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# COST ANALYSIS OF VARIOUS FACTORS ON GEOPOLYMERS 3D PRINTING FOR CONSTRUCTION PRODUCTS ON FACTORY AND CONSTRUCTION SITE

Supervisor: Professor Timo Kärki

# ABSTRACT

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**Cost analysis of various factors on geopolymer 3D printing for construction products on factory and construction site**

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90 pages, 22 figures and 21 tables

Supervisor: Professor Timo Kärki

Keywords: geopolymers, raw material transportation, Pre-treatment, parameter selection and strength requirements, construction site and factory site 3D printing

The construction industry is considered as of the main natural resource consumer such as rocks, cement, clays and sand. Ordinary Portland cement manufacturing process is associated with excess quantity of carbon dioxide emission that is searching for other alternative materials. Geopolymer is a promising new material used to replace the ordinary Portland cement. Different stages are involved to produce geopolymers, function as a binder. In this research, various stages such as raw material transportation, pre-treatments, parameters selections, strength requirements for GPC had been studied in terms of effect on geopolymer production economics. Literature was used to find pre-required stages for geopolymer printing. Moreover, initial investment needed for running each stage successfully is investigated. Compressive review on geopolymer 3D printing state of the art technologies is illustrated. The cost calculation and elements needed for construction site and factory site printing were discussed and evaluated. Potential opportunities and contingency of geopolymer printing on factory and construction site is analysed. Preliminary result suggested that 3D printing technology potential increases construction industry production and affordability of houses can be enhanced in Finland. Estimated one-ton 3D printed geopolymer production cost on construction site is 418.18 euros. Transportation cost has least effect on final product cost, whereas pre-treatments of raw material and mixing parameters influenced final cost of product significantly. Lastly, research work suggested required future work to make geopolymer 3D printing a feasible construction method.

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Qaisar Munir
Lappeenranta 20.9.2020

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**LIST OF SYMBOLS AND ABBREVIATIONS**

## LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| € | Euro |
| $ | Dollar |
| £ | Pound |
| °C | Degree Celsius |
| 3D | Three dimensional |
| Al | Aluminium |
| $CO_2$ | Carbon dioxide |
| CO | Carbon monoxide |
| K | Potassium |
| Na | Sodium |
| Si | Silicon |
| AM | Additive Manufacturing |
| C&D W | Construction and demolition waste |
| EU | European Union |
| FDM | Fused Deposition Modelling |
| GGBFS | Ground granulated blast furnace Slag |
| GPC | Geopolymer concrete |
| OPC | Ordinary portable cement |

# 1 INTRODUCTION

3D printing or additive manufacturing is considered as a flexible manufacturing technique among others manufacturing industries. (Campbell et al. 2018) Reduction in the machining cost, improvements in additive manufacturing machines and materials are major factors for 3D printing optimization (Durao et al. 2016). 3D printing of concrete technology in construction industry has gained convincing consideration in recent years. (Pierre & Rangeared 2016) Currently, 3D printing for construction products obtains compelling potential due to the manufacturing flexibility of complex and dimensionally accurate shape without adoption of extravagant formwork (Allouzi et al. 2020).

Traditionally, in construction industry around the globe the most extensively used material is concrete (Wangler 2019). High cost, waste generated in significant amount almost 80% of the total waste in the world, non-environmentally friendly materials and techniques used to generate concrete are the major issues in construction industry (Xia et al. 2016). Whole construction method, including material transportation, parameters selection, strength requirements, off site manufacturing, assembly, installation, and construction on site dissipate huge amount of energy and generate large amounts of greenhouse gases (Nematollahi et al. 2017). Additionally, to make conventional concrete OPC (ordinary Portland cement) is required, which is high carbon and energy demanding material (Naqi et al. 2019).

Above three billion tons of raw material is utilized to generate two billion tons of Portland cement (limestone 70%). Re-usable Sustainable materials are needed to protect virgin material (Ho et al. 2019). Emission of greenhouse gasses $CO_2$ (carbon dioxide) and CO (carbon monoxide) is one of the fundamental reasons of the global warming. It is estimated that approximately 5% to 8% emission of $CO_2$ is globally produced by the cement industries. Ultimately, GPC (geopolymer concretes) were produced to minimize $CO_2$ emission through eradicating the usage of Portland cement (Davidovits 1994). GPC minimize the cost with the usage of by products from the industries (Yacob 2016). GPC having magnificent heat resistance, low permeability, and good mechanical properties, have been acquiring proliferating consideration in construction industry. In order to produce one ton of OPC (ordinary Portland cement), 0.85 ton of $CO_2$ is released into the atmosphere, whereas the same amount of geopolymer cement production releases 0.1 to 0.15 ton of $CO_2$ emission, which reduced the emission to 80-90%. However, production of geopolymers has some challenges regarding production cost, rapid setting time adjustment and workability tolerance (Tao & Pan. 2019).

This research work figured out the cost analysis of geopolymers 3D printing for construction product on construction and factory side. Additionally, cost analysis of geopolymer pre-treatments, parameter selections and strength requirements are analysed. The required time, cost and quality of $50m^2$ geopolymer printing house are discussed. Overview of research work is presented as a flow chart in Figure 1 as shown below.

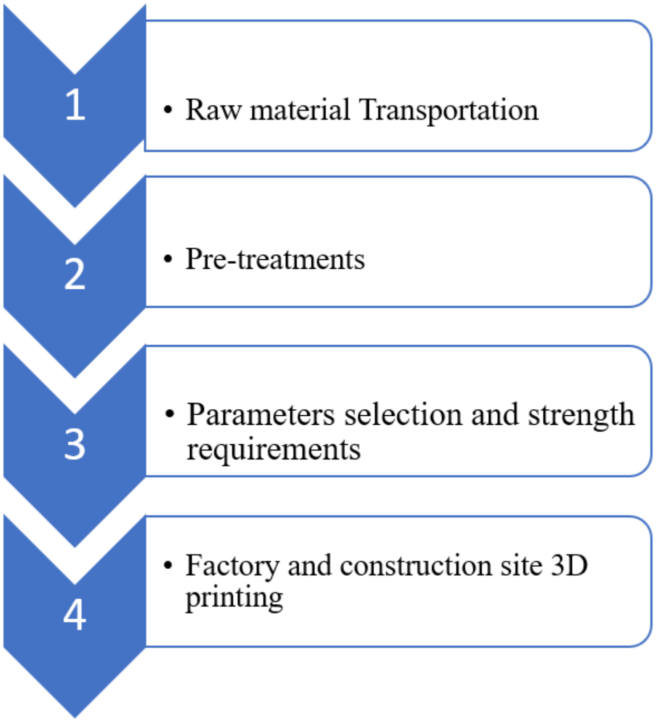

**Figure 1.** Research work overview.  Cost analysis of four main stages.

## 1.1 Background

Rapid development by utilizing natural resources generate harmful effects around the globe. Fast growth in the technology sector is one of the main reasons of rapid pollution growth on the earth. According to European Commission, the amount of the waste generated from construction industry is 36.4% as shown in Figure 2. Whereas the increasing demand of cement production generates $CO_2$ emission nearly 1599Mt as shown in Figure 3.

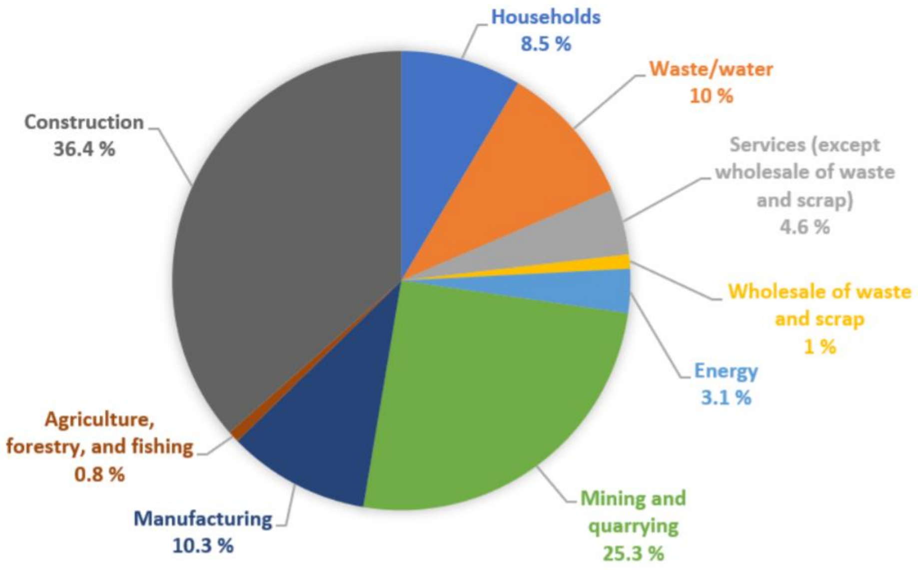

**Figure 2.** Waste generation by different sectors of the industry (eurostat 2019).

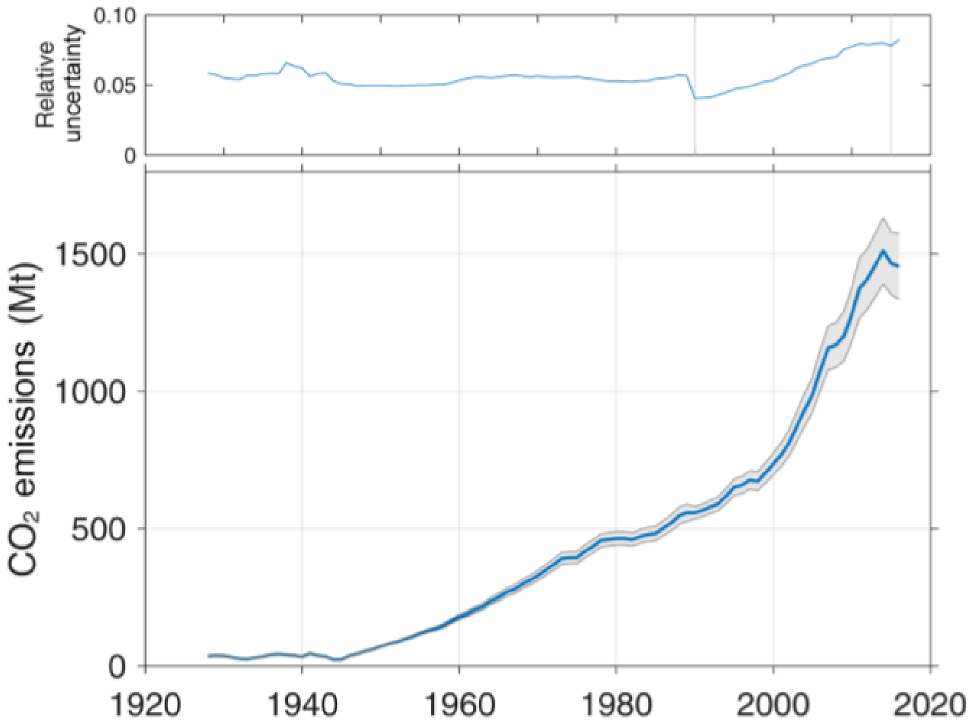

**Figure 3.** Emission of $CO_2$ from cement production globally (Andrew 2017).

Data presents that carbon dioxide emission is increasing rapidly, due to higher demand of cement for construction purposes. Rabid emission of harmful gases in the environment creates negative impact on nature (Alyousef et al. 2020). Waste produced as by-products from different industries can be reused and recycled in efficient and more sustainable way to create alternative of Portland cement, so that natural resources can be used more effectively for human needs (De Brito et al. 2018).

Geopolymers are treated as green material for the construction industry, having almost 80-90% less emission of $CO_2$ (Saeli et al. 2018). Thermal properties, durability and mechanical properties are proportionate with concrete made by the utilization of Portland cement (Shakor et al. 2019). In construction industry, two different methods of 3D printing are used. Concrete printing technique based on the utilization of the powder is a common method to make complex structure by jetting liquid binder through nozzle on printable powder. Without the utilization of support structures overhang components including D-shape can be easily manufactured by utilizing 3D powder- based concrete printing technique (Cesaretti et al. 2014). In construction industry, accuracy demand as compared to mechanical components is not high, whereas concrete printing based on powder technique is utilized for highly complex, accurate and for extremely precise ornamental shapes.

Additive manufacturing is highly advantageous, according to customization demand of the market environment, due to its flexibility, complexity in design and delivery of the product transportation cost. Currently, in industry two different types of (framed and non-framed) 3D printer is in use. Framed printers are only in use inside the factories. Difficulties in transportation and assembly of the printer outside the factories are the limitations of framed printers. The research will help to find 3D printing cost analysis for construction product on factory and on the construction site.

## 1.2 Research Aim

Primary aim of thesis is to investigate the cost analysis of geopolymers 3D printing for construction product. Project aims of the research is to use 3D printer economically having capacity of 12 to 15 thousand tons per year on the construction site.

## 1.3 Research questions

The purpose of this project work is to figure out geopolymer potential for manufacturing of different construction products by utilizing waste of different industries economically. The target of the research was achieved through the following questions:

- What kind of costs, material requirements and setup are required to do 3D printing of geopolymer economically on construction, as-well as on manufacturing side?
- What type of business models are convenient for geopolymer 3D printing?
- What are the limitations of using geopolymer 3D printer on construction side?
- How portable geopolymer 3D printing provide product dimensional freedom?
- How does pre-treatment, mixing and printing of geopolymer under one operational unit affect cost of final product?

## 1.4 Research methods

Quantitative research method was used to carry out this research. Due to limited nature and scope of the research, mainly secondary sources were used for data collection, and simplified data analysis was conducted to investigate comparative cost analysis of geopolymer 3D printing on construction and factory site. Initially, literature review was done, for which LUT-Finna was used as a major source of database, from which Scopus, SpringerLink, Science direct, Emerald insight, etc. were used as the main sources for journal articles. Case study strategy was applied to compare cost analysis of geopolymer 3D printing on construction site in Finland. Moreover, this research work was conducted to evaluate cost analysis of geopolymer 3D printing on construction and factory site along with major steps that had impact on cost structure. This thesis is divided into eight main chapters, which are illustrated below in Table 1.

**Table 1.** Structure of thesis.

| | |
|---|---|
| **Chapter 1** | Introduction |
| **Chapter 2** | 3D printing of geopolymers |
| **Chapter 3** | Geopolymers material selection |
| **Chapter 4** | Economical evaluation for geopolymers 3D printing |
| **Chapter 5** | Materials and methods |
| **Chapter 6** | Results |
| **Chapter 7** | Analysis and discussion |
| **Chapter 8** | Conclusions |

Publications related to cost analysis of geopolymer 3D printing, raw material transportation, parameters, and strength requirements for geopolymer were conducted in literature review. Relevant data from literature review were obtained and information was collected to analyse the specific data. Studies related to geopolymer raw material transportation, pre-treatments techniques for raw materials, geopolymer 3D printing with robot arm and gantry system, limitation and accessibility of factory and construction site 3D concrete printing where searched and screened.

## 1.5 Research scope

This research work gives comprehensive literature review about the cost analysis of geopolymers 3D printing and techniques that were used to investigate the performance of 3D printing economically, according to the demand of present time. Detailed literature review precisely gives limitations of equipment used for the printing of geopolymers concrete for construction products and different types of formwork used for printing. This project work plays an important role to understand different stages involved in 3D printing of geopolymers and required investment needed to perform all the stages economically.

## 1.6 Legislations

The transformation toward ecosystem demands value of materials, products, and resources for long periods of time as much as possible. For the competitive economy, minimal level of waste generation is required for low carbon, sustainable and resource proficient environment (Blengini 2019). Waste management policies of EU have the goal to minimize health and environmental effect of waste and to enhance the efficiency of the EU resources. The ultimate target of these policies is to minimize waste amount by safe disposal of waste and through gaining maximum levels of recycling (Badulescu et al. 2019).

Hazardous waste materials such as fly ash, silica fume and rice husks were disposed by landfill methods in the past, due to their limited applications. These landfilling approaches generate serious damage for the soils and water by producing harmful contents. Production of geopolymer cement by utilizing waste materials is considered as an efficient way to secure virgin materials (Jones et al. 2013).

Waste generated through economic and household activities in all EU states were 2538 million tons in 2016. Construction waste contributed 36.4%, whereas quarrying and mining produced 25.3%. Among other wastes, manufacturing and households have 10.3% and 8.5% respectively.

Expected growth in global wastes is estimated to grow approximately 3.4 billion tonnes by 2050 (world bank 2020). Waste required to be managed without having any harmful effect on human health, environments, animals, plants, air, soil and water.  Waste should be handled without creating any odours and noise through nuisance. Legislation of waste and EU members policy states shall adopt the following hierarchy of waste management as a preference order shown in Figure 4.

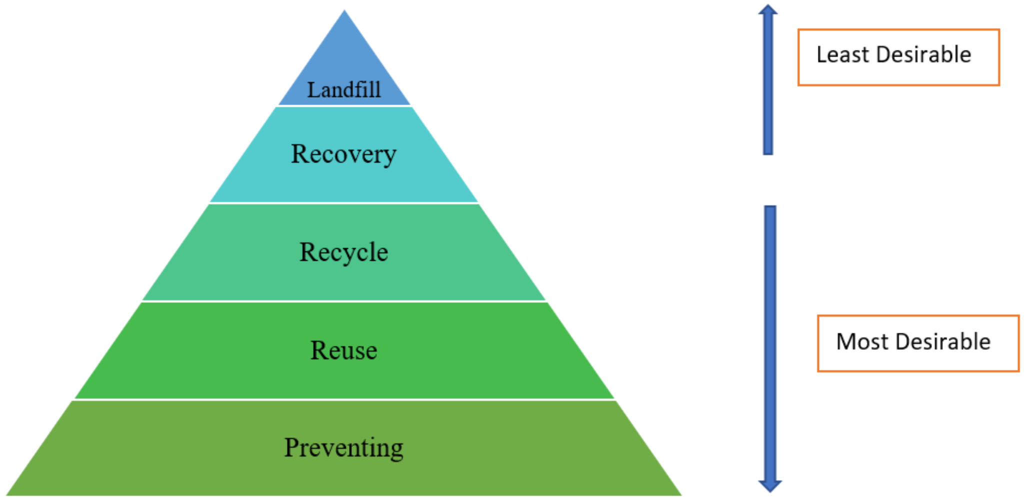

**Figure 4.** Waste hierarchy (Cucchiella et al. 2014).

Reduction in waste generation and minimizing the perilous content of the waste is considered as the highest preference of the waste hierarchy. Improvement in the manufacturing techniques and usage of greener products are the key factors that closely linked with the prevention of waste. Waste is considered to be an important entity that must be fed back into the economy. Prevention of environmental problems by adopting better usage of natural resources and minimizing reduction in pollution, conservations of natural resources, prevention for green house emission, green technologies enhancement and creations of new jobs are the driving advantages obtained by approaching positively towards waste hierarchy. (Cucchiella et al. 2014)

## 1.7 Waste management Trends globally

Insufficiency of natural resources is one of the most prominent megatrends in present era. Pressure on the natural resources is increasing due to rapid growth in urban population. Therefore, by 2050 more resource efficient economy is needed to accomplish the demand of materials (European commission 2011). Reduction and recycling of waste is among the priority issues related to sustainability and environmental protection. Policy instruments and regional operational environment have influence on the recycling rate of each country. Countries have less recycling rate compared to the countries that have numerous policy instruments for recycling of waste. Beside policy instruments, major factors that affect recycling rates are awareness of environment, living standard, strict legislation of waste management and waste management tariffs (Sahimaa 2017).

Countries having service-based economies tend to have bigger resource productivity compared to heavy industry-based economies, since lower material input demand is generally needed for service-based industries (EEA 2013). Netherlands, among the European union countries, has the highest resource productivity, whereas Luxembourg, The United-kingdom and Italy have 50% higher resource productivity compared to other EU states. Due to reduction in the utilization of fossil fuel carriers, construction industry post downturn slump and reduction for non-metallic minerals demand are prominent reasons to achieve higher resource productivity (EEA 2016).

Resource productivity enhancement are based on environmental consideration and mixture of economics. The most noticeable aspects are protectiveness of energy and raw materials is to increase competitiveness by decreasing the pressure on the environmental resources (EEA 2016). Most of the countries in Europe have already developed strategies about national raw materials. Additionally, natural resource sustainable management and efficient use by 2030 are the sustainable development targets of the decade (United nations 2015). Finland beside Germany and Austria are the countries which are following devoted strategies to obtain better efficiency of resources. European manufacturing industry has potential to save overall €630 billion through better usage of resources. Improvements in resource efficiency along the complete value chain could decrease 17-24% material inputs by 2030 (Cambridge Econometrics

2014). Improvements in materials efficiency by adopting economical use of natural resources is the aim of Finland´s national material efficiency programme 2014. It also includes waste volume reduction, material recycling at various life cycle phases and adopting adequate by-product management. Material efficiency programme goal is to achieve sustainable growth through material efficiency and natural resources. Sensible and effective usage of natural resources reduced harmful effect on environment (Ministry of Economic Affairs and Employment 2014).

# 2 3D PRINTING OF GEOPOLYMERS

This section contains brief review of different results presented in scientific lecture corresponding to geopolymer concrete, energy consumption for geopolymer, impact of geopolymer 3D printing on the environment, corrosion and fire resistance properties of geopolymer concrete and printer types used for 3D printing of geopolymer. This section illustrates various scientific literature link to different experimental methods adopted by various research institutes and numerous researchers for geopolymer concrete 3D printing development.

Sustainable material demand for construction industry is increased significantly. Utilization of environmentally friendly products has demanded alternative materials for OPC. (Panda et al. 2019) Customisation, design freedom, reduction in waste, automation, complex building structures by utilizing minimum materials and reduction in labour cost are important factors for improvements of 3D printed built structures. (Kashani & Ngo 2018) Concrete fresh properties, high early strength and optimum open time are important aspects to build structures successfully through 3D printing. Therefore, mixture that contains these properties is required to support successive 3D printing layers. Software and hardware parts are usually two main steps involved in printing process as illustrates in Figure 5. 3D software is used to build the object by defining size of each layer and generating G code pattern, whereas hardware part contains controller, material delivery system and extrusion system (deposits material layer by layer).

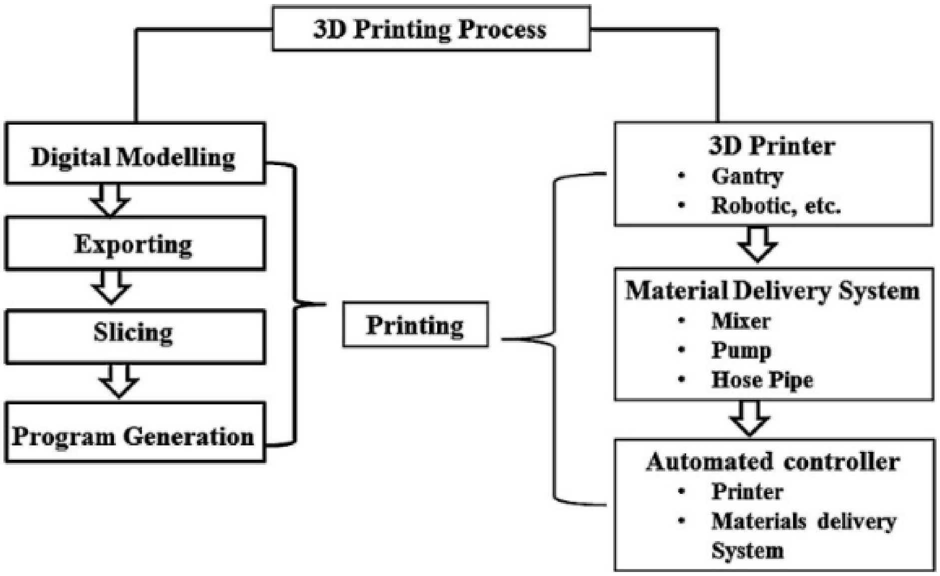

**Figure 5.** Steps involved in AM for construction product (Valente et al. 2019).

In the last few years, construction materials utilized for 3D printing revolutionizes conventional building techniques. However, to perform successfully printing, process adoption of reasonable cementitious materials is the key factor. After printing procedure, material viscosity is the main factor that should be addressed while printing process of concrete to maintain its shape and enough fluidity. Therefore, concrete mixture during flow should have low viscosity and at rest high yield strength is required. Materials that are able to maintain their shape and can be extruded easily, have been created for the cement production. (Marczyk et al. 2019) Table 2 illustrates the required properties and parameters regulating 3D printed concrete properties. Beside process parameters (printing speed, layer height, nozzle shape) material properties such as mechanical strength, buildability, extrudability and open time are major characteristics to control printed concrete properties (Panda et al. 2019).

**Table 2.** Controlling parameters for 3D printed concrete

| **Process parameters** | **Design Parameters** | **Material Properties** | **Post-Processing** |
|---|---|---|---|
| Nozzle shape | Shape and size | Extrudability | Reinforcement Placement |
| Printing speed | Over hanging | Buildability | Curing method |
| Layer height | Material distribution | Open time and mechanical strength | Pre-stressing |

Beside improvements in concrete production, this technology generates harmful impact on the environment through the emission of $CO_2$ and scalable reduction in virgin materials. Therefore, environmentally friendly materials are needed to generate products that can easily be usable as an alternative to Portland cement. Geopolymer that consists of amorphous, aluminosilicate inorganic polymer, has specific properties, composition and even can accomplish better mechanical properties considered as the best alternative for replacement of portable cement. Different raw materials obtained as a side stream from different industries such as fly ash, slag, C&D W, waste glass, and silica fumes are used as ingredients of geopolymers. Major wastes used in this research to produce geopolymer are shown in Table 3.

**Table 3.** Raw material generated from different industries annually.

| **Waste** | **Amount (tons)** |
|---|---|
| Green liquor sludge | 8000 |
| Fiber reject | 8000 |
| Flotation sand | 8000 |
| Construction and demolition wastes | 8000 |
| Fly ash (Agriculture, mining, metallurgy, and construction) | 8000 |

## 2.1 Additive manufacturing technologies for construction products

AM technologies have been developed in the last few years for construction industry. According to Valente et al. (2019) primary variation between different printing technologies depends upon concrete composition, printing apparatus design and final product applications. These technologies can be divided into extrusion and powder printing forms. The extrusion process is involved by extruding material layer by layer through a nozzle placed on a gantry. Fused Deposition Modelling (FDM) is analogous to extrusion printing process.

Currently, extrusion/ deposition 3D printing technique is the most extensively used process in digital construction field. Material pumping, extruding and deposition are among several steps involved in extrusion-based printing process. In order to have balanced material flow while early stage of process, material-based cement must have entire control on properties (Wangler et al. 2016). Extrusion process builds a structure by pumping concrete mixture with suitable rheology. An automated system and digital model are the main requirements for extrusion technique. Mixing, pumping, additional mixing, extrusion, deposition, and stability while deposition are different breakdown stages involved during the printing process. Identification of rheological properties can easily be monitored during the printing process of cement-based material by breaking down of each stage involved for whole process. In addition, flowability by maintain homogeneity during extrusion and transport procedure, control of layer deformation during deposition and layer interface quality treatment to eliminate structural weakness are integral parameters to control printing process. Printed structure stability at a given time, printing task parameters ( cross section shape of layer deposition, height and length of contour), relationship between advancement rate and flow rate must be defined to maintain sustained printing process. (Perrot & Rangeard 2019)

Material transition behaviour from liquid to solid is a crucial aspect of fresh concrete while performing printing process. Cement- based material in fresh state shows a complicated elasto-viscoplastic behaviour which indicates that flow of material can occur only when critical value is less than stress (yield stress). Cement material acts as linear elastic solid below the yield stress. To determine deformation occurs in printed structure under their own weight, elastic behaviour is an important factor. (Perrot & Rangeard 2019)

Powder- based printing process also known as three-dimensional printing is another additive manufacturing technique used to manufacture accurate structure having complex geometries through liquid binder deposition. D-shaped technique and emerging objects technique are two common examples of powder printing process and primarily designed for construction products printing. Powder printing technique is developed for pre-cast off-site component manufacturing in comparison with extrusion printing technique that has been aimed for the application of on-site construction with complex geometries and building components on larger scale (Xia et al. 2016).

According to Xia et al. ( 2016), for building component that can be assembled on site such as interior structure and permanent formworks on small scale, powder- based 3D printing method is highly suitable to produce intricate shapes with accurate details. Figure 6a illustrates 3D printing inkjet system, whereas binder interaction between the adject layers is show in Figure 6b. Printing head and a roller that are mounted together spread powder layer on the build plate base that has approximately 3mm thickness. Binder solution deposited to the print head from binder feeder after completion of layer. Binder solution controlling mechanisms is non-continuous approach that is widely used in desktop contemporary printing system. Potentially powder based 3D printing is considered as a suitable  technique for large amount of suitable materials such as composites, metals, polymers and ceramics available in powder form (Utela et al. 2008).

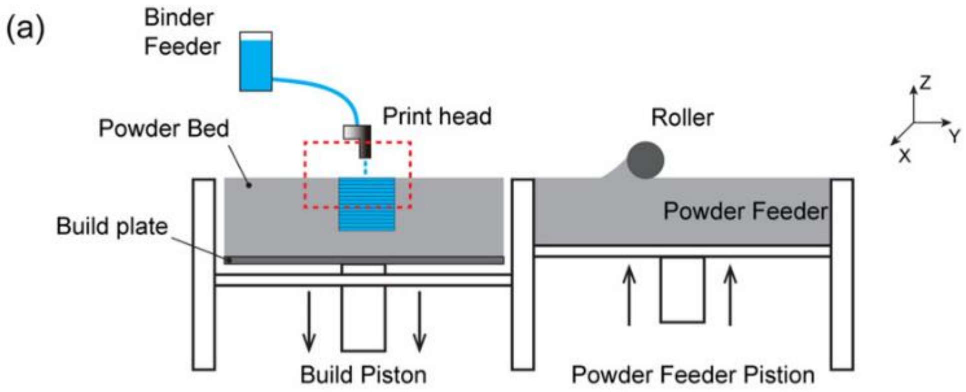

**Figure 6a).** 3D printing inkjet system (Xia et al. 2016).

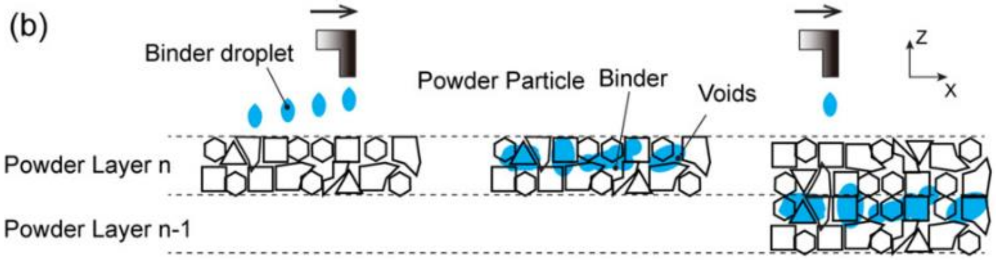

**Figure 6b).** Adjacent layer binder/ powder interaction (Xia et al. 2016).

## 2.2 Printing apparatus design

Printing apparatuses for 3D printing of concrete are mostly based on robotic arm, gantry, and a delta system. In 3D printed construction, commonly used delivery methods are gantry and robotic arm.

### 2.2.1 Gantry printer framework

In gantry system printer nozzle is capable to move in three axes by adopting cartesian coordinate system. Installation, transportation and size are main factors that limit applications and usage of gantry system (Labonnote et al. 2016). Cost, stability, and non-continuous printing (required to print entire building) are key drivers for gantry printer applications. Adoption of these technologies depends upon concrete composition and final product application (Sayegh et al. 2020).

Material flow control through gantry type printer can be achieved precisely by adopting hopper above the print head. Printer without usage of hopper prints the structure continuously, making it difficult for printing structure where specific parts are not required to be printed (such as place for window in a building structure). Additionally, gantry printer is capable of printing both smaller and larger building precisely having complex and high degree of details. Gantry printer can be used for both off site and on-site construction purposes (Cobod International A/S 2019).

### 2.2.2 Robotic arm-based framework

Robot arm is the most common technique used for concrete printing by connecting arm with material storage system. Figure 7 illustrates framework based on extrusion technique for robotic arm. According to Zaid et al. (2018) this framework is applicable in construction industry for different robotic arm through optimum usage of material. Less space is required for a robotic arm system in comparison with gantry system. Moreover, robot maximum reach is limited to the base moment generation. Onsite structure can be manufactured easily through a robotic arm that provides a moveable platform. However, this technique has workspace limitations (Al-Qutaifi et al. 2018).

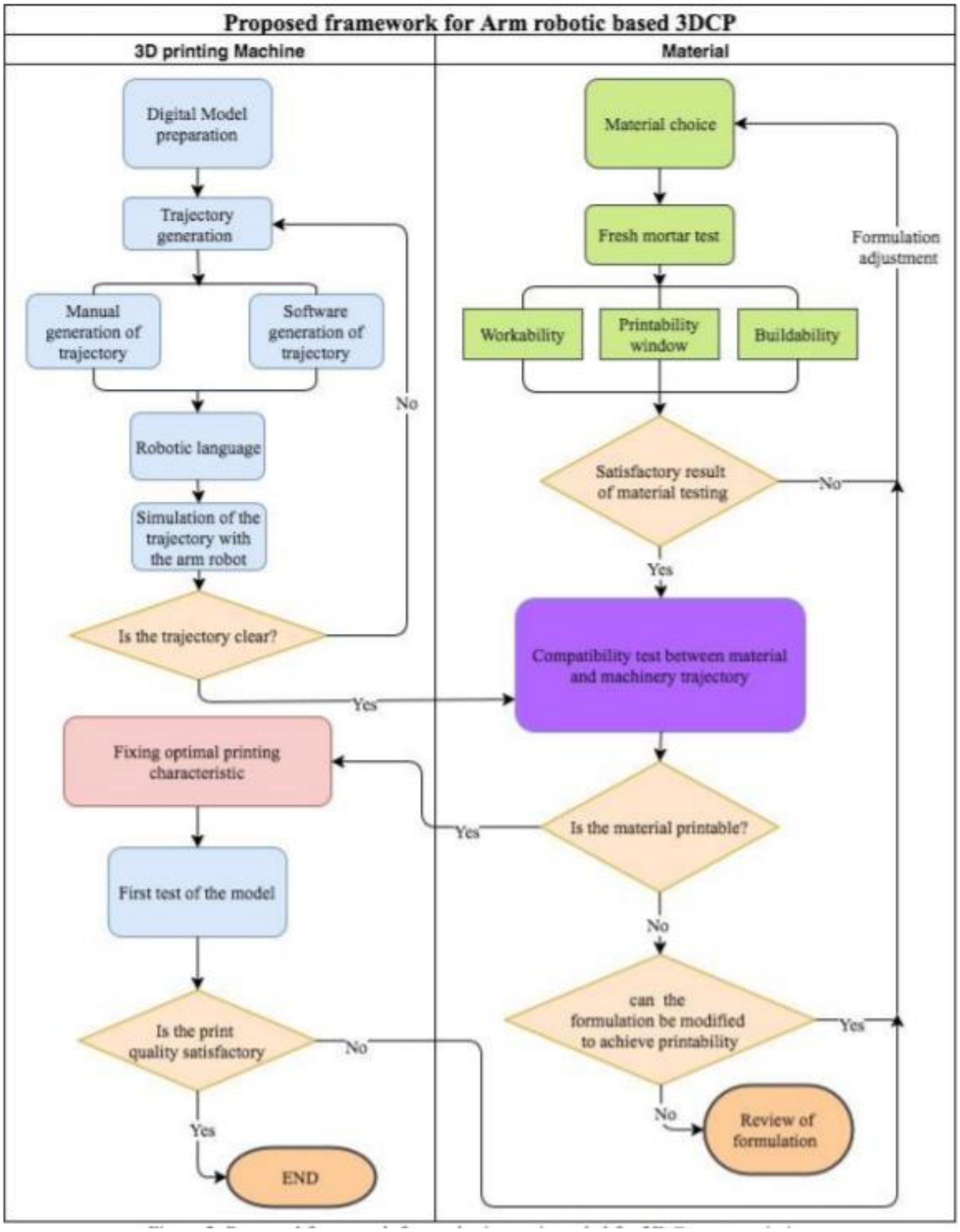

**Figure 7.** Framework based on extrusion technique for robotic arm (Zaid et al. 2018).

Robot type printers are practically unable to build unify buildings under the format of one go, due to printing area limitations. Therefore, different structures are built separately through this technique and assembled on site. Figure 8A and B illustrates off site and on-site robotic arm printing technique. Structure can be printed on-site or off site by adopting robotic arm printing technique. Off-site printer has more Controlled environmental operational condition, but transportation and assembly of the structures are required on site which make it more time-consuming. As 3D printed structure can only be transported after hardened enough, on site printing of components eliminate transportation is needed, but it requires assembly and components connection. On the other side, on site printing does not have fully controlled over environmental conditions (Cobod International A/S, 2019).

**Figure 8A.** Off-site 3D printing by robotic arm (*Constructions-3D MAXI PRINTER review - mobile construction 3D printer*,). **B.** on site printing by robotic arm (*3D concrete printers | CyBe Construction*,).

# 3 GEOPOLYMER MATERIAL SELECTION

Sustainable material selection for the construction of green buildings is an important objective of present time. Materials for construction sector are the primary elements. Mechanical, chemical, and physical properties of materials have significant impact on building mechanical strength and its structure durability. According to European directive 89/106/EE, products of construction in Europe must fulfil fundamental stability demand and mechanical strength. Products must also fulfil hygiene safety, environment, fire and health, safeguard against noise, heat retention and energy economy.

Sustainable Materials selection having better properties than traditional materials is an essential step for the design of green buildings. Recycling of non-hazardous waste can entirely or partially compensate natural material obtained from non-renewable means. Treatments such as washing, grinding, sintering, clink erization process consume excess amount of energy to achieve natural raw materials. Therefore, green building materials will lead to reduction in landfill material disposal, environment preservation, cost reduction and energy savage (Bignozzi 2011).

Geopolymer main components are alkali activators (Potassium or sodium hydroxide, carbonates, silicates, or mixture) and precursors. Alkali activator and precursor coupling needs to be considered to attain final products high performance. Certain activator, due to chemistry difference will not react efficiently, compared to other activators. Therefore, it is essential to choose the activators that will react efficiently such as solution of sodium silicate providing good activation to GGBFS. However, for fly ash alkali activation sodium hydroxide would give better result. (Hassan et al. 2019)

Hassan et al. (2019) illustrates geopolymer concrete production process using waste material fly ash, GGBFS and alkaline solution as shown in Figure 9. GPC strength lies on the waste material usage rather of virgin materials. Wastes of different industries such as ashes (agriculture, mining, metallurgy, construction), fiber, green liquor sludge and flotation sand produced as side stream of different industries, were considered as potential source of GPC.

Utilization of various materials for geopolymer manufacturing, produced as side stream or wastes from different factories located in south Karelia region. The frequent available material is green liquor sludge generated from pulp mills, flotation sand (frequent generated mining industry side stream) and fiber reject (forest industry side stream). Utilization of these side streams or waste into materials is comprehensively reducing environmental pressure by adopting green building materials having higher technical performance (Hassan et al. 2019).

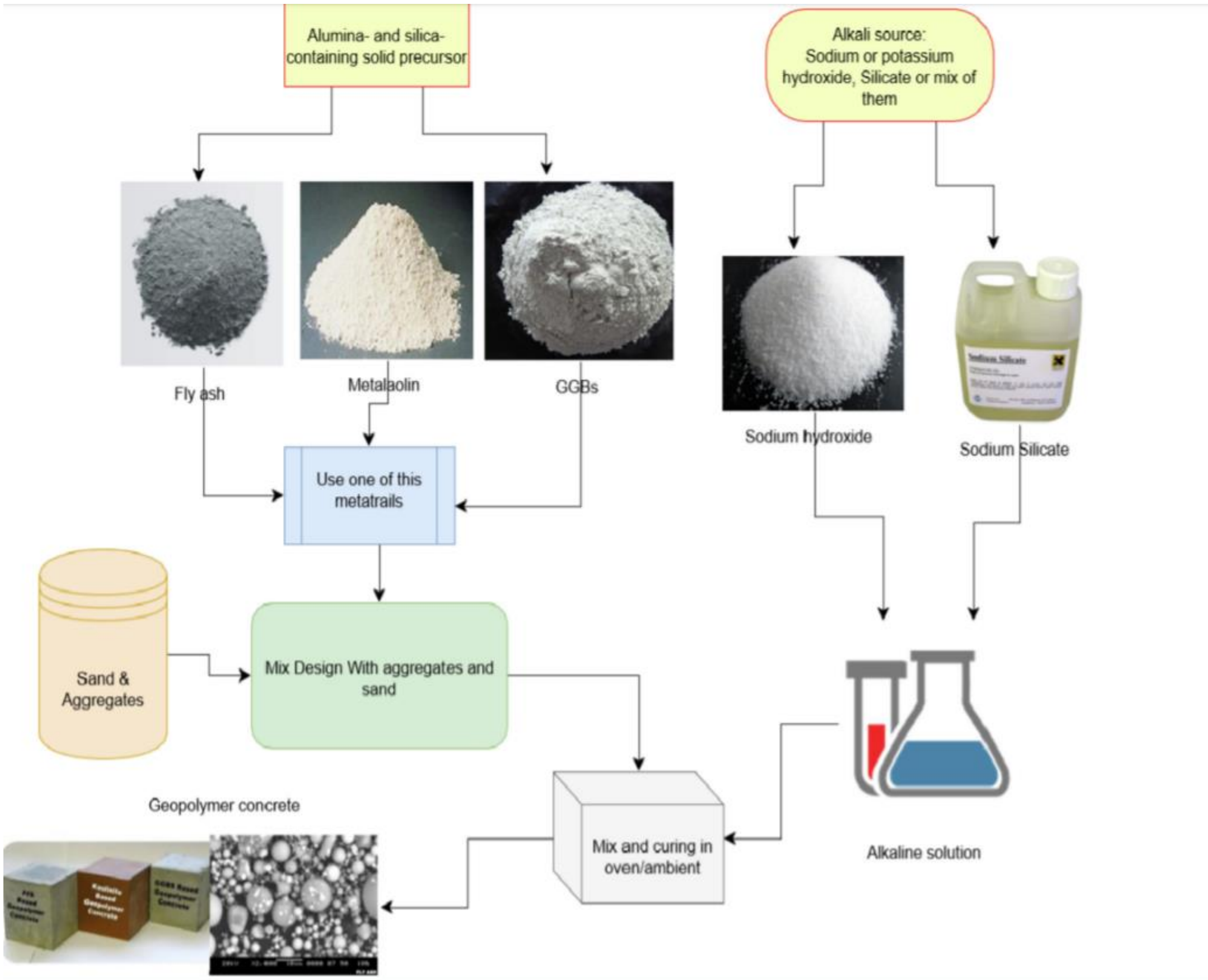

**Figure 9.** Geopolymers concrete production (Hassan et al. 2019).

## 3.1 Local available materials

Geopolymer cement and concrete are synthesized by using waste generated from different industries. Table 4 illustrates different waste generated from various industries in south Karelia region.

**Table 4.** Wastes generated from various industries in Finland (Tsytsyna 2019).

| **Classification** | **Company/mill** | **Side-stream** |
|---|---|---|
| Ashes | Hanasaari | Ash |
| | Helen Helsinki | Fly ash (coal) |
| | Kaukaan Voima | Fly ash (biomass power plant |
| | Metsä Group (Mestä Board) Simpele | Fly ash (peat + biomass |
| | Metsä Group ( Mestä Fibre) Joutseno | Ash (gasification of bark on CaCO3 bed) |
| | Metsä Group ( Mestä Fibre) Lappeenrannan saha | Ash (combustion of bark) |
| | Stora Enso Anjalankoski | Bottom ash (co-incineration) |
| | Stora Enso Anjalankoski | Fly ash (co-incineration) |
| | Stora Enso Imatra | Ash (bark combustion) |
| | UPM Pellos, Kristiina | Ash |
| Fiber reject | UPM Kaipola | Deinking flotation reject foam |
| Flotation sand | Nordkalk Lappeenranta | Tailings, coarse fraction |
| | Nordkalk Lappeenranta | Tailings, fine fraction (from carbonate mine) |

**Table 4 continues.** Wastes generated from various industries in Finland (Tsytsyna 2019).

| | | |
|---|---|---|
| Green liquor sludge | Stora Enso Imatra | Green liquor dregs |
| | UPM Kaipola | Mixed sludge (deinking sludge + biowaste + fiber waste) |
| | UPM Kaukas | Coating sludge |
| | UPM Kaukas | Green liquor dregs |
| Others | Metsä Group ( Mestä Fibre) Joutseno | Lime / slaked lime (CaO / Ca (OH)2) |
| | Metsä Group ( Mestä Fibre) Joutseno | Lime kiln dust |
| | Nordkalk Lappeenranta | Thickening pilot underflow (from carbonate mine) |
| | Ovako steel | Steel slag |
| | Stora Enso Imatra | CaCO3 (from chemical recovery cycle) |

## 3.2 Geopolymer construction products

This section will illustrate various geopolymer products that are used in various sectors. Recycling of non-hazardous waste generated from different factories are potentially utilized to make different construction products such as geopolymer concrete, geopolymer bricks and geopolymer cement. Reuse of industrial waste reduces harmful effect on the environment.

### 3.2.1 Geopolymer cement

Cement is a binder which can be manufactured by fractionally substituting contents of clinker with non-perilous waste. Geopolymer cement can be utilized as a substitute to conventional cement in construction, infrastructure for transportation and for offshore applications. Alumina silicate material and alkaline reagent (sodium or potassium) are needed to manufacture geopolymer cement as illustrated in Figure 10. Geopolymer cements attain their strength mostly within 24 hours. GPC cure rapidly compared to Portland based cement. Additionally, GPC has potential to make chemical bond strongly with most of the rock- based aggregates (Davidovits 2013).

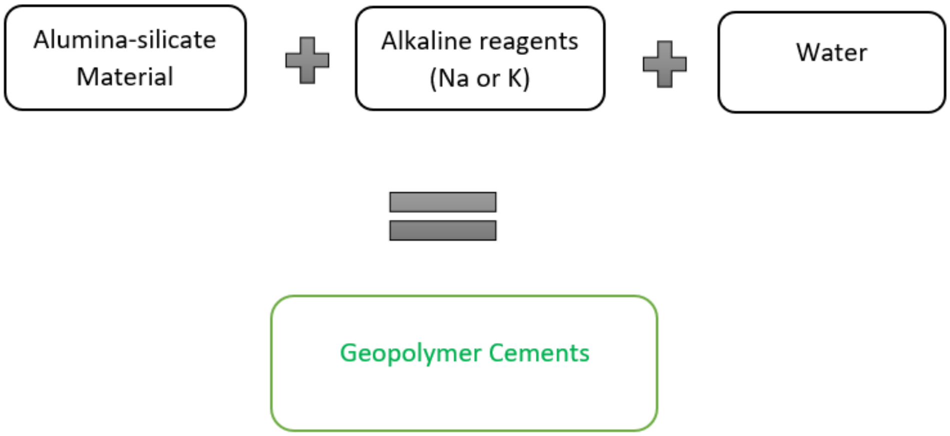

**Figure 10.** Required Material for creating geopolymer cements

Geopolymer cement categories are comprised as slag-based GPC, rock-based GPC, fly ash-based GPC (alkali activated fly ash GP, slag/fly ash-based GPC) and ferro-sialate- based GPC. Geopolymer cement does not depend on calcium carbonate as compared to Portland cement clinker, where calcium carbonate calcination creates excess amount of carbon dioxide emission.

According to Davidovits (2013), energy demand and $CO_2$ emissions for fly ash-based geopolymer cement, rock- based geopolymer cement and for regular Portland cement. The research illustrates energy and emission comparison between GPC and Portland cement having similar strength (40MPa average at 28 days) as explained in Table 5. Geological compound contains seventy percent by weight calcined at 700C temperature. Solution of alkali silicate (industrial user-friendly chemical) and blast furnace slag are involved in rock-based manufacturing of geopolymer cement. Room temperature hardening and mechanical strength enhancement are attainable through utilization of blast furnace slag.

**Table 5.** 1 tonne of Rock-based GPC and OPC energy demand and $CO_2$ emission (Davidovits 2013).

| **Energy needs (MJ/tonne)** | **Calcination** | **Crushing** | **Silicate sol.** | **Total** | **Reduction** |
|---|---|---|---|---|---|
| Portland cement | 4270 | 430 | 0 | 4700 | 0 |
| GP-cement, Slag by product | 1200 | 390 | 375 | 1965 | 59% |
| GP-cement, Slag manufacture | 1950 | 390 | 375 | 2715 | 43% |
| **$CO_2$ emission (tonne)** | | | | | |
| Portland cement | 1.000 | 0.020 | | 1.020 | 0 |
| GP-cement, Slag by product | 0.140 | 0.018 | 0.050 | 0.208 | 80% |
| GP-cement, Slag manufacture | 0.240 | 0.018 | 0.050 | 0.308 | 70% |

According to US Portland cement association (2006), energy needed for Portland cement is approximately 4700 MJ/tonne. Blast furnace slag as a by-product is obtained from the steel industry (no extra energy required) and non-granulated slag re- smelting are the parameters used for rock-based GPC. Rock- based GPC manufacturing consumes 59% less energy compared to Portland cement, whereas 80% reduction in the emission of $CO_2$ is achieved while manufacturing rock- based GPC having slag availability as a by-product.

### 3.2.2 Geopolymer concrete

Concrete is considered as an extensively utilized man-made material around the globe. Concrete is a composite material synthesized by adding cement to aggregates. Main component of concrete are cement, water, sand, aggregates, and air. All these components are added with proper proportion and by mixing them appropriately resulted the mixture called concrete.

Concrete mixture is left over for few hours to gain strength and hardened properties through chemical reaction called hydration. During the hydration process, chemical bond is formed between the water molecules and major compound of cement (Mindess 2019).

Concrete is considered as the most used construction material in the world, approximately 1.35 billion tons are made per year. Emission of $CO_2$ is the major environmental concern that leads to develop new sustainable alternative for production of concrete. Durability, high permeability, penetration of water and other harmful material, corrosion and carbonation problems are the main side effects of OPC concrete. Therefore, alkali- activated binders are the potential solution to overcome problem related to OPC concrete. Waste generated as a by-product (slag from iron production or from burning coal fly ash) is a sustainable choice for alkali activated binders.

Davidovits suggested that binders can be produced by alkaline liquid reaction with Si and Al from geological material source. Figure 11 explains environmental, economic, and service life advantages of geopolymer concrete.

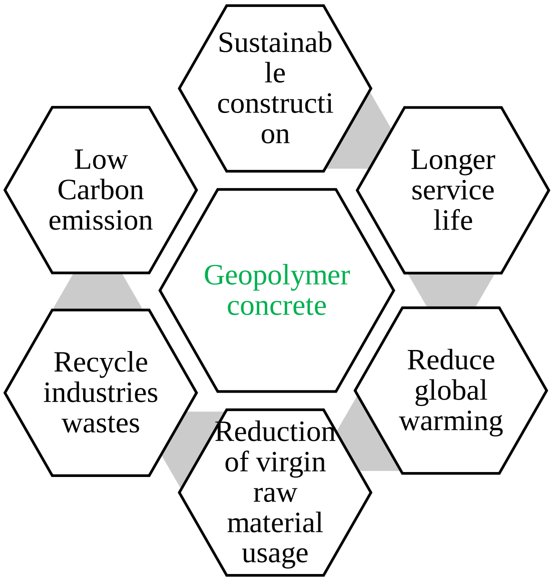

**Figure 11.** Geopolymer concrete usefulness in sustainable construction (Hassan et al. 2019).

The geopolymer relies on natural minerals that are thermally activated like industrial by- product or meta kaolinite such as fly ash or slag that provide Al and Si source. Si and Al is dissolved in solution, activated by alkaline agent and polymerized into molecular chain that form the binder (Duche et al. 2012). Figure 12 explains comparison between Portland cement concrete and geopolymer concrete

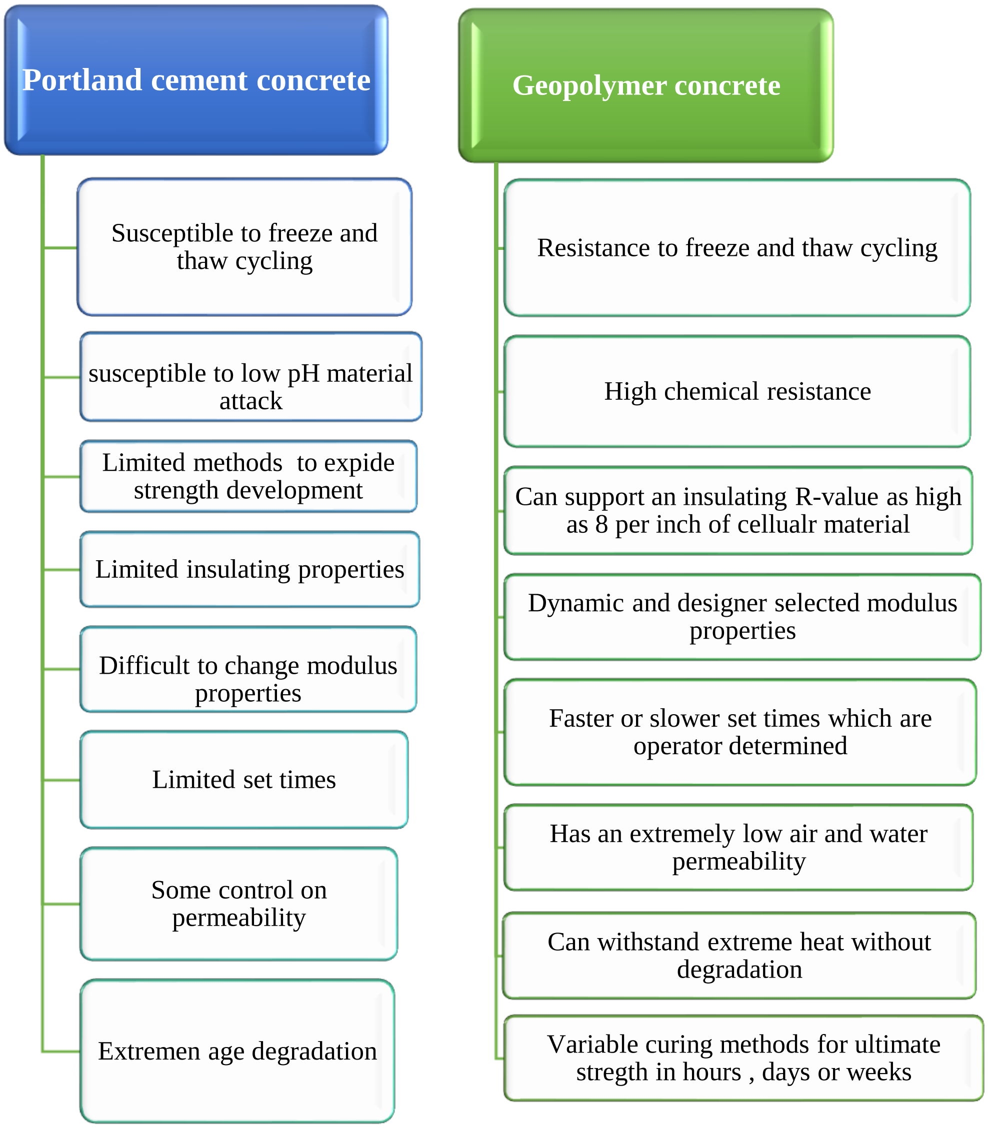

**Figure 12.** GPC concrete and OPC concrete performance comparison (Hassan et al. 2019).

### 3.2.3 Geopolymer bricks

Brick is extensively used material for construction purposes. The increasing demand for building materials and rapid enhancement in demolition and construction wastes require advancement of new materials for construction sector. The production of traditional bricks creates several negative impacts on human and environmental health. Therefore, manufacturing of bricks requires alternative materials such as geopolymers which demonstrate higher sustainability in construction sector. Geopolymer is produced by utilizing waste from different industries (fly ash, green liquor slag, blast furnace slag, etc). Geopolymer bricks production needs less energy and small cost in case of raw material (Petrillo et al. 2016).

# 4 ECONOMICAL EVALUATION FOR GEOPOLYMERS 3D PRINTING

AM in market environment from an aggregated perspective is the most advantageous technique due to its flexibility, customization, complexity in design and transportation costs for the product delivery. AM technology facilitates comparatively inexpensive product cost, rapid production, and design iterations. Therefore, any feasible product design compiled in 3D model is possible to manufacture by utilizing AM technique that can offer customized product according to demand of customers. (Weller et al. 2015)

GPC concrete is manufactured by utilizing different types of waste. Therefore, production of such type of concrete depends upon the availability of raw materials, transportation, and pre-treatments techniques. OPC from the prospect of raw material transportation is advantageous over 3D geopolymer concrete. Raw material supply in case of ordinary concrete operates fully on commercial scale, because of mature nature of ordinary Portland concrete market. Raw material depends upon transportation distance as it largely influences the price of product. Figure 13 shows flow chart of 3D printing GPC. Different stages illustrate production of raw materials,  transportation of raw materials and manufacturing of concrete respectively (Yao et al. 2020).

Manufacturing location is among one of the most important factors that have impact on geopolymer 3D printing. Higher transportation cost for the product delivery, raw material transportation costs, storage and heat treatments methods influence cost effectiveness of geopolymer product. Table 6 shows economic factors for geopolymer 3D printing. However, opportunities presented in the table can be influenced through several limitations.

**Table 6.** Geopolymers 3D printing economic factors and limitations.

| Geopolymer 3D printing economics factors | Influence methods |
|---|---|
| Product Innovation | Through Simplification and advancement. Design iteration, effectively rapidly available products. |
| Raw material availability | Dependence upon locally available raw materials and energy intensity. |
| Assembly work reduction | Adoption of one-step production |
| Product accessibility | Eliminating market entry barriers |
| Functional improvement, customization | Lightweight products |
| Customer friendly product | Adopting environmental, sustainable and reliability factors |
| Less scrap and raw materials | Skilled labour |
| High quality surface Finnish advancement | Improved 3D scanning |
| Production of product without cost penalty | Enhancement in production speed |
| Newly changed product | Reduction in extra setup |
| Defective batch probability | Decrease in manual work requirements |
| Delivery time | Local production implementation |

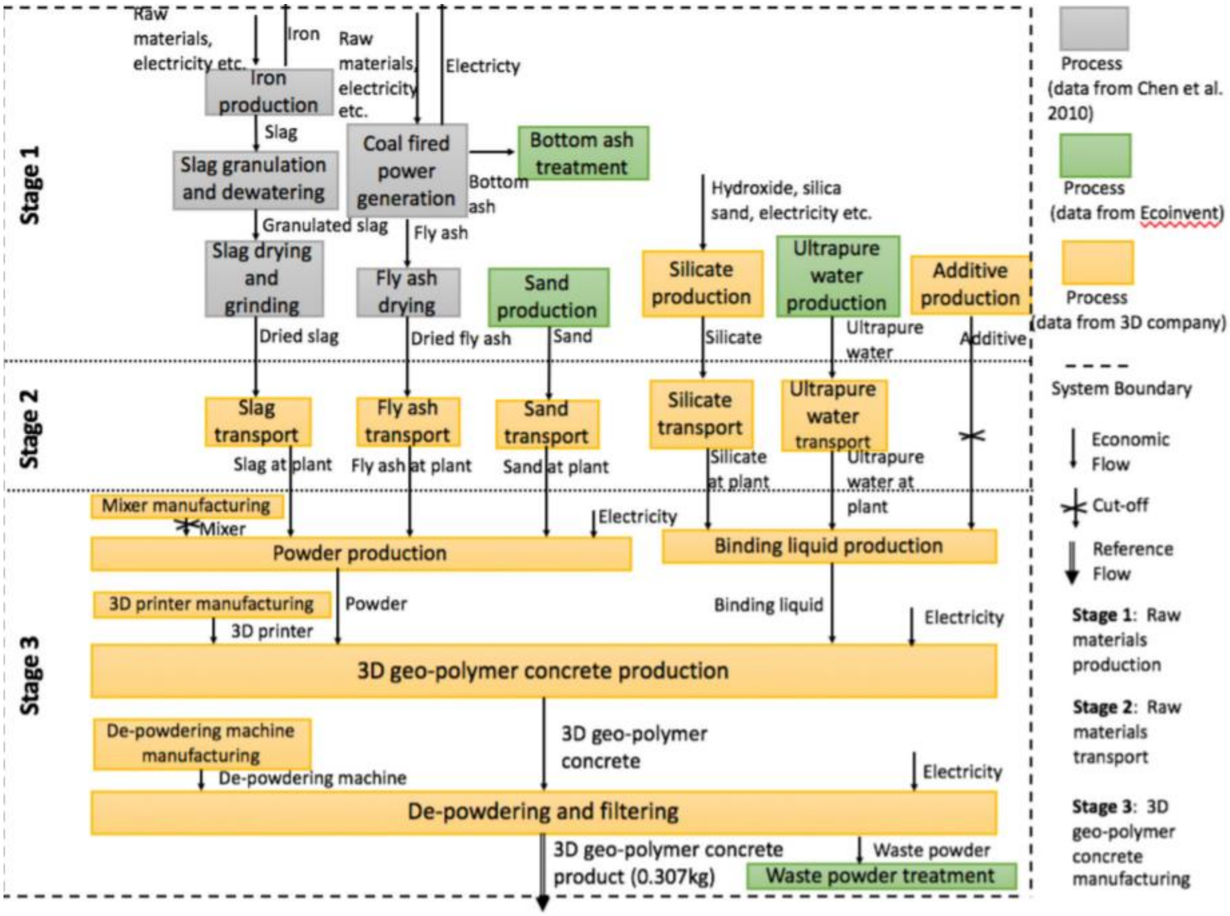

**Figure13.** 3D printing of geopolymer concrete flow chart (Yao et al. 2020).

## 4.1 Types of used materials

Geopolymer synthesis substantially requires two main components: raw material having alkaline liquid of hydroxides or silicates and alumino-silicate oxides. Geopolymer production requires raw materials that must be rich in Si and Al contents. Waste produced because of various industrial application (fly ash and GGBFS) contains excess amount of Al and Si that can be recycled for the process of geo-polymerisation (Mehta & siddique 2016).

Raw material source for geopolymers production depends upon 1:  material availability in specific area 2: concrete types being produced 3: objectives of sustainability 4: pre-treatments technique 5: cost. These factors influence the production of geopolymer. However, selected material must be alumino-silicate nature and cement production utility must be known before implementation on industrial level. Raw material grinding to produce fine particles can provide high percentage of undergoing material reaction. (Mohajerani et al. 2019)

Alkali activator cost produced commercially is among other major factors that influence implementation of geopolymers on wider scale. Torres-carrasco et al. (2017) inspected waste glass recycling potential as a fractional substitutional material for the alkali activator. This investigation explains that alkaline activator cost can be reduced through waste glass recycling. Rakhimova et al. (2015) studied that reactive high calcium sources give a balance between durability and strength. Calcium addition may also provide waste material of alumino-silicate with less reactivity to be implemented.

Large amount of solid waste is produced by mining industry. Isolated environment (impounding lakes) is needed to store mine tailing that contains mud like ore and highly toxic materials. The storage of these materials and their maintenance is quite expensive, as a result recycling of such waste production is financial and environmental concern. GP generated from GGBFS and sulphide mine tailings illustrates alkali activator and blend proportions influence. Waste generated from mining industry create larger amount of waste around the globe (Mohajerani et al. 2019).

Construction waste is another critical waste stream produced around the world. Larger amount of construction and demolition waste is in use for low volumes as limited-replacement aggregates. Construction waste generates higher amount of silt fine particles, having crystalline phases of alumino-silicate. Lampris et al. (2009) developed geopolymer by utilizing silt source from construction and demolition waste. Result illustrates that geopolymer contains 100% silt source contains 18.7 MPa compression strength in 7 days and is cured at room temperature.

Geopolymers can be produced by utilizing different types of wastes depending upon the availability and requirement condition for different products. Geopolymer production is an excellent way to recycle different industrial materials without usage of high energy thermal processing.

## 4.2 Unit price of materials for geopolymers

Material required and unit price to produce geopolymers depends upon various necessary steps. Waste material availability, transportation, pre-treatment techniques, particle size and mixing of mixtures are major parameters, that have influence on geopolymer economics. According to Janardhanan et al. (2016), cost production of geopolymer for higher grade concretes is 11% cheaper than lower grade concretes. Similarly, study conducted by Bondaret (2013), illustrates that geopolymer production reduced $CO_2$ emissions by 22 -72%. Geopolymer production cost depends upon location of raw material, energy source and transportation model. According to Assi (2017) geopolymer concrete, based on fly ash showing high compressive strength illustrates 20% higher production cost than OPC concrete, while 40% less carbon footprint than OPC concrete.

# 5 MATERIALS AND METHODS

The task of this research work is to figure out economically all the necessary stages required for 3D printing of geopolymer. The literature review is carried out to analyse requirements of essential steps for geopolymers printed structures. Needed cost and essential factors for each step are analysed based on utilizing organizational publication, scientific journals, and textbooks.

## 5.1 Raw materials transportation

Locally available wastes produced as a side stream from different industries, are used to create geopolymer. Waste materials are transported from industrial site to warehouse for further processing. Material transportation cost is calculated by using the formula:

Transportation cost= Transportation cost per mile X unit price

For logistics cost besides above-mentioned factors, mean of transportation, product specification, equipment/material loading and unloading cost, labours cost, management cost and taxes are also included to evaluate overall capital demand. The logistics cost is greatly depending upon companies' competition. Cost can be decreased in case of higher competitions. Similarly, in transportation product sophistication is an important factor, affecting decisive enhancement in transportation cost. Better packaging and measurement implementation are needed for sophisticated product throughout journey resulting higher increase in transportation charges. Additionally, distance between endpoints and the statement plays a mighty role in logistics cost, as fuel consumption is high if distance increases. Table 7 shows all the important factors which are considered while calculating material transportation cost from industrial site to warehouse.

**Table 7.** Transportation cost calculation factors

| **Factors** | **Considered values** |
|---|---|
| Distance | 50Km |
| Waste material | C&DW, fly ash, green liquor sludge, fiber rejected, flotation sand |
| Transport Management | Carrier, freight, and shipment |
| Transport organization/ operation | Operative, management, operation, and organization |
| Area utilization | Needed for 32000 tons |
| Packaging cost | Material sophistications |
| Time needed for one trip | 3 hours 20 Minutes |
| Maximum weight carries in one trip | 20 tons |

Five different type of wastes utilized to produce geopolymers are transported from industrial area to warehouse for purification processes. Different requirements and packaging procedure are used for each raw material transportation. Table 8 illustrates all the factors and required investment needed to perform transport management and operational task. The total operating time and cost estimates were based on literature review and previous experience. In reality, operating hours and cost estimation can vary.

Activities performed in warehouse and their cost are explained in Table 9. Labours Salaries for loading and unloading work is considered as 3000 euros/kk. The total operating time and cost estimates can vary in practice. Also, cost of labours for loading and unloading of material may be higher. To calculate transportation cost, 50 km distance was considered from industrial to warehouse site. Calculated cost illustrates required annual investment needed for the warehouse, whereas transportation management and organization cost are calculated on monthly basis.

**Table 8.** Cost needed for transport management, organization, and operative activities

| **Functions** | **Labor** | **Operating** | **IT related** | **Equipment** | **Area utilization** | **Labor quantity** | **Total cost/€** |
|---|---|---|---|---|---|---|---|
| **Transport Management cost** | | | | | | | |
| Carrier | 3000 | 500 | 1000 | 500 | | 1 | 4500 |
| Freight | 3000 | 400 | 1000 | | | 1 | 3400 |
| Shipment | 3000 | | | | | 1 | 3000 |
| **Total transport management cost** | 9000 | 900 | 2000 | 500 | | | 10900 |
| **Operational organization/ cost** | | | | | | | |
| Transport documents | 2500 | 500 | 500 | | | | 3500 |
| Operative contacts | 3000 | 500 | | 500 | | 1 | 4000 |
| Other documentation | 1500 | 500 | 500 | | | | 2500 |
| Total Operational organization/cost | 7000 | 1500 | 1000 | 500 | | | 10000 |
| **Total cost** | 20900 | | | | | | |
| **Management cost %** | 52.15 % | | | | | | |
| **Operational organization/ cost %** | 47.84 % | | | | | | |

**Table 9.** Cost needed for warehouse activities

| **Functions** | **Labor** | **Operating** | **IT related** | **Equipment** | **Area utilization** | **Labor quantity** | **Total cost/€** |
|---|---|---|---|---|---|---|---|
| Warehouse cost | | | | | | | |
| Loading cost | 150000 | 12500 | | | | 10 | 162500 |
| Quantity/quality of material | 15000 | | 500 | | | 1 | 15500 |
| Packing | 10000 | 2000 | | 1000 | | | 13000 |
| Unloading cost | 10000 | | | | | | 10000 |
| Product placement | 30000 | | 500 | | | | 30500 |
| Material storage | 30000 | | 500 | 1000 | 50000 | 2 | 81500 |
| Inventory cost | 15000 | | 500 | | | 1 | 15500 |
| Total cost | 328500 | 14500 | 2000 | 2000 | 50000 | | 328500 |
| **warehouse cost %** | 79.15% | 4.41% | 0.61% | 0.61% | 15.22% | | 100% |

It is estimated that 20900 euros is needed on monthly basis for organization and operative activities. As six months are needed to transport the material, therefore total investment needed for operative and organizational activities are 125,400 euros. 300 tons of material per day is estimated to be transported from industrial area to warehouse by utilizing 5 trucks. Therefore, in one month 6000 tons is transported and it is estimated that 5 to 6 months are needed to transport 32000 tons of raw material. Estimated investment cost needed for warehouse activities is 328500 euros. Therefore, total investment needed for transportation of 32000 tons of raw material is 453,900 euros, whereas estimated cost 14.18 euros is needed for the transportation of 1 ton of raw material. Since the printer capacity is 12 000-15 000 tons, which means that roughly $\frac{1}{2}$ of total weight of raw material can be utilized. This will lead 46.8% to the reduction of initial investment cost required for transportation. Steps involved from raw material transportation to geopolymers 3D printed product are shown in Figure 14.

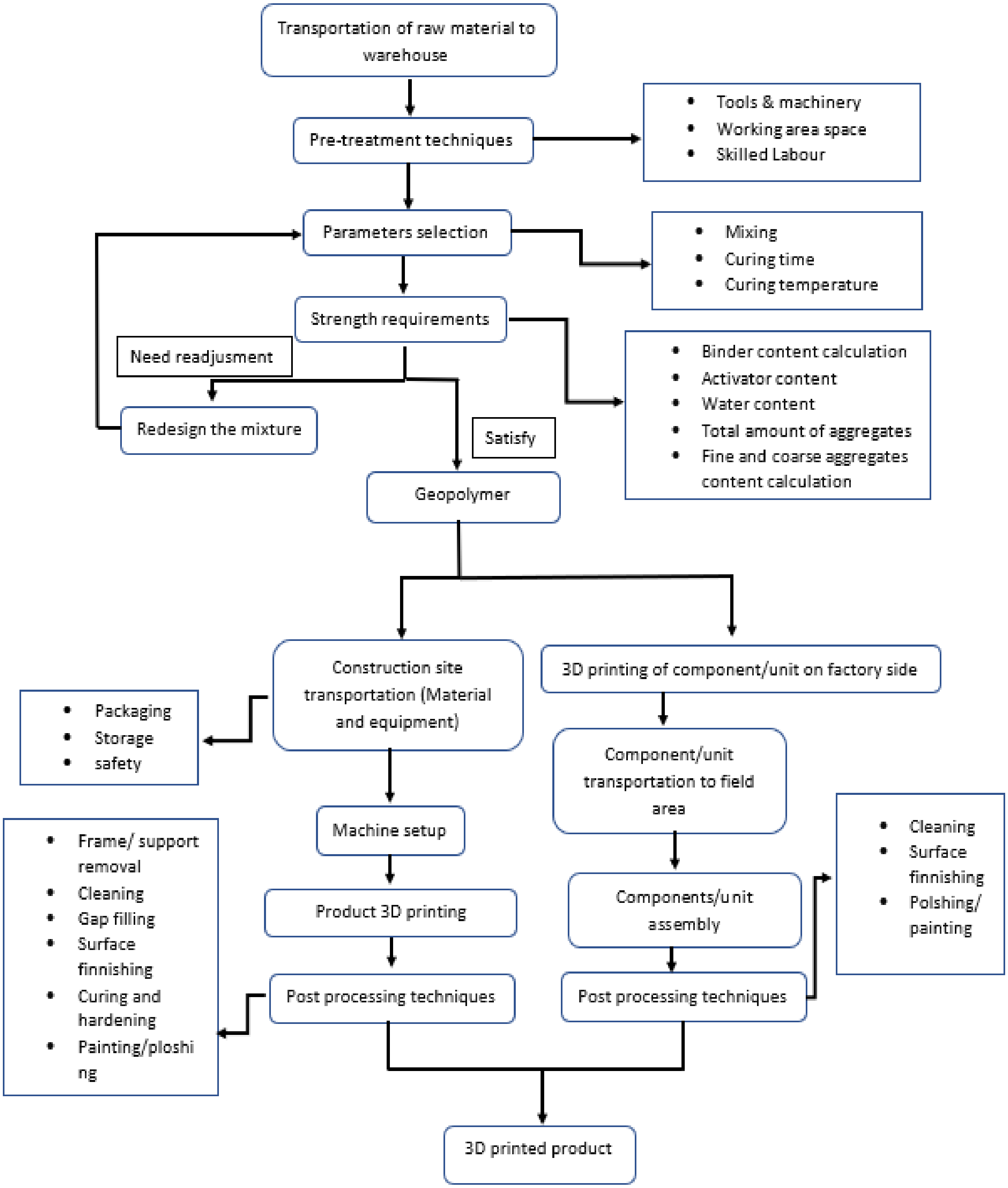

**Figure 14.** Flow chart illustrates steps involved from raw material transportation to 3D printed product.

## 5.2 Pre-treatments techniques

Different Pre-treatment techniques required for the waste material usage before 3D printing are studied and their annual operating cost is calculated. All five different types of wastes used in this study needed different treatments techniques, operating area, cost, equipment, energy demand and machinery. Factors considered to calculate pre-treatment cost for each individual waste are shown in Table 10. All the values used for calculation of pre-treatments cost are taken from research work Afshariantorghabeh (2019).

**Table 10.** Data used to calculate pre-treatments operating cost (Afshariantorghabeh 2019).

| **Factors** | **Cost calculation** |
|---|---|
| Labour cost | 30 euros/h |
| Supervision and accountant | 3500 euros/kk |
| Energy cost | 0.15 euros per KWh |
| Individual available waste capacity per year | 8000 tons |
| Process capacity | 20 tons per hour |
| Processing hour per year | 1000/h |
| Insurance cost | 1 % of total capital cost |

Table 11 shows required annual investment needed for the pre-treatment techniques. Cost calculation for each raw material is calculated by considering the sum of labour, maintenance, plant cost, equipment, installations, insurance, contingency, cement solidification and energy cost.

**Table 11.** Annual investment needed for pre-treatments of waste materials (Afshariantorghabeh 2019).

| **Item cost (€)** | **Green liquor sludge** | **Ash** | **Fiber rejected** | **Flotation sand** | **C&D W** | **Combined line** |
|---|---|---|---|---|---|---|
| Considered Plant area/$m^2$ | 400 | 800 | 400 | 300 | 2000 | 2500 |
| Equipment | 147350 | 199000 | 132000 | 112000 | 674000 | 789000 |
| Cement solidification process | | 400000 | | | | 400000 |
| Installations | 14700 | 20000 | 13200 | 11200 | 61500 | 73000 |
| Maintenance | 9000 | 11200 | 9500 | 7000 | 49500 | 58200 |
| Labor | 174000 | 204000 | 174000 | 144000 | 276000 | 426000 |
| Plant cost | 200000 | 400000 | 200000 | 150000 | 2000000 | 2500000 |
| Insurance | 3600 | 6300 | 3500 | 2700 | 27000 | 33000 |
| Contingency | 55000 | 114000 | 53200 | 43000 | 303000 | 412000 |
| Energy cost for Machineries | 9800 | 14900 | 7500 | 3700 | 33100 | 58300 |
| Energy cost for building services | 10200 | 20400 | 10200 | 7700 | 51000 | 63700 |
| **Total annual cost** | 623650 | 1389800 | 603100 | 481300 | 3475100 | 4813200 |

## 5.3 Parameters selection and strength requirements

Geopolymers strength depends upon selection of various parameters such as curing temperature, concentration of chemicals, ratio of solid solution, curing time, alkali solution molar ratio, elementary materials containing silica and aluminium concentration, type of additives, admixtures, and alkali solution type. To identify the effect of mix and particle size on compression strength of geopolymer, different grades of geopolymer concrete are considered. Mix proportion, required material, coarse aggregates size and unit price needed to produce 1 m$^3$ of geopolymer concrete is calculated as explained in Table 12.

**Table 12.** Cost production of 1m$^3$ geopolymer concrete.

| **Concrete grade** | **Mix proportion** | **Materials** | **Coarse aggregate mm** | **Price in euros** | **Unit** | **Quantity in Kg** | **Amount in euros** | **Total price** |
|---|---|---|---|---|---|---|---|---|
| M30 (Concrete standard grade) | Design Mix | Ash | 2-4mm | 156.8 | MT | 350 | 54.88 | 860.07 |
| | | C&D W | < than 4 mm | 416.4 | MT | 610 | 254 | |
| | | Green liquor sludge | | 75.5 | MT | 262 | 20 | |
| | | Flotation sand | 2-4mm | 59.1 | MT | 583 | 34.5 | |
| | | Fiber rejected | | 73.2 | MT | 420 | 30.8 | |
| | | Sodium silicate | | 4 | L | 116.36 | 465.44 | |
| | | Water | | 10 | Cubic meter | 45 | 0.45 | |

Numerous factors have to be considered to calculate production cost of geopolymer. Price of different raw material, that is utilized for cost production of geopolymer, is taken from literature review and collected directly by contacting the manufacturers. Therefore, predicted cost is based on the average price as shown in the Table above. Since there are no cost value is available for raw material needed to produce geopolymer on industrial scale in Finland, cost estimation presented for different grades of geopolymer is based on the data obtained from different university level studies and work experience.

## 5.4 Factory site 3D printing

3D printing of construction product on factory site is composed of four main stages: components 3D printing, transportation, assembly and post- processing techniques. The total cost of 3D printed product on factory site is calculated by combining the cost of net printing, transportation, assembly, and post processing techniques as shown below:

Factory site 3D printing cost = Net printing cost + Transportation cast + Assembly cost + post processing technique

Factory side printing depends upon numerous factors as shown in Table 13. 3D net printing cost of components is calculated by adding the sum of material, energy, manufacturing and labor costs. While calculating manufacturing cost, detailed design, equipment depreciation, machine maintenance and environmental protection factors are considered. Labor and material cost of 3D printing component on factory site are separately calculated from the labor and equipment cost on assembly stage. Therefore, assembly cost is calculated by summing the cost of labor, installation, energy and measure taking factors.

**Table 13.** Factory site 3D printing cost factors

| | |
|---|---|
| **Net Printing cost** | Labor cost |
| | Material cost |
| | Energy cost |
| | Manufacturing cost |
| | Management cost |
| **Manufacturing and management cost** | Detailed design cost |
| | Equipment depreciation cost |
| | Machine maintenance cost |
| | Environmental protection cost |
| | Accounting, management, and sales cost |
| **Assembly cost** | Labor cost |
| | Installation cost |
| | Energy cost |
| | Measure taking cost |
| **Post processing techniques** | Surface finishing cost |
| | Painting/polishing |
| | Cleaning cost |

### 5.5 Construction site 3D printing

Construction site 3D printed products are built on the foundation, according to pre-approved design and specification, whereas in factory site products are manufactured through uniform procedure in batches. Without formwork concrete structure build up is an important factor to enhance rate of production, design freedom and reduction in cost (Pierre & Rangeared 2016). To find out cost structure of product manufacture on construction site, the following formula is used as shown below:

Construction site 3D printing = Engineering cost +frame installation/ setup cost + transportation cost+ measure taking cost + post- processing technique

Engineering cost, transportation cost and construction methods are different among various countries due to difference of technique, economic situation, and natural resources. To calculate engineering cost and measure- taking cost, the following factors are considered as shown in Table 14.

**Table 14.** Engineering cost factors

| | |
|---|---|
| **Engineering cost** | Material cost |
| | Labor cost |
| | Machine cost |
| | Management cost |
| | VAT |
| **Measure taking cost** | Safety measures |
| | Cost for taking measure (countable) |
| | Cost for taking measure (uncountable) |
| **Post processing technique** | Frame/ support removal |
| | Surface finnishing |
| | Gap filling |
| | Curing and hardening |
| | Painting/ploshing |
| | Cleaning |

As there is no related standard and 3D printed houses in Finland, the cost estimation of 3D printed house based on the data obtained from 3D printed house manufactured by Russian company Apis Cor (Apis Cor 2020). To calculate the labour cost and material cost needed for the 3D printing of house in Finland, Apis Cor manufacturing prices for labor and material are replaced by the local Finnish price market. 3D printed house manufacture by Apis Cor is selected since it gives all fundamental cost details and technical information. Secondly, Apis

Cor build homes in -35 C temperature that can be suitable for Finnish climate. Since, Apis Cor manufactured house having area 38m$^2$ , whereas in this research work 50m$^2$ 3D printed house cost calculation were estimated. Table 15 shows required estimated cost needed to build 3D printed house on construction site. In reality, number of hours, labor cost, material cost and printing time can vary. Investment needed for the purchasing of 3D printer is not including in the cost estimation of 3D printed house. According to company web site, less than one day is spend to complete partitions, self- bearing walls and building envelope having total cost estimation is US $10,150. According to company, list of costs is summarized as Floor and roof cost US $2434, wiring US $ 242, traditional foundation US $277, window and door US $3548, printed walls US $ 1642, interior finishing US $ 1178 and exterior finishing US $ 831.

**Table 15.** Cost estimation of geopolymer 3D printed house on construction site.

| **Project components** | **Amount** | **Unit** | **Number of weeks** | **Number of hours** | **Material cost (€)** | **Estimated cost (€)** |
|---|---|---|---|---|---|---|
| **Primary cost of construction** | | | | | | |
| **Home area** | 50 | m² | | | | |
| **Foundation/structure** | | | | | | **11750** |
| Land preparing | 50 | m² | | | 35 | 1750 |
| Basic unit formation | 50 | m² | | | 200 | 10000 |
| **Walls construction** | | | | | | **28258.382** |
| Walls printing | 154 | m² | 1 to 2 weeks | 36 | 57.75 | 8893.5 |
| Insulation material for walls | | | | | | |
| Liquid Polyurethane composition | 84 | m² | | | 16 | 1344 |
| polystyrene | 45.32 | m² | | | 23.85 | 1080.882 |

**Table 15 continues.** Cost estimation of geopolymer 3D printed house on construction site.

| | | | | | | |
|---|---|---|---|---|---|---|
| Plaster | 154 | m² | 2 to 3 weeks | 104 | 110 | 16940 |
| **Roof and celling** | | | | | | **49112.85** |
| Roof frame | 121 | m² | 1 week | 37 | 168.45 | 20382.45 |
| Roof Installation | 71.2 | m² | 1 week | 30 | 242 | 17230.4 |
| Celling Installation | 50 | m² | 1 week | 25 | 230 | 11500 |
| **Door/windows** | | | | | | **19600** |
| Wooden and glass window | 8 | m² | | 20 | 1000 | 8000 |
| Main door | 1 | m² | | 4 | 2800 | 2800 |
| Internal door (wooden) | 4 | m² | | 24 | 2200 | 8800 |
| **Floor** | | | | | | **2250** |
| Wooden floor tiles | 9 | m² | 1 week | | 250 | 2250 |
| **Post processing techniques** | | | | | | **38406** |
| Floor finishing | 50 | m² | | 25 | | 3500 |
| Roof finishing | 72 | m² | 1 week | | 242 | 17424 |
| Ceiling finishing | 50 | m² | 1 week | | 230 | 11500 |
| Window and door finishing | 13 | m² | | 20 | | 3500 |
| Walls painting | 39 | m² | 1 week | | 38 | 1482 |
| Frame removal | 121 | m² | | 10 | | 1000 |
| **Services** | | | | | | **12950** |
| Sanitary services | 50 | m² | 1 week | | 150 | 7500 |
| Electrical services | 50 | m² | 1 week | | 75 | 3750 |
| Drainage | 50 | m² | 1 week | | 34 | 1700 |
| **Labor cost** | | | | | | 30000 |
| **Total cost** | | | | | | **192327.232** |

# 6 RESULTS

Construction process developments through automation is notable in recent era, concentrated by enhancing building construction and structures. 3D printing using geopolymers mixture is considered to be the most promising technology in recent years, that allows to build the structure by extruding the mixture in the form of layers. Investment cost that is needed to perform four major steps from raw material transportation to 3D printing is discussed in this section.

## 6.1 Transport Management and warehousing cost

Transportation cost is considered an important element of any economic structure. It affects overall product cost and trade flow directly. Transportation cost economics depends upon time accessibility and distance. Transport is considered as fundamental constituent of any production process from an economic viewpoint. Table 16 illustrates cost types and their effect on transport management cost structure.

**Table 16.** Transport management cost calculation factors

| **Factors** | **Role** |
|---|---|
| Equipment cost | Office equipment<br>Leasing and capital costs<br>Maintenance cost of equipment<br>Warehouse costs |
| Labor cost | Direct labor cost<br>Personal training cost<br>Bonuses |

**Table 16 continues.** Transport management cost calculation factor

| | |
|---|---|
| Operating cost | Operating cost contains<br>Fuel cost<br>Water, electricity, heating, cleaning, security, waste services<br>Insurances<br>Copying, printing, telephone charges, office accessories |
| IT cost | Software cost<br>Software programming<br>Maintenance |
| Area specific cost | It includes<br>Furniture cost<br>Office area cost |

Factors such as labor, equipment, IT and operating cost are considered for transport expenses. In transport management labor cost seems to be one of the most important factors influencing the price of overall product as shown in Figure 15.

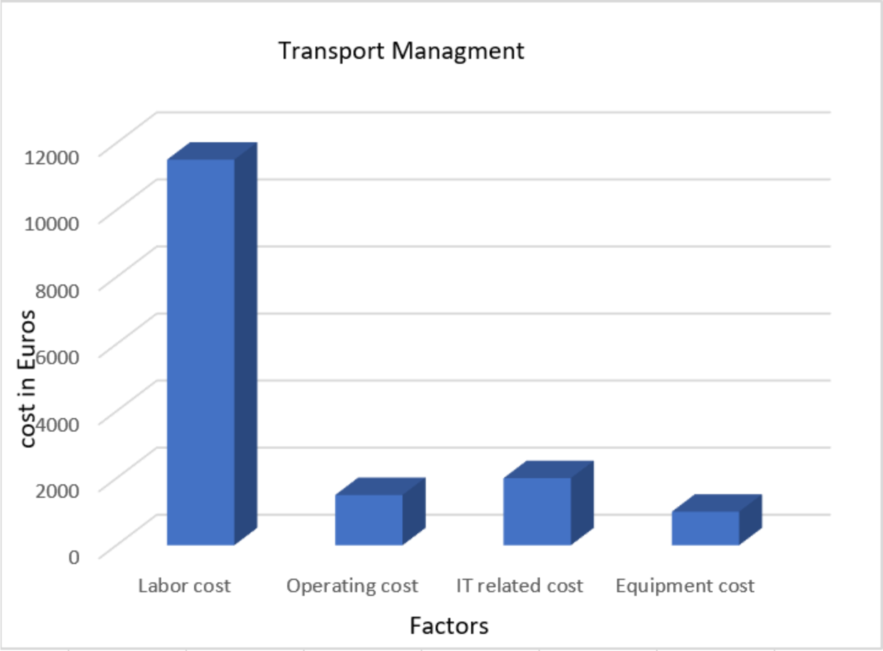

**Figure 15.** Factors affecting transport management cost

Figure 16a explains effect of labor cost in freight, carrier, and shipment sectors. Hiring subsidies, extra time payment and payroll taxes are the factors considered for calculating labor cost. In total, besides IT related expenses, labor cost is the most essential factor affecting overall price of whole transport management. Similarly, Figure 16b represents transport management consumed 52%, whereas transport operation and organization effect are 48% of the overall transportation cost.

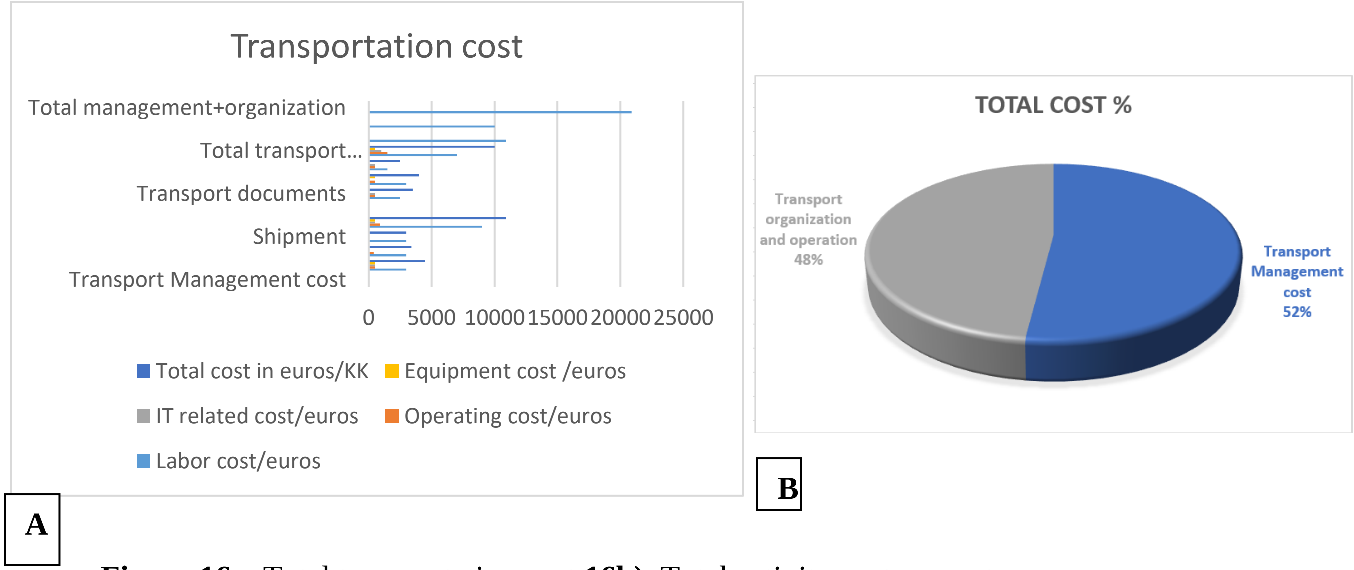

**Figure 16a.** Total transportation cost **16b).** Total activity cost percentage

Warehouse cost is calculated by considering the incoming raw material amount delivered from field area to warehouse. Five different type of raw materials are collected from industrial area and stored in warehouse. The amount of each raw material is eight thousand tons per year. Factors considered while calculating warehouse cost calculation are based on labor cost, operating cost, IT related cost, equipment cost, and area utilization cost. Labor cost is the biggest factor that affects 79% of overall pricing of warehouse as shown in the Figure 17. Each raw material needs different packaging, storage space, equipment's, and operating conditions.

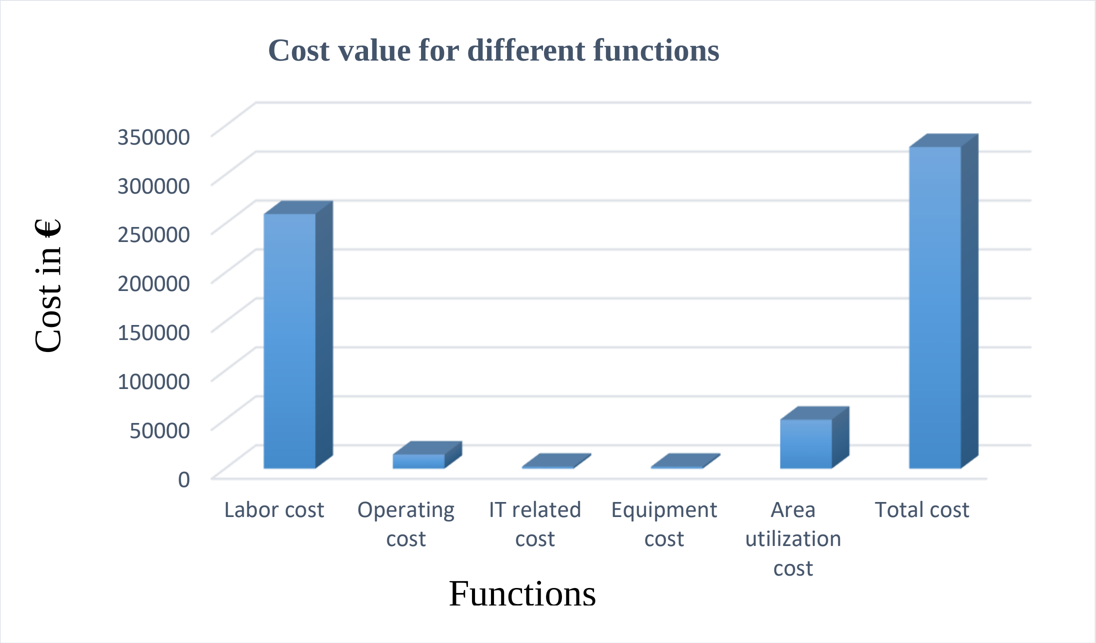

**Figure 17.** Factors effecting on warehouse pricing.

Processes considered for warehousing cost calculation are loading/ unloading, quality and quantity of material, packing, material storage, product placement and inventory cost as presented in Figure 18. Beside storage, loading is considered as a vital process affecting the whole warehousing cost significantly.

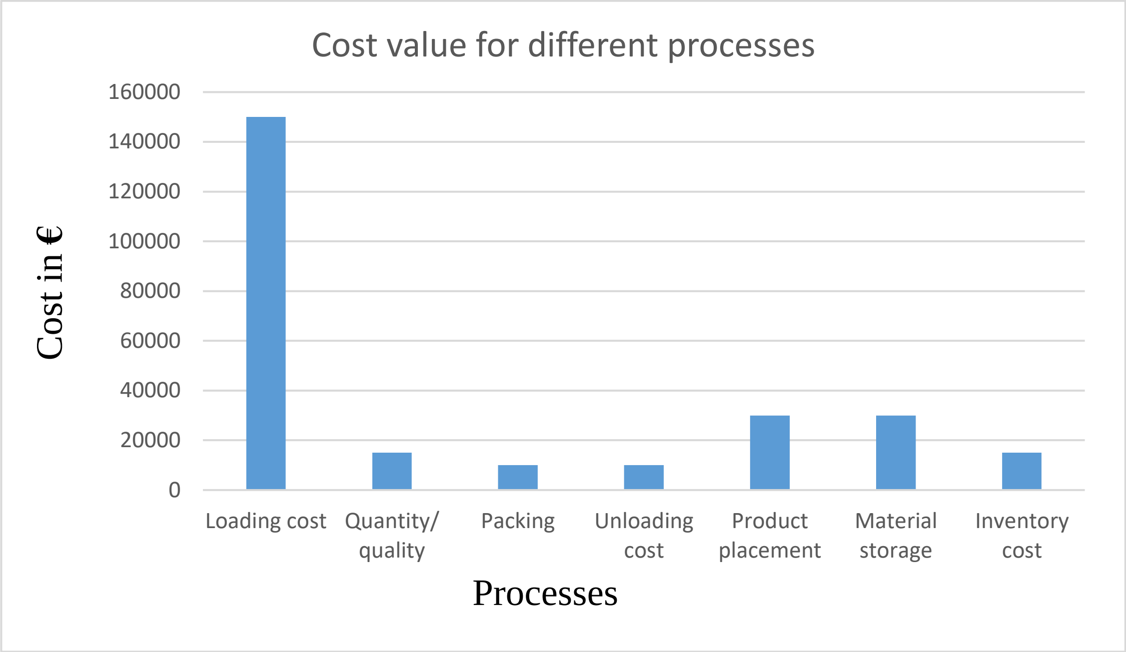

**Figure18.** Processes effecting warehouse cost

## 6.2 Pre-treatment cost

This section deals, with the total investment and energy cost required for each treatment line. Five different types of raw materials needed for geopolymer production. Each material required different pre-treatment techniques, plant area and energy requirement. According to Afshariantorghabeh (2019), total investment and energy cost needed for different raw material is illustrates in Figure 19. Total investment cost includes expenses of equipment, installations, maintenance, labor, plant cost, insurances, and contingency.

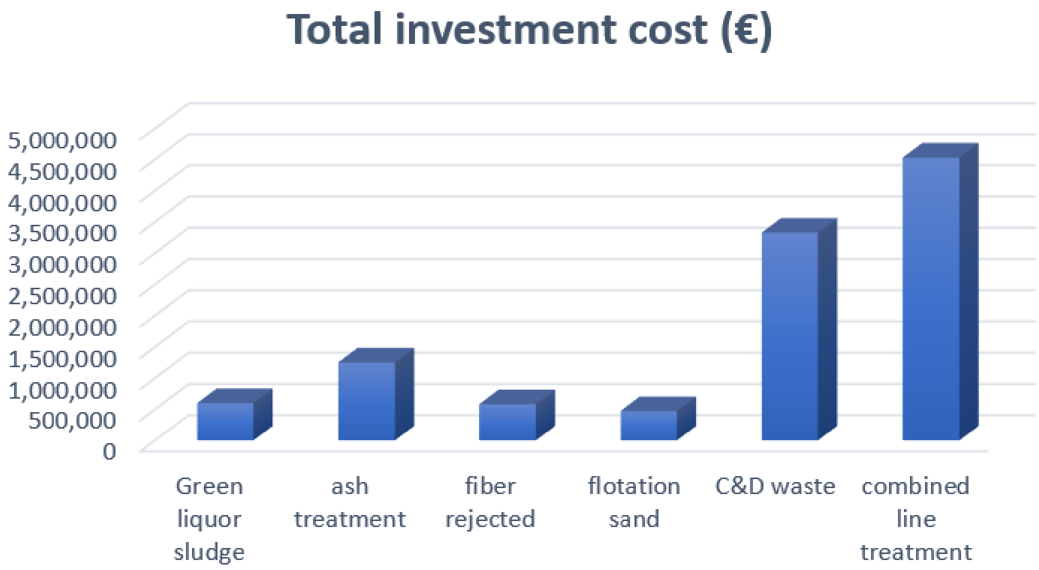

**Figure19.** Total annual investment cost for pre-treatment techniques of raw materials

Construction and demolition waste required the highest amount of total investment for pre-treatments techniques. It is estimated that the highest plant area (2000m$^2$) compared to other material, needed for 8000 tons of C&D W. Similarly, greater amount of energy is needed for C&D W pre-treatments. Figure 20 explains the total energy cost for pre-treatment of each waste.

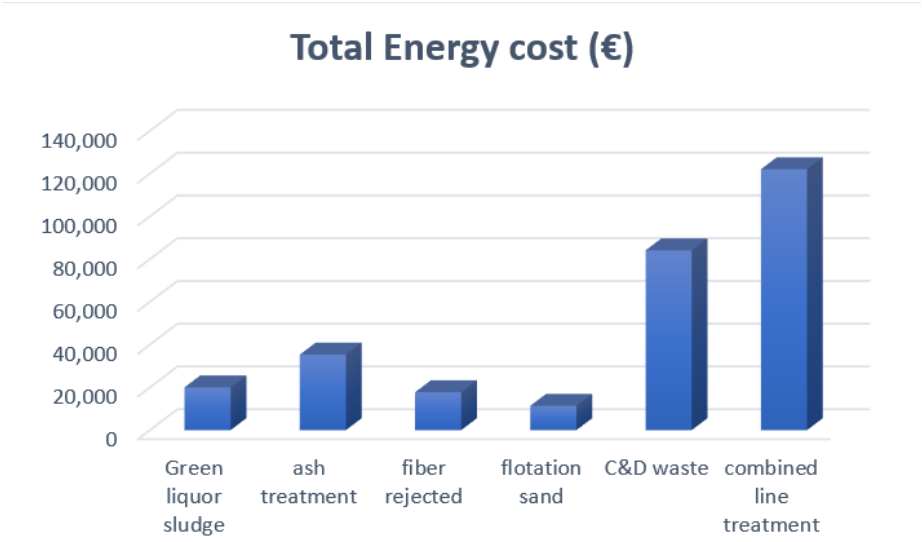

**Figure 20.** Total energy cost required annually for pre-treatments of raw materials

### 6.3 Strength requirements and parameters selections

Geopolymer strength depends upon selection of various parameters such as curing temperature, concentration of chemicals, ratio of solid solution, curing time, alkali solution molar ratio, elementary materials containing silica and aluminium concentration, type of additives, admixtures, and alkali solution type. Besides material selection, strength of geopolymer concrete is greatly influenced by the curing temperature conditions. Study conducted by V. Patil et al. (2019) shows that compressive strength of geopolymer concrete is higher in oven curing temperature compared to ambient curing temperature, as dissolution of alumina and silica in solution of alkaline is better at high temperature. Similarly, it is observed that with the age of concrete, slightly higher compression strength can be achieved. In practice, after curing the concrete for 28 days 30, 40 and 50 MPa strength should be achieved for M30, M40 and M50 grades of concrete. Compression strength after seven days of curing must be 70% of total required compression strength. The enhancement in fine aggregates percentage and coarse aggregates increased the strength to optimum level.

Based on the calculations shown in the Table 12, it may be noticed that production cost of geopolymers concrete is higher than ordinary Portland concrete, due to raw material pre-treatment techniques. Production cost of higher-grade GPC is slightly higher than lower grade geopolymer concrete. Initial material cost of GPC is higher compared to traditional concrete. Study conducted by Rajini et al. (2020) illustrated that initial material cost of GPC (M45) was almost 32% bigger than conventional concrete (M45). However, lots of natural resources, environment, sustainability, cost of maintenance and GPC properties would offset material initial cost production of GPC.

## 6.4 Factory site 3D printing

In factory side components are printed in batches. Components such as walls, foundations, floor, roof, windows, and doors are printed separately and assembled at the construction site. Following formula explained in Table 17 is presented to calculate cost of printed component in factory site.

**Table 17.** Cost calculation factors on factory site

| S. No | Factors | Price calculation |
|---|---|---|
| 1 | Printed components | Labor cost + material cost |
| 2 | Manufacturing cost | a) Design b) Planning c) Sourcing d) Machining e) Testing f) quality control g) electricity + water charges h) equipment I) environmental + labor protection cost J) maintenance cost k) components finishing l) Packing m) inside factory transportation (internal transportation) |
| 3 | Transportation cost | Distance per mile * unit price |
| 4 | Management cost | Organization+ accountant+ sale |
| 5 | Value added cost | 24% |
|  | Total cost of printed components | 1+2+3+4+5 |

### 6.4.1 Manufacturing cost of printed component

Manufacturing cost of the printed components contains all the steps that are done inside the company to produce printed components. In manufacturing shop, different tasks such as components designing, production preparation and sourcing, machining, testing, quality control, components finishing, packing and storage are considered in this research work. In manufacturing, labor cost is considered as one of the most crucial factors having significant impact on product final price. Industry experiences illustrate that labor cost effect may be even 60% of the final product cost. Factors influencing manufacturing cost are illustrated in Table 18.

**Table 18.** Manufacturing cost calculation

| **Factors** | | **Cost calculation** |
|---|---|---|
| 1 | Designing of components | Cost/h |
| 2 | Production sourcing | Cost/h |
| 3 | Material preparation | Cost/h |
| 4 | Machining | Cost/h |
| 5 | Testing | Cost/h |
| 6 | Quality control | Cost/h |
| 7 | Components finishing | Cost/h |
| 8 | Packing and storage | Cost/h |
| 9 | Components transportation inside factory | Cost/h |
| 10 | Environmental +labor protection | Agreement specific |
| 11 | Machine maintenance | Machine specific |
| | **Total manufacturing cost of printed component** | 1+2+3+4+5+6+7+8+9+10+11 |

### 6.4.2 Assembly and post processing cost

Major factors of cost composition at assembly stage of 3D printed components include sub-engineering cost, measure- taking costs and other project related costs. The equation shown in Table 19 is driven to calculate cost at assembly and post- processing stage.

**Table 19.** Cost calculation formula for assembly and post- processing.

| **S. No** | **Factors** | **Price calculation** |
|---|---|---|
| 1 | Engineering cost | a): Labor cost= Number of labor * cost Per hour<br>b): Machine cost= Number of machines * cost /h<br>c): Management cost= [a + b] *management cost<br>d): VAT |
| 2 | Safety measures cost | (known + unknown measures) * safety measures cost |
| 3 | Health, safety, and environmental cost | According to Agreement |
| 4 | Project cost | Additional work cost |
| 5 | Contracting management cost | Agreement specific |
| 6 | Installation expenses | Amount of material+ labor cost |
| 7 | Equipment procurement cost | Machine specific |
| 8 | Post processing cost | a) Cleaning b) frame removal c) surface finishing d) fixing e) filling f) painting |
|  | Total cost of assembly and postprocessing techniques | 1+2+3+4+5+6+7+8 |

Cost structure of components printed in factory site is divided into labor, material and equipment expenses. All the components such as internal walls, external walls, foundation, floor, roof, ceiling, doors, and windows are printed separately and assembled on the construction site.

## 6.5 Construction site 3D printing

3D printed constructed house elemental estimate vary significantly from traditional construction method as explained in table 15. It can also be noticed that 3D printed house needed less time of manufacturing as compared to traditional manufacturing techniques. Cost calculation structure of 3D printed products on construction site contains labor, material, equipment, engineering, management, and risk related cost. Cost composition of all the construction products includes installation, equipment, Post- processing, health, safety, and services related factors of the project. Figure 21 shows that roof and ceiling work contain the highest amount of cost with the value of (49112.85) euros compared to other factors. Estimated time needed to build complete house is between 13 to 16 weeks.

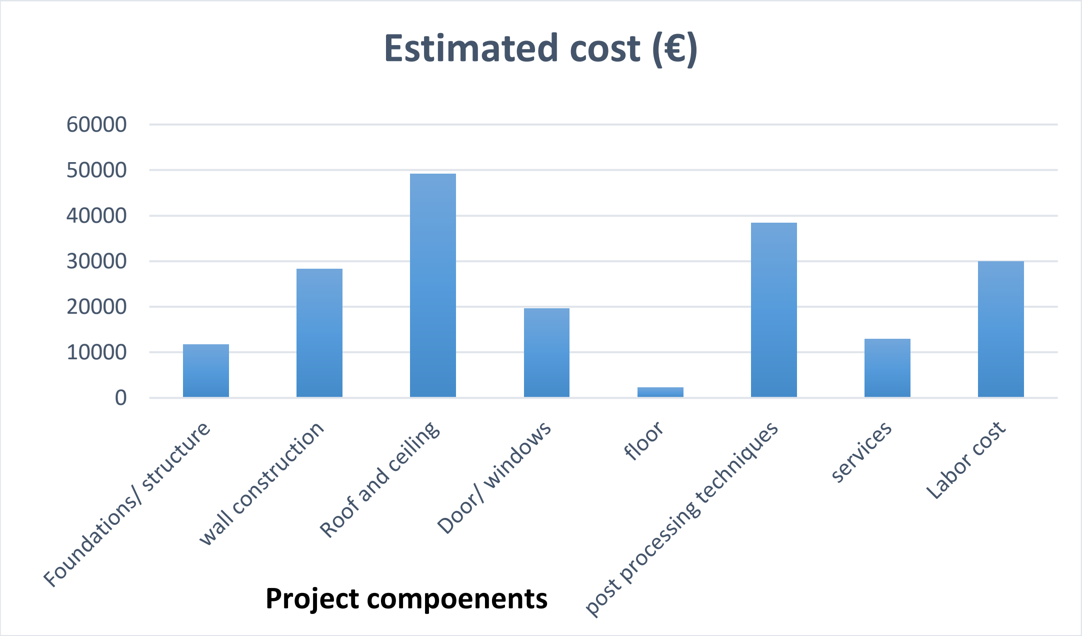

**Figure 21.** Project components effect on cost calculations of 50m$^2$ 3D printed home on construction site.

Investment cost per ton needed on each stage is presented in Figure 22. Raw material used after pre-treatments techniques to produce geopolymer concrete is the most vital stage that affects cost significantly, whereas transportation cost has the least effect on the cost structure. To calculate cost per ton on each stage, required initial investment is divided by the total amount of material. To transport 32000 tons of raw material 453,900 euros initial investment cost is needed for management and operational activities. Transportation cost required one ton of raw material is 14.18 euros. Similarly, for geopolymer concrete, 367 euros and Cost needed for Planning, Sourcing, printing, and finishing is estimated 37 euros per ton. *Therefore, total 418.18 estimated cost is needed for one ton of geopolymer 3 D printing. 3D printing machine cost and labor cost are not included in total cost.*

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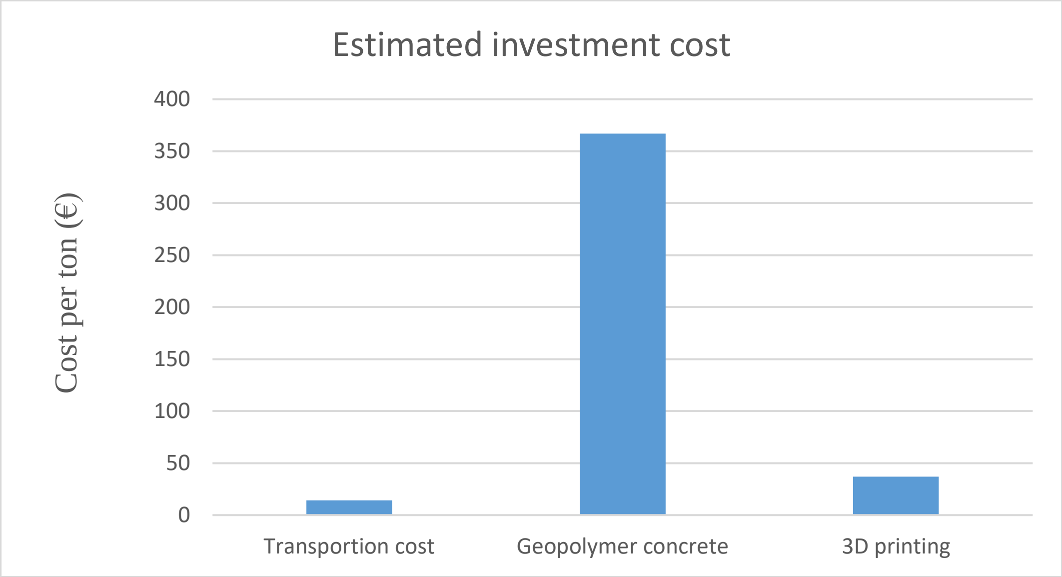


**Figure 22**. Investment cost needed per ton for each stage.

# 7 ANALYSIS AND DISCUSSION

The result obtained from literature, scientific journal, textbooks, and work experience are discussed and analysed in this section. Results for further clarification are compared with similar studies. This research work is conducted to figure out economically 3D printing of geopolymer for construction of houses. The most important sub steps, such as raw material transportation, pre-treatment techniques, parameters selection, strength requirement needed for geopolymer 3D printing and their economic effect on the whole printing process, are discussed and utilization of geopolymer 3D printing on industrial level is analysed.

The first step needed for 3D printing of geopolymer is availability of raw material and their transportation. All the raw materials needed for geopolymer production is transported from industrial area to warehouses for further processing. Approximately 8000 tons of each raw material is needed to be transported from different industrial site to warehouses. Functions and processes involved to transport the material are analysed economically and in terms of sustainability, to ensure smooth flow of material for further process. Different kinds of pre-treatment processes are needed to make these material useable for 3D printing purposes. Utilization of all processes and techniques is implemented economically and environmentally. The annual investment needed for pre-treatment processes of each individual raw material is studied.

To examine green strength of 3D printed geopolymer, such important parameters as curing duration and temperature, curing medium, compression strength direction are examined. Effect on compression strength, with the variation of temperature and curing days is studied. Additionally, cost analysis of different geopolymer grades is explained briefly. Cost analysis of GPC 3D printing on construction site and factory side is investigated. The literature review in the introduction part was carried out to figure out geopolymer 3D printing techniques for construction products on offsite and onsite. Various apparatus and their limitations used for GPC 3D printing were presented in part 2.2 of the research. The factors affecting geopolymer 3D printing economics are discussed in table 6. The acquired result about each stage is discussed below.

## 7.1 Raw material transportation

Transportation cost economic depends upon time accessibility and distance. Transport is considered as a fundamental constituent of any production process from an economic viewpoint. In this research work, 50 Km transportation distance is considered from picking to dropping point. Each raw material is transported to the required place through road transportation system.

Transportation cost along with inventory-keeping and inventory related costs are the essential steps to be considered while calculating raw material transportation. Transportation costs are considered an important element of any economic structure. They affect overall product cost and trade flows directly. Transport organization and transport management are the two main functions provided by the transportation services. Transport management arrange supplier and strategic related tasks. Operative tasks (preparing bills, carrier calling off) are handled through transport organization, whereas supplier and strategy- based tasks are managed through transport management. Three main types of process are included in transport management, such as carrier management, freight management and shipment management. Operational tasks such as transport documents, operative contacts and other documents are included in transport organization. Operational and management cost calculation is based on monthly expenses. In transportation services, transport organization consumed 52% of total expenses, whereas 48% of expenses are spend for other activities needed for transportation services.

While calculating transportation cost, it was assumed that company does not have its own transport fleet. Therefore, calculation is based on outsourced companies. Maintenance cost, insurances, taxes, fuel etc. are assumed to be included in costs of freight paid through carrier companies. While calculating labor cost in transport management, an average salary of specific area is considered. Labor cost is considered as a leading factor affecting transportation cost significantly. As, 8000 tons of each raw material is transported annually, therefore labor cost is the most influential factor, besides equipment and operative related task as illustrated in figure 14. For raw material transportation 5- axle truck without trailer is considered. It was assumed that the truck can carry 20 tons of material in one trip. As in Finland, high capacity truck ( 9 axle) can be operated freely with the maximum weight limit to 76 tonnes and 4.4 meters maximum height limit (Liimatainen et al. 2020). Middle amount of weight for one trip is chosen for trucks, so that delivery can be dropped to their final point with negligible harm to the environment, cheaper and faster ways. Making delivery timely and minimum damage of the goods is also kept in mind while transporting raw materials.

The primarily fuel cost depends upon the fuel prices in the state and constant consumption rate of fuel. The consumption of fuel is assumed to vary with the road slope and maximum speed limit allowed on primary or secondary road. While calculating labor cost it is assumed that speed limit on primary road is 70km/h and on secondary road is 60km/h. More precisely, an enhancement in the segment of road slope is the absolute value of one percent enhancement of fuel consumption. It is estimated that 20900 euros is needed on monthly basis for organization and operative activities. As six months are needed to transport the material, therefore total estimated investment needed for operative and organizational activities are 125,400 euros.

## 7.2 Warehouse

Large modern warehouses, which contain numerous associated elements composed of complicated technical structure, where various functions such as processing, generation and distribution can be done to transform material and goods among consumers. Due to variety of technological solutions, parameters, characteristics and equipment design, warehouse is a complicated technical structure. Material flows moving is not possible without paying attention to some specific areas of necessary supplies.

Movement in warehouses due to the material and labor cost, increases good’s final cost. Warehouses operation has essential effect on material movements, distribution costs and use of vehicles. Raw material (green liquor sludge, Ash, Fiber rejected, Flotation sand, C&D W and combined line) requires 400, 800, 400, 300, 2000 and 2500 $m^2$ plant area. Functions that are considered while calculating warehouse cost are labor, operating, IT-related, equipment and area utilization cost. Labor cost is the most crucial function affecting almost 79% of warehouse cost. Area utilization is the second biggest factor that has significant impact on warehouse cost.

Similarly, operating, IT and equipment cost are affecting warehouse cost accordingly. Variety of processes starting from loading to inventory are performed in warehouse to successfully place the material in correct order. Loading of raw material is considered as the most time-consuming and costly process in warehouse activities as illustrated in Figure 17. However, material storage and unloading cost are the second and third most expensive and time-consuming processes. Each raw material has its own specifications and transporting parameters, therefore different packaging material is used for each raw material. Inventory cost has the least value which has an impact on warehouse expenses. One thing should be noticed that these values may differ significantly for a specific store depending upon raw material and its structure.

Material resource planning and organization is the most essential branch of industrial activities (Hernandez et al. 2006). Warehouse is an integral part of supply chain. Therefore, it should not be deal in isolation to achieve outstanding fulfilment of primary functions and profitability. While designing the storage system all influencing factors and customized solution must be considered to make the process profitable. Proper storage and smooth execution of orders are the most fundamental purposes of any warehouse.

300 tons of material per day is estimated to be transported from industrial area to warehouse by utilizing 5 trucks. Therefore, in one month, 6000 tons is transported and it is estimated that 5 to 6 months are needed to transport 32000 tons of raw material. Estimated investment cost needed for warehouse activities is 328500 euros. Therefore, total investment needed for transportation of 32000 tons of raw material is 453,900 euros. The estimated cost 14.18 euros is needed for the transportation of one ton of raw material.

### 7.3 Pre-treatments

After waste material transportation, the second most crucial step is specific treatment techniques for each waste. These treatment techniques made the raw material (Fiber reject, ash, flotation sand, green liquor sludge and C&D W) useable for 3D printing purposes. Plenty of research have already been done about C&D W and ash utilization for concrete production, but green liquor sludge and fiber reject are not used widely as recycle material. Annual investment required to perform pre-treatment techniques is shown in Figure 18. Machineries, plant area cost, Maintenance, Installation and labor cost are considered to investigate annual investment cost for pre-treatments.

C&D wastes require the highest annual investment to perform pre-treatment processes. Investment cost needed annually for C&D W is 416.4 euros per ton.  Due to simple treatment technique, minimum annual investment with 59.1 euros per ton is required for floatation sand. Cost of treatment for green liquor sludge and fiber rejected is 75.5 and 73.2 euros per ton, correspondingly. According to Afshariantorghabeh (2019), the cost of energy needed to carry out these processes is approximately 2-3% of total annual investment. C&D W require the highest energy cost, whereas floatation sand require the least amount of cost for energy purposes. Similarly, the second cheapest material which is fiber rejected consumes half of the energy cost than ash. Annual investment needed per ton for combine line is much less than C&D W line due to its greater processing capacity. Therefore, annual investment cost can be minimized through the utilization of higher processing capacity. Processing capacity is directly related to profitability of annual investment for pre-treatment techniques. Investment cost can be minimized by enhancing the amount of processing capacity.

### 7.4 Cost calculation, Parameters selection and strength requirements

The production cost of 1 $m^3$ geopolymer concrete for 3D printing, based on the ingredient's quantities of grades M30 is evaluated. Locally available raw material is considered for the synthesis of different grades. Maximum 2-4mm coarse aggregates size and 28 curing days were considered to evaluate cost analysis of GPC grades. Result illustrated marginal difference in cost with the higher-grade production.  Similar Study conducted by Janardhanan et al. (2016) explained that cost production of lower grade (M30) GPC is 1.7% higher with the same grade of OPC concrete. However, for higher grade concrete (M50) GPC production cost is 11% lower than OPC. Cost saving can be achieved through the production of higher grades GPC.

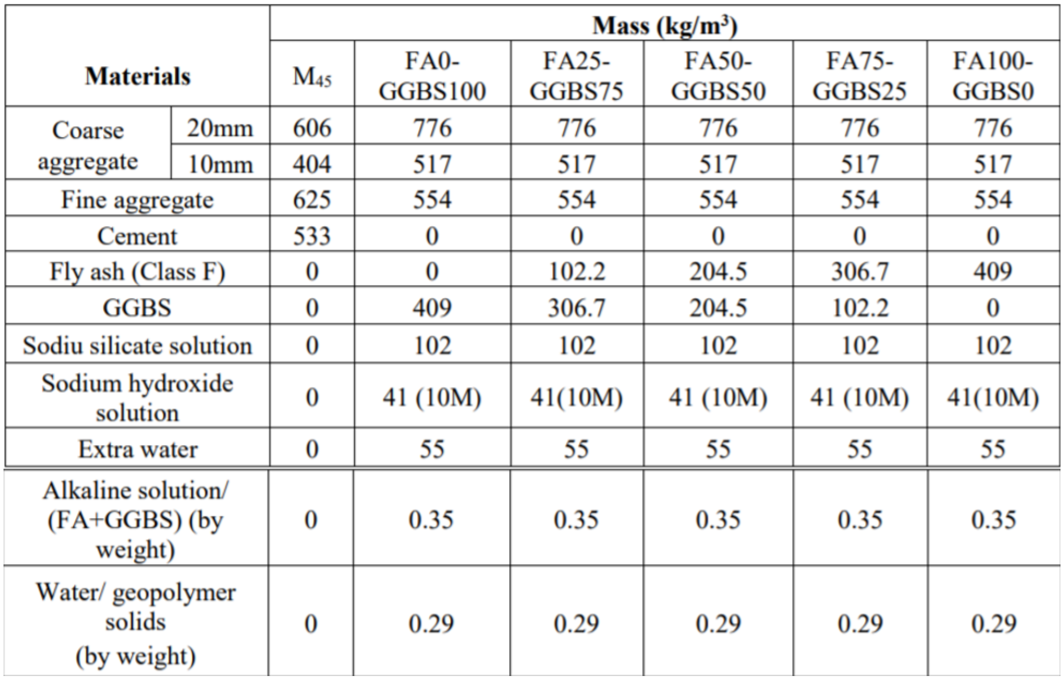
Generally, geopolymers are produced by combing the mixture of aluminosilicate source in the presence of alkaline activator. To dissolve aluminosilicates and for geo-polymerization, alkaline environment is needed. Raw material utilized for geopolymer synthesis depends upon raw material production in local area. Fly ash, C&D W and slag are the most potential source of by-product or waste materials utilizes for the synthesis of geopolymer. Various materials can be used to produce geopolymer such as fly ash, metakaolin, construction and demolition waste, fiber rejected. At room temperature geopolymer binder can harden and strength can increase with time. For geopolymer production there is no need of extra higher production temperature.

Curing temperature and duration, curing medium and compression strength direction are important factors to examine green strength of 3D printed powder- based geopolymer. The research conducted by Nematollahi et al. (2019) illustrated the influence of these factors on strength requirements. In four different curing mediums (2 Na, 2 K) with ($SiO_2$/M2O) alkali modulus Printed geopolymers cured with two different temperatures of 23°**C** and 60°**C** for 7 and 28-days, respectively. The result indicated that compression strength in 28 days at ambient temperature (23°**C**) was comparable to the compression strength of 7-days cured sample at 60°**C**. Therefore, geopolymer printed sample strength enhancement was achieved by curing in alkaline solution at ambient temperature. By performing curing at normal temperature, less energy intensive, more viable and comparable strength values were achieved.

Study conducted by Yip et al. (2008) explains that 20% calcium addition to metakaolin based GPC as a replacement enhance compression strength, whereas compression strength is decreased while adding 40% calcium amount. Study also explains that within two days strength requirements were almost complete and there was no significant effect on strength after seven days. In the research V. Patil et al. (2019), three different mix design M30, M40 and M50 were made having mass of fine aggregates and coarse 75-78% of total concrete density. GGBS used as GPC binder content and molarity (8M,10M) of NaOH was taken for M30, M40 and M50 GPC grade. The result indicates that higher compression strength for GPC is achieved at oven curing temperature compared to curing at ambient temperature. Research shows that alumina and silica dissolution in alkaline solution at high temperature is better compared to ambient temperature.

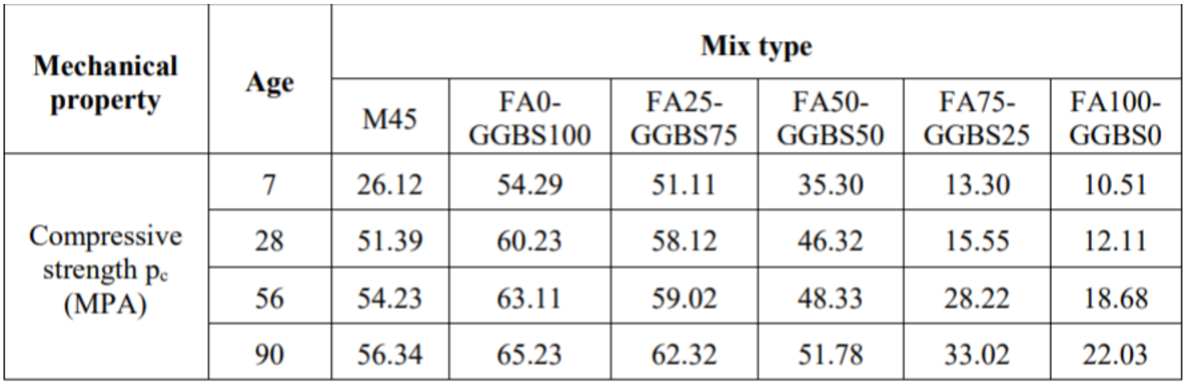
GGBS effect and geopolymer- based fly ash class, micro properties at various temperature are studied by Rajini et al. (2020). Proportions mixture used for geopolymer concrete is shown in Table 20. In research work sodium hydroxide and sodium silicate were used as alkaline activator. Compression strength values after 7, 28, 56 and 90 days of GPC are illustrated in Table 21. Coarse and fine aggregates was taken as 77% mass of the concrete. Activator solution ratio to GGBS to fly ash is between 0.3 and 0.4 range by mass. Sodium hydroxide solution kept 10M. Study explained that with increase of fly ash content in the mixture mechanical, strength decreases irrespective of 7, 28, 56 and 90 days of curing at room temperature. Study also showed that initial material cost for GPC was about 32% bigger compared to the same grade of conventional concrete (M45). Components such as sustainability, natural resource saving, maintenance cost, better mechanical and durable properties can be obtained through the production of geopolymer, which would offset material initial cost.

**Table 20.** Mix proportions used to evaluate compression strength (Rajini et al. 2020).



| Materials | | Mass (kg/m$^3$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | $M_{45}$ | FA0-GGBS100 | FA25-GGBS75 | FA50-GGBS50 | FA75-GGBS25 | FA100-GGBS0 |
| Coarse aggregate | 20mm | 606 | 776 | 776 | 776 | 776 | 776 |
| | 10mm | 404 | 517 | 517 | 517 | 517 | 517 |
| Fine aggregate | | 625 | 554 | 554 | 554 | 554 | 554 |
| Cement | | 533 | 0 | 0 | 0 | 0 | 0 |
| Fly ash (Class F) | | 0 | 0 | 102.2 | 204.5 | 306.7 | 409 |
| GGBS | | 0 | 409 | 306.7 | 204.5 | 102.2 | 0 |
| Sodiu silicate solution | | 0 | 102 | 102 | 102 | 102 | 102 |
| Sodium hydroxide solution | | 0 | 41 (10M) | 41(10M) | 41 (10M) | 41 (10M) | 41(10M) |
| Extra water | | 0 | 55 | 55 | 55 | 55 | 55 |
| Alkaline solution/ (FA+GGBS) (by weight) | | 0 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 |
| Water/ geopolymer solids (by weight) | | 0 | 0.29 | 0.29 | 0.29 | 0.29 | 0.29 |

**Table 21.** Compression strength after 7, 28, 56 and 90 days of GPC (Rajini et al. 2020).



| Mechanical property | Age | Mix type | | | | | |
|---|---|---|---|---|---|---|---|
| | | M45 | FA0-GGBS100 | FA25-GGBS75 | FA50-GGBS50 | FA75-GGBS25 | FA100-GGBS0 |
| Compressive strength $p_c$ (MPA) | 7 | 26.12 | 54.29 | 51.11 | 35.30 | 13.30 | 10.51 |
| | 28 | 51.39 | 60.23 | 58.12 | 46.32 | 15.55 | 12.11 |
| | 56 | 54.23 | 63.11 | 59.02 | 48.33 | 28.22 | 18.68 |
| | 90 | 56.34 | 65.23 | 62.32 | 51.78 | 33.02 | 22.03 |

## 7.5 Geopolymer 3D printing on factory site

Factory side 3D printing of components consists of two main stages, printing of industrial components and assembly stage on construction site. So far, in Finland, there are no houses that are constructed through the utilization of geopolymer 3D printing either on factory site or on construction site. There is no available technical and universal standard or system to calculate 3D printing. Based on work experiences, literature reviews and companies that have made 3D printed houses, the general formula is driven to calculate the cost of all stages needed for 3D printing on factory site. Similarly, there is no standard labor salaries in 3D printing of housing sector, therefore labor cost estimation is based on regular construction labor salaries.

Cost calculation of stages involved in factory site 3D printing, depends upon required properties and regulations. Materials and labor cost needed for printing components inside factory are calculated separately compared to the labours and materials cost needed for assembly on construction site. Cost calculations separately for labours and materials on both site (factory and construction) enhance total cost of the project. Similarly, components printed on factory site need special packaging materials to transport them on construction site. Components printed in factory site belong to manufacturing industry therefore, to calculate the price of those components designing, planning, sourcing, machining, quality control, electricity charges, components' finishing, inside factory transportation and machine maintenance costs are included. Labor, material, manufacturing, transportation, and management are the main factors that influence total cost of the printed components. Distance between factory site and construction site increases project cost, as transportation cost increases in case of higher distance between construction and factory site.

### 7.6 Construction site 3D printing

Cost calculation of 3D printing components on construction site is based on case study of a Russian company Apis Cor, (2020). Company constructed 38m$^2$ 3D printed house at -35 °C by utilizing geopolymer cement. Since in current research, 50m$^2$ is considered to evaluate cost of house. So far, besides walls, there is no company having constructed complete house through 3D printing. The walls on construction site without formwork can be printed. To obtain 3D printed house cost in Finland, components such as labor cost, material cost, concrete cost are replaced by the local price. The purpose is to identify limitation and advantages of printing through geopolymer on construction site. Time, cost, and quality are most important parameters considered to evaluate components printing. Data illustrated in Table 15 explains that 13-16 weeks are needed to print the house on construction site. There is no extra material and labor cost is needed separately on assembly and manufacturing site, as it is needed on factory site printing.

According to study conducted by Tobi et al. (2018), cost structure of a building house has four main parameters: materials, energy, labours and profit for the developer. 3D printed house cost can be 30% lower than traditional construction. Moreover, 3D printing equipment cost is not included in cost calculation of printed house. Initial investment needed for the machineries is considered as a major off setup cost. Greater quantity of 3D printed house will minimize printing technology cost. However, final printing cost is greatly influenced by raw material availability, transportation cost and labor salaries. Less numbers of hours are required to build printed house. Therefore, labour cost can lower by 90% through the utilization of printing technology.

3D printed villa is constructed by Winsun in January 2015, that cost about 105,000 £. Eight people worked in a month for the completion of villa. Company claimed that in three months 30 people are needed to build same villa through traditional manufacturing technique. Reduction of 91% is possible in working hours through the utilization of 3D printed construction technique. The construction of walls is done through 3D printer which needed less skilled worker and number of labours can also be reduced (Davison 2015). Winsun printed Dubai's office of the future by tilt up technology. All the printing components: walls, floor, ceiling are printed on the construction site and after printing, the components are tilted vertically. The whole printing and post- processing techniques were completed in 17 days at the cost of 140000 $. It is estimated that 50% cost reduction is achieved, compared to traditional construction techniques. Based on Ranjha et al. ( 2018), it is estimated that straight walled printed through robot has 36% labor, 45% material and 18 % equipment cost in overall printed house. Similarly, 3D printing of curved walled through robot arm has 38% labor, 44% material and 18% equipment costs. Overall, cost analysis evaluation of geopolymer 3D printed greatly depends upon raw material availability, processing capacity, parameters' selection and strength requirements.

Numerous benefits come from construction site geopolymer 3D printing technology. 3D printing cost benefits are evaluated on the basis of its potential to reduce construction time, waste, energy, framework and required tools. The most important ones could be summarized as lower printing cost of houses than on factory site printing, also storage and transportation of materials on construction site is limited. Automated printing decreases the possibility of fatalities and injuries. Less material waste is generated through the automated processes. Most importantly, the required time can be reduced considerably and high-quality product is obtained through minimum cost.

It is estimated from the data presented in Table 8 and 9 that total investment cost needed for transportation of 32000 tons of raw material is 453,900 euros. However, estimated cost 14.18 euros is needed for the transportation of one ton of raw material. Similarly, estimated cost needed to produce one ton of geopolymer concrete after pre-treatments techniques is 367 euros as illustrated in Table 12. Cost needed for Planning, Sourcing, printing, and finishing is estimated as 37 euros per ton as shown in Table 15. Therefore, totally 418.18 estimated cost is needed for one ton of geopolymer 3 D printing. 3D printing machine cost and labor cost are not included in total cost.

## 7.7 Sensitivity analysis of 3D printing cost parameters

Sensitivity analysis is carried out to evaluate an effect of each single stage factor on the predicted cost. The effect of every factor on each stage cost is examined, analysed, and investigated. Parameters which highly influence, such as transportation, pre-treatments, parameters selection, factory and construction site printing are investigated. While calculating transportation cost, 50 km distance and 20 tons average loading capacity of five axle truck in one trip is considered. Variation in transportation distance and enhancement in loading capacity by utilizing higher axle truck can influence final product cost. Similarly, raw material pre-treatment cost per ton is greatly influenced by the amount of material quantity. Processing capacity is directly related to the profitability. Higher processing capacity reduced investment and energy cost per ton significantly. Sensitivity analysis was also utilized in geopolymer concrete production stage. Higher and lower grade of geopolymer concrete have impact on cost structure of resulted product. Higher grade of geopolymer cost production is slightly higher than Portland concrete. Construction site 3D printing have lower printing cost of houses than on factory site printing due to the fact that storage and transportation of materials on construction site is limited. Automated printing decreased the possibility of fatalities and injuries and less material waste is generated through the automated processes. Most importantly, required time can be reduced considerably and high-quality product is obtained through minimum cost. Small changes in the parameters of each stage can influence the final product cost.

## 7.8 Future research

As discussed, the goal of this research work is to determine economics of all pre-needed essential stages for geopolymer printing. There are many aspects which have not been explored yet, due to the lack of availability of data. The suggested future research is presented:

- Transportation of raw material for printing. Conducting more precisely transportation and warehousing cost through an authentic data source.
- Development in new technologies for waste material pre-treatments is required to reduce the cost and increase efficiency.

- Curing condition, curing temperature and compression strength effect on printing time, quality and cost have to be investigated more precisely.
- Need to develop standards for the management and use of geopolymer 3D printing in Finland.
- Detailed analyses of technology cost implication are needed.
- New digital design workflow for industry must be established

# 8 CONCLUSIONS

Geopolymer technology gives a reasonable promise in terms of global warming reduction and $CO_2$ emission for construction industry as an alternative binder to OPC. GPC strength lies on waste material usage, since it promises sustainability and consumes less energy compared to same amount of OPC production. To eliminate concrete impact on environment, organic and inorganic waste materials can be utilized in cement industry as property modifiers and even as a filler. Although various source materials containing high percentage of silica and aluminium can be utilized for geopolymer synthesis. This research work is focused on cost analysis of four major factors needed for geopolymer 3D printing for construction purposes. Five different raw materials produced as a side stream of different industries in south Karelian region and economical utilization of these raw material for geopolymer 3D printing on construction and factory site were studied.

Literature review was carried out to figure out the initial investment needed for transportation, ware housing and pre-treatments techniques of these raw materials. Raw material transportation is divided into two main functions: transport organization and transport management. Cost analysis of supplier, strategic related tasks and operative tasks were evaluated. Annual investment cost needed for pre-treatments techniques of each raw material is illustrated.

Parameters selection for geopolymer synthesis, strength requirements for different geopolymer grade are studied. Curing temperature and duration, compression strength direction and duration are crucial factors to determine green strength of 3D printed powder- based geopolymer. Result obtained from literature review explained that strength enhancement of geopolymer printed sample can be achieved through an alkaline solution. Desirable structural, mechanical properties and excellent chemical and fire resistance properties possess in GPC make it a suitable choice for 3D concrete printing. Study also explained that initial material cost for GPC was about 32% bigger compared to the same grade of conventional concrete (M45). Components such as sustainability, natural resource saving, maintenance cost, better mechanical and durable properties can be obtained through the production of geopolymer, which would offset material initial cost.

Cost analysis of geopolymer 3D printing is directly related to social changes. Cost composition with consideration of both constructions, onsite as well as on factory site geopolymer 3D printing is investigated and a general formula is driven. This formula separately calculates printing of components, assembly, post processing techniques and fundamental difference between cost calculation of geopolymer 3D printing on construction and factory site. Time, cost and quality are considered for calculation as these factors are positively proportional to the cost calculation. Moreover, cost of 3D printing of house on construction site is much lower than traditional and factory site printing. Fatalities and number of injuries are reduced as the most dangerous and hazardous works done by onsite printers.

In the future, more detailed studies are needed to figure out cost analysis of raw material transportation, warehousing, pre-treatment, strength requirements and parameters selection. Additionally, with detailed data cost analysis of 3D printing on factory site and construction with benefits, limitations and challenges needed to be studied more precisely.

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