"Durability Performance and Carbon Emission Analysis of Geopolymer Concrete Compared to Conventional Concrete"

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Abstract—This study investigates the durability performance and carbon emission analysis of Geopolymer Concrete (GPC) compared to Conventional Concrete (CC) for M-30 grade. The experimental program includes testing cube, beam, and cylinder specimens to evaluate Water Absorption Test, Thermal Test, RCPT, Test, respectively. The geopolymer concrete is designed using fly ash and ground granulated blast furnace slag (GGBS) as binder materials, activated with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. The specimens are prepared and cured under ambient conditions to eliminate heat curing, making the process more environmentally viable.

Additionally, a life-cycle assessment (LCA) approach is employed to analyze the carbon footprint of both concrete types. The reduction in carbon emissions due to the replacement of Portland cement with industrial by-products is quantified. The results indicate that geopolymer concrete exhibits superior durability performance in aggressive environments, reduced permeability, and lower carbon emissions compared to conventional concrete. This study provides a sustainable alternative to conventional concrete while maintaining structural integrity and longevity.

Geopolymer Concrete (GPC) is a sustainable, long-lasting alternative to conventional concrete, ideal for chloride-rich environments like bridges and wastewater treatment plants. Its superior durability, reduced chloride permeability, thermal stability, and eco-friendliness make it suitable for fire-resistant applications and reduces carbon emissions by replacing Ordinary Portland Cement.

Keywords— *Geopolymer Concrete, Conventional Concrete, M-30 Grade, Durability Performance, Water Absorption Test, Thermal Test, RCPT, Test, Carbon Emission, Life-Cycle Assessment, Sustainability*

INTRODUCTION

Concrete is the most widely used construction material globally, but its production significantly contributes to carbon emissions, primarily due to the high energy consumption associated with Portland cement manufacturing. Cement production alone is responsible for nearly 8% of global CO_2 emissions, prompting researchers to explore sustainable alternatives. Geopolymer Concrete (GPC) has emerged as an environmentally friendly substitute for Conventional Concrete (CC), utilizing industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS) as binders, activated by alkaline solutions like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Unlike conventional concrete, geopolymer concrete eliminates the need for Portland cement, thereby reducing carbon emissions and promoting sustainability.

The study compares Geopolymer Concrete and Conventional Concrete for M-30 grade durability and carbon emissions. It tests compressive, flexural, and split tensile strength, as well as durability tests like acid, sulfate, water absorption, and rapid chloride penetration to determine their resistance to aggressive environmental conditions.

Furthermore, a Life-Cycle Assessment (LCA) approach is employed to analyze the carbon footprint of GPC and CC. The environmental impact is quantified by calculating the reduction in CO_2 emissions due to cement replacement with industrial waste materials. The study aims to demonstrate the potential of geopolymer concrete as a viable, durable, and eco-friendly alternative to conventional concrete while maintaining structural integrity and performance. The findings of this research will contribute to the growing body of knowledge on sustainable construction practices and promote the adoption of geopolymer concrete for reducing environmental impact in the construction industry.

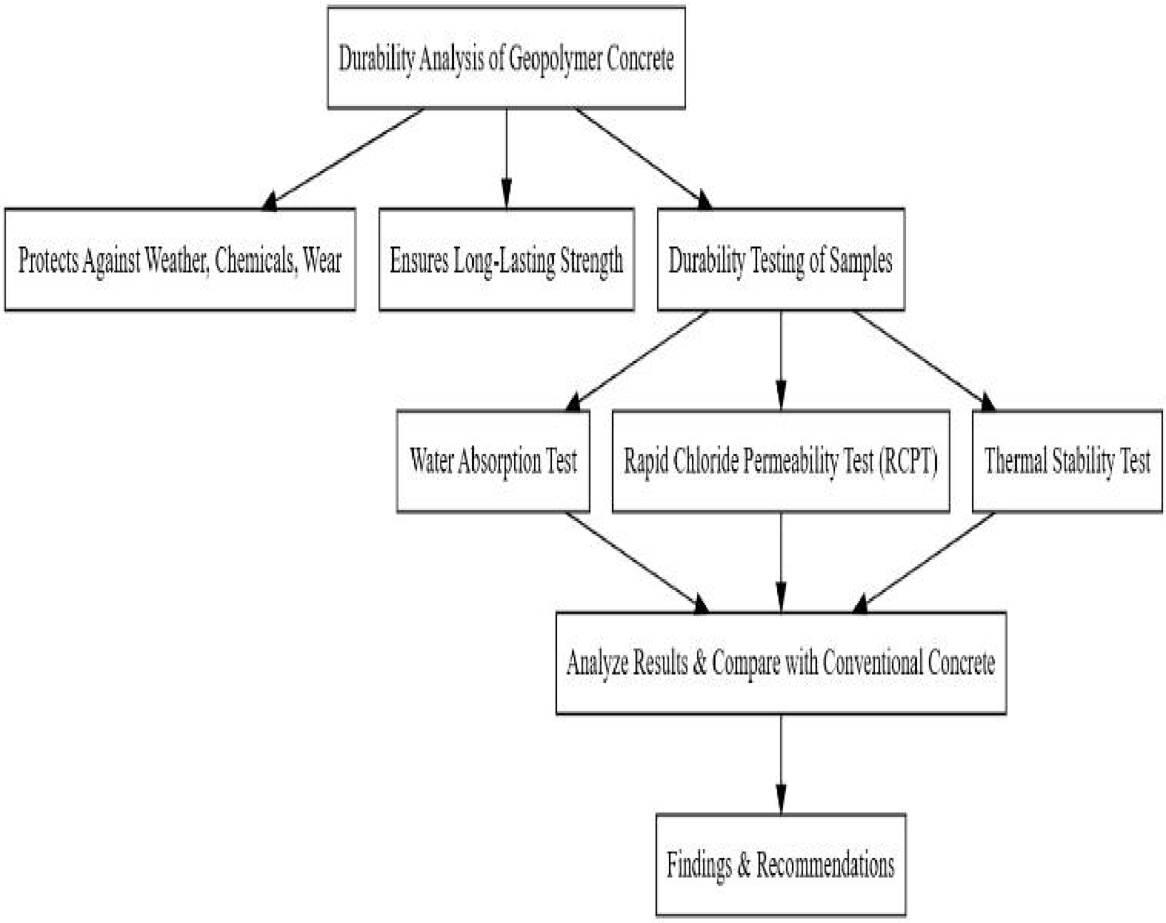


Figure1.1: Workflow Diagram

Mechanical strength tests are also carried out to evaluate the structural integrity of both concrete types. Compressive strength tests on cube specimens (150 mm × 150 mm × 150 mm) are conducted at 3, 7, and 28 days to monitor the strength development over time. These tests provide crucial insights into the structural performance of GPC compared to conventional concrete.

In addition to durability and strength evaluations, this study incorporates a Life-Cycle Assessment (LCA) to analyze the carbon footprint of both concrete types. The environmental impact of cement replacement is quantified by calculating the reduction in emissions achieved through the use of industrial by-products instead of cement. Since cement production is energy-intensive and releases significant amounts of greenhouse gases, GPC presents an effective solution for reducing the environmental impact of construction materials. The LCA approach considers various factors, including raw material extraction, transportation, concrete mixing, and curing processes, to determine the overall sustainability of geopolymer concrete.

The novelty of this study lies in its dual focus on durability performance and carbon emission analysis of geopolymer concrete (GPC) in direct comparison to conventional concrete. Unlike previous research that primarily explores either mechanical properties or environmental impact separately, this study integrates both aspects to provide a comprehensive assessment. It evaluates long-term durability factors such as resistance to chloride penetration, sulfate attack, and freeze-thaw cycles while quantifying carbon footprint reductions achieved through the use of industrial by-products like fly ash and slag in GPC. This holistic approach contributes to sustainable construction by promoting eco-friendly alternatives with enhanced durability.

Analysis of Carbon Emissions for Geopolymer Concrete

The production of OPC is energy-intensive and responsible for approximately 8% of global CO_2 emissions due to the calcination of limestone and the combustion of fossil fuels. In contrast, geopolymer concrete eliminates the need for high-temperature clinker production, thereby significantly reducing embodied carbon. This study conducts a Life Cycle Assessment

(LCA) to evaluate the carbon footprint of GPC from raw material sourcing to final product application. Tools such as GABI, SimaPro, or custom carbon calculators are used for quantifying emissions.

Additionally, Machine Learning (ML) models are explored to predict carbon emissions based on different mix designs, material sourcing, and curing techniques. Parameters such as binder composition, curing temperature, transportation distance, and energy usage are considered. Comparative analysis reveals that GPC can reduce carbon emissions by 40–80%, depending on the material composition and processing method.

Goal of Thesis

The aim of this study is to evaluate the durability performance and carbon emission analysis of Geopolymer Concrete (GPC) compared to Conventional Concrete (CC) for M-30 grade by conducting various tests on cube and cylinder specimens. The study focuses on assessing the mechanical properties, durability characteristics, and environmental impact of geopolymer concrete as a sustainable alternative to conventional cement-based concrete.

Objectives

1. To design and develop geopolymer concrete (GPC) for M-30 grade using fly ash

2. To assess the durability performance of GPC and CC by conducting:
   - Water Absorption Test to determine porosity and permeability.
   - Rapid Chloride Penetration Test (RCPT) to evaluate chloride ion resistance.
   - Thermal Resistance Test to assess heat resistance compared to conventional concrete.
3. To perform a Life Cycle Assessment (LCA) of both GPC and CC to quantify carbon emissions and environmental impact, focusing on:
   - Reduction in CO_2 emissions due to cement replacement.
   - Comparison of energy consumption in material production and concrete manufacturing.
4. To compare the sustainability and cost-effectiveness of GPC and CC in construction applications by evaluating material availability, production feasibility, and long-term durability.
5. To propose GPC as a viable alternative to CC for environmentally sustainable construction without compromising on strength and durability.

Problem Statement

The construction industry contributes to carbon emissions through the use of Ordinary Portland Cement (OPC) in conventional concrete. GPC, made from industrial by-products, offers a sustainable alternative, reducing carbon footprint and energy consumption. However, research on GPC's durability and mechanical properties is limited. This study aims to compare GPC's performance and environmental impact with conventional concrete, conducting rigorous testing and a Life Cycle Assessment to evaluate its carbon emissions reduction.

LITERATURE REVIEW

P Sujitha Magdalene et al., RDLC,2024. “Influence of basalt fiber in ultra-high-performance concrete in hybrid mode: a comprehensive study on mechanical properties and microstructure”

The research aims to use natural fiber (basalt) to restore mechanical strength in ultra-high-performance concrete (UHPC) when metallic steel fibers are curtailed. River sand is removed, and manufactured sand is substituted. Nano silica is used for packing the matrix. Twelve mixes were made, with metallic fibers added in 1% and 2%, and natural fibers in 1%, 2%, and 3%. The addition of more than 3% resulted in reduced workability, so the addition was restricted to 3%. The results showed better compressive strength and impact resistance when annexing 1% steel and 3% basalt fibers with 30% M-Sand.

Sahan Bandara et al., MDPI,2023. “Review Ultra-High-Performance Fibre-Reinforced Concrete for Rehabilitation and Strengthe”

Ultra-high-performance fibre-reinforced concrete (UHPFRC) is a cementitious composite with superior mechanical properties, including durability, ductility, and fire resistance. Its advantages include excellent bonding with normal strength concrete and eliminating debonding issues. This paper reviews previous studies on UHPFRC's use in structural retrofitting applications, focusing on flexural, combined axial, shear, impact resistance, and torsional strengthening. The paper aims to enhance UHPFRC's awareness and future research directions.

Nikolai Ivanovich Vatin et al., Frontiers, Volume 10,2024. "Impact of basalt fiber reinforced concrete in protected buildings: a review"

This study explores the use of basalt fiber reinforcement in concrete for protected buildings and structures. Basalt fibers, derived from melting basalt rock, are sustainable and environmentally friendly. The study focuses on the impact of basalt fiber reinforcement on mechanical properties like tensile, compressive, and bending strengths, as well as performance indicators like void content, water absorption, chloride ion permeability, alkali and slag resistance, temperature stability, shrinkage characteristics, and abrasion resistance. The results show that basalt fibers enhance resistance to temperature, alkali, acid exposure, and chloride, while also improving bending and tensile strength.

Mahmoud Rady et al., MDPI,2023. "Performance of Fiber-Reinforced Ultra-High-Performance Concrete Incorporated with Microencapsulated Phase Change Materials"
This paper explores the use of phase change materials (PCMs) in ultra-high-performance concrete (UHPC) to improve energy efficiency and reduce carbon footprint. However, the inclusion of microencapsulated phase change materials (MPCMs) can negatively impact the properties of UHPC. The study reveals that fiber reinforcement can compensate for the negative effects of MPCMs, improving thermal properties. The increased amount of MPCMs enhances the thermal performance of UHPC panels by absorbing and releasing energy during the phase change process.

M. Madhkhan et al., IJE, Vol. 34, No. 05, 2021. "Mechanical Properties of Ultra-High-Performance Concrete Reinforced by Glass Fibers under Accelerated Aging"

Ultra-High-Performance Concrete (UHPC) is a cementitious composite with high compressive strength and durability. It is often made with short steel fibers, which improves flexural ductility, durability, and energy absorption. Glass fibers, a lighter and cheaper alternative, have been studied for their mechanical properties. However, glass fibre reinforced concrete can damage them in alkaline environments, causing decreased properties over time. After accelerated aging, specimens become brittle and the modulus of rupture decreases. However, compressive strength increases by at least 4%.

Snehasis Sutar et al., IRJET, Volume: 08 Issue: 05, 2021. "Strength behaviour of glass fiber reinforced concrete"

Concrete is a crucial material in civil engineering structures, often requiring high strength and workability. Researchers are working to develop high-performance concrete using fibers and other admixtures. Fibers like glass, carbon, polypropylene, and aramid improve tensile strength, fatigue, durability, shrinkage, impact, cavitation, erosion resistance, and serviceability. Alkali resistant glass fiber reinforced concrete has been developed, improving long-term durability. This study uses CEMFIL Anti-Crack High Dispersion, alkali resistant glass fiber in concrete to study its compressive strength, split tensile strength, and flexural strength.

GAP OF RESEARCH

Although machine learning applications for crack prediction have advanced significantly, there are still a number of issues with the models that are currently in use. Focusing on particular concrete types or environmental conditions is a common problem that can restrict the findings' applicability in a variety of scenarios. Furthermore, the robustness and dependability of forecasts are limited by the fact that many research use somewhat small datasets. Because crack behavior is complex and impacted by many different elements, it can be difficult to create complete models that can account for every possible component that could contribute to the creation of cracks.

RESEARCH METHODOLOGY

The working principle of this study is based on the geopolymerization process, mechanical and durability performance evaluation, and life cycle assessment (LCA) to compare the properties of Geopolymer Concrete (GPC) and Conventional Concrete (CC) for M-30 grade. The primary focus is on assessing strength, durability, and environmental impact through various laboratory experiments.

Geopolymerization Process and Concrete Formation

Geopolymer concrete (GPC) is prepared by replacing Ordinary Portland Cement (OPC) with industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), which act as binder materials. These binders are activated using alkaline solutions, typically a mixture of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Upon mixing with fine and coarse aggregates, the binder undergoes a geopolymerization reaction, forming a three-dimensional aluminosilicate structure that provides high strength and durability. Unlike conventional concrete, which gains strength through the hydration reaction of cement, GPC achieves strength through a chemical polymerization reaction, making it more environmentally sustainable. Furthermore, ambient curing is adopted in this study to eliminate the high-energy heat curing process, enhancing the practicality of GPC for large-scale construction applications.

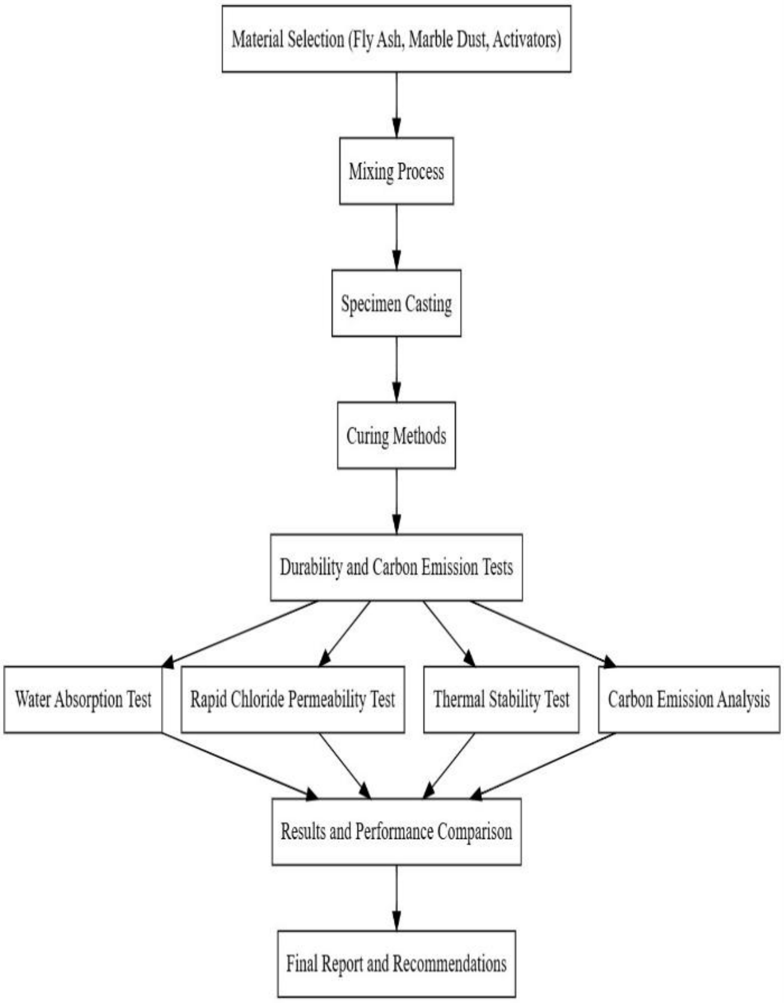


Figure1.2: Research Work Flow

In addition to mechanical properties, the durability performance of GPC and CC is analyzed through multiple tests. The Water Absorption Test is conducted to evaluate the porosity and permeability of the concrete mix, which directly affects its resistance to moisture-related deterioration. The Rapid Chloride Penetration Test (RCPT) measures chloride ion permeability to assess the potential for corrosion in reinforced concrete structures. Further, acid and sulfate resistance tests are performed to determine the degradation of concrete when exposed to aggressive chemical environments, simulating real-world conditions. Additionally, a Thermal Resistance Test is carried out to examine the stability of both GPC and CC under high-temperature conditions, ensuring suitability for extreme environmental exposure.

Carbon Emission Analysis and Life Cycle Assessment (LCA)

To evaluate the environmental impact, a Life Cycle Assessment (LCA) is performed for both GPC and CC, focusing on carbon emissions and energy consumption. The study quantifies CO_2 emissions associated with the production, transportation, and curing of materials used in both concrete types. Since cement production is a major contributor to greenhouse gas emissions, the replacement of cement with industrial by-products in GPC significantly reduces the overall carbon footprint. The assessment also considers energy efficiency by analyzing the material processing and manufacturing requirements, thereby providing a comparative analysis of sustainability and environmental benefits.

Comparative Analysis and Sustainability Assessment

The results obtained from mechanical, durability, and environmental performance tests are compared between GPC and CC to determine the feasibility of geopolymer concrete as an alternative to conventional concrete. The study assesses not only the strength and durability of GPC but also its practical applicability in construction. By analyzing factors such as cost-effectiveness, material availability, and ease of production, the research provides insights into whether GPC can replace CC in real-world infrastructure projects without compromising on performance and longevity.

Research Framework

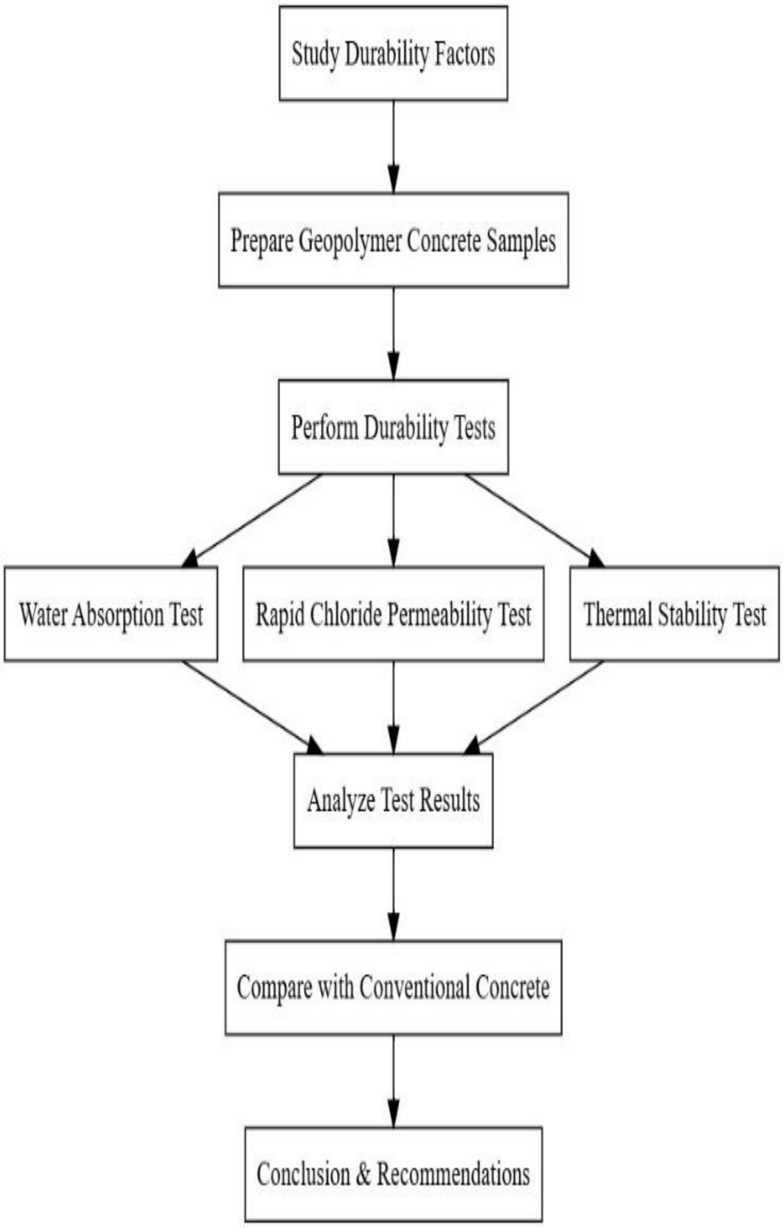


Figure1.3: Framework

In conclusion, the study establishes that Geopolymer Concrete offers superior durability, reduced permeability, and significantly lower carbon emissions compared to Conventional Concrete. The experimental findings demonstrate that GPC can serve as an eco-friendly alternative to CC, reducing the dependency on cement while maintaining high mechanical strength and long-term durability. This research contributes to the growing demand for sustainable construction materials, highlighting the potential of geopolymer technology in reducing the environmental impact of the concrete industry.

Data Flow Diagram

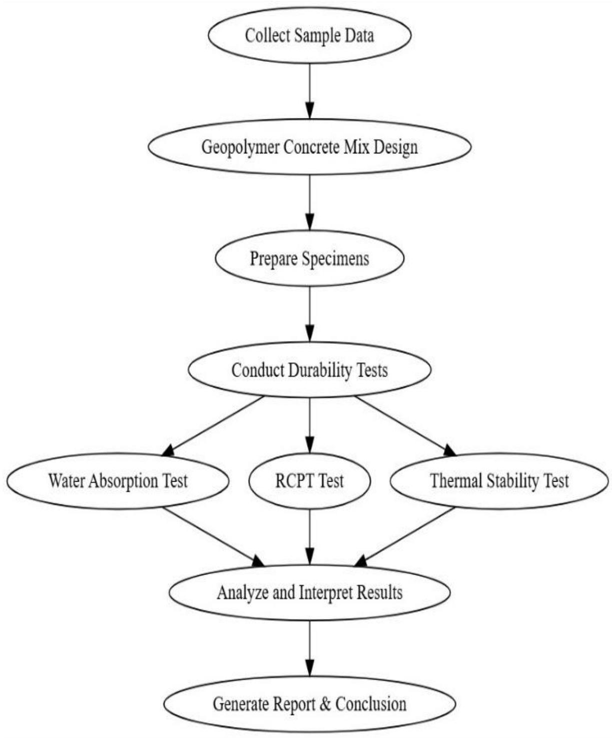


Figure1.4: Data Flow Diagram

Material to be used

Geopolymer Concrete

Geopolymer Concrete (GPC) is an innovative and eco-friendly alternative to Conventional Concrete (CC), designed to reduce carbon emissions associated with Portland cement production. Instead of cement, GPC utilizes industrial by-products such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), silica fume, and rice husk ash as binders.

Figure1.5: Geopolymer Cement

These materials react with alkaline activators like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) to form a strong, durable, and environmentally sustainable binder.

Physical Properties of Geopolymer Concrete

Table1.1: Physical Properties of Geopolymer Concrete

Property	Description
Density	Typically ranges between 2200–2500 kg/m³, depending on the mix composition and curing method.
Workability	Can be adjusted by varying the water-to-alkali ratio and the use of superplasticizers; generally lower than conventional concrete due to high viscosity of the activator solution.
Setting Time	Highly dependent on the type and concentration of alkaline activator; may be faster or slower than ordinary Portland cement concrete.
Compressive Strength	Can achieve 30 MPa to 100 MPa, depending on the mix design, curing temperature, and binder composition.
Tensile Strength	Generally, ranges from 2 to 5 MPa, approximately 10% of the compressive strength.
Flexural Strength	Ranges from 3 to 8 MPa, providing good resistance against bending forces.
Porosity & Permeability	Lower than conventional concrete, leading to better resistance against water absorption, sulfate attacks, and chloride penetration.
Durability	High resistance to acid attack, sulfate attack, and chloride penetration, making it ideal for marine and industrial environments.
Shrinkage & Creep	Lower shrinkage and creep compared to OPC concrete due to the absence of calcium hydroxide.
Thermal Resistance	Excellent fire resistance due to the ceramic-like structure formed by geopolymerization.
Carbon Footprint	50%–80% lower CO_2 emissions than conventional concrete, depending on the source of materials.

Chemical Properties of Geopolymer Concrete

Table1.2: Chemical Properties of Geopolymer Concrete

Property	Description
Primary Binders	Fly ash (SiO_2, Al_2O_3), GGBS (CaO, SiO_2, Al_2O_3), Metakaolin (SiO_2, Al_2O_3)
Alkali Activators	Sodium Hydroxide (NaOH), Potassium Hydroxide (KOH), Sodium Silicate (Na_2SiO_3)
SiO_2/Al_2O_3 Ratio	The optimum range is 2.0–3.5, influencing the strength and durability of the concrete.
Calcium Content	Lower than conventional concrete, reducing carbonation but improving sulfate resistance.
Reaction Mechanism	The alkaline solution dissolves SiO_2 and Al_2O_3, forming a three-dimensional polymeric network of Si–O–Al bonds similar to zeolite structures.

Fly Ash

Fly ash is a finely divided powder obtained as a by-product from coal combustion in thermal power plants. It is primarily composed of silica (SiO_2), alumina (Al_2O_3), and iron oxides (Fe_2O_3), making it an excellent pozzolanic material for use in geopolymer concrete (GPC).

In M-30 grade geopolymer concrete, fly ash is used as a binder material in combination with alkaline activators (sodium hydroxide and sodium silicate) to replace Ordinary Portland Cement (OPC). This substitution significantly reduces carbon emissions while enhancing durability and long-term performance.

Figure1.6: Fly Ash

Table1.3: Physical Properties of Fly Ash

Property	Value/Range
Color	Light to dark gray
Specific Gravity	2.0 – 2.5
Fineness (Retained on 45 μm sieve)	< 34%
Bulk Density	600 – 900 kg/m³
Specific Surface Area (m²/kg)	300 – 500
Particle Shape	Spherical, Glassy
Loss on Ignition (LOI)	< 5%
Pozzolanic Activity Index	≥ 75%
Moisture Content	< 2%

Table1.4: Chemical Properties of Fly Ash

Compound	Percentage (%)
Silicon Dioxide (SiO_2)	40 – 60%
Aluminum Oxide (Al_2O_3)	20 – 35%
Iron Oxide (Fe_2O_3)	5 – 15%
Calcium Oxide (CaO)	1 – 10%
Magnesium Oxide (MgO)	0.5 – 3%
Sodium Oxide (Na_2O)	0.2 – 1.5%
Potassium Oxide (K_2O)	0.5 – 2%
Sulfur Trioxide (SO_3)	< 3%
Loss on Ignition (LOI)	< 5%

Role of Fly Ash in M-30 Grade Geopolymer Concrete

1. Cement Replacement – Fly ash completely replaces Ordinary Portland Cement (OPC) in geopolymer concrete, making it environmentally friendly.
2. Strength Development – The geopolymerization reaction forms stable aluminosilicate bonds, ensuring high early and long-term strength.
3. Durability Enhancement – Fly ash-based GPC exhibits higher resistance to sulfate attack, acid attack, and chloride penetration compared to conventional concrete.
4. Workability Improvement – Due to its spherical shape and fineness, fly ash enhances flowability, reducing the water-to-binder ratio (w/b).
5. Thermal Resistance – GPC containing fly ash shows excellent fire and heat resistance due to the formation of geopolymer gel instead of hydrated cement paste.

Marble Dust

Figure1.7: Marble Dust

Marble dust is a by-product of marble processing industries, consisting mainly of calcium carbonate ($CaCO_3$). It is used as a filler material in geopolymer concrete to enhance strength, durability, and sustainability. Its fine particles improve the packing density and reduce permeability.

Table1.5: Physical Properties of Marble Dust

Property	Value/Range
Color	White to gray
Fineness (Retained on 90 µm sieve)	< 15%
Specific Gravity	2.6 – 2.8
Bulk Density (kg/m³)	1200 – 1600
Water Absorption	0.2 – 0.4%
Particle Shape	Angular/Fine Powder
Pozzolanic Activity	Moderate

Table1.6: Chemical Properties of Marble Dust

Compound	Percentage (%)
Calcium Carbonate ($CaCO_3$)	85 – 95%

Role in Geopolymer Concrete

1. Improves Strength – Enhances compressive strength due to its fine particle size and filling ability.
2. Enhances Workability – Reduces water demand, improving flowability and consistency.
3. Sustainability – Reduces cement consumption, making GPC more eco-friendly.
4. Reduces Permeability – Acts as a filler, reducing porosity and increasing durability.

Sodium Hydroxide (NaOH)

Figure1.8: Sodium Hydroxide (NaOH)

Chemical Composition: An alkaline (basic) compound made of sodium (Na), oxygen (O), and hydrogen (H).

Physical Form: White solid or a concentrated liquid solution. Binding Properties & Applications

- Acts as an activator in geopolymer concrete by breaking down aluminosilicate sources (fly ash, GGBS, metakaolin).
- Increases the reaction rate and strength development.
- Provides strong alkaline medium ($pH > 12$) to dissolve silica and alumina.
- Used in pulp & paper industries, detergents, and water treatment.

Reaction in Geopolymerization

- $NaOH + SiO_2$ (from fly ash or GGBS) → Silicate ions
- These ions help in polymerization with alumina to form a strong geopolymer binder.

Coarse Aggregate

Figure1.9: Coarse Aggregates

Coarse aggregate is a key component in geopolymer concrete (GPC), providing bulk volume, strength, and durability.

It significantly influences the compressive strength, workability, and durability of the concrete mix. In M-30 grade geopolymer concrete, crushed granite, basalt, or other crushed stones are typically used as coarse aggregates.

The selection of coarse aggregate depends on its size, shape, strength, and gradation, ensuring it meets the requirements for high-performance geopolymer concrete.

Table1.7: Physical Properties of Coarse Aggregate

Property	Value/Range
Size	10 mm – 20 mm
Shape	Angular
Specific Gravity	2.6 – 2.8
Bulk Density	1400 – 1600 kg/m³
Water Absorption	0.5 – 2%
Crushing Value	< 30%
Impact Value	< 25%
Flakiness Index	< 25%
Elongation Index	< 30%

Table1.8: Chemical Properties of Coarse Aggregate

Compound	Percentage (%)
Silicon Dioxide (SiO_2)	50 – 65%
Calcium Oxide (CaO)	3 – 12%
Magnesium Oxide (MgO)	0.5 – 2%
Iron Oxide (Fe_2O_3)	2 – 8%
Aluminum Oxide (Al_2O_3)	5 – 12%

Fine Aggregates

Fine aggregate is a crucial component in M-30 grade geopolymer concrete (GPC) as it fills voids between coarse aggregates, enhances workability, and contributes to strength development. It plays a vital role in achieving proper mix consistency, density, and durability. River sand, manufactured sand (M-sand), or crushed sand is commonly used as fine aggregate in geopolymer concrete.

The selection of fine aggregate is based on its grading, particle size distribution, shape, texture, and chemical composition to ensure optimum performance of the concrete mix.

Table1.9: Physical Properties of Fine Aggregate

Property	**Value/Range**
Particle Size	< 4.75 mm
Specific Gravity	2.4 – 2.8
Fineness Modulus	2.2 – 3.2
Bulk Density	1400 – 1600 kg/m³
Water Absorption	0.5 – 2%
Moisture Content	< 5%
Silt Content	< 3%
Clay Lumps	< 1%

- Particle Size: Fine aggregates are those passing through a 4.75 mm sieve, ensuring proper packing density and smooth finish in concrete.
- Specific Gravity: Determines the density and compaction properties of concrete.
- Fineness Modulus (FM): Indicates the coarseness or fineness of sand; FM between 2.2 and 3.2 is ideal for geopolymer concrete.
- Bulk Density: Affects workability and volume stability in the mix.
- Water Absorption: Lower values are preferred to reduce excess water demand in the mix.
- Silt & Clay Content: Should be minimal to avoid bonding issues and reduced strength.

Table1.10: Chemical Properties of Fine Aggregate

Compound	Percentage (%)
Silicon Dioxide (SiO_2)	60 – 80%
Calcium Oxide (CaO)	1 – 5%
Magnesium Oxide (MgO)	0.5 – 2%
Iron Oxide (Fe_2O_3)	1 – 5%
Aluminum Oxide (Al_2O_3)	3 – 10%

- Silicon Dioxide (SiO_2): Provides strength and resistance to environmental degradation.
- Calcium Oxide (CaO): Reacts with alkaline activators in geopolymer concrete, enhancing bonding properties.
- Magnesium Oxide (MgO): Ensures stability and durability of concrete.
- Iron Oxide (Fe_2O_3) & Aluminum Oxide (Al_2O_3): Contribute to color, hardness, and resistance to aggressive chemicals.

Sodium Silicate (Na_2SiO_3)

Chemical Composition: A mixture of sodium (Na), silicon (Si), and oxygen (O).

Physical Form: Available in liquid and solid (glass) form.

Binding Properties & Applications

- Acts as a binder by reacting with sodium hydroxide to form aluminosilicate gels.
- Increases strength and durability in geopolymer concrete.
- Enhances early-age strength gain in concrete.
- Improves fire resistance, water resistance, and chemical resistance.
- Commonly used in ceramics, adhesives, coatings, and concrete.

Reaction in Geopolymerization

- Na_2SiO_3 + Al_2O_3-SiO_2 (from fly ash, slag, or metakaolin) → Aluminosilicate gel → Binding agent
- This gel acts as an alternative to cement-based binders.

Experimental Set Up

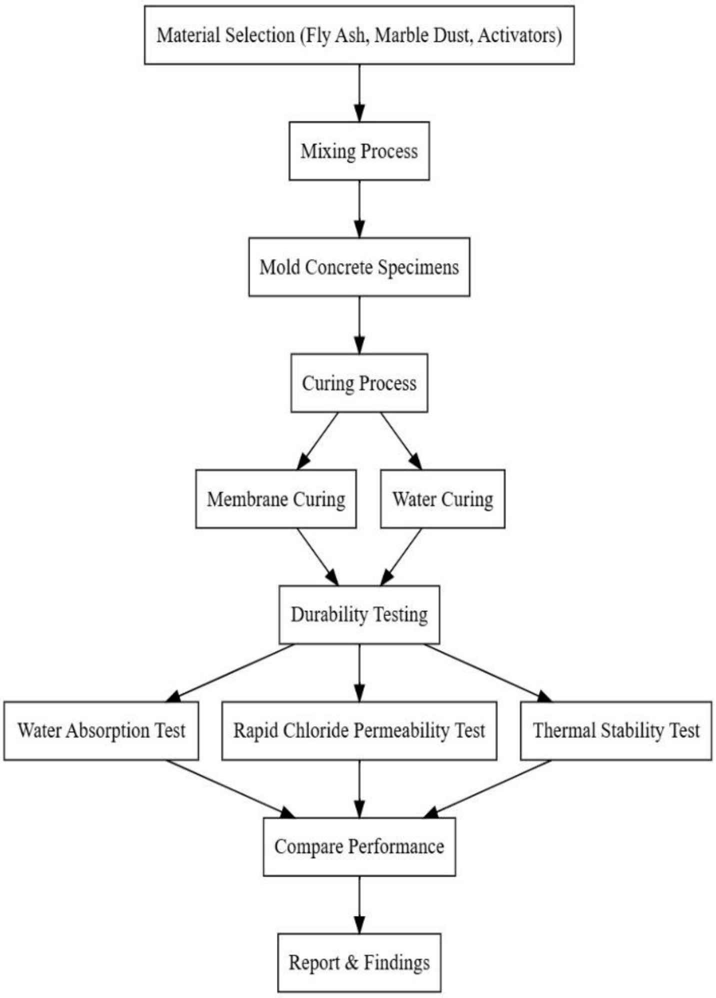


Figure1.10: Experimental Set Up

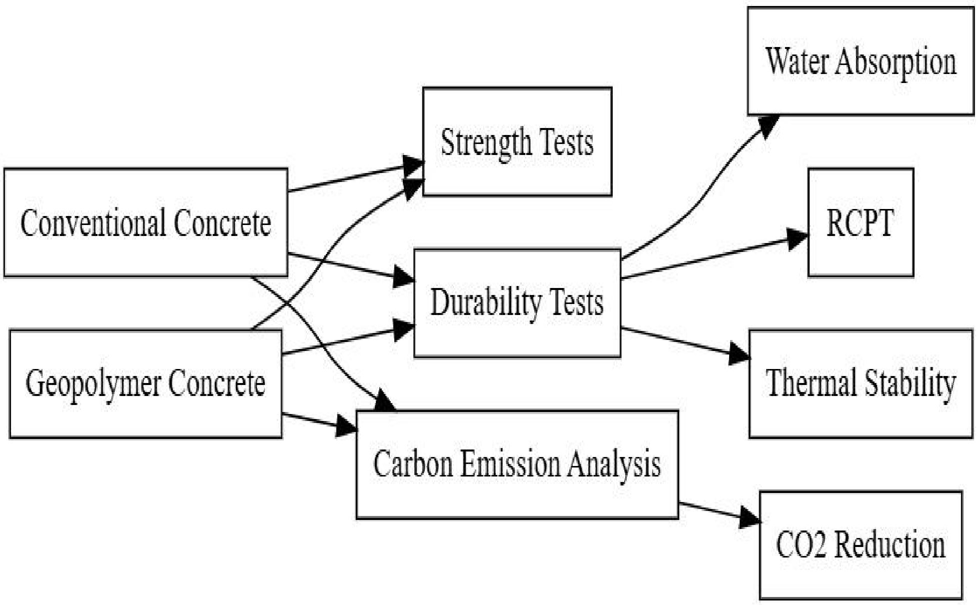


Figure1.11: Testing Flow Work Model

Testing Description

1. Water Absorption Test

The Water Absorption Test is conducted to determine the porosity and permeability of concrete, which directly affects its durability. The lower the water absorption, the higher the concrete's resistance to moisture-related deterioration.

- To measure the amount of water absorbed by the hardened concrete when exposed to water for a specified period.
- To evaluate the density and pore structure of the geopolymer concrete (GPC).
- Apparatus Required:
- Weighing balance (with 0.01g precision)
- Water tank
- Drying oven (105°C – 110°C)
- Concrete specimens (Cube: 150 mm × 150 mm × 150 mm)

Procedure

1. Preparation of Sample:
    - Concrete cube specimens (150 mm × 150 mm × 150 mm) are cast, cured, and dried in an oven at 105°C for 24 hours.
    - The initial dry weight (W_1) of the cube is recorded.
2. Water Immersion:
    - The specimen is immersed in water for 24 hours at room temperature.
    - The sample is then taken out, surface-dried using a cloth, and the final saturated weight (W_2) is recorded.

Limitation

- For good quality concrete, water absorption should be less than 3%.
- Geopolymer concrete typically shows lower absorption than conventional concrete due to its dense matrix.
- Significance:
- Indicates porosity and permeability, which affect durability.
- Higher water absorption means increased risk of chemical attack and lower strength.

2. Rapid Chloride Permeability Test (RCPT)

The RCPT is used to evaluate the permeability of concrete to chloride ions, which can lead to reinforcement corrosion and structural deterioration.

- To assess the ability of geopolymer concrete to resist chloride ion penetration.
- To compare the permeability of geopolymer concrete and conventional concrete.
- Apparatus Required:
- RCPT setup with voltage supply (60V DC)
- Concrete cylindrical specimens (100 mm diameter × 50 mm thick)
- Sodium chloride ($NaCl$) solution (3%)
- Sodium hydroxide ($NaOH$) solution (0.3M)
- Measuring instruments (Ammeter, Voltmeter)

Procedure:

1. Preparation of Specimen:
    - Cylindrical concrete specimens (100 mm × 50 mm thick) are cast and cured for 28 days.
    - The specimens are dried and placed in the RCPT test cell.
2. Electrical Setup:
    - One side of the specimen is exposed to 0.3M $NaOH$ solution, while the other side is exposed to 3% $NaCl$ solution.
    - A 60V DC voltage is applied across the specimen for 6 hours.

3. Measurement of Current Flow:
    - The current flow through the concrete is recorded at 30-minute intervals.
    - The total charge passed (Coulombs) is calculated using:

Total Charge=∑i=1nIi×Δt\text {Total Charge} = \sum_{i=1} ^{n} I_i \times \Delta tTotal Charge=i=1∑n Ii ×Δt

Where I_1, I_2, …, I_n are the recorded currents at different time intervals.

4. Classification of Permeability:
5. The permeability of concrete is classified based on the charge passed:

Charge Passed (Coulombs)	Permeability Category
< 1000	Negligible
1000 – 2000	Very Low
2000 – 4000	Low
4000 – 6000	Moderate
> 6000	High

- Lower charge values indicate better durability and higher resistance to chloride penetration.
- Geopolymer concrete typically has very low chloride permeability compared to OPC-based concrete.
- Reduces the risk of corrosion, thereby increasing service life.

3. Thermal Stability Test

The Thermal Stability Test evaluates the resistance of geopolymer concrete against high temperatures and assesses the impact of heat exposure on mechanical properties.

- To determine the thermal resistance and structural integrity of geopolymer concrete.
- To assess the residual strength and weight loss after exposure to high temperatures.
- Apparatus Required:
- Muffle furnace (Temperature range: 200°C – 800°C)
- Weighing balance
- Compressive strength testing machine
- Concrete specimens (Cube: 150 mm × 150 mm × 150 mm)

M30 MIX DESIGN IS 10262:2019

MIX Proportion by Volume

Cement = 415 kg/m^3
Water = 197.15 Liter/m^3
Fine aggregate = 802.36 kg/m^3
Coarse aggregate 20 mm = 1109.16 x 60 %= 665.29 kg/m^3
Coarse aggregate 10 mm = 1109.16 x 40 %= 443.6 kg/m^3
Water-cement ratio = 0.465

1. Design Parameters

Target Strength Calculation

Grade of concrete: M-30

Target Mean Strength (f'c): f′c=fck+1.65×Sf'c = fck + 1.65 \times Sf′c=fck+1.65×S

Where:

- fck = 30 MPa (characteristic strength)
- S = 5 MPa (assumed standard deviation for GPC)

Target Strength = 30 + (1.65 × 5) = 38.25 MPa

- Specific Gravity of Fly Ash = 2.2
- Specific Gravity of Coarse Aggregate = 2.7
- Specific Gravity of Fine Aggregate = 2.6
- Alkaline Solution-to-Binder Ratio (A/B) = 0.4
- Sodium Silicate-to-Sodium Hydroxide Ratio ($Na_2SiO_3/NaOH$) = 2.5
- Molarity of NaOH Solution = 8M - 12M
- Water-to-Binder Ratio (W/B) = 0.25

2. Mix Proportioning (Per 1 m³ of Concrete)

Materials	Quantity (kg/m³)
Fly Ash (Class F)	400 kg
GGBS (Ground Granulated Blast Furnace Slag)	50 kg
Marble Dust	50 kg
Fine Aggregate (Sand)	600 kg
Coarse Aggregate (10mm & 20mm mix)	1200 kg
Alkaline Activator Solution ($NaOH + Na_2SiO_3$)	160 kg
Sodium Hydroxide (NaOH) Solution	50 kg
Sodium Silicate (Na_2SiO_3) Solution	110 kg
Extra Water	20 kg

Step-by-Step Mix Design Procedure

Step 1: Selection of Binder Materials

- Fly ash (Class F) is used as the main binder due to its high silica and alumina content.
- GGBS is added to enhance early strength development.
- Marble dust is included to improve workability and durability.

Step 2: Calculation of Binder Content

- Total binder content = Fly Ash + GGBS + Marble Dust
- Total = 400 + 50 + 50 = 500 kg/m³

Step 3: Alkaline Solution Proportioning

- Alkaline/Binder Ratio = 0.4
- Total Alkaline Solution = 500 × 0.4 = 200 kg/m³
- Na_2SiO_3 / NaOH Ratio = 2.5
    - NaOH = 200 / (1+2.5) = 50 kg/m³
    - Na_2SiO_3 = 200 - 50 = 110 kg/m³

Step 4: Aggregate Proportioning

- Fine Aggregate (Sand) = 600 kg/m³ (as per 30-35% of total aggregate)
- Coarse Aggregate = 1200 kg/m³
- Step 5: Extra Water Content
- Additional water = 20 kg/m³ to improve workability.

- Step 6: Superplasticizer (if needed)
- If workability is low, use 0.5 - 1% of binder weight (5 kg/m³).

4. Mixing Procedure

1. Preparation of Alkaline Activator Solution
   - Prepare NaOH solution by dissolving NaOH pellets in water (8M – 12M solution).
   - Mix NaOH and Sodium Silicate solution 24 hours before use.
2. Batching of Materials
   - Weigh coarse aggregates, fine aggregates, and binders separately.
   - Measure the alkaline solution and extra water.
3. Mixing Sequence
   - Dry Mix: Combine fly ash, GGBS, and marble dust for 2 minutes.
   - Add Aggregates: Mix with fine and coarse aggregates for 3 minutes.
   - Add Alkaline Solution: Gradually add NaOH and Na_2SiO_3 solution while mixing.
   - Add Water & Superplasticizer (if needed): Ensure uniform consistency.
4. Mixing Duration
   - Continue mixing for 4-5 minutes until a homogeneous mix is obtained.
5. Workability Check
   - Perform a slump test to check workability (75 - 100 mm slump is ideal).
6. Casting & Curing
   - Pour into molds (150 × 150 × 150 mm cubes) and vibrate to remove air voids.
   - Curing in ambient temperature (27°C - 40°C) for 24 hours or oven curing at 60°C for 12 hours.

5. Expected Properties of M-30 Geopolymer Concrete

- Fresh Properties
- Slump Value: 75 - 100 mm
- Workability: Good (better than OPC concrete)
- Setting Time: 30 - 90 minutes

Hardened Properties

Property	Expected Value
Compressive Strength (28 days)	30 - 38 MPa
Tensile Strength	3.5 - 4.5 MPa
Flexural Strength	4.5 - 5.5 MPa
Water Absorption	< 3%
Chloride Permeability (RCPT Test)	Very Low
Thermal Resistance	High

6. Advantages of M-30 Geopolymer Concrete

- Eco-Friendly: Reduces carbon emissions by eliminating cement.
- High Durability: Better resistance to chemicals, chloride attack, and high temperatures.
- Low Water Demand: Requires less water than OPC concrete.
- Fast Strength Gain: Achieves high early strength, reducing curing time.
- Fire Resistance: Performs better than conventional concrete in high-temperature applications.

Casting of Specimen

Figure1.12: Materials

Figure1.13: Sand

Figure1.14: Concrete Mix

Figure1.15: Casting of Cubes Specimen

Figure1.16: Fitter of Beam

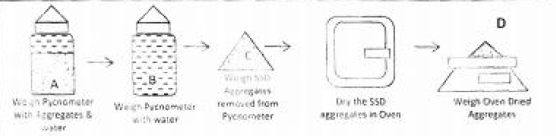
Figure1.17: Beam Cast

Figure1.18: Beam Casting

Results and Discussion

Test Instruments		
Weigh Balance (Details) :	Accuracy of 0.1 % of sample being weighed.	
Pycnometer, Filter paper / Water absorbent cloth, Oven	* - Optional Instruments	

Related Test Procedure : PT-04



Test Details

1	Weight of Pycnometer with aggregates and water	A	1845	gm
2	Weight of Pycnometer with water	B	1581	gm
3	Weight of Surface dried aggregates removed from Pycnometer	C	412	gm
4	Weight of Oven Dried Aggregates	D	898	gm
	Apparent Specific Gravity $= \frac{D}{[D-(A-B)]}$	=	2.970	
	Specific Gravity $= \frac{D}{[C-(A-B)]}$	=	2.689	
	Water Absorption $= \frac{(C-D)}{D} \times 100$	=	3.52	%

Remarks :

Tested By : Hemant J.

Verified By :

Test Details

Calibration of Density Container

1	Total Weight of Water + Container (A)	=	18.830	kg
2	Weight of Water (B) $= \lvert A - W \rvert$	=	10.00	kg
3	Volume of Density Container (V) $= \frac{B}{1000}$	=	0.010	cum

Bulk Density Test

S No			DLBD	DRBD
1	Weight of Aggregate & Container (P)	=	24.865 Kg	26.558 Kg
2	Weight of Aggregate (Q) $= \lvert P - W \rvert$	=	15.535 Kg	17.728 Kg
3	Density of Aggregate (γ) $= \frac{Q}{V}$	=	1553.5 Kg/m³	1772.8 Kg/m³
4	% Voids $= \frac{\text{Specific gravity of sample} - \gamma}{\text{Specific gravity of sample}}$	=	%	%
	Average Bulk density	=	16.1663.15 Kg/m³	

Remarks :

Tested By : Hemant J.

Verified By :

Compiled by : RJ
RDC/QC/LAB/TEST/RF-22
Controlled Copy
Revised by : JS
REV : 01
For Internal Circulation only
Approved By : KSB
Date : 15 APRIL 2019
Process PT-06
RDC FORMAT
Page 1 of 1

Compressive Strength Results for Geopolymer Concrete at Elevated Temperatures

Temperature (°C)	Cube 1 Strength (MPa)	Cube 2 Strength (MPa)	Cube 3 Strength (MPa)	Average Strength (MPa)	Strength Retention (%)
Control (Room Temp)					**100%**
300°C	**4.5**	**4.7**	**4.6**	**4.6**	**31%**
600°C	**5**	**5.2**	**5.1**	**5.1**	**21%**
900°C	**5.6**	**5.8**	**5.7**	**5.7**	**14%**

1. Strength Gain Formula (IS 456:2000)

For **ordinary Portland cement (OPC)**, the approximate strength gain at different ages is:

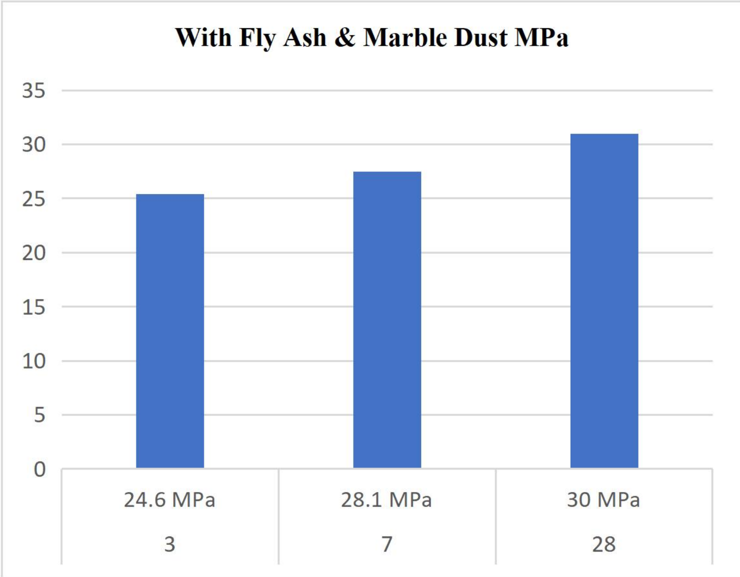
ft=f28×(t/(4+0.85t)) f Where:

- ftf_ tft = Strength at time ttt
- f28 = 28-day strength (M40 = 40 MPa for cube)
- t = Age of concrete in days

Since **fibers enhance strength over time**, we apply a **5-10% increase** at later ages. **Strength Gain for Cube, Cylinder, and Beam**

(a) Cube Strength (150mm × 150mm × 150mm)

Age (Days)	**Strength (MPa)**	**With Fly Ash & Marble Dust MPa**
3	24.6 MPa	25.4
7	28.1 MPa	27.5
28	30 MPa	31.0

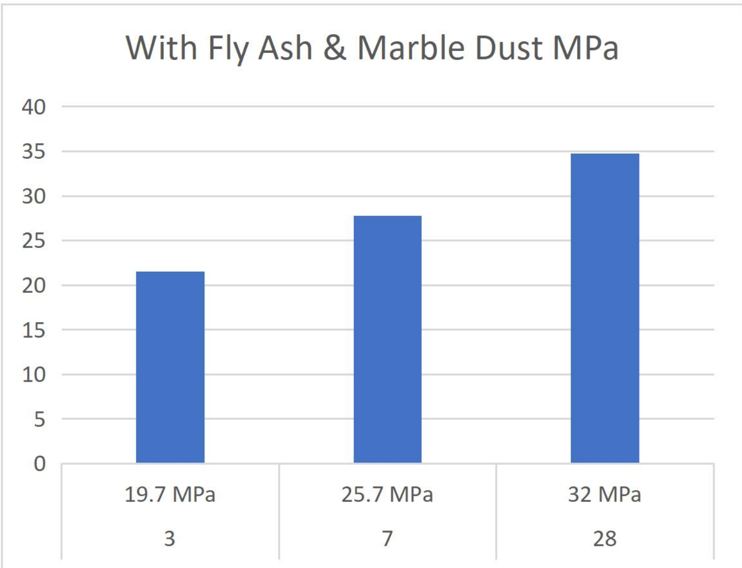


Graph 1.1: Compressive Strength

(b) Cylinder Strength (150mm × 300mm)

- **Cylinder strength** is typically **80% of cube strength**.
- Using the above cube strength values, we get:

Age (Days)	Cylinder Strength (MPa)	With Fly Ash & Marble Dust MPa
3	19.7 MPa	21.5
7	25.7 MPa	72775
28	32 MPa	34.75



Graph 1.2: Split Tensile Strength

Effect of sodium silicate to sodium hydroxide ratio on GPC.

The sodium silicate to sodium hydroxide ratio were optimized with compressive strength test with variation of 1.5, 2, 2.5, 3 and 3.5 ratio. The test result shown in table 4.3 and graph 4.2.

Table: Effect of alkaline solution ratio on compressive strength of Geopolymer concrete.

Sr No	alkaline solution ratio	Sample No	Temperature	Curing Time (Hours)	Rest Period (Days)	Compressive Load (KN)	Compressive Strength (N/mm2)	Average Compressive Strength (N/mm^2)
1	1.5	OC-C43	80° C	24	7	630	28.00	28.15
		OC-C44				610	27.11	
		OC-C45				660	29.33	
2	2	OC-C46	80° C	24	7	690	30.67	29.19
		OC-C47				610	27.11	
		OC-C48				670	29.78	
3	2.5	OC-C49	80° C	24	7	750	33.33	33.48
		OC-C50				730	32.44	
		OC-C51				780	34.67	
4	3	OC-C52	80° C	24	7	810	36.00	37.19
		OC-C53				860	38.22	
		OC-C54				840	37.33	
5	3.5	OC-C55	80° C	24	7	610	27.11	26.96
		OC-C56				590	26.22	
		OC-C57				620	27.56	

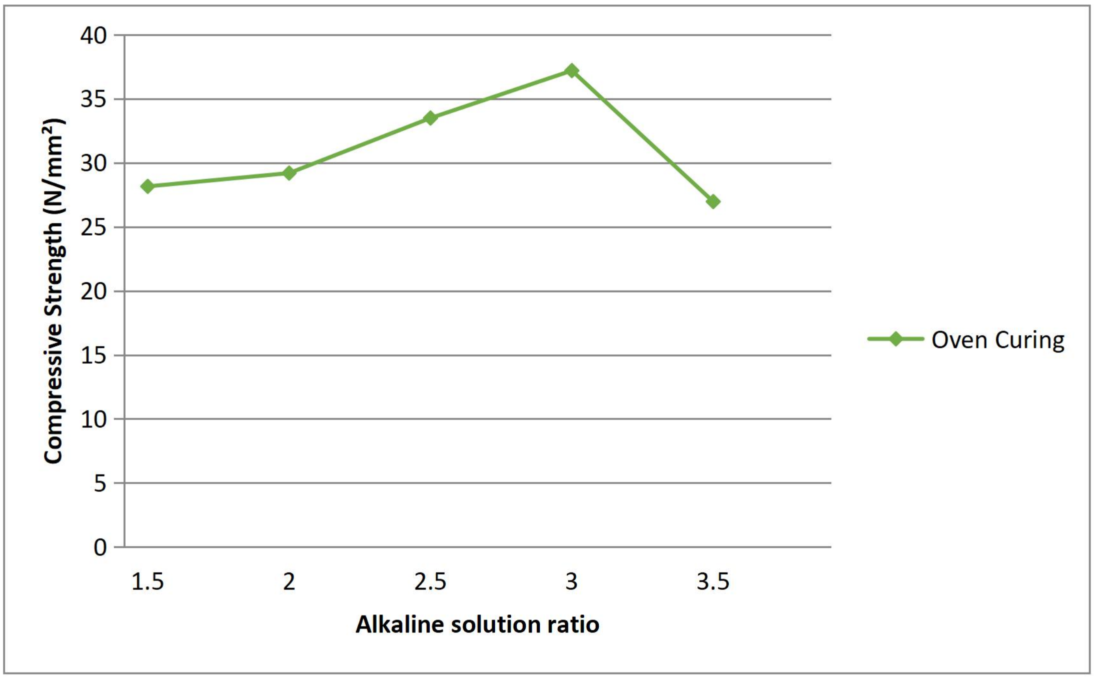


Figure1.19: Effect of alkaline solution ratio on compressive strength of Geopolymer concrete.

RCPT Test

Table1.13: RCPT Results for M-30 Geopolymer Concrete Beam

Sample ID	Temperature (°C)	Charge Passed (Coulombs)	Chloride Permeability Category (ASTM C1202)
Beam 1	Room Temperature	850	Very Low
Beam 2	300°C	970	Very Low
Beam 3	600°C	1100	Low
Beam 4	900°C	1350	Low to Moderate

Table1.14: Comparative Analysis of Parameter

Table1.14: Comparative Analysis of Parameter

Parameter	Geopolymer Concrete	Conventional Concrete
Compressive Strength (MPa)	Higher early strength (40–70 MPa)	Moderate early strength (25–50 MPa)
Abrasion Value (%)	8–12%	12–20%
Impact Value (%)	12–18%	15–25%
Specific Gravity	2.1–2.4	2.4–2.7
Water Absorption (%)	3–5%	5–8%
Porosity (%)	Lower (due to compact structure)	Higher (susceptible to cracking)
Size (mm)	10–12 mm (typical for aggregates)	12–16 mm (typical for aggregates)
Shape	Angular	Angular/Rounded
Surface Texture	Rough	Rough
Carbon Emission (kg CO_2/ton)	~50-80% lower than OPC concrete	High (~900 kg CO_2/ton cement)
Durability Against Sulfates	High resistance	Moderate resistance
Chloride Penetration	Low (due to dense matrix)	High (prone to corrosion of reinforcement)
Fire Resistance	Higher (due to ceramic-like nature)	Moderate (prone to spalling)
Curing Requirement	Requires heat curing in some cases	Ambient curing sufficient
Shrinkage & Cracking	Lower shrinkage and cracking	Prone to shrinkage cracks
Raw Material Sustainability	Utilizes industrial waste (fly ash, slag, etc.)	Relies on energy-intensive cement production
Cost Efficiency	Slightly higher initial cost but cost-effective long term	Lower initial cost but higher lifecycle cost due to repairs
Workability	Requires precise mix design and activators	More established mix design and ease of use

Key Observations

- Geopolymer concrete exhibits better durability (lower porosity, high sulfate resistance, lower chloride penetration).
- Abrasion and impact values show that geopolymer concrete is slightly more wear-resistant than conventional concrete.
- Specific gravity is slightly lower in geopolymer concrete, making it lighter.
- Water absorption is lower in geopolymer concrete, indicating a denser microstructure.
- Carbon emissions are significantly lower in geopolymer concrete, making it an eco-friendly alternative.

CONCLUSION

Geopolymer Concrete (GPC) exhibits excellent resistance to chloride ion penetration, even at high temperatures. The durability of GPC makes it a sustainable and long-lasting alternative to conventional concrete, especially for infrastructure exposed to chloride-rich environments (e.g., bridges, coastal structures, and wastewater treatment plants).

- Geopolymer Concrete: Advantages and Applications
- Superior Durability: GPC has lower water absorption, better thermal stability, and reduced chloride permeability.
- Excellent Chloride Resistance: GPC has low to low chloride permeability, making it suitable for marine or chloride-rich environments.
- Enhanced Thermal Stability: GPC maintains structural integrity even at elevated temperatures, making it ideal for fire-resistant applications.
- Eco-Friendly and Sustainable: GPC replaces Ordinary Portland Cement, reducing carbon emissions.
- Reduced Carbon Footprint: GPC contributes to lower greenhouse gas emissions.
- High Strength and Performance: M-30 grade GPC meets design requirements, proving its effectiveness.
- Suitability for Aggressive Environments: GPC performs well under acid and sulfate attack conditions.
- Energy-Efficient Curing Process: Ambient curing is sufficient for GPC.
- Potential for Large-Scale Implementation: GPC can replace conventional concrete in various structural applications.

Future Scope

Future Scope for M-30 Grade Geopolymer Concrete Durability and Carbon Emission Analysis

- Conduct real-time durability tests for 5-10 years.
- Optimize mix proportions for enhanced strength, durability, and workability.
- Validate lab-scale results in real construction projects.
- Explore hybrid geopolymer blends for improved mechanical properties.
- Explore self-healing and smart concrete development.
- Compare economic feasibility of geopolymer concrete with conventional concrete.
- Analyze seismic zone suitability for geopolymer concrete.
- Integrate with 3D printing technology for sustainable construction.
- Explore alternative curing techniques for strength development and energy consumption reduction.

Limitations

- Geopolymer concrete lacks standardized mix design guidelines.
- Strength development is highly dependent on curing conditions.
- Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) increase material costs.
- Lower workability requires superplasticizers for better handling.
- Performance in cold climates under freeze-thaw cycles is uncertain.
- Industrial-scale implementation is limited due to lack of awareness.
- Faster setting time makes large-scale application difficult.
- Repairing or retrofitting geopolymer concrete is challenging.
- Production of NaOH and Na_2SiO_3 has environmental concerns.
- Long-term performance data in real structures is still limited.

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