Geopolymer with ambient temperature curing

Research Report

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Abstract

Concrete made with geopolymer binders instead of conventional Portland cement is called geopolymer concrete. It is an alternative to conventional concrete and has several advantages in terms of material performance and environmental sustainability. In this study, the geopolymer concrete mixtures were prepared with different water-fly ash ratios and cured under ambient conditions and high temperatures in the oven. Slump and compressive tests were carried out to analyse the effects of the water-fly ash ratio and curing conditions. Experiment results show that different water/fly ash ratios influenced the workability, and different curing conditions influenced the strength of the geopolymer concrete. The compressive strength was higher at heat-cured samples in 7 days. Similarly, a higher water-fly ash ratio gave better workability. The compressive strength of up to 45MPa was recorded at heat curing in seven days, and 18MPa was recorded at ambient temperature in 28 days.

1. Introduction

Cement concrete is a popular choice for construction worldwide because of its ease of use, strong mechanical properties, and affordability compared to other materials. In the cement concrete mixture, the cement serves as a binder, and calcium silicate hydrate, created by the cement's and water's chemical interaction, gives the concrete strength. To achieve the desired strength, a large amount of water is required for curing over a long period of time. Cement concrete relies heavily on Portland cement, which is in high demand due to the increasing need for construction. However, cement production releases carbon dioxide into the atmosphere. Typically, an equal amount of carbon dioxide is released into the atmosphere while producing the same amount of Portland cement. (Davidovits, 1994). The production of Portland cement emits around 1.35 billion tons of greenhouse gases each year, accounting for approximately 7% of total greenhouse gas emissions (Hardjito et al., 2004). In addition, cement production requires a substantial amount of natural resources and energy. Therefore, it is crucial to consider alternative materials instead of some or all of the cement in concrete to minimise pollution and energy use.

In the future, the use of geopolymer cement (GPC) found by Prof. J. Davidovits in 1978 can significantly reduce Ordinary Portland Cement (OPC) usage. The primary raw materials for geopolymer concrete are aluminosilicate resources, alkali activators, aggregates, and water. Unlike the chemical reactions in traditional concrete between cement and water, the main concept behind this geopolymer concrete is the polymerisation of the silicate and aluminium bond that develops when aluminosilicate source materials are mixed with alkaline activating solution such as NaOH + Na2SiO3 or KOH + K2SiO3.

The current project is a collaboration between the research group Centre of Expertise Biobased Economy (CoEBBE) and the Beton Lab. In a biobased economy, biomass is used instead of fossil fuels to produce non-edible items such as materials, chemicals, and transportation fuel. The Centre of Expertise Biobased Economy is a collaboration between HZ University of Applied Sciences and Avans University, established by the Ministry of Education in the Netherlands to promote the biobased economy. The goal of CoEBBE is to connect higher education to the region's economic needs. It does this by assisting companies in achieving their bio-based goals while also providing students with the chance to take part in designing the transition towards a bio-based society. In this project, the term "client" refers to CoEBBE. Beton Lap is a company run by a family that supplies building materials and structural products to contractors for both residential and non-residential construction projects.The company aims to meet future sustainability requirements by testing innovative ideas, such as geopolymer concrete. Furthermore, Beton Lab is ambitious to use bio-based materials in its products.

1.1 Background

Geopolymer concrete often has outstanding early-age performance, relatively high strength, low creep, low shrinkage, good acid resistance, excellent fire resistance, and can absorb hazardous ions compared to regular concrete. Among other properties, Compressive strength is a crucial property of geopolymer concrete, which also relies on curing time and curing temperature for geopolymer concrete. The temperature and the heating time are decisive factors for the activation process that improves the strength of geopolymer concrete (Patankar et al., 2015d). However, Geopolymer concrete requires more energy for curing as it is cured in an oven after being cast. The curing temperature ranges from 60 to 90 degrees Celsius for 24 to 72 hours (Aliabdo et al., 2016), significantly impacting the cost of geopolymer concrete. If the curing temperature or curing time can be reduced without affecting the properties of the concrete, the production costs of geopolymer concrete would be reduced immensely.

Moreover, geopolymer has the potential to substantially reduce CO2 emissions in the construction industry while also making use of waste materials like fly ash. Yao et al. (2014) found that fly ash-based geopolymer emits 45% less carbon dioxide than a typical Portland cement concrete mixture. When coal is utilized in thermal power plants to generate energy, it produces fly ash as waste. Unfortunately, despite global fly-ash production reaching around 780 million tons yearly, only a small percentage of 17-20% of fly ash is being utilized, and a vast amount of fly ash is currently treated as waste and dumped into valuable land (Hardjito et al., 2004).

More crucially, because geopolymers are typically made by chemically activating industrial solid waste under favourable circumstances, their production leaves a smaller carbon footprint than cement concrete (Y. Chen et al., 2020b). Therefore, using waste materials in the production of geopolymer concrete aligns with sustainable practices. The selection of source materials used in geopolymer concrete is based on various factors, including their availability, cost, intended application, and the end users' specific needs.

The ability of a material to be easily placed in any formwork is determined by its workability. When the workability of concrete is too high, the materials may separate. On the other hand, if the workability is too low, the concrete may not be able to reach all areas of the formwork, resulting in a weak structure. Also, low workability can make achieving strong bonding with reinforcement difficult. Achieving enough workability with geopolymer concrete is challenging because of the alkali solution's high viscosity and less water. The workability also depends on the fineness of the material used in the mixture. There are few research studies on improving geopolymer concrete's workability and strength properties.

1.2 Problem Statement

Using geopolymer instead of cement helps to cut off CO2 emissions and energy consumption that has been alarming to the environment. Therefore, geopolymer concrete is becoming an alternative to conventional cement concrete. Although geopolymer has made advancements in the construction field, two significant practical challenges still hinder the production of geopolymer concrete. As a result, the usage of geopolymer concrete remains limited.

Firstly, Geopolymer concrete achieves high compressive strength through only heat curing. As a result, it must be cured at a high temperature of 60 to 90 degrees Celsius for 24 to 72 hours after being cast. This curing method consumes more energy and limits the use of geopolymer concrete only for precast elements.

Secondly, adding more water to improve workability without affecting compressive strength is another challenge that needs further research. Pavithra et al. found in 2016 that the use of an alkaline solution in geopolymer concrete can reduce its workability. However, using the same amount of water in normal concrete improves workability because the alkaline solution has a higher viscosity than normal water.

1.3 Objective

This project aims to explore the effects of adding more water to the geopolymer mixture to improve workability without compromising compressive strength and to investigate room temperature curing instead of oven curing so that geopolymer concrete is more sustainable and can be used in in-situ concrete works without relying on heat curing. This objective is achieved through literature review and experimental research. In addition, the mechanical and physical properties of the material produced will be tested and compared with conventional cement concrete properties.

1.4 Research Question

The performance of geopolymer concrete is evaluated from mechanical and physical properties, which include compressive strength, tensile strength, shrinkage, porosity and density, flexural strength, modulus of elasticity, Fire resistance, Permeability, Segregation, Bleeding, and workability. Among these properties, compressive strength is the first important.

By adding the ideal amount of water and avoiding heat curing, this research seeks to boost geopolymer concrete's compressive strength and workability. These objectives were developed to address the main research question that is going to be researched and tested.

Therefore, the main research question is:

"How can varying water consistency and room-temperature curing affect the properties of geopolymer concrete?"

The above question serves as a general overview. To obtain more specific research answers, the following questions are asked:

- ***How does the workability of geopolymer concrete change with different water-fly ash ratios?***
- ***What is the optimum amount of water to increase the workability of geopolymer?***
- ***When does the geopolymer reach enough strength with ambient temperature curing?***

1.5 Boundary Conditions

Technical:

- The mixture must have a minimum of 400 kg/m3 density or higher.
- The strength under compression should be more than 30 MPa.
- The mixture should take at least 45 minutes to initially set and no longer than 6.5 hours to set finally.
- It must be capable of being finished properly, either against the formwork or by means of trowelling or other surface treatment.
- Using the aggregate in the mixture must be below 70% of the total volume.

Functional:

- It must be easily mixed and transported.
- It is desirable for the production cost of the material to be lower than that of conventional concrete.
- It should have good workability.
  - It must be uniform throughout a mix.
  - It must keep its fluidity during the transportation and casting period.
  - It should have flow properties so that it can easily fill the formwork.
  - It must have the ability to be fully compacted without segregating.

2. Theoretical Framework

2.1 Geopolymer

Davidovits used the term "geopolymer" in 1978 to designate a group of mineral binders having an amorphous microstructure and the chemical composition of zeolites (Myasia, n.d.). Contrary to conventional cement, The structural strength of geopolymers is provided by the silica and alumina rather than by the development of calcium-silicate hydrates, which is what is needed for matrix formation and stability. Alkaline liquids and aluminosilicate source materials are the two primary components of geopolymers. The raw materials should be aluminosilicate-based and abundant in Si Al. These could be by-product materials such as fly ash. Geopolymers are also unique compared to other aluminosilicate materials. Geo-polymerisation has a higher solids concentration than aluminosilicate gel or zeolite synthesis (Myasia, n.d.-b).

To Produce geopolymer cement concrete mixes (GPCC), aluminosilicate sources, fine aggregates and coarse aggregates are used with a chemical liquid system: It is a chemical activator solution for geopolymer production (Mishra, 2021). This solution combines alkali silicates, hydroxides, and distilled water. An alkaline activator solution is used to activate Si and Al-containing geopolymeric source materials, like fly ash (Mishra, 2021). As GPCCs are a novel class of materials in contrast to traditional cement concretes, conventional mix design approaches are not generally applicable. Creating the GPCC mixes necessitates extensive and systematic research on the available materials. The materials for GPCCs can be mixed in mixers similar to those used for ordinary cement concretes, such as pan and drum mixers (Parshwanath et al., 2011).

Although GPC hasn't become well known or employed in the construction business as cement concrete, it has been used worldwide to build reinforced box culverts, foundations, bridges, pavements, pipes, and precast structural elements. Other buildings constructed with GPC include the Brisbane Wellcamp Airport, a 20-story residential building, Lipetsk, a 9-story residential building in Ukraine, and a residential building (Oluwafemi et al., 2022).

2.1.1 Fly Ash in Geopolymer Concrete.

Fly ash comes in two forms, one with low calcium levels and the other with high calcium levels (Ma et al., 2022). HCFA is often created by burning lignite and sub-bituminous coals, and it contains at least 50% pozzolanic chemicals and more than 10% CaO. Instead, LCFA is frequently produced by burning bituminous and anthracite coals, comprising at least 70% pozzolanic chemicals and fewer than 10% CaO. Moreover, burning coal produces a significant amount of fly ash, a by-product that poses a substantial environmental danger and must be disposed of or recycled. The prospect of using fly ash geopolymer concrete instead of OPC has recently received much attention (Abdulrahman et al., 2022).

Fly ash with a high concentration of silica and alumina components exhibits pozzolanic capabilities and binding qualities. Because of its small particle size, and spherical and porous characteristics, fly ash offers greater slump levels and good fluidity ratios than other aluminosilicate source materials (Zhang et al., 2020).

The setting time is reduced when the amount of ultrafine fly ash is increased. However, the fly ash-based GPC requires around 16% finer fly ash, which increases the hardening time, and The amount of finer fly ash used rises around 8%, lowering the geopolymer material porosity.

Fly ash geopolymer concrete is further distinguished by superior compressive and tensile strength, outstanding defence against sulfate attacks, high fire resistance, and qualities that make it an excellent repairing agent. The strong pozzolanic reaction and the improved particle morphology, which are evident in the spherical shape of the grains and fine structure, are principally responsible for these favourable characteristics. So, fly ash binders are potential eco-friendly building materials, and it is crucial to develop material qualities for application in structural design (Abdulrahman et al., 2022).

2.1.2 GGBFS-Based GPC

Ground granulated blast-furnace slag (GGBFS) is a waste material when manufacturing iron in blast furnaces. It is composed mainly of silicate and aluminosilicate of melted calcium that must be periodically removed from the furnace. The chemical makeup of GGBFS varies based on the raw materials used to produce iron, much like fly ash. Meanwhile, the cooling process used to solidify the molten materials affects the physical properties of GGBFS (El-Chabib, 2020).

2.1.3 Curing of Geopolymer Concrete

The curing temperature dramatically influences the setting and hardening of the geopolymer concrete. The hardening of fresh geopolymer can take a maximum of 5 days without compromising quality when the ambient temperature is below 15 °C. The GPC specimens only take a day to acquire mechanical strength after being cured at a higher temperature. However, the quality strength of the freshly mixed concrete increased after 28 days instead of the strength rising in just one day. Gaining strength with temperature depends critically on curing time as well. During the curing process, when the temperature increase from 30 °C to 90 °C, the GPC's compressive strength also improves (Hadi et al., 2019).

For greater strength to develop, the curing temperature is advantageous. If the setting time of fly ash-based GPC prevents curing at ambient temperature, the long curing time improves the geopolymerization process. Long-term curing of GPC samples at higher temperatures results in microcavities in the microstructure, which, as a result of water evaporating from the matrix, results in cracks in the sample (Heah et al., 2011). Compared to cement concrete with the same compressive strength, geopolymer concrete has a higher flexural strength. Compressive strength in the natural pozzolanic-based GPC rises with time and temperature. Removing the microcracks from the samples improves the compressive strength of the mixed samples (Chen, 2020).

The properties of geopolymer concrete increase as the curing time increase from 24 h to 72h. However, 48 hours of heat curing is enough to get good strength. Pre-curing before heat curing at a temperature above 95% humidity helps the development of strength. By speeding the reaction rates, the longer curing time is to blame for the early strength growth. The curing time increases the compressive strength from 6 hours to 72 hours. However, the samples' property development is only completed after 24 hours of curing (Elyamany et al., 2018). With increased curing temperature, the geopolymerization reaction intensifies, giving rise to the GPC's initial strength. The GPC samples that were dried in the fog exhibit substantial levels of moisture absorption. It was found that the room temperature-cured samples only achieved around 50% strength after 21 days, while the heat-cured samples achieved 90% in 2 days (Islam et al., 2015). The curing temperature of GPC has a direct impact on its elastic modulus. The matrix water evaporation decreases the elastic modulus of the GPC specimens during temperature curing (Bondar et al., 2011).

2.1.4 Characteristics of Geopolymer Concrete

Water and/or superplasticiser are needed to improve the workability of geopolymer mortar and concrete, as the concentration of sodium silicate and NaOH can decrease flowability and workability. However, using a superplasticiser reduces the strength of the geopolymer mortar (Wongkvanklom et al., 2021). Geopolymer mortar experiences autogenous shrinkage due to chemical shrinkage rather than self-desiccation in fresh condition. Due to the maximum capillary pressure, the Alkali-Activated Fly ash/Slag (AFS) mortar exhibits greater drying shrinkage than the OPC specimens (Lee et al., 2014).

Compared to OPC mortar samples, the Alkali-Activated Fly ash/Slag (AFS) mortar exhibits greater compressive strength, flexural strength, and lower water absorption (Chi, 2017b). Increasing the water-to-binder ratio improves the Alkali-Activated Fly ash/Slag mortar's fluidity and workability. The workability of mortar instantly degrades when the amount of fine aggregate increases in the binder.

The strength of the geopolymer mortar decreases after 800 °C, although it increases as temperature rises. The link between the binder and aggregates determines the compressive strength of geopolymer mortar, and adding more particles to the mortar slows the geopolymerization procedure (Liimatainen et al., 2018). The primary component affecting the mortar's ability to withstand heat is the thickness of the geopolymer paste, and variations in the aggregate as well as the mass ratio of paste to fine aggregate, have an impact on the thickness of the paste.

2.1.5 Mechanical Properties of Geopolymer Concrete

Singh et al. (2015) compared multiple tests on the mechanical properties of geopolymers. Several tests were conducted focusing on compression, flexural and tensile strength. These tests were compared and differed from one another since every sample had a different composition and conditions. The compression strength ranges between 10 and 80 MPa, tensile strength between 2.5 and 5.5 MPa and flexural strength between 2.5 and 12 MPa (Singh et al., 2015). Due to high compressive strength, geopolymer materials can be used in construction, while flexural strength is valuable for situations where there is a need for robustness and the ability to withstand deformation. Tensile strength is the ability to withstand pressure without the material breaking. Usually, the tensile strength is lower than the compressive strength, which may lead to the common occurrence of brittle failure. Researchers are exploring using fibres such as miscanthus to enhance the tensile strength of geopolymer composites (Açıkel, 2011b).

Compressive strength: Without any special curing, compressive strength of 20 to 25 MPa is reached in 7 days with the suitable mix composition of the constituents. It can be possible with a proper mix design (Parshwanath et al., 2011).

Stress-Strain Curves: The connection between stress and strain is influenced by the components of GPCCs and the curing time (Parshwanath et al., 2011).

Strength Development: Compared to cement, This is significantly faster in geopolymer concrete (Parshwanath et al., 2011).

Workability: The fresh GPC has an initial workable time of up to 120 minutes without any strength deterioration. Up to 30 minutes of hand mixing time boosts the fresh GPC's workability. Increased mixing time significantly delays the fresh concrete's ability to set (Verma et al., 2022d).

2.1.6 Reinforced Structural Element of GPCC

GPCC beams: The traditional elastic theory is typically used to evaluate reinforced concrete structures, like assuming a linear moment-curvature relationship. Yet, the non-linear moment-curvature connection is considered in actual beam behaviour. Three straight lines with various slopes can be used to represent the moment-curvature relation in an idealized manner. As an increase in load alters the behaviour of the beam, these lines' slopes vary. Each straight line thus represents a different stage in the history of the beam. Moment-curvature interactions between GPCCs and CCs fundamentally resemble each other (Parshwanath et al., 2011).

The fact that GPCC beams' ductility factor may be slightly lower than that of CC beams suggests that GPCC beams are stiffer overall. The GPCC beams' observed crack patterns resemble those of the CC beams (Parshwanath et al., 2011).

2.2 Alkali Activator

The kind of alkali activators used in geopolymer mixture affects the strength, durability, and resistance to chemical attacks of geopolymer concrete, as well as its formation rate and the geopolymerization process (Mendes et al., 2021). The chemical composition of the source materials influences the choice of activator solution for alkali activation. Sodium and potassium-based activators, such as NaOH and KOH, or a combination of both, as well as sodium or potassium-based silicate solutions and carbonates, are commonly used (Rahim et al., 2014).

Regarding cost and availability, researchers tend to choose hydroxides and silicate solutions based on sodium or potassium (Andrews-Phaedonos, 2014). It has been discovered that mixing sodium hydroxide with sodium silicate solution to create an alkali activator solution result in higher compressive strength than using only sodium hydroxide in fly ash-based geopolymer. It is because the volume of micropores in the resulting composite decreases, creating a more compact and denser matrix (Cho et al., 2017).

Aluminosilicate is dissolved by NaOH, and Na2SiO3 acts as a binder, plasticizer, or dispersion for NaOH. Preliminary laboratory research has demonstrated that NaOH alone cannot increase the compressive strength of geopolymers (Kwek et al., 2021). Research has revealed that several factors, including the activator concentration, activator ratio, and liquid-to-solid ratio, affect how well a geopolymer binder performs. A 2.5 alkaline activator ratio produces good compressive strength in the majority of geopolymer mixtures. The workability, strength, and initial and final setting time of the activated mixture is all impacted by changing the Na2SiO3 component. The proper activator ratio will sustain any geopolymer created from various raw components. The raw materials' characteristics impact the requirement for an activator. To encourage geopolymerization, fly ash to liquid ratio of three is necessary. The ideal NaOH concentration is 12 M, which impacts geopolymer strength. Alkali activation, which depends on the SiO2 and Al2O3 composition, can create high strength among cementitious qualities (Kwek et al., 2021). In order to improve the development of strength, it is recommended to maintain a molar ratio. If the ratio goes beyond this range, it may cause a decrease in strength due to inadequate reactivity of geo-polymerization (Cho et al., 2017b).

2.2.1 Impact of Molar Ratios of Alkaline Solution in Geopolymer.

The addition of sodium silicate significantly enhances the early strength development of the hybrid geopolymer system. After the more liquid silicate in the geo-polymeric mix, there is no interface between the aggregate and geo-polymeric paste. Binders, mortars, and concrete, which are stable geopolymer products, are produced through geo-polymerization. With rising GPC compressive strength, the ratio of Na2SiO3 and NaOH (by mass) increases. When the amount of alkaline solution in the mixture rises, the compressive strength declines while the setting time and workability rise. The addition of fly ash creates an alumino-silicate gel that gives the GPC samples improved workability and mechanical characteristics when hardened. The mix design's requirement for fine aggregate is reduced due to the increased Na2SiO3/NaOH ratio, while the mix design's need for more water is increased (Verma et al., 2022d).

2.3 Water

Water is mixed with the geopolymer to increase the workability of concrete in its initial setting time. However, it does not help to gain the strength of the concrete once it hardens. During the polymerization process, it was noted that water was released from the mixture. When the source material is finer, the water demand increases, even if the workability remains unchanged. The minimum amount of water required is determined based on factors such as workability and size of aggregates (Patankar et al., 2013).

2.4 Aggregates

In concrete preparation, aggregates are mineral materials that fill up to 75-80% of the volume. For geopolymer concrete, a combination of fine and coarse aggregates is blended to reduce the gaps in the concrete. The grading of fine aggregate also affects the workability of geopolymer concrete, just like cement concrete. Thus, the proposed mix proportioning method considers the grading of fine aggregate to determine the ideal fine-to-total aggregate ratio (Patankar et al., 2015b). Geopolymer concrete with smaller aggregates of less than 10 mm can cause spalling and extensive cracking. On the other hand, geopolymer concrete with larger aggregates exceeding 10 mm tends to be more stable in elevated temperatures (Kong & Sanjayan, 2008).

2.5 Geopolymer mixture design

In a study conducted by Pavithra et al. (2016), it is suggested that a specific strength of GPC can be achieved by using the corresponding AAS/FA ratio obtained from the modified American Concrete Institute (ACI) strength versus the w/c ratio curve. With the proposed methodology, fly ash-based GPC can be produced with strengths ranging from 23 to 53 MPa by targeting a specific AAS/FA ratio.

According to Provis (2014b), it is essential to understand that the structure of geopolymers is greatly influenced by the amount of calcium in the precursors. Suppose the system has high calcium levels, like in alkali-activated blast furnace slag. In that case, it will have a dominant calcium aluminosilicate similar to the tobermorite. While binders made with low calcium systems, such as those using metakaolin or fly ash, tend to produce a gel called alkali aluminosilicate (N-A-S-H), which has a complex, unordered structure resembling zeolite. This gel can be present in binders that combine both high-calcium and low-calcium materials.

3. Methodology

3.1 Method of Research

Currently, little research is available regarding the effect of increasing water content and curing at room temperature on the production of GPC. Therefore, this project aimed to analyse how changing water consistency and curing at room temperature affect the workability and compressive strength of fly ash-based GPC.

Two types of research were conducted during this research to achieve the project's objective. Firstly, literature research was carried out to review the related studies to find detailed information about geopolymer concrete. During the literature research, different types of mixture designs with different aluminosilicate sources were analysed, and a fly ash-based geopolymer mixture was chosen to carry out further experiments in this study. The fly-ash-based geopolymer was chosen because fly-ash is easily available everywhere, treated as waste material, and needs proper usage instead of dumping into valuable land.

Secondly, experimental research was done by making different mixtures with varying water-fly ash ratios and curing them under different temperature conditions, such as at room temperature (18°C to 21°C) and in the oven (at 60°C). Finally, the slump test with fresh geopolymer concrete after mixing and the compressive strength test with hardened geopolymer concrete in the 7th and 28th days were carried out. The conclusion was drawn based on the literature review findings and the experimental results.

Experiment involved:

- Mix designs.
- Testing raw material.
- Preparing mixture, making test cubes and conducting property tests.

3.2 Method of Tests

3.2.1 Sieve analysis test

The grain size analysis test aims to determine the percentage of different grain sizes present in a soil and gravel sample. This data is used to construct a grain size distribution curve, which helps classify the soil and predict its behaviour.

The method of sieve analysis is employed to ascertain the grain size distribution of soils with a diameter higher than 0.075 mm. It is typically used for sand and gravel, but it cannot be the only technique for figuring out the distribution of grain sizes in finer soil. This method uses woven wire sieves with square openings. This testing procedure is mainly used to assess the quality of aggregates. The outcomes are utilized to check if the particle size distribution meets the relevant specifications and to gather essential information for managing the production of diverse aggregate products and mixtures that have aggregates (Hossain, 2021). The test is carried out based on NEN-EN 933-2 for gravel and NEN-EN 12620 for sand.

3.2.2 Fresh density test

A test is conducted in the laboratory using a known weight and volume container. Fresh-concrete mortar is added, and the container is vibrated until there is no further compaction, ensuring it is full. The container is then weighed on a high-capacity scale. The density is determined using the following formula based on the results obtained.

$$D = (M_{full} - M_{container}) / V_{containe}$$

3.2.3 Slump test

The slump test is a method used to measure the consistency of concrete, whether in a laboratory or at a site. It indicates the uniformity of concrete in different batches and information on its workability and quality based on the shape of the concrete slumps. The concrete's segregation tendency can also be determined by tapping the rod on the base plate. This test has been in use since 1922 due to its simple apparatus and easy procedure, with the shape of the slump cone providing insight into the concrete's workability.

Concrete slump value refers to the amount of water added to the mix and indicates its workability. The gravity flow of the surface of the concrete cone measures it. The shape of the slump may differ based on the consistency of the mixture (CementConcrete, 2022).

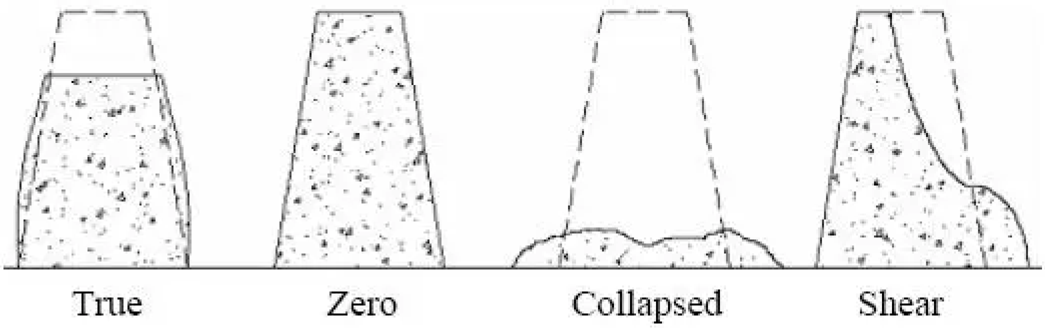

Figure 1:Dfferent types of slumps

3.2.4 Compressive strength test

Compressive strength refers to a material or structure's ability to withstand compression without cracking or breaking. This strength is determined by the material's resistance to cracks and fissures. During this test, force is applied to both faces of the concrete specimen to determine the maximum compression it can withstand without failure. This information is recorded for analysis. In this study, to determine the compressive strength of concrete, a concrete press or pressure bench is used at the Scalda laboratory.

Before conducting any test, it is necessary to weigh every geopolymer concrete cube that is produced. The press requires manual start-up but will stop automatically when the sample breaks or collapses. The machine's screen displays information on both the maximum applied force and the measured strength of the concrete cube. The data is recorded for future comparison of the various samples. This test is done in accordance with NEN-EN 12390-3.

3.2.5 Tensile strength test

Concrete's tensile strength is its capacity to withstand a pulling force without fracturing or collapsing. It measures how much force the concrete can withstand before breaking under tension. The Tensile strength measurement of concrete is based on the amount of force applied per cross-sectional area. The unit used to measure Tensile strength is either Mpa or N/mm2.

The same concrete press at Scalda is used for the tensile strength test. For this test, two wooden sticks are positioned beneath and above the geopolymer concrete cube, with one on each centred side. The machine is manually started and stops automatically when the concrete fails. The relevant load measurements are displayed on the screen.

3.3 Material used in this study.

Any material with a suitable aluminium silicate composition in its amorphous form can be used as a source material for creating a geopolymer binder. Geopolymer concrete is made up of a combination of geopolymer paste and aggregates. Numerous studies have explored various mineral and industrial by-product materials. Materials that have been calcined show stronger properties than materials that have not been calcined (Barbosa et al., 2000). This section discusses the materials used in this study to make geopolymer concrete.

3.3.1 Fly ash

The quantity and fineness of fly ash are decisive factors for the activation process of geopolymers. As mentioned earlier, fly ash's amount and fineness affect geopolymer concrete's strength. Similarly, higher fineness shows higher workability and strength at short heating times.

This study used Class F fly ash as the primary component for the aluminosilicate geopolymer binder, and it had a specific gravity of 2.2, and 95% of it was able to pass through a 45 µm sieve.

Figure 2: Fly ash used in this study.

3.3.2 Aggregates

In this study, locally available natural coarse aggregate sizes of 0 to 16mm and river sand sizes 0 to 5.6mm were used.

Figure 3:Aggregates used in this study.

3.3.3 Alkaline Activator

The most important component in geopolymer mixes is alkaline activators. They ignite the Al and Si in the cementitious binder, causing geo-polymerization and giving the mix its binding properties. In this study, the activator solution was made using a combination of sodium hydroxide (NaOH) and sodium silicate (Na2SiO3). Pure NaOH pellets weighing 40g/mol were mixed with tap water to make the desired sodium hydroxide solution. These two chemicals were obtained from a local commercial producer in Netherlands.

Figure 4: Sodium Hydroxide Pellets.

Figure 5: Alkali Sodium Silicate Liquid.

3.4 Sample Preparation.

The process of making geopolymer concrete samples involves 4 steps. These include mixing two chemicals, mixing dry materials such as gravel, sand and fly ash, mixing the activator and water, and finally, combining all ingredients in a mechanical mixer.

When NaOH and sodium silicate solutions are combined, it creates a reaction that releases heat and generates high temperatures of up to 80 degree Celsius. The literature suggests different approaches to address the issue of temperature increase. One involves pre-mixing the solution and waiting for it to reach ambient temperature before adding it to the mix. The other method recommends adding the solution during the dry mixing process. In the present study, the alkaline solution was first prepared by keeping the mixing container in cold water and changing the water when it became hot.

Then, in the second step, the coarse and fine aggregates were mixed with fly ash in a pan mixer to mix the dry material homogeneously. In the third step, water was added to the alkaline liquid and was mixed well. After preparing the dry mix, the liquid mixture was added and mixed for 4 minutes.

Once the mixing process was completed, the slump cone test was carried out to check the workability of the mixture. Then, the geopolymer concrete mixtures were poured into moulds size 150x150x150 mm to create specimens for compressive tests. Afterwards, the samples were subjected to 2 minutes of vibration on a vibrating table to eliminate any remaining air bubbles. The moulds were kept at room temperature, which ranged between 18 and 21 degrees Celsius. The top surface of the moulds was left uncovered. The samples were de-moulded in 7 days after casting and tested on 7 and 28 days.

The mixing procedure was the same for the samples that were cured in the electric oven. But, for heat curing, the cubes were de-moulded 24 hours after casting and then heated for 24 hours at 60 °C in an oven. After 24 hours of heating was reached, the oven was turned off, and the cubes were cooled down. Then the compression test was carried out on 7th and 28th days from casting.

3.5 Variant of mixture

Compared to conventional concrete, geopolymer concrete has been less researched so far. Consequently, there is neither a set of rules nor conventional procedures for mix design. The only way to create mix design is to search the literature. Based on the literature research, this study used a mix design of Patankar et al. (2015d) as a baseline geopolymer mix. According to Patankar et al. (2015d), the baseline mix is in Table 3, and the actual result of the baseline mix is in Table 4.

Mixtures	Materials (Kg/m3)						Method of curing
	Fly ash	NaOH	Na2SiO3	Water	Sand	Gravel	
Baseline (Mix3)	405.00	70.88	70.88	78.79	683.13	1268.66	Curing at 60°C for 24 hours

Table 1: Baseline mixture Patankar et al. (2015d)

Observation	Results Obtained by Patankar et al. (2015d)
Workability	Medium
Dry density	2601.48 kg/m3
Compressive strength	37.22 Mpa

Table 2: Properties of baseline mixture by Patankar et al. (2015d)

In addition to the baseline mix design, this study experimented with three other mix designs. Since this research mainly focuses on increasing the water consistency and curing at room temperature conditions, only two changes were made with the baseline mix to create three different variants. Those changes are changing the water-fly ash ratio and curing methods.

The client decided on the amount of extra water. According to the client's requirements, the amount of water was increased from 78.79 kg/m3 to 100 kg/m3, which resulted in a change in the water-fly ash ratio from 0.19 to 0.25.

Table 5 shows all four mixture variants.

Mixtures	Materials (Kg/m3)						Method of curing
	Fly ash	NaOH	Na2SiO3	Water	Sand	Gravel	
Mix 1	405.00	70.88	70.88	78.79	683.13	1268.66	Ambient Temperature
Mix 2	405.00	70.88	70.88	100.00	683.13	1268.66	Ambient Temperature
Mix 3	405.00	70.88	70.88	78.79	683.13	1268.66	Curing at 60°C
Mix 4	405.00	70.88	70.88	100.00	683.13	1268.66	Curing at 60°C

Table 3:Geopolymer concrete mix designs variants

3.6 Multi-Criteria Analysis (MCA)

Multi-Criteria Analysis involves comparing various solutions or designs based on specific criteria to determine their effectiveness. Each variant is evaluated based on specific criteria, and scores are assigned accordingly. These scores are then multiplied by the corresponding weight factor for each criterion. The final points of a design option are calculated by summing its scores for all considered aspects. The preferred option or winning variant depends on whether the scoring system favours the alternative with the highest or lowest overall points.

3.6.1 Method of MCA Calculation

The method adopted for this analysis is the Analytical Hierarchy Process (AHP), a structured decision-making technique developed by Saaty (1987b). It is a methodology used to analyse complex problems and make decisions by breaking them down into a hierarchy of criteria and alternatives. AHP provides a framework for systematically comparing and prioritising multiple criteria or factors to make a rational and consistent decision.

The AHP process involves the following steps:

1. Problem structuring: Identify the main objective and break it down into a hierarchical structure of criteria and sub-criteria. The hierarchy typically includes a goal, criteria, sub-criteria, and alternatives.
2. Pairwise comparisons: Compare each criterion and sub-criterion with every other criterion regarding their relative importance or priority. These comparisons are made using a scale of preferences that are shown in Table 6.

Scale	Numerical Rating	Reciprocal
Extremely Preferred	9	1/9
Very strong to extremely	8	1/8
Very strongly preferred	7	1/7
Strongly to very strongly	6	1/6
Strongly preferred	5	1/5
Moderately to strongly	4	1/4
Moderately preferred	3	1/3
Equally to moderately	2	1/2
Equally preferred	1	1

Table 4: Scale of Relative Importance, Saaty (1987b)

3. Derive priorities: Calculate the priorities of the criteria and sub-criteria by analysing the matrix of pairwise comparisons. This is done using mathematical calculations, such as eigenvalue or matrix algebra, to determine the relative weights or priorities of the elements in the hierarchy.
4. Consistency check: Assess the consistency of the pairwise comparisons made in Step 2. The AHP method includes a consistency ratio calculation to ensure that the judgments made by the decision-maker are logical and consistent. Inconsistent judgments may require reassessment or adjustment.
5. Aggregation and synthesis: Combine the priorities obtained from pairwise comparisons to derive the alternatives' overall ranking or priority. This is done by multiplying the priorities in the hierarchy to obtain the overall priority for each alternative.
6. Sensitivity analysis: Assess the sensitivity of the results to changes in the judgments or criteria. AHP allows decision-makers to evaluate the impact of different scenarios and assumptions on the final decision.

The following formula gives the calculation of the consistency index (CI).

$$CI = \frac{\lambda max - n}{n - 1}$$

The fixed value of RI is shown in Table 7.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 5: Random Consistency Indices (RI)

The calculation of the consistency rate (CR).

$$CR = \frac{CI}{RI}$$

3.6.2 Criteria

To conduct a multi-Criteria Analysis, it is necessary to establish the criteria by which the alternatives will be evaluated. These criteria represent the key aspects that are most important to meet the client's requirements for the final product.

Criteria	Definition
Workability	Workability refers to how easy the mixture is to work with and how fluid the mixture is. The workability of the material is determined by performing a slump test. A slump of 2.5 cm-5 cm indicates low workability, while a range of 5 cm-10 cm indicates medium workability. A slump range of 10cm-17.5cm indicates high workability. For the best outcome, it's recommended to use a mixture with moderate workability. If the mixture is too workable, there's a greater chance of material segregation, which occurs when heavier aggregates sink and lighter materials float, resulting in separation.
Density/Self-weight	Traditional concrete has the drawback of being heavy. A lightweight material with good compressive strength would be a suitable alternative to address this issue.
Compressive strength	According to the client's requirements, the final product as a material that can be used instead of cement concrete, should have a minimum compressive strength of 30 MPa. The compressive strength test measures this criterion. From this, it can be determined that the higher the strength, the better the variant is.
Cost	This criterion is crucial to stakeholders as it directly impacts the cost of producing geopolymer concrete. The energy used for curing is directly proportional to the cost, making it a significant factor to consider.
Sustainability	When working with sustainable practices, stakeholders must ensure that the product they develop is also sustainable. The level of sustainability is determined by how natural resources are utilized.

Table 6:MCA Criteria

4. Results

In this study, various combinations of fly ash-based GPC mixes were created to analyse the impact of extra water and curing methods on the properties of geopolymer concrete. The forthcoming sections provide a thorough analysis and discussion of the findings and results of this research.

4.1 Sieve analysis test

The dry sample of sand and gravel, respectively 1000g and 2000g, were used to perform the sieve analysis test. The sample material was dumped into the sieve column and sieved for several minutes to separate the sample. Afterwards, each fraction was carefully weighed and entered the result on the data form.

Identification sample: River Sand				
Used method: Dry sieving				
Mass dry total (M1) = 1000 gram				
Sieve (mm)	Mass residue R1 (g)	Percentage material rest R1/M1*100%	Cumulative percentages sieve residue	Cumulative percentage fall 100%-sieve residue
8	0	0	0	100
5.6	37	3.7	3.7	96.3
4	61	6.1	9.8	90.2
2	185	18.5	28.3	71.7
1	684	68.4	96.7	3.3
0.5	15	1.5	98.2	1.8
0.25	8	0.8	99	1
0.125	4	0.4	99.4	0.6
0	5	0.5	99.9	0.1

Table 7:Seive Analysis form for Sand

Identification sample: Natural Stone				
Used method: Dry sieving				
Mass dry total (M1) = 2000 gram				
Sieve (mm)	Mass residue R1 (g)	Percentage material rest R1/M1*100%	Cumulative percentages sieve residue	Cumulative percentage fall 100%-sieve residue
31.5	0	0	0	100
22.4	0	0	0	100
16	57	2.85	2.85	97.15
11.2	718	35.9	38.75	61.25
8	731	36.55	75.3	24.7
5.6	379	18.95	94.25	5.75
4	95	4.75	99	1
2	8	0.4	99.4	0.6
1	1	0.05	99.45	0.55
0	1	0.05	99.5	0.5

Table 8: Sieve Analysis form for Gravel

The outcome of the sieve analysis confirms that the coarse and fine aggregates used in this study are indeed the sizes: 0 to 16 mm for gravel and 0 to 5.6 mm for sand.

4.2 Density

The density of each mixture was tested before the compressive strength test. Table 11 shows the average density of each mixture.

Mixture	Density (Kg/m3)
Mix 1	2352.30
Mix 2	2304.00
Mix 3	2291.56
Mix 4	2237.93

Table 9:Density of Different Mixture

The samples cured in the oven had a slightly lower density than those cured at room temperature. Moreover, the mixture with a high water-fly ash ratio had a slightly lower density than that of a low water-fly ash ratio.

4.3 Slump Test

After the mixture was prepared, the workability of the fresh geopolymer concrete was measured by a slump test. Table 12 below shows the slump test results, the consistency class and the water-fly ash ratio. The consistency class is determined based on the measured degree of deformation of the geopolymer concrete using the Eurocode table of consistency classes NEN 8005, which is used to measure the slump of cement concrete.

Mixture	Slump(mm)	Consistency Class	Type of Slump	Water/Fly-ash Ratio
Mix 1	0	-	Zero	0.19
Mix 2	90	S2	TRUE	0.25
Mix 3	0	-	Zero	0.19
Mix 4	90	S2	TRUE	0.25

Table 10:Slump, Consistency class and Water-Fly ash ratio.

From the slump test results, it was observed that the workability of the geopolymer concrete increases when the water-fly ash ratio is increased from 0.19 to 0.25. It was also observed that increasing the water content helped to mix all the ingredients homogeneously in a short time compared to a lower water-fly ash ratio.

Figure 6:Slump reading of Mix 2.

4.4 Compressive Strength Test

In this study, two different geopolymer mixtures were prepared, of which three cubes per mixture were cured at room temperature and two cubes per mixture were cured in an oven at 60 degrees Celsius for 24 hours. As a result of using two different curing conditions on two different mixtures, there were four variants of samples to check the compressive strength.

The heat-cured samples were tested on the 7th and 28th days, while the room-temperature-cured samples were tested on the 7th, 14th, 21st and 28th days since the compressive strength test of the room-temperature cured sample on the seventh day gave an unusual result which was considered a failure because the cube collapsed without showing any strength.

Figure 7:Ambient cured geopolymer concrete (Mix1) cubes in 7 days.

Figure 8:failed cube (Mix1) at 7days

Mixture	Compressive Strength (Mpa)	Average Compressive strength (Mpa) in 28 days
Mix 1	19	18.67
	18	
	19	
Mix 2	17	16.67
	18	
	15	
Mix 3	43	45.50
	48	
Mix 4	41	42.50
	44	

Table 11:Summery of Compressive strength

4.4.1 Compressive Strength Comparison Based on Water-fly ash Ratio.

Table 13 shows the compressive strength of concrete specimens made with different water-fly ash ratios. The water-fly ash ratio of mix 1 and 3 was 0.19, and the water-fly ash ratio of mix 2 and 4 was 0.25. When comparing the strength of mix 1 and mix 2, which were cured at ambient temperature, mix 1 had a higher compressive strength than mix 2. Similarly, If compared mix 3 and mix 4, which were cured at 60 degrees Celsius for 24 hours, Mix 3 had a higher strength than Mix 4. This observation shows that the compressive strength decreases as the water-fly ash ratio increases. The same pattern can be observed in cement concrete, where increasing the water-cement ratio decreases the compressive strength.

4.4.2 Compressive Strength Comparison Based on curing method.

As already mentioned, heat curing greatly influences the strength of geopolymer concrete because the high temperature increases the polymerization process and helps achieve high strength. In this experiment, mix 1 and 3, and mix 2 and 4 are the same mixtures but cured in different temperature conditions. Mix 1 and 2 were cured at room temperature, and Mix 2 and 4 were cured at 60 degrees Celsius for 24 hours. If comparing the compressive strength difference between the two curing conditions, heat-cured samples reached a strength of 45.50 Mpa in 7 days, while ambient-cured samples reached only 13 MPa in 14 days and almost no strength at 7 days.

4.5 Result of Multi-Criteria Analysis

Step 1: Hierarchy Creation

Goal: Choosing the best geopolymer mixture

Criteria: Workability, Self-weight, Compressive strength, Cost and sustainability

Variants: MIX 1, Mix 2, Mix 3 and Mix 4

Step 2: Determine the relative importance of criteria.

The pairwise comparison was done to Determine the relative importance of the criteria. The pairwise comparison results are shown in Table 14; the criteria in the table's left column are compared to those in the next column based on which is more crucial to the project. The values shown in Table 6 are then used to determine a score. The sum of each column is then computed and displayed in the table. The values in the pairwise matrix were used to calculate the weight of each criterion, which was then done by dividing the values in each column by the sum of each column. The Normalized Weight column was then calculated using the arithmetic mean of each row. Table 15 shows the normalized weight of the criteria. In this project, the compressive strength was given the highest weight of 49% as it aligns with the project's goal the most. On the other hand, the cost was given the least weight as it was considered less important compared to the other criteria in achieving the final goal.

	Workability	Self-weight	C. strength	Cost	Sustainability
Workability	1	8	1/4	5	3
Self-weight	1/8	1	1/8	1/4	1/8
C. strength	4	8	1	6	5
Cost	1/5	4	1/6	1	1/5
Sustainability	1/3	8	1/5	5	1
Sum	5.66	29.00	1.74	17.25	9.33

Table 12:Pairwise comparison matrix

	Workability	Self-weight	C. strength	Cost	Sustainability	Normalized weight
Workability	0.18	0.28	0.14	0.29	0.32	0.24
Self-weight	0.02	0.03	0.07	0.01	0.01	0.03
C. strength	0.71	0.28	0.57	0.35	0.54	0.49
Cost	0.04	0.14	0.10	0.06	0.02	0.07
Sustainability	0.06	0.28	0.11	0.29	0.11	0.17

Table 13: Pairwise Matrix (Weight of criteria)

Step 3: Consistency calculation of pairwise matrix

The consistency of the values in the table was checked after the weights for each criterion had been determined; this is a feature of the AHP approach that is used to confirm whether the choices made are rational. The format of this step of the procedure is the same as the previous steps completed so far. The weight for the relevant criterion is then multiplied by the values in the pairwise matrix column.

	Workability	Self-weight	C. strength	Cost	Sustainability	Sum i	Normalized weight (w)	Sum i/w
Workability	0.04	0.01	0.07	0.02	0.05	0.20	0.24	0.81
Self-weight	0.01	0.00	0.04	0.00	0.00	0.04	0.03	1.43
C. strength	0.17	0.01	0.28	0.02	0.09	0.57	0.49	1.18
Cost	0.01	0.00	0.05	0.00	0.00	0.07	0.07	0.96
Sustainability	0.01	0.01	0.06	0.02	0.02	0.12	0.17	0.69

Table 14:Consistency check

$$\lambda max = \frac{\Sigma(\frac{Sum\ i}{w})}{n} \qquad \lambda max = \frac{5}{5} = 1$$

$$CI = \frac{\lambda max - n}{n-1} \qquad CI = \frac{1-5}{5-1} = -1$$

$$CR = \frac{CI}{RI}$$

$$CR = \frac{-1}{1.12} = -0.89$$

-0.89 is below 0.01. Therefore, consistency check is okay.

Step 4: Calculating the final score.

The table 17 shows the results of the MCA carried out in this study for the different alternatives and their scores. The weighting of the criteria was determined by pairwise comparisons. From Table 17, the alternative with the highest score was mix 4, which had a score of 1.60. The second highest-scoring alternative was mix 2. The difference between the first and the second was only 0.68.

	Workability	Self-weight	C. strength	Cost	Sustainability	Score
Mix1	0.08	0.01	0.11	0.12	0.28	0.60
Mix2	0.40	0.02	0.11	0.12	0.28	0.92
Mix3	0.08	0.04	0.68	0.02	0.06	0.88
Mix4	0.40	0.06	1.06	0.02	0.06	1.60

Table 15:MCA Results

5. Comparison and Discussion

Tests were conducted on various Geopolymer concrete (GPC) mixtures with various water-fly ash ratios and curing conditions, and the results indicating slump value and compressive strengths were tabulated. From the results, it can be seen that the slump value increased with the increase in water-fly ash ratio. A similar trend can be observed in cement concrete, where the slump increases with the water-cement ratio. And the targeted slump value for the baseline geopolymer mixture was medium. However, the value obtained in this experiment was zero. Thus, the baseline mixture was not workable in this study. This is because apart from the amount of water used in the concrete, the size of the other ingredients used in the mix also affects the workability of the concrete (Shetty, 1987b).

Fresh GPC is usually less workable than regular concrete. Due to the presence of silicates, fresh GPC is inherently viscous and cohesive, resulting in a lower slump value (Fang et al., 2018). In this study, when the water-fly ash ratio increased from 0.19 to 0.25, the workability increased from 0 to 90 mm. That slum condition was enough to achieve compaction by table vibrator without segregation and rough surface or air voids on the surface and corners.

When comparing the compressive strength between the heat-cured samples and the samples cured at room temperature, the heat-cured samples reached a strength of 45.50 Mpa after 7 days, while the samples cured at room temperature showed almost no strength after 7 days.

There was a noticeable colour variation between heat-cured and room-temperature cured samples after 7 days. Moreover, the surface of ambient cured samples was covered with grey dust after 14th day.

5.1 Comparison between cement concrete and geopolymer concrete

When comparing the fresh geopolymer concrete with fresh cement concrete, it was observed that after making a homogeneous mix, the fresh fly ash-based geopolymer concrete was found to be dark colour, and cohesive compared to fresh cement concrete. Although the volume of alkaline solution in geopolymer and water in cement concrete was the same, geopolymer concrete had lower workability than cement concrete. This is because the alkaline activator solution used in geopolymer, which was made by mixing NaOH and Na2SiO3, resulted in high viscosity and cohesion.

When it was fresh concrete, the colour of the newly created geopolymer concrete mixtures was the same as that of fresh cement concrete.

When comparing the strength improvement of cement and geopolymer concrete, cement concrete reaches 16% of its strength after one day and 99% of its strength after 28 days in water curing. In contrast, geopolymer concrete reaches 16% of its strength after 14 days of being cured at ambient temperature. However, if heat-cured, geopolymer concrete reaches 99% of its strength within 7 days.

The strength of traditional concrete depends on the amount of curing. When cement is used to make concrete, the usual way to cure it is to keep the surface moist for about 28 days. However, when it comes to geopolymer concrete, heat curing is necessary to increase its strength instead of using water. This research has found that heating geopolymer concrete to around 60ºC for 24 hours is the best way to quickly achieve good strength in geopolymer concrete. Heat curing can be started after 24 hours of casting.

6. Conclusions and Recommendations

Based on the experimental investigations carried out on different geopolymer concrete mixtures and the literature review, the following conclusions and recommendations can be drawn:

6.1 Conclusion

- This study found that the compressive strength and workability of the baseline mix based on the studies of Patankar et al. (2015d) and the current experiment were different. Comparing the results of Patankar et al. (2015d) and this experiment, in this study, the workability decreased from medium to zero, and the compressive strength increased from 37.22 MPa to 42.50 MPa. This difference could be due to the particle size of the aggregates and fly ash because the aggregate size used in this study was different from the study of Patankar et al. (2015d).
- When increasing the water-fly ash ratio from 0.19 to 0.25%, the workability of fly ash-based geopolymer concrete is significantly improved. However, adding more water leads to a reduction in the properties of the concrete; for example, the compressive strength of mix 2 and 4, which had a high water-fly ash ratio, achieved slightly lower compressive strength than mix 1 and 3, which had low water-fly ash ratio.
- The optimum amount of additional water in the geopolymer mixture is 100 kg/m3.
- This study showed that the compressive strength of geopolymer concrete while cured at room temperature increases with time. Even though it does not gain any strength up to 7 days, after 7 days, it gradually gains strength. On the other hand, this study confirmed that heat curing at 60 degrees Celsius for 24 hours dramatically increases the compressive strength in 7 days.
- It was found out that 99% of strength could be reached in 7 days by curing the geopolymer concrete at 60 degrees Celsius for 24 hours.
- The geopolymer concrete prepared from fly ash and NaOH + Na2SiO3 as an alkaline activator gave a higher compressive strength of 45.5 MPa at 7 days when initially cured at 60 degrees Celsius for 24 hours. However, when the same mixture was cured at an ambient temperature, no strength was reached up to 7 days.
- In addition to having cost advantages over conventional concrete, GPC also allows for the sustainable disposal of waste, which are the main ingredient in geopolymer concrete, using the by-product supports sustainability in the construction industry. Mass production of GPC will also help to reduce carbon emissions into the atmosphere and help to use energy efficiently.
- Achieving significant compressive strength through ambient temperature curing is possible, although it may take longer.

6.2 Recommendations

- Geopolymer concrete is a type of concrete that can rapidly reach high strength when heat cured. This makes it an excellent choice for creating precast structural elements like railway sleepers, paving blocks, sewer pipes, slab panels, partition walls, and solid blocks. Additionally, using geopolymer concrete on a large scale can result in efficient energy use. Therefore, this study recommends using the heat-curing method of geopolymer concrete to produce precast structural elements.
- Geopolymer concrete has good structural and durability capabilities. However, it is not commonly used in structural elements because of the difficulties of the heat curing method and effective mix design procedures. Due to this, it is crucial to research different mix designs for ambient curing. This study recommends using the same mixture experimented in this study for further improvement in future since this mix design can be used as a baseline for ambient cured geopolymer concrete.
- This study recommends that one of the best ways to create different mixtures designs is by adjusting the alkaline ratios, which could be explored as a potential avenue for further investigation.
- Geopolymer concrete with the same mix designs used in this study could also be applicable in constructing roads in high-temperature regions using ambient temperature curing because the high ambient temperature could help achieve strength.
- This study found that the compressive strength of geopolymer concrete without heat curing can be achieved up to 18 MPa. This strength is more than enough for non-load-bearing structures; therefore, this mixture could be used to produce non-load-bearing structures such as partition walls and blocks.
- In this study, compressive strengths were tested only until 28 days. But geopolymer concrete may also increase its strength after 28 days. Therefore, it is highly recommended that the compressive strength should be checked after 50 days or 100 days.
- This study only tested the compressive strength and workability of the geopolymer concrete. However, it is recommended that future research should also include testing for other properties such as tensile strength, fire resistance, and modulus of elasticity.
- Since heat-cured geopolymer concrete can achieve high compressive strength and has high self-weight, it is recommended that reducing the amount of aggregate in the mix and adding natural fibres can make the geopolymer concrete more sustainable and lightweight with reasonable compressive strength.

7. References

Singh, N., & Middendorf, B. (2020). Geopolymers as an alternative to Portland cement: An overview. *Construction and Building Materials*, *237*, 117455. https://doi.org/10.1016/j.conbuildmat.2019.117455

Verma, M., Dev, N., Rahman, I., Nigam, M. R., Ahmed, M., & Mallick, J. (2022). Geopolymer Concrete: A Material for Sustainable Development in Indian Construction Industries. *Crystals*, *12*(4), 514. https://doi.org/10.3390/cryst12040514

Verma, M., Dev, N., Rahman, I., Nigam, M. R., Ahmed, M., & Mallick, J. (2022b). Geopolymer Concrete: A Material for Sustainable Development in Indian Construction Industries. *Crystals*, *12*(4), 514. https://doi.org/10.3390/cryst12040514

Parshwanath, R. N., Nataraja, M. C., & Lakshmanan, N. (2011, November 1). *An introduction to geopolymer concrete*. ResearchGate. https://www.researchgate.net/publication/285666741_An_introduction_to_geopolymer_concrete

Wongkvanklom, A., Posi, P., Kampala, A., Kaewngao, T., & Chindaprasirt, P. (2021). Beneficial utilization of recycled asphaltic concrete aggregate in high calcium fly ash geopolymer concrete. *Case Studies in Construction Materials*, *15*, e00615. https://doi.org/10.1016/j.cscm.2021.e00615

Lee, N., Park, S., & Lee, H. (2014). Shrinkage characteristics of alkali-activated fly ash/slag paste and mortar at early ages. *Cement & Concrete Composites*, *53*, 239–248. https://doi.org/10.1016/j.cemconcomp.2014.07.007

Chi, M. (2017b). Effects of the alkaline solution/binder ratio and curing condition on the mechanical properties of alkali-activated fly ash mortars. *Science and Engineering of Composite Materials*, *24*(5), 773–782. https://doi.org/10.1515/secm-2015-0305

Verma, M., Dev, N., Rahman, I., Nigam, M. R., Ahmed, M., & Mallick, J. (2022d). Geopolymer Concrete: A Material for Sustainable Development in Indian Construction Industries. *Crystals*, *12*(4), 514. https://doi.org/10.3390/cryst12040514

Liimatainen, H., Abdollahnejad, Z., Kinnunen, P., & Illikainen, M. (2018). One-part alkali-activated materials: A review. *Cement and Concrete Research*, *103*, 21–34. https://doi.org/10.1016/j.cemconres.2017.10.001

Zhang, P., Gao, Z., Wang, J., Guo, J., Hu, S., & Wang, K. (2020). Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. *Journal of Cleaner Production*, *270*, 122389. https://doi.org/10.1016/j.jclepro.2020.122389

Deb, P., Nath, P., & Sarker, P. K. (2014). The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at ambient temperature. *Materials in Engineering*, *62*, 32–39. https://doi.org/10.1016/j.matdes.2014.05.001

Ryu, G., Lee, Y. H., Koh, K., & Chung, Y. (2013). The mechanical properties of fly ash-based geopolymer concrete with alkaline activators. *Construction and Building Materials*, *47*, 409–418. https://doi.org/10.1016/j.conbuildmat.2013.05.069

Lee, N. Y., & Lee, H. (2013). Setting and mechanical properties of alkali-activated fly ash/slag concrete manufactured at room temperature. *Construction and Building Materials*, *47*, 1201–1209. https://doi.org/10.1016/j.conbuildmat.2013.05.107

Somna, K., Jaturapitakkul, C., Kajitvichyanukul, P., & Chindaprasirt, P. (2011). NaOH-activated ground fly ash geopolymer cured at ambient temperature. *Fuel*, *90*(6), 2118–2124. https://doi.org/10.1016/j.fuel.2011.01.018

Abdel-Ghani, N. T., Elsayed, H., & AbdelMoied, S. (2018). Geopolymer synthesis by the alkali-activation of blastfurnace steel slag and its fire-resistance. *HBRC Journal*, *14*(2), 159–164. https://doi.org/10.1016/j.hbrcj.2016.06.001

Hosan, M. A., Haque, S., & Shaikh, F. U. A. (2015, December 11). *Comparative study of sodium and potassium based fly ash geopolymer at elevated temperatures*. ResearchGate. https://www.researchgate.net/publication/323475915_Comparative_study_of_sodium_and_potassium_based_fly_ash_geopolymer_at_elevated_temperatures

Hadi, M. N. S., Zhang, H., & Parkinson, S. (2019). Optimum mix design of geopolymer pastes and concretes cured in ambient condition based on compressive strength, setting time and workability. *Journal of Building Engineering*, *23*, 301–313. https://doi.org/10.1016/j.jobe.2019.02.006

Heah, C., Kamarudin, H., Bakri, A. M. A., Binhussain, M., Luqman, M., Nizar, I. K., Ruzaidi, C., & Liew, Y. M. (2011). Effect of Curing Profile on Kaolin-based Geopolymers. *Physics Procedia*, *22*, 305–311. https://doi.org/10.1016/j.phpro.2011.11.048

Chen, T. (2020). Optimum curing temperature and duration of alkali-activated glass inorganic binders. *Journal of the Chinese Institute of Engineers*. https://doi.org/10.1080/02533839.2020.1777206

Elyamany, H. E., Elmoaty, A. E. M. A., & Elshaboury, A. M. (2018). Setting time and 7-day strength of geopolymer mortar with various binders. *Construction and Building Materials*, *187*, 974–983. https://doi.org/10.1016/j.conbuildmat.2018.08.025

Islam, A., Alengaram, U. J., Jumaat, M. Z., Bashar, I. I., & Kabir, S. M. L. (2015). Engineering properties and carbon footprint of ground granulated blast-furnace slag-palm oil fuel ash-based structural geopolymer concrete. *Construction and Building Materials*, *101*, 503–521. https://doi.org/10.1016/j.conbuildmat.2015.10.026

Bondar, D., Lynsdale, C. J., Milestone, N. B., Hassani, N., & Ramezanianpour, A. A. (2011). Engineering Properties of Alkali-Activated Natural Pozzolan Concrete. *American*

Concrete Institute, Journal Of, *108*(1). https://doi.org/10.14359/51664217

Kwek, S. Y., Awang, H., & Cheah, C. B. (2021). Influence of Liquid-to-Solid and Alkaline Activator (Sodium Silicate to Sodium Hydroxide) Ratios on Fresh and Hardened Properties of Alkali-Activated Palm Oil Fuel Ash Geopolymer. *Materials*, *14*(15), 4253. https://doi.org/10.3390/ma14154253

Mignon, A., Snoeck, D., D'halluin, K., Balcaen, L., Vanhaecke, F., Dubruel, P., Van Vlierberghe, S., & De Belie, N. (2016). Alginate biopolymers: Counteracting the impact of superabsorbent polymers on mortar strength. *Construction and Building Materials*, *110*, 169–174. https://doi.org/10.1016/j.conbuildmat.2016.02.033

Chen, Y., Wu, F. F., Yu, Q. Q., & Brouwers, H. J. (2020). Bio-based ultra-lightweight concrete applying miscanthus fibers: Acoustic absorption and thermal insulation. *Cement & Concrete Composites*, *114*, 103829. https://doi.org/10.1016/j.cemconcomp.2020.103829

Shi, J., Liu, Y., Xu, H., Gencel, O., Peng, Y., Yuan, Q., & Gao, J. (2022). The roles of cenosphere in ultra-lightweight foamed geopolymer concrete (UFGC). *Ceramics International*, *48*(9), 12884–12896. https://doi.org/10.1016/j.ceramint.2022.01.161

Hamada, H. M., Shi, J., Jawahery, M. S. A., Majdi, A., Yousif, S. T., & Kaplan, G. (2023). Application of natural fibres in cement concrete: A critical review. *Materials Today Communications*, *35*, 105833. https://doi.org/10.1016/j.mtcomm.2023.105833

Mudoi, M. P., Sinha, S., & Parthasarthy, V. (2022). Optimizing the alkali treatment of cellulosic Himalayan nettle fibre for reinforcement in polymer composites. *Carbohydrate Polymers*, *296*, 119937. https://doi.org/10.1016/j.carbpol.2022.119937

Abdulrahman, H., Muhamad, R., Sheikh, A. H., & Shukri, A. (2022). Mechanical properties and bond stress-slip behaviour of fly ash geopolymer concrete. *Construction and Building Materials*, *327*, 126909. https://doi.org/10.1016/j.conbuildmat.2022.126909

Oluwafemi, J., Adedeji, A., Ofuyatan, O. M., Bankole, D. T., & Justin, L. (2022). Reliability assessment of ground granulated blast furnace slag/ cow bone ash- based geopolymer concrete. *Journal of Building Engineering*, *64*, 105620. https://doi.org/10.1016/j.jobe.2022.105620

Topark-Ngarm, P., Chindaprasirt, P., & Sata, V. (2015). Setting Time, Strength, and Bond of High-Calcium Fly Ash Geopolymer Concrete. *Journal of Materials in Civil Engineering*, *27*(7). https://doi.org/10.1061/(asce)mt.1943-5533.0001157

Parshwanath, R. N., Nataraja, M. C., & Lakshmanan, N. (2011, November 1). *An introduction to geopolymer concrete*. ResearchGate. https://www.researchgate.net/publication/285666741_An_introduction_to_geopolymer_concrete

Singh, B. P., Ishwarya, G., Gupta, M., & Bhattacharyya, S. P. (2015a). Geopolymer concrete: A review of some recent developments. *Construction and Building Materials*, *85*, 78–90. https://doi.org/10.1016/j.conbuildmat.2015.03.036

Açıkel, H. (2011b). The use of miscanthus (Giganteus) as a plant fiber in concrete production. *Scientific Research and Essays*, *6*(13), 2660–2667. https://doi.org/10.5897/sre10.1139

Patankar, S. V., Ghugal, Y. M., & Jamkar, S. S. (2015). Mix Design of Fly Ash Based Geopolymer Concrete. In *Springer eBooks* (pp. 1619–1634). https://doi.org/10.1007/978-81-322-2187-6_123

Hossain, M. S., PhD PE. (2021, January 14). *Sieve Analysis*. Pressbooks. https://uta.pressbooks.pub/soilmechanics/chapter/sieve-analysis/

CementConcrete. (2022). Slump Test of Concrete, slump cone for Workability – Procedure, Apparatus. *Cement Concrete*. https://cementconcrete.org/concrete/concrete-slump-test/2171/

Davidovits, J. (1994). Global Warming Impact on the Cement and Aggregates Industries. *ResearchGate*. https://www.researchgate.net/publication/236503901_Global_Warming_Impact_on_the_Cement_and_Aggregates_Industries

Hardjito, D., Wallah, S. E., Sumajouw, D. M. J., & Rangan, B. V. (2004). On the Development of Fly Ash-Based Geopolymer Concrete. *American Concrete Institute, Journal Of*, *101*(6). https://doi.org/10.14359/13485

Davidovits, J. (1991). Geopolymers. Journal of Thermal Analysis, 37(8), 1633–1656. https://doi.org/10.1007/bf01912193

Patankar, S. V., Jamkar, S. S., & Ghugal, Y. M. (2013). Effect of Fineness of Fly Ash on Flow and Compressive Strength of Geopolymer Concrete. *ResearchGate*. https://www.researchgate.net/publication/275340413_Effect_of_Fineness_of_Fly_Ash_on_Flow_and_Compressive_Strength_of_Geopolymer_Concrete

El-Chabib, H. (2020). Properties of SCC with supplementary cementing materials. In *Elsevier eBooks* (pp. 283–308). https://doi.org/10.1016/b978-0-12-817369-5.00011-8

Mendes, B. C., Pedroti, L. G., Vieira, C. M. F., Marvila, M. T., De Azevedo, A. R. G., De Carvalho, J. R. M., & Ribeiro, J. L. P. (2021). Application of eco-friendly alternative activators in alkali-activated materials: A review. Journal of Building Engineering, 35, 102010. https://doi.org/10.1016/j.jobe.2020.102010

Rahim, R. A., Rahmiati, T., Azizli, K. A., Man, Z., Nuruddin, M. F., & Ismail, L. (2014). Comparison of Using NaOH and KOH Activated Fly Ash-Based Geopolymer on the

Mechanical Properties. *Materials Science Forum*, *803*, 179–184. https://doi.org/10.4028/www.scientific.net/msf.803.179

Andrews-Phaedonos, F. (2014). Specification and use of geopolymer concrete. *Austroads Bridge Conference, 9th, 2014, Sydney, New South Wales, Australia*. https://austroads.com.au/publications/bridges/abc-sas203-14

Cho, Y. M., Yoo, S., Jung, S., Lee, K., & Yang, K. (2017). Effect of Na2O content, SiO2/Na2O molar ratio, and curing conditions on the compressive strength of FA-based geopolymer. *Construction and Building Materials*, *145*, 253–260. https://doi.org/10.1016/j.conbuildmat.2017.04.004

Cho, Y. M., Yoo, S., Jung, S., Lee, K., & Yang, K. (2017b). Effect of Na2O content, SiO2/Na2O molar ratio, and curing conditions on the compressive strength of FA-based geopolymer. *Construction and Building Materials*, *145*, 253–260. https://doi.org/10.1016/j.conbuildmat.2017.04.004

Rony, J. (2022). What is Flax Fiber | Properties and Uses of Flax Fiber. *Fashion2Apparel*. https://fashion2apparel.com/properties-and-uses-of-flax-fiber/

Goudenhooft, C., Bourmaud, A., & Baley, C. (2019). Flax (Linum usitatissimum L.) Fibers for Composite Reinforcement: Exploring the Link Between Plant Growth, Cell Walls Development, and Fiber Properties. *Frontiers in Plant Science, 10*. https://doi.org/10.3389/fpls.2019.00411

Harlow, M., Michel, C., & Nosch, M. (2014). Prehistoric, Ancient Near Eastern and Aegean Textiles and Dress: an interdisciplinary anthology. In *Oxbow Books* (Issue 18, p. 308). https://hal.archives-ouvertes.fr/halshs-01186391v1

Goudenhooft, C., Bourmaud, A., & Baley, C. (2019b). Flax (Linum usitatissimum L.) Fibers for Composite Reinforcement: Exploring the Link Between Plant Growth, Cell Walls

Development, and Fiber Properties. *Frontiers in Plant Science*, *10*. https://doi.org/10.3389/fpls.2019.00411

Patankar, S. V., Ghugal, Y. M., & Jamkar, S. S. (2015b). Mix Design of Fly Ash Based Geopolymer Concrete. In *Springer eBooks* (pp. 1619–1634). https://doi.org/10.1007/978-81-322-2187-6_123

Pavithra, P., Reddy, M. V., Dinakar, P., Rao, B. D., Satpathy, B. K., & Mohanty, A. K. (2016). A mix design procedure for geopolymer concrete with fly ash. *Journal of Cleaner Production*, *133*, 117–125. https://doi.org/10.1016/j.jclepro.2016.05.041

Barbosa, V. C. F., MacKenzie, K. J. D., & Thaumaturgo, C. (2000). Synthesis and characterisation of materials based on inorganic polymers of alumina and silica: sodium polysialate polymers. *International Journal of Inorganic Materials*, *2*(4), 309–317. https://doi.org/10.1016/s1466-6049(00)00041-6

García-Lodeiro, I., Palomo, Á., & Fernández-Jiménez, A. (2007). Alkali–aggregate reaction in activated fly ash systems. *Cement and Concrete Research*, *37*(2), 175–183. https://doi.org/10.1016/j.cemconres.2006.11.002

Aliabdo, A. A., Elmoaty, A. E. M. A., & Salem, H. S. E. (2016). Effect of water addition, plasticizer and alkaline solution constitution on fly ash based geopolymer concrete performance. *Construction and Building Materials*, *121*, 694–703. https://doi.org/10.1016/j.conbuildmat.2016.06.062

Provis, J. L. (2014b). Alkali-activated materials. *Cement and Concrete Research*, *114*, 40–48. https://doi.org/10.1016/j.cemconres.2017.02.009

Patankar, S. V., Ghugal, Y. M., & Jamkar, S. S. (2015c). Mix Design of Fly Ash Based Geopolymer Concrete. In *Springer eBooks* (pp. 1619–1634). https://doi.org/10.1007/978-81-322-2187-6_123

Saaty, R. (1987b). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, *9*(3–5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Patankar, S. V., Ghugal, Y. M., & Jamkar, S. S. (2015d). Mix Design of Fly Ash Based Geopolymer Concrete. In *Springer eBooks* (pp. 1619–1634). https://doi.org/10.1007/978-81-322-2187-6_123

Shetty, M. S. (1987b). *Concrete Technology: Theory and Practice*. http://fipak.areeo.ac.ir/site/catalogue/18349289

Fang, G., Ho, W. K., Tu, W., & Zhang, M. (2018). Workability and mechanical properties of alkali-activated fly ash-slag concrete cured at ambient temperature. *Construction and Building Materials*, *172*, 476–487. https://doi.org/10.1016/j.conbuildmat.2018.04.008

Kong, D., & Sanjayan, J. (2008). Damage behavior of geopolymer composites exposed to elevated temperatures. *Cement & Concrete Composites*, *30*(10), 986–991. https://doi.org/10.1016/j.cemconcomp.2008.08.001

Yao, Y., Li, Y. Y., Liu, X., Sun, H., Jiang, S., & Feng, C. (2014). Performance and energy calculation on a green cementitious material composed of coal refuse. *Clean Technologies and Environmental Policy*, *16*(2), 281–290. https://doi.org/10.1007/s10098-013-0620-8

Myasia. (n.d.). *Strike*. Strike. https://ipmann.wordpress.com/

Mishra, G. (2021). Geopolymer Concrete: Properties, Composition and Applications. *The Constructor*. https://theconstructor.org/concrete/geopolymer-concrete-ecofriendly-construction-material/9430/

Ma, S., Zhang, Z., & Liu, X. (2022). Comprehensive Understanding of Aluminosilicate Phosphate Geopolymers: A Critical Review. *Materials*, *15*(17), 5961. https://doi.org/10.3390/ma15175961

Pore structure in blended cement pastes - PDF Free Download. (n.d.). http://docplayer.net/45753941-Pore-structure-in-blended-cement-pastes.html

Verma, M., Dev, N., Rahman, I., Nigam, M. R., Ahmed, M., & Mallick, J. (2022e). Geopolymer Concrete: A Material for Sustainable Development in Indian Construction Industries. *Crystals*, *12*(4), 514. https://doi.org/10.3390/cryst12040514

Vasant Matsagar (eds.) - Advances in Structural Engineering_ Materials, Volume Three 3(2015, Springer India).pdf. (n.d.). Scribd. https://www.scribd.com/document/408511430/Vasant-Matsagar-eds-Advances-in-Structural-Engineering-Materials-Volume-Three-3-2015-Springer-India-pdf#

8. Appendix

8.1 Pictures of samples

Figure 9: Mixture 1

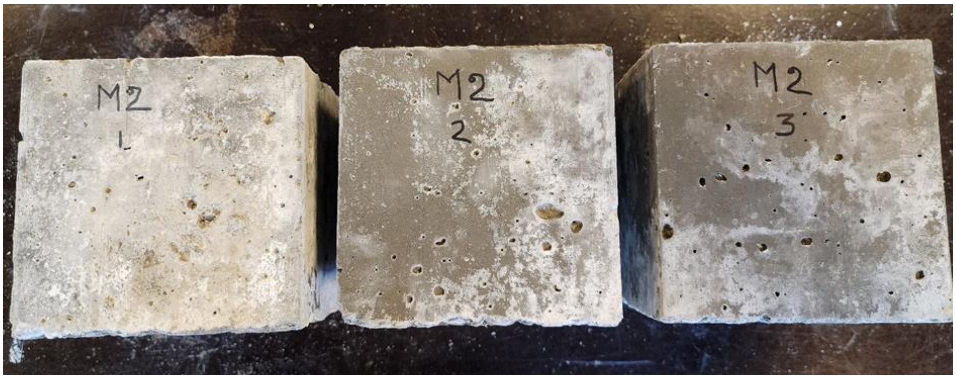

Figure 10:Mixture 2

Figure 11:Mixture 3

Figure 12: Mixture 4

8.2 Pairwise Matrix

Workability	Mix1	Mix2	Mix3	Mix4
Mix1	1	1/5	1	1/5
Mix2	5	1	5	1
Mix3	1	1/5	1	1/5
Mix4	5	1	5	1
Sum	12.00	2.40	12.00	2.40

Self-weight	Mix1	Mix2	Mix3	Mix4
Mix1	1	1/3	1/2	1/4
Mix2	1/5	1	1/3	1/2
Mix3	2	3	1	1/2
Mix4	4	2	2	1
Sum	7.20	6.33	3.83	2.25

C. strength	Mix1	Mix2	Mix3	Mix4
Mix1	1	1	1/8	1/7
Mix2	1	1	1/9	1/8
Mix3	8	9	1	1/3
Mix4	7	8	3	1
Sum	17.00	19.00	4.24	1.60

Cost	Mix1	Mix2	Mix3	Mix4
Mix1	1	1	5	5
Mix2	1	1	5	5
Mix3	1/5	1/5	1	1
Mix4	1/5	1/5	1	1
Sum	2.40	2.40	12.00	12.00

Sustainability	Mix1	Mix2	Mix3	Mix4
Mix1	1	1	5	5
Mix2	1	1	5	5
Mix3	1/5	1/5	1	1
Mix4	1/5	1/5	1	1
Sum	2.40	2.40	12.00	12.00

8.3 Normalized Weight

Workability	Mix1	Mix2	Mix3	Mix4	Weight
Mix1	0.08	0.08	0.08	0.08	0.33
Mix2	0.42	0.42	0.42	0.42	1.67
Mix3	0.08	0.08	0.08	0.08	0.33
Mix4	0.42	0.42	0.42	0.42	1.67

Self-weight	Mix1	Mix2	Mix3	Mix4	Weight
Mix1	0.14	0.05	0.13	0.11	0.43
Mix2	0.03	0.16	0.09	0.22	0.49
Mix3	0.28	0.47	0.26	0.22	1.23
Mix4	0.56	0.32	0.52	0.44	1.84

C. strength	Mix1	Mix2	Mix3	Mix4	Weight
Mix1	0.06	0.05	0.03	0.09	0.23
Mix2	0.06	0.05	0.03	0.08	0.22
Mix3	0.47	0.47	0.24	0.21	1.39
Mix4	0.41	0.42	0.71	0.62	2.17

Cost	Mix1	Mix2	Mix3	Mix4	Weight
Mix1	0.42	0.42	0.42	0.42	1.67
Mix2	0.42	0.42	0.42	0.42	1.67
Mix3	0.08	0.08	0.08	0.08	0.33
Mix4	0.08	0.08	0.08	0.08	0.33

Sustainability	Mix1	Mix2	Mix3	Mix4	Weight
Mix1	0.42	0.42	0.42	0.42	1.67
Mix2	0.42	0.42	0.42	0.42	1.67
Mix3	0.08	0.08	0.08	0.08	0.33
Mix4	0.08	0.08	0.08	0.08	0.33