# Performance Comparison of Fly Ash Based Geopolymer Concrete with Ordinary Portland Cement Concrete

**Darshan Jeevi Ghimire[1], Samrat Poudel[2], Nirmal Prasad Baral[3]**

[1]Research Student, Department of Civil Engineering, IOE, PashchimanchalCampus, Tribhuvan University, Nepal

[2]Assistant Professor, Department of Civil Engineering, IOE, Pashchimanchal Campus, Tribhuvan University, Nepal

[3]Assistant Professor, Department of Civil Engineering, IOE, Pashchimanchal Campus, Tribhuvan University, Nepal

Corresponding Author Email: darshanjeevighimire@gmail.com

**Abstract**— This research aims to compare the compressive strength of fly ash based geopolymer concrete (GPC) with ordinary Portland cement (OPC) concrete and to evaluate the potential of GPC as a sustainable alternative to OPC concrete. The study was conducted in two phases. In the first phase, GPC was prepared using low calcium (Class F) fly ash activated by a mixture of sodium hydroxide (14M) and sodium silicate, with a ratio of sodium silicate to sodium hydroxide of 2.5. The concrete cubes were cast and cured under oven conditions at 60°C. Simultaneously, OPC concrete cubes were prepared to serve as a benchmark. The compressive strength of the GPC was measured at 7 and 28 days, yielding values of 6.4 MPa and 11.9 MPa, respectively. These results indicated that the GPC did not achieve the targeted strength, showing lower early and final compressive strengths compared to OPC concrete whose 7 days and 28 days compressive strength were 12.67 MPa and 20.68 MPa respectively.

To address these issues, a revised mix design was implemented in the second phase of the study. The new GPC mix incorporated 70% fly ash, 10% silica fume, and 20% OPC, with all other materials and methods remaining consistent. This revised mixture was cured under normal room temperature conditions. The compressive strength tests revealed significant improvements, with the 7-day and 28-day strengths recorded at 15.39 MPa and 25.81 MPa, respectively. The enhanced strength is attributed to the inclusion of silica fume and OPC, which facilitated the geo-polymerization process by promoting the dissolution of silicon and aluminum atoms from the fly ash, creating a more alkaline environment, and forming a combination of different gel networks, including N-A-S-H, C-A-S-H, and C-S-H. This also eliminated the need for elevated temperature curing for fly ash based geopolymers.

The findings demonstrate that the modified GPC mix not only meets but exceeds the performance of traditional OPC concrete, highlighting its potential as a viable, eco-friendly alternative with a lower carbon footprint. This research underscores the importance of continued exploration in this field to further enhance the properties and applications of geopolymer concrete, contributing to the reduction of CO2 emissions and promoting sustainable construction practices.

**Keywords**: Compressive strength, Geo-polymerization, Geopolymer Concrete, OPC, Silica Fume

## I. INTRODUCTION

Concrete, a fundamental building material, has long been pivotal in construction due to its versatility, durability, and strength. However, the conventional method of concrete production, predominantly reliant on Portland cement, poses significant environmental challenges. The manufacturing process of Portland cement entails high energy consumption and releases substantial carbon dioxide (CO2) emissions, making it a notable contributor to global greenhouse gas emissions (Scrivener et al., 2018). This issue has prompted a quest for sustainable alternatives with lower carbon footprints.

The environmental impact of conventional concrete production is substantial. Approximately 8% of global CO2 emissions stem from cement production alone, owing to the energy-intensive processes involved, particularly the calcination of limestone and it is estimated that the production of one ton of cement emits approximately 0.8 to 1.0 ton of CO2(Scrivener et al., 2018). Moreover, the extraction of raw materials and transportation add to its ecological footprint.

The rapid growth of the world population and the escalating pace of global urbanization have significantly intensified the demand for construction materials. Particularly the conventional concrete is used extensively in infrastructure projects. The surge in demand is expected to escalate further in coming years. The primary component of conventional concrete is ordinary Portland cement (OPC). The yearly production of OPC is estimated to reach 5bn tons by 2030 (Statista, 2020).

It's undeniable that global warming, fueled by greenhouse gases from human activities, poses a significant threat to our planet. Carbon dioxide (CO2) standing out as the primary contributor. The cement industry ranks as the third-largest emitter of CO2 worldwide. When we delve into the chemistry behind it, the production of Ordinary Portland Cement (OPC) reveals a clear contribution to global warming.

$5CaCO_3 + 2SiO_2 \Rightarrow (3CaO.SiO_2)(2CaO.SiO_2) + 5CO_2$

For every 1 ton of produced cement, 0.55 tons of chemical $CO_2$ are emitted an additional 0.4 tons of $CO_2$ are required for the combustion of carbon fuel (Benhelal et al., 2013).

Recognizing these challenges, researchers and industry players have sought alternative formulations that mitigate environmental harm while maintaining performance standards.

Geopolymer concrete has emerged as a promising solution to these challenges. It leverages industrial by-products, such as fly ash, Ground Granulated Blast Furnace Slag (GGBFS), Rice Husk Ash (RHA), silica fume, metakaolin etc., which are rich in alumina and silica. These materials, when activated by alkaline solutions, form a geopolymer binder, eliminating the need for Portland cement (Davidovits, 1994). Consequently, geopolymer concrete offers a pathway to reduce waste while concurrently curbing CO2 emissions associated with cement production.

The impetus behind this research is multifaceted. Firstly, there is a pressing need to address the environmental impact of conventional concrete. With climate change looming large, the construction industry must transition towards more sustainable practices. Geopolymer concrete presents an opportunity to significantly reduce the carbon footprint of construction activities by utilizing industrial by-products that would otherwise be discarded.

Moreover, while geopolymer concrete shows promise, comprehensive performance evaluations are essential for its widespread adoption. Previous studies have highlightedits mechanical properties and environmental benefits (Davidovits, 2008). However, there remains a gap in understanding its performance across various conditions and applications, as well as its feasibility for large-scale implementation.

## I.I. PROBLEM STATEMENT AND OBJECTIVE OF THE STUDY

The cement industry plays a pivotal role in global construction, providing the essential binding material for infrastructure development. However, traditional methods of cement production pose significant environmental and sustainability challenges worldwide. The high energy consumption, carbon dioxide (CO2) emissions, and resource depletion associated with conventional manufacturing processes raise concerns about their long-term viability and environmental impact.

One of the key issues facing the cement industry is the environmental impact of cement production. The energy-intensive nature of cement manufacturing, coupled with reliance on fossil fuels and raw material extraction, contributes to air pollution, greenhouse gas emissions, and ecosystem degradation. Additionally, the disposal of cement kiln dust and other by-products presents waste management challenges, further exacerbating environmental concerns.

Another significant problem is the carbon footprint associated with cement production. With many cement plants still reliant on fossil fuels, including coal and diesel, the carbon intensity of cement production remains high. This not only contributes to local air pollution but also exacerbates global climate change, impacting both the environment and public health.

Furthermore, the sustainability of cement production is contingent on the availability and responsible management of raw materials. The extraction of limestone and other natural resources for cement production can lead to habitat destruction, deforestation, and loss of biodiversity. As the demand for cement continues to rise globally, ensuring the sustainable utilization of raw materials becomes paramount to safeguarding natural ecosystems and long-term development prospects.

In light of these challenges, there is an urgent need to explore alternative approaches to cement production that prioritize environmental sustainability, resource efficiency, and climate resilience on a global scale.

The main objective of this research work is to develop an environment friendly and sustainable concrete with low carbon footprint as an alternative of ordinary concrete. This research concludes the following objectives:

- To develop a mix design for the fly ash based geopolymer concrete.

- To compare the compressive strength of geopolymer concrete with ordinary Portland cement concrete.

- To find the suitability of use of geopolymer concrete as an alternative of ordinary concrete.

### I.II. SCOPE OF THE STUDY

The scope of the thesis work is listed as follows:

- Low calcium (American Society for Testing and Materials (ASTM) Class F) fly ash was used as base material and it was collected from only one source.

- Only compressive strength of the geopolymer concrete are tested and studied.

### I.III. LIMITATIONS OF THE STUDY

The limitations of this thesis work are listed below:

- To confirm the type of fly ash the Rapid EDTA (Ethylenediamine tetra-acetic acid) test was carried out as there was no XRF machine.

- There was no facility of steam curing in the laboratory so specimens were directly heated in oven at a constant temperature.

- All the materials used in this thesis research were collected from only one source, the effect of variations of type of materials (source) on compressive strength of geopolymer concrete were not studied.

## II. LITERATURE REVIEW

In the 1970s, Davidovits laid the groundwork for geopolymer chemistry through his pioneering research centered on kaolinite. This pivotal work paved the way for the establishment of geopolymer chemistry. To develop nonflammable and noncombustible polymeric materials with stone-like properties, principles of geochemistry were used to create mineral polymers, now commonly known as geopolymers. The first mineral fire-resistant resin comprising metakaolin and soluble alkali silicate, was patented in 1975. Subsequently, in 1984, Davidovits and Sawyer developed and patented the first geopolymer cement in US named as "Early High-Strength Mineral Polymer". Since then, geopolymer building materials have made significant strides in advancing sustainable infrastructure (Zoi G & Ralli,2020).

Geopolymer concrete has seen extensive use in both precast production and on-site applications. Beyond structural uses, geo-polymer mortars have been employed for repair purposes, such as the 2019 restoration of a sewer lining in Ohio (Royer, 2019). Numerous global projects have utilized structural geopolymer concrete, with Australia leading the way. The Global Change Institute, constructed entirely from geopolymer concrete in 2013, was the first public building of its kind (Bligh and Glasby, 2013). This was followed by the West Wellcamp Airport in Brisbane in 2014 (Glasby et al., 2015), and more recently, in 2019, Sydney initiated the first public road construction trials using entirely geopolymer concrete (City of Sydney, 2019).

In addition to Australia, other significant projects include a pedestrian bridge in Skolkovo, Russia, and the foundations of a Gazprom Neft storage facility, both built entirely from geopolymer concrete (RENCA, 2018). The next frontier for this innovative material is additive manufacturing. In 2018, the first geopolymer 3D printed house was constructed in Siberia (RENCA, 2018).

Geopolymer is an amorphous alumino-silicate cementitious material synthesized through the polycondensation reaction of geo-polymeric precursor and alkali poly-silicates. The geo-polymerization mechanism is generally described in three stages: (1) dissolution of silicon (Si) and aluminum (Al) atoms from the source material by hydroxide ions, (2) transportation, orientation or condensation of the precursor ions into monomers and (3) setting or polycondensation/polymerization of these monomers into polymeric structures. Each material used in geopolymer plays a specific role in the chemical reactions and mechanisms involved (Abdullah et al., 2011).

The alkali activation of alumino-silicate materials is a complex process. Initially, the reaction in a strong alkaline environment leads to the breakdown of Si-O-Si bonds. Subsequently, new phases emerge, and their formation mechanism appears to involve synthesis via a solution. A key aspect of this reaction is the incorporation of aluminum (Al) atoms into the original Si-O-Si structure. This process primarily results in the formation of alumino-silicate gels, or geopolymer precursors. Depending on the starting materials and reaction conditions, Calcium Silicate Hydrate(C-S-H) and Calcium Aluminate Hydrate (C-A-H) phases may also form. Additionally, secondary H2O can be produced during these polycondensation reactions. The products can range from amorphous (gel-like) to partially amorphous or crystalline substances, depending on the nature of the raw materials and the reaction conditions (F. Skvara, 2007).

The most common alkaline activator used in geo-polymerization is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate (D. Hardjito, 2005).

The type and concentration of the alkali solution significantly influence the dissolution of fly ash. Generally, the leaching of Al3+ and Si4+ ions is more pronounced with sodium hydroxide solution than with potassium hydroxide solution. Consequently, the concentration of the alkali solution is a critical factor in controlling the leaching of alumina and silica from fly ash particles, the subsequent geo-polymerization process, and the mechanical properties of the hardened geopolymer (Rattnasak and Chindaprasirt, 2009).

In a study by Duchesne et al., (2010) it was found that the presence of NaOH in the activating solution accelerates the reaction and results in a less smooth gel. Analysis of the gel composition in samples activated with a mixture of sodium silicate and NaOH showed an enrichment in sodium (Na) and aluminum (Al).

In a study conducted by Xu and Van Deventer (2000) found that incorporating sodium silicate solution into sodium hydroxide solution as the alkaline activator improved the reaction between the source material and the solution. And between Sodium

Hydroxide (NaOH) and Potassium Hydroxide (KOH), in geo-polymerization NaOH gives higher extent of dissolution of Alumino-Silicate minerals which helps in better initialization as well as faster gel formation.

The polymerization process is characterized by a rapid chemical reaction under alkaline conditions involving Si-Al minerals. This reaction forms a three-dimensional polymeric network and ring structures composed of Si-O-Al-O bonds as follows:

Mn [-($SiO_2$) z – $AlO_2$] n. w$H_2O$

Where, M = the alkaline element or cation such as potassium, sodium or calcium

n = the degree of polycondensation or polymerization, z = 1, 2, 3 or higher.

n ($Si_2O_5$, $Al_2O_2$) + 2n$SiO_2$ + 4n$H_2O$ + NaOH or KOH

(Si-Al materials) ↓

$Na^+$, $K^+$+n$(OH)_3$-Si-O-$Al^-$-O-Si-$(OH)_3$

| ↓

$(OH)_2$

(Geopolymer precursor)

n$(OH)_3$-Si-O-$Al^-$-O-Si-$(OH)_3$ + NaOH or KOH

|

↓

$(OH)_2$

| | |

($Na^+$, $K^+$) - (-Si-O-$Al^-$-O-Si-O-) + 4n$H_2O$

| | |

O O O

| | |

(Geopolymer Backbone)

As the schematic formation of geopolymer material is shown above, the chemical reaction comprises the following steps:

- Dissolution of Al and Si atoms of the source material by the action of hydroxide ions.

- Transportation or orientation or condensation of precursor ions into monomers.

- Setting or polycondensation/polymerization of monomers into polymeric structures.

These three steps can overlap with each other and occur almost simultaneously, so making it hard to isolate and inspect each of these steps separately (Chanh et al., 2008).

Muhammad et al, (2019) conducted a study to investigate how the concentrations of alkali solution (8M, 10M, 12M), heat curing temperature, and heat curing duration affect the strength of fly ash based geopolymer concrete. In ambient curing condition the specimens were left in room temperature of 26°C until the day of testing. In heat curing condition, the specimens were cured at 60°C, 70°C, 80°C and 100°C temperature for 24-hour duration and after that the specimens were kept in room temperature until the day of testing. In both curing conditions, the geopolymer concrete with a 12M concentration demonstrated higher compressive strength. The optimum curing temperature was found to be 80°C.

Adam and Horianto, (2014) stated that the optimum curing temperature and duration of curing plays important role in geopolymerization to achieve higher compressive strength of fly ash based geopolymer concrete. In their experiment fly ash based geopolymer mortars were prepared under different curing temperature of 80°C, 100°C and 120°C for the curing duration of 4, 6 and 20 hours. The specimens cured at 120°C for 20 hours showed the higher compressive strength. The experiment also reported that the geopolymer mortar cured at elevated temperature exhibited higher strength as compared to OPC mortar and air cured geopolymer mortar however in heat cured geopolymer mortar there was no further increase in strength after 14days. The air cured geopolymer mortar has lowest early strength but continue to increase at constant rate.

Herwani et al., (2018) presented an experimental investigation studying the effects of alkaline activator solution molarity on compressive strength of fly ash based geopolymer concrete. Concentration of sodium hydroxide solution used were of 10M, 12M and 14M with ambient curing condition, The test results showed that higher concentrations of sodium hydroxide (NaOH) solution result in an enhancement of the compressive strength of geopolymer concrete. And at 14M of NaOH concentration the compressive strength achieved was optimum.

The study by Reddy et al., (2021) examined the impact of $SiO_2/Na_2O$ ratio in Sodium silicate ($Na_2SiO_3$) solution, the $Na_2SiO_3/NaOH$ ratio, and the molarity of NaOH on the compressive strength of fly ash based geopolymer concrete. Geopolymer mixes were designed with various compositions, maintaining a constant fly ash content and an alkali activator solution (AAS)/fly ash (FA) ratio of 0.5. The $SiO_2/Na_2O$ molar ratio in the $Na_2SiO_3$ solution was adjusted from 1.5 to 3.00, considering different ratios of $Na_2SiO_3/NaOH$ (2.0, 2.5 and 3.0), and varying molarities of NaOH (8M, 10M, 12M, 14M, 16M and 18M). The test specimens were cured using oven heating at 60°C for 24 hours. The results indicated that using 16M NaOH resulted in higher compressive strength, particularly when the $SiO_2/Na_2O$ ratio in the $Na_2SiO_3$ solution ranged from 2.00 to 2.40 and the $Na_2SiO_3/NaOH$ ratio was 2.5.

In an experiment conducted by Tabassum and Khadwal (2015), different geopolymer concrete mixes were designed for M30 grade of concrete using fly ash as a source material, Sodium hydroxide and Sodium silicate as alkaline solution. The different concentrations (8M, 12M and 16M) of NaOH were used while the alkaline liquid to fly ash ratio is kept 0.4 and NaOH to $Na_2SiO_3$ ratio kept as 2.5. Heat curing is carried out for all specimens in an oven at 65°C. The result found out that with increase in concentration of NaOH the compressive strength increases. Maximum compressive strength of 40.21 $N/mm^2$ was observed in 16M concentration of NaOH at 28 days.

Sharma and Ahmad (2017) examined the impact of various factors on the compressive strength of geopolymer concrete made from fly ash. The factors studied include the ratio of alkaline liquid to fly ash, the concentration of sodium hydroxide (NaOH), curing duration, and curing temperature. Fly ash serves as the primary material for developing the geopolymer concrete, which is activated using a mixture of sodium silicate and sodium hydroxide. The experimental variables consisted of different molarities of sodium hydroxide (12M, 14M, 16M and 18M), a fixed ratio of NaOH to $Na_2SiO_3$ at 2.5 and various ratios of alkaline liquid to fly ash (0.35, 0.40, 0.45 and 0.50). The geopolymer concrete cubes were cured at temperature of 75°C, 90°C and 105°C for durations of 12, 18 and 24 hours using hot oven curing method. The result reported that the compressive strength of fly ash based geopolymer concrete increases with the increase in alkaline solution to fly ash ratio up to

0.45. However, at the ratio of 0.50, there is a slight decline in strength due to increase in water content in the alkaline solution. Also, with the increase in concentration of NaOH up to 16M the compressive strength increased, but for 18M there is no significant changes in compressive strength but the cost of production increases. At a temperature of 75°C, the compressive strength exhibits a gradual increase as the curing period extends up to 24 hours. At a temperature of 90°C, the samples achieved 95% of their strength after 18 hours of curing. Beyond this curing period, only minor increments in strength were observed. The compressive strength of Geopolymer Concrete (GPC) samples increased significantly up to a 12-hour curing period at a temperature of 105°C. However, it declines when cured for 24 hours at the same temperature.

Hardjito et al., (2004) suggested curing for longer time improves the polymerization process resulting in higher compressive strength. By using (up to 2% by the weight of fly ash) Naphthalene-based superplasticizer, the workability of the fresh concrete can be improved without resulting in any segregation and degradation in the compressive strength. Increasing curing temperature increased the compressive strength of geopolymer concrete specially up to 75°C.

Ghafoor et al., (2020) examined the impact of alkaline activators on the mechanical properties of GPC cured under ambient conditions. Different geopolymer concrete (GPC) mixes were prepared using locally available fly ash (Class F), incorporating various concentrations of sodium hydroxide (NaOH) 8M, 10M, 12M, 14M and 16M, sodium silicate to sodium silicate ($Na_2SiO_3$) to sodium hydroxide ratios ranging from 1.5 to 2.5 and alkaline activator to fly ash (AA/FA) ratios from 0.4 to 0.6. Optimum compressive strength for ambient cured (23 ± 2°C) GPC was achieved with a NaOH concentration of 14M, $Na_2SiO_3$/ NaOH ratio of 1.5 and AA/FA ratio of 0.5.

Okoye et al., (2015) conducted an experimental study to find out the impact of silica fume replacement on fly ash (Class F) based geopolymer concrete. Various geopolymer mixes were designed using fly ash as a source material, mixture of NaOH (14M) and NA2SiO3 as an alkaline activator solution while varying the percentage of silica fume (5%, 10%, 15%, 20%, 30%, and 40%) by weight of fly ash cured at a temperature of 100°C for 72-hour duration. In this experiment the compressive strength increased continuously up to 40% (maximum silica fume in this experiment) as the percentage replacement of fly ash with silica fume increased. The tensile and flexural strength also increased with the increase in silica fume content.

Adak et al., (2014) studied the impact of colloidal nano silica on the compressive strength of Class F fly ash based geopolymer mortars under ambient curing condition. In an experiment various geopolymer mortars were prepared using different molar concentrations of NaOH (8M, 10M, and 12M) and sodium silicate in the proportion 1:1.75 (by weight) as alkali activator solution along with varying percentage of nano silica (0%, 4%, 6%, 8%, and 10%) by weight of fly ash. The result showed that at 6% of colloidal nano silica addition by weight of fly ash had the highest compressive strength.

The results from the experiment conducted by Lateef et al., (2016) showed that in absence of heat curing, the early and final compressive strength of fly ash based geopolymer concrete can be improved by using Portland Cement as a partial replacement of fly ash. The optimum Portland cement replacement was considered to be 10% as the compressive strength at 1 day is improved by 82% and the 28 days compressive strength was improved by 52% compared with free Portland cement geopolymer concrete. According to findings from Scanning Electron Microscopy (SEM) analysis, incorporating Portland cement in the mixture absorbed excess water generated during the geo-polymerization process. This absorption not only minimized the formation of tiny cracks by reducing shrinkage but also introduced additional alkaline compounds like calcium hydroxide. These compounds accelerated the reaction between fly ash and the activating solution. Moreover, the replacement of Portland cement had a noticeable impact on the permeable void ratio, leading to a marked decrease as the amount of Portland cement in the mixture increased.

Mehta and Siddique (2017) presented an experiment investigating how inclusion of OPC as fly ash replacement affects the compressive strength and permeation properties (water absorption, sorptivity, porosity and rapid chloride permeability) of geopolymer concrete made with low calcium fly ash. The experiment was conducted varying the percentage OPC as fly ash replacement (0%, 10%, 20% and 30%). The results showed that with the addition of OPC the compressive strength kept increasing up to 20% i.e. highest at 20% and beyond that the strength decreased due to the formation of relatively lower geopolymeric binders than hydrated calcium-based binders. The inclusion of OPC up to 20% as fly ash replacement also reduced sorptivity, porosity and water absorption. The results from the microstructure analysis, Scanning Electron Microscope (SEM) and X Ray Diffraction (XRD) also verified that with addition of OPC better compacted and dense microstructure of geopolymer concrete was attained.

Anuradha et al., (2012) conducted an experimental study to determine the mix ratios for different grades of geopolymer concrete by trial-and-error approach. A new design procedure relevant with the Indian Standard (IS 10262-2009) was developed for Geopolymer Concrete. The study evaluated the applicability of the existing Mix Design for Geopolymer Concrete. Two systems were investigated, one with a complete replacement of cement by ASTM class F fly ash and the other with a total replacement of sand by M-sand. The test results indicated that the Indian Standard mix design could be adapted for Geopolymer Concrete with some modifications.

## III. METHODOLOGY

### III.I. MATERIALS AND METHODS

**Fly Ash**: Fly ash for this research is brought from the United Cement Factory, Khani Khola Dhading. Fineness test of fly ash is carried out using the wet sieving method as per IS 3812 (Part1). As ASTM (American Society for Testing and Materials) C 618 specified Class C (high calcium) and Class F (low calcium) fly ash, rapid Ethylenediaminetetraacetic Acid (EDTA) test is carried out to find the calcium amount present in fly ash. The collected fly ash in this case is found to be Class F fly ash as the percentage of CaO in fly ash was found to be 3.2%.

**Fine and Coarse Aggregates**: Locally available fine and coarse aggregates were collected from Pokhara, Kaski for this thesis experiment. Sieve analysis of sand as per IS Code 383:2016 was carried out and sand conforms to Zone III. Specific gravities of sand and coarse aggregates were found to be 2.66 and 2.672 respectively. Sieve analysis, Impact value test, Los Angeles Abrasion Test and Water Absorption Test were carried out for coarse aggregates too.

**Water**: For the preparation of alkaline solution and mixing of fly ash with aggregates, the tap water possessing pH level of 7.0 available in laboratory was used in all experiments.

**Silica Fume**: The silica fume used for this thesis was collected from Hemja RMC, Pokhara.

**Alkaline Solution**: For the preparation of alkaline solution hydroxide of either sodium or potassium and silicate of either sodium or potassium could be used. In our case Sodium based solutions are used as they are cheaper than Potassium based solution.The mixture of sodium hydroxide and sodium silicate acts as an alkali activator, initiating and accelerating the geopolymerization process where aluminosilicate materials (fly ash) react to form a three-dimensional polymer network. Sodium hydroxide provides the necessary hydroxide ions to dissolve the alumino-silicate precursor, while sodium silicate acts as a source of silicate ions that participate in polymerization. Alkaline solution after reacting with fly ash materials acts as binding agent, providing geopolymer concrete its integrity and durability.

The ratio of sodium silicate to sodium hydroxide in alkaline solution is kept 2.5.

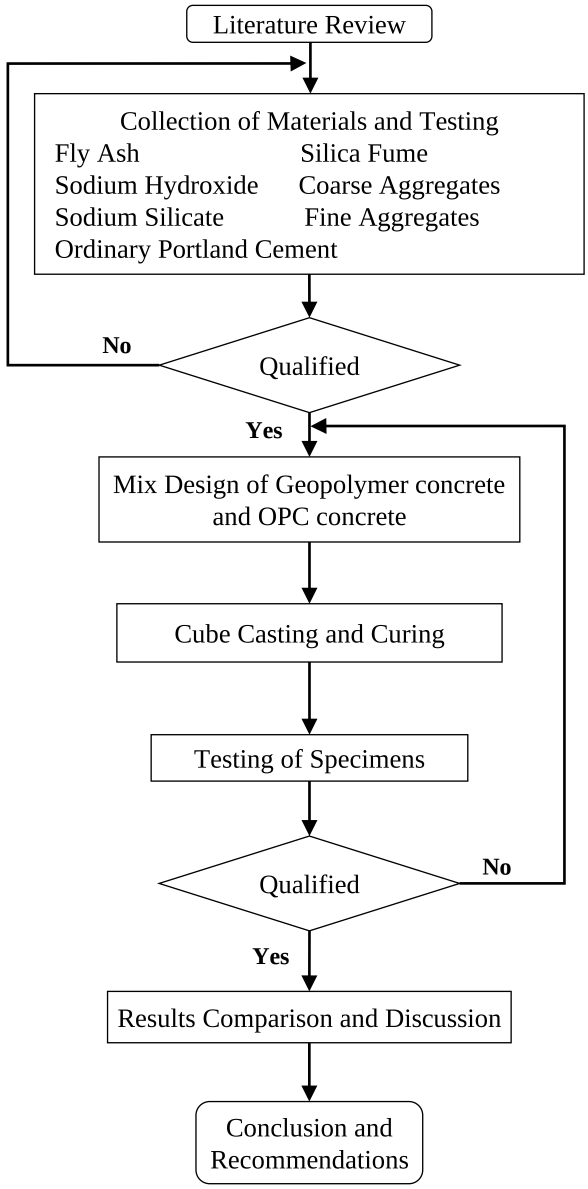


Figure 1: Flowchart of Research Methodology

Figure 2: Fly Ash

Chemical Requirements of Fly Ash (ASTM C 618)

| | | |
|---|---|---|
| $SiO_2+Al_2O_3+Fe_2O_3$ | Min % | 70 |
| $SiO_3$ | Max % | 5 |
| Moisture Content | Max % | 3 |
| Loss on Ignition(LOI) | Max % | 5 |

Fly Ash

| Test | Results | Test Method |
|---|---|---|
| Fineness Test (wet sieving method 45micron sieve) | 32% by weight retained (not more than 34 % should be retained according to IS:3812(Part I) | IS:3812(Part I) |
| Rapid EDTA | % of CaO< 10% (Class F fly ash) | Rapid EDTA |

Fine Aggregates

| Test | Result | Test Method |
|---|---|---|
| Sieve Analysis | Zone III | IS:383-2016 |
| Specific Gravity | 2.66 | IS:2386 (PartIII) |

Coarse Aggregates

| Test | Result | Test Method |
|---|---|---|
| Sieve Analysis | - | IS:383-2016 |
| Specific Gravity | 2.672 | IS:2386 (Part III) |
| Impact Value (%) | 20.49 | IS:2386 (Part IV) |
| Water Absorption (%) | 0.91 | IS:2386 (Part III) |
| Los Angeles Abrasion | 27.896 | IS:2386 (Part IV) |

Figure 3: Preparation of Alkaline Solution

The commercially available sodium hydroxide (NaOH) pellets were collected from the local chemical market of Pokhara and Sodium Silicate ($Na_2SiO_3$) solution was brought from Ruku Chemicals, Biratnagar.

Sodium hydroxide solution (NaOH) was prepared by mixing the sodium hydroxide flakes in water. Here we use sodium hydroxide solution of concentration 14 Molarity.

Preparation of 14M NaOH solution

1 Molarity of NaOH solution = 1 moles/ liter of solution

14 Molarity of NaOH solution = 14 moles/ liter of solution

Here, 1 mole of NaOH solution = 40grams of NaOH

14 M of NaOH solution = 14 x 40 = 560grams of NaOH solids per liter

The sodium hydroxide solution was prepared 24 hours before and mixed with sodium silicate 30 minute before casting of cube.

**Phase I:**

In the initial phase, the geopolymer mix design was formulated using hundred percent fly ash and concrete cubes underwent oven curing at temperature of 60°C.Also, Ordinary Portland Cement (OPC) concrete cubes were also casted simultaneously using same fine and coarse aggregates as in geopolymer concrete. The detail procedure is illustrated in the following section.

Mix Design: The mix design for geopolymer concrete in this thesis is done following the Modified Guidelines for Geopolymer Concrete Mix Design Using Indian Standard by Anuradha et al., (2012).

The result of mix design is illustrated below:

Table 1: Mix Proportion

| **SS** | **SH** | **Water** | **Fly Ash** | **FA** | **CA** |
|---|---|---|---|---|---|
| 160 kg/m3 | 64 kg/m3 | 8 kg/m3 | 400 kg/m3 | 573.10 kg/m3 | 1194.08 kg/m3 |
| 0.56 | | 0.002 | 1 | 1.433 | 2.985 |

SS: Sodium Silicate, SH: Sodium Hydroxide.

FA: Fine Aggregates, CA: Coarse Aggregates.

**Mixing, Casting and Curing**

Procedure:

The Sodium Hydroxide was prepared 24 hours prior to the experiment. Sodium silicate solution was mixed with sodium hydroxide 30 minutes before casting of specimens. Initially, the fly ash, fine aggregate, coarse aggregate, sodium hydroxide, and sodium silicate were meticulously weighed in a weighing machine according to the mix design proportion. Subsequently, dry mixing of fly ash, fine aggregate, and coarse aggregate was conducted thoroughly, followed by the careful pouring and proper blending of the alkaline solution. Additional water was incorporated as necessary. Test samples were molded in molds measuring 150 x 150 x 150 mm. These samples were then allowed to set for 24 hours before being placed in an oven maintained

Figure 4: Picture Highlights of Phase I

at a constant temperature of 60˚C. After 24 hours in the oven, the samples were removed and, upon cooling, immersed in water at normal room temperature for curing.

As outlined in the above procedure, the samples were cast in molds and allowed to cure for 24 hours at normal room temperature. However, in practice, it required 3 to 4 days for the concrete to fully set before demolding and subsequent placement in the oven for curing. Following setting, the concrete specimens were demolded and transferred to an oven set at a constant temperature of 60°C for a duration of 24 hours. Upon completion of oven curing, the samples were removed and left to cool at room temperature. Subsequently, the cooled samples were immersed in water for curing until the testing day.

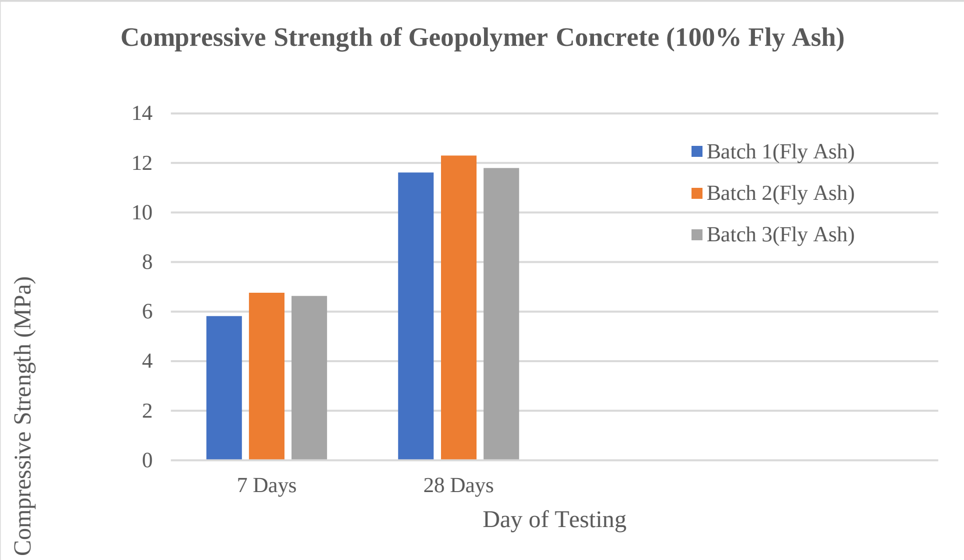


Figure 5: Compressive Strength Test Result of Geopolymer Concrete at Phase I

As illustrated in the chart, six cubes were cast daily over a period of three days and categorized into batches named batch 1(casted in day 1), batch 2 (casted in day 2), and batch 3 (casted in day 3) for both geopolymer and OPC concrete. For each batch, three cubes underwent testing at intervals of 7 days and 28 days, respectively. The chart presents the average results derived from the testing of three cubes per batch. For the cubes casted with 100% fly ash in day1, day2, and day 3 are noted as Batch 1 (fly ash), Batch 2 (fly ash) and Batch 3 (fly ash) respectively.

The average compressive strength of GPC (100% Fly Ash) concrete (Batch 1) in 7 days is 5.8 MPa and in 28 days is 11.62 MPa.

The average compressive strength of GPC (100% Fly Ash) concrete (Batch 2) in 7 days is 6.77 MPa and in 28 days is 12.3 MPa.

The average compressive strength of GPC (100% Fly Ash) concrete (Batch 3) in 7 days is 6.63 MPa and in 28 days is 11.8 MPa.

As illustrated in the chart, six cubes were cast daily over a period of three days and categorized into batches named batch 1OPC (casted in day 1), batch 2 OPC (casted in day 2), and batch 3 OPC (casted in day 3) for OPC concrete. For each batch, three cubes underwent testing at intervals of 7 days and 28 days, respectively. The chart presents the average results derived from the testing of three cubes per batch.

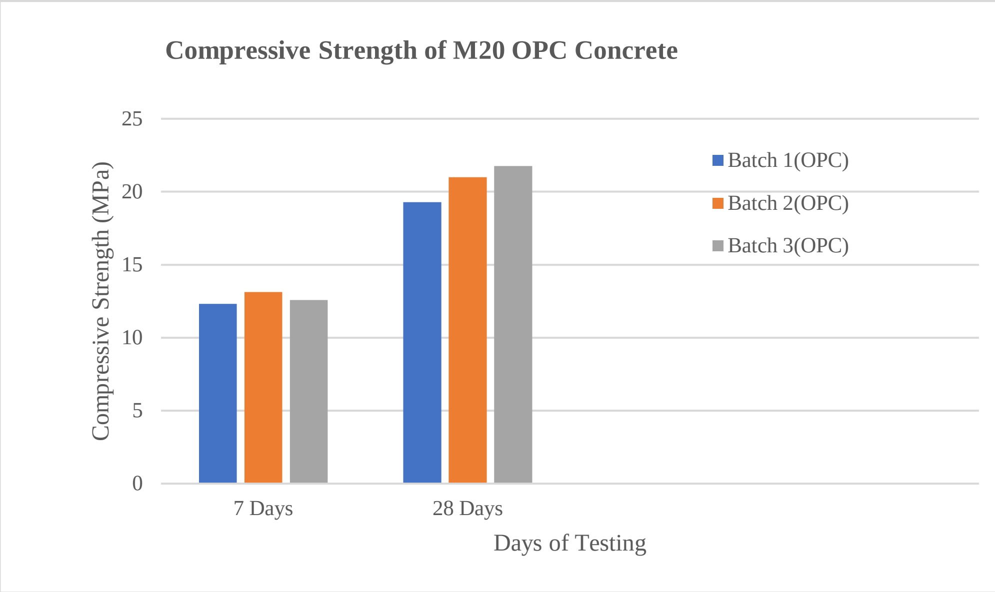


Figure 6: Compressive Strength Test Result of OPC Concrete at Phase I

The average compressive strength of OPC concrete (Batch 1) in 7 days is 12.31 MPa and in 28 days is 19.28 MPa.

The average compressive strength of OPC concrete (Batch 2) in 7 days is 13.12 MPa and in 28 days is 21 MPa.

The average compressive strength of OPC concrete (Batch 3) in 7 days is 12.59 MPa and in 28 days is 21.77 MPa.

## IV. RESULTS AND DISCUSSIONS

The geopolymer concrete were designed for M20 grade, and the result we get is not satisfactory. The probable reasons for not acquiring the targeted strength, are listed below:

- The curing conditions and curing temperature play a pivotal role in achieving the targeted compressive strength of geopolymer concrete. Steam curing is recommended for this type of concrete; however, due to the unavailability of this facility in our laboratory, we employed oven curing instead. In oven curing, the cube specimen is placed directly in an oven at a consistently monitored temperature, which in our case was 60°C. The temperature and curing method aid in accelerating the geo-polymerization reaction within the concrete. However, when the concrete specimens were placed directly in the oven for curing, the heat distribution within the concrete cube was uneven. This uneven heat distribution caused the concrete to lose moisture, resulting in microcracks forming from the exterior to the interior of the cube.

- Geopolymer concrete made with low calcium fly ash (Class F) requires a significant amount of time to set, taking 72 to 96 hours in our observations. The geo-polymerization reaction is slow for this type of fly ash-based geopolymer concrete. Consequently, the curing temperature and method used are not suitable for this type of geopolymer concrete, and we were unable to achieve the targeted strength.

## V. CONCLUSION

From the aforementioned experiment, it can be inferred that to enhance the polymerization reaction in concrete and achieve both high early and final compressive strength, appropriate curing conditions and temperature are essential for this type of fly ash-based geopolymer concrete. As we aim to find a future alternative to Ordinary Portland Concrete, we need to design a concrete mix that can be cast and utilized directly on-site. Therefore, we require additives or materials that enable early setting, high early, and final compressive strength, while eliminating the need for temperature curing in an oven or other machines. Temperature curing restricts the use of this concrete to precast applications only. So, to overcome these limitations we redesigned the mix in next phase.

## Phase II

In order to expedite geo-polymerization, enhance early and final compressive strength and eliminate the need for temperature curing, an extensive review of past literature and studies was done. Subsequently, a new mix design was formulated maintaining all parameters constant except for the substitution of 10% of fly ash with Silica Fume and 20% of fly ash with Ordinary Portland Cement.

Molarity of NaOH = 14M

Sodium Silicate to Sodium Hydroxide ratio by weight = 2.5

Silica Fume = 10% of Fly Ash

OPC = 20% of Fly Ash

New mix design proportion is shown in tabulated form below:

Table 2: New Mix Proportion

| **SS** | **SH** | **Water** | **Fly Ash** |
|---|---|---|---|
| 160kg/m$^3$ | 64kg/m$^3$ | 8kg/m$^3$ | 280kg/m$^3$ |
| 0.56 | | 0.002 | 1 |
| **Silica Fume** | **OPC** | **FA** | **CA** |
| 40kg/m$^3$ | 80kg/m$^3$ | 573.10kg/m$^3$ | 1194.08kg/m$^3$ |
| 0.1 | 0.2 | 1.433 | 2.985 |

**Procedure:**

Same as in phase I Sodium Hydroxide was prepared 24 hours prior to the experiment. Sodium silicate solution was mixed with sodium hydroxide 30 minutes before casting of specimens. Initially, the fly ash, silica fume, OPC, fine aggregate, coarse aggregate, sodium hydroxide, and sodium silicate were meticulously weighed in a weighing machine according to the mix design proportion. Subsequently, dry mixing of coarse aggregate, fine aggregate, fly ash, silica fume and OPC was conducted thoroughly, followed by the careful pouring and proper blending of the alkaline solution. Naphthalene based superplasticizer (2% by weight of fly ash) is added to reduce the water demand and enhance workability. Additional water was incorporated as necessary. Test samples were molded in molds measuring 150 x 150 x 150 mm. These samples were then allowed to set for 24 hours before being demolded and immersed in water at normal room temperature for curing until the day of testing.

As illustrated in the chart, six cubes were cast daily over a period of three days and categorized into batches named batch 1 GPC (casted in day 1), batch 2 GPC (casted in day 2), and batch 3 GPC (casted in day 3) for geopolymer concrete. For each batch, three cubes underwent testing at intervals of 7 days and 28 days, respectively. The chart presents the average results derived from the testing of three cubes per batch.

Figure 7: Picture Highlights of Phase II

## VI. RESULTS AND DISCUSSIONS

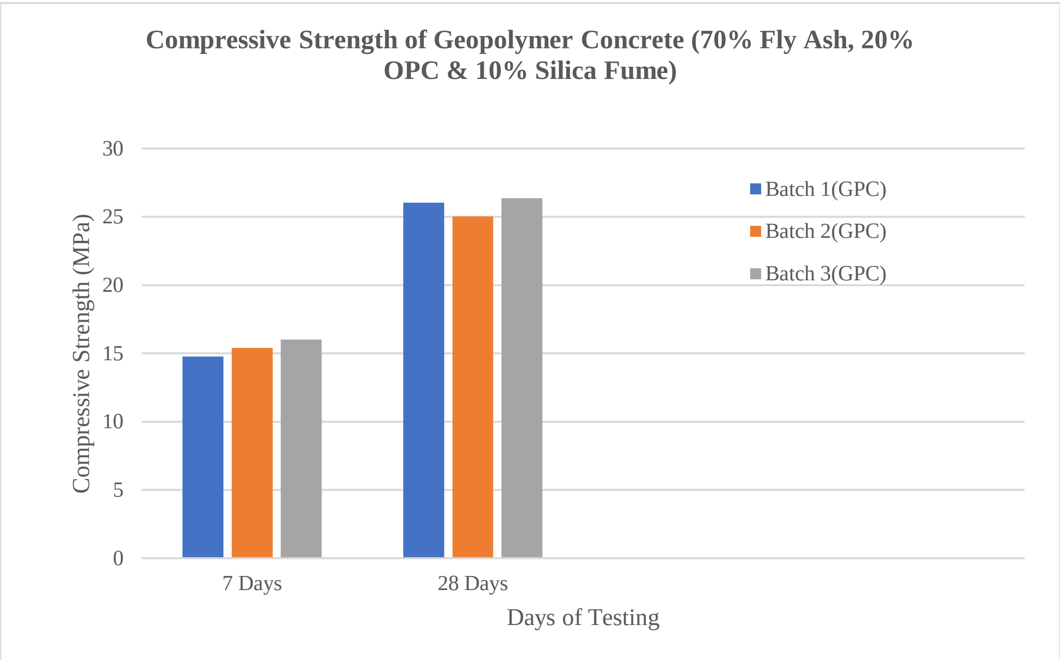


Figure 8: Compressive Strength Test Result of GPC (70% Fly Ash, 10% Silica Fume and 20% OPC)

The average compressive strength of GPC (70% Fly Ash, 10% Silica Fume and 20% OPC) concrete (Batch 1) in 7 days is 14.77 MPa and in 28 days is 26.04 MPa.

The average compressive strength of GPC (70% Fly Ash, 10% Silica Fume and 20% OPC) concrete (Batch 2) in 7 days is 15.4 MPa and in 28 days is 25.02 MPa.

The average compressive strength of GPC (70% Fly Ash, 10% Silica Fume and 20% OPC) concrete (Batch 3) in 7 days is 16 MPa and in 28 days is 26.37 MPa.

With the incorporation of silica fume and OPC into fly ash, there is a noticeable improvement in both early and final compressive strength compared to using only fly ash.

Silica fume, a byproduct of silicon and ferrosilicon alloys production is highly reactive pozzolanic material composed of ultra fine particles of amorphous silicon dioxide. When added with fly ash in geopolymer concrete, it helps to reduce the early setting time, and enhance the initial and final compressive strength. Here is how it helped is explained below:

Silica fume particles are extremely fine which helps in providing a large surface area for the nucleation of hydration products. This increased nucleation accelerates the initial hydration reactions leading to faster setting time. In geopolymer concrete silica fume enhances the dissolution of aluminosilicate species from fly ash. Which increases the availability of reactive species, speeding the geo-polymerization process.

The fine particles of silica fume fill the gaps between the larger particles of fly ash leading to the denser packing. Silica fume reacts with the alkaline activators used in geopolymer concrete to form additional Calcium Silicate Hydrate (C-S-H) gel and other binding phases. This results in a more cohesive and robust microstructure which enhances the early compressive strength. Over time, Silica fume react with the calcium hydroxide and other by products of the hydration and in geo-polymerization process. This pozzolanic reaction produces additional C-S-H gel which significantly contributes to long term strength. The ultra fine particles of silica fume fill micro pores within the geopolymer matrix, leading to a denser and less porous concrete. The presence of silica fume improves the bond between the geopolymer binder and the aggregates which ultimately helps in improving the final compressive strength.

Similarly, OPC contains calcium silicates (C3S, C2S) that hydrate in the presence of water to form calcium silicate hydrate (C-S-H) and calcium hydroxide ($Ca(OH)_2$). Due to this additional alkaline environment created by calcium hydroxide the rate of geo-polymerization is increased. The reaction produces geo-polymeric gels like N-A-S-H (Sodium-alumino-silicate-hydrate) gel from the geo-polymerization of fly ash components and C-A-S-H (Calcium-alumino-silicate-hydrate) gel from the interaction of calcium (from OPC) with dissolved aluminosilicates (from fly ash). The formation of hybrid gels, coexistence of C-S-H, NASH and CASH gels improves the bonding and packing leading to a denser and potentially durable matrix. So, addition of OPC helps in rapid hydration and produces different hybrid gels which helps to build a compact structure leading to high early as well as final strength.

## VII. CONCLUSIONS AND RECOMMENDATIONS

This thesis aimed to compare the performance of fly ash based geopolymer concrete and OPC concrete, focusing specifically on compressive strength. In this thesis experiment, geopolymer concrete is prepared in two phases: Phase I utilizes 100% fly ash cured by oven curing, while Phase II uses a mix of 70% fly ash, 10% silica fume, and 20% OPC cured at normal room temperature. Additionally, OPC concrete is prepared simultaneously to compare the compressive strength test results.

At phase I the compressive strength test of geopolymer concrete made with only fly ash under oven curing was lower than the compressive strength of OPC concrete. At phase II the compressive strength of geopolymer concrete made with a mix of 70% fly ash, 10% silica fume and 20% OPC cured at room temperature showed higher strength than conventional OPC concrete.

The test result of phase I suggests that, the reason behind the low compressive strength of 100% fly ash used geopolymer concrete cured at oven is due to i) slow geo polymerization reaction due to low calcium in fly ash, lack of additional alkaline environment to enhance the speed of dissolution of Silicon and Aluminum species to create a hybrid gel network which helps in early setting and strength of concrete, ii) the lack of proper steam curing which is recommended for Class F fly ash used geopolymer concrete, in oven curing the heat distribution on the cube is uneven creating a series of minor cracks extending outer to inner side of the concrete cube.

The test result of Phase II suggests that incorporating silica fume and OPC in fly ash lowered the setting time, enhanced the early polymerization reaction so that helped in getting desired early and final compressive strength. It also eliminated the need for temperature curing which was a main hindrance for the cast in site applications. Silica fume helped in dissolution of alumino silicate materials from fly ash, since it is extremely fine materials it filled the gaps of fly ash making it dense and compact. Similarly, the OPC addition created an additional alkaline activator (Calcium Hydroxide) which speeded the geopolymerization reaction helping in dissolution of Silicon and aluminum ions from fly ash. It helps in creating hybrid gel network like C-A-S-H (Calcium Alumina Silicate Hydrate), N-A-S-H (Sodium Alumina Silicate Hydrate) and combination of those gel network that helps to strengthen the bond of structure enhancing the setting and gain of compressive strength.

## VIII. RECOMMENDATIONS

The fly ash utilized in this experiment was sourced exclusively from a single location. This limitation may affect the generalizability of the research findings, as variations in the properties of fly ash from different sources could influence the results. To enhance the robustness and applicability of future studies, it is recommended to collect and analyze fly ash samples from a broader and more diverse range of sources. This approach will help ensure that the findings are more representative and widely applicable across different contexts and conditions.

The shape and size of the coarse aggregates were not considered in this research. Variations in the shape and size of coarse aggregates could yield different results. Therefore, it is recommended to investigate how changes in the shape and size of coarse aggregates affect the compressive strength of geopolymer concrete. Such a study would help identify the optimal aggregate characteristics that result in the highest compressive strength, thereby enhancing the overall performance of geopolymer concrete.

Curing conditions play a crucial role in developing the compressive strength of geopolymer concrete. Therefore, conducting a study that utilizes appropriate steam curing methods and thoroughly analyzes the results would provide significant support for the use of geopolymer concrete in precast applications. This approach would help to optimize curing processes and improve the overall performance and applicability of geopolymer concrete in the construction industry.

This research was conducted in the Civil Laboratory of Pokhara, Kaski. Future studies should explore different environmental conditions, such as hot and cold weather, to determine how temperature variations affect the properties of geopolymer concrete. Understanding these effects will enable the development of methods and strategies to optimize the application of geopolymer concrete across diverse environmental conditions, thereby enhancing its versatility and reliability in various climates.

In conclusion, the study demonstrates that fly ash-based geopolymer concrete can achieve higher compressive strength than conventional OPC concrete, both at early and later ages. This positions geopolymer concrete as a promising sustainable alternative for the construction industry, offering enhanced performance and significant environmental benefits. By addressing the remaining challenges and implementing the proposed recommendations, the industry can leverage the full potential of geopolymer concrete to build a more sustainable future.

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