# Life Cycle Assessment of Geopolymeric Materials

Master degree in Civil Engineering-Building Construction

ALI MLINDE

Leiria, March of 2024

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Project Report under the supervision of Professor Florindo José Mendes Gaspar and Professor Nelson Simões Oliveira.

Leiria, March of 2024

# Originality and Copyright

This dissertation is original, made only for this purpose, and all authors whose studies and publications were used to complete it are duly acknowledged.

# Dedication

I dedicate my work dissertation to my family and friends. A special feeling of gratitude to my beloved parents, Mlinde Oussoufi and Mdahoma Fatima who always be beside me for encouragement and push for tenacity ring in my ears. My special thanks to my uncles, Mohamed Ali and Soulaimana Soule who have never left my side and are very special. I dedicate also this work and give special thanks to my all family and friends as well as IPLeiria Professors and staff.

# Acknowledgments

First and foremost, I want to take this opportunity to sincerely thank my two supervisors, Professors Nelson Simões Oliveira and Florindo José Mendes Gaspar, for their assistance and direction with my master's dissertation. I appreciate their patience, determination, enthusiasm, and vast knowledge. Their advice was helpful to me throughout the entire project. In addition to my supervisors, I would like to express my gratitude to the remaining first and second-year professors, IPLeiria staff, and the IPLeiria Department of Civil Engineering (ESTG).

# Abstract

Recently, there have been significant technical advancements in the development of construction materials, particularly geopolymer materials (GPM). The emphasis on the environmental sustainability in the cement and construction industry has led to efforts to reduce greenhouse gas emissions and energy consumption. This trend has prompted the exploration and optimization of new environmentally friendly building materials and technologies.

Geopolymer materials are gaining widespread acceptance in the realm of construction materials, offering technological properties that rival those of conventional Portland cement materials. To gain a comprehensive understanding of these emerging materials, this research focuses on the sustainability of GPM and compares it to Portland cement materials (OPCM). The comparison is carried out through a life cycle assessment (LCA), considering some factors such as the impact of climate change, water usage, renewable primary energy, toxicity, and cancer effects. To achieve this objective, the research utilizes the LCA for Experts software and the Ecoinvent databases as tools for evaluating and analyzing the environmental impact. Various formulations of GPM are compared with OPCM to assess their environmental performance. Additionally, the study incorporates an evaluation of the mechanical performance of both materials (GPM and OPCM).

The findings of the Life Cycle Assessment (LCA), and information gathered from the five separate studies indicate that GPM may exhibit higher mechanical performance, particularly high compressive strength, and lower environmental impact than OPCM. However, the extent of these advantages depends on the specific materials used and the proportion of the composite materials in the mixture composition. The use of a typical alkaline activator (sodium hydroxide + sodium silicate) in GPM has a substantial environmental impact. Using diverse precursors in alkali-activated systems results in a variety of outputs. Furthermore, sodium silicate, used in the manufacturing of GPM, is the second-highest contributor to environmental impact, following PC.

**Keywords**: geopolymer materials, life cycle assessment, materials performance, sustainability, environmentally friendly.

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# List of Abbreviations and Acronyms

| | |
|---|---|
| Al2O3 | Aluminum oxide |
| ASTM | American Society for Testing and Materials |
| BFA | Biomass fly ash |
| CaO | Calcium oxide |
| CMK | Clay metakaolin |
| CS | Compressive Strength |
| EAFS | Electric Arc Furnace Slag |
| ESTG | School of Technology and Management |
| FAAG | Fine aggregate |
| FA | Fly ash |
| GP | Geopolymer material |
| GC | Geopolymer Concrete |
| LCA | Lice Cycle Assessment |
| MS | Manufacture sand |
| MK | Metakaolin |
| OPC | Ordinary Portland Cement |
| OPCM | Ordinary Portland Cement mortar |
| SS | Sodium silicate (Na2SiO3) |
| SF | Sulphur furnace |
| SP | Superplasticizer |
| Wt | Weight percentage |
| w/b | Water /binder |
| w/c | Water/cement ratio |

# 1. Introduction

Substituting binders with a higher environmental impact (as cement) for recycled or recovered materials is one of the most crucial aspects of the building and construction sector's sustainability (Elgarahy et al., 2023).

The adoption of novel binders with lower environmental impacts has compelled the development and study of innovative technologies, lower carbon footprint materials, and the implementation of fresh construction methodologies.

Geopolymer materials (GPM) are one of the materials that have been emphasized in recent decades in the building industry to respond to the sustainability of the construction sector. Those materials are inorganic binders that use alternative materials or materials derived from industrial waste with a high aluminosilicate content, such as fly ash, metakaolin, or others. When these aluminosilicate content materials are coupled with an alkaline solution, such as sodium hydroxide (NaOH), sodium silicate ($Na_2SiO_3$), potassium silicate ($K_2SiO3$), or a combination of two or three of them, a chemical reaction occurs that permits the material to polymerize and harden.

In this context, Portland cement concrete appears to be the second-most important material in the construction sector after water, but it is also can generate an environmental impact because the cement production which can generate a lot of dust, noise, and greenhouse gases, especially carbon dioxide, which degrade the environment and hasten climate change (Singh et al., 2020). To minimize cement's impact on the environment, geopolymers have gained popularity as an alternative to conventional cement materials in the building materials industry due to their strong performance and their environmentally friendly quality (Cong & Cheng, 2021). Nivedithat and Koniki (Niveditha & Koniki, 2020) have found that geopolymer materials are the most environmentally friendly building materials in the construction industry. Depending on how the composite material was treated or produced, it may use less energy, emit less pollution, and have a lower overall environmental effect according to the raw materials and the alkali solution used.

Nevertheless, a significant number of researchers (McGrath et al., 2018; Salas et al., 2018; Weil et al., 2009) are delving into the extent to which geopolymers can mitigate environmental impact and the significance of their influence on various environmental impact indicators. As described in the international standard ISO 14040 (ISO 14040:2006, 2022), Life Cycle Assessment (LCA) is characterized as a systematic approach for documenting and analyzing all inputs, outputs, and potential environmental impacts of a product or system throughout its life cycle. This encompasses stages from raw material extraction through manufacturing, distribution, use, and final disposal. LCA is widely regarded as one of the most systematic and scientifically rigorous environmental assessment tools for evaluating the environmental impact of buildings in the contemporary era.

The objective of this research is to discover and compare the key benefits of using geopolymer materials over OPCM in terms of climate change, water consumption, renewable primary energy, toxicity, and cancer. Furthermore, the performance of both materials was evaluated. Additionally, some research has been conducted on the composition of GPM mixes, as well as the effects of altering the primary materials and it proportion on the GPM mixture.

Based on the information gathered from five distinct studies and the outcomes of the Life Cycle Assessment (LCA), GPM might outperform in term of compressive strength and have less negative environmental impact over OPCM. However, the extent to which these benefits are obtained depends on the specific components used and the proportion of the composite materials in the GPM mixture composition.

To reach the objective of this study, an investigation was conducted into the advantages in terms of environmental impact and the importance of employing GPM materials in the construction industry over OPCM. The following strategies, approaches, and work structures have been developed:

- Evaluation of some characteristics of the component materials regarding their physical and chemical composition.
- Analyze and compare the 5 different mixture proportions used in this study in terms of strength and sustainability.
- Outlines the LCA of those two kinds of materials (OPCM and GPM) by using the LCA for Experts and Ecoinvent database.

Two ordinary Portland cement materials (OPCM) and three GPM formulations are considered in this study. In each GPM formulation, sodium silicate and sodium hydroxide were employed as alkali activators, whereas metakaolin (MK) and fly ash (FA) were used as binder materials. In addition to these materials, fine aggregate, superplasticizer, water, and Portland cement were used.

# 2. Geopolymer materials – properties and application

Opting for the optimal and most suitable materials plays a role in the construction industry, influencing decisions in both the design and construction stages. It is crucial to safeguard the structures against fire and other dangerous situations. Geopolymer is a novel substance that has a wide range of applications. Compared with Portland cement materials, it has superior inherent fire resistance. Depending on its component, it can tolerate high temperatures. This temperature resistance is a result of their abilities and traits, which are controlled by the internal structural composition (Cong & Cheng, 2021). When this material is exposed to high temperatures, thermal expansion or contraction will occur, which might cause macroscopic cracks. To control the thermal deformation, the water content during the mixture process must be regulated (Niveditha & Koniki, 2020). In addition to performance and temperature resistance, Niveditha and Koniki, have emphasized the following GPM advantages features (Niveditha & Koniki, 2020).

- The material's pore structure contributes to its good durability.
- When compared to OPCM, it loses less mass and strength, and it is highly resistant to acid attacks.
- The durability properties of geopolymer concretes are enhanced with time.

Figure 2-1 and 2-2 illustrate the GPM manufacture process, the application, and the characteristics that impact the selection of the geopolymer matrix. These graphs are not a general graphs of all GPM materials but it can change based on the materials used in the mixture composition. According to McLellan et al research (McLellan et al., 2011), GPM cost will decrease as a significant alkali solution orders are required for wide-scale geopolymer. Nevertheless, there appears to be a good deal of promise for geopolymers to be both economically and environmentally beneficial by recycling and reusing the construction materials (McLellan et al., 2011).

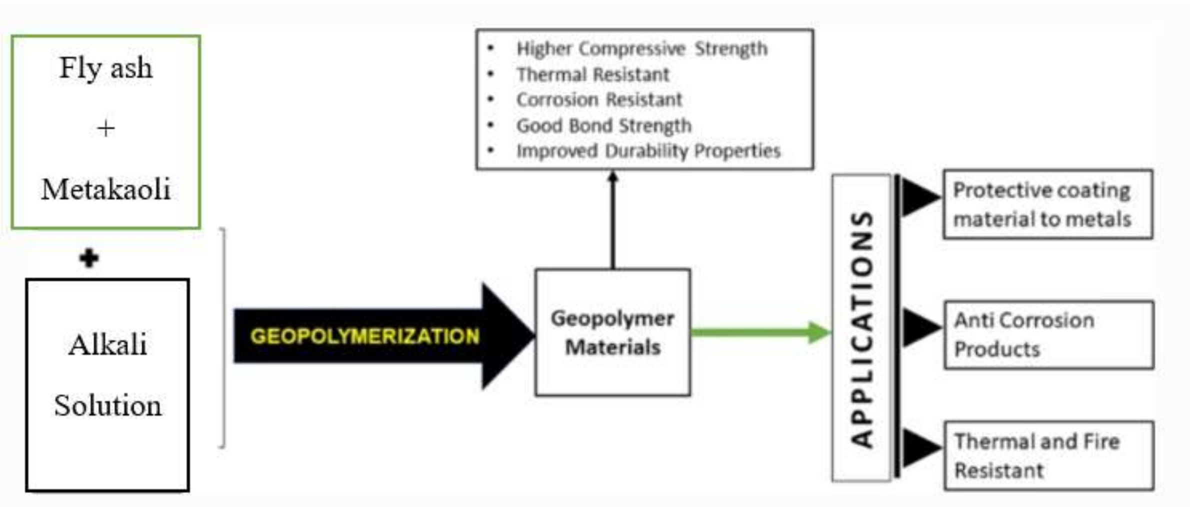


Figure 2-1-GPM manufacture process & Application (Adapted from (Abdulkareem et al., 2014)).

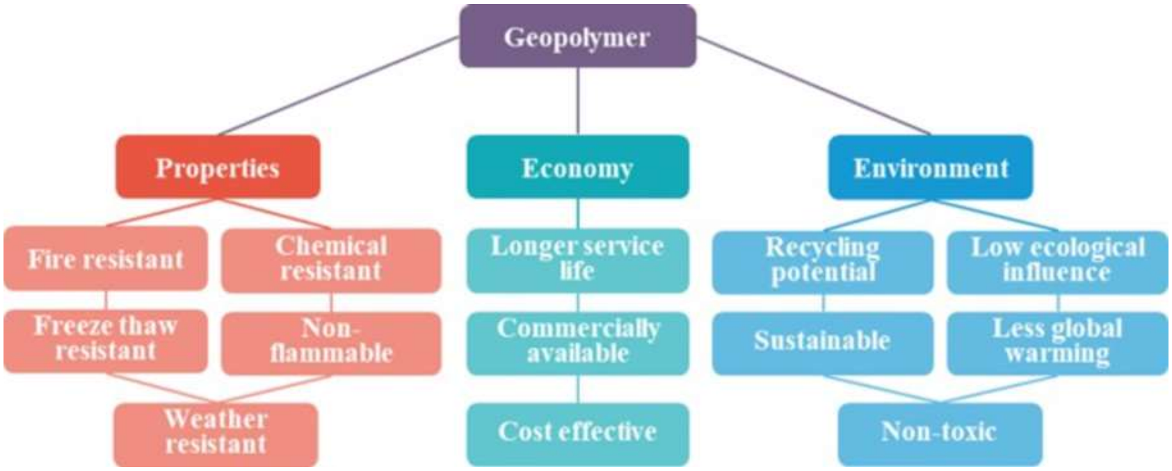


Figure 2-2- characteristics that impact the selection of the geopolymer matrix (Saeed et al., 2022).

## 2.1.Properties of geopolymer materials

Compared to other building materials, GPM offers special qualities in the construction sector due to the fact that GPM is an ecological and sustainable materials (Cong & Cheng, 2021). As composite materials, their characteristics are contingent upon various factors depend on a variety aspect, the raw materials employed in the mixture, their workability, the proportion of the mixture, curing time, volume variation at different temperature, durability and resistance. Furthermore, Marvila et al (Marvila et al., 2021), investigate the behavior of MK-based geopolymers activated using sodium hydroxide and silicate at elevated temperature condition. Their study reveals that the material's properties remained unchanged at temperatures up to 1050 ºC. Another study conducted by Sbahieh et al (Sbahieh et al., 2023) found that GPM compression strength can last longer than OPCM. On other study, Cong and Cheng's research reveals that, changing the raw materials in the mixture may increase both compressive strength and tensile strength. This is demonstrated by the fact that, when geopolymer concrete was prepared with 20% ground granulated blast furnace slag (GGBS) and 10% high-magnesium nickel slag (HMNS) instead of FA, the 28-day compressive and split tensile strength rose by 58% and 100%, respectively (Cong & Cheng, 2021). Figure 2-3 demonstrates that, GPM can be manufactured in different classification materials.

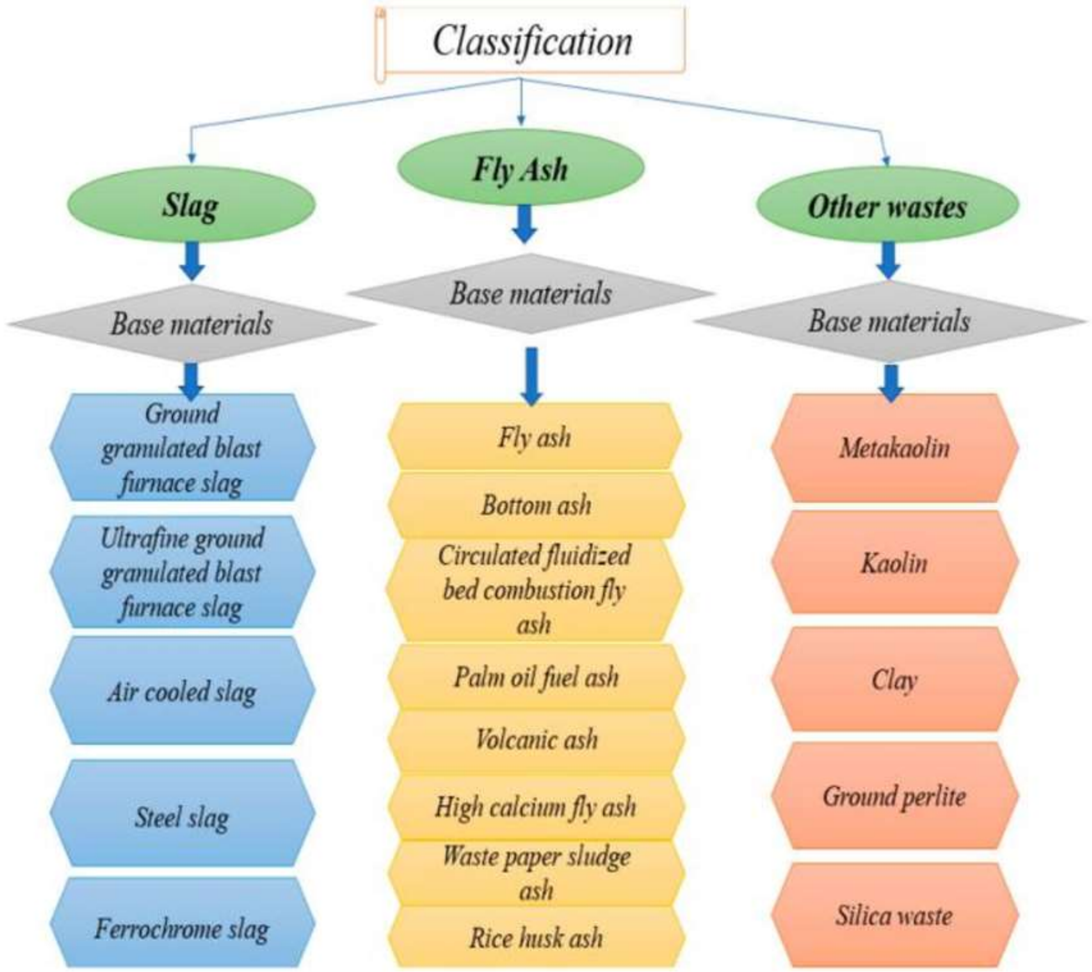


Figure 2-3- Same raw materials used in geopolymer production (Saeed et al., 2022)

GPM generated from various sources may have some similar characteristics, but the physical, chemical, and mechanical properties of those materials might differ significantly depending on the type of raw material used. In the building industry, those materials provide several advantages: (a) they can significantly reduce the carbon footprint of their products. (b) the low cost of production due to the use of alumino-silicate materials, which are derived from industrial wastes like fly ash and blast furnace slag and occur naturally in great abundance on earth as clay minerals; (c) the environmental protection on which a variety of waste materials can be transformed into high-value new products; (d) the manufacture of geopolymeric materials results in lower greenhouse gas emissions (Wu et al., 2019).

On the other hand, the GPM original strength may be maintained above 60%, and the linear shrinkage is about 0.2% - 1% and 0.2% - 2%, respectively, at 400 °C and 800 °C. This demonstrates improved mechanical strength at higher temperatures (McLellan et al., 2011).

Because of its low shrinkage, high early strength, resistance to sulphate attack and corrosion, and high resilience to thawing and freezing, the use of GPM binder has been thoroughly considered in the construction industry. When used in civil engineering, it can considerably accelerate the cycle of operations, and increase building construction speed (McLellan et al., 2011). The mechanical strength of geopolymer mortar ranges from 24 to 58 MPa, and the workability of GPM is enhanced by adding NaOH solution without compromising the strength (Saeed et al., 2022).

## 2.2. Application of geopolymer materials

Applications of geopolymers can be categorized based on their functions and types. For the function, these materials can be employed for a variety of building purposes, including nuclear power plants, insulation walls, fire prevention, isolation, heat preservation, and the adsorption of hazardous ions (Cong & Cheng, 2021). According to Ahmed M et al (Ahmed M. et al., 2023), geopolymer can categorized into three groups. The first group, named conventional geopolymers, are geopolymers which are synthesized using standard procedures or routes without any modifications to the final geopolymer products. Porous geopolymers which is categorized to the second group, are regarded as traditional GPM that undergo further alterations in order to increase the unmodified geopolymers' specific surface area and, improve their capacity to remove harmful contaminants from water. The third category, pervious geopolymers, are defined as a kind of GPM with high porous and permeable materials (Ahmed M. et al., 2023).

Figure *2-4* shows precast geopolymer concrete floor sections. They are built of slag or fly ash-based geopolymer concrete known as Earth-Friendly Concrete (EFC). Figure *2-5* depicts Queensland University's GCI building, which has three suspended floors built of structural geopolymer concrete. It is a four-story building for public use. This is the world's first building employ geopolymer concrete for structural purposes (Hassel Architect, 2013).

Figure 2-4- Stack of reinforced slabs and slag/Fly ash-based geopolymer concrete (Hassel Architect, 2013).

Figure 2-5- Geopolymer concrete structure  (Hassel Architect, 2013).

# 3. Materials for Geopolymer

The basic components of geopolymers are silicon and aluminium, which are produced from thermally activated (such as kaolinite) or waste based (like fly ash) materials. An alkaline activating solution is then used to polymerize these materials into molecular chains and networks, which create a hardened binder (Gopal Mishra, 2021).

## 3.1. Alkaline activators

The geopolymerization reaction happens exclusively in GPM when alkaline activators are present (Jindal et al., 2023). Alkaline activators cause reactive amorphous aluminosilicates to dissolve, allowing oligomers to polycondensate and form a compact microstructure. As a result, the chemical and physical properties of alkaline solutions have a large influence on the behavior of consolidated or activated materials (Jindal et al., 2023). In various GPM compositions, NaOH and KOH are the most often utilized alkali solutions for geopolymer synthesis (Jindal et al., 2023).The metal ions in these solutions have various effects on the polymerization reaction as well as the microstructural and structural features (Toniolo et al., 2018).

Larger potassium cations, $K^+$, are utilized to increase the rate of condensation and speed up the reaction kinetics, while smaller sodium cations, $Na^+$, from NaOH are used to improve the dissolution rate and aid in the better stabilization of the silicate monomers in the solution (Xu & Van Deventer, 2000). Potassium cations have been identified as a catalyst for the creation of larger silicate oligomers, which results in optimum setting, compact structure, and high compressive strength (Xu & Van Deventer, 2000).

In this study, sodium silicate (SS) and sodium hydroxide (SH) are considered as alkaline activators. These two substances can be found as a liquid or powder. They are also available in white, blue, and other colors (Vamsi Krishna et al., 2012). It is important to understand that those substances are non-explosive, non-toxic (depending on the use), and non-flammable solutions. However, because they are an alkaline material, it is likely to be harmful to the eyes and skin. The physiological difficulties caused by SS and SH interaction may differ depending on the alkalinity of the various silicates contained or involved. The issues could vary from severe chemical burns to irritation (Vamsi Krishna et al., 2012).

### 3.1.1. Production of Sodium Silicate

This section describes one of the various methodologies used to produce sodium silicate in an industry supplier. The technique is described in the, results the production of sodium silicate solution. As is described in Figure 3-1, the solution is produced by chemical attack of silica with caustic soda (NaOH) via two steps:

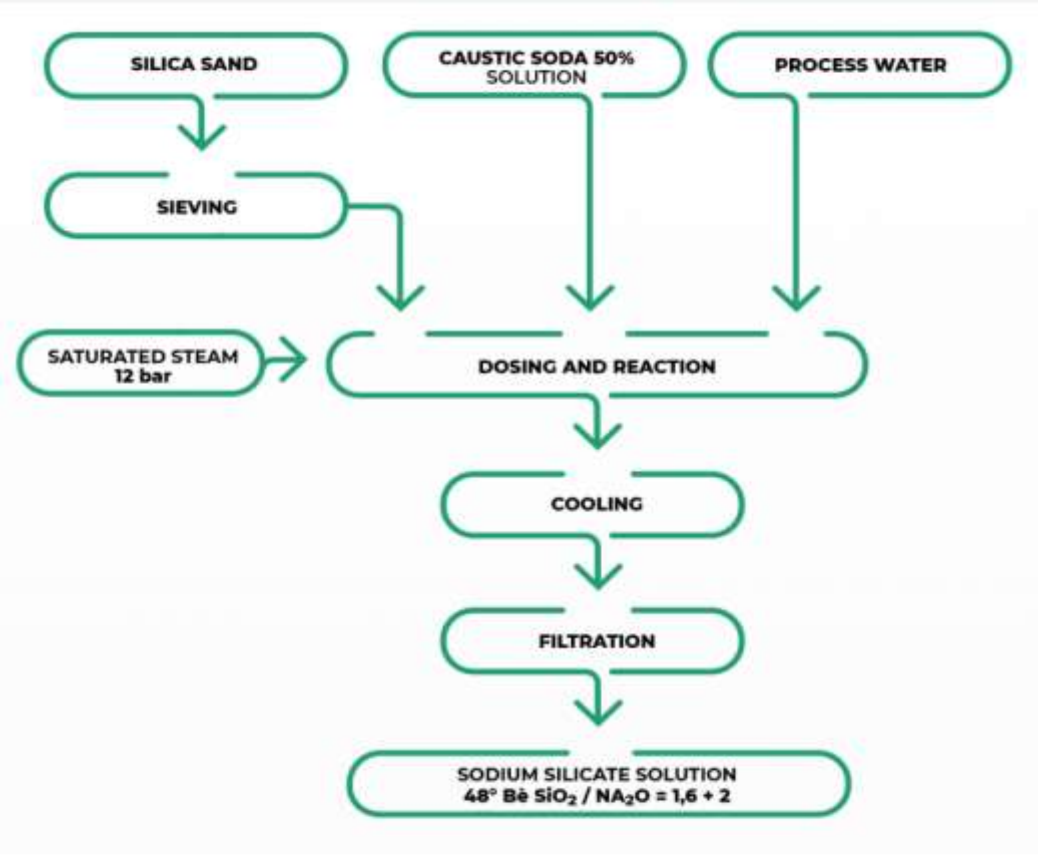


Figure 3-1- Sodium silicate production process (Marsina Engineering S.R.L, 1997).

Sodium silicate is produced by the dissociation of sodium hydroxide (also known as caustic soda) in the reactors, which combine with the silica in the sand to form sodium silicate. The reaction is carried out batch-wise inside stirred reactors, autoclaves type, in the presence of 12 bar pressure saturated steam, where silica sand, sodium hydroxide solution at 50%, and water are charged in appropriate quantities. The total exothermicity of the reaction path is 565 kJ/kg of reacted NaOH. The resulting sodium silicate solution had a percentage of dry materials of 41.8% and a water content of 58.2%. The silica sand is charged into the reactors through screw conveyors, while the caustic soda solution and water are fed via pipelines according to batch requirements. Two simultaneous autoclave-style reactors were employed during the procedure.

The reactors operational conditions were kept constant for the 8-hour cycle, at 11-12 bar of pressure and 188-192 ℃. On the final stage, SS is filtrated before its final stage (Marsina Engineering S.R.L, 1997).

### 3.1.2. Production of Sodium Hydroxide

Sodium hydroxide has a corrosive effect on a variety of materials and its chemical composition can affect human health (National Library of Medicine, 2023). Depending on the concentration, pure NaOH has a strong affinity for water and may create hydrates. At ambient temperature, carbon dioxide and NaOH react quickly in the presence of moisture to generate sodium carbonate. More caution, therefore, is needed. In this section, the production of NaOH from sodium chloride (NaCl) comprises three major sections and the production can differ from one supplier to another regarding their production methodology: (1) brine (water with high concentration of sodium chloride) purification; (2) electrolysis; and (3) product recovery (Scott Jenkins, 2021).

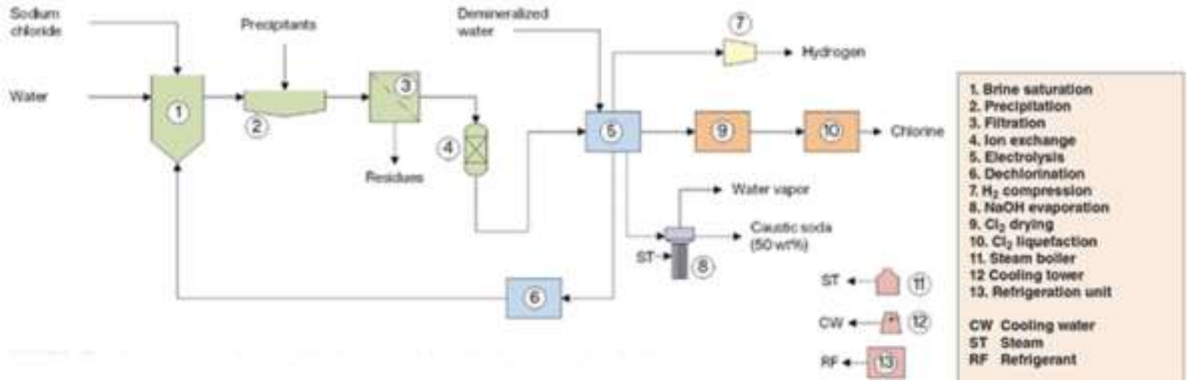


Figure 3-2- industrial production process for NaOH (Scott Jenkins, 2021).

In the first step, ***brine purification***, water is added to regenerate depleted brine before being re-saturated with new NaCl. Therefore, precipitants are added to the brine so that the metals will precipitate and create sludge, which will then be removed by settling in a clarifier. Finally, the clarified solution is filtered and then purified by ion-exchange resins to remove residual hardness and achieve acceptable levels.

In the second step, ***the electrolysis***, where the primary inputs are ultrapure brine and energy. At the anodes, chlorine gas is produced, and sodium ions flow through the membranes into the catholytes. Following dichlorination, the depleted brine from the anode compartments is brought back to the brine saturation stage. Then, water is electrolyzed on the catholyte side, producing hydrogen gas and hydroxyl ions. The membranes restrict these hydroxyl ions from migrating into the anolytes where they would react with the sodium ions to generate caustic soda. And then, demineralized water is added to maintain the correct level of catholyte concentration.

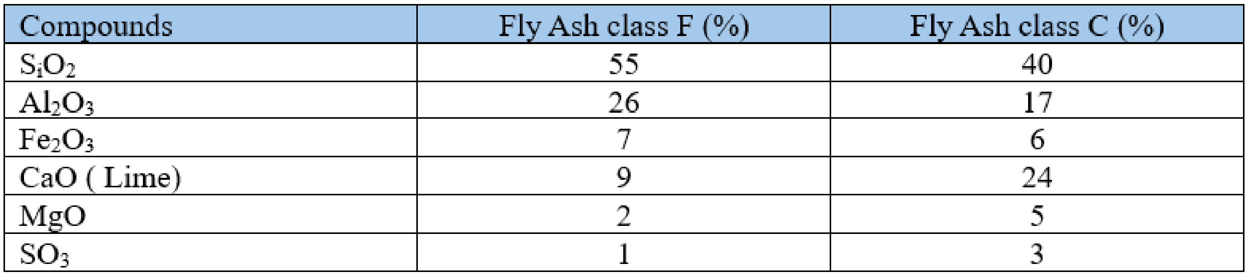
In the final stage, which is defined as the ***product recovery***, the compressed hydrogen produced by the electrolysis process is sent to consumers. The caustic soda solution is concentrated to a saturated 50 wt.% NaOH solution. The generated chlorine gas is routed via drying towers in a system where concentrated sulfuric acid is circulated as a dehydrator. The dry chlorine gas is compressed and then liquefied before being sent to storage vessels (Scott Jenkins, 2021).

## 3.2.Fly-ash

Fly ash (FA) is a product from coal combustion in electric utility or industrial boilers. According to the United States Department of Transportation, there are four fundamental types of coal-fired boilers: (a) pulverized coal (PC), (b) stoker-fired or travelling grate, (c) cyclone, and (d) fluidized-bed combustion (American Coal Ash Association, 2003).

Fly ash has numerous commercial and industrial applications, but it is best known for improving the toughness and workability of concrete mixtures. Fly ash is also used as a filler in metal, plastic paints, and adhesives. It is commonly used as a road structural filler and can also be used to make Portland cement, ready-mix cement, bricks, ceramic tiles, plaster, and other products. Fly ash is classified into two classes based on its chemical and physical properties: Class F and Class C. Class F fly ash is coated in a specific form of molten glass, which strengthens its resistance to sulphates and alkali-aggregate reactions and reduces the probability of concrete expansion. Class C fly ash is more beneficial for reinforcing structural concrete because of its higher amount of calcium oxide (American Coal Ash Association, 2003).

Table 3-1-Composition of Fly ash (American Coal Ash Association, 2003)



| Compounds | Fly Ash class F (%) | Fly Ash class C (%) |
|---|---|---|
| $S_iO_2$ | 55 | 40 |
| $Al_2O_3$ | 26 | 17 |
| $Fe_2O_3$ | 7 | 6 |
| CaO ( Lime) | 9 | 24 |
| MgO | 2 | 5 |
| $SO_3$ | 1 | 3 |

### 3.2.1. Production of fly ash

Every industry has its production process and approach. This part describes one of the methodologies utilized by FA industry suppliers to produce FA (American Coal Ash Association, 2003). Typically, coal is pulverized and pumped into the boiler's combustion chamber with air, where it instantly ignites, producing heat and molten mineral waste (American Coal Ash Association, 2003).

Heat is extracted from the boiler via boiler tubes, which cools the flue gas and causes the molten mineral residue to harden and create ash. Coarse ash particles, known as bottom ash or slag, settle at the bottom of the combustion chamber, while finer ash particles, known as fly ash, remain suspended in the flue stream. Fly ash is removed from the flue gas before it is exhausted by particulate emission control equipment such as electrostatic precipitators or filter cloth baghouses (American Coal Ash Association, 2003).

Figure 3-3 illustrates the production process of fly ash, as described by the United States Department of Transportation. Coal should be treated to obtain FA as final product. This approach proved that FA is produced by processing coal in innovative system that starts with a coal pulverizer system and finishes with FA silo dry storage. The dried FA extracted from the silo can be used to manufacture the GPM. This system is not the only way to extract FA from coal, but it is one of several alternatives for FA production.

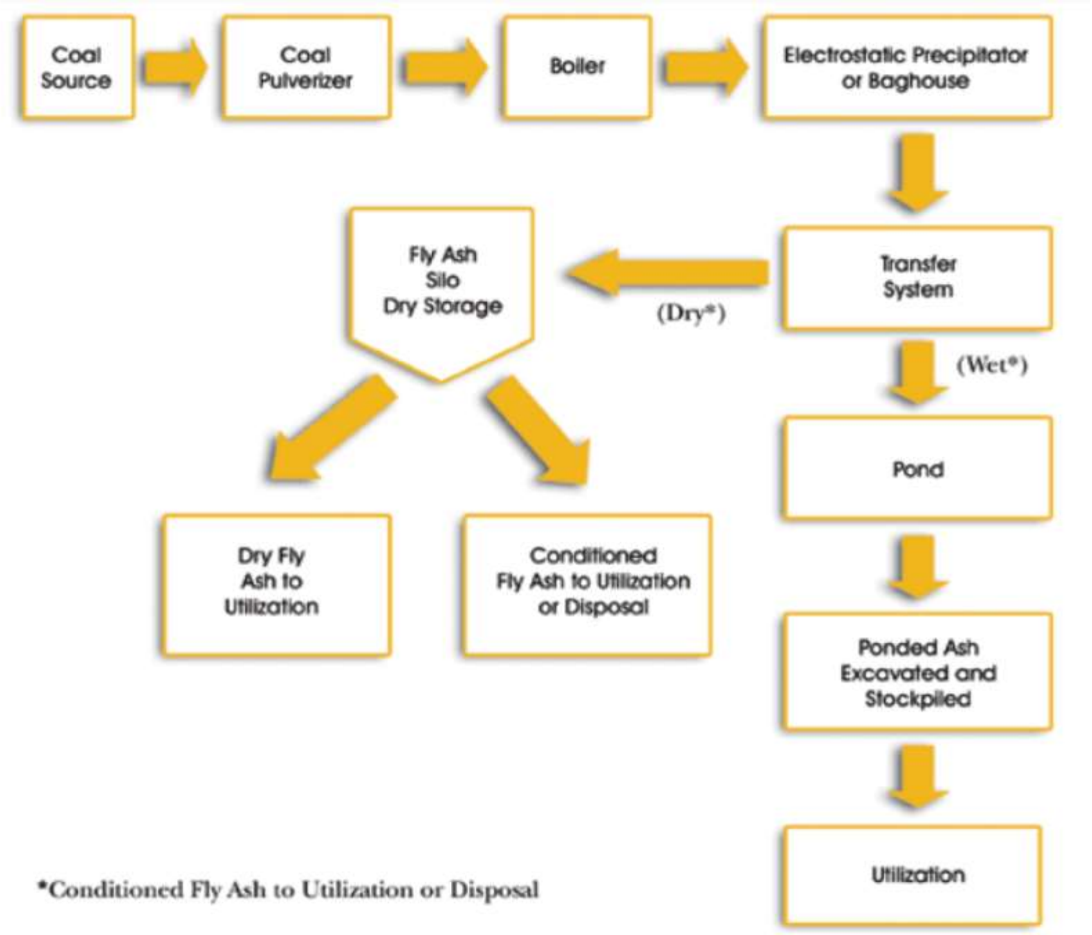


Figure 3-3- Fly ash production process (American Coal Ash Association, 2003)

As fly ash can be either dried of wetted, dried fly ash was taken into account in this investigation. One of the most important variables to consider during the LCA analysis is the energy consumption of FA drying process. In the drying process, the powder and granular fly ash are delivered to the feeder by belt feeding machine in the first phase, and then transported from the feeding machine to the drying drum. To achieve its intended function of transmitting heat for drying, the fly ash is stirred by shovelling a plate in the drying drum and distribute to make full contact with hot air. Finally, the finished FA products are discharged at the end of the drum, conducted by the discharging belt to arrive at the final storage area. A significant amount of energy was required throughout the drying process, and many parameters were established to evaluate the energy consumption of the fly ash dryer plant based on its power, capacity, and working time. Table 3-2 summarizes the technique parameters of the dryer fly ash plant according to Yuf China Heavy Machinery (YFM) group. These factors will allow the energy usage during the dry process to be calculated (Yufchina heavy machinery, 2012). This formular has been used to compute the energy needed in the drying process as following:

$$E = P \times t \qquad \text{Equation 3-1}$$

Where E is the energy in kWh; P is the power in kW and t is the time in hour.

Based on the information mentioned in Table 3-2, namely the power and capacity, the energy consumption and specific energy were calculated. For the first specification GT1.6-15, assuming a constant power of 85 kW with a maximum capacity to produce 12 tons per hour, the dryer would consume about 7.08 kWh/ton. The energy, along with other specifications, has been determined using the corresponding power and time for each specification in a similar manner et the calculation is based on the maximum capacity of all the parameters.

Table 3-2-Fly ash dryer technique parameters (Yufchina heavy machinery, 2012)

| Specification | Capacity (ton/h) | Initial Moisture (%) | Output Moisture (%) | Total power (kW) | Max temperature (℃) | Specific energy (kWh/ton) |
|---|---|---|---|---|---|---|
| GT1.6-15 | 8-12 | 20±5 | ≤5 | 85 | 700~750 | 7.08 |
| GT1.9.6-16.5 | 12-16 | 20±5 | ≤5 | 109 | 700~750 | 6.81 |
| GT2.2-18 | 16-20 | 20±5 | ≤5 | 128 | 700~750 | 6.4 |
| GT2.5-19.5 | 20-26 | 20±5 | ≤5 | 143 | 700~750 | 5.5 |
| GT2.8-22.5 | 26-36 | 20±5 | ≤5 | 210 | 700~750 | 5.83 |

### 3.2.2. Chemical and physical properties of fly-ash

According to the American Society for Testing and Materials (ASTM), the fineness of the fly ash should be assessed using both dry and wet sieving. The fly ash sample is sieved through a 45 µm sieve, and the proportion of fly ash retained on the sieve is determined. Fly ash has a specific gravity ranging from 1.90 for sub-bituminous ash to 2.96 for iron-rich bituminous ash (Ram & Masto, 2014).

The chemical and mineral constituents of the FA determine its color. A dark grey to black color is often attributable to a high un-burned percentage (according to ASTM). Based on particle size distribution, FA can be classified as sandy silt to silty sand. It has a large specific surface area but a low bulk density.

The proportion of unburned carbon and iron in FA affects its color, which can range from orange to deep red, brown, or white to yellow (Ahmaruzzaman, 2010).

Fly ash product

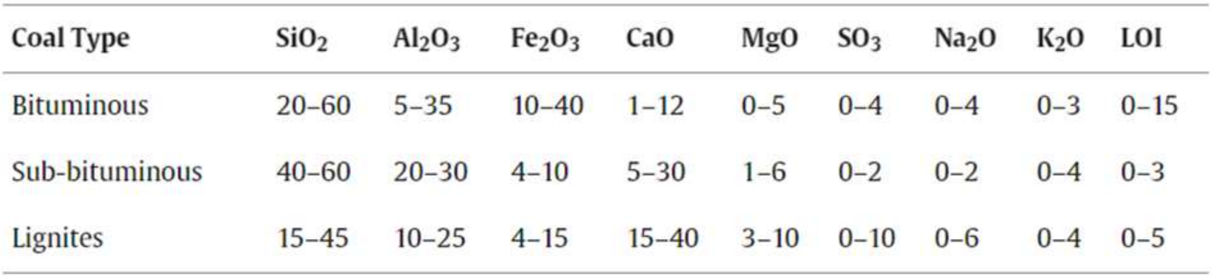
Fly ash in microscopic

Figure 3-4-Fly ash (National Precast Concrete Association, 2017)

The components of FA vary greatly depending on the source and content of the coal burned. The chemical composition of FA is determined by the type of coal used and the procedures utilized for coal burning. Table 3-3 illustrates the chemical composition of fly ash from various coals (Kumar et al., 2022).

The Figure *3-4* and Table 3-3 demonstrate that FA may appear in different types and colors, and it appears to be a powder product. Fly ash is both inorganic and inert in terms of performance. Furthermore, due of spheric shape and its stability, it helps to preserve its dimensional stability in the face of temperature and moisture variations (National Precast Concrete Association, 2017). According to the table, the chemical composition of FA varies from one another. It depends on the type and the origin of the coal.

Table 3-3-Chemical composition of FA obtained from different type of coal (%) (Singh et al., 2020)



| Coal Type | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $SO_3$ | $Na_2O$ | $K_2O$ | LOI |
|---|---|---|---|---|---|---|---|---|---|
| Bituminous | 20–60 | 5–35 | 10–40 | 1–12 | 0–5 | 0–4 | 0–4 | 0–3 | 0–15 |
| Sub-bituminous | 40–60 | 20–30 | 4–10 | 5–30 | 1–6 | 0–2 | 0–2 | 0–4 | 0–3 |
| Lignites | 15–45 | 10–25 | 4–15 | 15–40 | 3–10 | 0–10 | 0–6 | 0–4 | 0–5 |

## 3.3.Metakaolin

Metakaolin (MK) is a calcined anhydrous variant of clay mineral kaolinite. It has traditionally been utilized in the production of porcelain. Its particle sizes are smaller than cement particles but not as fine as silica fume (SF). It is a calcinated product from natural material, which is calcinated at temperatures ranging from 740 to 840 °C (Theodore et al., 2022).

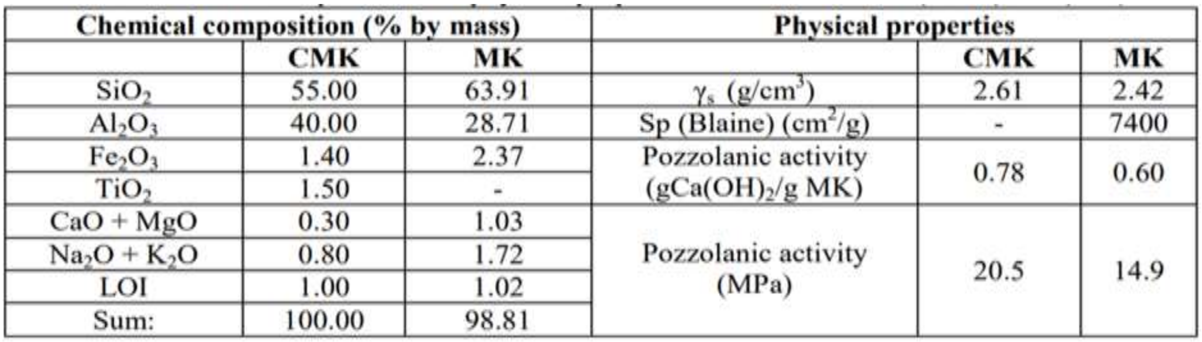
Once raw clays are heated, three key actions associated with the aluminosilicate material can be distinguished: dehydration, dihydroxylation, and recrystallisation. The amplitude and temperature range of dehydration is affected by a variety of parameters, including storage conditions, clay mineral crystallinity, and the type of cations in the interlayer area. Therefore, a higher dehydration temperature (and more energy) is needed to remove the additional water for divalent compared to monovalent interlayer cations (Theodore et al., 2022).

Figure 3-5-Metakaolin in different colors (Abbas et al., 2020)

### 3.3.1. Physical and chemical composition of metakaolin

When compared to Portland cement, metakaolin has a smaller particle size (1-2 μm) and a higher surface area, but has a larger particle size than Sulphur furnace (SF)(Holland et al., 2016). Metakaolin responds quickly and has a lower diffusion coefficient than ordinary Portland because of its small particle size and high surface area (Holland et al., 2016). Table 3-4 tabulated the chemical composition of metakaolin. Two types of metakaolin are mentioned in this table. Coal-bearing metakaolin (CMK), which is produced by calcination of coal-bearing kaolinite at 600-900 °C, and metakaolin (MK), can be produced by calcining kaolin at 600-900 °C. For the three different mixes proportions used in this present study, MK has been used.

Table 3-4-Chemical composition and physical properties of metakaolin (Holland et al., 2016)



| Chemical composition (% by mass) | | | Physical properties | | |
|---|---|---|---|---|---|
| | CMK | MK | | CMK | MK |
| $SiO_2$ | 55.00 | 63.91 | $\gamma_s$ (g/cm$^3$) | 2.61 | 2.42 |
| $Al_2O_3$ | 40.00 | 28.71 | Sp (Blaine) (cm$^2$/g) | - | 7400 |
| $Fe_2O_3$ | 1.40 | 2.37 | Pozzolanic activity (gCa(OH)$_2$/g MK) | 0.78 | 0.60 |
| $TiO_2$ | 1.50 | - | | | |
| CaO + MgO | 0.30 | 1.03 | Pozzolanic activity (MPa) | 20.5 | 14.9 |
| $Na_2O$ + $K_2O$ | 0.80 | 1.72 | | | |
| LOI | 1.00 | 1.02 | | | |
| Sum: | 100.00 | 98.81 | | | |

### 3.3.2. Production of Metakaolin

Metakaolin is obtained from clay calcination. A rotating furnace device is used during the production process in some industry suppliers. In a rotating furnace, the hydrated kaolin powder is heated /fired to around 700 °C. The heating procedure eliminates the water from the kaolin powder, producing anhydrous calcined kaolin ($2SiO_2*Al_2O_3$). Calcination at lower temperatures in the range of 600 to 800 °C is defined as Metakaolin. Thus, it is produced by controlled thermal treatment of kaolin. Different researchers have proposed different ideal temperatures and heating times to generate MK from kaolin with a high pozzolanic index (Dai et al., 2022; Khaled et al., 2023; Ozer & Soyer-Uzun, 2015). Through the production path, increasing the curing time at

600 °C from 30 to 60 minutes increased the amorphous nature, and reduced peak intensity, and hence improved pozzolanicity (Zhang et al., 2007). Increasing the temperature to 700 °C for 60 minutes causes material recrystallization (increased intensity of quartz peaks). Thus, the calcination process at 600 °C for 60 minutes converted the crystalline kaolin into a more reactive aluminosilicate precursor that is more suited for geopolymerization (Zhang et al., 2007). Table 3-5 summarizes different types of kaolin used in previous studies from different experiments around the world to create MK-AABs (alkali-activated binder) and Figure 3-6, gives one of the various procedures to obtain MK from kaolin.

According to Table 3-5, the chemical composition of kaolin varies greatly depending on the extraction area (Khaled et al., 2023). In Table 3-5 , it can be concluded that there is a wide variety of MK’s characteristics which can depend on the extraction area. Generally, the different kaolin grades and alumina contents depend on the kaolin oxide enrichment relative to mineral impurities such as quartz and Ti-Fe oxyhydroxide minerals. Consequently, there are many ideal firing circumstances, activator types, and curing regimes to generate MK-AABs (Alkali Activated Binders) with high mechanical properties. Because the kaolin mining area varies, there are no clear and explicit criteria that can be specified for the manufacturing of MK-AAB (Khaled et al., 2023). There are several MK production process models. In the current work, two distinct MK production processes were examined.

MK Production Process Model with Natural Gas (NG) +Air Combustion and MK Production with Solid-Fuel Combustion. After comparing these two models, the MK Production Process Model with NG + Air Combustion appears to be the most adaptable in this study because this model, kaolinite is the only raw material that reacts to create MK (Tasiopoulou et al., 2023).This model, every stage, ambient atmospheric pressure conditions and ambient temperature (25 °C) for the intel stream of raw materials are used. In comparison with this model, MK Production with Solid-Fuel combustion use solid fuels instead of NG +Air to provide the required calcination heat. The addition of an alternative-fuel section to partially substitute the basic solid fuel and provide a portion of the kiln heat demand can be complicate the process and the model control. The process and model control may get more complex as an alternate fuel section is included (Tasiopoulou et al., 2023). Both models try to simulate the basic thermal treatment steps of an MK production unit, where kaolinite is calcined in a rotating kiln at temperatures between 650 and 850 °C.

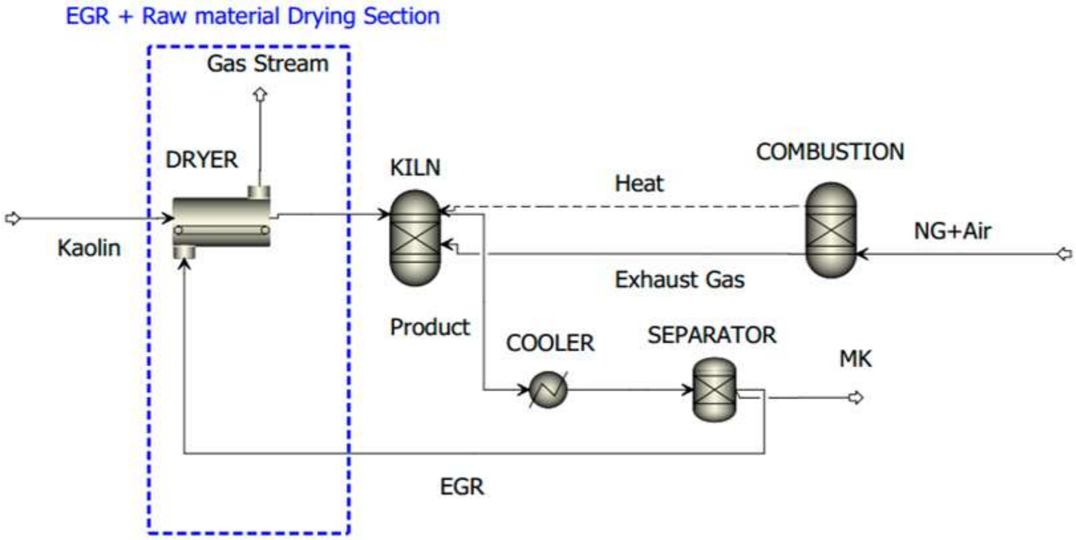


Figure 3-6- Process-model flowsheet for MK production (Tasiopoulou et al., 2023)

The primary reason to choose his model is because it offers the simplest version of the MK manufacturing chain.

Table 3-5- Previous literature that adopted Metakaolin Alkali-activated binder fabrication

| Country | Size | Firing condition | Curing | Compressive Strength at 28 days | References |
|---|---|---|---|---|---|
| Mexico | 0.38 µm | 800 °C/3hrs | 60 °C for 28 days | 20 MPa | (García-Mejía & de Lourdes Chávez-García, 2016) |
| Turkey | N/A | 700 °C/1hrs | 60 °C for 1 day | 23 MPa | (Ozer & Soyer-Uzun, 2015) |
| Morocco | N/A | 750 °C/3hrs | 70 °C for 1 day | 34.81 MPa | (Khaled et al., 2023) |
| China | 10 µm | 700 °C/10hrs | Ambient temperature | 64.18 MPa | (Dai et al., 2022) |
| Jordan | < 75 µm | 800 °C/3hrs | 55 ± 2 °C for 1 day | 14 MPa | (Ababneh et al., 2022) |
| Cameroon | 90 µm | 800 °C/3hrs | Ambient temperature | 30.2 MPa | (Tchakoute et al., 2015) |

### 3.3.3. Energy balance for clay calcination

The theoretical heat necessary for clay calcination can be determined using enthalpic data at constant pressure and a reference temperature of 25 °C, according to Schieltz and Soliman study (Schieltz & Soliman, 1964). Theoretical heat is calculated on the assumption that the calcination products (dehydroxylated clay and water) return to standard conditions (25 °C and 1 atm).

However, the latent heat of vaporization of water is not easily recoverable in heat integration. The lowest energy demand for clay calcination can now be computed by recovering the latent heat (2269 kJ/kg) and therefore, the minimum energy demand for metakaolin production from kaolin is 1513 kJ/kg (Theodore et al., 2022).

Figure *3-7* presents the minimum energy required for the calcination process according to the moisture content. It is evident that as the moisture content becomes more significant, there is an increased demand for energy during the drying process. In this present study, it is assumed that the metakaolin has a moisture content between 9 to 10 % and the energy required for the calcination which was considered during the LCA analysis was 1600 kJ/kg.

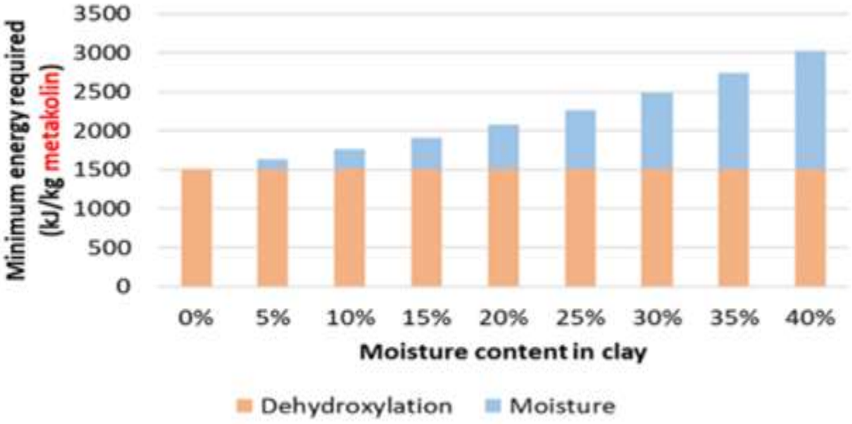


Figure 3-7- Minimum energy required for the calcination of kaolinite (Theodore et al., 2022)

### 3.3.4. Heat-Demand Predictions: Parametric Studies

As stated in section 3.3.3 the higher the moisture content of the product, the greater the heat demand and more energy consumed. Figure 3-8 depicts the influence of calcination temperature on the process of heat requirement resulting from two discrete models representing respective operational scenarios: (a) baseline model and (b) EGR model (with drying). In all cases, the source material (kaolinite) had an average moisture content of 15 %. Heat requirement rose with kiln temperature. As can be observed in Figure *3-8*, when the baseline model was used, the heat demand increased from 0.89 MWh/tonne$_{MK}$ (at 650 °C) to 1.25 MWh/tonne$_{MK}$ (at 850 °C).

It was assumed that when the Exhaust Gas Recirculation (EGR) system (EGR model) was employed, the raw materials can entirely dried (at 175 °C) before entering the kiln. After the calculation, it was found, however, that employing EGR stream mass flow rate (at 200 °C) was insufficient for raw material to dry completely, and an additional heat demand of 0.05 MWh/tonne$_{MK}$ (for all used kiln temperatures) is required to complete the dry process (Theodore et al., 2022).

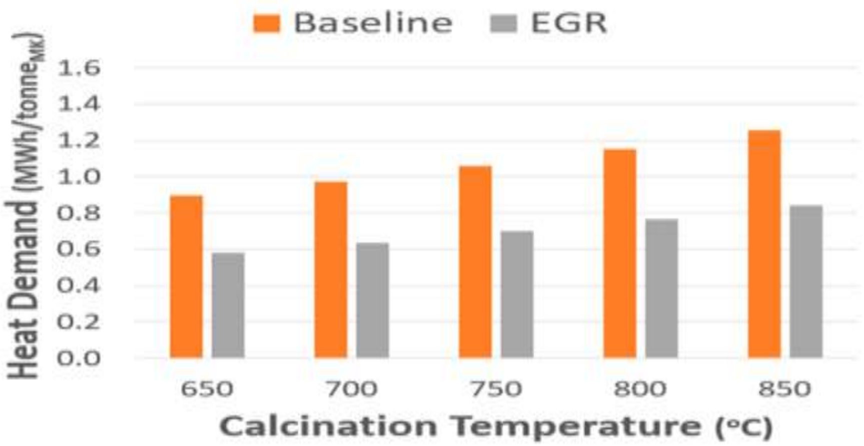


Figure 3-8- Calculated MK production process heat demand (Theodore et al., 2022)

## 3.4.Fine aggregate: Sand silicate

In this section, fine aggregate information was collected from Ecoinvent database. This database may create reasonable sustainable consumption and production regulations using life cycle assessment (LCA) data.

Companies, industries, production suppliers and researchers can get different information sources about innovation and strategic sustainability. In the same aspect, Global LCA Data Access (GLAD) has been created to increase data accessibility and interoperability. Using the network's interface, users would be able to search for and access life cycle inventory datasets from diverse suppliers. It is the most detailed directory of Life Cycle Assessment (LCA) datasets. It collects data from independent LCA database providers around the world, making it an invaluable resource for scholars, industry and experts. However, it is important to understand that, GLAD itself is not an LCA database; rather, it functions as a search engine, assisting users in finding the LCA data they need.

Therefore, according to Ecoinvent data set, Silica sand is a particular sand with a $SiO_2$ (Quartz) composition of more than 85% (w/w). If the $SiO_2$ content exceeds 98%, the silica sand is known as pure silica sand or industrial sand. If the sand is pure silica sand with a $SiO_2$ content of above 99%, this kind of sand is called "Vitreous" and has a heavy metal content (particularly iron compounds) of less than 0.05%.

In general, there are no changes in quarrying conditions for silica sand and regular sand. The key distinction between these two sands is that silica sand is dried. It is expected that the moisture level before drying is roughly 5% and then drops to around 1%.

## 3.5.Water

In this phase, it is assumed to employ water treatment during the mixture proportion. This water is considered to be processed in power plants by precipitation or carbonates for use as cooling water. The decarbonization process was employed to purify water in this part. This process successfully removes carbon dioxide from water, limiting the risk of mineral salt carbonate precipitation. According to the Ecoinvent database, 1 kilogram of decarbonization water has been generated.

# 4. Compositions analyzed

This study considered five different studies for comparative purposes. The goal of employing different studies, which are composed of three OPCM and two GPM with various materials and mixture proportions, is to assess the important points in the context of the environmental impact of geopolymer production. Furthermore, based on the LCA analysis result, it will be possible to define and identify the significant differences between OPCM and GPM in terms of environmental impact and performance. Additionally, understanding the three distinct GPM investigated in this study will help to understand the role of binders and alkali solutions that may be used in the mixture proportion, as well as the optimal proportion of those materials that should be used to produce a better GPM in terms of environmental impact and performance (compressive strength).

The five distinct mixing proportions used in this study are depicted in Table 4-1 for the preparation of GPM and OPCM. As alkaline solutions, sodium hydroxide (SH) and sodium silicate (SS) were used, and fly ash and metakaolin were used as binding materials in the GPM mixing proportions.

Furthermore, the mixing proportions 4 and 5 (Table 4-1), fine aggregate, cement, water and superplasticizer were used as complementary and supplementary component materials. Each study will be summarized, and the pertinent features, such as performance and strength, as well as their environmental impact will be underlined.

Three different mixtures with the same raw materials (FA and MK) and alkali solution (SS and SH) in varied percentages were used in order to better understand their differences in term of strength and environmental impact. It is also important to understand how the variation of the binders materials and the alkali solution in the mixture can affect both performance and the LCA analysis outcome.

Therefore, metakaolin was used in considerable quantities in contrast to the amount of fly ash in the mixture-1. Meanwhile, in the second mixing proportion, metakaolin and fly ash are used in the same amount. For mixture-3, fly ash is used in greater proportions than metakaolin as tabulated in Table 4-1.

In terms of alkali solution, the sodium silicate by sodium hydroxide ratio ($Na_2SiO_3$/NaOH) was used, and it is clear that mixture-1 and 3, sodium silicate, was widely used. Sodium silicate is needed as an activator for geopolymer throughout its polymerization process. However, the shortage of sodium silicate on the mixture plays a significant factor for hindering the development of geopolymers (Cong & Cheng, 2021). It is also discovered by Rajan et al (Rajan & Kathirvel, 2021) that Sodium silicate and sodium hydroxide (NaOH) are common activators for geological polymer composites. Polymerization in acidic conditions might reduce the performance of geopolymer concrete. As fine aggregate (FAAG) is one of the major constituents of mortar which can influence mortar mix design, the value of FAAG is more important in mixture-4 and 5.

This is because FAAG can increase the strength and resistance of the mortar. It is also important to consider the alkali solution to binder material ratio. This can affect and change the properties of the materials such as the compressive and the lifetime as well as the durability of the materials (Zhang et al., 2022).

Superplasticizers (SPs), commonly referred to as high-range water reducers, have been utilized in the fourth mixing proportion. This product is a set of additives for use in the production of mortar or self-compacting concrete that has high strength (Ban & Ramli, 2010). In order to evaluate two different OPC mortars and figure out the differences between the mortars with and without superplasticizer in terms of resistance and strength, Ban and Ramli employed SPs on the 4 mixture proportions for comparison purposes (Ban & Ramli, 2010).

Table 4-1- Mixture proportion for different materials with different studies

a) Mixture proportion of Geopolymer Materials

| Mixture | MK (kg/m$^3$) | FA (kg/m$^3$) | NaOH (kg/m$^3$) | $Na_2SiO_3$ (kg/m$^3$) | $Na_2SiO_3$/NaOH | FAGG (kg/m$^3$) | Alkaline solution /binders | Water (g/m$^3$) | Water/ binders | References |
|---|---|---|---|---|---|---|---|---|---|---|
| Mix-1 | 429 | 184 | 89 | 445 | 5.0 | 613 | 0.871 | 100 | 0.366 | (Zhang et al., 2022) |
| Mix-2 | 285.6 | 285.6 | 205.8 | 174.3 | 0.846 | 1144.5 | 0.665 | 4.2 | 0.007 | (Tomás et al., 2023) |
| Mix-3 | 60.68 | 242.75 | 28.5 | 174.83 | 6.134 | 910.3 | 0.670 | 54 | 0.19 | (Rajamma et al., 2012) |

b) OPC Mortar mixes proportions and quantities of constituent materials with and without superplasticizer

|  | Cement (kg/m$^3$) | Water (kg/m$^3$) | FAGG (kg/m$^3$) | C/FAAG | S.P (kg/m$^3$) | W/C | Reference |
|---|---|---|---|---|---|---|---|
| Mix-4 | 684 | 239 | 1538 | 0.444 | 12.65 | 0.349 | (Ban & Ramli, 2010) |
| Mix-5 | 702 | 281 | 1404 | 0.5 | 0.00 | 0.400 |  |

## 4.1.Mixture -1

In order to achieve the sustainability of the construction, Peng Zhang focused on analyzing the role of the alkali activator and the using raw materials in GPM instead of non-renewable ones (Zhang et al., 2022).

MK and FA class 1 were chosen as binder materials. MK constituents vary according to the extraction area (country or region) and the chemical composition is presented in the original study (Zhang et al., 2022). The MK had a diameter of 1.2 μm and was manufactured in China. The FA utilized is also from China, coming from the Luoyang power plant, and has specific gravity and bulk density of 2.1 and 0.78 g/cm$^3$, respectively. Furthermore, the water glass solution ratio ($SiO_2/Na_2O$ molar ratio of 3.0), and mass percentage of $Na_2O$ and $SiO_2$ at 8.36% and 25.94%, respectively, and sodium hydroxide flakes (NaOH, purity 99.0%) has been used to prepare the alkali solution.

### 4.1.1. Mechanical performance of mixture-1

According to Zhang et al (Zhang et al., 2022), the compressive strength is substantially dependent on the $SiO_2/Na_2O$ ratio. The compressive strength increased as the $SiO_2/Na_2O$ molar ratio increased from 1.1 to 1.2, but it began to decline when the $SiO_2/Na_2O$ ratio exceeded 1.2. When the $SiO_2/Na_2O$ ratio was 1.2, a maximum compressive strength of 46.5 MPa was established. However, when compared to the highest compressive value at a molar ratio of 1.2, the compressive strength was lowered by 6.7%, 13.5%, 24.1%, and 38.5%, with $SiO_2/Na_2O$ molar ratios of 1.1, 1.3, 1.45, and 1.6, respectively (Zhang et al., 2022). For this modification, 1.2 is the optimal $SiO_2/Na_2O$ molar ratio that has been observed to provide high compressive strength in this type of mixture.

The sample specimen, which is made up of fly ash and metakaolin and has a $SiO_2/Na_2O$ ratio of 1.2, was taken into consideration in this investigation. This is due to the fact that, as is illustrated in Figure 4.1, the $SiO_2/Na_2O$ ratio with a 1.2 value has the maximum compressive strength when compared to the other $SiO_2/Na_2O$ ratio when the same materials are used in the mixed proportion with the adjustment of the quantity of alkali solution.

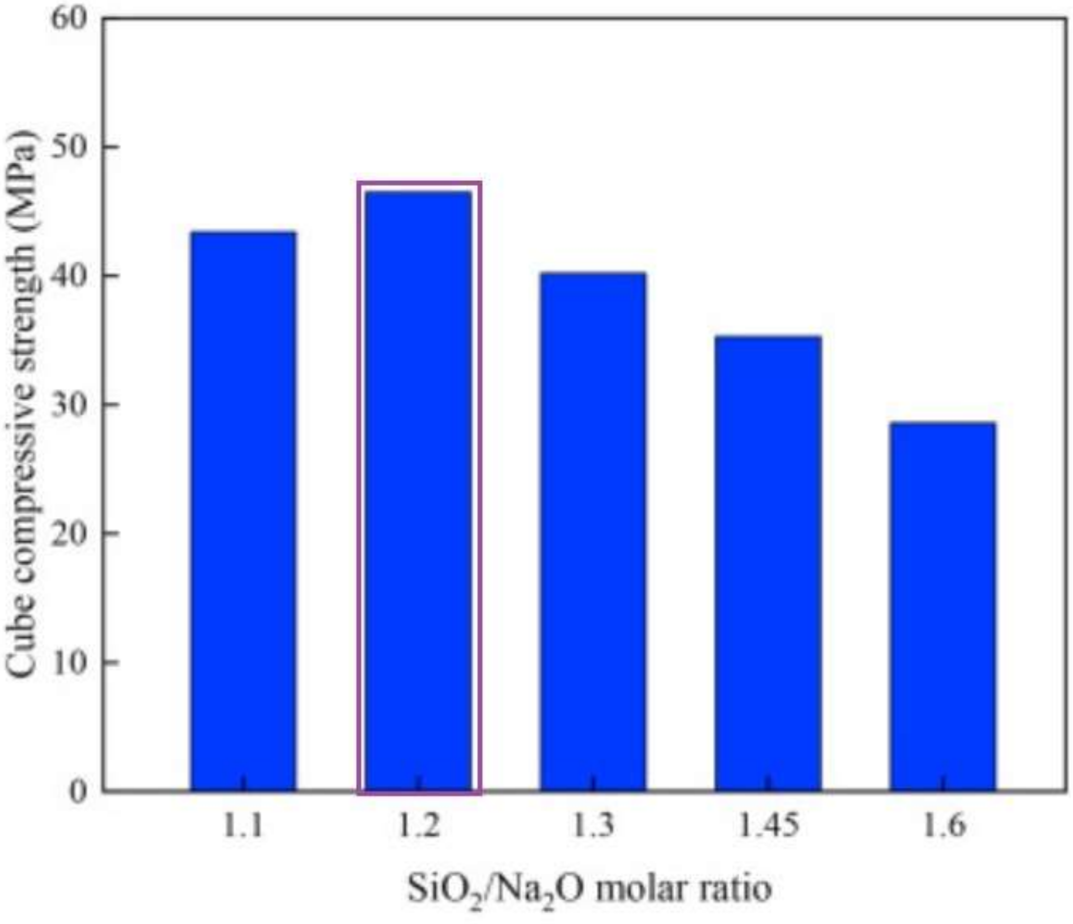


Figure 4-1-Cube compressive strength of specimen (Zhang et al., 2022)

For the mechanical and durability of the sample specimens with varying $SiO_2/Na_2O$ molar ratios, numerous parameters were observed. As the $SiO_2/Na_2O$ molar ratio rose from 1.1 to 1.2, the splitting tensile and flexural strength of specimen increased. However, as the molar ratio continued to rise, both the splitting tensile and flexural strength of specimen decreased. With a molar ratio of 1.2, the splitting tensile and flexural strengths of specimen reached maximum values of 4.41 and 5.4 MPa, respectively. Thus, analysis findings that a 1.2 ratio of $SiO_2/Na_2O$ has the highest compressive (with MK & FA mixture composition). On other side, to ensure the materials' performance, Zhang et al (Zhang et al., 2022) analyzed the F-test, which is defined to evaluate the tensile strength of concrete or mortar of unreinforced concrete beam or slab to withstand failure in bending. According to the result, the compressive, splitting tensile, flexural strength, elastic modulus, water permeability, and cracking resistance of the specimen were all significantly affected by the $SiO_2/NaO$ molar ratio in the range of 1.1-1.6 (Zhang et al., 2022).

## 4.2.Mix-2: Influence of metakaolin in GPM

Mixture-2 was based on the work of Tomás et al (Tomás et al., 2023). The geopolymer mortar was manufactured utilizing alkaline activators, MK, biomass fly ash (BFA), and Electric Arc Furnace Slag (EAFS). The MK used in this study was supplied by Mota Ceramic Solutions (Alvares, Portugal), while the BFA EAFS was supplied respectively by Greenvolt (Lisboa, Portugal) and Harsco Environmental (Maia, Portugal)(Tomás et al., 2023).

Six distinct formulations of the precursors, fine aggregate (sand), alkali solution (SS and SH), and water were used to make the mortars. These six formulations are allowed to evaluate how well they perform differently when the balance between activators and alkali is altered. To obtain the correct ratios and improve material performance, the alkaline mix must be altered in each formulation. This was achieved by adjusting the ratios of the sodium hydroxide and sodium silicate solutions and adding extra water or solid sodium hydroxide (Tomás et al., 2023).

To prepare the mortar for casting, the weighted precursors and alkaline solution were first added to the mixer and then the mortar was mixed for 120 seconds at 140 rpm, pausing for 60 seconds to scrape the mixer bowl.

The freshly created mortars were cast and poured at room temperature into a 160 x 40 x 196 mm mould. The specimens were taken out of the mould once they had acquired the required standard strength and could withstand the demoulding process. The specimens were then allowed to keep curing until the end of the seventh day after casting while remaining at room temperature. Following a seven-day curing period, the GPM mortar samples underwent an assessment of unconfined compressive strength using a universal mechanical testing machine (Instron 4505). For each formulation, six samples in total were tested.

Since several formulations were utilized in the original study, each formulation was tested to assess how its compressive strength changed regarding the raw materials used and the alkali solution /binders ratio in the mixing procedure. Figure 4-2 shows how such variations in compressive strength differ from one another.

According to Figure 4-2, MK is clearly one of the best raw materials that can be used to manufacture geopolymer mortar in terms of compressive strength. In order to examine the compressive strength and assess its LCA, the fourth formulation (MK&BFA) from the original study has been taken into account in this study.

### 4.2.1. Compressive strength of (MK+BFA) mortar content

According to the compressive strength is affected by the raw material composition as well as the amount of $SiO_2$+$Al_2O_3$ or the $SiO_2$/Al2$O_3$ ratio. It shows that MK has a high compressive strength when employed alone, compared to a mixture of MK and FA or other compositions. As a result, the formulation of the combination proportion and the characteristics of the raw materials can significantly affect the performance of the GPM.

Mixture M4 (MK+BFA), which has a compressive strength of nearly 20.5 MPa, has been taken into consideration for the LCA analysis in this section. Out of the six mixing proposals that were employed in the original study, M4 stands in third place in terms of strength, behind M1 and M4 with approximately 62 and 30 MPa, respectively.

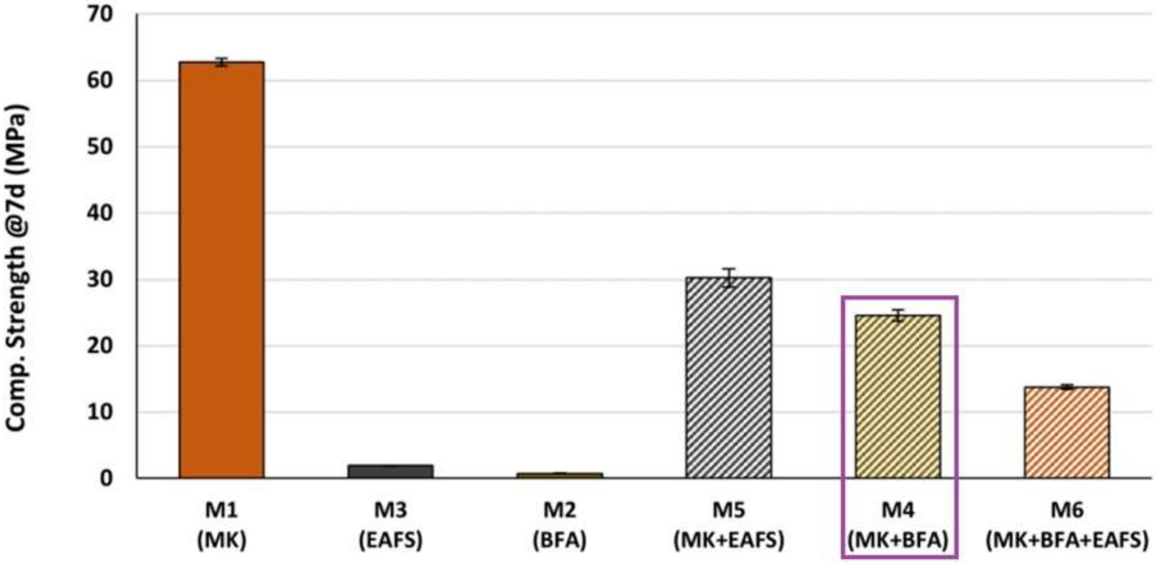


Figure 4-2- Compressive Strength of GPM mortars after 7 days of curing (Tomás et al., 2022)

On other hand, the compressive strength results obtained (illustrated in Figure 4.3) allow us to conclude that the number of dissolved aluminosilicates is a significant factor in the mechanical performance of the GPC mortar because the trend of compressive strength is very similar to that of the estimated total dissolved $SiO_2$ and $Al_2O_3$.

## 4.3.Mixture-3: Alkali activation of biomass fly ash/metakaolin blends

The focus of the third mix proportion lies in utilizing biomass fly ash (BFA) and metakaolin (MK) for the production of Geopolymer Materials (GPM). A blend of BFA and the commercial MK ARGICAL 1200 served as the binder materials. Alkali activators were formed using sodium silicate and sodium hydroxide solutions with varying molar volumes. Mechanical strength testing was conducted after a 10-day curing period, during which the ashes were dried at 60 °C to eliminate excess moisture. Additionally, the mixture included fine silica sand and superplasticizer. Prior to mixing, the fly ashes underwent sieving through a 75μm filter to minimize agglomeration.

### 4.3.1. Mixture compositions of alkali activated biomass FA–MK pastes

To prepare the mortar, metakaolin and biomass fly ash were used as binder components. Fine silica sand was used in this study in order to increase the strength of the mortar and the sand was sieved through a 6mm screen after being dried at 60 °C for 24 hours to regulate the moisture content.

As an activation liquid composition for the mortar, an alkali solution with a sodium hydroxide and water glass ratio of 1:2 was chosen. To investigate the influence of NaOH on mechanical characteristics, two different concentrations of NaOH solution (10 M and 18 M) have been studied. Before the mixing process, the components were first weighed in a laboratory mixer. After all the mixture components have been prepared and weighed, the following steps were realized to process the mixture process: (i) adding the dry raw materials in the mixer and mixing it together until there are cohesions between all the materials; (ii), adding alkali solution to the mixer while the mixer is running at a low rotation speed of 60 rpm; and (iii) finally, adding superplasticizer and water in the mixer bowl. After adding all the mixture components, the mixing process began (Rajamma et al., 2012).

### 4.3.2. Compressive strength measurements

According to Rajamma et al. research, increasing the concentration of the alkali activator, specifically the amount of sodium silicate contained in the activator solution, improved the fluidity of the mixes. The strength of the biomass fly ash compositions increases as the NaOH content increases. The strength of the biomass fly ash compositions is seen to rise when the NaOH content does (Rajamma et al., 2012b). However for NaOH greater than 10 M, the compressive strength tends to decrease as is illustrated in Figure 4-3. This is due to the quick setting for adding an extra alkali activator. To reinforce the mortar, an addition of sodium silicate solution is added. Based on the results shown in Figure *4-3*, 10 M NaOH can be considered the best concentration to achieve a satisfactory strength in contrast to other compositions (Rajamma et al., 2012).

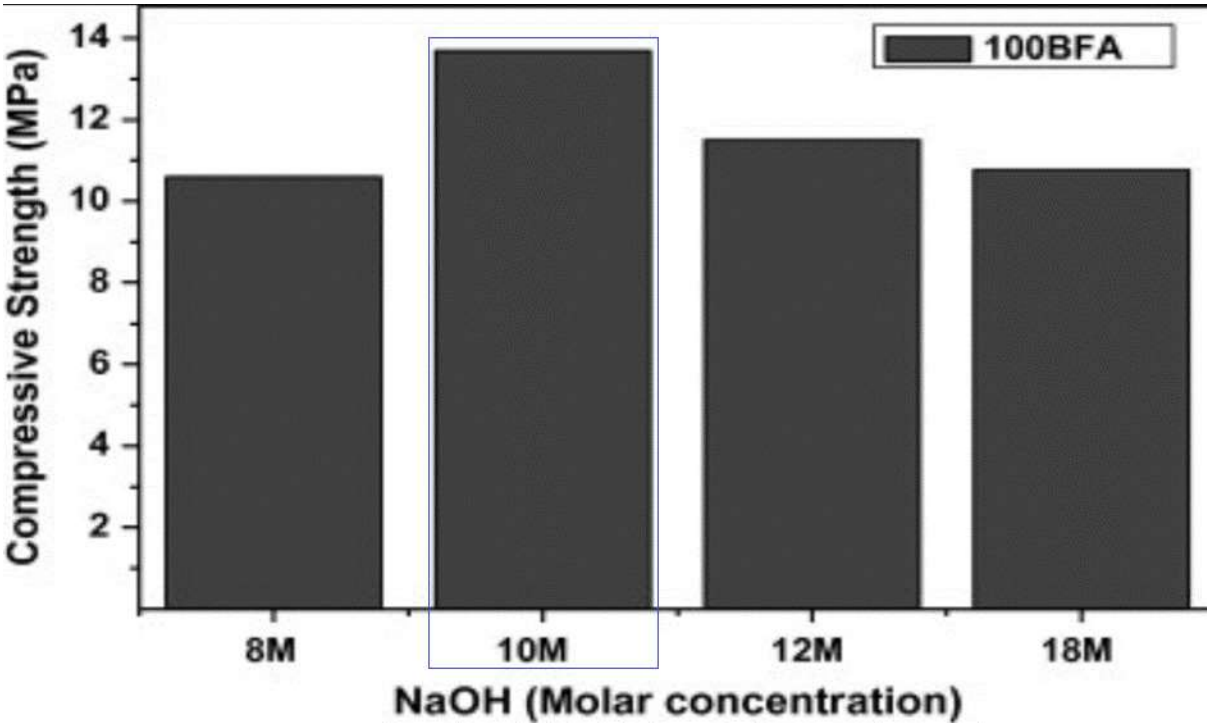


Figure 4-3- NaOH molar concentration vs. compressive strength of alkali activated biomass fly ashes ($Na_2SiO4$:NaOH = 2:1) (Rajamma et al., 2012)

Figure 4-4 demonstrates the fact that the strength of the mortar manufactured from biomass fly ash and sand was greater in comparison to other mix compositions. GPM Samples containing biomass fly ashes gained compressive strength values of 18 MPa and 14 MPa for 10 M and 18 M NaOH concentrations, respectively. The greatest value was achieved from samples containing 40% metakaolin with 60% BFA: 38 MPa with a concentration of 10 M NaOH. This is the composition under consideration in this section. Those containing 20% metakaolin had an intermediate value of 30 MPa (Rajamma et al., 2012).

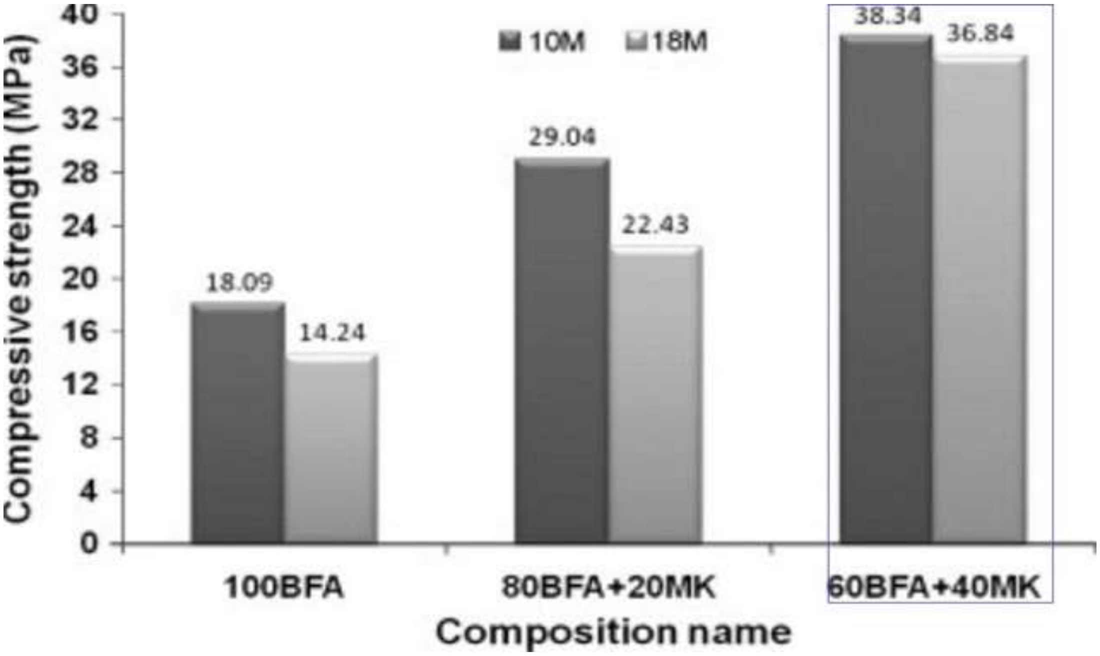
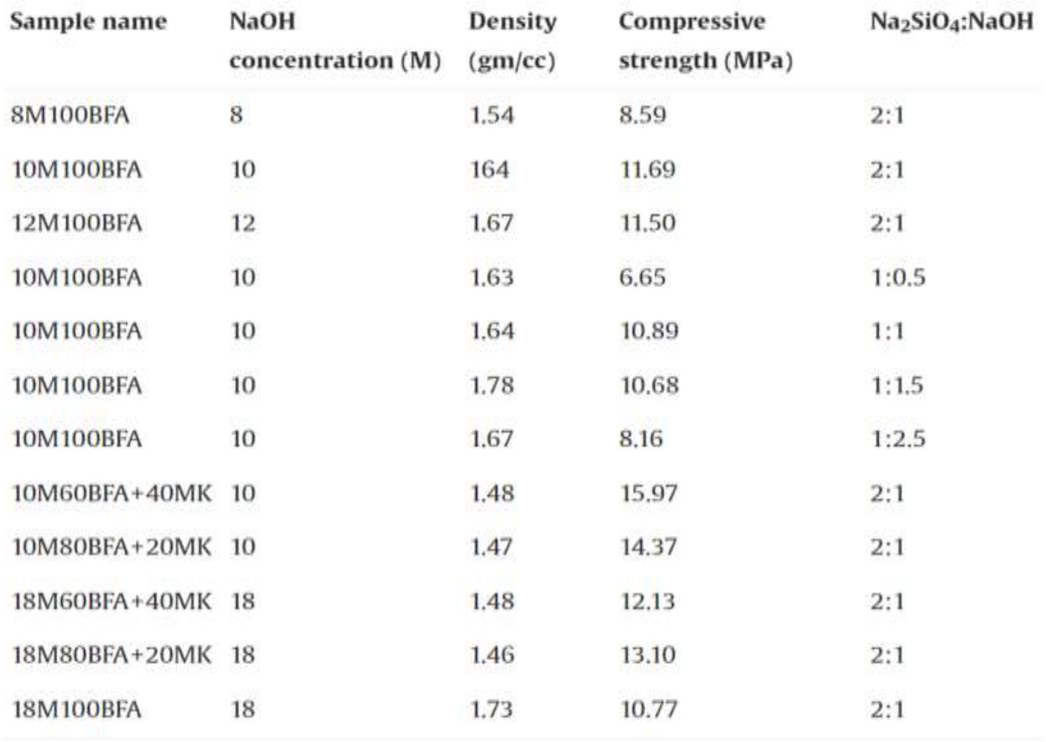


Figure 4-4- Compressive strength values of biomass fly ash–metakaolin mortars (Rajamma et al., 2012)

Table 4-2, lists several mortar samples that were produced by altering the concentration of NaOH. By referencing the data information from the original study elaborated by Rajamma et al., the compressive strength of fly ash and metakaolin with a 2:1 ratio and 10 M concentration was evaluated in this current investigation. As a consequence, the 2:1 alkali solution ratio with 10 M (molar concentration) and FA&MK materials composition have stronger compressive strength than the other mixture proportions.

Based on these findings, we can conclude that MK content in the mixture proportion is more essential than FA in terms of compressive strength. Thus, the percentage of MK should be regarded as having a significant value in the mixing proportion of GPM.

Table 4-2- Mechanical properties of alkali activated BFA–MK paste compositions (Rajamma et al., 2012)

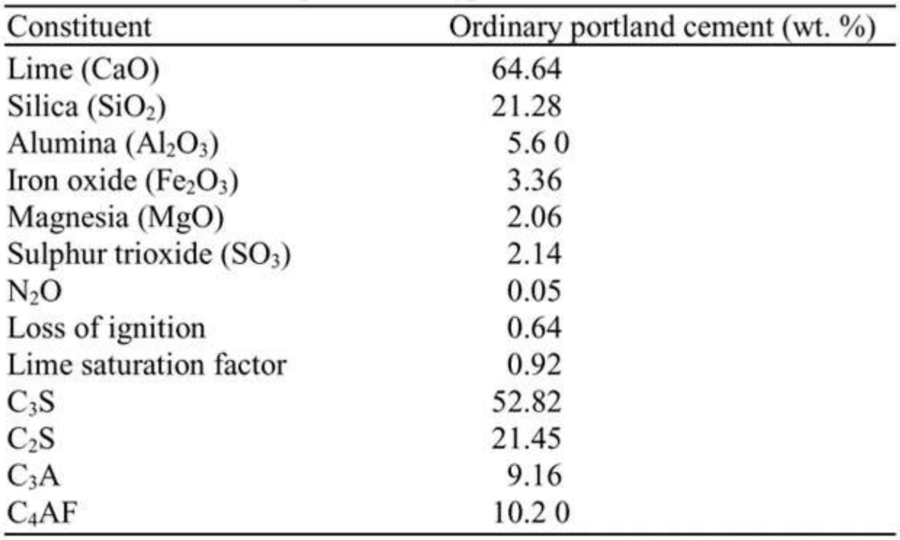


| Sample name | NaOH concentration (M) | Density (gm/cc) | Compressive strength (MPa) | $Na_2SiO_4$:NaOH |
|---|---|---|---|---|
| 8M100BFA | 8 | 1.54 | 8.59 | 2:1 |
| 10M100BFA | 10 | 164 | 11.69 | 2:1 |
| 12M100BFA | 12 | 1.67 | 11.50 | 2:1 |
| 10M100BFA | 10 | 1.63 | 6.65 | 1:0.5 |
| 10M100BFA | 10 | 1.64 | 10.89 | 1:1 |
| 10M100BFA | 10 | 1.78 | 10.68 | 1:1.5 |
| 10M100BFA | 10 | 1.67 | 8.16 | 1:2.5 |
| 10M60BFA+40MK | 10 | 1.48 | 15.97 | 2:1 |
| 10M80BFA+20MK | 10 | 1.47 | 14.37 | 2:1 |
| 18M60BFA+40MK | 18 | 1.48 | 12.13 | 2:1 |
| 18M80BFA+20MK | 18 | 1.46 | 13.10 | 2:1 |
| 18M100BFA | 18 | 1.73 | 10.77 | 2:1 |

## 4.4.Mixtures- 4 and 5

To compare with the prepared GPM in mixtures 1 to 3, it is important to compare them with Ordinary Portland Cement. One of the main aspects to consider is the inclusion or not of superplasticizers in the mixture proportion. Ban et Ramli (Ban & Ramli, 2010) emphasized on OPC mortar with and without superplasticizer. Table 4-4 summarizes the compressive strength of the two distinct OPC mortars. As a binder, cement type I with a specific gravity of 3.15 was utilized according to ASTM specifications. The fine aggregate utilized had a specific gravity of 2.83 and an outside diameter of 5 mm. The fine aggregate was dried before being used as a constituent material in the mixing process. Fine aggregates were graded in accordance with BS812-102: 1990 (British Standards Institution, 1990) and the grading of fine aggregates used complies with the overall grading limits of BS 882:1992 (British Standards Institution, 1992). Superplasticizer Type F is used in certain mix compositions to maintain the desired level of workability. For all mixes, water from the nearby water supply network was used as the mixing liquid.

Table 4-3- Chemical Composition of cement type I (Ban & Ramli, 2010)

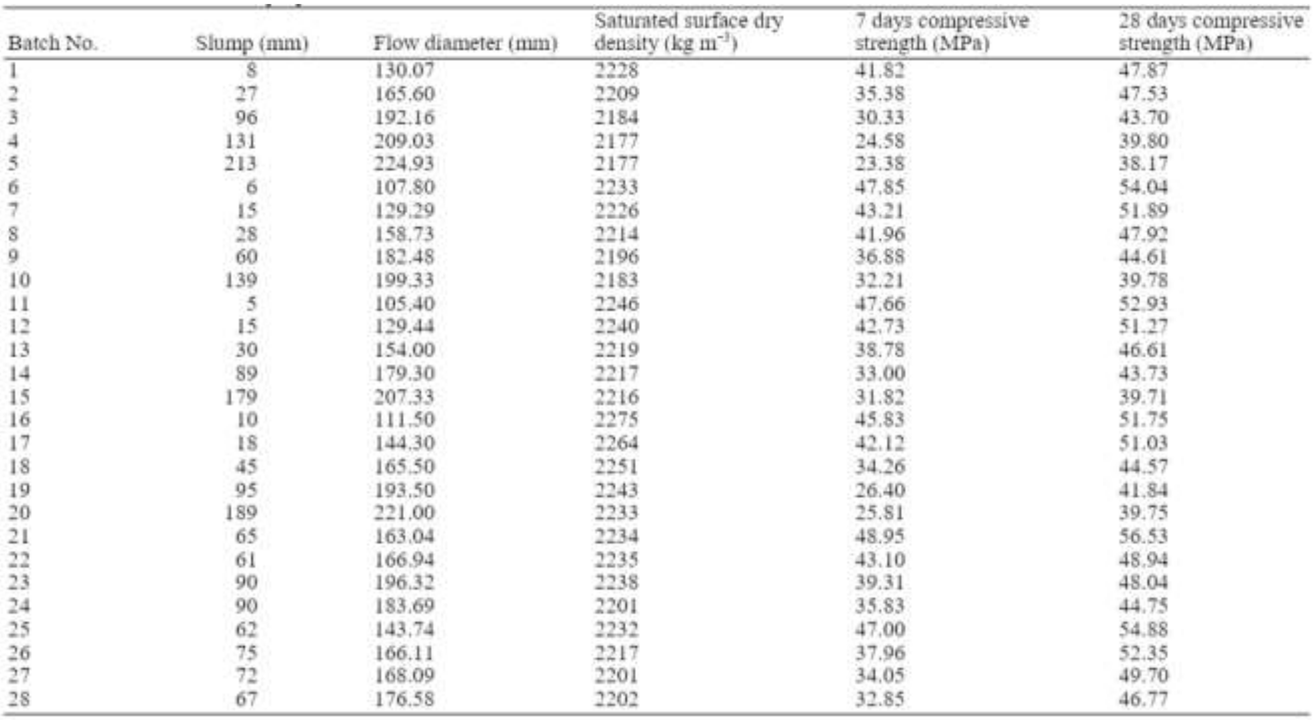


| Constituent | Ordinary portland cement (wt. %) |
|---|---|
| Lime (CaO) | 64.64 |
| Silica ($SiO_2$) | 21.28 |
| Alumina ($Al_2O_3$) | 5.6 0 |
| Iron oxide ($Fe_2O_3$) | 3.36 |
| Magnesia (MgO) | 2.06 |
| Sulphur trioxide ($SO_3$) | 2.14 |
| $N_2O$ | 0.05 |
| Loss of ignition | 0.64 |
| Lime saturation factor | 0.92 |
| $C_3S$ | 52.82 |
| $C_2S$ | 21.45 |
| $C_3A$ | 9.16 |
| $C_4AF$ | 10.2 0 |

### 4.4.1. Mix proportions and mixing methods

The quantity of materials used in the mixture proportion is tabulated in Table-2 from the original study (Ban & Ramli, 2010) and on section 4, Table *4-1* on this present study. In the first part of the laboratory investigation, a total of 20 batches of mortar mix with cement: Sand ratio of 1: 2.0, 1:2.25,1:2.5 and 1:2.75 each, with water binder ratio varied from 0.40-0.5 was manufactured. For the second phase of the laboratory experiment, an additional 8 batches of mortar mix (Batch 21-28) with cement: sand ratios of 1:2.25 and 1:2.5, and various water/binder ratios of 0.35-0.425 were produced. To maintain the slump of the mix within the range of 50-90 mm, a super plasticizer was used in the dosage. This slump range is prescribed in BS EN 206-1:2000 (British Standards Institution, 2000) as medium workability concrete (S2 Slump Class). After 7 and 28 days, a compressive test was carried out for the different samples produced. Table *4-4* provides a summary of the compressive strength of mortar mixtures at the ages of 7 and 28 days (Ban & Ramli, 2010).

Table 4-4- Fresh and hardened properties of mortar mixes (Ban & Ramli, 2010)



| Batch No. | Slump (mm) | Flow diameter (mm) | Saturated surface dry density (kg $m^{-3}$) | 7 days compressive strength (MPa) | 28 days compressive strength (MPa) |
|---|---|---|---|---|---|
| 1 | 8 | 130.07 | 2228 | 41.82 | 47.87 |
| 2 | 27 | 165.60 | 2209 | 35.38 | 47.53 |
| 3 | 96 | 192.16 | 2184 | 30.33 | 43.70 |
| 4 | 131 | 209.03 | 2177 | 24.58 | 39.80 |
| 5 | 213 | 224.93 | 2177 | 23.38 | 38.17 |
| 6 | 6 | 107.80 | 2233 | 47.85 | 54.04 |
| 7 | 15 | 129.29 | 2226 | 43.21 | 51.89 |
| 8 | 28 | 158.73 | 2214 | 41.96 | 47.92 |
| 9 | 60 | 182.48 | 2196 | 36.88 | 44.61 |
| 10 | 139 | 199.33 | 2183 | 32.21 | 39.78 |
| 11 | 5 | 105.40 | 2246 | 47.66 | 52.93 |
| 12 | 15 | 129.44 | 2240 | 42.73 | 51.27 |
| 13 | 30 | 154.00 | 2219 | 38.78 | 46.61 |
| 14 | 89 | 179.30 | 2217 | 33.00 | 43.73 |
| 15 | 179 | 207.33 | 2216 | 31.82 | 39.71 |
| 16 | 10 | 111.50 | 2275 | 45.83 | 51.75 |
| 17 | 18 | 144.30 | 2264 | 42.12 | 51.03 |
| 18 | 45 | 165.50 | 2251 | 34.26 | 44.57 |
| 19 | 95 | 193.50 | 2243 | 26.40 | 41.84 |
| 20 | 189 | 221.00 | 2233 | 25.81 | 39.75 |
| 21 | 65 | 163.04 | 2234 | 48.95 | 56.53 |
| 22 | 61 | 166.94 | 2235 | 43.10 | 48.94 |
| 23 | 90 | 196.32 | 2238 | 39.31 | 48.04 |
| 24 | 90 | 183.69 | 2201 | 35.83 | 44.75 |
| 25 | 62 | 143.74 | 2232 | 47.00 | 54.88 |
| 26 | 75 | 166.11 | 2217 | 37.96 | 52.35 |
| 27 | 72 | 168.09 | 2201 | 34.05 | 49.70 |
| 28 | 67 | 176.58 | 2202 | 32.85 | 46.77 |

For mortar mixes without superplasticizer, with a cement: sand ratio of 1:2.25 demonstrate the maximum compressive strength for all water/binder ratios at 28 days age, as illustrated in Figure 4-5 a and b (Ban & Ramli, 2010). When the cement:sand ratio is altered from 1:2.00-1:2.75, the compressive strength of the mix at 7 days age increases to a maximum (as demonstrated graphically from the original study (Ban & Ramli, 2010).

Figure 4-5-b, the compressive strength of the mix without superplasticizer and cement:sand ratio of 1:2.5 and water/binder ratio of 0.400 outperforms the one of the 1:2.25 mix for a water/binder ratio range of 0.400-0.425. By comparing the strength of mortar mixes with a cement:sand ratio of 1:2.25 and water/binder ratios of 0.400 and 0.425 with and without superplasticizer, it was discovered that the addition of superplasticizer to mortar mixes resulted in the reduction of the compressive strength of hardened in the 28 days of age. The same pattern may be seen in cement mixes: The loss in 28 day compressive strength caused by the introduction of super plasticizer in mortar mix with cement:sand ratio of 1:2.25 is greater than the one with cement:sand ratio of 1:2.25.

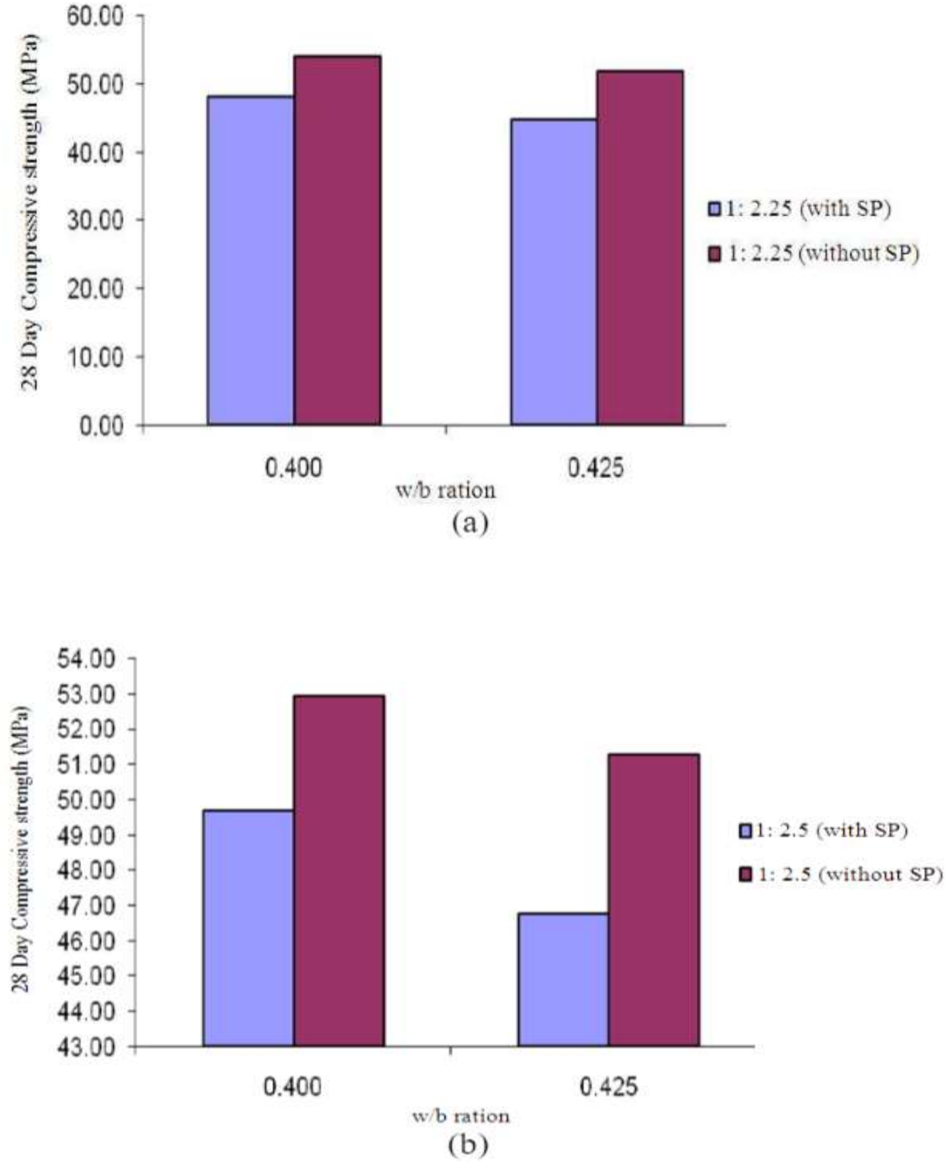


Figure 4-5- Compressive strength for 28 days, with and without superplasticizer at different w/b ratios (Ban & Ramli, 2010)

In this perspective, three criteria are taken into account. Composition of mortar both with and without superplasticizer, the cement/sand and w/b ratio. These three criteria are the most crucial elements taken into account for every composition in this section. Regarding the two ratios that were employed, the cement/sand ratio of 1:2.5 and the w/b ratio of 0.400 were determined to have the highest compressive strength. This leads to the conclusion that compressive strength increases as the amount of water/binder decreases.

# 5. Life cycle assessment of geopolymer material

One of the most systematic and scientifically environmental assessment tools for assessing the environmental impact of building materials throughout their life cycle, its life cycle assessment (LCA). It is defined as a systematic method of recording and analyzing all inputs, outputs, and potential environmental impacts of a product or system throughout its life, from raw material extraction, manufacture, distribution, use, and final disposal (Barbhuiya & Das, 2023). More information about LCA in detail can be found in the international standard ISO 14040 (ISO 14040:2006, 2022) and ISO 14044 (ISO 14044:2006, 2022). On the other hand, LCA can be used to assess a single product or a group of products in the context of buildings.

As this study is based on construction materials, the LCA analysis of this study is based on EN 15804+A2:2019. This standard has been utilized on the fact that it is established as the basis of product category rules (PCR) for Type III environmental declarations for any building product or service. This standard does not address the evaluation of social and economic performance at the product level.

According to the SimaPro help center, the EN 15804 standard which has been used in this project covers Environmental Product Declarations (EPD) of construction products.

This chapter presents the goal and scope of this study, the life cycle inventory, the life cycle impacts assessment, and the interpretation of the results from the LCA analysis of the five different mixture proportions.

## 5.1. Goal and scope

This study employed a quantitative life cycle impact assessment, grounded in the fundamental theory and technological framework of LCA, to conduct a comprehensive evaluation of the life cycles of GPM and OPCM for comparative purposes. Five distinct mix proportions, comprising three GPM and two OPC mortars, were scrutinized in this study. The aim was to analyze and compare their characteristics, performances, and life cycle assessments through an in-depth LCA analysis.

It's important to note that downstream processes such as building operation, maintenance, and demolition were excluded from the scope of this research. The primary objective of the study is to deepen our understanding of GPM materials, underscore their significance over OPC materials in terms of performance, and highlight the distinctions between them regarding environmental impact.

The findings from the analysis aim to enhance the awareness of scientists and technicians regarding geopolymer materials and underscore the potential advantages of utilizing them instead of OPC materials in the construction sector.

These two materials (GPM and OPCM) are deemed to be manufactured and utilized in Portugal. Therefore, the Global LCA Data Access Network and Ecoinvent 3.9 were both utilized as guidelines during the selection of the materials and the LCA analysis. As the database is wide and more information is presented in the Ecoinvent database platform, during the selection of the materials from the database, the majority of materials have been found to be manufactured in Europe, in particularly Germany. Although the data were collected for Germany products, it is assumed that it should be sufficiently similar and representative of production in Portugal. Sensitivity analysis will be necessary to assess this assumption.

As a consequence of this, it is considered in this present analysis that FA, MK, SS, SH and superplasticizers will use proxy data set, and cement and water are considered to be produced in Portugal, using data set from Portugal.

Assumptions have been utilized to assess the system boundaries under consideration. The system boundary phase begins with material extraction and concludes with the GPM mortar manufacturing process stage, as shown in Figure *5-1*. The functional unit is declared as 1.0 $m^3$ GPM mortar with the similar mechanical properties of OPCM. By referring to the Global LCA database, FA, MK, SH, and SS are assumed to be produced in Portugal and have the same characteristics with the ones produced on Germany. Therefore, the system covers the transportation from the point of commercialization/production to the mixing area (industrial area of Marina Grande, Portugal).

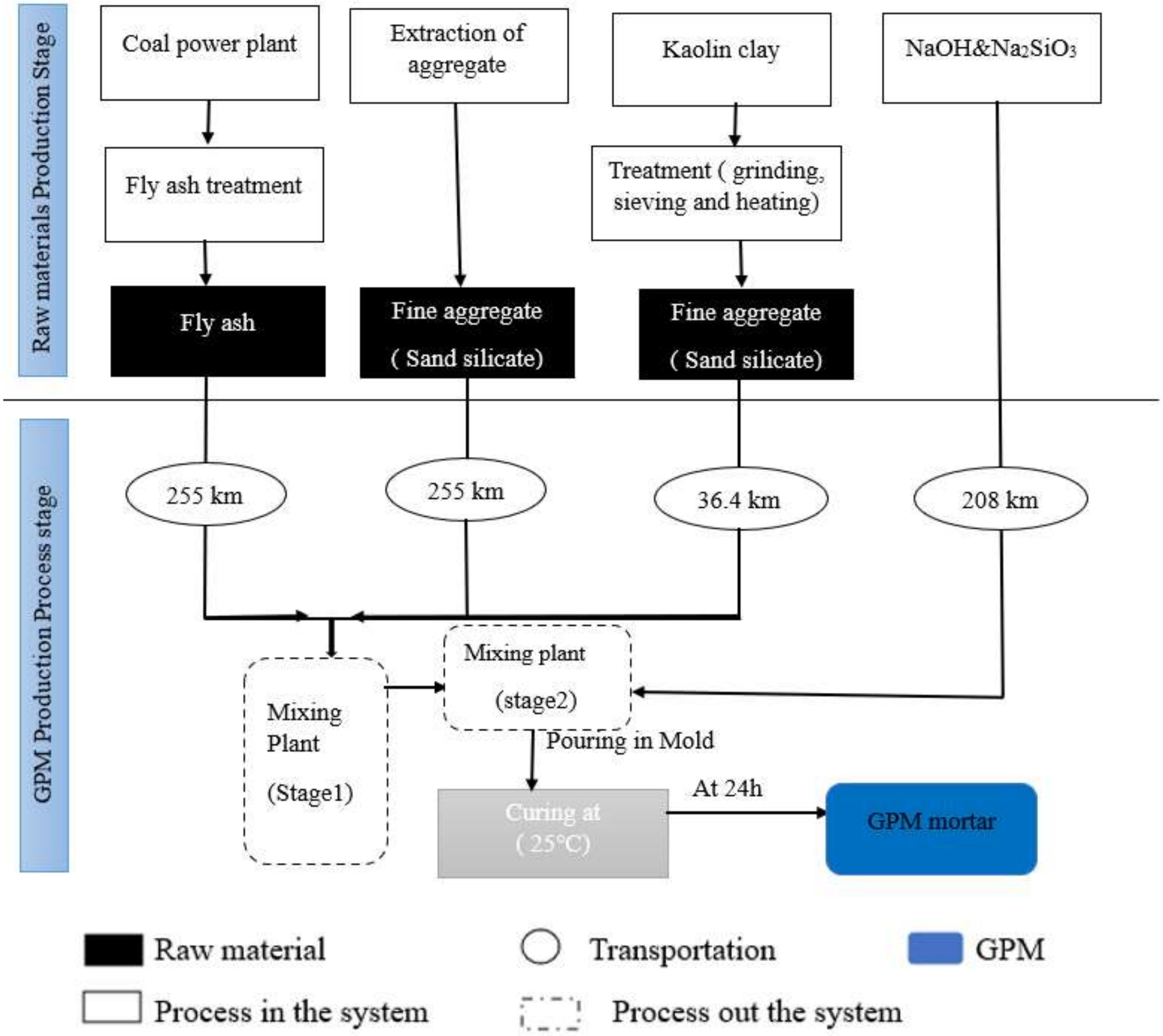


Figure 5-1-system boundary

## 5.2.Life cycle inventory

The life cycle inventory (LCI) is used to quantify the input and output of material and energy flows connected with each step of the unit process, namely elementary flows and intermediate flows. These flows include water, energy, and raw material inputs as well as emissions to air, water and soil, and land use. A system flow model is created by utilizing input and output data to construct the inventory.

To achieve this, an analysis of each unit process within the system is conducted, and various processes and data are assumed to conduct the LCA in this study. The scale-up process is built around the production/treatment of raw materials, transportation, mixture proportions and procedure, and, lastly, the manufacture of geopolymer materials.

### 5.2.1. Mortar mix plant

In different mixing plant, to calculate the energy needed for mixing, the power consumption curve (power consumption vs. mixing time) is utilized for monitoring the evolution of the concrete during the mixing time.

According to United States Environmental Protection Agency (UEPA), the ready-mix concrete industry in the United States uses an average of (18.4 kJ/kg) of specific energy, according to Portland Cement Association (PCA) survey (Geoplast US Corp., 2017). However, this number can vary according to the plant parameters used and the local environment. Regarding to the Geoplast data information (Geoplast US Corp., 2017) 2.775 MJ of energy is needed to prepare one cubic meter of concrete (1.19 kJ/kg of concrete). Further information obtained from HAOMEI machinery industry (Haomei, 2024), 2250 kJ energy required to mix 4 $m^3$ of concrete (0.24 kJ/kg of concrete). Due to varying energy data from several mixer industrial plants, the LCA analysis's energy consumption was determined by using a specific industrial mixer unit. This unit is a concrete mixer (Figure *5-2*) suitable for processing concrete or aggregates with large diameter, producing up to 15 cubic meters of compound every hour. It has a power electric motor of 5.6 kW and mixing capacity of 450 L.

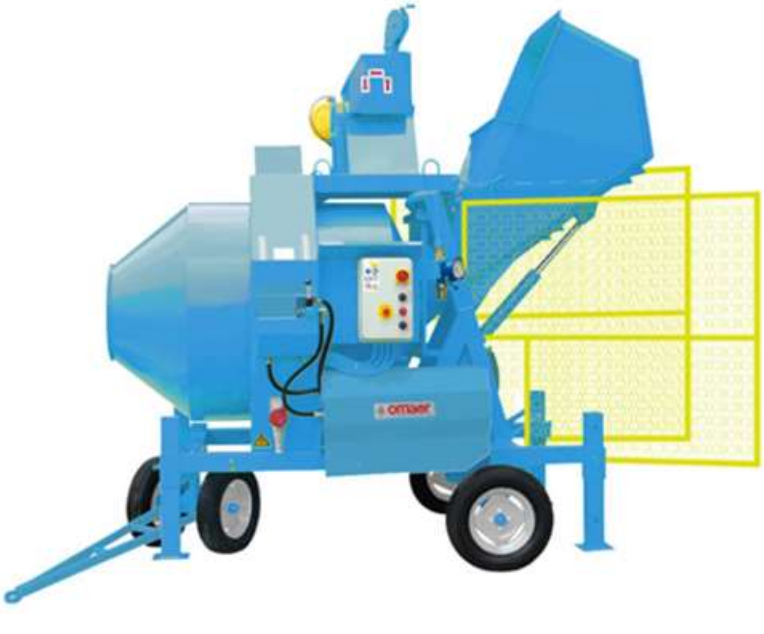


Figure 5-2-Industrial concrete mixture (Omaer, 1962)

The purpose of using this industrial unit is to highlight some information about the quantity of energy that can be utilized during the mixing process. The device was utilized since different industries has different mixer plant and thus, can generate different energy information as each plant has distinct power specifications that will allow the energy consumption to be calculated. Therefore, this unit was chosen as a mixer device in order to gain a sense of insight into the energy usage during the mixing process. In different mixer, the mixing process time can differ. José et al (José A et al., 2019) was studied the influence of mixing time on fresh and hardened Cast-in-place Concrete. Different samples were evaluated with varying mixing times on a portable rotating drum mixer. They discovered that, mixing time and environmental temperature have not a considerable impact on the mixe's slump, meanwhile the compressive strength may increase marginally with increasing mixing time. Different samples have been analyzed with different mixing time. It was revealed however that, the recommended mixing time, with a rotation speed of 28 rpm, is 2.5 minutes, which differs from standard procedure in the mixing area (José A et al., 2019). In this present study, it was assumed that the mixing time is 3 minutes. Based on the general energy calculation formular described in section 3.2.1, Equation-1, the electrical energy consumed during the mixing process is 2.24 MJ/m$^3$ of mortar (0.961 kJ/kg).

### 5.2.2. Alkali activators

In this study, sodium silicate and sodium hydroxide are used in three different mixing proportion. Rajamma, Tomás and Zhang (Rajamma et al., 2012; Tomás et al., 2023; Zhang et al., 2022) quantified the amount and quantities of alkali solution for each of the three GPM mixture used in this present study. The unite employed in this investigation to generate a uniform unit of all five varied mixture proportions is kg/m$^3$ of concrete. The alkali solution information data utilized was obtained from the Ecoinvent 3.9 data set. The production technique and some characteristics of these two alkali solutions (SS, SH) are detailed in section 3.1.

### 5.2.3. Fine aggregate: sand silicate

Different FAAG was used for each of the five distinguished mix proportions evaluated in this study. During the LCA analysis, sand silicate has been chosen to be used in the mix proportion, which the information was obtained from the Ecoinvent 3.9 data set, as described in section 3.4. In the mix proportion, 1 kg of sand silicate generated by drying sand was assumed to be used during the mixing proportion.

### 5.2.4. Preparation method of geopolymers

Firstly, and most importantly, all materials should be treated (like MK) or dried (like FA). The materials, including the solid activator and the precursor material, are weighted according to the mix proportion. In the second phase, the solid materials (FA, MK, and FAAG) are combined in the mixer bowl. After properly mixing the raw materials (FA, MK with FAAG, or OPC with FAAG), the liquid components (SS, SH and water) were added to the mixture. In order to make the mixture uniform, concrete vibration table or hammer should be used. Vibration is a necessary procedure for concrete compaction to improve the strength, density, and durability of the concrete once it has set. Its removes entrapped air pockets which will also help to achieve a smoother concrete finish. Finally, the freshly produced mixture is carefully poured into the mould and allowed to cure the mortar for 24 hours.

### 5.2.5. Curing process energy estimation

The qualities of concrete in the early and late ages directly correlate with the effect of steam curing temperatures. In general, depend on the raw materials used, the curing temperature of GPM is ambient temperature between 23-25 ℃ (Zhang et al., 2014). Curing temperature is adjusted depending on the need for rate of strength gain and ultimate strength, because a high steam curing temperature leads to low strength at later ages (Adjei et al., 2022). According to Ajei et al (Adjei et al., 2022), the geopolymer displayed lower strength when cured at ambient conditions but developed higher strength with increasing temperature.

It should be highlighted that, even though the amount of FA utilized is identical by weight in different mixture proportion, the FA moisture content can impact the amount of energy required. Thus, the moisture content of different type of FA varies. The higher the moisture content, the higher the required thermal energy to dry the materials, and hence the higher the energy consumption. For this study, it is assumed air dried FA. In section 3, Table *3-2*, Yufchina industry has tabulated the electrical energy and temperature needed for the dryer to treat the FA (Yufchina heavy machinery, 2012). It should be kept in mind that the electrical energy consumption can be differentiated regarding the dryer plant used, estimated from 24.4 kJ/kg up to 30.6 kJ/kg of FA.

For metakaolin treatment, Theodore et al (Theodore et al., 2022) studied the production of metakaolin and the theoretical heat required to generate metakaolin from pure kaolinite (dry basis) is 1145 kJ/kg metakaolin, which is 36% less than that of PC clinker. However, this does not take into consideration the moisture content (Theodore et al., 2022). They demonstrated that the minimum energy required for MK calcination is 1513 kJ/kg as is described in section 3.3.3 in this present study. Theodore Hanein et al (Hanein et al., 2022) are studied the clay calcination technology and they demonstrated that, by returning the latent heat, clay calcination requires a minimum of 2269 kJ/kg of energy.

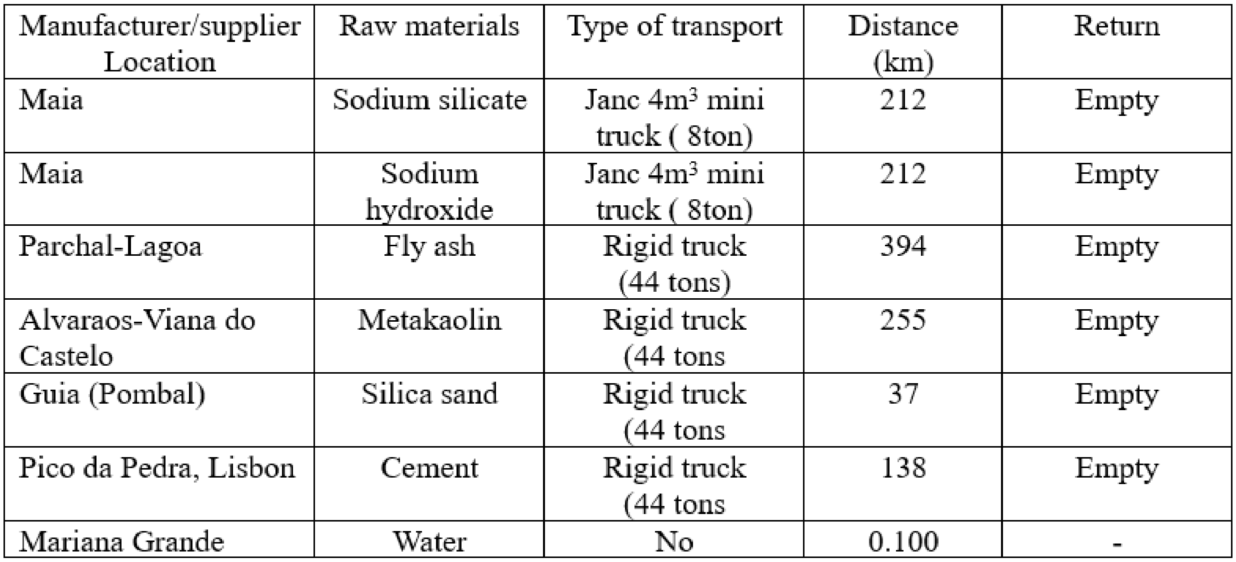
In other study, some estimations revealed that the energy required to produce one tonne of MK is approximately equal to 2 GJ (2015 kJ/kg) (Hanein et al., 2022) and the heating kaolin temperature should be 700°C. By other research, MK prefeasibility study (NLK Consultants Inc, 2002) demonstrated that 2.5 GJ/tonneMK (2484 kJ/kg) and 3.3 GJ/tonneMK (3312 kJ/kg) needed respectively in MK calcination proceed and in overall MK production.

According to all the sources consulted for this study, the required energy need for MK production is between 1500 (0% of moisture content) to 3312 (30% moisture content) kJ/$kg_{Mk}$. This energy variation was determined by the heat demand to remove the MK's moisture content. The higher the moisture content, the higher the heat demand and the greater the energy needed.

### 5.2.6. Transport

The transportation of raw materials between suppliers and mixing facilities represents an important factor in the industrial scale situation. Although the location of the mixing plant is preferred to be in the same area with the raw materials extraction in order to speed up the process, reduce the transportation costs, and reduce the environmental impact. The distances between the supplier and the mixture location have been found using Google Maps. The distances from the raw materials production site to the mixing site point are listed in Table *5-1*. With the exception of water, it is assumed that all components have been transported from different production place in various regions of Portugal to CDRSP-IPLeiria in Marinha Grande (mixing point).

Table 5-1-Transport inventory



| Manufacturer/supplier Location | Raw materials | Type of transport | Distance (km) | Return |
|---|---|---|---|---|
| Maia | Sodium silicate | Janc $4m^3$ mini truck ( 8ton) | 212 | Empty |
| Maia | Sodium hydroxide | Janc $4m^3$ mini truck ( 8ton) | 212 | Empty |
| Parchal-Lagoa | Fly ash | Rigid truck (44 tons) | 394 | Empty |
| Alvaraos-Viana do Castelo | Metakaolin | Rigid truck (44 tons | 255 | Empty |
| Guia (Pombal) | Silica sand | Rigid truck (44 tons | 37 | Empty |
| Pico da Pedra, Lisbon | Cement | Rigid truck (44 tons | 138 | Empty |
| Mariana Grande | Water | No | 0.100 | - |

### 5.2.7. LCI table and reference Flow

LCI data sheets summaries the inputs and outputs needed to make the GPM manufacture from raw materials treatment/production to mixing stage. The data sheet presented in Table *5-2* highlights details pertaining to GPM manufacturing, metakaolin production, and the treatment of fly ash.

The following assumptions and adaptations are made for all MK production cases: it is assumed that the same rotary kiln is utilized and all other electricity consumption remain constant; the refractory, the cement production plant and the industrial mixer machines are assumed to be the same in all mixtures; for MK production with natural gas combustion, fuel consumption is assigned to be natural gas; it is assumed also that the three different mixtures has received the same FA treatment in the same way.

The production of 1 $m^3$ of mixture-1 has been used as the reference flow in this research as there are three different GPM mixture proportions and it is presented in Figure 5-3.

Table 5-2-LCI table data sheet

| 5.2 - a) unit process - Production of GPM | | | |
|---|---|---|---|
| Inputs | Data set ( Ecoinvent) | Units | Quantities |
| Na Silicate | RER: sodium silicate production, furnace liquor, product in 37% solution state | kg | 445 |
| NaOH | GLO: sodium hydroxide to generic market for neutralizing agent | kg | 89 |
| Water | RoW: market for tap water | kg | 100 |
| Machinery | RER: market for industrial machine, heavy, unspecified | kg | 6.67E-06 |
| Fly ash | Fly ash treatment –5.2- b) unit process | kg | 184 |
| Metakaolin | Metakaolin production – 5.2- c) unit process | kg | 429 |
| Conveyor belt | GLO: conveyor belt | m | 3.33E-08 |
| Ener | PT: market for electricity, low voltage | MJ | 2.28 |
| Silica | CH: market for sand | kg | 613 |
| Outputs | Geopolymer | $m^3$ | 1 |
| 5.2 - b) unit process - Fly ash treatment | | | |
| Inputs | Data set ( Ecoinvent) | Units | |
| Energy | PT: market for electricity, low voltage | kWh | 0.0085 |
| Transport | RER: market for transport, freight, lorry, unspecified | tkm | 2.5 |
| FA | PT: hard coal ash | kg | 1 |
| outputs | PT: hard coal ash | kg | 1 |
| 5.2 -c) Metakaolin production | | | |
| Inputs | Data set ( Ecoinvent) | | |
| Energy | PT: market for electricity, low voltage | kWh | 0.0085 |
| kaolin | RER: kaolin production | kg | 1.162 |
| heat | RER: market group for heat, district or industrial, natural gas | MJ | 1.075 |
| outputs | Kaolin calcined, granular or powder | kg | 1 |

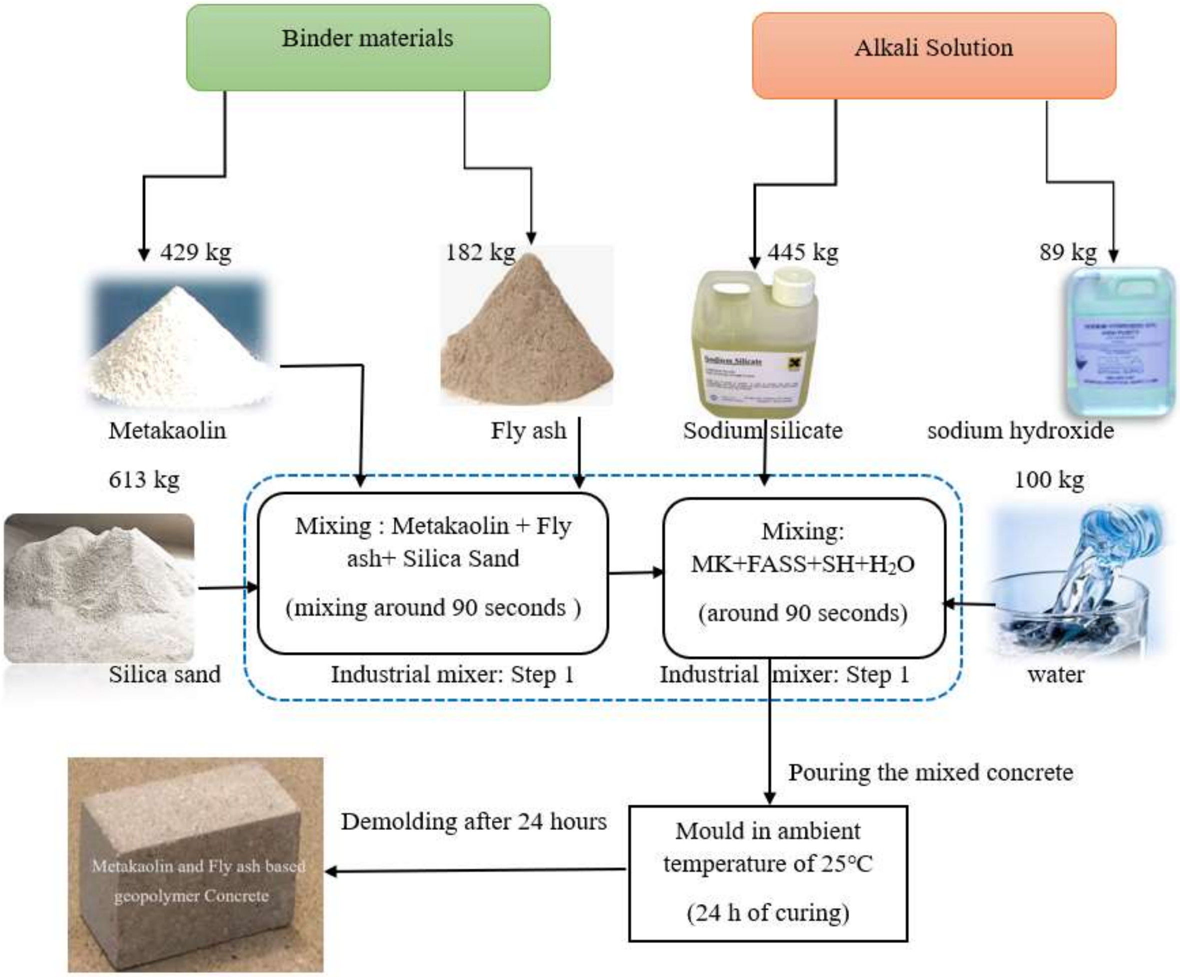


Figure 5-3- Reference flow

## 5.3.Life Cycle Impact Assessment (LCIA)

In its most basic form, LCIA is the assessment of prospective effects on any system as a result of some action. LCIA often categorize consumption and loading data from the inventory stage into different effect categories. According to European Platform on LCA (EPLC), environmental impact categories and indicators are linked to the outcomes of the Life Cycle Impact Assessment (LCI) phase.

The system inventory primarily contains unit processes with elementary flows and intermediate flows, and links to unit processes with secondary data that need to be converted into elementary flows. These elementary flows correspond to environmental loads for air, water and soil. The classification of elementary flows makes it possible to identify each environmental load with a particular effect on the environment, with a mid-point environmental impact category.

The LCI results are attributed to impact categories representing specific environmental impact. Characterization is based on two fundamental procedures. First, each input and output of LCI result is transformed using a characterization factor, based on an environmental mechanism for that impact category (ISO, 1998; J. William Owens, 1997).The transformed LCI data are then combined or joined together to create the category indicator (ISO DIS 14042 (ISO, 1998)).

The information gathered during the life cycle inventory phase must be evaluated for its environmental impact during the life cycle impact assessment stage. This involves figuring out the effects of emissions as well as analyzing the potential implications of each stage of the product's life cycle on the environment and human health.

This section contains a brief description of the environmental effect category results for each of the five mixing proportions. To limit this research, the impacts categories that has been developed from the EN15804+A2 were climate change, water use, total use of renewable primary energy resource, resource use (mineral and metals) as well as some basic information regarding human toxicity (cancer) of GPM and OPCM. The climate change, water use, resource use and human toxicity of EN15804+A2 are based on the Environmental Footprint 3.1.

### 5.3.1. Climate change

Sustainable alternatives materials to Ordinary Portland cement ones in construction materials are becoming a significant challenge in the construction industry. Portland cement is produced by heating a mixture of limestone and other minerals, which produces a lot of carbon dioxide ($CO_2$) (Frederick M. Lea, 2022). By replacing cement with other raw materials, the amount of $CO_2$ in the atmosphere could be reduced.

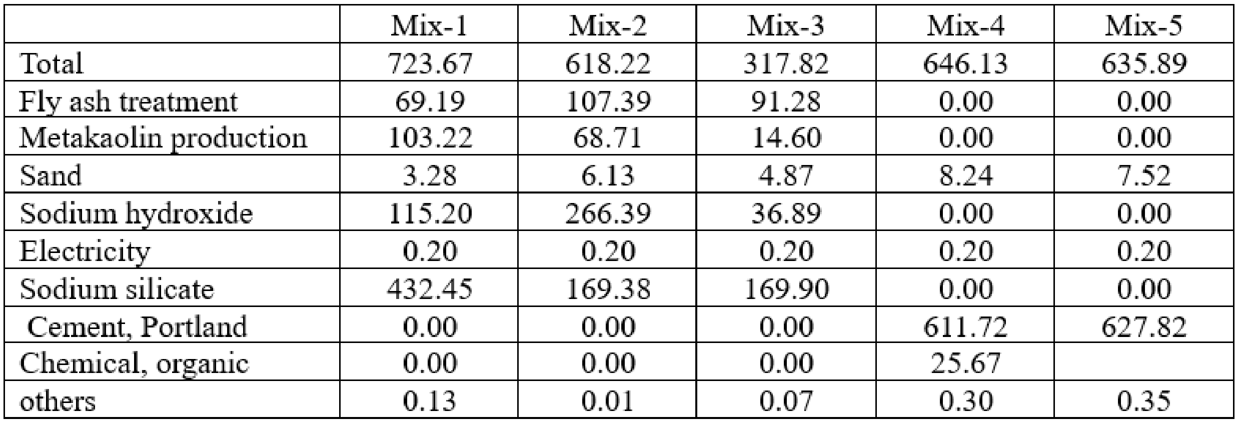
This can reduce $CO_2$ emissions by between 50% to 75%, depending on the technology used. In addition to lowering $CO_2$ emissions, employing those materials (raw materials) instead of cement, may enhance strength and durability and also improving sustainability by reusing industrial waste. Table *5-3* presents the results regarding climate change potential for the diverse materials used in the five mixtures proportion employed in this study.

When comparing Portland cement climate change potential with 611.72 and 627.82 kg CO2eq to FA and MK in all mixtures (Table 5-3), it is discovered that Portland cement cause great impact on climate change potential than those materials.

Therefore, replacing OPC to MK and FA in the mixture, the $CO_2$ emissions can be reduced significantly. With regard to the overall outcome in, Table *5-3* and taking into account the production of MK and FA in mix-2 where the quantity of FA and MK are identical, we may draw the conclusion that MK production has a greater impact on climate change than FA.

On the other hand, it's conceivable to conclude that Portland cement have a greater influence in climate change than all other materials by taking in account the environmental effect of each individual material. According to the result tabulated in Table *5-3* mixe-1 have more significant impact on climate change than OPC materials in terms of overall climate change potential generated.

Table 5-3-Climate change potential-total [kg $CO_{2eq}$]



| | Mix-1 | Mix-2 | Mix-3 | Mix-4 | Mix-5 |
|---|---|---|---|---|---|
| Total | 723.67 | 618.22 | 317.82 | 646.13 | 635.89 |
| Fly ash treatment | 69.19 | 107.39 | 91.28 | 0.00 | 0.00 |
| Metakaolin production | 103.22 | 68.71 | 14.60 | 0.00 | 0.00 |
| Sand | 3.28 | 6.13 | 4.87 | 8.24 | 7.52 |
| Sodium hydroxide | 115.20 | 266.39 | 36.89 | 0.00 | 0.00 |
| Electricity | 0.20 | 0.20 | 0.20 | 0.20 | 0.20 |
| Sodium silicate | 432.45 | 169.38 | 169.90 | 0.00 | 0.00 |
| Cement, Portland | 0.00 | 0.00 | 0.00 | 611.72 | 627.82 |
| Chemical, organic | 0.00 | 0.00 | 0.00 | 25.67 | |
| others | 0.13 | 0.01 | 0.07 | 0.30 | 0.35 |

The influence of OPC on climate change is mainly due to the fact that the production of sodium silicate, sodium hydroxide, and metakaolin, with values of 432.45, 115.20, and 103.22 kg $CO_{2eq}$, respectively, contributes significantly to this impact. When it comes to climate change, mix-3 outperform the other four mixtures. It shows that mix-1 has a higher climate change potential than the other two GPM mixtures. This is related to the fact that mix-1 used more MK and SS, which their production release more $CO_2$ than the other GPM component materials.

Moreover, after OPC, sodium silicate is the second biggest source of environmental effects. This is because the technique for producing sodium silicate necessitates a high-temperature reaction that uses a lot of energy and fuel. Sodium silicate makes approximately 30 to 50 percent of the overall environmental impact in all categories (Pujitha Ganapathi et al., 2023). In this study, sodium silicate contributes approximately 60% of the overall environmental impact in mix-1. Additionally, it is demonstrated that when the amount of sodium silicate in the mixture reduces, the total environmental impact has decreased in mixes 2 and 3. According to Pujitha et al study (Pujitha Ganapathi et al., 2023), this can be explained by the melting and vitrification processes that take place at extremely high temperatures and pressures in furnaces during the production of sodium silicate.

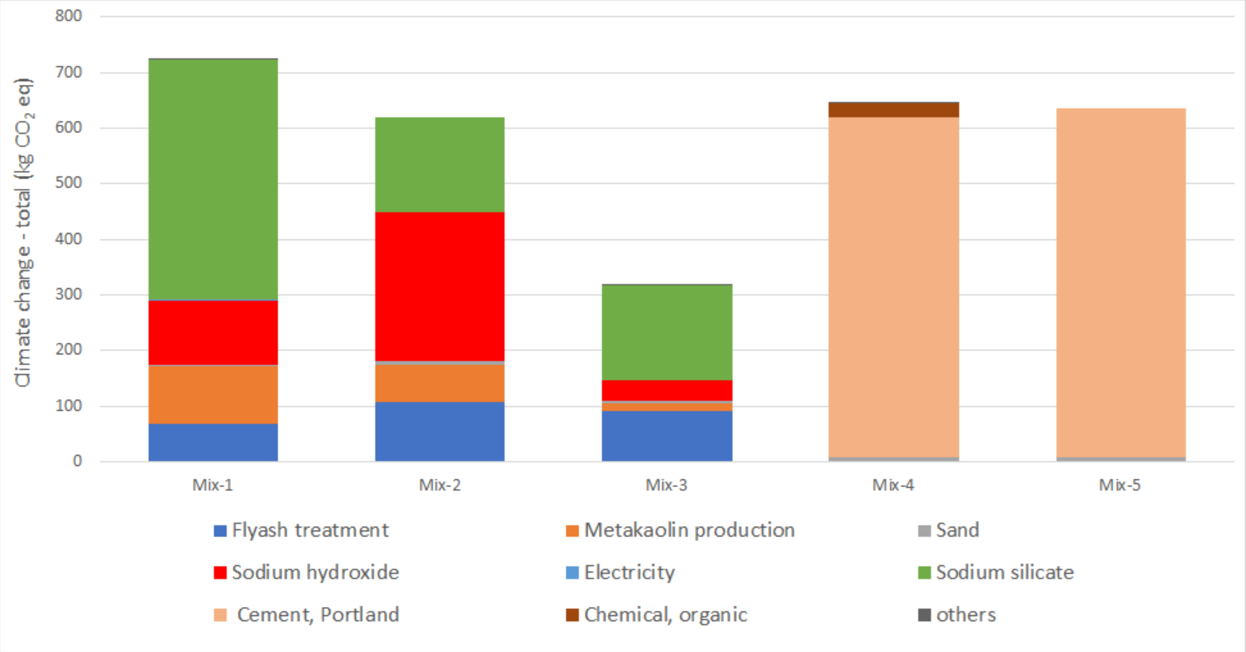


Figure 5-4- Climate change potential-total [kg $CO_{2eq}$]

### 5.3.2. Water use

Water is a commodity that is often used in the construction sector. The precise amount of water in a mixture is an important consideration. Because superplasticizers may now be employed to reduce some quantity of water in mortar, the modern concrete is provided to replace water by other component materials in the mixture proportion. Hence, a number of factors were noted in the current study to highlight some concepts surrounding the amount of water that should be used for GPM manufacture, starting with the raw material production and ending with the mixing stage, in comparison to the manufacture of OPCM. This context takes into account the water used in the mixing proportions as well as the water used in the treatment and manufacturing of the products, such as FA, MK, SS, and SH. Table 5-4 provides a summary of the water use by each material from the treatment step to the mixing stage.

When considering the overall analysis based on the amount of water mentioned in Table 5-4, it is well shown that the two first materials (GPM materials) used a significant amount of water, with a value of 465.10 $m^3$ and 496.39 $m^3$ in comparison to the OPC materials with a value of 178.36 and 155.40 $m^3$.

**Table 5-4- Water use [$m^3$ world$_{equiv}$]**

| | Mix-1 | Mix-2 | Mix-3 | Mix-4 | Mix-5 |
|---|---|---|---|---|---|
| Total | 465.10 | 496.39 | 201.78 | 178.36 | 155.40 |
| Fly ash treatment | 6.57 | 10.19 | 8.66 | 0.00 | 0.00 |
| Metakaolin production | 79.80 | 53.13 | 11.29 | 0.00 | 0.00 |
| Sand | 37.75 | 70.48 | 56.06 | 94.71 | 86.46 |
| Sodium hydroxide | 119.79 | 277.01 | 38.36 | 0.00 | 0.00 |
| Electricity | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sodium silicate | 217.96 | 85.37 | 85.63 | 0.00 | 0.00 |
| Cement, Portland | 0.00 | 0.00 | 0.00 | 58.48 | 60.02 |
| Chemical, organic | 0.00 | 0.00 | 0.00 | 17.57 | 0.00 |
| others | 3.15 | 0.00 | 0.00 | 7.52 | 8.84 |

Based on the data presented in the above table, SS, MK, and SH have the highest contribution for the water use than the other materials, with values of 217.96, 79.80, and 119.79 $m^3_{worldeq}$, respectively for mix-1. These products (SH, MK, and SS), water consumption amounts are significantly higher than other components. Even though in mixes 1 to 3 the quantity of water used in the mixing stage are less than the OPCM ones, but the amount used for the treatment and production of the GPM component materials plays a significant impact in the LCA analysis result.

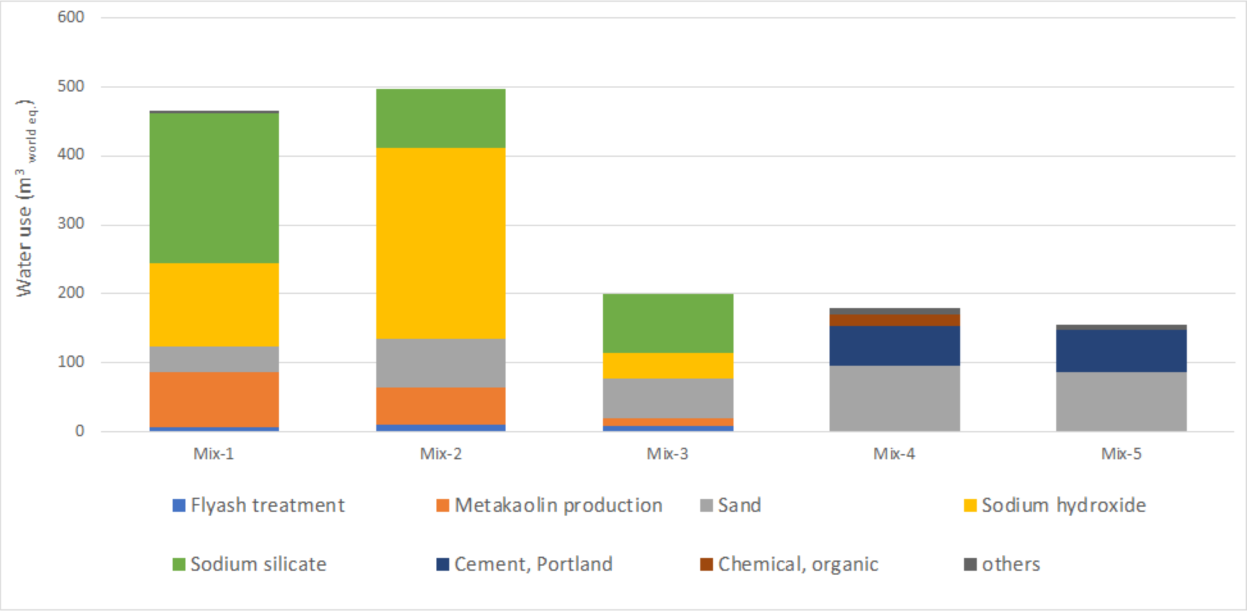


Figure 5-5-Water use [$m^3$ world$_{equiv}$]

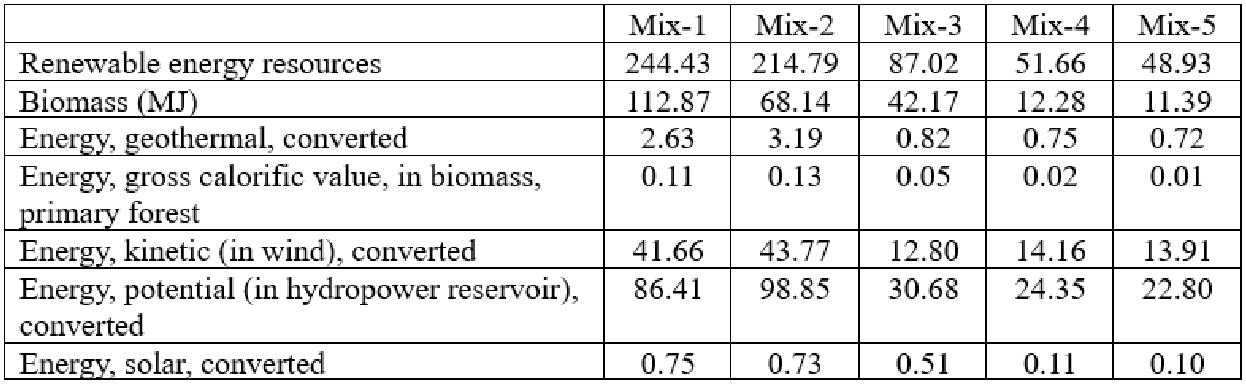
The findings in this section reveal that, while we intend to reduce the amount of water in construction sector by substituting OPCM with GPM, a significant amount of water is still used during the treatment and manufacture of the materials prior to the application of the GPM. A deep investigation should be conducted to compare water consumption from raw material production or treatment to GPM production.

### 5.3.3. Total use of renewable primary energy sources

Energy is necessary for all technological processes. The majority of operations in the construction industry require energy, including manufacturing materials and processing product as well as performing some specific tasks. When taking into account the energy consumed during the treatment and manufacture of the composite materials for the 5 different mixture proportions, it is well known that Fly ash dryer and metakaolin production employ an innovative high-efficiency energy during the drying and treatment process, which requires heat and energy.

Table *5-5*, presents the type of energy resource considered to the total renewable energy value used in the production/treatment of all the different materials under consideration in this study.

Table 5-5-Total use of renewable primary energy resources (PERT) [kWh]



| | Mix-1 | Mix-2 | Mix-3 | Mix-4 | Mix-5 |
|---|---|---|---|---|---|
| Renewable energy resources | 244.43 | 214.79 | 87.02 | 51.66 | 48.93 |
| Biomass (MJ) | 112.87 | 68.14 | 42.17 | 12.28 | 11.39 |
| Energy, geothermal, converted | 2.63 | 3.19 | 0.82 | 0.75 | 0.72 |
| Energy, gross calorific value, in biomass, primary forest | 0.11 | 0.13 | 0.05 | 0.02 | 0.01 |
| Energy, kinetic (in wind), converted | 41.66 | 43.77 | 12.80 | 14.16 | 13.91 |
| Energy, potential (in hydropower reservoir), converted | 86.41 | 98.85 | 30.68 | 24.35 | 22.80 |
| Energy, solar, converted | 0.75 | 0.73 | 0.51 | 0.11 | 0.10 |

The energy differs in accordance with the materials used in each composition. According to the energy values tabulated above, Biomass source of energy is the most widely used for all GPM compositions, followed by hydropower, wind and then the others. Gross calorific value, in biomass, primary forest energy is the lowest of all energies used in this present study.

On the other hand, mix-1 employed significant amount of sodium silicate and a significant quantity of energy is needed to produce this substance. Therefore, it is well shown in Table 5-6 that mix-1 is on the top level in terms of energy consumption. This high energy is generated in great part by the production of metakaolin and sodium silicate with the values of 50.41 and 135.9 kWh respectively.

Table 5-6-Total use of renewable energy primary energy resources (PERT) [kWh]

| | Mix-1 | Mix-2 | Mix-3 | Mix-4 | Mix-5 |
|---|---|---|---|---|---|
| Total | 243.57 | 213.94 | 86.46 | 51.54 | 48.82 |
| Fly ash treatment | 4.87 | 7.56 | 6.42 | 0.00 | 0.00 |
| Metakaolin production | 50.41 | 33.56 | 7.13 | 0.00 | 0.00 |
| Sand | 2.10 | 3.93 | 3.12 | 5.28 | 4.82 |
| Sodium hydroxide | 49.84 | 115.25 | 15.96 | 0.00 | 0.00 |
| Sodium silicate | 135.90 | 53.23 | 53.39 | 0.00 | 0.00 |
| Cement, Portland | 0.00 | 0.00 | 0.00 | 42.36 | 43.48 |
| Chemical, organic | 0.00 | 0.00 | 0.00 | 3.40 | 0.00 |

When comparing MK and OPC production, MK production from mix-1with a value of 50.41 kWh consumes more energy than OPC production. In addition to FA treatment and MK production, sodium hydroxide and sodium silicate play an important factor in term of energy used for the manufacture of GPM. As a result, the overall amount of energy consumed is related to the composite material production and treatment processing.

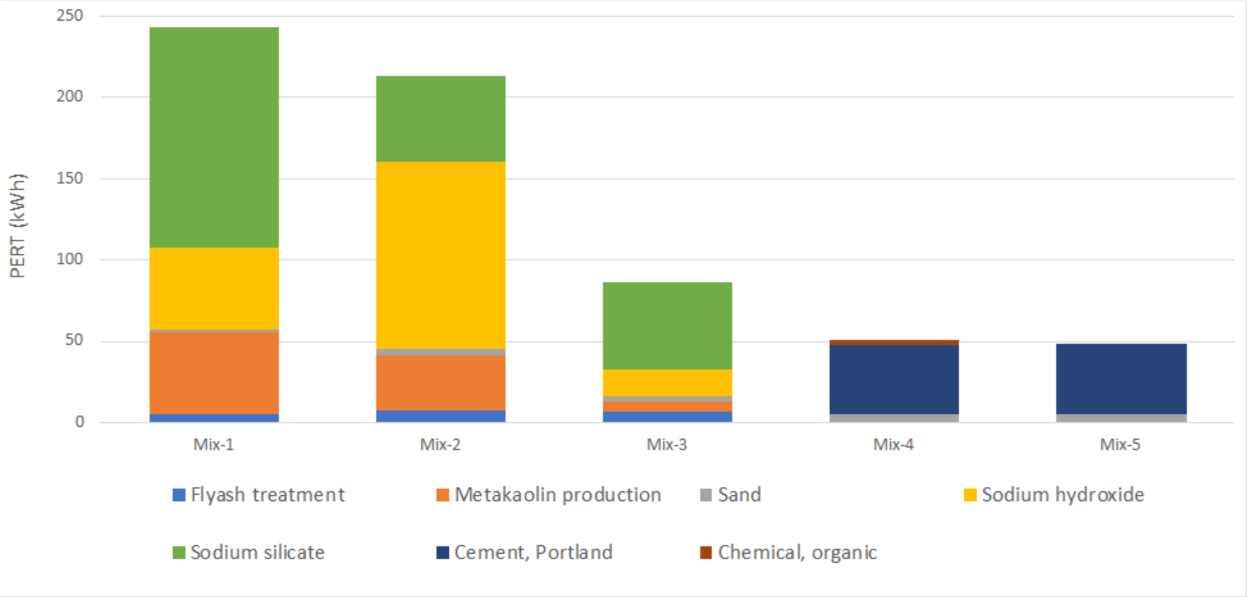


Figure 5-6-Total use of renewable energy primary energy resources (PERT) [kWh]

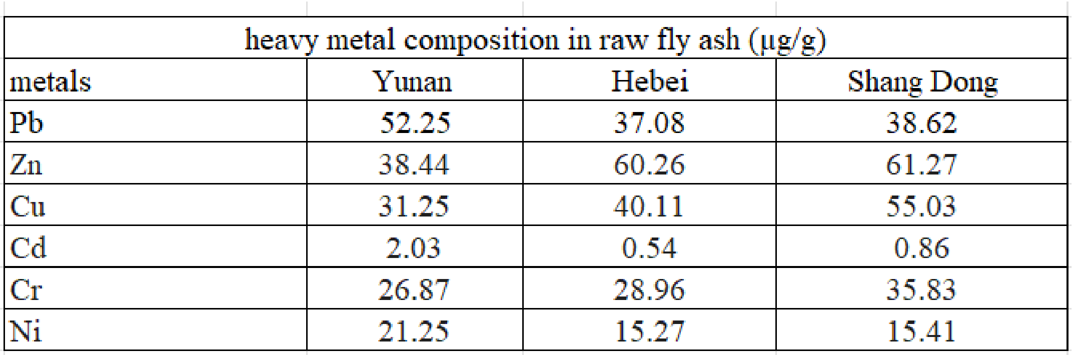
### 5.3.4. Resource use, mineral and metals

In any global economy, mining and metals are essential components, according to the World Economic Forum in September 2015 (world Economic Forum, 2015). At every level, there is constant pressure on the mining and metals industries to alter their practices to better fit a global movement towards sustainability. This constant pressure is due of the fact that metallic materials are found naturally in the environment (world Economic Forum, 2015). In contrast, these materials can also become harmful when they accumulate inside of organisms.

Yuan et al (Yuan et al., 2023) has studied the characterization of heavy metals in fly ash stabilized by carbonation. They measured the main heavy metal such as Pb, Zn, Cu, Cd, Cr, and Ni in fly ash, and the fly ash has to be entirely decomposed.

The FA heavy metal result is tabulated in Table *5-7*. As it is discussed in previous sections, the composition of fly ash varies depending on the production area. Yuan and al has chosen various types of fly ash for three different Chinese cities (Yuan et al., 2023). It can be observed that, the composition of FA and the heavy metal composition content of these different fly ash varies from one city to another.

Table 5-7- Heavy metal content in raw fly ash (Yuan et al., 2023)



| heavy metal composition in raw fly ash (μg/g) | | | |
|---|---|---|---|
| metals | Yunan | Hebei | Shang Dong |
| Pb | 52.25 | 37.08 | 38.62 |
| Zn | 38.44 | 60.26 | 61.27 |
| Cu | 31.25 | 40.11 | 55.03 |
| Cd | 2.03 | 0.54 | 0.86 |
| Cr | 26.87 | 28.96 | 35.83 |
| Ni | 21.25 | 15.27 | 15.41 |

For sodium silicate, heavy metal ions ($Mg^{2+}$ and $Mn^{2+}$) are presented on the composition which can contribute some amount value of the total metal in the GPM materials (Fang et al., 2018). Apart of the above cited materials, sodium hydroxide and metakaolin contain certain percentage of heavy metal in their compositions.

Table 5-8 depicted the various mineral and metal resources used in the manufacture/treatment of the composite materials used in the mixtures. It is demonstrated that more mineral and metal resources were utilized to produce the GPM constituent materials. Furthermore, Super Plasticizer contains a substantial amount of minerals and metals, making it essential to use not only to reduce water use but also to profit from its components. Therefore, according to Table 5-7 and Table *5-8* GPM manufacture used and contain more mineral and metal resources than OPCM.

Table 5-8- Resource use, mineral and metals [kg Sb eq]

| | Mix-1 | Mix-2 | Mix-3 | Mix-4 | Mix-5 |
|---|---|---|---|---|---|
| Total | 1.06E-02 | 6.45E-03 | 4.24E-03 | 7.24E-04 | 6.26E-04 |
| Fly ash treatment | 2.16E-04 | 3.36E-04 | 2.86E-04 | 0.00 | 0.00 |
| Metakaolin production | 2.09E-04 | 1.39E-04 | 0.00 | 0.00 | 0.00 |
| Sodium hydroxide | 1.03E-03 | 2.38E-03 | 3.29E-04 | 0.00 | 0.00 |
| Sodium silicate | 9.08E-03 | 3.56E-03 | 3.57E-03 | 0.00 | 0.00 |
| Cement, Portland | 0.00 | 0.00 | 0.00 | 5.67E-04 | 5.82E-04 |
| Chemical, organic | 0.00 | 0.00 | 0.00 | 1.09E-04 | 0.00 |

In other hand, pollution from heavy metals is not only degrades soil function but also progressively accumulates in the human body via the food chain, causing human health problem (Mitra et al., 2022). Among, the heavy metals can also cause harm to the environment and the most common of them including mercury, cadmium, arsenic, nickel, copper, lead, and chromium (Mitra et al., 2022).

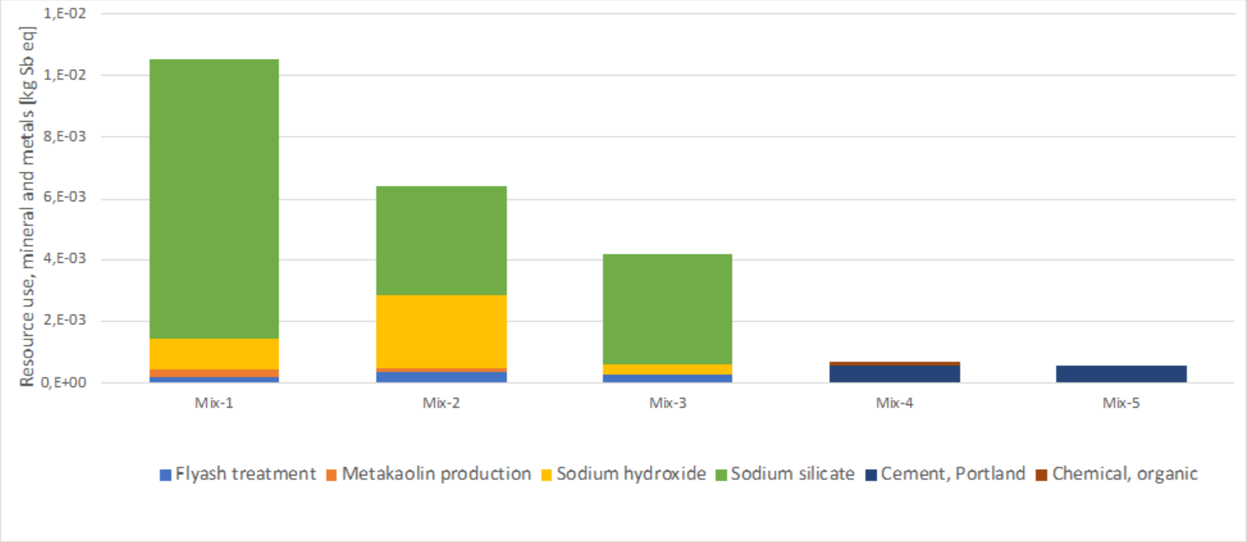


Figure 5-7-Resource use, mineral and metals [kg Sb eq]

It is evident from the result displayed in Figure 5-8 that the production of sodium silicate used more mineral and metal resources than the other components in all the three GPM. Sodium hydroxide on other side, is demonstrated to be the second material that requires more resources to be produced. Based on the figure, the most commonly resources used for the production/treatment of the materials are tellurium, gold and cooper respectively. On the other hand, it appears that fly ash treatment used fewer resources than metakaolin treatment and the other materials.

As we have seen in Table 4-1, section 4, a large amount of SS is utilized in mix-1, resulting a significant quantity of mineral and metal resources used, mainly tellurium and gold, in its production.

Based on these findings, we may conclude that SS may change the sustainability properties of GPM if it is utilized in excessive or in an inappropriate proportion.

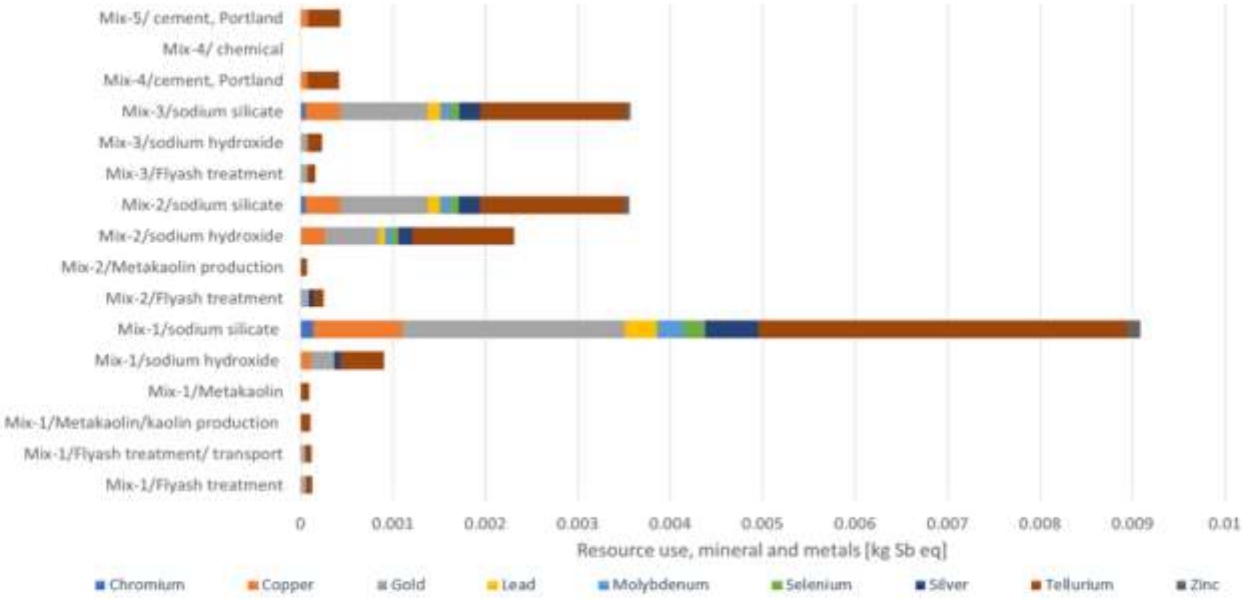


Figure 5-8-Resources use of each materials production/treatment of the materials [kg Sb eq]

### 5.3.5. Human toxicity, cancer

When we consider the characteristics and chemical compositions of the materials in the five different mixing proportions, we can conclude that some of these components contain elements such as Zn, Cu, Pb, and Cr, which can be hazardous to humans and may cause cancer (Kim et al., 2015).

For the different materials used in the mixes proportions, fly ash is made up of $SiO_2$, lime (Cao), $FeO_2$, and $Al_2O_3$. It may contain one or more heavy metals such as arsenic (As), beryllium (Be), boron (B), cadmium (Cd), chromium (Cr), cobalt (Co), and lead (Pb), depending on its source(Fu et al., 2019). These heavy metals, depending on how and what quantities they are used. Some of these heavy metals can be hazardous, and it can be therefore, a potential threat to human health and the environment (Shabiimam.A M et al., 2017) . For sodium silicate, contact with human skin, it will cause a chemical burn resulting in severe redness, itching and pain. Contact with the eyes will cause intense burning and pain. Possible damage to the eye tissues can occur (National Library of Medicine, 2023).

For cement production, according to United States Environmental Protection Agency (UEPA), sulphury dioxide, nitrogen oxide, and carbon monoxide emissions from cement plants cause negative environmental effects, including ground-level ozone, acid rain, global warming, deterioration of water quality, and vision impairment.

According to the UEPA, the kiln is the principal source of these potentially air pollutants emitted during the manufacture of Portland cement. It has also been shown that the combustion of fuels and the heating of feedstock may have a significant negative impact on the environment.

Figure 5-9 depicts the potential health effects of the composite materials from the five distinct mixtures. Based on the total components utilized in the mix proportions, the result shows that sodium hydroxide and sodium silicate have a significant impact on human health compared to other components.

Figure 5-9, indicates that the three GPM may cause significantly more toxicity and cancer than the two OPCM. Clearly, the sodium silicate presents in the GPM formulations is the fundamental cause of these outcomes. The risk of toxicity and cancer that GPM can cause increases with the amount of SS used in the mixture. This makes sense given that mix-1, which uses more SS than the other mixes, is more likely to be more toxic and cause cancer.

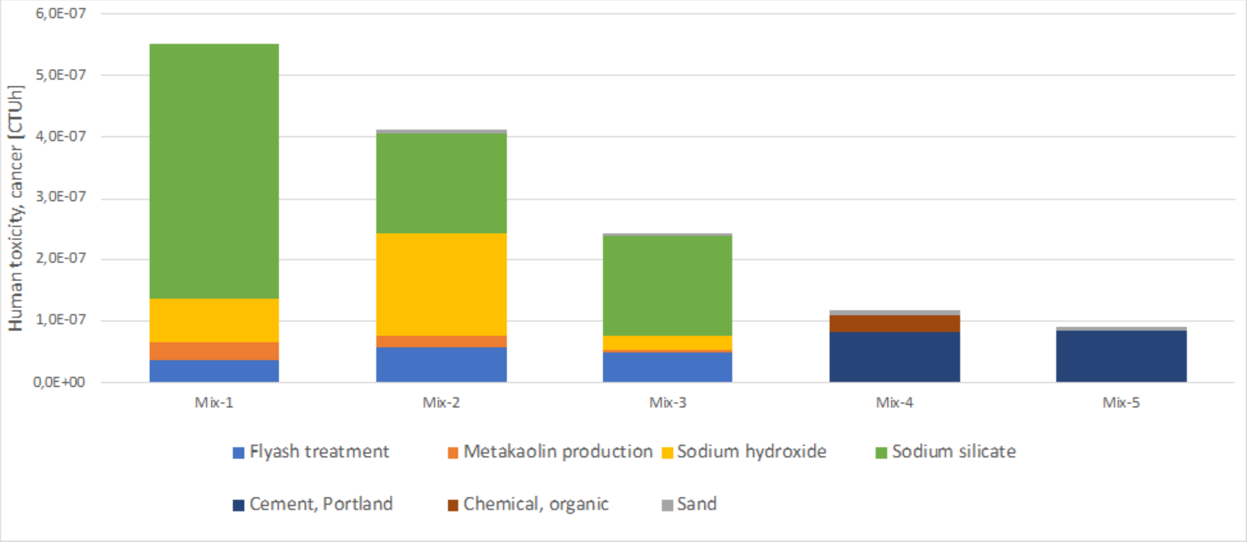


Figure 5-9-Human toxicity, cancer [CTUh]

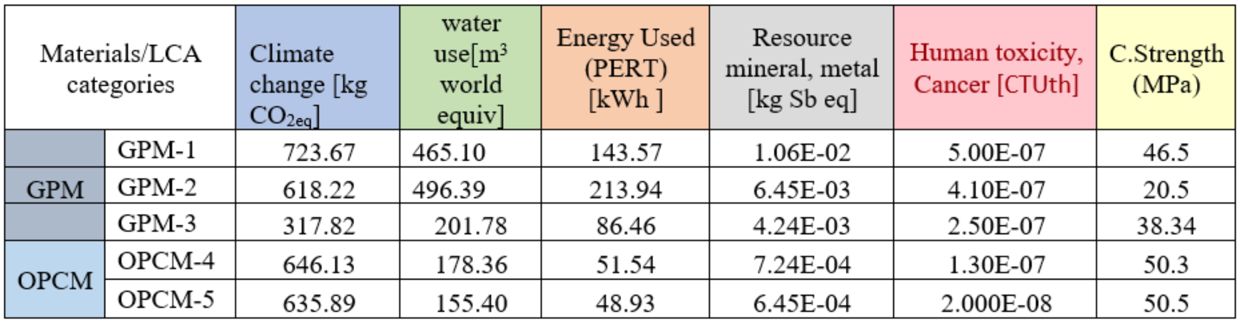
# 6. Discussion

Different variables characteristics was used to select a single sustainable designed mixture materials that delivers the best mechanical and durable qualities, while also having a low environmental impact. To get better and sustainable materials, the compressive strength of the materials should be maximized, while the total environmental impact of different mix designs should be reduced.

Table 6-1 summarizes the compressive strength and the LCA category values, as well as their combined single score, for the five distinct mixture proportions employed in this research.

The LCA analysis demonstrates that GPM uses more energy and water and has a greater environmental impact than OPCM. This is related to the component materials used. The quantity of alkali solution, the amount and types of raw materials, and the methodology used to produce/treat the raw materials all play an important role for the LCA analysis result as well as the materials performances. As a result, more research is needed to improve material strength while reducing GPM overall environmental impact.

Table 6-1- Values of different compressive strength and LCA categories and their combined single scores



| Materials/LCA categories | | Climate change [kg $CO_{2eq}$] | water use[$m^3$ world equiv] | Energy Used (PERT) [kWh ] | Resource mineral, metal [kg Sb eq] | Human toxicity, Cancer [CTUth] | C.Strength (MPa) |
|---|---|---|---|---|---|---|---|
| GPM | GPM-1 | 723.67 | 465.10 | 143.57 | 1.06E-02 | 5.00E-07 | 46.5 |
| | GPM-2 | 618.22 | 496.39 | 213.94 | 6.45E-03 | 4.10E-07 | 20.5 |
| | GPM-3 | 317.82 | 201.78 | 86.46 | 4.24E-03 | 2.50E-07 | 38.34 |
| OPCM | OPCM-4 | 646.13 | 178.36 | 51.54 | 7.24E-04 | 1.30E-07 | 50.3 |
| | OPCM-5 | 635.89 | 155.40 | 48.93 | 6.45E-04 | 2.000E-08 | 50.5 |

When the three GPM materials are compared, Mix-1 has the highest compressive strength but the worst in terms of environmental impact, water use, energy use, and human toxicity. This low performance is explained by the fact that Mix-1 employed a significant amount of MK and sodium silicate, and the treatment and manufacture of these two materials require more energy and water.

In regard to Mix-2 composition, the same proportions of FA and MK were used, along with a higher percentage of sodium hydroxide was employed compared to the sodium silicate one. Compared to Mix-1, this mixture has less negative effects on the environment, lessen the excessive water usage, reduce the energy use, and toxicity. Conversely, this mixture has in other hand lower compressive strength by nearly half, from 46.5 to 20.5 MPa.

As demonstrated in Table 4-1 in section 4, Mix-3 has the lowest MK and FA percentages when compared to Mix-1 and 2. Less quantity of sodium hydroxide was used in the alkali solutions and decreased from 89 and 205.8 to 28.5 from Mix-1 and 2 respectively. By reducing the binders materials and alkali solution, the formulation reduced the toxicity, the negative environmental impact, and excessive use of water and energy. In other side, by altering the constituent materials from Mix-1 and 2, its compressive strength increased from (20.5 to 38.34 MPa) from Mix-2 but dropped from (46.5 to 38.34 MPa) from Mix-1.

In comparison to the five different mixture compositions, the mixture composition without superplasticizer (Mix-5) has a higher compressive strength (50.5 MPa) and the one with superplasticizer has an approximative value of 50.30MPa.

Figure 6-1 reveals that Mix-4 and 5 use less energy and water and have a lower total environmental effect than Mix-1. However, it appears that manufacturing some types of GPM materials requires more water and energy as well as some amount of alkali solution, which may result an overall negative impact on the environment.

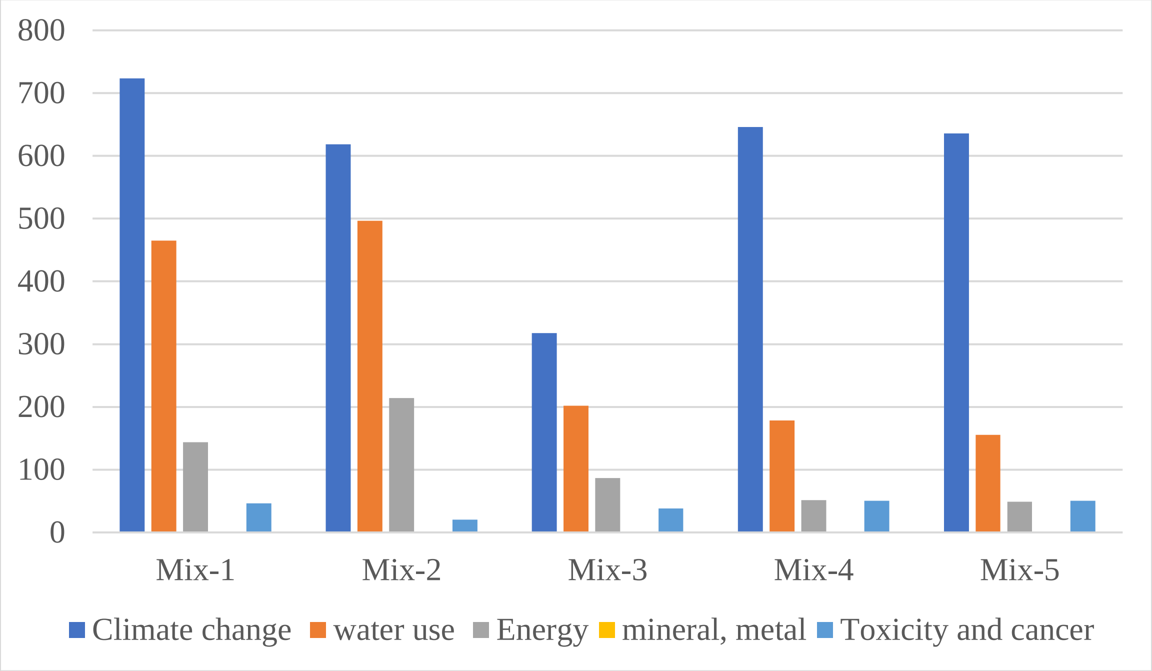


Figure 6-1:Illustration for the LCA categories for the 5 different mixtures

Figure 6-2, illustrates the evaluation of the GPM by changing the composite materials in the mixtures. It is also demonstrated the differences in LCA categories among the five materials examined in this study.

Observing the different lines presented in Figure 6-2 , the resources line drops substantially from Mix-1 to Mix-5. This indicates that there is a significant difference between GPM and OPCM, as well as a minor distinction between OPCM with and without superplasticizer in terms of resource use, mineral, and metal.

Regarding climate change, it was discovered that mix-1 has the highest climate change potential, which reduced from mix-1 to mix-3 but increased from mix-3 to mix-5.

The figure also shows that there is no significant difference between OPCM with and without superplasticizer in terms of water use, human toxicity, and cancer. Depending on the amount of superplasticizer that has been added to the mixture, there may be variations in the amount of water used in the LCA categories analysis results.

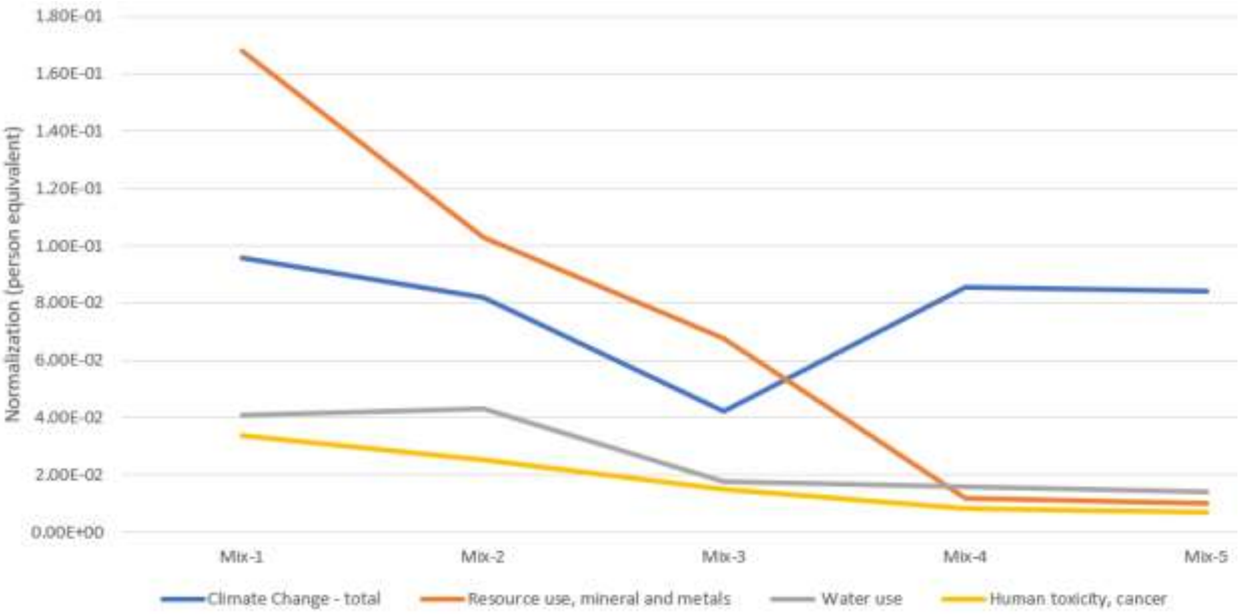


Figure 6-2: Correlation between the LCA categories for the 5 different material

Based on Table 6-1 and Figure 6-1, it can be deduced that, adjusting the quantity of raw materials and the amount of alkali solution, can result more strength and sustainability of GPM. Hence, in order to achieve more sustainable and good GPM characteristics, raw materials and alkali solution should be set in an effective manner (percentage) to produce more sustainable and highly compressive strength materials than OPCM.

# 7. Conclusion

The life cycle assessment of geopolymer materials, which is based on the LCA analysis and the five distinct investigations conducted for this research, comes to the following conclusion:

In terms of climate change, GPM has a considerable environmental impact, with a value of 723.67 kg $CO_{2eq}$ (mix-1), according to LCA data analysis results. This consequence is driven by the large-scale manufacturing of sodium silicate (432.45 kg $CO_{2eq}$), sodium hydroxide (115.20 kg $CO_{2eq}$), and the production/treatment of MK and FA (103.22 and 69.19 kg $CO_{2eq}$, respectively). When compared to the overall emission levels generated through the manufacture of OPCM (646.13 and 635.89 kg $CO_{2eq}$, respectively in mix-4 and 5), GPM (Mix-1) has a greater environmental impact than OPCM.

From the standpoint of water consumption, sodium silicate is the most water-intensive used component material in this study, with a value of 217.96 $m^3$, followed by sodium hydroxide, with a value of 119.79 $m^3$. The production process of these two materials (SS and SH) required the usage of such vast volumes of water. On other side, with a value of 79.8 $m^3$, metakaolin production contribute a significant amount of water used throughout its production process. In comparison, FA, with a water consumption of 6.57 $m^3$, it may be the best binder material in term of water saving compared to the other materials.

Based on the total renewable energy needed for the treatment, production, and mixing process, sodium silicate production consumes a significant amount of energy during the production, with a value of 135.9 kWh. Metakaolin, on the other hand, requires significant energy to be produced compared to the other component materials. The heat demand during the entire production process of MK, from kaolin to metakaolin, is attributed to this substantial consumption of energy. This high energy depends on the moisture content of the MK. The higher the moisture content, the higher the heat demand and the greater the energy needed. To avoid using this excessive amount of energy, moisture content should be naturally eliminated by exposing the materials (MK) to air and sun before entering them into the kiln to remove the remaining moisture.

In terms of the resources (mineral and metal) component, of the various materials utilized in different mixture, sodium silicate used the highest amount of mineral and metals for its production.

It also reveals that metals and minerals are essential materials for many different sustainable energy solutions. Overall results show that, in comparison to OPCM, mixes 1 -3 used more metal and minerals in the production of their constituents. Although minerals and metals are necessary in different areas for material production purposes and can be found easily in the environment, these materials on the other side can be hazardous when they build up inside organisms. On the other hand, heavy metals can deteriorate not only the function of soil but also gradually build up in the human body through the food chain, resulting in health issues.

For the different constituents employed in the five mixes, sodium silicate and sodium hydroxide, have been connected to a variety of health issues, including poisoning and cancer. It is clearly shown that sodium silicate and sodium hydroxide are the most composite materials that can represent a substantial risk to human health, if necessary, safeguards are not taken. This risk could develop during the substance's production and use. More precautions and protection are required to avoid any human infection that can result in toxicity or cancer. Portland cement, on the other hand, has been linked to toxicity and cancer throughout the production process since it is the first material in the study to emit the most $CO_2$ emission.

To summarize the research findings, replacing cement with other binder materials such as MK, FA, and others may increase not only the strength of construction materials but also reduce their environmental impact, thereby protecting the environment. This can happen depending on the material components and the proportions utilized during the material's manufacturing. GPM, on the other hand, has the potential to reduce waste and free up some land space by utilizing certain deposit materials at various land disposal sites. Because some materials, such as SS and SH, can create human health problems during the production process, replacing OPC these materials is an important factor to consider and analyze before the application.

Aside from environmental protection, material selection for GPM manufacture is an important aspect because it improves the characteristics and quality of the construction materials. When the 5 different mixture proportions assessed in this study were compared, it was discovered that OPCM has more compressive strength and less environmental impact than GPM, but GPM may be more sustainable and have a higher strength depending on the mixture constituent materials. The compressive strength of GPM can be increased or decreased not only by altering the alkali solution but also by changing the raw materials used in the mixing composition.

Another crucial consideration is the amount of alkali solution. This is because the GPM's properties vary depending on the amount and type of alkali solution used in the mixed proportion. As a result, the proportions of sodium silicate and sodium hydroxide must be properly maintained, and the ratios of alkali to binders or binders to alkali should be well-placed. Through the analytical results, we have observed that sodium silicate is the material that has play an important factor to change the characteristics or sustainability of GPM. It is the component that uses high energy, requires a high quantity of minerals and metals and has a significant negative environmental for its production, and can cause a possible risk to human health. To achieve a suitable outcome for the of GPM, it will be appropriate to utilize a small amount of sodium silicate in the mix or to substitute this item with another alkali solution.

Further analysis indicates that GPM may contribute to making the construction industry more sustainable, but because of the energy required to produce and treat its composite materials such as fly ash, metakaolin and the alkali activator, it might be more costly in certain developing countries. To be able to compare the OPCM manufacture in different countries worldwide, especially in developing countries, various criteria, including energy utilization, transportation, and the cost of the composite materials, must be carefully evaluated and studied.

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