DEVELOPMENT OF SUSTAINABLE GEOPOLYMER BLOCK INCORPORATING METAKAOLIN

Final Year Project

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This is to certify that the

Final Year Project Titled

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has been accepted towards the requirements
for the undergraduate degree in

CIVIL ENGINEERING

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DEDICATION

This thesis is dedicated to our families and loved ones, whose unwavering support and encouragement have been our constant source of strength and motivation. To our parents, who have always believed in our potential and provided us with the emotional and financial support needed to pursue our academic dreams, we owe our deepest gratitude. Your sacrifices, patience, and endless love have been the foundation upon which we have built our educational journey.

To our siblings and extended family, thank you for your constant encouragement and for being our cheerleaders throughout this challenging yet rewarding journey. Your words of wisdom and unwavering belief in us have kept us going during times of doubt and difficulty.

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Lastly, we dedicate this work to our mentors and teachers, whose guidance and support have been invaluable. Your dedication to education and your passion for knowledge have inspired us to strive for excellence and to push the boundaries of our capabilities. This thesis is a testament to the collective support and encouragement we have received from all of you. Thank you for being an integral part of our journey.

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ABSTRACT

In today's building industry, sustainability is paramount, driving the search for alternative materials that reduce environmental impact while maintaining performance. Moreover, traditional sources of Alumino-Silicate materials, such as fly ash and slag, are limited, necessitating alternative options. Metakaolin, a naturally occurring alkaline binder, steps in as a viable solution. Adding metakaolin to geopolymer concrete (GPC) blocks not only enhances their strength but also significantly reduces greenhouse gas (GHG) emissions, marking a significant step towards a greener future. The research focuses on optimizing the mix of binders, alkaline solutions, and aggregate content to improve GPC performance.

Experimental results show that GPC reaches a compressive strength of 9.7 MPa, higher than the 6.31 MPa of ordinary Portland cement (OPC). It also has better durability, with a water absorption rate of 5.9% compared to OPC's 6.8%. A Life Cycle Impact Assessment (LCIA) found that GPC cuts GHG emissions by 40% compared to OPC.

These findings highlight the benefits of using metakaolin-based GPC, providing insights for optimizing its mix design and encouraging its use in the construction industry as an eco-friendly, high-performance material.

Keywords

Geopolymer concrete, metakaolin, Alumino-Silicate materials, greenhouse gas emissions, Life Cycle Impact Assessment, environmental sustainability, geopolymer blocks.

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CHAPTER 1

INTRODUCTION

1.1 Background

Experimental Show the situation in Pakistan; the construction industry depends a lot on concrete block masonry in terms of cost, readily availability of material and well-equipped labors. Although some of the components used in the making of concrete blocks such as cement is produced in enormous proportions and leads to emission of greenhouse gases such as carbon dioxide which is known to enhance global warming. It therefore calls for higher measures of control as well as the effort to find environmentally more friendly building products.

Among the strategies that can be adopted, the following hold lots of potential as far as the improvement of environmental conditions affected by cement production is concerned; the incorporation of industry waste products such as metakaolin. The purposes of this paper are simple – those of introducing and explaining the potential of metakaolin, which is produced through the calcination of natural clay and is bestowed with many of the characteristics of cement, including a low impact on the environment. Another solution that can be considered is Geopolymer Concrete (GPC), introduced as a viable replacement for Ordinary Portland Cement (OPC) in structures because of its environmental advantages and energy saving features.

They differentiated geopolymer concrete from other normal concrete since it is created via a series of chemical reactions known as geopolymerizations, in which silicon and aluminium are derived from other products such as clay and industrial residues (e. g. As reported in the literature (Fly ash) with strong alkali activators. This process yields a binder like calcium silicate hydrate found in OPC, but it is of different composition. For instance, the metakaolin based geopolymer concrete (MK-GPC) incorporates metakaolin with sodium hydroxide and sodium silicate as activators, which demonstrate improved particularly compressive strength and have minimum adverse effects on the environment.

As for MK-GPC, research on it more or less focuses on its performance angles. Features of MK-GPC Many research works have been conducted regarding the performance of MK-GPC, yet these are quite limited. Research has been done on the impact of altering of $Na2SiO3$ /NaOH concentrations on such characteristics as, flexural strength, water permeability and electrical conductivity. Other research has looked at the effects of water to sodium oxide molar ratios, the amounts of aggregate, the proportions of metakaolin incorporation, and recycled aggregates on the MK-GPC's mechanical properties and workability. Moreover, the Findings on transport properties of dried and MK-GPC show its stability Even in situations such as freeze – thaw cycle and the MK-GPC has also been tested for its durability of high temperature which makes it suitable to be used as a construction material.

In conclusion, metakaolin based-CAS mineral alkali activated concrete is a sustainable solution to ordinary Portland cement in view of the negative effects of cement manufacturing and industrial waste products disposal on the environment.

1.2 Sustainable Construction Practices

Sustainable construction practices, particularly in the context of Pakistan's reliance on concrete block masonry, are crucial for several reasons highlighted by the provided content: Sustainable construction practices, particularly in the context of Pakistan's reliance on concrete block masonry, are crucial for several reasons highlighted by the provided content:

- **Reduction in Greenhouse Gas Emissions:** The production of cement continues to release a large amount of greenhouse gases with every ton of cement produced estimated to emit a ton of $CO2$ into the atmosphere. Some effective and environmentally friendly concrete such as GPC minimize these releases. Some of the advantages of using GPC blocks over traditional concrete blocks involve the use of metakaolin as a replacement for cement, an industrial by-product that makes the process more environmentally friendly and helps in fighting off climate change.

- **Enhanced Durability and Performance:** Studying shows that GPC especially, those derived from metakaolin can possess the following favorable characteristics; high compressive strength, low water absorption, and better resistance to effects of freezing as well as high temperatures. These properties contribute to the durability and strength of construction materials, which means that they do not wear out easily and thereby eliminate the need to constantly replace construction materials, which can be time-consuming and hence require more energy during the lifespan of the building.
- **Cost-Effective Solutions:** While they are more expensive than traditional materials at the pre-manufacturing stage, geopolymer materials are much more durable, and require far less maintenance in the long run again pointing towards a more economical solution. Moreover, these materials, like kaolin, should be sourced locally to lower the costs of their transportation and increase local revenues.
- **Meeting Environmental Regulations:** Knowing that the restrictions on emissions of greenhouse gases are being tightened in the global and local scenes, incorporation of environmentally sustainable construction practices helps to meet these requirements and to avoid being stung by the penalties. It also helps companies establish themselves as top sustainability leaders, which would open ways to improving the companies' image and advantage in terms of competition.
- **Encouraging Innovation:** Development of materials as an alternative to metakaolin in geopolymer concrete make a way for further innovation, technology in construction sustainability. This is a good sign because it creates the opportunity to discover new materials and techniques that would reduce environmental risks and enhance construction techniques.

Therefore, incorporating sustainable construction practices such as geopolymer concrete provide a remarkable crucial value to minimize environmental effects and depletion, increase material performance, increase cost efficiency, meet rules and standards, and encourage innovation in construction industry. The aforesaid practices are going well with other measures taken across the world to fight climate change and encourage sustainable development.

1.3 Problem Statement

With traditional sources for geopolymer concrete (GPC) depleting, there is an urgent need for sustainable alternatives. Metakaolin (MK) offers promise due to its superior mechanical properties and lower emissions compared to ordinary Portland cement (OPC). However, the specific impacts of various factors influencing MK's performance in GPC blocks remain largely unexplored. Bridging this gap is critical to unlocking metakaolin's full potential in producing eco-friendly construction materials.

1.4 Objectives

Considering the content provided, the objectives of this study are: Considering the content provided, the objectives of this study are:

1. **Evaluate Environmental Impact:** Evaluate the impacts of utilizing geopolymer concrete blocks in constructions as compared to regular concrete blocks for the purpose of absorbing and or reducing Green House Gas emissions, especially those released by cement industries. This assessment will employ Life Cycle Assessment (LCA) to measure and express the effects of the whole life cycle of the material and construction processes, thus giving a detailed analysis of the sustainable side of the coin.

2. **Material Characterization:** Undertake a literature review on the physical and chemical characteristics of metakaolin in geopolymer concrete and its applicability as the main phase; assess the accessibility of metakaolin and its contribution in geopolymer concrete as well as evaluate the suitability of locally sourced metakaolin.
3. **Optimization of Geopolymer Mix:** Enhance the properties of geopolymer concrete with metakaolin through determining the optimum combination of sodium hydroxide and sodium silicate as activators. This involves understanding the relationship between the various factors in order to find out the right proportion that will produce the most desired characteristics such as the compressive strength, work ability and durability of the concrete.
4. **Performance Analysis:** Promote a mechanical characterization of the geopolymer concrete blocks produced and aiming at obtaining an optimum of 4 MPa in compressive strength. Secondly, we should consider other properties like water absorption, porosity, density and so on, resistance to environmental conditions like free frost from and high temperatures.
5. **Comparison with Conventional Blocks:** bearing in mind previously used conventional materials like burnt bricks and normal concrete blocks, it will be quite pertinent to establish the performance and longevity of metakaolin based geopolymer concrete blocks to show the possibility and viability of geopolymer technology in construction.
6. **Addressing Waste Management:** Assess the prospect of metakaolin based geopolymer concrete to incorporate industrial waste materials to establish how metakaolin waste material affects the concrete as well as the environmental aspects of construction.
7. **Documentation and Knowledge Enhancement:** To systematically improve the current practices and theories of metakaolin geopolymer concrete and its formulation, and to

potentially contribute to the scientific theory and practice of geopolymer concrete as a whole, document the study results.

CHAPTER 2

LITERATURE REVIEW

2.1 Development of Geopolymer Concrete (GPC)

Geopolymer concrete (GPC) offers a sustainable alternative to traditional Portland cement concrete, providing enhanced durability, a lower environmental impact, and the potential to use waste materials as precursors. GPC is synthesized through a process called geopolymerization, which occurs at low temperatures and mimics natural rock formation. This involves a chemical reaction between alumino-silicate materials, such as fly ash and slag, and alkaline activators like sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), resulting in an environmentally friendly form of concrete.

The flexibility of GPC stems from its ability to utilize a variety of precursor materials, such as Ground Granulated Blast Furnace Slag (GGBFS), Fly Ash (FA), Metakaolin (MK), silica fume, and rice husk ash (RHA). These materials, when activated by alkaline solutions, enhance GPC's adaptability to different environmental and performance requirements. This versatility allows GPC to effectively incorporate industrial by-products, thereby reducing waste and addressing waste management issues. Furthermore, GPC production is more energy-efficient than that of traditional Ordinary Portland Cement (OPC) concrete, leading to a substantially lower carbon footprint.

Optimizing GPC mix designs involves adjusting the types and proportions of precursors and fine-tuning the alkali-activator percentages. This can result in GPC with high compressive and flexural strength, while also being cost-efficient, energy-efficient, and environmentally friendly. The benefits of GPC are numerous: it has superior tolerance to extreme temperature changes, enhanced fire resistance, and offers a cost-effective solution for modern construction needs. By diverting waste from landfills and reducing associated health hazards, GPC significantly contributes to environmental sustainability, making it a promising material for the future of sustainable construction.

2.2 Development of Standard Mix Design for Geopolymer Concrete

The development of a standard mix design for geopolymer concrete (GPC) is crucial for advancing its widespread adoption as a viable alternative to conventional concrete. Despite substantial research in the realm of geopolymers, there remains a notable scarcity of literature, particularly regarding mix design methodologies. Achieving the desired strength properties and workability in GPC necessitates the development of a user-friendly and rational mix design approach.

Various research studies have focused on optimizing mix proportions and key variables such as binder content, activator ratios, and molarity to achieve the desired strength parameters. The use of industrial by-products like fly ash, metakaolin, Ground Granulated Blast Furnace Slag (GGBFS), and recycled aggregates has shown promising results in enhancing the mechanical properties of GPC while reducing its environmental impact. However, the complexity of GPC mix design arises from various influencing factors, including the concentration of activators (such as NaOH molarity), the silicate-to-hydroxide ratio, the silicate modulus, curing time and temperature, the pH of the activator, the water-to-solids ratio, the chemical composition and type of source material, the ratio of Si to Al in the geopolymer system, mixing time, and the rest period. These variables play a pivotal role, rendering the mix design more intricate.

The absence of a rational mix design methodology for developing GPC using fly ash and GGBFS as binder materials further complicates the situation. Existing or proposed mix design methods for

GPC have largely relied on a trial-and-error approach. These methods often overlook the specific gravity of raw materials and either fix the total aggregate content or determine coarse and fine aggregate content solely based on weight, posing challenges in achieving consistent results, especially with variations in the physical properties of raw materials.

To address these limitations, MS. Reddy et al. proposed a mix design methodology that includes specific gravity considerations for raw materials. This methodology recognizes the pivotal role of Alkaline Activator Content (AAC) in achieving the desired compressive strength, similar to how the water-to-cement ratio governs the ultimate compressive strength in ordinary concrete. The proposed approach integrates the ACI strength versus water-to-cement ratio curve of normal concrete, the absolute volume method, and the combined grading concept. This user-friendly methodology provides the flexibility to choose between the desired compressive strength and specific AAC to binder solids ratio or vice versa. This research also suggests a modified strength versus alkaline activator content to binder solids ratio curve based on the obtained test results. Establishing standardized mix design protocols for GPC is essential to streamline its production and application in construction projects, ensuring consistency and reliability in its performance. By leveraging the benefits of GPC, including reduced carbon emissions and the utilization of industrial by-products, the construction industry can move towards more sustainable and environmentally friendly practices.

2.3 Role of Metakaolin in development of sustainable geopolymer blends

Metakaolin, derived from the calcination of kaolinite clay, possesses significant pozzolanic properties that contribute to its effectiveness as a supplementary cementitious material (SCM) in concrete mixes. These properties include its high silica and alumina content, as well as its amorphous structure, which enables it to react with calcium hydroxide (CH) produced during cement hydration, leading to the formation of additional calcium silicate hydrate (C-S-H) gel. This reaction contributes to denser concrete microstructures, reduced permeability, and enhanced mechanical properties.

Research findings consistently demonstrate the positive impact of incorporating metakaolin on various aspects of concrete performance. Studies have shown improvements in compressive strength, flexural strength, and durability properties such as resistance to chemical attacks and sulfate ingress. Additionally, metakaolin's fine particle size distribution enhances the packing density of concrete mixes, leading to improved workability and reduced water demand.

The research studies aim to strike a balance between cost-effectiveness and performance enhancement, with different applications often requiring different optimal replacement levels. Furthermore, investigations into the synergistic effects of combining metakaolin with other supplementary cementitious materials, such as fly ash and silica fume, have shown promising results in further enhancing concrete properties.

However, challenges and limitations associated with the incorporation of metakaolin have also been documented. These include potential alkali-silica reaction (ASR) when higher replacement levels are used, which can lead to concrete deterioration over time. Extended setting times and changes in rheological properties have also been observed, necessitating careful mix design and quality control measures to mitigate these issues.

The incorporation of metakaolin as a substitute for OPC in concrete block manufacturing presents a viable strategy for improving both the performance and sustainability of construction materials. However, further research efforts are essential to refine mix designs, address challenges, and facilitate widespread adoption within the construction industry, ultimately contributing to more sustainable practices and reducing the environmental footprint of concrete production.

2.4 Experimental Investigation on Geopolymer Masonry Block Units

Experimental investigations on geopolymer masonry block units have provided valuable insights into their mechanical properties, durability, and potential applications in construction. Geopolymer technology presents a promising avenue for sustainable construction practices, offering alternatives to traditional masonry materials by eliminating the need for cement and incorporating supplementary cementitious materials like fly ash, metakaolin and ground granulated blast furnace slag.

Research endeavours have aimed to assess the efficacy of geopolymer technology in producing masonry blocks with superior properties compared to conventional units. Studies have explored the influence of various factors, including the type and proportion of supplementary materials, alkaline activators, and curing conditions, on the performance of geopolymer masonry block units.

Compressive strength, a critical parameter for evaluating the structural integrity of masonry units, has been a primary focus of experimental investigations. Tests conducted on geopolymer masonry blocks have demonstrated promising results, with compressive strengths exceeding those of traditional masonry materials. The optimization of mix designs and curing regimes has played a significant role in enhancing compressive strength properties.

Water absorption characteristics, crucial for assessing the durability and resistance to moisture ingress of masonry units, have also been extensively studied. Experimental findings indicate that geopolymer masonry blocks exhibit low water absorption rates, indicating their potential for long-term durability in various environmental conditions. Factors such as pore structure, curing methods, and binder composition have been investigated to understand their influence on water absorption behaviour.

Moreover, comparative studies between geopolymer masonry blocks and conventional materials, such as fly ash bricks or OPC-based blocks, have provided valuable insights into the advantages of geopolymer technology. These comparisons have highlighted the superior mechanical properties and environmental sustainability of geopolymer masonry block units, further substantiating their potential for widespread adoption in the construction industry.

Life cycle impact assessment (LCIA) studies have complemented experimental investigations by evaluating the overall environmental footprint of geopolymer masonry block units. Preliminary assessments suggest significant reductions in greenhouse gas emissions and energy consumption associated with geopolymer-based construction practices, underscoring their alignment with sustainability objectives.

Furthermore, experimental investigations have assessed the performance of geopolymer masonry blocks under different loading conditions and environmental exposures. This includes evaluating their resistance to seismic forces, fire, moisture ingress, and chemical attacks, providing valuable data for structural design and material selection.

Overall, experimental investigations on geopolymer masonry block units have contributed significantly to understanding their mechanical behavior, durability, and suitability for construction applications. Further research is needed to optimize production processes, address challenges, and promote the widespread adoption of geopolymer masonry blocks as a sustainable alternative in the construction industry.

In conclusion, experimental investigations on geopolymer masonry block units have demonstrated their potential to revolutionize the construction industry by offering sustainable alternatives to traditional materials. By systematically exploring factors influencing compressive strength and water absorption characteristics, researchers have laid the groundwork for optimizing geopolymer formulations and production processes. Continued research efforts are warranted to further refine geopolymer-based construction practices and facilitate their widespread adoption, ultimately advancing sustainability goals in the built environment.

CHAPTER 3

MATERIALS AND METHODS

3.1 Materials

This research aimed to revolutionize the conventional methods of material selection and mix design in concrete technology by pursuing sustainable and innovative techniques. The focus was on investigating environmentally friendly substitutes, particularly the incorporation of metakaolin as an alternative binder to Ordinary Portland Cement (OPC) in geopolymer concrete. The materials used in this study included metakaolin, OPC, fine and coarse aggregates, and a superplasticizer, each selected for their unique properties and contributions to the overall mix. Several variables, including the amount of NaOH present, the binder ratio, the sodium silicate to sodium hydroxide ratio, and the overall amount of binder, were considered while designing the mix. To prepare for a thorough examination of the performance of geopolymer concrete, the study entailed a thorough assessment of materials properties, mix design concerns, and a complete testing methodology.

3.1.1 Metakaolin

Metakaolin, a highly reactive pozzolan, is produced by calcining kaolinite clay at temperatures ranging from 650°C to 800°C in a muffle furnace. High purity metakaolin was sourced from the calcination of kaolin obtained from Tharparkar, Sindh, Pakistan. The calcination process was conducted at 750°C for 2 hours. The resulting metakaolin had a particle size distribution ranging from 20 to 50 micrometers. This material was selected due to its excellent reactivity and ability to act as an alternative binder in geopolymer concrete, enhancing the concrete's strength and durability while reducing reliance on Ordinary Portland Cement (OPC).

Figure 1: Metakaolin after calcination of kaolin in muffle furnace

3.1.2 Ordinary Portland Cement (OPC)

Ordinary Portland Cement (OPC) is a traditional binder used in concrete production. For comparative purposes, Type I OPC conforming to ASTM C150 specifications was used in the control mixes. This allowed for a direct comparison of the performance enhancements provided by metakaolin in the geopolymer concrete blocks. The OPC was carefully stored and handled to prevent any contamination or premature hydration.

3.1.3 Fine Aggregate

Natural river sand, conforming to ASTM C33 standards, was used as the fine aggregate in this study. The sand had a fineness modulus of 2.8 and was free from impurities such as silt, clay, and organic matter. The particle size distribution was meticulously graded to ensure optimal packing density and workability in the concrete mix. The specific gravity and water absorption of the fine aggregate were determined to ensure consistency in the mix design.

3.1.4 Coarse Aggregate

Crushed granite aggregates, ranging in size from 4.75 mm to 20 mm, were used as the coarse aggregate. The aggregates were tested for physical properties such as specific gravity, water absorption, and bulk density according to ASTM C127 and C128 standards. Proper grading ensured minimal voids and enhanced the overall strength of the concrete blocks. The use of coarse aggregates was optimized to balance the workability and mechanical properties of the geopolymer concrete.

3.1.5 Superplasticizer

The high-range water-reducing superplasticizer (SP) Viscocrete 5110 was chosen based on literature findings to enhance the workability and flowability of the geopolymer concrete mixture. The purpose of the superplasticizer is to promote slump retention and boost early and ultimate compressive strengths by dispersing cement particles and lowering water content. The superplasticizer was added to the geopolymer concrete mixture at a dosage of 2% of the total weight of cementitious components. To ensure the concrete attained the required workability without sacrificing its overall strength, 10% extra water was cautiously added to the mixture in solution with this dosage.

3.1.6 Alkaline Activators

Metakaolin activation with extremely alkaline solutions is vital for geopolymer production. Sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) are widely used activators. These activators initiate the geopolymerization process, transforming the metakaolin into a robust and durable binder. A 12 M solution of NaOH was used, and a Na_2SiO_3 to NaOH ratio of 2:1 was maintained for optimal performance. The concentration and ratio of these solutions were carefully selected based on existing literature and preliminary trials to achieve optimal performance in the geopolymer concrete.

Figure 2: Preparation of alkaline activator solution

3.2 Methodology

The methodology for developing sustainable geopolymer concrete blocks with metakaolin started with preparing the alkaline solution an hour before casting. It involved mixing sodium hydroxide solution and sodium silicate liquid, which were prepared a day earlier to ensure their effectiveness. We carefully measured sodium hydroxide flakes and mixed them with water to create a solution with a concentration of 12 Molar, suitable for one kilogram per cubic meter of concrete. To ensure the aggregates were evenly coated, we mixed metakaolin, coarse aggregate, and fine aggregates in a drum mixer for two minutes. Then, we gradually added the alkaline solution and continued mixing for another two minutes for thorough integration. All tests followed ASTM guidelines. We conducted compression tests on block specimens (100 mm x 150 mm x 300 mm) at 7, 14, and 28 days, following ASTM C-129 standards. Additionally, we tested water absorption and density according to ASTM C-90 standards. Our approach involved analyzing materials, designing mixes, implementing curing methods, and conducting extensive testing to comprehensively evaluate the mechanical and overall performance of geopolymer concrete blocks. Once prepared, we poured the finished concrete into block molds, demolded them after a day, and then stored them under ambient conditions until the test dates. This systematic methodology ensured a thorough examination of the sustainable geopolymer concrete blocks, providing valuable insights into their properties and performance.

The key stages included:

- **Procurement:** Sourcing high-quality raw materials such as metakaolin, OPC, fine and coarse aggregates, and superplasticizer.
- **Calcination:** Processing kaolinite clay to produce metakaolin through controlled calcination.
- **Mix Design Optimization:** Developing and optimizing mix designs for geopolymer concrete blocks, varying the metakaolin content.

- **Mixing and Casting:** Preparing concrete mixes, casting blocks, and curing them under appropriate conditions.
- **Testing:** Conducting comprehensive testing to assess compressive strength, water absorption, and density.
- **Life Cycle Impact Analysis:** Evaluating the environmental impact of concrete blocks using LCIA.

3.3 Mix design

In our preparation for testing, we took great care to ensure consistency and precision across our test matrix. Each mix design was meticulously handled and mixed separately, starting with the precise measurement and selection of raw materials tailored to the specified proportions for each mix. Metakaolin, fine aggregate, coarse aggregate, sodium hydroxide, sodium silicate, superplasticizer, and water were all meticulously weighed and combined according to their designated mix designs. The materials were then thoroughly mixed in a drum mixer to ensure a uniform distribution of components, critical for maintaining the integrity and representativeness of our samples. Once mixed, the freshly prepared concrete was poured into individual molds, with meticulous attention to detail to ensure each mold was filled completely, avoiding any voids or irregularities. Following casting, the samples underwent a curing process under controlled conditions to allow for the gradual strengthening and durability development over time. Throughout this period, we strictly adhered to ASTM guidelines to minimize external factors and ensure the accuracy and reliability of our test results. After the curing period, the samples were delicately demolded and ready for testing. Each sample was carefully labeled with its respective mix design and test parameters to enable precise data collection and analysis. The samples then underwent a series of tests, including compression tests to evaluate strength, as well as tests for water absorption and density, in accordance with ASTM standards. We maintained meticulous records throughout the testing process, diligently tracking the performance of each sample and noting any trends or deviations. The results of these tests were compiled into a comprehensive test matrix, providing a detailed summary of the performance of each mix design across various parameters. This matrix serves as a valuable tool for assessing the effectiveness of different mix designs in achieving the desired properties of geopolymer concrete blocks, guiding further refinement and optimization of our concrete formulations.

Table 1: Mix Design

Mix Design	**MK**	**OPC**	**FINE AGGREGATE**	**COARSE AGGREGATE**	**NaOH (12M)**	**Na2SiO3**	**Na2Sio3/NaOH**	**S.P**	**Water**
GPC 1	415 g	-	830 g	1037g	89 g	186 g	2	2%	20 g
GPC 2	960 g	-	2400 g	4800 g	224 g	448 g	2	2%	40 g
GPC 3	800 g	-	1600 g	8000 g	120 g	240 g	2	2%	40 g
GPC 4	800 g	-	1600 g	8000 g	146 g	292 g	2	2%	40 g
GPC 5	1340 g	-	1600 g	8000 g	180 g	360 g	2	2%	40 g
OPC	-	400 g	1600 g	8000 g	-	-	-	2%	670 g

Note: MK, OPC and S.P represent Metakaolin, Ordinary Portland Cement and super plasticizer respectively.

3.4 Casting & Demolding

In our block casting and demolding process, meticulous attention was dedicated to ensuring the accuracy and reliability of our testing. Block specimens, measuring 100 mm by 150 mm by 300 mm, were cast following standardized procedures. Post-casting, each specimen underwent careful smoothing with a steel trowel to eliminate surface irregularities. After a 24-hour curing period, the specimens were demolded and left to naturally cure at room temperature until the scheduled test dates. The process of developing premium metakaolin-based geopolymer concrete (GPC) blocks involves a thorough approach to casting and molding, pivotal for achieving the desired characteristics and performance of the blocks. Here, we explore the key strategies employed in each phase:

- **Preparation of GPC Mix Design:** A cornerstone in crafting high-quality GPC blocks is the meticulous preparation of the mix design, aimed at optimizing various factors. Metakaolin powder acts as the primary binder due to its strong reactivity with alkaline activators. Fine aggregates are added to enhance workability and packing density, while coarse aggregates contribute to strength and dimensional stability. The alkaline activator solution, typically comprising sodium silicate and sodium hydroxide, initiates the geopolymerization process, with its molar ratio crucial for determining strength and setting time. Careful control of water content is essential to achieve the desired workability and strength of the mixture.
- **Mixing Procedure:** Proper mixing of GPC ingredients is imperative to ensure homogeneity and workability of the concrete. Dry components are first blended, followed by the gradual addition of the alkaline activator solution while maintaining continuous

mixing. Factors such as mix design, batch size, and desired workability influence the duration and intensity of mixing.

- **Mold Selection and Preparation:** Selecting an appropriate mold material, such as steel, is crucial to ensure dimensional stability and durability during the casting process. The use of a mold release agent facilitates easy demolding while preserving the surface texture of the blocks. Thorough cleaning of the mold before each use helps prevent surface defects on the cast blocks.
- **Casting Process:** Controlled pouring is essential to ensure uniform filling of the mold while minimizing issues such as air entrapment and segregation. Vibrating methodologies, either internal or external, aid in compacting the GPC mixture, reducing air voids and enhancing strength and density. Optimal compaction further improves block quality, strength, and durability
- **Curing Process:** The curing period plays a crucial role in the initial setting and development of concrete strength. Various curing methods, including temperature and humidity control, may be employed to achieve the desired properties of the blocks. Tailoring the curing duration to the mix design and target strength is essential for achieving optimal block qualities.
- **Demolding and Finishing:** After the curing process, blocks are carefully demolded to prevent damage. Any surface imperfections can be addressed through gentle sanding or grinding, although proper casting practices and mold making techniques minimize the need for extensive finishing. By meticulously following these key strategies in the development of GPC blocks, builders can create high-quality, durable, and sustainable alternatives to

conventional Portland cement concrete blocks, suitable for a wide range of construction applications.

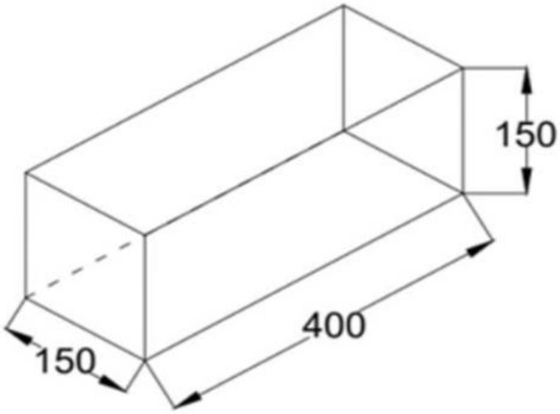


Figure 3: Mold dimensions

Figure 4: Mold for casting of blocks

3.5 Testing Scheme

The strength properties of the test samples were evaluated in accordance with ASTM standards to ensure accurate and reliable results. The testing scheme involved conducting tests at 7, 14, and 28 days to assess the compressive strength development over time. For each mix design, three samples were tested at each time interval, totalling 18 samples for each duration and six mix designs overall. This comprehensive testing approach allowed for a thorough examination of the performance of each mix design across different curing periods. The testing scheme and relevant ASTM standards are summarized in the table below:

Table 2: Testing Matrix

MIX DESIGN	Number of Samples at 7 Days	Number of Samples at 14 Days	Number of Samples at 28 Days
SAMPLE SIZE	4" * 6" * 12"	4" * 6" * 12"	4" * 6" * 12"
GPC 1	3	3	3
GPC 2	3	3	3
GPC 3	3	3	3
GPC 4	3	3	3
GPC 5	3	3	3
OPC	3	3	3
TOTAL NUMBER OF SAMPLES	18	18	18

This testing scheme ensures a robust evaluation of the strength properties of the geopolymer concrete samples at various stages of curing, providing valuable insights into their performance and durability over time. The complete details of the testing scheme and the relevant standards are listed in Table.

Table 3: Testing Scheme

TEST	AGE (DAYS)	CODE	DIMENSIONS
Compressive Strength Test	7, 14, 28	ASTM C-129	4" * 6" * 12"
Water Absorption Test	7, 14, 28	ASTM C-90	4" * 6" * 12"

Figure 5: Block sample after demolding for curing

3.5.1 Compressive Strength Assessment:

An automated compression testing machine (CTM) was utilized to assess the compressive strength of the specimens. Tests were conducted at both 7 and 28 days after casting to monitor the concrete's strength development over time. This rigorous testing procedure enabled us to accurately evaluate the performance and durability of our block molds. Compressive strength tests adhered to ASTM C39 standards, ensuring consistency and reliability. Concrete blocks underwent testing at 7, 14, and 28 days of curing to comprehensively assess their mechanical properties. The results were meticulously compared to analyze the strength development and the influence of metakaolin replacement levels on the blocks' mechanical characteristics. This thorough evaluation provided valuable insights into the effectiveness of incorporating metakaolin in enhancing the performance of the concrete blocks.

To determine the stress-strain data of the test specimens at 7,14 and 28 days, we meticulously adhered to standardized procedures. The rate of loading was precisely set according to the standard at 0.25 MPa per second, ensuring consistent and controlled testing conditions. This rate corresponded to a strain rate of 1 mm per minute in the strain-controlled CTM machine. As part of our testing protocol, the machine was programmed to automatically shut off when the load dropped to 60% of the peak load. This precautionary measure helped prevent any potential damage to the specimens and ensured the safety and integrity of the testing process. By following these stringent protocols, we were able to accurately capture the stress-strain behavior of the specimens under controlled loading conditions, providing valuable data for further analysis and interpretation.

Figure 6: Compressive testing setup

3.5.2 Water Absorption and Density Assessment

Water absorption and density assessment tests are pivotal in comprehensively evaluating the durability and porosity of geopolymer concrete blocks. Adhering to ASTM C90 standards, these tests are meticulously conducted to gather critical insights into the performance of the blocks under varying environmental conditions. The water absorption tests entail subjecting the blocks to a rigorous process: initially, the blocks are oven-dried to ensure complete removal of any moisture content. Subsequently, they are submerged in water for a predetermined duration of 24 hours. Following immersion, the blocks are carefully retrieved and re-weighed to ascertain the percentage of water absorbed. This data provides invaluable information regarding the blocks' ability to resist moisture ingress, a crucial factor in determining their long-term durability and structural integrity. Concurrently, density measurements are undertaken to gauge the mass per unit volume of the blocks. By assessing density, insights into the structural compactness and overall quality of the blocks are gained. Together, these tests offer a comprehensive evaluation of the geopolymer concrete blocks' performance, aiding in their optimization and suitability for diverse construction applications.

Figure 7: Samples placed in oven for oven dry

3.5.3 Life Cycle Impact Assessment

In conducting a Life Cycle Impact Assessment (LCIA) for geopolymer concrete blocks, a methodical approach is pivotal to thoroughly evaluate the environmental impacts throughout the blocks' life cycle. Initially, the assessment entails delineating the study's scope and boundaries, which encompasses defining the functional unit, system boundaries, and pertinent impact categories. Subsequently, an exhaustive inventory analysis is undertaken, gathering data on energy consumption, emissions, resource utilization, and waste generation across all stages – from the extraction of raw materials to disposal. This phase involves sourcing data from diverse outlets, including literature reviews, industry databases, and engagements with stakeholders, to ensure the integrity and inclusivity of the inventory data.

Once the inventory analysis is completed, impact assessment methodologies are employed to interpret the amassed data into impact scores spanning various environmental domains, including global warming potential, acidification, eutrophication, and climate change. This process entails leveraging established impact assessment models such as the ReCiPe and CML methods, ensuring a scientifically rigorous evaluation of the environmental impacts. Furthermore, sensitivity analyses and scenario assessments may be conducted to scrutinize uncertainties and fluctuations in the findings, fostering a robust and nuanced understanding of the assessment outcomes.

3.5.4 Conclusion

In conclusion, the methodology employed in this study presents a comprehensive framework for the development and evaluation of sustainable geopolymer concrete blocks incorporating metakaolin. Through rigorous testing procedures, including compressive strength tests adhering to ASTM standards, water absorption, and density assessments, and Life Cycle Impact Assessment (LCIA), we gained valuable insights into the mechanical and environmental performance of the blocks. By meticulously adhering to standardized protocols and leveraging established assessment models, we were able to accurately evaluate the blocks' strength development over time, durability, and environmental impacts. These findings contribute to the advancement of sustainable construction practices, providing a robust foundation for further research and optimization in the field of geopolymer concrete technology. Overall, this methodology serves as a valuable tool for guiding the development and implementation of eco-friendly building materials, paving the way towards a more sustainable built environment.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 SEM Analysis of Metakaolin

The Scanning Electron Microscopy (SEM) analysis of metakaolin was conducted to examine its microstructural properties and its role in the geopolymerization process. The SEM images reveal a detailed view of the metakaolin particles, showing a fine and homogenous texture that is essential for the effective formation of geopolymer concrete. The high-resolution images highlight the intricate surface morphology, which contributes to the material's reactivity and bonding capabilities. The accompanying elemental analysis, as shown in the eZAF Quant Result table, indicates a high concentration of silicon (Si) and aluminum (Al), with weight percentages of 55.1% and 44.9%, respectively. These elements are crucial for the geopolymerization process, forming strong Si-O-Al bonds that enhance the material's overall strength and durability.

The SEM analysis provides a deeper understanding of the microstructural characteristics of metakaolin, which directly impact the performance of GPC blocks. The presence of high levels of silicon and aluminum suggests a robust network of bonds within the geopolymer matrix, contributing to the superior compressive strength and lower water absorption rates observed in the GPC blocks. The detailed microstructural examination underscores the quality and suitability of metakaolin as a primary binder in the GPC mix. This analysis highlights the significant advantages of using metakaolin in geopolymer concrete, providing a foundation for developing high-performance, sustainable construction materials.

Hence the metakaolin demonstrated the highest compressive strength. This improvement is attributed to the increased availability of silica ions (Si++), which facilitate the formation of

Alumino-Silicate-Hydrate (A-S-H) within the geopolymer matrix, these high percentages resulted in better geopolymerization reaction, thereby enhancing the material's mechanical properties.

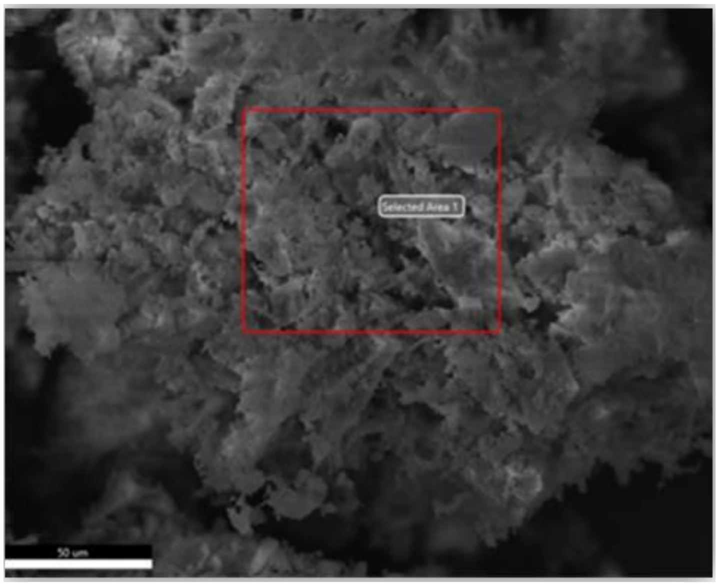


Figure 8: High resolution SEM image of Metakaolin

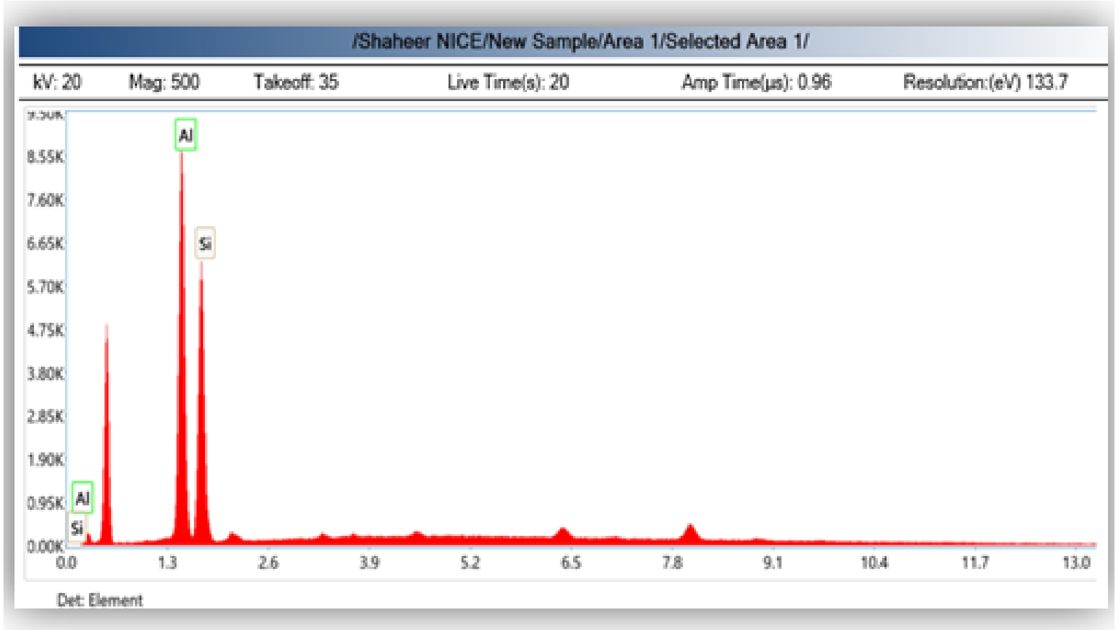
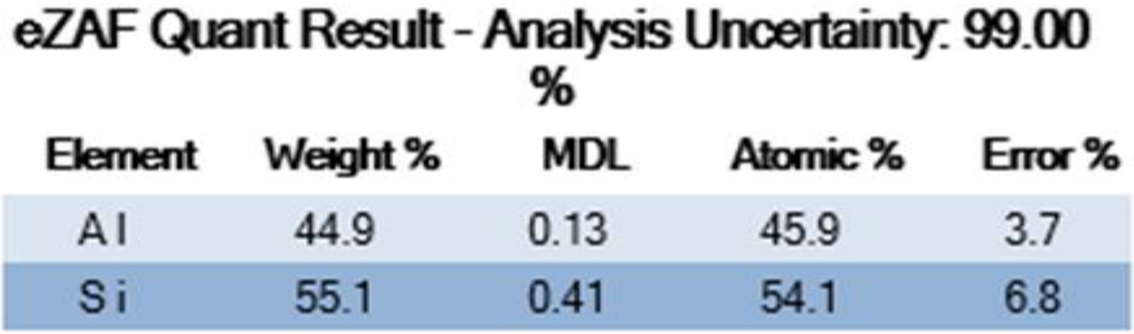


Figure 9: SEM Analysis of Metakaolin



eZAF Quant Result - Analysis Uncertainty: 99.00 %

Element	Weight %	MDL	Atomic %	Error %
Al	44.9	0.13	45.9	3.7
Si	55.1	0.41	54.1	6.8

Figure 10: eZAF Quant Result Table for metakaolin

4.2 Evaluation of compressive strength

The compressive strength test was conducted to evaluate the mechanical performance of geopolymer concrete (GPC) blocks made with metakaolin in comparison to ordinary Portland cement (OPC) blocks. This test adhered to ASTM C-129 standards to ensure consistency and reliability. The test results, illustrated in the accompanying graph, indicate a significant increase in compressive strength over time for both GPC and OPC. At 7 days, the GPC blocks showed a compressive strength of approximately 4 MPa, while the OPC blocks exhibited around 2.5 MPa. This early strength development in GPC is indicative of its rapid initial setting and curing process. By 14 days, the GPC blocks continued to outperform OPC, reaching about 6 MPa compared to OPC's 3 MPa. The superior strength gain in GPC is attributed to the effective geopolymerization process facilitated by metakaolin.

At 28 days, the disparity in performance became even more pronounced, with GPC blocks achieving the compressive strength of the geopolymer concrete ranging from 6.17 MPa to 15.87 MPa whereas OPC blocks reached only about 6.316 MPa. This variation in strength is primarily attributed to the optimization of the mix design and the specific materials used. This substantial improvement highlights the enhanced durability and load-bearing capacity of GPC blocks. The results underscore the effectiveness of metakaolin in strengthening the GPC mix, making it a viable alternative to traditional OPC blocks. The superior compressive strength of GPC blocks suggests their potential for use in high-performance non-structural applications, providing a sustainable and robust building material that can significantly reduce the environmental impact associated with conventional cement-based concrete.

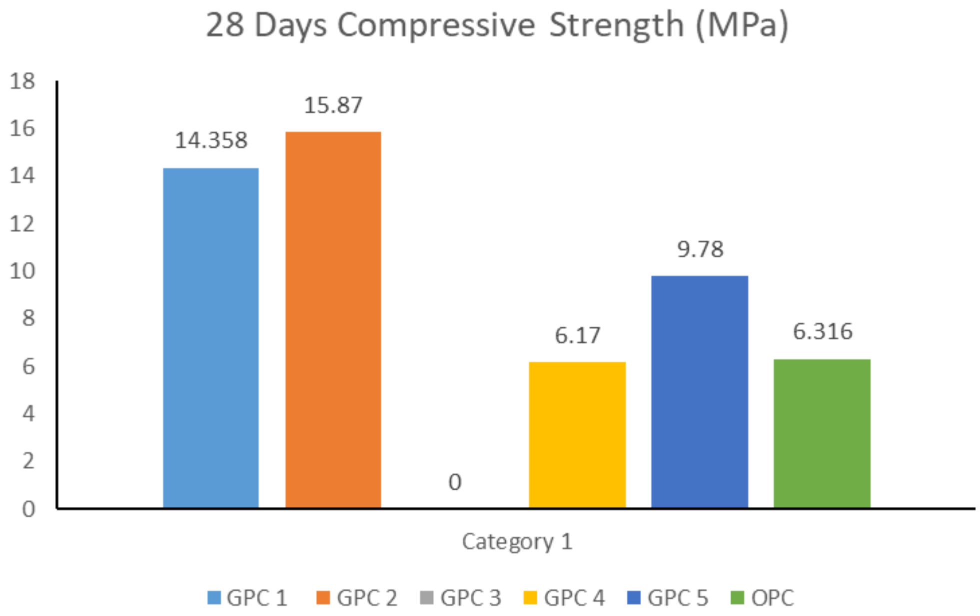


Figure 11: Comparison of 28 Days Compressive strength

4.2.1 Compressive Strength at 28 Days of Metakaolin

The graph represents the 28-day compressive strength (in MPa) of various metakaolin geopolymer concrete (GPC) blocks, each with differing proportions of metakaolin (MK), compared to a traditional ordinary Portland cement (OPC) concrete block. This comparison provides insights into the mechanical performance of geopolymer concrete with specific focus on the role of metakaolin content.

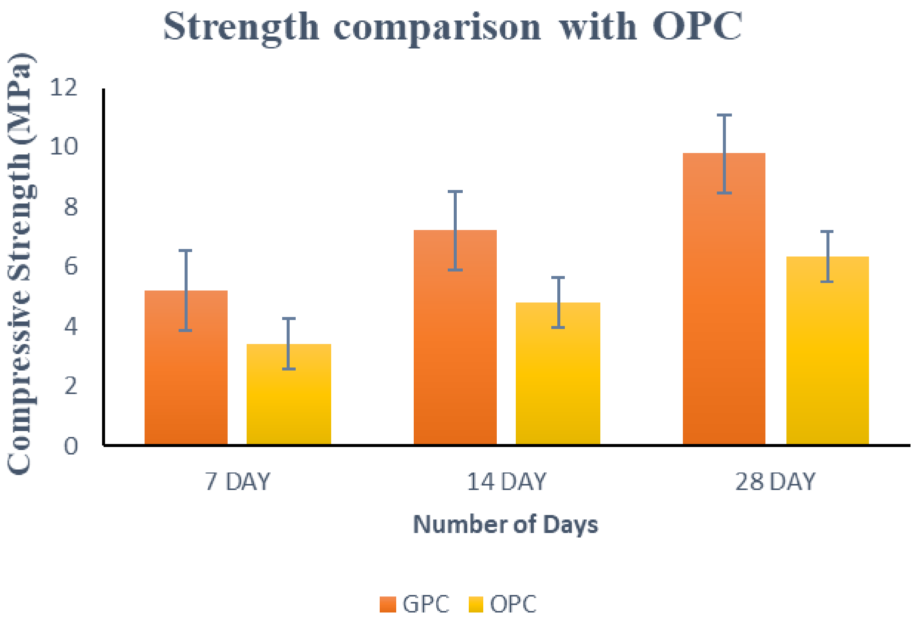


Figure 12: GPC strength comparison with OPC

The compressive strength of GPC 1, with 415 grams of metakaolin, is approximately 14.35 MPa. This demonstrates that even with a relatively lower amount of metakaolin, the geopolymer concrete can achieve a moderate compressive strength. In contrast, GPC 2, which contains 960 grams of metakaolin, exhibits the highest compressive strength among all the geopolymer samples, reaching around 15.87 MPa. This significant increase in strength suggests that a higher content of metakaolin greatly enhances the mechanical properties of the concrete.

On the other hand, GPC 3, with 800 grams of metakaolin, shows a that the sample does have any compressive strength because of the segregation of the sample during curing period. Despite having a higher metakaolin content compared to GPC 1, its zero strength indicates the other factors, that is the lower Alkaline Binder ratio, might be adversely affecting its performance. Interestingly, GPC 4, which also contains 800 grams of metakaolin, exhibits a compressive strength of approximately 6.17 MPa. This indicates that even with the same amount of metakaolin, variations in alkaline binder ratio can result in higher strengths.

GPC 5, which similarly includes 800 grams of metakaolin, achieves a compressive strength of around 9.78 MPa. This value is closer to the strength observed in GPC 2, suggesting that while the content of metakaolin is crucial in addition to the Alkaline Binder proportion, the mix design and curing process are also significant factors in determining the final strength of the concrete.

For comparison, the OPC concrete block has a compressive strength of approximately 6.31 MPa. This serves as a reference point for evaluating the performance of geopolymer concrete. When compared, GPC 1 outperforms the OPC block by 50%, demonstrating that even with a lower metakaolin content, geopolymer concrete can achieve higher strength. GPC 2, with around 16 MPa compressive strength, greater the two times of the OPC block, highlighting the substantial impact of increased metakaolin content.

In contrast, GPC 3's strength, despite its higher metakaolin content, is lower than that of the OPC block, indicating that the lower alkaline binder proportion. GPC 4 equals the OPC block with a compressive strength of 6.17 MPa, though it does not reach the strength of GPC 2. Finally, GPC 5 significantly exceeds the OPC block's strength with its 9.78 MPa compressive strength, demonstrating the effectiveness of its mix design.

4.2.2 Variation in Compressive Strength with Alkaline to Binder Ratio

The graph illustrates the variation in compressive strength (in MPa) of geopolymer concrete blocks at 28 days, corresponding to different alkaline to binder ratios. This comparison sheds light on how varying ratios of alkaline solution to binder components affect the mechanical properties of geopolymer concrete.

At a ratio of 0.45, the compressive strength of geopolymer concrete is zero. This suggests that insufficient alkaline solution relative to the binder components hinders the development of optimal chemical reactions necessary for achieving binding between the mixed ingredients. With an increased ratio of 0.55, the compressive strength rises to around 6 MPa. This demonstrates that a moderate increase in the alkaline solution content can lead to a substantial improvement in compressive strength, indicating a more effective activation of the binder materials. Further increasing the ratio to 0.6 results in a compressive strength of approximately 9 MPa. This significant enhancement in strength suggests that an optimal balance between alkaline solution and binder components is achieved, leading to the higher level of chemical activation and subsequent strength development. Similarly, increasing the ratio to 0.7 to get the highest compressive strength of 15.8 MPa, leading to highest level of chemical activation and strength development.

The observed trend highlights the critical role of the alkaline to binder ratio in determining the compressive strength of geopolymer concrete. Insufficient alkaline solution may hinder the activation of binder materials, leading to lower strength, while an optimal ratio facilitates optimal chemical reactions and higher strength. The medium alkaline to binder ratio appears to strike a balance between effectiveness and economy, yielding a substantial increase in strength without excessive use of alkaline solution. Conversely, a higher ratio enhances strength further but may incur additional costs associated with increased alkaline solution usage.

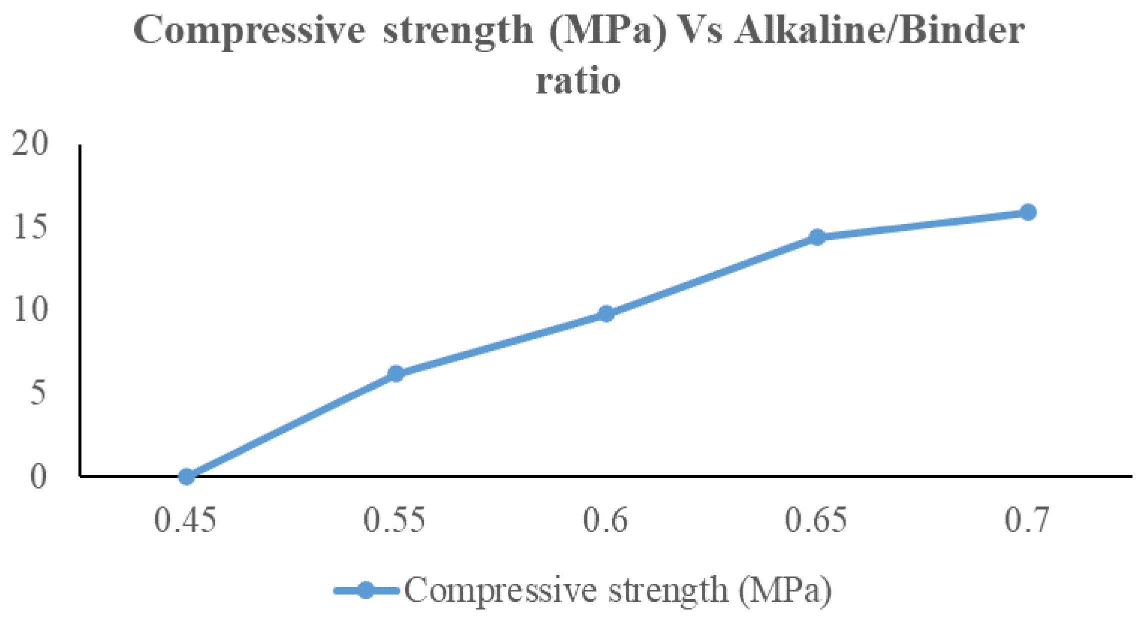


Figure 13: Compressive strength comparison with Activator to Binder ratio

4.3 Evaluation of Water Absorption

Water absorption tests were performed to assess the durability and porosity of geopolymer concrete (GPC) blocks, following ASTM C90 standards. The process involved oven-drying the blocks to remove any moisture content, submerging them in water for 24 hours, and then re-weighing them to determine the percentage of water absorbed. The results, presented in the table, show that GPC blocks with metakaolin have significantly lower water absorption rates compared to OPC blocks. For instance, GPC 2, GPC 4, and GPC 5 exhibited water absorption rates of 5.3%, 5.6%, and 5.9%, respectively, while OPC 6 had a higher rate of 6.8%. These lower absorption rates indicate that

GPC blocks have a denser, less porous structure, which is beneficial for long-term durability and resistance to environmental factors.

The analysis revealed several key trends in water absorption rates. The baseline mix designated as "OPC" exhibited a water absorption rate of 6.8%. This rate is considered standard for the given mix composition, indicating a well-balanced binder matrix with maximum porosity.

The mix "GPC 1" which could not participate in the test because of higher molarity of the sample mix which caused efflorescence on the sample. In “GPC3” the segregation of the ingredients during the curing because of very low alkaline binder ration also resulted in sample not performing water absorption test. Anyways, variations in the proportions of metakaolin and NaOH significantly influenced the water absorption properties. For instance, increasing the metakaolin substitution in “GPC 2” resulted in lowest water absorption rates to 5.3%. This result is likely due to the reduced porosity induced by the increased reactivity and concentration effect of the binder when excess metakaolin is used.

For comparison, the OPC concrete block has a water absorption of approximately 6.8%. This serves as a reference point for evaluating the performance of geopolymer concrete. When compared, GPC 2 outperforms the OPC block by 5.3%, demonstrating that with a higher metakaolin content, geopolymer concrete can achieve lesser water absorption. GPC 4, with around 5.6% absorption, still lesser than that of the OPC block, highlighting the substantial impact of increased metakaolin content. Similarly, in GPC 5, the water content absorption is 5.9% which is still substantially lower than the OPC block represents that at each proportion of metakaolin, the sample give higher resistance to water absorption than any traditionally used ordinary Portland cement concrete block.

Table 4: Water Absorption of samples

MIX DESIGN	SSD WEIGHT	OVEN DRY WEIGHT	WATER ABSORPTION
GPC 1	NA	NA	NA
GPC 2	9.453 KG	8.95 KG	5.3 %
GPC 3	NA	NA	NA
GPC 4	9.256 KG	8.73 KG	5.6 %
GPC 5	9.475 KG	8.91 KG	5.9 %
OPC	9.680 KG	8.98 KG	6.8 %

The reduced water absorption in GPC blocks can be attributed to the effective geopolymerization process and the quality of metakaolin used. Lower water absorption rates suggest that GPC blocks are less susceptible to moisture ingress, which is a critical factor in preventing degradation over time. This characteristic enhances the longevity and reliability of structures built with GPC blocks, especially in environments exposed to moisture and varying weather conditions. The improved durability and reduced porosity of GPC blocks make them an ideal choice for sustainable construction, offering a resilient alternative to traditional OPC blocks.

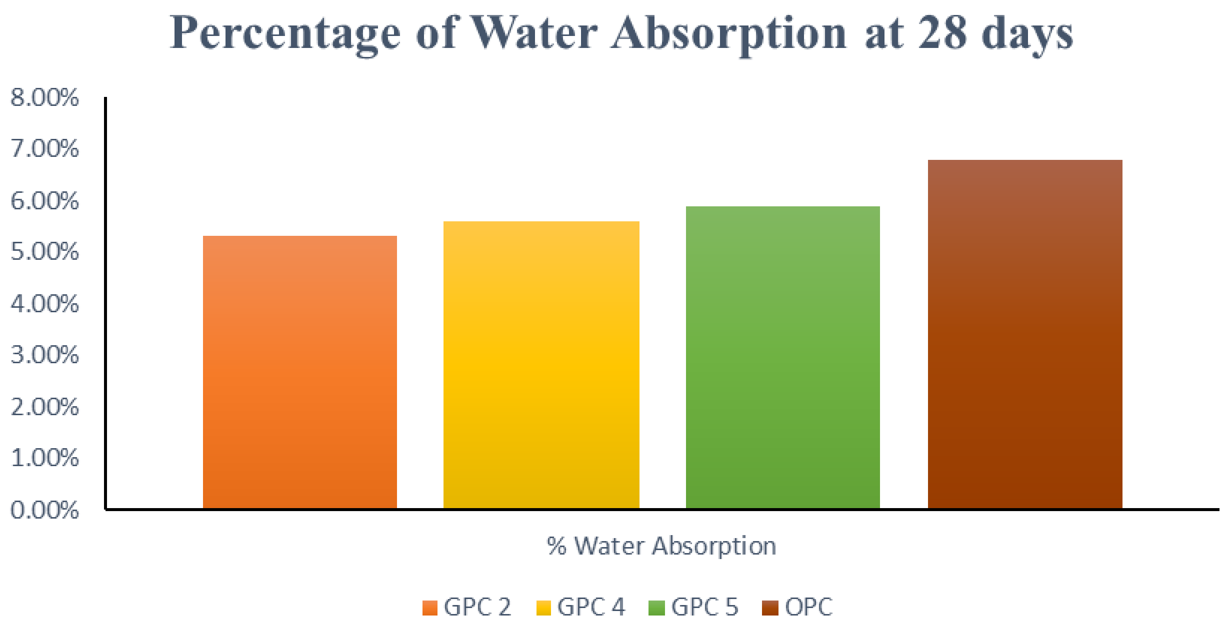


Figure 14: Water absorption percentage at 28 days

4.4 Evaluation of Density

The density of the concrete blocks was measured to evaluate the mass per unit volume, providing insights into their structural compactness and overall quality. The density assessment was carried out by recording the Saturated Surface Dry (SSD) weight and oven-dry weight of the GPC and OPC blocks. The results, displayed in the table, show that the SSD weights of GPC 2 and GPC 5 were 9.453 kg and 9.475 kg, respectively, with oven-dry weights of 8.95 kg and 8.91 kg. In comparison, OPC 6 exhibited an SSD weight of 9.680 kg and an oven-dry weight of 8.98 kg. Although GPC blocks are slightly lighter, their density is comparable to that of OPC blocks, which is consistent with their lower water absorption rates and higher compressive strength.

Table 5: Density Evaluation of Samples

MIX DESIGN	SSD WEIGHT	OVEN DRY WEIGHT	DENSITY
GPC 1	NA	NA	NA
GPC 2	9.453 Kg	8.95 Kg	1890 Kg/ft3
GPC 3	NA	NA	NA
GPC 4	9.256 Kg	8.73 Kg	2014 Kg/ft3
GPC 5	9.475 Kg	8.91 Kg	2042 Kg/ft3
OPC	9.680 Kg	8.98 Kg	2255 Kg/ft3

These measurements indicate that GPC blocks maintain a high-quality, compact structure, which contributes to their superior mechanical properties. The comparable density of GPC blocks, despite being slightly lighter, suggests that the geopolymerization process involving metakaolin results in a well-compacted material with fewer voids and improved structural integrity. This characteristic enhances the overall performance of GPC blocks, making them a reliable and durable option for construction. The density assessment confirms the suitability of GPC blocks for various applications, providing a sustainable and efficient alternative to traditional OPC blocks.

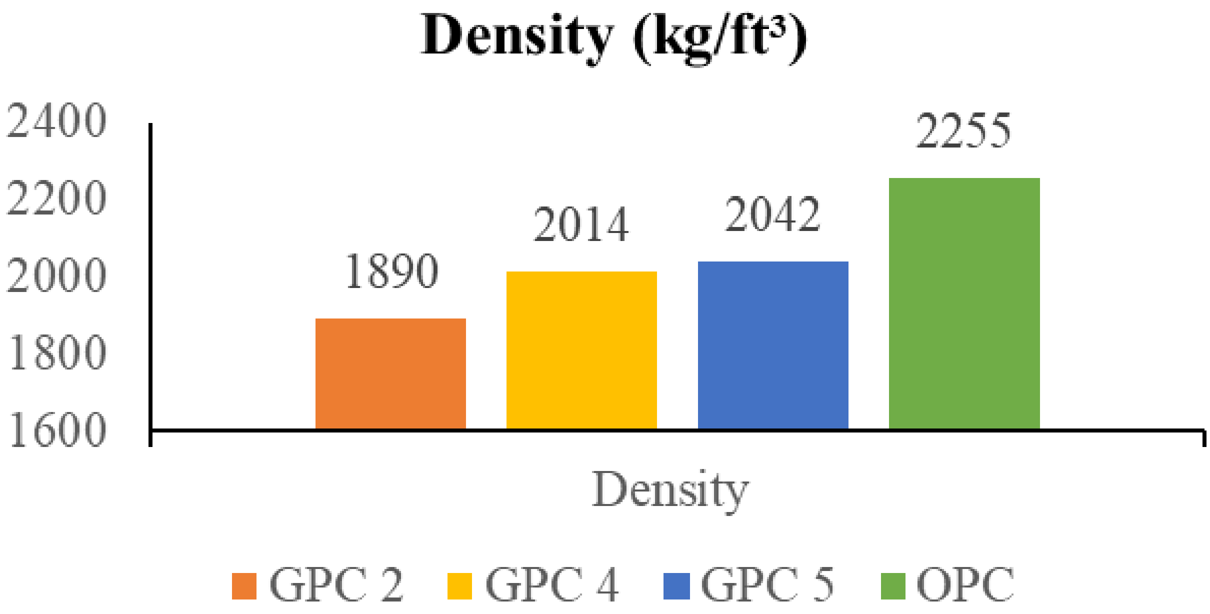


Figure 15: Densities of GPC & OPC samples

CHAPTER 5

LIFE CYCLE IMPACT ANALYSIS

The ReCiPe Midpoint LCIA strategy, which includes a wide range of impact classifications to evaluate the environmental implications of a product system, was adopted for the life cycle impact assessment. 4 major impact categories—Climate change, Marine eutrophication, Photochemical Ozone formation and Terrestrial eutrophication—were chosen for this study. The table displays all the impacts' units.

Table 6: Impact categories for LCA

Impact Categories	**Units**
Climate Change	kg CO_2-Eq
Marine Eutrophication	kg N-Eq
Photochemical Ozone Formation	kg NMVOC Eq
Terrestrial Eutrophication	Molc N Eq

5.1 Interpretation and Results

The outcomes for the Life Cycle Assessments of 1 Standard Concrete block and a geopolymer block with metakaolin of Equivalent volume were evaluated and reported in this section.

This section illustrates the corresponding results for the life cycle assessments for conventional concrete block and a geopolymer concrete with metakaolin. In LCA several environmental impacts are considered specified by the product category rule for the construction materials. Similarly, various LCA studies conducted for concrete in the past have considered various aspect's apart from CO_2 emissions.

5.2 Results and Recommendations from Life Cycle Assessment

The results of the LCA enable a detailed comparison of environmental impacts associated with Ordinary Portland Cement (OPC) and Geopolymer Concrete (GPC) for four major impact categories including climate change, marine eutrophication, ozone depletion and terrestrial acidification.

5.2.1 Climate Change

As far as climate change is concerned, OPC is considered as a baseline impact at 100% which denotes the average greenhouse gas emissions that can be linked to its production and use. Such emissions are very significant in terms of global warming and climatic changes. On the other hand, GPC has a remarkable decrease in its climate change impact thus reducing greenhouse gas emissions by approximately 60% compared to OPC. This great reduction is due to alternative materials used in combination with low carbon footprint and less energy-intensive manufacturing processes which geopolymer technology incorporates. Consequently, GPC stands out as being more sustainable by mitigating the effects of climate change on a large scale. Thus, it makes GPC an ideal material that can be employed in counteracting global warming thereby reducing construction industry’s carbon print significantly.

5.2.2 Marine Eutrophication

The Baseline for OPC, which measures nutrient pollution in the marine environment as a share of it is 100%. This leads to pollution that brings about harmful algal blooms (HABs), water quality degradation and damages marine eco-systems drastically. GPC makes a great effort in reducing this impact, presenting only 62% of the nutrient pollution impact as compared to OPC. This suggests that the employment of GPC might contribute significantly into cutting down on the amount of nutrients that are allowed to flow into the sea, thus decreasing HABs incidents and improving overall water clarity. The lower nitrogen and phosphorus emissions during the production and use make GPC's nutrient pollution less than at OPC so it can be recommended for preservation of marine health.

5.2.3 Ozone Depletion

Considering ozone depletion, which is a measure of potential of the substance to release substances that destroys ozone layer, OPC's impact has been set at 100%. Ozone layer is crucial for life protection from harmful UV rays. GPC has a mild effect on ozone depletion with its impact being reduced to 60% of that of OPC. This reduction means that GPC releases less of Ozone depleting substances (ODS) for example chlorofluorocarbons (CFCs). The environmental value attached here is high enough as having a healthier ozone layer implies limited exposure to UV radiations thus reducing chances of skin cancer and other health problems as well as maintenance of ecological balance. Consequently, GPC provides a significant benefit in terms of limiting chemical emissions contributing to depletion of the ozone layer.

5.2.4 Terrestrial Acidification: Terrestrial Acidification

Nonetheless, under terrestrial acidification category which demonstrates the potential for causing acid rain and land degradation through emissions of acidic substances such as sulfur dioxide (SO2) and nitrogen oxides (NOx), the results are not favorable for GPC as indicated by its score. OPC acts as a reference point by being given an impact value of 100%. In comparison to OPC's 100%, GPC registers a marginal increase of 105%. This means that while GPC surpasses all other environmental categories in terms of performance; it may lead to slightly higher levels of terrestrial acidification. The difference could be due to specific types of raw materials used or chemical processes employed during geopolymer concrete production. But this conclusion does provide support for more research on formulating and processing optimization so that this disadvantage can be minimized from 105% back to 100%. The EPA has highlighted this area for improvement, suggesting that continued innovation and refinement in the production of GPC could address this challenge, making GPC an even more sustainable alternative across all environmental impact categories.

5.2.5 Summary of LCIA

According to LCA Results, the environmental impact of Geopolymer Concrete (GPC) in parameters such as climate change, marine eutrophication and ozone depletion is almost half of that of Ordinary Portland Cement (OPC). Nonetheless, this aggregate derived from GCV has a marginally higher imprint of modifying the terrestrial system's acid index. Nonetheless, GPC comes out as a more efficient option than OPC and has a significant likelihood of decreasing the carbon footprint and negative impacts on the environment of the construction industry of the country, while it is crucial to consider the slight rise in the acidification of the terrestrial regions they be taken. An overall 40% reduction in GHG emissions is noticed.

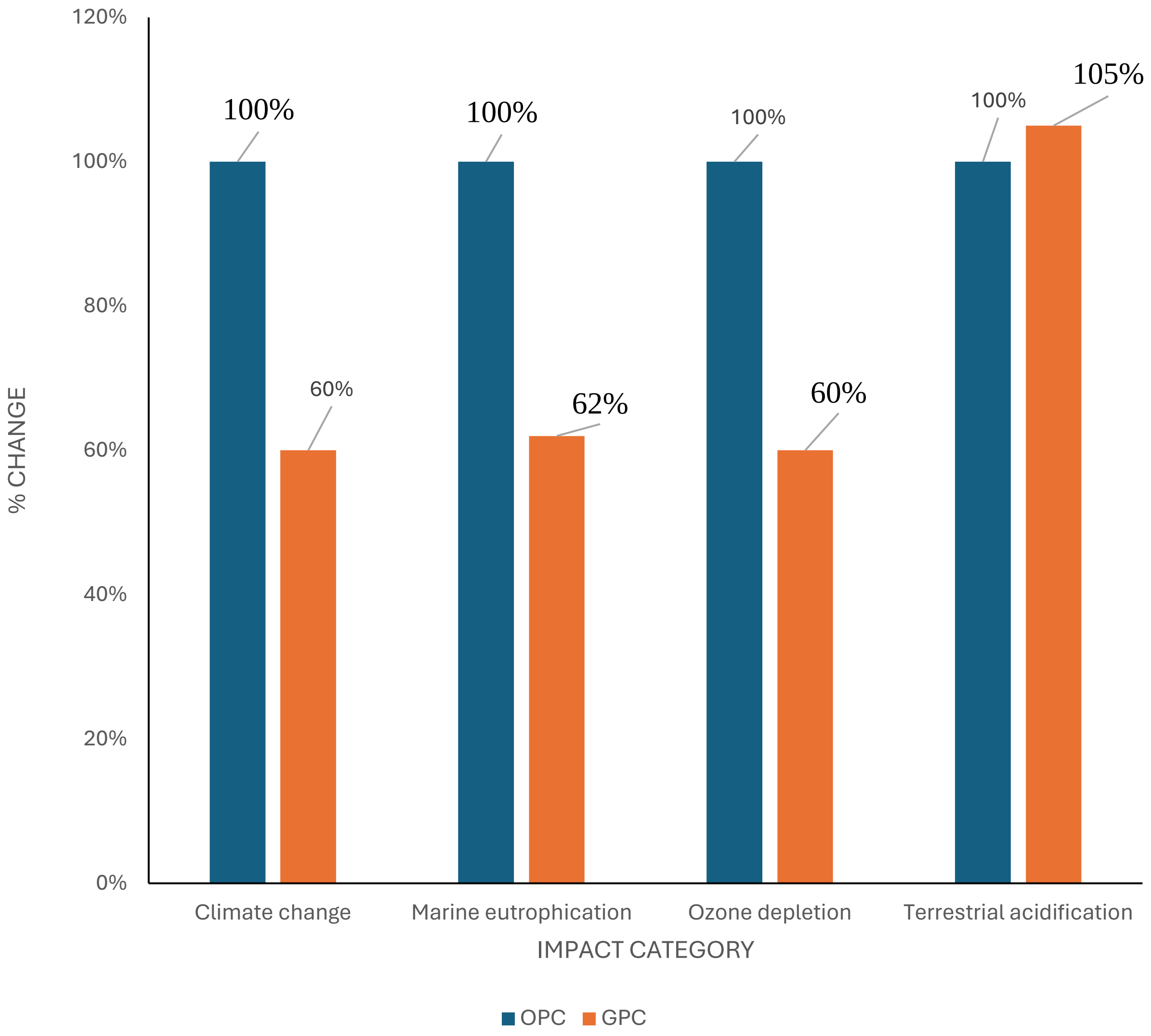


Figure 16: Life Cycle Impact Assessment Results

SUMMARY OF RESEARCH WORK

The primary goal of the research was to develop sustainable geopolymer concrete blocks by incorporating metakaolin, aiming to reduce carbon emissions in the construction industry. The project began with the procurement and calcination of raw kaolin clay into metakaolin. This was followed by optimizing the mix design to determine the ideal percentage of metakaolin in the concrete mix. Metakaolin was selected not only for its superior mechanical properties but also for its economic and environmental benefits, as it is approximately half the price of cement and significantly more eco-friendly.

The comprehensive performance evaluations revealed that the compressive strength of the metakaolin-based geopolymer blocks met ASTM C-129 standards, making them suitable for non-load-bearing structures. The water absorption rate of these blocks was significantly lower than that of Ordinary Portland Cement (OPC) blocks, with a rate of approximately 5.3% compared to OPC's 6.5%. The mechanical testing indicated a compressive strength of 9.78 MPa, aligning with the requirements for practical applications.

To further substantiate the environmental advantages, a Life Cycle Impact Assessment (LCIA) was conducted. The LCIA results demonstrated a 40% reduction in greenhouse gas emissions compared to OPC, highlighting the substantial environmental benefits of using metakaolin. This reduction is crucial in the construction industry's efforts to minimize its carbon footprint and achieve sustainability goals.

The study also included a detailed examination of the failure mechanisms of the geopolymer concrete samples, focusing on cracking patterns. Significant differences were observed between the samples with and without metakaolin, providing insights into the material's potential for deformation and failure modes. The use of metakaolin as a replacement for cement not only enhances the mechanical properties of the concrete but also offers a cost-effective and sustainable alternative, contributing to reduced construction costs and environmental impact.

A thorough literature review supported these findings, underscoring various studies that have explored metakaolin's role in improving geopolymer concrete properties. The results of this research contribute to the development of sustainable building materials with enhanced mechanical qualities and reduced environmental impact. This work supports Sustainable Development Goals (SDGs) related to industry innovation (SDG 9) and promoting sustainable cities and communities (SDG 11), demonstrating a significant step forward in the pursuit of eco-friendly construction practices.

CONCLUSIONS

This study investigated the performance of metakaolin-based geopolymer concrete (GPC) compared to traditional Ordinary Portland Cement (OPC). The analysis focused on the impact of various factors on GPC, including the molarity of the activating solution, superplasticizer content, and mix design ratios. The results reveal promising potential for GPC in achieving superior mechanical properties and water resistance, paving the way for more sustainable and resilient construction practices.

1. The molarity of NaOH significantly affects the mechanical properties and workability of GPC. Common concentrations used are 12M and 14M. Combination with Na2SiO3, a balanced ratio of NaOH and Na2SiO3 is crucial for achieving optimal geopolymerization. The typical ratios seen in the mixes include variations like 1:1.5 to 1:2, which influences the compressive strength and durability of the concrete.
2. Superplasticizers are added to enhance the workability of the mix without increasing water content. Typically, 2% of SP is added to improve the mix's flowability and reduce the water-to-binder ratio, which is critical for maintaining high mechanical strength.
3. Tests on GPC and OPC blocks showed contrasting results. GPC blocks had a wider range of compressive strengths compared to the consistent strength of OPC. This implies GPC, especially with optimized mixes (1:2 NaOH: Na2SiO3, 12M), could offer superior strength. Notably, GPC Block 2 displayed exceptional performance.
4. Overall, GPC blocks ranged from 6.173 MPa to 15.87 MPa in strength, while OPC blocks held around 6.316 MPa. These findings suggest geopolymer concrete mixes with specific ratios of NaOH and Na2SiO3 can achieve greater strength than traditional OPC mixes. This research highlights GPC's potential as a stronger alternative in construction.

5. Water absorption rates across concrete mixes show a clear trend: GPC 2 boasts the lowest absorption (5.3%), followed by a gradual increase through GPC 5. Notably, OPC 6 exhibits the highest absorption (6.8%). Compared to OPC, geopolymer mixes (ranging from 5.3% to 5.9%) consistently outperform with lower absorption rates. This suggests superior water resistance for metakaolin-based geopolymer concrete.
6. Lower absorption in GPC likely stems from the dense microstructure formed during geopolymerization, reducing porosity and water penetration. Notably, GPC 2 shines with the lowest absorption, making it ideal for applications demanding exceptional water resistance. This analysis highlights a key advantage of metakaolin-based geopolymer concrete – promoting sustainable and resilient construction practices by offering superior water resistance.

FUTURE RESEARCH RECOMMENDATION(S)

The following section outlines future recommendations based on the findings of this thesis, focusing on further research and practical applications to enhance the sustainability and performance of metakaolin-based geopolymer concrete. These suggestions aim to guide future studies and industry practices for broader adoption and optimization of this eco-friendly construction material.

1. Conducting extensive durability tests to assess the long-term performance of metakaolin-based geopolymer concrete blocks is crucial. Understanding the durability and behavior under various environmental conditions ensures the reliability and safety of structures built with geopolymer concrete.
2. Performing detailed microstructural analysis using techniques like Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) is vital. These insights will help understand the interaction between metakaolin and other components, leading to improved mix designs and enhanced performance.
3. Evaluating the thermal properties and fire resistance of geopolymer concrete blocks is necessary. Assessing how geopolymer concrete behaves under high temperatures is essential for its application in fire-prone areas and for ensuring the safety of structures during fire events.
4. Exploring the optimization of mix designs to enhance the mechanical properties and durability of geopolymer blocks is important. Optimizing the mix design can lead to better performance characteristics, making geopolymer concrete a more viable alternative to traditional concrete.

5. Implementing pilot projects to test the performance of metakaolin-based geopolymer concrete blocks in real-world construction applications is highly recommended. Real-world data from field testing can provide valuable insights into the practical challenges and benefits of using geopolymer concrete, aiding in its broader adoption in the construction industry.
6. Performing a detailed cost assessment is crucial to determine the economic feasibility of using metakaolin-based geopolymer concrete on a larger scale, including initial costs, long-term savings, and potential incentives for reducing carbon emissions.

These recommendations focus on critical aspects of material performance, safety, and practical application, which are essential for the successful integration of metakaolin-based geopolymer concrete into mainstream construction practices.

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