&D sites, the aggregates can be provided locally so that the requirement for importing aggregates is reduced, also at the end of the project, it can be transferred to another project. However, this sort of plant has its own disadvantages such as low modality end products due to lack of cleaning equipment as well as creating noise and dust problems for the neighbors. (Kumbhar et al., 2013.)

On the other hand, stationary sites usually contain primary and secondary crushers and separation machines besides cleaning facilities to prevent producing low-quality products. Additionally, stationary plants are more efficient compared to the mobile one because of the possibility of producing diverse recycling products with different grading. Albeit, this type of plant is costlier and transportation is increased to move the waste to the site. (Kumbhar et al., 2013.)

1.3.6 Hazardous materials in the waste

There are various hazardous materials that can be existed in mining, industrial and construction wastes that must be extracted before recycling if they are totally banned to use or they cross the regulated thresholds. Some of them are heavy metals with negative influences on human health like lead, cadmium, mercury, and arsenic. In addition to the damages to the human health and environment, these heavy metals cannot be degraded so that they might expose to the foods later. (Guinee et al, 2000).

Among those elements, Cadmium is mainly found in the wood so that it can be one of the compositions of wood ash, green liquor sludge and fiber rejects. The main negative effect of the cadmium is that it can harm the kidneys and cause cancers (Järup, 2003).

In addition, construction and demolition wastes may contain some toxic elements including asbestos, mercury, arsenic, and lead. The main effect of asbestos is that it can damage the human lungs and cause cancer. Moreover, mercury can last in the environment for a thousand years and that is the significant reason for preventing the use of mercury which is a harmful material. Arsenic is the other material that can cause cancer in conditions of breathing or swallowing. Depending on the source, C&DW may contain woods. Sometimes for the wood in contact with the ground or the air, treatment is needed to save it from impairment. Arsenic is one of the materials that can be used for wood treatment. However, some countries like Norway and Denmark have prohibited the use of arsenic for wood protection, still it is utilized for this application in some other countries. (Wiley and Sons Ltd, 2009; Townsend, 2001.)

Among the possible existing plastics in construction and demolition waste, polyvinyl chloride (PVC) can be harmful because of its carcinogen nature due to the presence of lead on its composition. Consequently, for recycling PVC, the allowed amount of lead should be considered carefully. Also, it should be mentioned that through incomplete combustion of wood, a special hazardous material for human health can be formed in ashes which is polycyclic aromatic hydrocarbons (PAHs). (Nuutinen, 2016.)

Limitations for using these materials are highly depended on the target application. Table 4 shows the defined thresholds for those elements in the aforementioned waste materials for different applications in Europe or Finland.

Table 4. Thresholds for using hazardous materials in different applications

Waste stream	**Possible hazardous element**	**Threshold for using**
Green liquor sludge Fiber reject Ash	Cadmium	20 mg Cd/kg P2O for fertilizers in EU Finnish legislation: Higher suggested amount of 20 mg/kg for major land users like industrial or transport sites and lower suggested amount of 10 mg/kg for all the other land uses. (Netinger Grubeša and Barišić, 2016.)
Construction and demolition waste	Asbestos	The use of asbestos has been banned in Europe from January 2005 based on the 1999/77/EC directive.
Construction and demolition waste	Mercury	EU, 2017: banning numerous products containing mercury, such as thermometers, batteries, switches and blood pressure monitors

Table 4 continues. Thresholds for using hazardous materials in different applications

Waste stream	**Possible hazardous element**	**Threshold for using**
Construction and demolition waste	Mercury	banning all industrial processes using mercury and placing emission limits on other environmental emissions (e.g. from coal burning at power generation sites). Finnish legislation: Higher suggested amount of 100 mg/kg for major land users like industrial or transport sites and lower suggested amount of 50 mg/kg for all the other land uses. (Netinger Grubeša and Barišić, 2016.)
Construction and demolition waste	Lead	2015/628/EU: The maximum amount of lead in a product must be 0.05% by weight. Finnish legislation: Higher suggested amount of 750 mg/kg for major land users like industrial or

Table 4 continues. Thresholds for using hazardous materials in different applications

Waste stream	**Possible hazardous element**	**Threshold for using**
Construction and demolition waste	Lead	transport sites and lower suggested amount of 200 mg/kg for all the other land uses. (Netinger Grubeša and Barišić, 2016.)
Construction and demolition waste	Arsenic	EU, 2014: Maximum 60 mg/kg dry matter for primary and secondary nutrient fertilizers Maximum 1000 mg/kg micronutrient in micronutrient fertilizers Maximum 120 mg/kg dry matter in liming materials Finnish legislation: Higher suggested amount of 100 mg/kg for major land users like industrial or transport sites and lower suggested amount of 50 mg/kg for all the other land uses. (Netinger Grubeša and Barišić, 2016.)

Table 4 continues. Thresholds for using hazardous materials in different applications

Waste stream	**Possible hazardous element**	**Threshold for using**
Ash	polycyclic aromatic hydrocarbons (PAHs)	according to EU 1272/2013: "PAHs of 0.5 mg kg-1 for plastic and rubber components of toys/childcare articles, and 1 mg kg-1 for all other consumer articles, in direct and prolonged, or short -term repetitive, contact with the skin or oral cavity"

1.3.7 Environmental impact

One important question about recycling waste materials is related to the efficiency of recycling. How much these kinds of recycling can help the environment? Could it be possible that their recycling process makes more negative impacts than disposing or landfilling? These are the questions which can be answered by implementing a life cycle assessment for these materials and their recycling process.

Life cycle assessment basically evaluates the environmental effects of a product in its whole lifetime. It assesses various stages such as raw material acquisition, production procedure, usage, and finally disposing or R3 applications (figure 8). LCA contains four main stages; specifying the aim and scope, defining the lifespan inventory which contains all the inputs and outputs of the specified product, evaluating the effects and lastly analysis of the outputs. (International Council of Chemical Associations, 2019; Khasreen et al., 2009.)

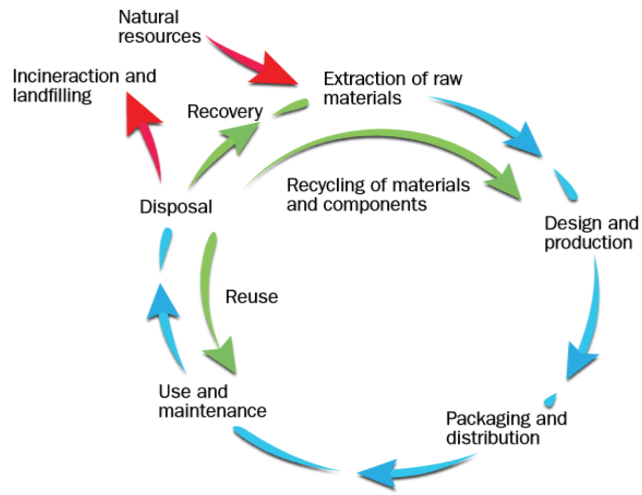

Figure 8. Different aspects of life cycle assessment (International Council of Chemical Associations, 2019).

In this part, a literature review has been carried out about different LCA researches regarding recycling of the specific waste materials of this research for use in various applications with the focus on the environmental impacts of the material production phase. However, it should be mentioned that most of the presented researches in this part are about C&D W and ash as these materials are investigated widely all around the world, but the other materials are quite rare that still they are not used broadly.

Turner and Collins (2013) compared the CO2 emissions of producing concrete with OPC cement and geopolymer contains fly ash. OPC production generally causes high CO2 emissions contributing to about 7 % of the global CO2 emissions. As a result, finding other materials which can substitute OPC with lower environmental impacts requires more investigations. Geopolymer based on the waste fly ash is one option in this regard. The results of this research demonstrate that CO2 emission for producing OPC concrete is 354 kg CO2-e/m3 and this amount for the considered composition of geopolymer with fly ash of their research is about 320 kg CO2-e/m3. Consequently, through using a geopolymer from waste ash, the CO2 emissions are reduced to almost 9%. In addition, Petrillo et al. (2016) evaluated the CO2 emissions of OPC concrete and geopolymer derived from the construction and demolition waste and their results show about a 16% reduction in CO2 emissions for geopolymers.

Abdulkareem et al. (2019) investigated the environmental impacts of fiber reinforced alkali-activated concretes (FRAAC), conventional concrete (CC) and steel fiber reinforced conventional concrete (SFRCC). The key point for making alkali-activated binders is using materials with a high concentration of aluminum and silicate. Fly ash is one proper material for this regard and it is utilized in this research. LCA results demonstrate that FRAAC has the least environmental impacts compared to other materials like conventional concrete in all categories instead of Abiotic Depletion Potential (fossil) and Marine Aquatic Ecotoxicity Potential.

In another article, Kurda et al. (2018) financially and environmentally investigated the use of recycled concrete aggregate from C&D W as well as fly ash for making concrete. They made a vast literature review in regard to life cycle assessment of concrete production and the main results show that the use of recycled aggregate can decrease the environmental effects of concrete production. However, the contribution of aggregates in the total released emission of concrete is not notable, but due to the reason that aggregates are 70% of concrete so that the reduction of their environmental impacts becomes significant. In addition, they mentioned that reusing the recycled concrete aggregates can have better impacts compared to their disposal, but also it depends on the required transportation distances. Another important result is that by utilizing fly ash and recycled concrete aggregates simultaneously, the production of concrete becomes more cost-efficient. However, it worth noticing that there is one environmental concern about using fly ash for making concrete and it is due to the great amount of heavy metals in fly ash. Still, there is a debate about the possibility of using fly ash concrete for drinking water applications and it is recommended not to utilize fly ash concrete for instance for making drinking water tanks.

The following table is from the same research that they conducted a comparison between different kinds of raw materials for producing concrete. The term EI stands for environmental impacts on this table. CEM 1 is one of the typical sorts of cement and generally it has high environmental impacts. CEM 2 is another type of cement which is cheaper than CEM 1. + symbol shows the depletion of the effect, ++ shows great depletion of the effect, and _ shows the increase of the effect. As it can be seen from the table, recycled concrete aggregates are the most environmentally friendly material. However, their recycling process is quite expensive. (Kurda et al., 2018.)

Table 5. Financial and environmental effects of various raw materials in concrete production (Kurda et al., 2018).

Raw materials	**€**	**EI**	**€ and EI**
CEM I	–	–	–
CEM II	+	+	+
River aggregate	+	+	+
Crushed aggregate	–	–	–
Granitic coarse aggregate	–	+	–
Limestone coarse aggregate	+	–	+
Coarse RCA	++	++	++
SP	–	+	+

Cochran (2006) also considered different scenarios for the management of four materials from C&D W and the results of their life cycle assessment regarding various aspects can be found in the next figure. The results of this research show that the best way of management for shingles, drywalls and most of the time for concrete is recycling rather than disposing or landfilling. However, for wood the best scenario is incineration.

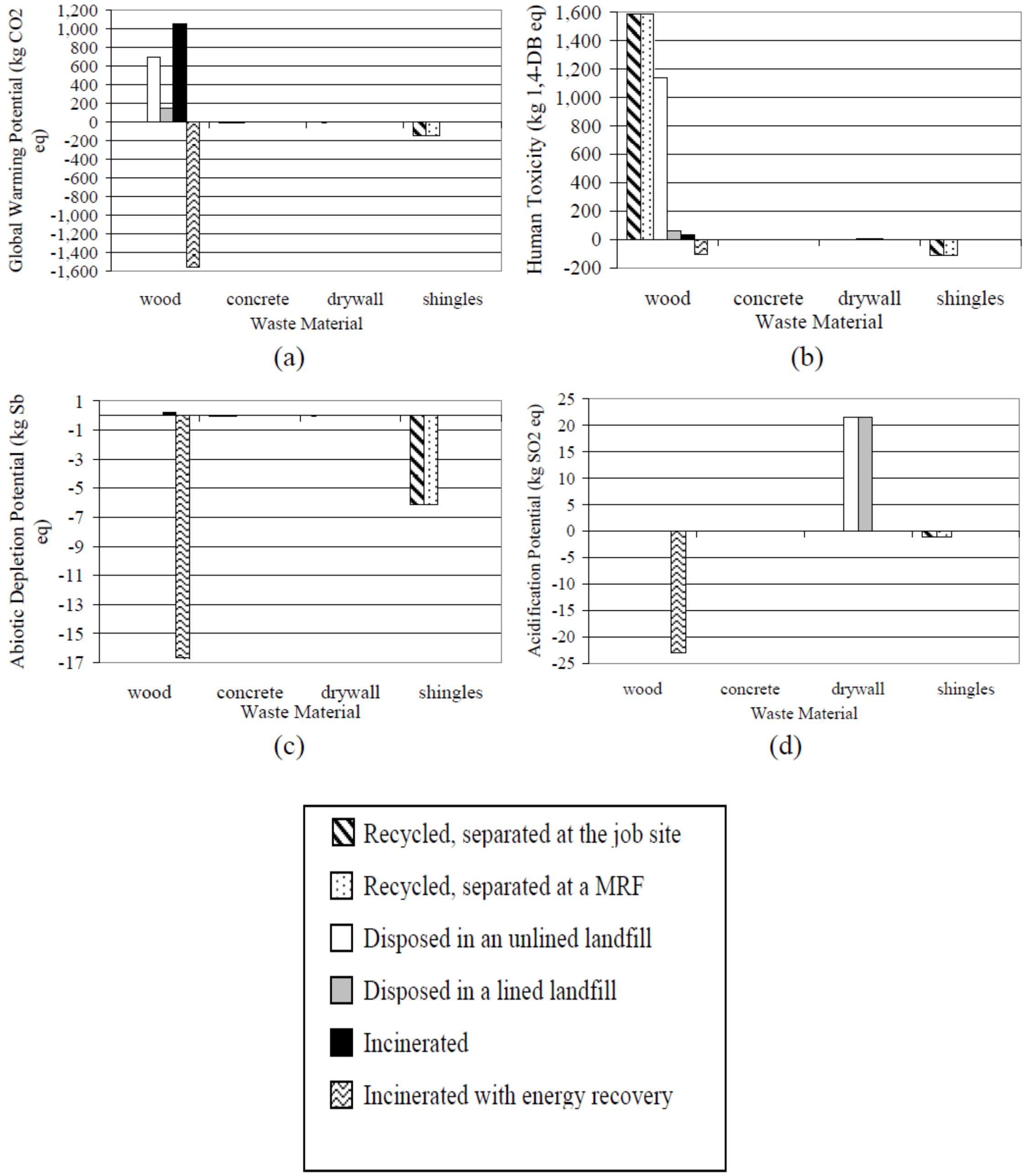

Figure 9. Environmental impacts of various waste management scenarios for four C&D W materials (Cochran, 2006).

Additionally, United States Environmental Protection Agency (2008) carried out a case study regarding using fly ash in RPM (reclaimed pavement materials). They found out that using fly ash for this application can reduce energy consumption and CO2 emissions. Their evaluation can be seen in figure 10. One important outcome of this research is about the material production phase. As it can be seen from the figure, the energy consumption for producing RPM with fly ash is almost equal to RPM and it requires transportation as well so that in this phase of recycling more energy is used with higher CO2 generation. This is evidence that raw material production from recyclable materials still requires more attention to become environmental-friendlier.

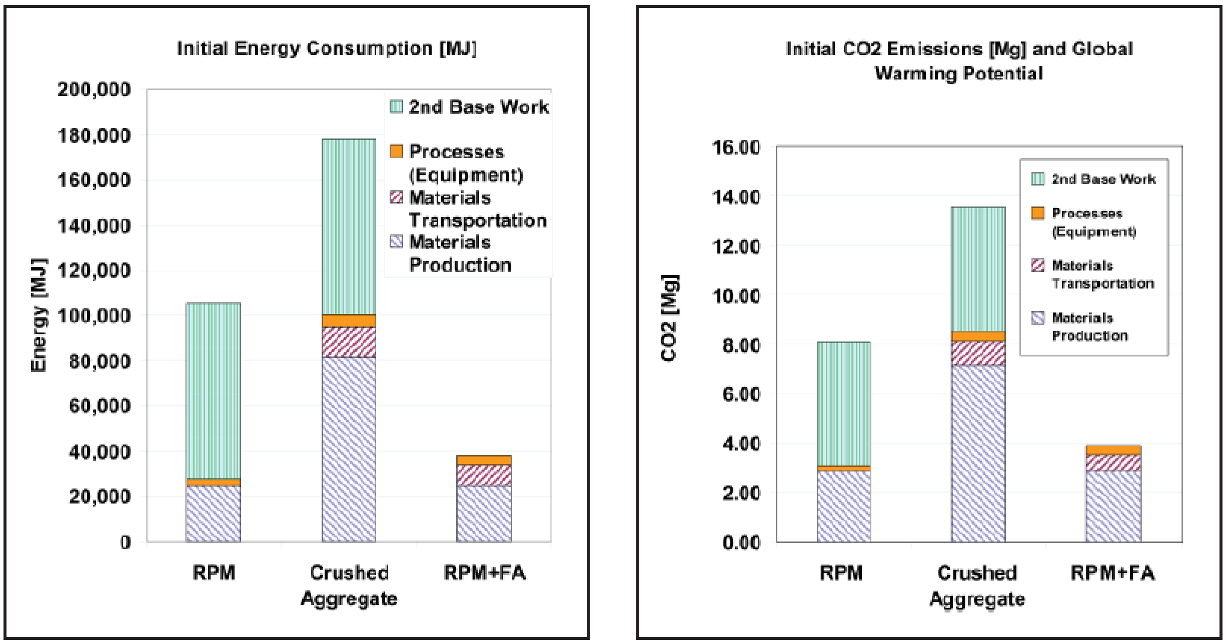

Figure 10. Comparison of energy consumption and CO2 emissions for RPM and RPM with fly ash (United States Environmental Protection Agency, 2008).

Furthermore, Huber et al. (2018) studied different scenarios for the treatment of municipal solid waste incineration (MSWI) fly ash in order to dispose it of. Two of their considered scenarios contain the same treatments which can also be used for ash recycling. Those are the cement solidification and thermal treatment which are required to remove the heavy metals from ash. They mentioned that both processes have considerable environmental impacts. However, some aspects can significantly reduce the negative environmental impacts of these processes like the amount of cement used for cement solidification as well as using different fuels for the thermal treatment process. they stated that it is important to precisely find the optimum required cement for cement solidification as they reduced the cement from 1000 kg to 300 kg and environmental impacts decreased greatly. Their results are presented below.

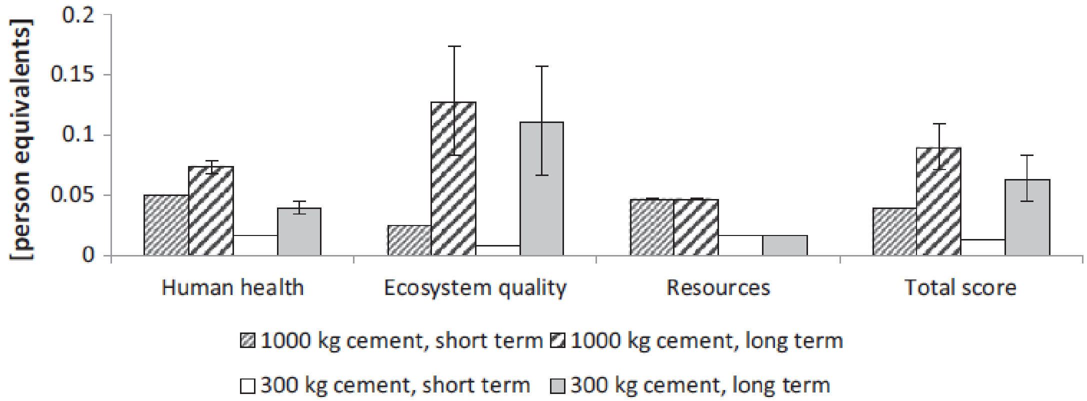

Figure 11. Effects of reducing cement in the cement solidification process in terms of environmental impacts (Huber et al., 2018).

Additionally, they investigated the effects of using diverse fuels for thermal treatment and their results demonstrate that utilizing natural gas can decrease the risks for human health and ecosystem compared to the use of hard coal (figure 12).

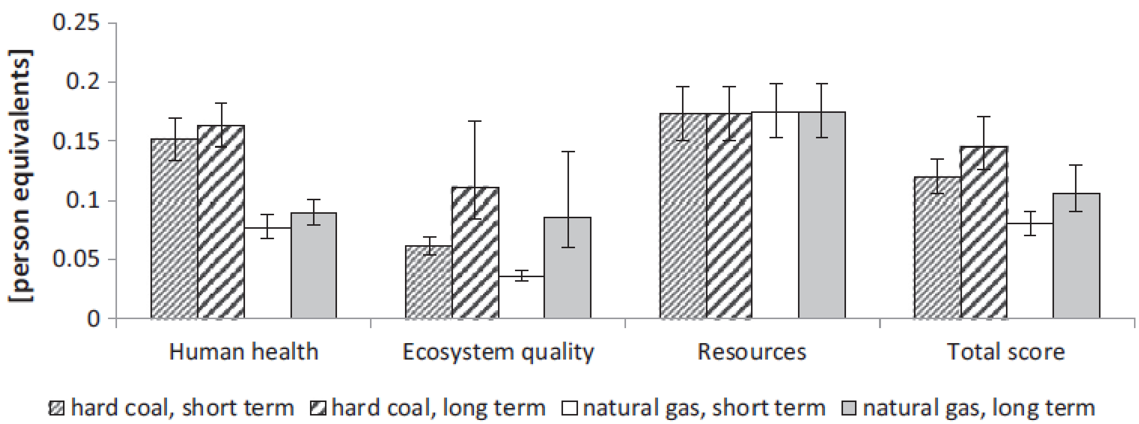

Figure 12. Effects of using different fuels for thermal treatment process in terms of environmental impacts (Huber et al., 2018).

Moreover, Dahlbo et al. (2015) evaluated the environmental impact and profitability of recycling five different source-separated C&D W in their different stages. Also, they evaluated the efficiency of these materials in terms of material recovery and energy recovery. Their considered processes for each of pretreatments, treatments, and recycling or recovery are shown in figure 13. In the next table, the LCA and cost results of the pretreatment processes of this research is shown. In addition, based on their results, metals have the highest material recovery share so that it is highly profitable as well. On the other hand, wood is mostly beneficial for the energy recovery and the rate of material recovery from wood is low. Concrete and mineral are just good for material recovery otherwise they are not environmentally friendly. miscellaneous is at a moderate range both in terms of environmental impacts and profitability. Finally, mixed waste which goes to landfill has the highest negative impacts on the environment.

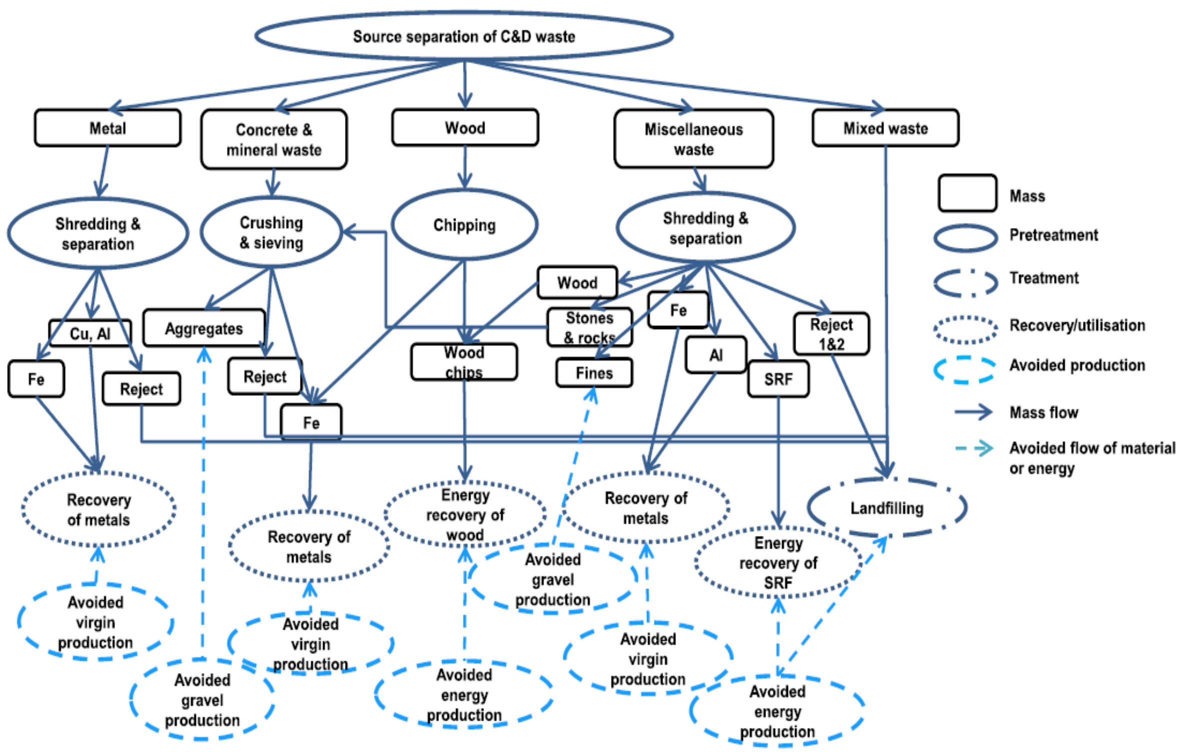

Figure 13. Considered processes for LCA analysis of C&D W (Dahlbo et al., 2015).

Table 6. LCA and cost results for the pretreatment phase of C&D W management (Mod. Dahlbo et al., 2015).

Waste fraction	**Pretreatment**	
	CC impact (kg CO2-eq/t of C&D W)	**Cost (€/t of C&D W)**
Metal	2.1	0.57
Concrete and mineral	0.67	2.9
Wood	1.3	0.82
Miscellaneous	4.3	1.3
Mixed waste	-	-
Overall C&D W	8.4	5.6

Furthermore, Coelho and Brito (2013) also evaluated the produced emissions from each of the treatment processes which are required for recycling C&D W. The exact amount of the produced Co2 emissions are shown in the next table. Their evaluations demonstrate that using the resulted materials from these processes instead of virgin materials in different applications can significantly reduce the emissions.

Table 7. Energy consumption and produced emissions from treatment processes for recycling C&D W (Coelho and Brito, 2013).

Equipment	**Power(kW/unit)**	**Energy utilized**	**Primary energy consumption for all installed units (kgoe/year)**	**CO2eq emission for all installed units (kg CO2eq/year)**
Scales	0.05	Electricity	35	42
Excavator	90	Diesel	18,576	56,322
Vibrating feeder	16.2	Electricity	11,275	13,530

Table 7 continues. Energy consumption and produced emissions from treatment processes for recycling C&D W (Coelho and Brito, 2013).

Equipment	**Power(kW/unit)**	**Energy utilized**	**Primary energy consumption for all installed units (kgoe/year)**	**CO2eq emission for all installed units (kg CO2eq/year)**
Magnet (ferrous metals)	6.5	Electricity	4524	5429
Manual separation cabinet	0.28	Electricity	136	164
Crusher	110	Electricity	76,560	91,872
Horizontal screen 1	18.5	Electricity	12,876	15,451
Air sifter	6.3	Electricity	9135	10,962
Eddy current separator (non-ferrous metal)	16.4	Electricity	7990	9588
Horizontal screen 2	22.3	Electricity	15,5544	18,653
Air jig	127	Electricity	476,189	571,427
Spirals	27	Electricity	114,631	137,557
Conveyors	variable	Electricity	49,010	58,812

Table 8. Prevented emissions by using recycled materials from the C&D recycling plant instead of virgin materials in different applications (Coelho and Brito, 2013).

C&D recycling facility output	**Replaced portion of the industrial process**	**Virgin raw material to be replaced**	**Industrial processes:**		**prevented energy and CO2 emissions**
			Primary energy (kWh/tones)	**Primary energy (kgoe/ton)**	**Emissions (kgoe/tons)**
Ferrous metals	From extraction to final stage input	Iron ore	2740	236	805
Non-ferrous metals (mainly aluminum)	From extraction to final stage input	Bauxite ore	47,083	4048	9944
Heavy metals	From extraction to final stage input	Ores of	Mercury Nickel Cadmium	24169 45559 -	2078 3917 -
Concrete aggregates (coarse) Concrete aggregates (fine)	From the extraction to the factory output gate	Limestone crushed aggreagtes	12.39	1.07	3.1

Table 8 continues. Prevented emissions by using recycled materials from the C&D recycling plant instead of virgin materials in different applications (Coelho and Brito, 2013).

C&D recycling facility output	**Replaced portion of the industrial process**	**Virgin raw material to be replaced**	**Industrial processes:**		**prevented energy and CO2 emissions**
			Primary energy (kWh/tones)	**Primary energy (kgoe/ton)**	**Emissions (kgoe/tons)**
Ceramic aggregates (coarse) Ceramic aggregates (fine)	From the extraction to the factory output gate	River/sea sand	9.58	0.82	2.2
Paper and cardboard	From the extraction to the factory input gate	Cellulose	5452	469	862
Plastics Woods	From the extraction to the factory output gate	Oil derivatives, wood particleboard and fiberboard	22,363 972	1923 84	3310 168

1.4 Processes and equipment

Depended upon the properties of the waste materials and requirements of the target application, different processes are needed for their treatment. In this part, various processes and machineries which are required for treatment of aforementioned materials are explained and shown in detail.

1.4.1 Separation

Sedimentation and filtration

Generally, sedimentation is a gravity-based method since the solids are settled and separated from the liquid material due to gravity. Three main equipment for performing sedimentation are thickeners, classifiers, and clarifiers. For large capacities, thickeners and clarifiers are quite inexpensive so that they are suitable for the pre-concentration of materials to be filtered. Although the main role of thickeners is to increase the concentration in the mixture of solid and liquid, clarifiers are implemented to separate the solid particles in order to generate clean sewage. In addition, the separation principle in classifiers is based on grain sizes. (Sorsamäki and Nappa, 2015.)

Both the thickeners and clarifiers contain a big round tank including blades at the bottom which are turning. For thickeners, the solid-liquid mixture is entered from the top and the clean liquid is egressed from the right side in the top, but the settled solid particles are exited from the bottom. The clarifiers are the same machines which they are mainly applied for producing clean liquid from watery suspension. (Sorsamäki and Nappa, 2015.)

According to Kinnarinen et al. (2016) and Golmaei (2018), for performing the sedimentation of the green liquor, the proposed equipment is the clarifier. The sludge blanket clarifier is one option in which the solid-liquid mixture is entered below a layer of flocculated slurry. It is appropriate for performing in large volumes, but it requires a lot of flocculants. The function of flocculants is to speed up separating as well as make it more effective. The other option can be the conventional clarifier, in the conventional one, the waste is passed through a dispensation case in the center of the clarifier in order to guarantee the equal distribution in each of the orientations in the clarifier.

On the other hand, the principle of the filtration process is that solid particles in a slurry are separated by using a porous medium which keeps the solids and flows the clean liquid. For clearing the porous medium, water is always enforceable. However, acid cleaning is sometimes utilized, and another option is to change the medium from time to time. Tubes, cassette, and cross-flow are the common equipment for filtration process, and (hyperbaric) precoat disc filters and chamber filter presses are suitable for detaching and washing of sludges. (Sorsamäki and Nappa, 2015; Kinnarinen et al., 2016.)

Based on the Golmaei (2018), the filtration process can be the cross-flow filtration or cake filtration. Cake filtration might be done by using or without using a precoat layer. In the case of not using the precoat layer, filtration is implemented via using a cassette filter besides as horizontal and vertical chamber filter presses. The end of the filtration process is whenever the sludge reaches its required thickness. Another investigated aspect of this article is related to the different parameters that can influence the filtration process. The results stated that the filtration properties can be improved by utilizing a filter cloth with higher penetration properties and applying elevated temperatures for the filtration process. Kinnarinen et al. (2016) made a comparison between possible equipment for performing sedimentation and filtration processes of the green liquor sludge which is shown in the next table.

Table 9. Advantages and disadvantages of different types of machineries for sedimentation and filtration processes (Mod. Kinnarinen et al., 2016).

Equipment	**Advantage**	**Disadvantage**
Clarifier	durability; reliability; small energy usage; functional for separating iron from green liquor	Poor efficincy in alkali recovery; require additional washing step; require utilizing a precipitating agent
Cassette filter	Does not need precoat; high alkali removal	poor stability of separated dregs; usually need additional thickener
Cross-flow filter	Does not need precoat; functional for separating suspended solids	Need for higher pressure to achieve enough capacity
Pressurized vessel disc filter w/ precoat	Higher filtration capacity; simultaneous separation and washing	increase in the number of discharged solids due to the precoat

Magnetic separation

Magnetic separation is one of the required steps for the treatment of different kinds of wastes. The principle behind the magnetic separation is to detach the magnetic materials from the non-magnetic materials. Generally, magnetic separation can be implemented in a wet or dry manner. Different sorts of magnetic separators are mentioned in Dobbins et al. (2007) study as follows:

- Wet high-intensity electromagnetic separators (WHIMS)
- Wet low-intensity drum separators (LIMS)
- Dry high intensity induced roll magnetic (IRM) separators
- Dry low-intensity drum-type separators or ‘scalper’ magnets
- Dry high-intensity rare-earth drum (RED) separators, and
- Dry high-intensity rare-earth roll (RER) separators

Based on the Dobbins et al. (2007), although IRM separation is formerly applied in the mineral industry sector, nowadays RER separators have substituted them due to their higher capacity with lower costs. Usually, before using RER separators, materials which are extremely magnets like chromite and garnets are extracted. Also, RER is a suitable model for the last cleaning stage for those valuable materials like rutile and zircon. The RED model is suitable for a higher production rate than the RER one. A good comparison between different magnetic separators can be found in the following table from the mentioned research.

Table 10. A comparison between available magnetic separators (Mod. Dobbins et al., 2007).

Criteria	**Roll separator**	**Dry drum separator**	**SLon WHIMS**
Ferromagnetic material (magnetite, tramp iron)	Scalper model (poor strength) with a durable thick belt	Small amount tolerated (<1%), utilizing release bar	Needs to be scalped first by LIMS
Highly paramagnetic material (ilmenite, garnet)	Average-strength with high throughput, durable thick belt	High-strength, release bar needed, high feed rate, lower separation sharpness compared to the roll	High efficiency if wet process is desired
Moderately paramagnetic (biotite, leucoxene, monazite)	Great efficiency, greater grade and recovery in contrast with electromagnets	No use	High efficiency if wet process is desired
Weekly paramagnetic (muscovite, amphiboles, pyrite, cleaning of quartz, feldspar, zircon, rutile)	High efficiency, greater grade and recovery in contrast with electromagnets	No use	Moderate efficiency
Operations and maintenance	Minimal attendance, simple substitution process for belt	Minimum requirement for presence of operator, substituting drum shell needs qualified shop work	Minimal attendance, significantly lower than a horizontal WHIMS model
High throughput	150 mm models supplying 1.5x throughput of 100 mm roll	Large throughput with 610 mm diameter drums. Bigger drums are accessible as well.	80-150 tph with biggest model 2500
Elevated temperature	+120 °C if required	Up to 100°C	No use

Table 10 continues. A comparison between available magnetic separators (Mod. Dobbins et al., 2007).

Criteria	Roll separator	Dry drum separator	SLon WHIMS
Process control	Broad range of parameters, highly flexible for controlling	Average possibility for adjustements	Average possibility for adjustements

Triboelectrostatic separation

The system contains three main sections. In Section 1, the material is fed to the triboelectrostatic separator with the help of air. In the second section, the charge is produced by friction roller and chamber wall. Increasing the speed of the friction roller leads to producing more charges. Finally, section 3 is where the charged particles are conducted to negative or positive electrodes and become separated. The next figure schematically shows the structure of a triboelectrostatic separator. (Zhang et al., 2018.)

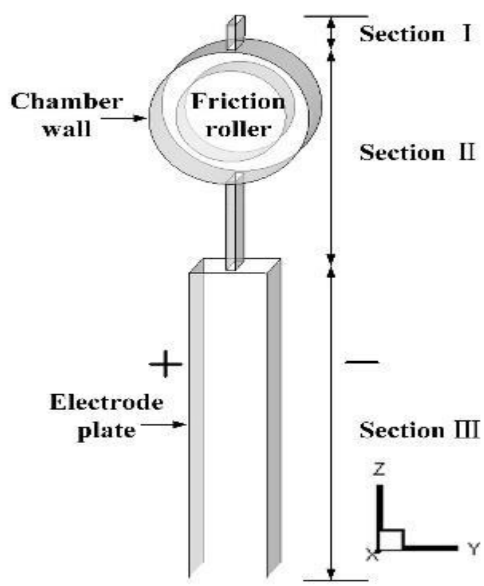

Figure 14. Triboelectrostatic separator (Zhang et al., 2018).

According to Zhang et al. (2018), the plate voltage is a factor that can have a great effect on the separation quality. Different voltages were examined in this research and the optimum separation efficiency was observed at the 24 kV. Based on the Soong et al. (1999) study, another significant factor that can impact the efficiency of separation is the material of tribocharger. For instance, the advantage of Teflon tribocharger compared to the copper one is its higher separation rate. In addition, for Teflon tribocharger most of the particles are accumulated in the negative electrode, but copper is in the positive electrode.

Air classifier

In an air classifier, materials are separated according to their different density, size or shape in the presence of airflow. The efficiency of separation is higher if the particles moving rotationally due to the centrifugal force. The pros and cons, in this case, are inexpensiveness, simplicity of equipment but with too much dead flow. (Vesterinen, 2003.)

Various types of air classifiers are accessible in the market. The easiest structure of air classifiers belongs to the falling bed aspirator in which the material drops due to the gravity with the present of an air current. The light material passes with the air and the coarser one drops. This type is suitable when there is a wide difference between material densities and sizes. Another type of air classifier is the rotary air classifier. These models are also called dynamic or whizzler. This model contains a rotary circular disc in which the material falls on. Under that disc, there is a fan to produce airflow. Heavy material falls from the disc to hopper, while the light material, which is carried with air upward, is conducted to another hopper. These types of classifiers are cheap, but they are only efficient for the materials between 300 µm to 40 µm. Finally, for some cases that high accuracy is demanded, turbo classifiers can be used. In this model, the airflow is generated by another device rather than the classifier. In this type the rotating rotor is used for separating material depending upon their size. (DeCenso, 2009.)

Hydrocyclone

Hydrocyclone principally separates the material based on their size or density with the help of centrifugal force. Hydrocyclone is greatly utilized for clarifying liquids, washing and thickening purposes, and separating the solids. Some of the privileges of hydrocyclones compared to the gravity-based separators include plain design, inexpensiveness, high feeding rates, simple maintenance, and its small size. Furthermore, another advantage of hydrocyclones for the mining sector is that they can be designed as portable equipment so that it decreases investment cost as there is not a need to transfer the sand to the ponds and it can be processed directly in the mining site. The following figure shows the structure of a typical hydrocyclone. (Ghadirian et al., 2015.)

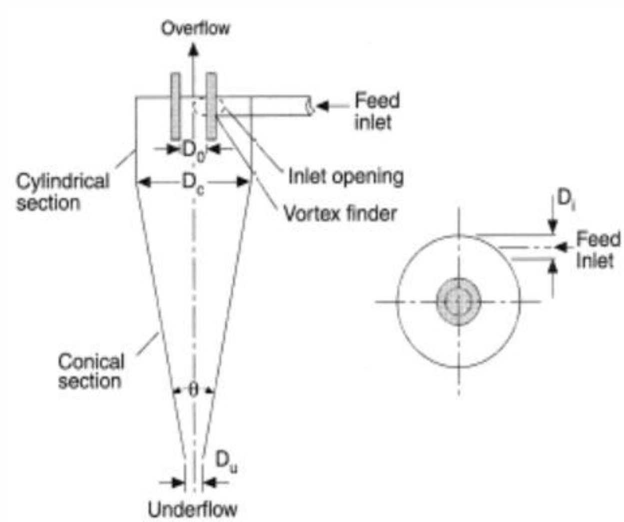

Figure 15. Hydrocyclone structure (Bradley, 2011).

Optical sorting

The creation of light spectrophotometry (LSP) method backs to the chemical industry sector as they used this method for the separation of chemicals based on their color. Afterward, this method was introduced to the recycling sector as well. One advantage of this technique is that it can be utilized for separating various glasses with different colors from each other as well as separating glass from ceramic. The principle behind this method is that different colors have their own wavelengths than can be then used as the base of separation. Consequently, the optical sorters separate materials by identifying their wavelengths. Since this is a complex process, for achieving high efficiencies, developed equipment is required. (P. Duffy, 2015.)

After the LSP method, the technology was developed and the near-infrared (NIR) separators were introduced. The difference between NIR and LSP is that NIR sensors can separate materials based on the density besides color which makes them capable of separating various sorts of plastics in addition to glass. Both the LSP and NIR sensors are integrated with a device that produces a current of air so that the air can conduct the particles to their proper collecting area. (P. Duffy, 2015.)

Nowadays, there are quite a lot of different optical sorters in the market as the technology of optical sorters have been developed significantly. Various sorts of optical sorters include Mid Infrared (MIR); Visual Imaging Sensor (VIS); Cyan, Magenta, Yellow, and Black sensors (CMYK); Red, Green and Blue sensors (RGB); extended-spectrum color sensors; and high-resolution color cameras which is for separating different types of materials and fibers. The efficiency of the process is much higher by applying two or more optical sorters simultaneously. Using combined optical sorters can increase the speed of the separation process to about 4 to 6 meters per second. Through this process, the efficiency rate of the separation can be up to 90 %. Optical sorters are applicable for separating various kinds of materials from glass and plastic to diverse sorts of fibers. They can be programmed to separate different materials in different runs. (P. Duffy, 2015.)

Eddy current separation

Eddy current separator is applied for separating non-ferrous metals like aluminum. This method is more efficient for separating particles which are bigger than 5mm. A common structure of drum eddy current is shown in figure 16. The trajectory of materials which are not metals in figure 16 is shown with 2 and route 1 presents the trajectory of non-ferrous metals. Depended upon the direction of the rotating rotor, eddy current separators are classified to forward mode (B in figure 16) which is in the exact direction of head drum and backward (A in figure 16) mode which is in the opposite direction. (Gulsoy et al., 2010.)

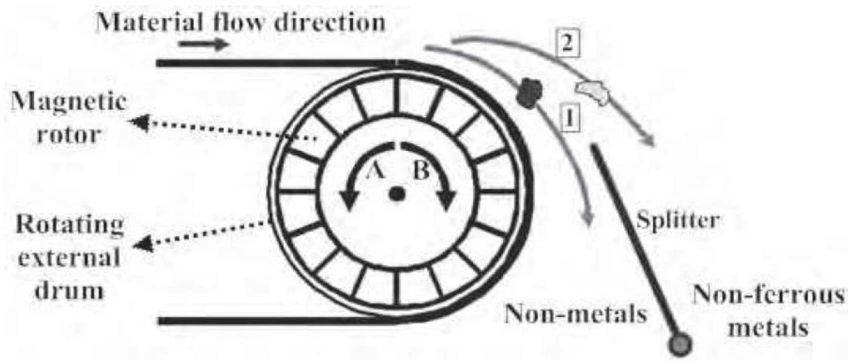

Figure 16. Eddy current separation (Gulsoy et al., 2010).

Based on the results of Gulsoy et al. (2010) research, through eddy current separation, up to 70 % of non-ferrous metals can be separated. High electrical conduction and low density can help to increase the efficiency of eddy current separation.

1.4.2 Washing and dewatering

Generally, depended on the demanded solid content, different equipment can be used for dewatering. Thickeners and hydrocyclones are suitable for thickened slurries in order to give them the desired drying content. Drum and filters are mostly applied for products which are not highly moist. (Lottermoser 2010; Davis, 2007.)

According to Golmaei (2018) for performing the washing stage for green liquor sludge, washing clarifiers, vacuum filter, and pressure filters are suitable. The advantage of utilizing the vacuum precoat filter compared to the washing clarifier is that it needs less water. However, the rate of loss of alkali is much greater. Also, in some new plants dregs centrifuge and decanter-type centrifuges are exerted as well.

1.4.3 Crushing

Crusher is a piece of equipment which is used to crush things and make them smaller. Crushers are mainly utilized for waste materials to decrease their size or alter their shape in order to simplify their disposal or recycling. Also, for mixed waste materials, when they are in smaller sizes, they can be classified easier. The process of crushing is done in such a way that a mechanical force is applied to the object which is handled between two surfaces and makes them deformed or fractured. (Balasubramanian, 2017.)

Generally, crushers are categorized into two head types including compression crushers which crush the materials by high pressure between two surfaces and impact crushers which use striking for crushing. Compression crushers include jaw, cone, gyratory, and roller machines and impact crushers are impactors and hammer mills. (Metso, 2011.)

Jaw crushers

Jaw crushers are generally one of the primary crushers. The target is to reduce the size of materials to be handled in belt conveyors for further crushing steps. There are two jaws in which one of them can move and one cannot. Crushing carries out between these two. Two main sorts of jaw crushers are the single and double toggle. The privilege of single toggle compared to the double one is its higher capacities. Structure of the single toggle and double toggle crushers can be seen in the next figures. (Metso, 2011.)

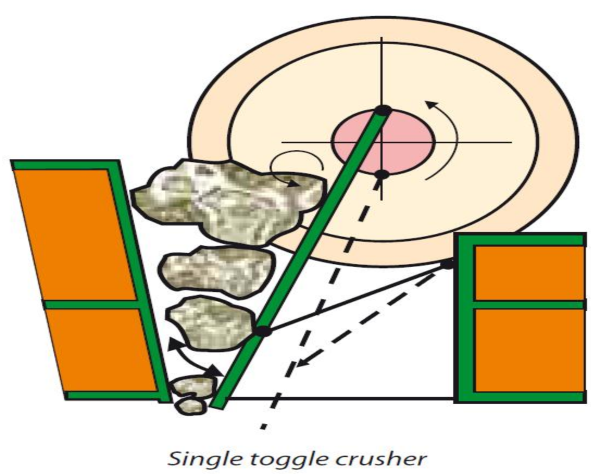

Figure 17. Single toggle crusher (Metso, 2011).

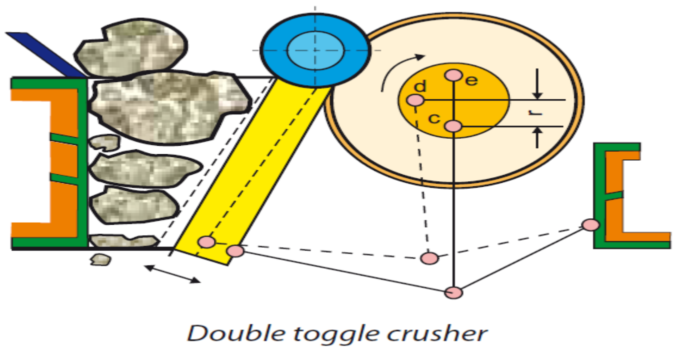

Figure 18. Double toggle crusher (Metso, 2011).

gyratory crushers

The operating principle of gyratory crushers is the same as jaw crushers. The aim of designing these crushers is to give an optimum feeding rate for primary crushing and to raise the crushing capacity rate in the mining industry. The next figure demonstrates the structure of a gyratory crusher. (Balasubramanian, 2017.)

Figure 19. Gyratory crusher (Metso, 2011).

Cone crusher

Cone crushers have four different sorts including compound, spring, hydraulic, and gyratory. The operating principle of cone crushers is the same as gyratory crushers but with lower precipitousness in the crushing place and more parallel area in the crushing area. This kind of crusher is proper for crushing rocks with mid to high hardness. (Balasubramanian, 2017.) Figure 20 shows the structure of this kind of crusher.

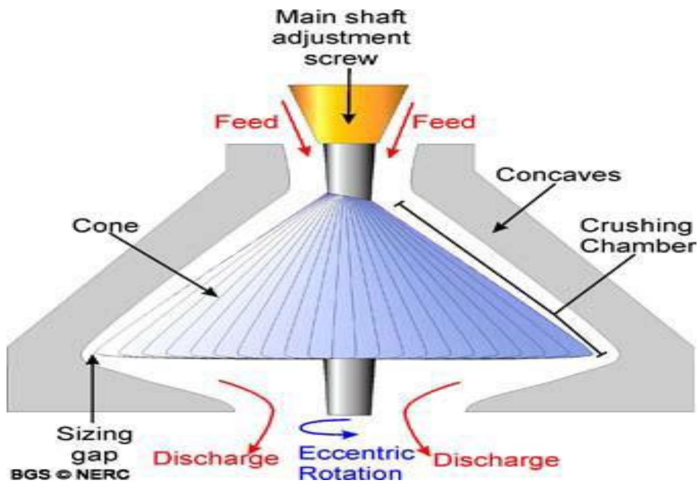

Figure 20. Cone crusher (Metso, 2011).

Impact crusher

Impact crushers are classified into two major sorts. HSI contains horizontal shaft and VSI consists of a vertical shaft. These kinds of crushers are suitable for making cubic objects and if the feeds are not too small, their size can be considerably reduced with these crushers. The advantage of this option is that for a lot of cases, with performing just one crushing step, the desired size can be achieved and there is not a need to perform many crushing steps as it is usually needed for other crushers. Impact crushers are generally utilized for non-abrasive materials. (Metso, 2011.)

The next figures demonstrate the structure of these two categories of impact crushers.

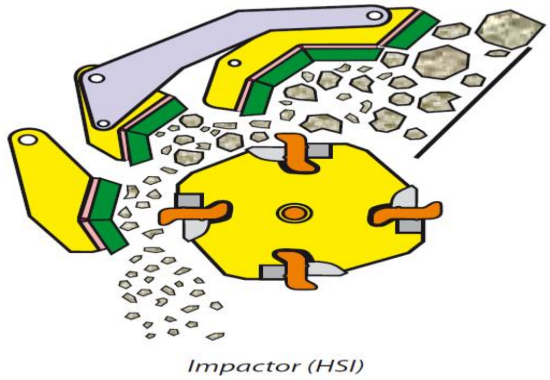

Figure 21. horizontal-shaft impact crusher (Metso, 2011).

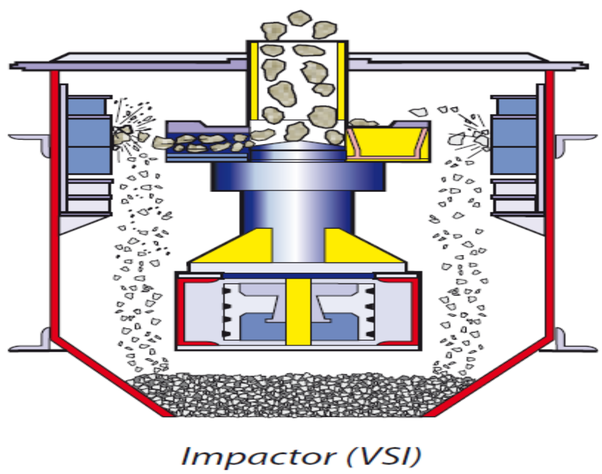

Figure 22. vertical-shaft impact crusher (Metso, 2011).

Hammer mills

Operation principle of hammer mills is the same as impact crushers just for hammer mills, their rotor contains a lot of axis hammers on it and its exit part contains a lattice that the material should pass it. Hammer mills are suitable for abrasive and soft materials. (Metso, 2011.)

The following table is provided from the Metso Group brochures and it indicates the specifications of different types of crushers which can be used in various process stages.

Table 11. Specification of different types of crushers (Metso, 2011).

Major crusher type	**Typical process stage**	**Feed size up to (mm)**	**Typical maximum end product size (mm)**	**Typical capacities (t/h)**	**Abrasiveness**		**Number of fines produced**	**Product shaping**
					Low	High		
Gyratory crusher (large)	Primary	1500	200-300	Over 1200		×	Low	
Jaw crusher	Primary	1400	200-300	Up to 1600		×	Low	
Horizontal impact crusher	Primary/ secondary	1300	200-300	Up to 1800	×		Medium/ high	Yes
Cone gyratory crusher	Secondary	450	60-80	Up to 1200	×	×	Low	
Cone gyratory crusher	Tertiary	300	0-30	Up to 1000	×	×	Low/ medium	Yes
VSI Barmac, B series	Tertiary	40	0-30	Up to 600	×	(×)	High	Yes

1.4.4 Screening

The principle of screening is to separate materials based on their sizes from 300 mm to 40 µm. However, for the smaller materials, the efficiency is lower compared to bigger feeds. Usually, dry screening is capable of separating materials at a minimum of 5 mm size, but wet screening can separate materials to about 250 µm. Separating to 40 µm size can be done by screening and lower than to 250 µm can be performed by classification. For choosing screening or classification, one important point should be considered that for tiny materials separation, a big surface area for screening is required which makes it more expensive compared to classification in this case. Screens commonly have a lattice with a lot of holes in equal sizes. If the particles are bigger than the holes, they remain on the surface and if they are smaller than the holes, then they pass it. (Wills and Napier-Munn, 2005.)

Screen types

Various kinds of screening machines have been produced. The most common type in the industry sector is the vibrating screen which itself has different sorts. Some of the screening machines are explained below, but some more screens are also available in the market like static, trommel, rotaspiral, flip-flow, roller, linear, circular, and dewatering screens. (Wills and Napier-Munn, 2005.)

Vibrating screens

Vibrating screens contain a surface area for screening and big opening and exit parts. Vibrating screens are suitable for separation, dewatering and washing purposes. There is a possibility to produce a vibrating screen with two or more screening deck. In these types of screens, the material is fed to the top screen and then the smaller fraction pass to the next decks. In this way, various fraction sizes of materials can be achieved in just one screening step. (Wills and Napier-Munn, 2005.)

Inclined screens

Inclined screens are one of the popular screens in which the rotating can happen contra-flow or in-flow. The benefit of contraflow is its higher efficiency due to smaller speed, while inflow can handle higher capacities. (Wills and Napier-Munn, 2005.)

Grizzly screens

Grizzly screens are one of the inclined screens which are used for very large materials. Their inclined angle is generally set on the 20 degrees and they drop the material circularly. The equipment capacity is more than 5000 tons per hour. This kind of screens is usually used before the primary and secondary crushing stages. (Wills and Napier-Munn, 2005.)

Horizontal screens Horizontal, low-head or linear vibrating screens

These screens have a horizontal or almost horizontal surfaces so that they have smaller headroom compared to the inclined screening equipment. In addition, they are more accurate than inclined screens, but they can handle lower capacities as passing the material is less helped by gravity. This model is proper for applications which demand efficient sizing. (Wills and Napier-Munn, 2005.)

Resonance screens

They are one of the categories of horizontal screens in which their frame is attached to the screen with the help of rubber buffers with the same natural resonance frequency to each other. (Wills and Napier-Munn, 2005.)

Banana screens Banana or Multi-slope screens

These screens are generally applied for high volume materials in which efficiency is significant as well. Their capacity is usually triple or quadruple of the other common vibrating screens. These screens generally contain a linear-stroke vibrator. (Wills and Napier-Munn, 2005.)

1.4.5 Shredding

One of the required treatments for fiber rejects is shredding. The shredding process aims to provide the demanded size of the particles for the next stages. Based on the process, shredding can be carried out in one step but most of the time, it is performed in two steps, coarse and fine shredding. The suitable equipment for coarse shredding is double-shaft (rotary shears) or single-shaft shredders. However, for the fine shredding, high-speed single-shaft shredders are suitable as they can provide uniform fragment dispensation. Most of the time, for pressing the material plus the rotor and knives, hydraulic pressure is applied. After the shredding, the material usually goes to the screening process. To control the material size, aperture sizes, and knife shapes can be changed. (Andritz, no date.)

1.5 Research scope and objectives

The main target of this project is to investigate the best methods in which the local wastes and side stream materials can be utilized to produce geocomposite by the 3D printing process. The study focuses on five different waste materials from the South-Karelian market in Finland including flotation sand, green liquor sludge, construction and demolition waste, ash and fiber reject.

To fulfill this aim, the current legislation about waste management in Europe is investigated to detect the governing rules about this specific field. Various possible separation, pretreatment and treatment procedures, as well as the required equipment, are evaluated. These practices are compared regarding different aspects including the environmental impact of each of these processes in terms of energy consumption as well as the economic aspect of the selected methods to identify the most cost-effective process.

2. MATERIALS AND METHODS

This project seeks to inclusively inspect the best practices for the treatment of waste materials which are using to make geocomposite. The literature review is carried out to review the available researches in this regard as well as to support choosing the most appropriate processes and equipment which are needed in the system. The emphasize is on utilizing scientific journals, textbooks and organization publications. The legislation is accessed by using published European directives.

After the selection of the processes, the required annual investment and energy cost for running such a project are calculated. For estimating the investment, the cost of machineries is obtained by contacting the vendors and for the other items like the factory building costs, installations, maintenance, insurance and labors, some estimations are carried out based on the previous experiences. Also, for evaluating the energy cost, specifications of each equipment are utilized to find their energy consumption and the energy expenses are calculated based on the cost of 0.15 euros per kWh which contains the cost of electricity, transfer cost as well as basic fuse payment.

Finally, the environmental effect of the selected processes is evaluated in terms of their required energy consumption derived from the specifications of machineries. In addition, for assessing the reliability of these results, they are compared with the results of some other researches in this respect.

3. RESULTS

3.1 Processes

In this section, all the possible processes for the treatment of the intended materials are presented. The specifications of the provided machineries in this part have been collected by contacting the manufacturers or using the provided information on their websites. However, since some of them are confidential information, they are just presented without indicating the companies' names and equipment models and the aim is to evaluate the treatment of wastes materials by utilizing the available equipment in the market. The considered capacity of the waste materials for this research is about 8000 tons per year for each material. The machineries which are selected can handle the processing capacity of 20 tons per hour.

3.1.1 Green liquor sludge

Figure 23 shows the procedure for treatment of green liquor sludge. Based on the results of the previous researches for separating the sludge from the green liquor as the filtration has higher efficiency than that of the sedimentation, filtration with a cross-flow filter is selected in this research. Cross-flow filter is picked because of its wide use in the industry. Afterward, the washing and dewatering are performed using a vacuum drum filter with the specifications presented in Table 13. The privilege of vacuum drum filter compared to the other available equipment is its less requirement for water utilization.

If the hazardous materials like Cd, Zn, Pb, and Ni existed in the composition of green liquor sludge, then the hydrocyclone is required for their separation. In the composition of the available green liquor for the current research, those materials do not exist so that implementing hydrocyclone process is not needed in this case.

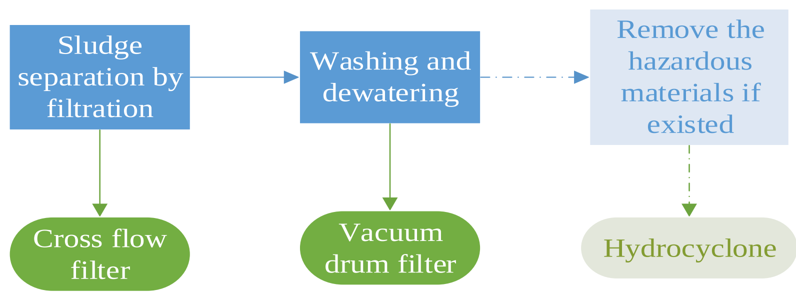

Figure 23. The required processes and equipment for green liquor sludge treatment.

Based on the available capacity and considered throughput of the equipment, the cross-flow filter, model 5 of the next table is selected.

Table 12. Dynamic membrane cross-flow filter specifications.

Type	**Filter area (m^2)**	**No. of filter modules (-)**	**Filter diameter (mm)**	**Drive (kW)**
1-	0.013	1	145	0.5
2-	0.13	5	145	3
3-	0.4	10	200	< 5.5
4-	1.8	12	335	< 15
5-	8 / 4.8	20 / 12	550	≤ 55
6-	12	12	850	≥ 45

By considering the same strategy for selecting the proper cross-flow filter and based on the properties of the available green liquor sludge, for performing the washing and dewatering stage, the vacuum drum filter with the following specification is selected.

Table 13. The information of vacuum drum filter for washing and dewatering of the green liquor dregs.

Material	Stainless steel
Power	1.5 kW
Diameter of drum	600 mm
Diameter of mesh	20 µm

If performing the hydrocyclone process is required, then the model 10 from the next specification can be a suitable option for this case.

Table 14. Hydrocyclone specifications.

Model	Diameter (mm)	Inlet pressure (MPa)	Capacity (m^3/h)	Cut size (µm)
1	840	0.04-0.15	500-900	74-350
2	710	0.04-0.15	400-550	74-250
3	660	0.04-0.15	260-450	74-220
4	610	0.04-0.15	200-300	74-200
5	500	0.04-0.2	140-240	74-200
6	400	0.06-0.2	100-170	74-150
7	350	0.06-0.2	70-160	50-150
8	300	0.06-0.2	45-90	50-150
9	250	0.06-0.3	40-80	40-100
10	200	0.06-0.3	25-40	40-100
11	150	0.08-0.3	14-35	20-74
12	125	0.1-0.3	8-20	25-50
13	100	0.1-0.3	8-20	20-50
14	75	0.1-0.4	4-10	10-40
15	50	0.1-0.4	2-5	7-40
16	25	0.1-0.6	0.3-1	5-20
17	10	0.1-0.6	0.05-0.1	1-5

In each of the treatment lines between the processes, conveyors are required to transfer the materials to the next process. A conveyor with a capacity of 20 tons per hour needs almost 3 kW power.

3.1.2 Ash

The following flow charts show three proposed processes and their required equipment for ash treatment.

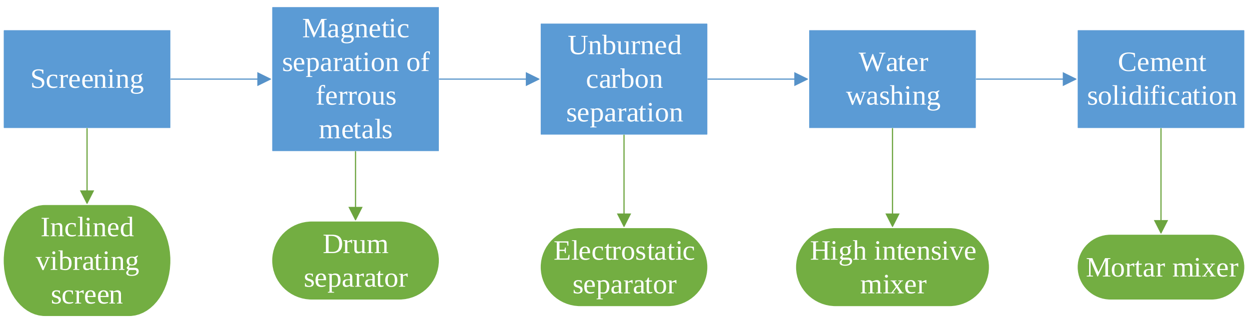

Figure 24. The first proposed process and their required equipment for ash treatment.

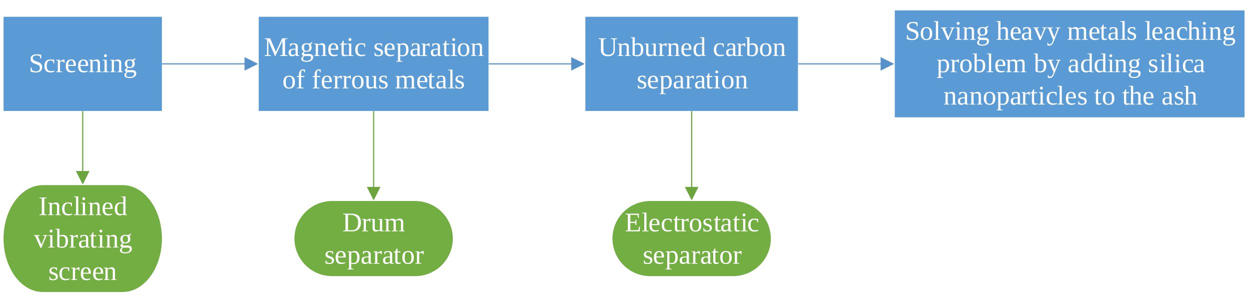

Figure 25. The second proposed process and their required equipment for ash treatment.

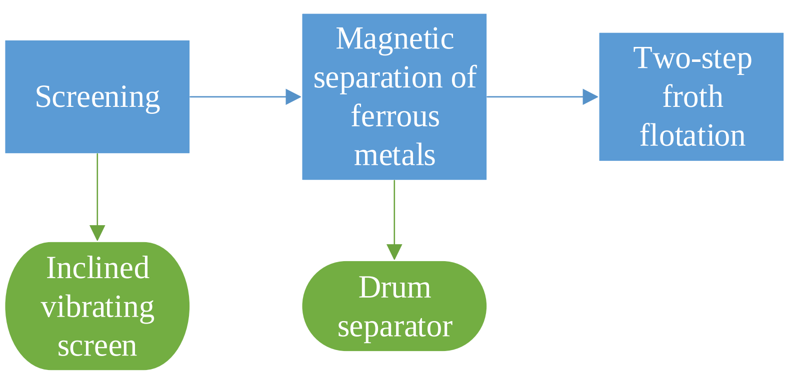

Figure 26. The third proposed process and their required equipment for ash treatment.

The first step in ash treatment is screening for removing different undesired impurities existing in ashes. Screening can be done using the inclined vibrating screen equipment. Vibrating screens can efficiently separate the fine particles and they can be used for both wet and dry feeds, so they are suitable for screening of ashes. The available ashes for this research are in the size of 2-4 mm. Consequently, based on the size and the needed capacity, the following machine is appropriate for this requirement.

Table 15. Inclined vibrating screen specifications.

Machine size (mm)	1830 × 4878
Machine weight (kg)	6805
Bearing bore	140 spherical roller bearings
Max feed size (mm)	200
Operating angle (degrees inclined)	15-20
Max required power (Kw electric motor)	18.5
Eccentric operating speed (RPM)	800-860

The second required step is magnetic separation by a drum separator. Drum separators can be efficient even in separating week magnetic particles. The specifications of the selected equipment for this purpose is as follows.

Table 16. Drum separator specification.

Type	Dry processing
Magnet	Rear earth permanent magnet
Overall dimensions (mm)	1880 × 1180 × 1460
Approx. self-weight (kg)	3500
Diameter of permanent drum (mm)	600
Length of permanent drum (mm)	1200
Number of permanent drums	1
Magnetic intensity on drum (Gs)	3000

Table 16 continues. Drum separator specification.

Feeding size (mm)	-18
Processing capacity (t/h)	-35
Rotating speed of drum (r/min)	16-30
Power of motor (Kw)	2

Afterward in the first and second processes, the electrostatic separator is required for carbon extraction. Both the triboelectrostatic or high-tension roller separators can be used for this regard. The advantage of triboelectrostatic separator is that it is a newer version compared to the high-tension roller and it consumes less amount of power. However, the number of manufacturers for triboelectric separator is limited. Based on the Zou (2008) research, for triboelectrostatic separator, approximately 1 kWh power consumption per ton of material is required.

Next in the first process, for removing the salts and heavy metals water washing and cement solidification are suggested which are the most used methods in the industry sector. Water washing can be performed using deionized water. Different kinds of mixers can be utilized for this regard like the conventional paddle mixers, but the high-intensive mixers require less usage of water. A mixer which has the capacity of about 1900 liter working volume, consumes about 45 kW power and generally their cycle time can be about 6 minutes. For cement solidification, the process can be performed in a mortar mixer. A mortar mixer with the capacity of 12 cubic feet (almost 0.34 cubic meter) requires 5 horsepower (almost 3.73 kW).

In the second process, adding silica nanoparticles is proposed for eliminating the leaching problem of heavy metals as they trap the heave metals and they do not allow them to leach out. This method is studied by a research group in Singapore and it is not used on a wide scale. However, it has great potential to be dominated in the future since the washing process requires consuming a lot of water which is finally contaminated with salts and heavy metals and needs another treatment to be cleaned.

In the third process, the treatment steps are reduced by performing two-step froth flotation. This is an inventory method proposed in the Liu et al. (2017) research. Currently, this method is only feasible in the lab-scale and it is not used in the industry widely compared to the washing/solidification, but the advantage of this method is using less equipment which can considerably affect the energy consumption and the cost. However, in the condition of using this method for big volumes, water consumption should be carefully investigated.

One point should be considered about removing heavy metals in the first and third processes. Both the washing/solidification and the froth flotation can remove Al from the materials. As a result, in some conditions like producing geocomposites which Al should be kept in the composition, this becomes a challenge.

3.1.3 Fiber reject

The main steps for treatment of fiber rejects are like the following flow chart.

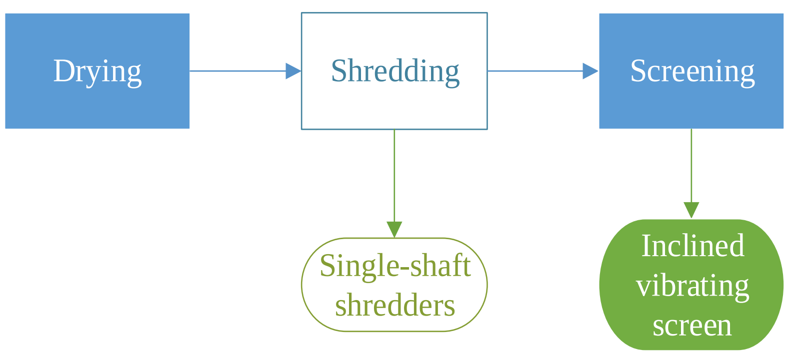

Figure 27. The required processes and equipment for fiber reject treatment.

Fiber rejects can be wet after the pulping process, drying might be needed to not have negative effects on the bonding between fiber and matrix. However, performing this step is strongly depended on the target application. If it is needed, then they can be dried by exposing them to the open air. Fiber rejects, in this research project, are outlined to be utilized as reinforcing fiber for producing geocomposites and in this case, the moisture content is required for good performance in the geocomposite and drying is eliminated for this application.

For the next step, as it has been explained in the part 1.4.3, performing the shredding stage is depended on finding the optimum length of the fibers as reinforcing fiber in geocomposites which is not in the scope of this research. If shredding is needed, then the selected equipment is model 2 from the next table.

Table 17. shredding machine specification.

Model	**Funnel (mm)**	**funnel volume (m^3)**	**Motor power (Kw)**	**Dimensions L×B×H (mm)**	**Weight (Kg)**	**Emission dB (k=4Db)**
1	510×810	0.4	15	1750×1100×1640	1000	75
2	630×810	0.6	18.5-22	1750×1200×1640	1200-1400	75
3	830×1000	1	18.5-37	2290×1420×1750	1500-1700	76
4	1030×1235	1.5	22-45	2460×1980×1750	2000-3000	76
5	1230×1235	2	22-45	2460×1980×1750	2500-3500	77
6	1530×1235	2.5	30-75	2460×2100×1750	3000-4000	78

Finally, the presence of some tiny particles between fiber rejects can cause different problems like dusting. For solving these problems, the screening process with an inclined vibrating screen is applied. The machine specification is the same as the screen used in the part 3.2.2 for ashes.

3.1.4 Flotation sand

Generally, coarse and fine flotation sands are separated from the water in tailing dams through the natural sedimentation process. As it is explained in the part 1.4.4, CO_2 can be added to the tailing before the sedimentation process to decrease the tailing volume and to adjust the water PH as well as to speed up the sedimentation process. The available flotation sand in this project is already in the desired size for 3D printing which is 2-4 mm so that crushing is not needed in this case. Finally, because of the possibility of existing some impurities in the remained flotation sand, a screening step should be carried out to remove those impurities. For implementing this step, the exact vibrating screen which is introduced in the part 3.2.2 for ashes is performed here as well. This procedure can be seen in the next figure.

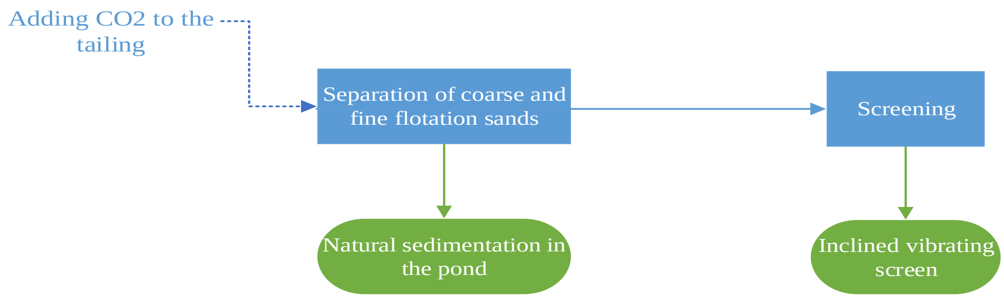

Figure 28. The required processes and equipment for flotation sand treatment.

3.1.5 Construction and demolition waste

The following flow chart shows the whole procedure for the treatment of C&D wastes and it presents all the separation methods for detaching different materials that can be existed in the C&D wastes. Depending on the target application, some materials might be needed to remain in the waste and not separated for recycling so that based on the end application, the required separation techniques must be selected and performed. The available C&D waste for this research is specifically underflow of the screen. They are the tiny crushed particles detached from the material flow with a maximum size of 16mm.

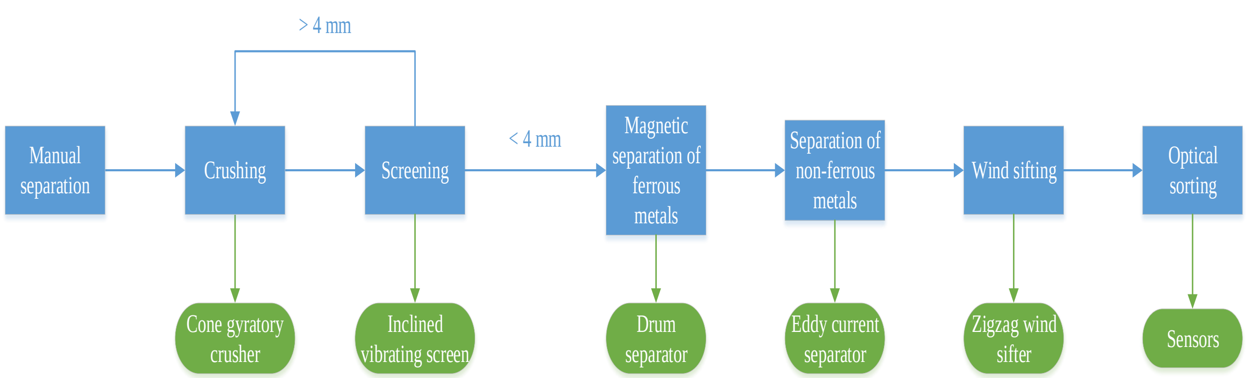

Figure 29. The required processes and equipment for C&D W treatment.

As can be seen from the above flow chart, firstly coarse woods, plastics, and metals are separated manually. Through this process, those materials like metallic ones that can cause damages to the crushers are separated.

The largest available construction and demolition wastes in this project are about 16 mm in size and the demanded size for 3D printing of the raw material is 2-4 mm. The capacity of the raw material for processing is about 8000 tons per year. Regarding these data, the selected crushing machine for the construction and demolition waste is cone crusher from the following table, and as the demanded end size cannot be reached right away by one crushing process, performing a screening process and secondary crushing are required.

The aim of the screening step is to provide two fractions of materials. Those particles which are bigger than 4mm will return to the crusher for secondary processing and underflows of the screen which are smaller than 4mm will transfer directly to the magnetic separation process. Due to the same reasons as ashes, the machine concept for screening is exactly like the previously used screen in the part 3.2.2.

*Table 18. Cone crusher specification***.**

Maximum feed opening (mm)	95
Minimum discharge opening (mm)	10
Weight (kg)	5300
Capacity (t/h)	20
Max required power (kW electric motor)	37-45
Eccentric operating speed (RPM)	630

Thereupon, magnetic separation is implemented for separating ferrous metals. For this step, the drum separator which is introduced for ashes has been selected with the aforementioned specifications. The function of eddy current separator is to remove the non-ferrous metals, specifically it is useful for separating aluminum from the waste materials. The model with 20 tons per hour capacity is selected for this regard from table 19.

Table 19. Eddy current separator specification.

Name	**Maximal productivity (t/h)**	**Quantity of electric engines, pcs.**	**Overall power consumption (kw)**	**L (mm)**	**B (mm)**	**H (mm)**	**Diameter of magnetic roller (mm)**	**Width of operation, area B1, (mm)**	**Weight (kg) no more**
1-	1		3.3		1420			200	800
2-	3		3.7		1615			300	900
3-	7		6.0		1815			500	1200
4-	10		6.0		1915			600	1300
5-	15	2	8.5	2200	2115	1000	322	800	1700
6-	20		8.5		2390			1000	2000
7-	25		11.0		2600			1200	2400
8-	30		14.0		2915			1600	3000

As it is explained previously, for separating wood, plastics, and dust, the wind sifter is needed. The chosen equipment for this purpose is a wind sifter with a capacity of 20 tons per hour and 50 kW energy consumption. Additionally, demolition waste might contain glass and ceramic which cannot be separated through wind sifting since their density causes them to end up in the heavy fraction. As a result, for separating glass and ceramic another process is required. Optical sorting via using a sensor is the chosen process for this regard. The selected machine specification is as follows.

Table 20. Optical sorter specifications.

Machine width (mm)	1000, 1500
Capacity ceramics (tons/h)	15-22.5
Capacity colors (tons/h)	5-7.5
Efficiency (%)	98
Electricity (kW)	2-3
Compressed air (psi/bar)	100/7

3.1.6 Combined line

The main idea of this part is to present a combined line which it has the required facilities for treating all the materials. In this line, ash, fiber reject, flotation sand, and construction and demolition waste are treated so that the processing capacity of this line is 32000 tons per year. Only the green liquor sludge cannot be treated through these processes and it is required its own separated treatment line which is presented in part 3.2.1. All the machineries for the treatment of these materials are the same as what are introduced in the parts 3.2.1 to 3.2.5. Additionally, in table 22, the required treatments for each material in this combined line are defined precisely. It should be mentioned that in this line waste materials are not mixed and each of them is treated separately. The flow chart of combined treatment line is as follows.

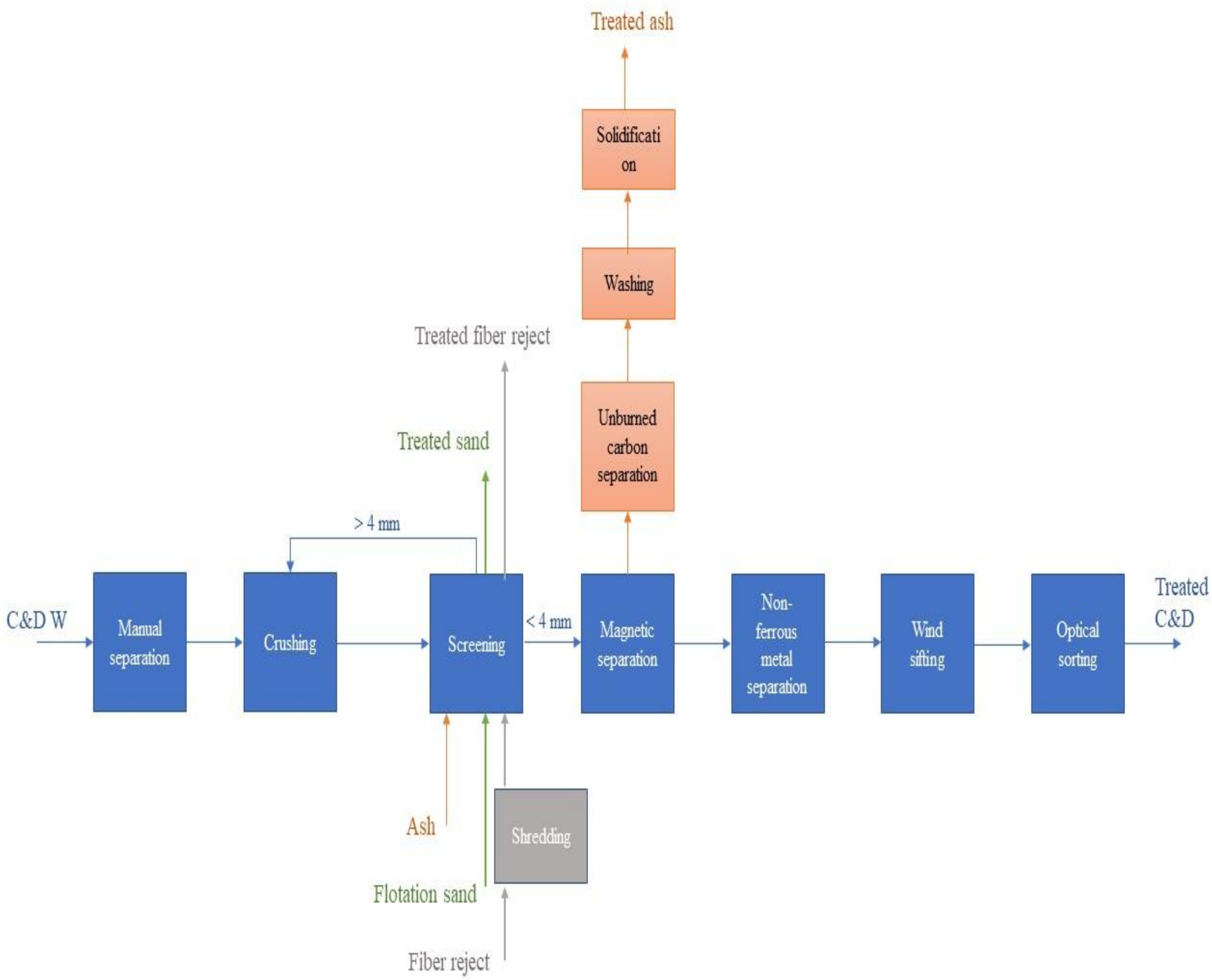

Figure 30. Combined line for treatment of wastes materials.

Table 21. The required treatment processes for each material in combined line.

Material **Process**	**Ash**	**Flotation sand**	**Fiber reject**	**C&D W**
Manual separation				√
Crushing				√
Screening	√	√	√	√
Magnetic separation	√			√
Non-ferrous metal separation				√
Wind sifting				√
Optical sorting				√
Shredding			√	
Unburned carbon separation	√			
Washing	√			
Solidification	√			

3.2 Economic analysis

The main target for this part is to find the required annual investment for starting and running such a project for the treatment of intended waste materials and to evaluate the possibility of this project being carried out. The required data are collected, capital and operating costs are calculated and consequently, the required annual investment is presented.

3.2.1 Capital costs

Capital costs are the fixed expenses which are required to provide the facilities for starting a project. Capital costs include the cost of purchasing machineries, building, and installations (Manouchehri, 2004).

In this research, the machinery cost for all items has been collected directly by contacting the manufacturers, and for some machines, the cost is predicted based on the cost of its lower capacity machine. The cost of the building is calculated based on the considered plant area which is presented in table 22. Cost of construction of the plant for green liquor sludge, ash, fiber reject and flotation sand are considered 500 € per meter square and for C&D W and combined line, this amount is considered 1000 € per meter square. According to the (Sari, 2014), the installation cost is basically contains costs of foundations, platforms, supports, and erection of equipment as well as installation labors. 10% of machineries cost is the estimated cost for installations based on previous experiences.

3.2.2 Operating costs

Operating costs are those costs which are needed during the operation of the project. Different items of operation costs are maintenance and repair, labor, insurance, and energy consumption. (Manouchehri, 2004.)

Maintenance costs contain the cost of lubrication and repair, maintenance labors, and tooling. As a rule of thumb, a good estimation for considering the lubrication and repair cost for power-based equipment is to calculate the required lubrication for about 15 % of the machine’s fuel expense. The repair cost can be 3% of the machine’s cost if they are aged for five years or less and 5% for more than 5 years old (Pflueger, 2005). Maintenance labors are the persons who fix and maintain the equipment. All the equipment needs to be checked regularly in order to keep the efficiency of the machines. Changing the tools is the other item in the maintenance cost. For some machines like the crushers and shredders, it is needed to change the tools in regular time as a part of maintenance tasks. Depended upon the machines and required treatments, the cost of maintenance labors and changing of the tools are estimated for each line.

For estimating the labor cost, salaries of operating labors, supervisors, accountant and gatekeeper is considered. The number of operating labors and supervisors is selected based on the required treatment processes. The salary of operating labors is calculated based on the 30 euros per hour. For accountant and supervisor about 3500 euros per month and for the gatekeeper, 2500 euros per month is considered.

Energy cost is calculated based on 0.15 euros per kWh. This cost contains the cost of the electricity itself, transfer cost, as well as the basic fuse payment. The capacity of all the available materials in this research is about 8000 tons per year. The machineries have been selected based on the processing capacity of 20 tons per hour. As the machines cannot work all the time with their full capacity due to unevenness of material flow and their required service breaks, the processing hour per year is about 1000 hours. As a result, according to the power consumption of the machines and the required processing hours, their energy consumption and the energy expenses are calculated with the mentioned cost.

In addition, the cost of the required energy for factory building has been estimated as well. The main electricity in a building is needed for lighting as well the HVAC system which means heating, ventilation, and air conditioning. Based on the IEA (2006), the average lighting energy consumption in the industrial sector per year is between 37-107 kWh/m2. In this research 72 kWh/m2 is considered which is the average of these two amounts. In addition, Ling (2006) collected data about energy consumption in various factory buildings in Singapore and results show that the HVAC systems consume electricity almost 36 % higher than lighting. Consequently, according to these data as well as the required area for each recycling line, the factory building energy consumption is estimated. Lastly, the insurance cost is predicted to be 1% of the total capital costs.

3.2.3 Cost calculations

In this part, all the required capital and operating costs for each treatment line are presented in the following tables and at the end of this part, the annual investment and energy cost per ton of waste materials are presented in two diagrams. Although energy cost is a part of operation cost and it should be included in the investment calculations, due to the importance of energy consumption for this research, the energy cost is excluded from investment cost and it is presented in separate tables and diagram.

In addition, for each of the investment costs, a contingency of about 10% of the whole investment is considered. This cost is added to the investment because some of the expenses are predicted based on the previous experiences and probably they might happen with that amount, but some uncertainty should be considered for those cases.

Furthermore, one thing which should be mentioned about calculating the total investment costs is the cost of cement solidification process and the crusher cost. For these two items, their cost is predicted between two amounts which for calculating the total investment, their average amount is considered. Also, for calculating the cost of the cement solidification process for ash treatment, the cost is predicted based on the data of Vavva et al. (2017) which indicates the estimated cost of 25-50 euro per ton of residues.

Table 22. Considered plant area for treatment of waste materials.

Treatment line	**Considered treatment plant (m^2)**
Green liquor sludge	400
Ash	800
Fiber reject	400
Flotation sand	300
C & D W	2000
Combined line	2500

Table 23. Required annual investment for green liquor sludge treatment.

Items		**Cost (€)**
Equipment	Cross-flow filter	65,000
	Vacuum drum filter	13,000
	Hydrocyclone (if needed)	1350
	Conveyors	18,000
	Material handling equipment	50,000
Installations		14,700
Maintenance		9000
Labor		174,000
Plant cost		200,000
Insurance		3600
Contingency		55,000
Total investment		604,000

Table 24. Annual energy cost for green liquor sludge treatment.

Items	**Cost (€)**
Energy required for machineries	9,800
Energy required for building services	10,200
Total	20,000

Table 25. Required annual investment for ash treatment.

Items		**Cost (€)**
Equipment	Inclined vibrating screen	50,000
	Drum separator	22,000
	Electrostatic separator	35,000
	Intensive mixer	5000
	Mortar mixer	1000
	Conveyors	36,000
	Material handling equipment	50,000
Cement solidification process		200,000-400,000
Installations		20,000
Maintenance		11,200
Labor		204,000
Plant Cost		400,000
Insurance		6300
Contingency		114,000
Total investment		1,254,500

Table 26. Annual energy cost for ash treatment.

Items	**Cost (€)**
Energy required for machineries	14,900
Energy required for building services	20,400
Total	35,300

Table 27. Required annual investment for fiber reject treatment.

Items		**Cost (€)**
Equipment	Single-shaft shredder (if needed)	14,000
	Inclined vibrating screen	50,000
	Conveyors	18,000
	Material handling equipment	50,000
Installations		13,200
Maintenance		9,500
labor		174,000
Plant Cost		200,000
Insurance		3500
Contingency		53,200
Total investment		585,400

Table 28. Annual energy cost for fiber reject treatment.

Items	**Cost (€)**
Energy required for machineries	7,500
Energy required for building services	10,200
Total	17,700

Table 29. Required annual investment for flotation sand treatment.

Items		**Cost (€)**
Equipment	Inclined vibrating screen	50,000
	Conveyors	12,000
	Material handling equipment	50,000
Installations		11,200
Maintenance		7000
Labor		144,000
Plant Cost		150,000

Table 29 continues. Required annual investment for flotation sand treatment.

Items	**Cost (€)**
Insurance	2700
Contingency	43,000
Total investment	473,000

Table 30. Annual energy cost for flotation sand treatment.

Items	**Cost (€)**
Energy required for machineries	3,700
Energy required for building services	7,700
Total	11,400

Table 31. Required annual investment for C&D waste treatment.

Items		**Cost (€)**
Equipment	Inclined vibrating screen	50,000
	Cone crusher	120,000- 260,000
	Wind Sifter	90,000
	Drum separator	22,000
	Eddy current separator	48,000
	Optical sorter	100,000
	Conveyors	54,000
	Material handling equipment	50,000
Installations		61,500
Maintenance		49,500
Labor		276,000
Plant cost		2,000,000
Insurance		27,000
Contingency		303,000
Total investment		3,331,000

Table 32. Annual energy cost for C&D waste treatment.

Items	**Cost (€)**
Energy required for machineries	33,100
Energy required for building services	51,000
Total	84,100

Table 33. Required annual investment for combined line treatment.

Items		**Cost (€)**
Equipment	Inclined vibrating screen	50,000
	Cone gyratory crusher	120,000- 260,000
	Wind sifter	90,000
	Drum separator	22,000
	Eddy current separator	48,000
	Optical sorter	100,000
	Single shaft shredder (If needed)	14,000
	Electrostatic separator	35,000
	Intensive mixer	5000
	Mortar mixer	1000
	Conveyors	114,000
	Material handling equipment	50,000
Cement solidification		200,000-400,000
Installations		73,000
Maintenance		58,200
Labor		426,000
Plant cost		2,500,000
Insurance		33,000
Contingency		412,000
Total investment		4,531,000

Table 34. Annual energy cost for combined line treatment.

Items	**Cost (€)**
Energy required for machineries	58,300
Energy required for building services	63,700
Total	122,000

According to the data in these tables, in the next figure, the annual investment cost of waste treatment per ton is presented for each of the waste materials. For calculating the investment cost per ton, the total investment is divided by the capacity of each line. The capacity for each treatment line is 8000 tons and for the combined line, this amount is 32000 tons as it contains four waste materials. These costs cannot be the exact amounts since there was no data for some cost items and some estimations have been made in those cases, but they give good estimations about the treatment conditions.

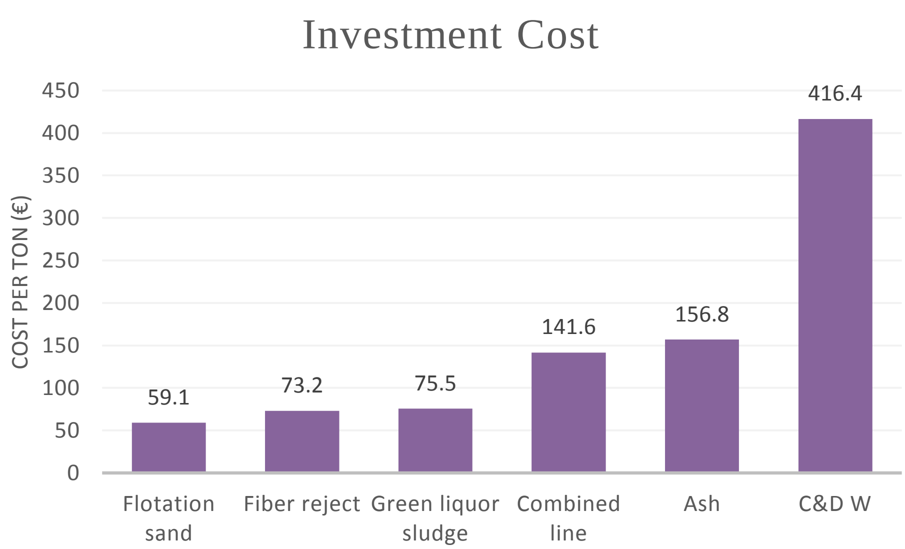

Figure 31. Required annual investment for treatment of waste materials per ton.

In the next figure, cost of energy required for treatment lines is shown. Also, for calculating the energy cost per ton, the total energy cost is divided by the capacity of each line.

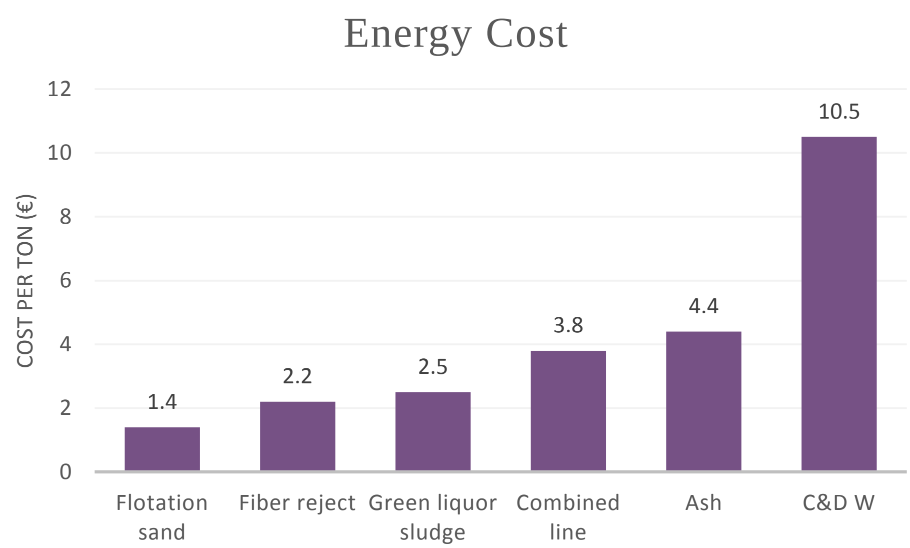

Figure 32. Energy cost for treatment of waste materials per ton.

3.3 Environmental analysis

One important factor that can have great environmental effects is energy consumption of the processes as producing and using energy have considerable impacts on the air, water, and land. In this part, the energy consumption of processes for treatments of each of the aforementioned waste materials is presented. The energy consumption of each treatment line of waste materials is calculated based on the facilities with 20 tons per hour capacity and considering 1000 working hours for 8000 tones capacity for each separate treatment line and a total of 32000 tons for combined treatment line. The results are shown in the following diagram and table.

Based on these results, flotation sand is the most environmental-friendly material as it is just needed to be screened. On the other hand, C&D W consumes a great amount of energy due to its broad range of treatments. Fiber reject, green liquor sludge and ash are placed between these two materials, respectively. Moreover, as can be seen from the following table, with performing the combined line, the energy consumption per ton becomes lower than the C&D and ash treatment lines.

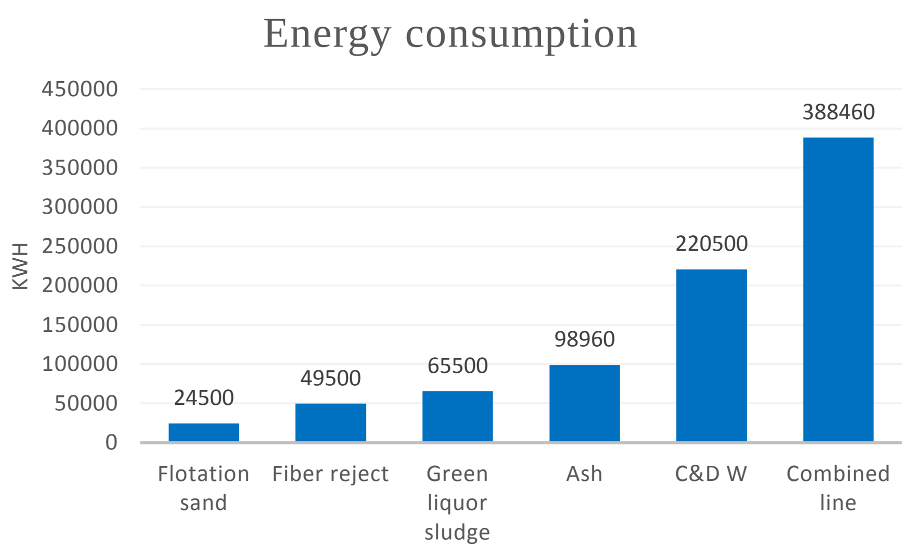

Figure 33. Energy consumption (kWh) for treatment of 8000 tons of waste materials for each of the separated treatment lines and a total of 32000 for combined treatment line.

*Table 35. Energy consumption for the treatment of waste materials per ton***.**

Waste material	**Energy consumption per ton (kWh/ton)**
Flotation sand	3.1
Fiber reject	6.2
Green liquor sludge	8.2
Combined line	12.1
Ash	12.4
C&D W	27.6

In order to evaluate the results of the energy consumption of this research, the results of another research have been compared with this research in this part. Coelho and Brito (2013) investigated how much energy is needed for recycling C&D W and also how much CO2 is produced through these recycling processes. Their facilities are for 350 tons per hour processing and they considered 2400 working hours per year. Their results are presented in table 7 in the part 1.4.7.

In this table, Coelho and Brito (2013) presented the energy consumption with the unit of kgoe/year. they mentioned that they used the coefficient of 0.29 to convert the kWh to kgoe. As it can be seen from the table, the considered processes in this research are partly similar to the current research so that the common process between these two studies are selected and compared and for example the excavator and air jig of this research, as well as optical sorting of the current research, are excluded from the calculations. Their result shows that the total energy consumption of the common processes in this research is about 605 652 kWh with 2400 processing hours. In the current research, the total energy consumption of the common processes for C&D W is about 217 500 kWh with 1000 working hours.

In the mentioned research, their processing hours is 2.4 times higher than the current research and their machines' capacity is much higher. However, the comparison of their data and specifications of current research indicates that when the capacity of the machines is increased, their energy consumption does not increase significantly, and they are slightly higher than the lower capacities machines. Consequently, the difference in energy consumption from these two researches mainly comes from the difference in working hours as their energy consumption is about 2.8 times higher than the current research and it is mostly affected by the working hours.

4. DISCUSSION

Annually, a vast amount of waste is produced all over the world which finding a proper solution for their management has made a challenge for the global community. Disposal and landfilling are the conventional methods which require using big land areas and they pose a lot of risks to the environment and human health. Due to these reasons, performing the R3 concept which includes reusing, recycling, and recovering has become important. In order to help increasing the rate of implementing R3, authorities have defined various legislations such as the European Union legislations including producer responsibilities, waste taxes and fees, and determined recycling rates for various wastes which should be achieved by the European members like the legislation regarding C&D W in which it is mentioned that 70 % of the non-hazardous construction and demolition wastes are needed to be recycled by 2020.

Legislations indicate the significance of recycling. However, it should be pointed out that although recycling is one of the important parts of waste management and nowadays it is extensively used, it still has considerable economic, technological, and environmental barriers which require more investigations to make it possible to use recycled materials as raw material for different applications.

South Karelian region is one of the active parts of Finland in the wood, mining, and construction industry. There are a lot of waste materials from these sectors which mostly do not have another use. Green liquor sludge, fiber reject, ash, flotation sand, and C&D wastes are among those waste materials. Due to the high concentration of aluminum and silica in these materials, they can be proper candidates for making geocomposites to reduce the use of non-environmentally friendly cement in the construction sector. Ash and C&D wastes have already been used for making concrete and a lot of researches have been carried out for utilizing them, but fiber reject, flotation sand, and green liquor sludge are special materials that they are not widely investigated for recycling purposes.

Various kinds of treatments are needed to be applied to these materials to make them usable for producing geocomposites. The current research focused on all required pretreatments for these wastes. Additionally, these pretreatment processes were economically and environmentally investigated to gain an insight into the possibility and feasibility of using these waste materials for making geocomposites. The literature review was carried out in the introduction part about the used treatments for these waste materials for different applications, but according to the requirements of the target application which is making geocomposite through the 3D printing process, the suitable treatments for these intended materials were presented in part 3.1 of the research.

Figure 23 shows that green liquor sludge requires filtration, washing and dewatering processes. In the case of the existence of hazardous materials like cadmium in its composition, performing hydrocyclone process is needed to remove them.

Ash is one of the promising materials for making geocomposites as it has been already used to make concrete as well. Part 3.1.2 shows that three different ways can be used for treating ash. Screening and magnetic separation are the first two required processes in all the options to remove the impurities and separate the ferrous metals from ash. Afterward, the wet or dry method can be selected to remove the unburned carbon from ash. Electrostatic separation is the dry method which is presented in the first and second routes and it was also recommended in the Zhang et al. (2018) since no water is utilized in this case. On the other hand, in the third option, the wet method which is froth flotation is selected. This process is suggested in the Liu et al. (2013) article because of its cheapness and higher efficiency than electrostatic separation.

The last required treatment for ash is a process to remove salts and heavy metals. In the first option (figure 24), washing and cement solidification have been chosen which are the most used methods in the industry due to their efficiency and inexpensiveness. However, the washing process has a big drawback as a high amount of water is consumed for this purpose and it needs to be treated for further use. Moreover, one negative point of this process for making geocomposite is that through this method aluminum is removed from the ash composition besides the heavy metals and presence of aluminum in the ash for this case is a necessity so that again the aluminum should be added later, and it causes extra work. In the second route, using silica nanoparticles has been suggested. One important thing about this method is that it is an introduced method in a research and it has not been tested for large industrial scale, but it is an interesting method for the purpose of current research as the aluminum remaines in the composition and silica is added which is another essential element for making geocomposites. Lastly, in the third route, froth flotation was used for removing heavy metals. A two-step froth flotation has been presented in the H. Q. Liu et al. (2017) research which the first one is for eliminating unburned carbon and the second one is for heavy metals. Also, about this method, it should be noticed that it is a proposed method in a lab-scale research.

The other material of this research is fiber reject. The aim is to use this material as a reinforcing fiber in geocomposites. Fiber rejects might be wet after the pulping process but as the moisture content is needed for making geocomposite, those fiber rejects should not be dried. Length of fibers is a significant factor that can affect the properties of geocomposite so that separate research can be done to find the optimum length for fibers for this specific application and then shredding is the suitable process that can be used to make the desired length for fibers. Finally, fiber rejects are required to be screened to remove their impurities.

Flotation sand has the easiest treatment insomuch it is just needed to be screened after it has been collected from the pond. Since the available flotation sands for this research are in the size of 2-4 mm which is the desired size for 3D printing, the crushing stage is eliminated for this material.

Construction and demolition wastes are the most challenging materials compared to the others. They require quite vast treatments and so that high investment. Firstly, coarse materials should be separated from C&D W manually. Thereafter, they should be crushed as the other separation processes can be more efficient with homogenous materials. Since most of the time, the desired size cannot be reached with one crushing stage, screening and then another crushing process is needed afterward. Next, Magnetic and eddy current processes are performed to recover the ferrous and non-ferrous materials. Thereafter, wind sifter removes the dust, wood and light-weight materials and finally optical sorting is used to separate glass and ceramic.

Finally, at the end of processes (part 3.1.6), the idea of the combined line has been presented. The capacity of all the waste materials in the current research is about 8000 tons per year which is not a high amount. The target of presenting the combined line is to evaluate the cost-efficiency of providing a processing line for different materials as in this case more materials will be processed and because some machineries are common for the treatment of each separated line, then less equipment and presumably less investment is required. The presented combined line is for processing ash, fiber reject, flotation sand, and C&D waste. Green liquor sludge is not included in this line as it needs its own equipment which their functions are completely different from the machineries for other waste materials.

After the processes and machineries have been selected, in part 3.2, an economic analysis was carried out for investigating the required annual investment and energy cost per ton of each waste materials. For estimating investment, the cost of plant area, machineries, installations, maintenance, insurance, and operating labors were considered. Also, for energy cost, the cost of energy required for equipment and factory building services were taken into account. One notable thing about this cost analysis is that lack of proper data for some costs like some machineries, and services increases the sensitivity of these estimations. However, for those cases that exact data were not available, the estimations were carefully performed according to the previous experiences.

Calculations of annual required investment per ton in figure 31 show that C&D W and ash which are the most promising materials for making geocomposites require the highest annual investments among the others. Albeit, the ash investment cost is almost the third of C&D W which costs 416.4 euros per ton. Moreover, the cost of treatment of fiber reject and green liquor sludge is in the moderate range and almost same as each other with 73.2 and 75.5 euros per ton, respectively. Also, it can be seen that the most inexpensive treatment line with 59.1 euros per ton is for flotation sand and it could be predicted as well due to its simple treatment process.

Furthermore, calculations of energy cost in figure 32 demonstrate that the cost of energy is approximately between 2-3% of the total annual investment. As can be seen from figure 32, flotation sand has the least energy cost. Fiber reject is the second cheapest material in this regard which its cost is half of that of ash. Like the trend of investment cost, C&D W costs higher than other lines regarding energy expenses.

An important result of the investment and energy calculations is related to the combined line where its annual investment and energy cost per ton is a little lower than ash treatment line and much lower than the C&D W line. Although this cost is still almost twice the cost of fiber reject line and triple of the flotation sand, it is a profitable choice while it proceeds the valuable ash and C&D with lower investments. The reason for this cost of the combined line is its higher processing capacity. The same result can also be observed from the Oliveira Neto et al. (2017) research. In this research, they evaluated the economic aspect of C&D recycling plants. They presented the capital and operating costs for three different capacities of different treatment lines. The following table derived from their results for their current advanced process which is partly similar to the considered processes of the current research.

Table 36. Capital and operating cost per ton for recycling C&D waste in (Oliveira Neto et al., 2017) research.

Capacity (tones)	**Annual investment per ton (€)**
100,000	84
300,000	37
600,000	23

This table shows how the processing capacity can affect the investment cost per ton of the waste materials. However, the considered processes of this research are partly different from the current research, but the expensive cost of almost 416 € per ton from the results of current research which is obtained for 8000 tons processing capacity becomes more conceivable.

Eventually, in part 3.3, the environmental effects of each treatment line have been investigated regarding their energy consumption point of view. Table 35 shows that C&D W has the highest energy consumption with about 27.6 kWh per ton so that it has the highest environmental impacts in this regard. The second-highest rank is for ash with 12.4 kWh per ton which is a little bit higher than the combined line. Green liquor sludge has the middle energy consumption among all with 8.2 kWh. Fiber reject energy consumption is twice the flotation sand which has the least energy consumption with 3.1 kWh per ton.

For evaluation of energy consumption calculations, results of Coelho and Brito (2013) research was also presented in the environmental analysis part. They investigated the energy consumption of different processes for treatment of C&D W. Since their processes were not completely the same as the current research, the common processes with their research and current research were selected and compared in this part. Two main aspects of energy consumption calculations for processes are power consumption of machineries as well as annual working hours. In the Coelho and Brito (2013) research, the machineries capacities were selected for 350 tons per hour which is far greater than the current research with 20 tons per hour facilities. Also, they considered 2400 processing hours per year which is 2.4 times higher than the current research with 1000 hours.

This comparison shows that their energy consumption is almost 2.8 times greater than the current research and so it is mainly affected by working hours. The reason for this result is that the specifications of equipment demonstrate that although the capacity of their equipment is higher than the current research, the power consumption is slightly higher so that it does not have big influence on the difference of energy consumption between two researches and the difference mostly comes from the variation of working hours. Consequently, it can be concluded that providing higher capacity facilities is more proper as it leads to lower energy consumption per ton.

Overall, the results of this research with the currently available capacities show that flotation sand is the most efficient material for producing geocomposite both environmentally and economically. Although C&D W and ash are the most investigated materials in the global recycling industry for various applications, both require high annual investment cost and considerable use of energy for treatments compared to the three other waste materials. However, outcomes of the combined line idea and also the comparison of this research with Coelho and Brito (2013) and Oliveira Neto et al. (2017) research clarifies that the processing capacity has a great impact on the investment cost and energy consumption per ton of waste materials. These evaluations show that when the processing capacity is increased significantly, the investment cost and the energy consumption are increased with much lower rates than the capacity so that these kinds of investments become more profitable for higher capacities.

As a result, one suggestion to decrease the investment cost of these treatment lines is to increase the processing capacities. Currently, these investment costs have resulted from the capacity of the waste materials from the South Karelian region in Finland which is not high amount. If these waste materials can be collected also from other parts of Finland or even from close cities near Finland, these investments become more profitable. However, as transportation distances have a great effect on the environmental footprint of these processes, then choosing the location for constructing the treatment plant becomes important and it should be carefully studied in order to find the best location with the least required transportations.

Moreover, the costliness of the required investments illuminates the necessity to find new technologies and processes for the treatment of waste materials. Novel solutions can be detected to increase the efficiency of treatment processes with less requirement for investment and energy consumption which can attract the market to invest on these secondary raw materials rather than virgin materials.

5. CONCLUSION

Recycling waste materials in order to replace the virgin raw materials has received wide attention globally due to the problems caused by the disposal of the waste materials as well as the depletion of natural resources. Nowadays, recycled materials are utilized in different kinds of applications. The purpose of this study was to evaluate the technological, environmental, and economic aspects of required pretreatments for different waste materials that can be used as the raw material for making geocomposites. The studied materials were some wastes from the South Karelian region in Finland including green liquor sludge, ash, fiber reject, construction and demolition waste, and flotation sand. These materials were selected due to the high concentration of aluminum and silica in their composition which is a necessity for making geocomposites.

The literature review was carried out to understand the utilized methods for the treatment of these materials and based on the requirements of the target application which is producing geocomposite, the most suitable methods were selected and presented for each of the materials. Furthermore, an economic analysis was done to find the required investment for initiating and running such a project in a year. Lastly, the environmental effect of the chosen processes regarding energy consumption was assessed.

The results of this research indicate that flotation sand is the best choice among all the materials as it requires the least investment and energy consumption owing to its simple treatment process. On the other hand, C&D W requires a broad range of treatments which makes it the most expensive and energy-intensive option compared to other materials. Fiber reject, green liquor sludge, and ash are placed between these two materials respectively both in terms of required investment and energy consumption. It should be emphasized, all the calculations and assumptions were done based on the available capacity of these waste materials in the local market and due to lack of proper data for some items, predictions were carried out for those cases founded on the previous experiences which increase the sensitivity risk of calculations.

In addition, it is worth mentioning that assessing the idea of combined treatment line for the intended materials and comparison of the results of this research with other researches like Coelho and Brito (2013) and Oliveira Neto et al. (2017) show that profitability of these kinds of investment is highly depended on the processing capacity and increasing the capacity can significantly decrease the investment cost and energy consumption per ton of waste materials. For increasing the capacity, materials should be collected from other regions in Finland or cities near Finland. Albeit for this condition since long transportations are required, the environmental effects should be carefully investigated in further studies to find the best location for constructing the treatment plant which mitigates the risks for the environment.

Moreover, further studies are needed to focus on developing new technologies for the treatment of the waste materials in order to increase efficiency and decrease the cost so that the secondary raw materials can compete the virgin materials in the market. In addition, the cost analysis can be done more precisely in the future researches if more accurate financial data is available.

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