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by Madhuri Bhagat

"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.
Durability tests such as water absorption, acid resistance, sulfate resistance, and rapid chloride penetration test (RCPT) are conducted to compare the long-term performance of geopolymer concrete with conventional concrete. Compressive strength tests on cube specimens (150 mm × 150 mm × 150 mm) are performed at 3, 7, and 28 days to assess strength development and split tensile strength tests on cylinder specimens (150 mm × 300 mm) are carried out at 28 days to evaluate the mechanical properties.
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.

This study focuses on evaluating the durability performance and carbon emission analysis of Geopolymer Concrete in comparison to Conventional Concrete for M-30 grade. The research aims to assess the mechanical properties and long-term durability characteristics of both concrete types through experimental testing of cube, beam, and cylinder specimens. The compressive strength of cube specimens (150 mm × 150 mm × 150 mm), flexural strength of beam specimens (100 mm × 100 mm × 500 mm), and split tensile strength of cylindrical specimens (150 mm × 300 mm) are examined at different curing ages. Additionally, durability tests such as acid resistance, sulfate resistance, water absorption, and rapid chloride penetration test (RCPT) are conducted to determine the resistance of both concrete types 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.

Concrete is the most commonly used construction material worldwide due to its high strength, durability, and versatility. However, the environmental impact of cement-based conventional concrete (CC) is a growing concern, as cement production is a major contributor to global carbon dioxide (CO_2) emissions. To address this issue, Geopolymer Concrete (GPC) has emerged as a promising alternative that significantly reduces carbon emissions by replacing Portland cement with industrial by-products such as fly ash and Ground Granulated Blast Furnace Slag (GGBS). This study aims to investigate the durability performance and carbon emission analysis of GPC compared to CC for M-30 grade concrete, with a particular focus on key durability and strength parameters.

The experimental program includes the testing of cube, beam, and cylinder specimens to evaluate Water Absorption Test, Thermal Test, and Rapid Chloride Penetration Test (RCPT), respectively. The GPC mix is designed using fly ash and GGBS as primary binder materials, activated with sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. Unlike conventional concrete, GPC specimens are cured under ambient conditions to eliminate heat curing, making the production process more energy-efficient and environmentally sustainable. This feature enhances the practical applicability of geopolymer concrete, making it an attractive solution for eco-friendly construction.

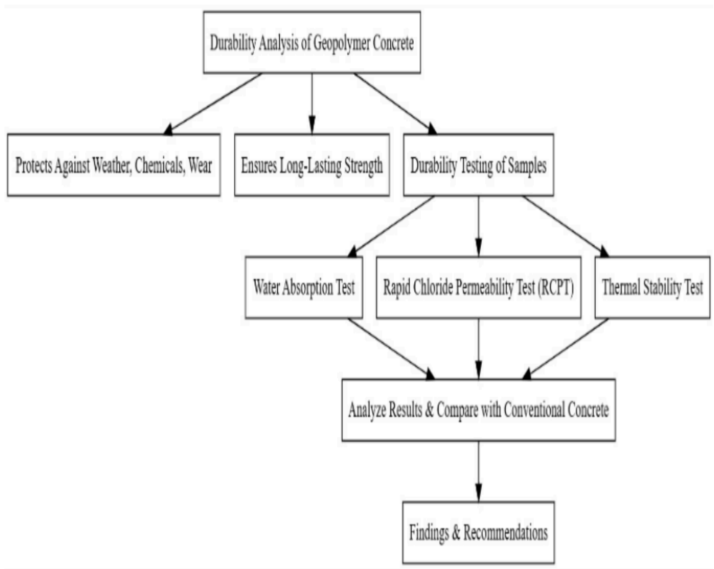


Figure1.1: Workflow Diagram

To assess the durability performance of both geopolymer and conventional concrete, a series of tests are conducted. Water absorption tests are performed to evaluate the permeability and porosity of the concrete specimens, which directly influence their resistance to moisture ingress and potential degradation over time. Thermal tests analyze the heat resistance and thermal stability of GPC compared to CC, ensuring its suitability for applications in high-temperature environments. Additionally, Rapid Chloride Penetration Tests (RCPT) measure the chloride ion permeability of the concrete, which is crucial in assessing its resistance to corrosion in marine and chloride-rich environments.

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 findings of this research indicate that geopolymer concrete exhibits superior durability performance compared to conventional concrete, particularly in aggressive environments. GPC demonstrates lower permeability, enhanced resistance to chemical attacks, and improved thermal stability, making it a viable alternative for sustainable construction applications. Moreover, the significant reduction in carbon emissions associated with GPC highlights its potential contribution to global efforts aimed at mitigating climate change.

By replacing conventional cement-based concrete with geopolymer concrete, the construction industry can take a significant step toward reducing its carbon footprint while maintaining the required structural integrity, strength, and durability. This study underscores the practical viability of geopolymer concrete as a long-term sustainable solution, paving the way for further research and implementation in various infrastructure projects.

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

Geopolymer concrete (GPC) has emerged as a sustainable alternative to Ordinary Portland Cement (OPC) concrete due to its potential for significant carbon emission reduction. This study focuses on analyzing the carbon emissions associated with the production and utilization of geopolymer concrete, highlighting its environmental advantages over conventional concrete. Geopolymer concrete is typically synthesized using industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume, activated by alkaline solutions like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3).

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.

The analysis not only demonstrates the potential of geopolymer concrete in mitigating climate change but also provides insights into optimizing mix design for maximum environmental and structural performance. The findings support the transition to low-carbon construction practices in alignment with global sustainability goals.

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 and ground granulated blast furnace slag (GGBS) as binder materials activated by alkaline solutions (NaOH & Na_2SiO_3).
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.
   - Acid and Sulfate Resistance Tests to examine durability in aggressive environments.
   - 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 is one of the largest contributors to carbon emissions due to the extensive use of Ordinary Portland Cement (OPC) in conventional concrete (CC). The production of cement releases a significant amount of CO_2, contributing to environmental pollution and climate change. Additionally, conventional concrete faces challenges related to durability in aggressive environments, including chloride penetration, sulfate attack, and acid resistance, which can lead to structural deterioration and increased maintenance costs over time.

In contrast, Geopolymer Concrete (GPC), made from industrial by-products like fly ash and ground granulated blast furnace slag (GGBS), offers a sustainable alternative by eliminating the need for OPC, thereby reducing carbon footprint and energy consumption. However, limited research exists on the durability performance and mechanical properties of GPC in comparison to CC, particularly for M-30 grade concrete under real-world conditions. The impact of ambient curing conditions, strength development over time, and resistance to environmental degradation needs further investigation to determine its suitability for large-scale construction applications.
This study aims to address these gaps by comparing the mechanical, durability, and environmental performance of GPC and CC through rigorous testing on cube, beam, and cylinder specimens. Furthermore, a Life Cycle Assessment (LCA) will be conducted to evaluate the carbon emissions reduction associated with GPC, ensuring a more sustainable and eco-friendly construction material without compromising structural integrity.

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.

Ahmed M. Tahwia et al., MDPI, 2023. "Chopped Basalt Fiber-Reinforced High-Performance Concrete: An Experimental and Analytical Study"

Researchers have investigated the impact of chopped basalt fiber on the workability, compressive strength, and impact resistance of high-performance concrete (HPC). They used various lengths and volume fractions of BF in sixteen mixes, measuring their compressive strength and impact resistance. Scanning electron microscopy analysis revealed that adding BF improved the compressive strength and impact resistance, with the strength increasing with a dosage of 8 kg/m3. The BF accumulated in pores and the cement surface, enhancing the strength and ductility of the HPC.

M. Murillo et al., ELSEVIER, 2024. "Use of animal fiber-reinforcement in construction materials: A review"

Animal fibers (AFs) have been used as reinforcement in construction materials for millennia, but recent studies have focused on vegetal fibers over AFs. This paper presents a comprehensive review of different types of AFs and their use in four specific CM matrices. The study found that AFs can improve physical, thermal, mechanical, damage, and durability properties of CMs, provide environmental benefits, and reduce costs. However, there are still research gaps in the use of specific AFs and combinations between AFs and CMs, and these gaps are recommended for future studies.

GAP OF RESEARCH

Despite significant advancements in machine learning applications for crack prediction, several limitations persist within current models. A common issue is the focus on specific types of concrete or particular environmental conditions, which can limit the generalizability of findings across diverse contexts. Moreover, many studies rely on relatively small datasets, which restrict the robustness and reliability of predictions. The intricate nature of crack behavior, influenced by a multitude of variables, presents challenges in developing comprehensive models capable of accounting for all potential factors contributing to crack formation.

Areas for Further Investigation

Addressing the identified gaps in current research is crucial for advancing the field of crack prediction in geopolymer concrete. Future research should prioritize the development of generalized models applicable across various types of geopolymer concrete and diverse environmental conditions. Expanding datasets to incorporate real-time monitoring data from multiple structures will enhance the robustness of machine learning models. Additionally, investigating the integration of advanced sensing technologies and the Internet of Things (IoT) can facilitate real-time data acquisition and analysis, promoting proactive maintenance strategies. Exploring the interactions between various influencing factors, such as temperature fluctuations, humidity levels, and load variations, will deepen insights into crack formation mechanisms, ultimately leading to improved predictive accuracy and structural resilience.

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.

Mechanical and Durability Performance Evaluation

To assess the mechanical properties of GPC and CC, various laboratory tests are conducted on cube, beam, and cylinder specimens. Compressive strength tests on cube specimens (150 mm × 150 mm × 150 mm) are performed at 3, 7, and 28 days to evaluate strength development over time. These tests help in understanding the overall structural performance of both concrete types under different loading conditions.

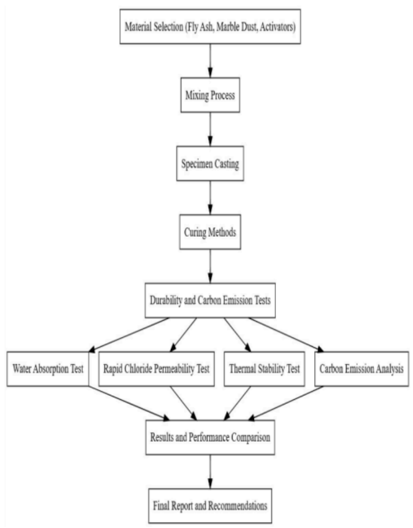


Figure1.2: Research Work Flow

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

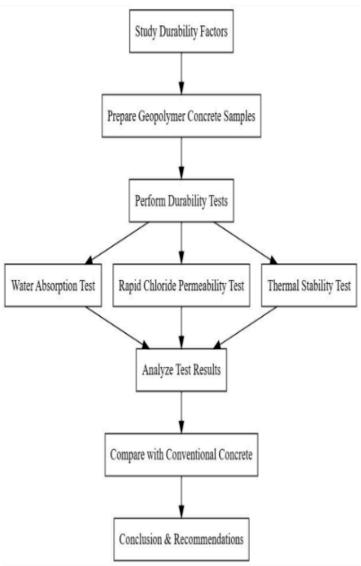


Figure1.3: Framework

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

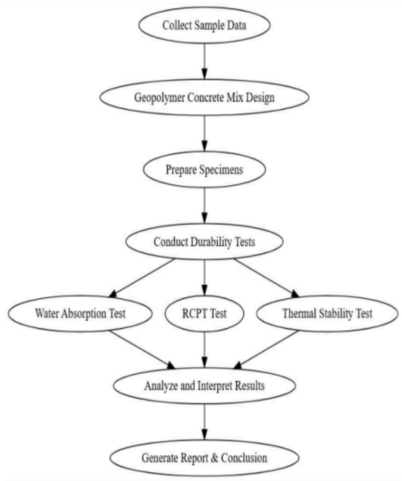


Figure1.4: Data Flow Diagram

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.

The absence of cement in geopolymer concrete significantly lowers its carbon footprint, making it a promising material for sustainable construction. GPC exhibits superior durability, chemical resistance, and mechanical performance compared to conventional cement-based concrete.

Physical Properties of Geopolymer Concrete

Table1.1: Physical Properties of Geopolymer Concrete

Property	Description
Density	Typically ranges between 2200–2500 kg/m^3, 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 attack, 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.

Chloride Resistance	Higher resistance due to low permeability, reducing steel corrosion in reinforced structures.
Acid Resistance	Superior to OPC concrete, as it does not contain calcium hydroxide (Ca $(OH)_2$), which reacts with acids to form soluble salts.
Sulfate Resistance	Excellent due to the absence of gypsum-related compounds that cause expansion and cracking.
Efflorescence Formation	Minimal due to the reduced presence of free calcium compounds.

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.

Fly ash plays a crucial role in geopolymer concrete, contributing to strength, durability, and sustainability. Its chemical composition and physical properties make it an efficient alternative to OPC, reducing carbon emissions while enhancing performance in aggressive environments. The use of fly ash in M-30 grade GPC offers a cost-effective and eco-friendly solution for modern construction applications.

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%

1. Fineness & Particle Size Distribution – Fly ash particles are typically spherical and fine, improving the workability and flowability of concrete.
2. Specific Gravity – The low specific gravity (compared to OPC) helps reduce the overall density of concrete.
3. Bulk Density – Lower bulk density reduces segregation and improves packing density in the mix.
4. Pozzolanic Activity – The high pozzolanic index contributes to the formation of additional C-S-H (Calcium-Silicate-Hydrate) gel in combination with alkaline activators.
5. Loss on Ignition (LOI) – A lower LOI indicates less unburnt carbon, ensuring better cementitious properties.

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%

1. High Silica (SiO_2) and Alumina (Al_2O_3) Content – These oxides react with alkaline activators (NaOH & Na_2SiO_3) to form geopolymer gel, providing strength and durability.
2. Iron Oxide (Fe_2O_3) – Enhances strength and improves resistance to corrosion and aggressive environments.
3. Calcium Oxide (CaO) – Influences the setting time and strength development. Lower CaO content in low-calcium fly ash (Class F) ensures better durability.
4. Magnesium Oxide (MgO) and Sulfates (SO_3) – Present in minimal quantities to avoid expansion and cracking.
5. Alkali Content (Na_2O & K_2O) – Helps in alkaline activation but should be controlled to prevent efflorescence.

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%
Silicon Dioxide (SiO_2)	2 – 8%
Aluminum Oxide (Al_2O_3)	0.5 – 2%
Iron Oxide (Fe_2O_3)	0.3 – 1%
Magnesium Oxide (MgO)	0.5 – 1.5%

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 influence 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%

- Size & Shape: Angular aggregates (typically 10 mm to 20 mm) provide better interlocking and mechanical strength.
- Specific Gravity: Determines the density and compactness of the aggregate, affecting the overall density of concrete.
- Bulk Density: Indicates how well the aggregate packs together, impacting workability and strength.
- Water Absorption: Affects water demand in the mix; lower absorption is preferred to maintain workability.
- Crushing & Impact Values: Ensure strong and durable aggregates, reducing cracking and failure under load.
- Flakiness & Elongation Index: Controls aggregate shape and grading, ensuring better bonding and reduced voids.

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%

- Silicon Dioxide (SiO_2): Improves strength and durability in concrete.
- Calcium Oxide (CaO): Affects binding and hydration reactions in GPC.
- Magnesium Oxide (MgO): Provides stability and resistance to shrinkage.
- Iron Oxide (Fe_2O_3) & Aluminum Oxide (Al_2O_3): Influence hardness and resistance to environmental attacks.

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

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

Experimental Set Up

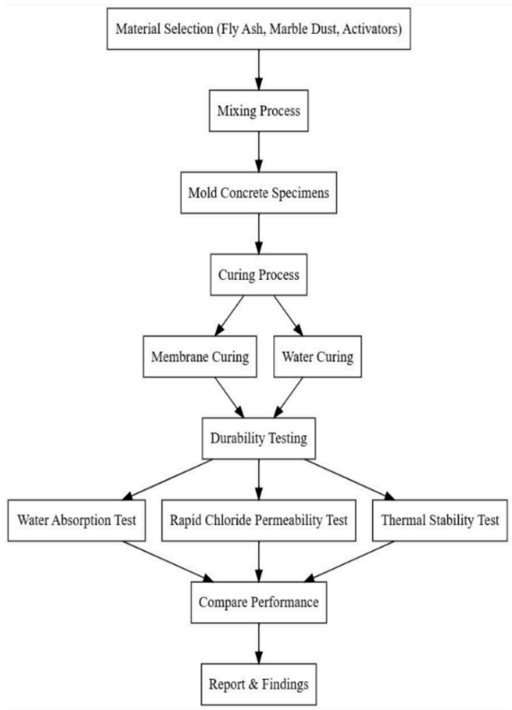


Figure1.10: Experimental Set Up

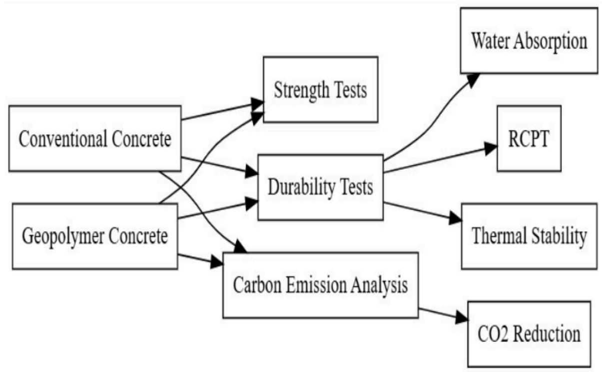


Figure1.11: Testing Flow Work Model

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.

Calculation of Water Absorption:

Water Absorption(%)=(W2−W1W1)×100\text{Water Absorption} (\%) = \left(\frac{W_2 - W_1}{W_1} \right) \times 100Water Absorption(%)=(W1W2−W1)×100

- W_1 = Dry weight (in grams)
- W_2 = Wet weight after immersion (in grams)

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∑nIi×Δt

Where $I_1, I_2, \ldots, I_n$ 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)

Procedure:

1. **Specimen Preparation:**
   - Standard M-30 grade geopolymer concrete cubes (150 mm × 150 mm × 150 mm) are cast and cured for 28 days.
   - The initial weight of the cube is recorded before heating.
2. **Heat Exposure:**
   - Specimens are placed in a muffle furnace and subjected to different temperature ranges (200°C, 400°C, 600°C, 800°C) for 2 hours.
   - The temperature is increased gradually to prevent thermal shock.
3. **Cooling and Weight Measurement:**
   - After heating, the cubes are cooled naturally to room temperature.
   - The final weight of each cube is recorded to calculate the weight loss.
4. **Compressive Strength Testing:**
   - The residual compressive strength is determined using a universal testing machine (UTM).
   - The strength retention percentage is calculated using:

Residual Strength (%) =(Strength after heating Initial Strength)×100\text{Residual Strength} (\%) = \left(\frac{\text{Strength after heating}}{\text{Initial Strength}} \right) \times 100Residual Strength(%)=(Initial Strength after heating)×100

Weight loss and strength reduction are analyzed for different temperatures.

- Geopolymer concrete shows better resistance to high temperatures compared to OPC concrete, with strength retention of above 70% at 600°C.
- Significance:
- Determines the fire resistance capability of geopolymer concrete.
- Helps in designing heat-resistant and fireproof structures.
- Useful in industrial and high-temperature applications (e.g., furnaces, chimneys).

M30 MIX DESIGN IS 10262:2019

Concrete Mix Design for M – 30 Grade of Concrete

Following steps for concrete mix design procedure as per IS Code 10262 – 2019

Step-1 Calculate Target Mean Strength of Concrete

In order that not more than the specified proportion of test results are likely to fall below the characteristic strength, the concrete mix has to be proportioned for higher target mean compressive strength f 'ck.
The Target mean characteristic strength is given by the following relation:

f'ck = fck + 1.65 S   or   f'ck = fck + X

whichever is higher.
Were,

f'ck = Target mean strength (compressive) at end of 28 days, in N/mm2;
S = standard deviation, in N/mm2 (see 4.2.1); and
X = Factor as per Grade of Concrete, as per Table 1.

Value of X for Concrete Mix Design as Per IS Code 10262 – 2019
Table – 2 Assumed Standard Deviation
For M -20 Grade of Concrete,

Standard Deviation for Concrete Mix Design as Per IS Code 10262 – 2019
Target Mean Compressive Strength (f'ck) = fck + 1.65 S
= 30 + 1.65 x 5 (S = 5.0 for M – 30)
= 38.25 N/mm²

Target Mean Strength ($f'ck$) = $fck + X$

$= 30 + 5.5$

$= 35.5\ N/mm^2$

Always select a higher value. Therefore, for the M-30 grade of concrete, we will try to achieve 38.25 N/mm^2 strength.

Step-2 Selection of Water-Cement Ratio

It is stated for concrete mix design as per is code that in general different types of cement, aggregates of various maximum size and supplementary cementitious materials, grading, surface texture, shape, and other characteristics may produce concrete of different compressive strength for the same free water–cement ratio.

Therefore, a proper relationship between the water-cement ratio and the strength of concrete should preferably be established for the materials actually to be used.

In case such data is not available, related water-cement ratio (by mass) (w/c) corresponding to the compressive strength at 28 days may be selected from the relationship shown in Fig.1, for the expected 28 days strength of cement.

Water-Cement ration Graph for Concrete Mix Design as Per IS Code 10262 – 2019
So, for the M – 30 Grade of concrete, we have a target mean strength of 38.25 N/mm^2 and we have OPC – 53 grades of cement.
As per our cement grade OPC -53, we have to follow Curve 3.
From the graph, for 38.25 N/mm^2 concrete strength at 28 days bisect the curve 3 at 0.475 free water-cement ratios.
Where supplementary cementitious materials are used, that is, mineral admixtures, the water cementitious materials ratio (w/cm) shall be calculated, in accordance with Table 5 of IS 456 and this w/cm shall be as per Table 3 and Table 5 of IS 456 or as specified

So, we select water-cement ratio for M- 30 grade of concrete is 0.475.

Suggestion: Always prefer a higher water–cement ratio for your concrete because IS code tests and studies are done in a controlled manner in laboratories which procedure and care are not possible on construction sites. So, my suggestion is to select a higher water-cement ratio for your concrete grade. (Higher means, for M -30 grade of concrete IS code indicates 0.475)

Step-3 Estimation of Air Content

The approximate volume of entrapped air content to be expected in normal (non-air-entrained) concrete is given in Table 3.

Estimated Air Content for Concrete Mix Design
We have a nominal maximum size of aggregate of 20 mm.
From the above table, the approximate air content as a percentage of the volume of concrete is 1 %

Step-4 Selections of Water Content and Admixture Content

The water content in concrete is generally affected by various factors, such as aggregate size, aggregate shape, aggregate texture, workability, water-cement ratio, cement, and other supplementary cementitious materials type and content, chemical admixture, and environmental conditions.

As aggregate maximum size increases, a reduction in water–cement ratio and slump, and the use of rounded aggregate and water reducing admixture will reduce the water demand.

On another side, if the cement content, slump, water–cement ratio, aggregate angularity, temperature, and a decrease in the proportion of the coarse aggregate to fine aggregate will increase water demand.

The amount of water content per unit volume of concrete may be determined from Table 4.

The water content given in Table 4 is for angular coarse aggregate and for 50 mm slump.

The water content given in Table 4 can be reduced by approximately 10 kg for sub–angular aggregates, 15 kg for gravel with some crushed particles, and 20 kg for rounded gravel to produce the same workability.

So, if required more workability means slump value more than 50 mm, the required water content may be increased or decreased by about 3 percent for each increase or decrease of 25 mm slump or may be established by trial.

We have a nominal maximum size of aggregate of 20 mm.
From the above table, the water content for the nominal maximum size of aggregate is 186 kg (Liter). (Slump 50 mm)
We want to increase the slump up to 100 mm. so we have to increase it twice by 25 mm. As per IS code we have increase water by about 3 percent for every additional 25 mm slump so here estimated water content for 100 mm slump.
For one 25 mm (3%) and second 25 mm (3%). Total increase in water content is 6%

= 186 + 186x(6/100)

= 197.16 Liters

Note: Increase Water Content as per for following

Slump Value	**Increase in Water in %**
50 mm	–
75 mm	3%
100 mm	6%
125 mm	9%
150 mm	12%

For 75 mm slump increase 3%, for 100 mm increase 6%, increase 9 % for 125 mm slump, increase 12 % for 150 mm slump & increase 15 for 175 mm slump.

Step-5 Estimation of Cement Content

We have water content and water–cement ratio. So, from this data, we can calculate cement content for concrete,
Water-Cement Ratio = 0.475
Water / Cement = 0.475
197.16 / Cement = 0.475
Cement = 197.16/0.475
Cement = 415.07 Kg.
From Table 5 of IS 456, minimum cement content for 'moderate' exposure conditions is 300 kg/m³ but taken 415.07 kg/m³ > 300 kg/m³ hence ok.

Step-6 Estimation of Coarse Aggregate Proportion

It is essential to use the specified nominal maximum size, type and grading will produce concrete of satisfactory workability when a given volume of coarse aggregate per unit volume of total aggregate is used.

Approximate values for this aggregate volume are given in Table 5 for a water-cement/water cementitious materials ratio of 0.45, which may be suitably adjusted for other ratios,

The proportion of the volume of coarse aggregates to that of total aggregates is increased at the rate of 0.01 for every decrease water cement/cementitious materials ratio by 0.045 and decreased at the rate of 0.01 for each increase in a water-cement ratio by 0.045.

Sometimes, it is required more workable concrete such as when placement is by pump or when the concrete is required to be worked around congested reinforcing steel. In such a case, it is desirable to reduce estimated coarse aggregate content determined using Table 5 up to 10 percent.

We have a maximum size of aggregate = 20 mm and which confirming the zone – II.
As per table number 5 of IS 10262:2019 volume of coarse aggregate for 20 mm nominal size aggregate and fine aggregate (Zone III) for having a water–cement ratio of 0.45 =0.475 (a

In the present case, the water–cement ratio is 0.475. Therefore, the volume of coarse aggregate is required to be decreased to increase the fine aggregate content.
As the water–cement ratio is higher by 0.12. the proportion of the volume of coarse aggregate is decreased by 0.014 (at the rate of -/+ 0.01 for every ± 0.05 change in the water-cement ratio).

= 0.12/0.05 = 2.4 % decrease in coarse aggregate content

= 0.475 – 0.62 x(2.4/100)

= 0.475 – 0.014

= 0.461

Therefore, the correct proportion of the volume of coarse aggregate for the water–cement ratio of 0.475 = 0.461

Or pumpable concrete these values should be reduced up to 10%.
Therefore, Coarse aggregate Volume =0.461 x 0.9 =0.4149
Fine Aggregate Volume = 1 – 0.4149 = 0.5841

Step-7 Mix Calculation for 1 m³

Material quantity calculation for concrete mix design as per IS Code – 10262: 2019,

A) Volume of concrete = 1 m³

B) Volume of Air Content wet concrete = 0.01m³

C) Volume of cement = [Mass of cement] / {[Specific Gravity of Cement] x 1000}

= 415/ {3.15 x 1000} = 0.1317 m³

D) Volume of water = [Mass of water] / {[Specific Gravity of water] x 1000}
= 197.15/ {1 x 1000} = 0.197 m³

E) Volume of all in aggregate = [(A-B)-(C+D)]
= [(1-0.01) -(0.1317+0.197)] = 0.99-0.297
= 0.6613 m³

F) Weight of coarse aggregate= E x Coarse Aggregate Volume x Specific Gravity of coarse Aggregate x 1000
= 0.6613 x 0.6 x 2.795 x 1000
= 1109.00 kg/m³

G) Weight of fine aggregate= E x Volume of Fine Aggregate x Specific Gravity of Fine Aggregate x 1000
= 0.6613 x 0.46 x 2.517 x 1000
= 765.66 kg/m³

MIX Proportion by Volume

Cement = 415 kg/m³
Water = 197.15 Liter/m³
Fine aggregate = 802.36 kg/m³
Coarse aggregate 20 mm = 1109.16 x 60 %= 665.29 kg/m³
Coarse aggregate 10 mm = 1109.16 x 40 %= 443.6 kg/m³
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
Superplasticizer (if required)	0.5 - 1% of binder weight

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

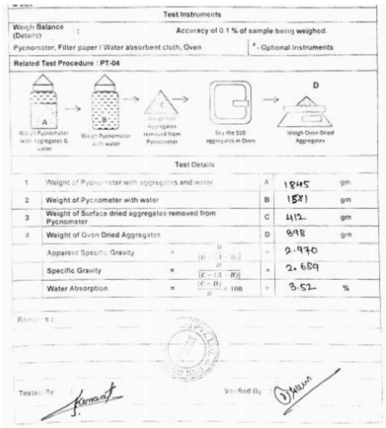
Figure1.15: Casting of Cubes Specimen

Figure1.16: Fitter of Beam

Figure1.17: Beam Cast

Figure1.18: Beam Casting

Results and Discussion



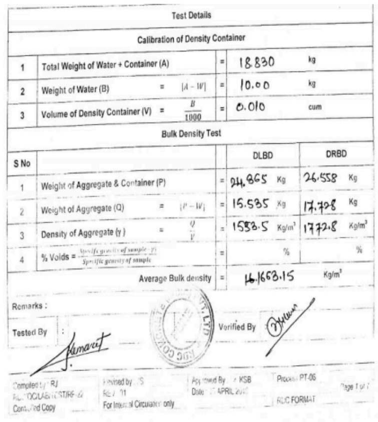
Test Instruments				
Weigh Balance (Details) :	Accuracy of 0.1 % of sample being weighed.			
Pycnometer, Filter paper / Water absorbent cloth, Oven	* - Optional Instruments			
Related Test Procedure : PT-04				

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	398	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 : Verified By :



Test Details

Calibration of Density Container

1	Total Weight of Water + Container (A)	=	18.830	kg
2	Weight of Water (B) = $[A-W]$	=	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) = $[P-W]$	=	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 : Verified By

Compiled by : RJ | Revised by : S | Approved By : KSB | Process: PT-06 | Page 1 of 1
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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:

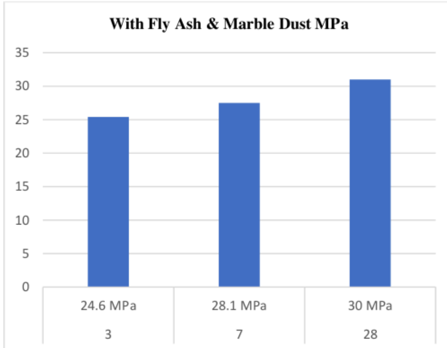
ft=f28×(t/(4+0.85t)) f Where:

- 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

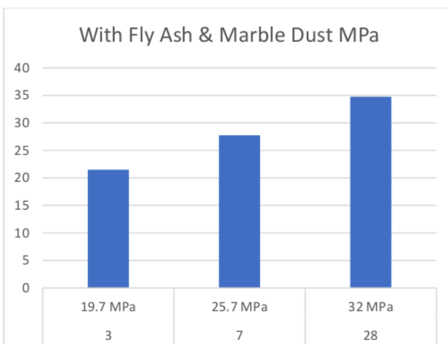


Graph 1.1: Compressive Strength

(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

11

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/mm²)
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	

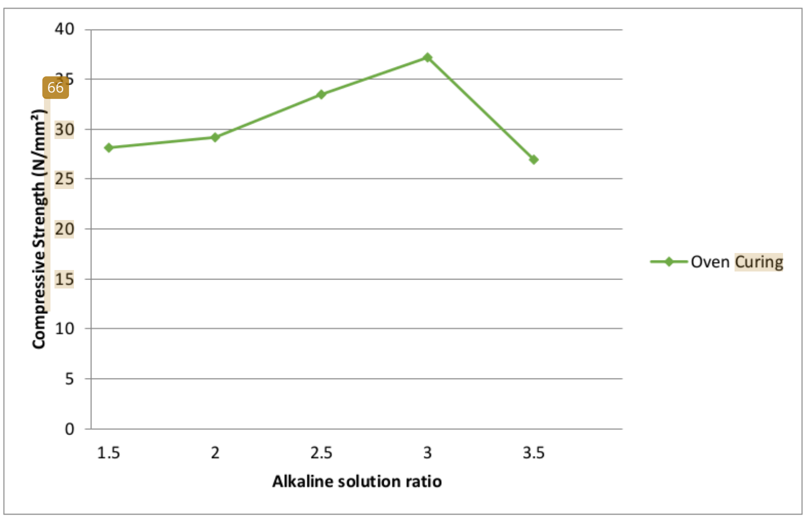


Figure1.19: Effect of alkaline solution ratio on compressive strength of Geopolymer concrete.

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

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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REFERENCES

[1] Sevar Dilkhaz Salahaddin et al., ELSEVIER,2024. "Rheological and mechanical characteristics of basalt fiber UHPC incorporating waste glass powder in lieu of cement"

[2] Mahmoud H. Akeed et al., ELSEVIER,2024. "Ultra-high-performance fiber-reinforced concrete. Part I: Developments, principles, raw materials"

[3] Ali H. AlAteah et al., ELSEVIER,2023. "Engineering characteristics of ultra-high performance basalt fiber concrete incorporating geranium plant waste"

[4] M.V. Molodtsov et al., MCE, 2020. "Behavior of concrete beams reinforced with fiberglass composite rebar under load"

[5] 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"

[6] Shaik Hussain et al., JJCE, Volume 17, No. 2, 2023. "Mechanical and Durability Performances of Alkali-resistant Glass Fiber-reinforced Concrete"

[7] Suhana Subair et al., IJRES, Volume 11 Issue 6, 2023. "The Effect of Fibre in Ultra High-Performance Concrete (UHPC): A Review"

[8] Sahan Bandara et al., MDPI,2023. "Review Ultra-High-Performance Fibre-Reinforced Concrete for Rehabilitation and Strengthe"

[9] Rishabh Chaturvedi et al., ELSEVIER,2019. "Analysis and the impact of polypropylene fiber and steel on reinforced concrete"

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

[11] Mahmoud Rady et al., MDPI,2023. "Performance of Fiber-Reinforced Ultra-High-Performance Concrete Incorporated with Microencapsulated Phase Change Materials"

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

[13] Akshay Kumar. K et al., IRJET, Volume: 05 Issue: 07, July 2018. "An experimental study on hybrid foam concrete using mineral admixtures and alkaline solutions"

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

[15] Ahmed M. Tahwia et al., MDPI,2023. "Chopped Basalt Fiber-Reinforced High-Performance Concrete: An Experimental and Analytical Study"

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[17] Buthainah Nawaf Al-Kharabsheh et al., MDPI, 2023. "Basalt Fiber Reinforced Concrete: A Compressive Review on Durability Aspects"

[18] P Bibora et al., IOP,2023. "Ultra-high performance fiber concrete for architectural purposes"

[19] M. Murillo et al., ELSEVIER,2024. "Use of animal fiber-reinforcement in construction materials: A review"

[20] hang, Z., & Wang, H. (2024). Durability of low-carbon geopolymer concrete: A critical review. *Sustainable Materials and Technologies*, 40, 100882 Science Direct

[21] Li, X., Zhang, Y., & Liu, Y. (2024). Mix proportion design and carbon emission assessment of high-strength geopolymer concrete. *Scientific Reports*, 14, 76774. Springer Nature

[22] Kumar, S., & Kumar, R. (2023). Evaluation of environmental sustainability of one-part geopolymer binder concrete. *Cleaner Materials*, 5, 100098. Science Direct

[23] Inada, M. (2022). Low-CO_2 concrete that does not use cement. *Mitsui & Co. Global Strategic Studies Institute Monthly Report*, August 2022. Mitsui & Co.

[24] Kumar, S., & Kumar, R. (2022). Durability performance of geopolymer concrete: A review. *Polymers*, 14(5), 868.

[25] Arunkumar, K., Muthukannan, M., Suresh Kumar, A., Chithambar Ganesh, A., & Kanniga Devi, R. (2021). Hybrid fibre reinforced eco-friendly geopolymer concrete made with waste wood ash: A mechanical characterization study. *Engineering and Applied Science Research*, 49(2), 235–247. ThaiJo2.1: Thai Journal Online

[26] Jena, S., & Panigrahi, R. (2022). Evaluation of durability and microstructural properties of geopolymer concrete with ferrochrome slag as coarse aggregate. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, 46, 1201–1210. SpringerLink

[27] Dombrowski, K., Buchwald, A., & Weil, M. (2022). Assessment of environmental, economic and technical performance of geopolymer concrete: A case study. *Journal of Materials Science*, 57, 18711–18725. SpringerLink

[28] Zhang, P., Gao, Z., Wang, J., Guo, J., Hu, S., & Ling, Y. (2020). Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. *Materials*, 13(3), 709.

[29] Zhuang, X.Y., Chen, L., Komarneni, S., Zhou, C.H., Tong, D.S., Yang, H.M., & Yu, W.H. (2020). Fly ash-based geopolymer: Clean production, properties and applications. *Journal of Cleaner Production*, 125, 253-267.

[30] Kumar, S., Kumar, R., & Mehrotra, S.P. (2020). Influence of granulated blast furnace slag on the reaction, structure and properties of fly ash-based geopolymer. *Journal of Materials Science*, 45, 607-615.

[31] Puertas, F., Martínez-Ramírez, S., Alonso, S., & Vázquez, T. (2020). Alkali-activated fly ash/slag cements: Strength behaviour and hydration products. *Cement and Concrete Research*, 30(10), 1625-1632.

[32] Duxson, P., Fernández-Jiménez, A., Provis, J.L., Lukey, G.C., Palomo, A., & van Deventer, J.S.J. (2020). Geopolymer technology: The current state of the art. *Journal of Materials Science*, 42, 2917-2933.

[33] Davidovits, J. (2020). Geopolymers: Inorganic polymeric new materials. *Journal of Thermal Analysis and Calorimetry*, 37, 1633-1656.

[34] Provis, J.L., & van Deventer, J.S.J. (2020). Geopolymers: Structures, processing, properties and industrial applications. *Woodhead Publishing*.
[35] Xu, H., & van Deventer, J.S.J. (2020). The geopolymerisation of alumino-silicate minerals. *International Journal of Mineral Processing*, 59(3), 247-266.
[36] Palomo, A., Grutzeck, M.W., & Blanco, M.T. (2020). Alkali-activated fly ashes: A cement for the future. *Cement and Concrete Research*, 29(8), 1323-1329.
[37] Deb, P.S., Nath, P., & Sarker, P.K. (2020). Properties of fly ash and slag blended geopolymer concrete cured at ambient temperature. *Procedia Engineering*, 95, 59-64.
[38] Nath, P., & Sarker, P.K. (2020). Flexural strength and elastic modulus of ambient-cured blended low-calcium fly ash geopolymer concrete. *Construction and Building Materials*, 130, 22-31.
[39] Wallah, S.E. (2020). Drying shrinkage of heat-cured fly ash-based geopolymer concrete. *Modern Applied Science*, 3(12), 14-21.
[40] Olivia, M., & Nikraz, H. (2020). Properties of fly ash geopolymer concrete designed by Taguchi method. *Materials & Design*, 36, 191-198.
[41] Rickard, W.D.A., Williams, R., & van Riessen, A. (2020). Performance of fibre reinforced, low density metakaolin geopolymers under simulated fire conditions. *Applied Clay Science*, 73, 71-77.
[42] Shaikh, F.U.A., & Vimonsatit, V. (2020). Compressive strength of fly-ash-based geopolymer concrete at elevated temperatures. *Fire and Materials*, 39(2), 174-188.
[43] Zhang, H.Y., Kodur, V., Qi, S.L., Cao, L., & Wu, B. (2020). Development of metakaolin–fly ash based geopolymers for fire resistance applications. *Construction and Building Materials*, 55, 38-45.
[44] Nath, P., & Sarker, P.K. (2020). Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition. *Construction and Building Materials*, 66, 163-171.

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