Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X
Volume 3, Issue 5, 2025

PARAMETRIC STUDY ON THE ROLE OF SUPPLEMENTARY MATERIALS IN MODULATING THE PERMEABILITY COEFFICIENT OF GEOPOLYMER CONCRETE

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DOI: https://doi.org/10.5281/zenodo.15461770

Keywords
Fly ash, Marble powder, Waste Additives, Geopolymer, Structural Strength

Article History
Received on 09 April 2025
Accepted on 09 May 2025
Published on 19 May 2025

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Abstract
Geopolymer concrete represents an emerging trend within the concrete industry, serving as a potential alternative to traditional cement concrete. It offers numerous advantages compared to conventional cement-based materials. Geopolymer concrete is an environmentally friendly concrete composed of waste materials produced by thermal plants in various power generation industries. The alkaline activators in geopolymer concrete exhibit excellent heat resistance and strong adhesion between aggregates, leading to superior mechanical properties. Furthermore, geopolymer concrete exhibits significantly greater durability compared to conventional cement concrete. This study utilized marble waste and fly ash as raw materials for the production of geopolymer concrete. The materials were subjected to identical curing conditions to assess their mechanical properties. The investigation's results indicated that geopolymer concrete based on Marble can be produced under various curing conditions, demonstrating excellent physical and mechanical properties. The tests to evaluate the mechanical properties included split tensile, compressive, and water penetration assessments. The optimum mixes utilized in this research include 100% fly ash, 75% fly ash and 25% marble powder, 50% fly ash and 50% marble powder, and 25% fly ash and 75% marble powder. The alkaline activator to binder ratio is 0.40 [7]. The research focused on investigating geopolymer concrete's mechanical and physical properties.

INTRODUCTION

The increasing infrastructural demands have resulted in significant growth in construction operations globally. Conventional concrete serves as a fundamental material in various construction projects, encompassing the construction of roads, bridges, dams, residential buildings, and historical sites. Cement is produced in different plants and factories in Pakistan, including Bestway Cement, Fauji Cement, and Kohat Cement Company. The manufacturing process involves using fuel to heat raw materials in a kiln at approximately 1400°C. This process converts limestone ($CaCO_3$) into lime (CaO), during which carbon dioxide (CO_2) is emitted, contributing significantly to global warming. Research indicates that one tonne of cement produces carbon dioxide in the atmosphere. [2] Cement plants contribute approximately 5% to the overall CO_2 emissions in the environment. The ongoing utilization of cement in construction activities at the present rate poses potential challenges to the survival of humans and other living species on Earth. Conversely, numerous sectors, including the iron industry, alumina industry, mineral industry, and thermal power plants, produce a range of waste materials, such as slag (SG), red mud, mineral wastes, and fly ash (FA). Researchers and environmentalists express significant concern regarding managing and eliminating industrial waste and pursuing alternatives to cement. Consequently, it is essential to investigate and determine the most effective strategies for mitigating land and atmospheric pollution by utilizing industrial wastes as binders, such as alkali-activated cement (AAC), rice husk ash, waste ceramic materials, and super sulfated cement, among others [3-4].

In 1978, Davidovits introduced the term "geo-polymer" to define a category of materials characterized by networks of inorganic molecules. This material is recognized as a third-generation binder alongside traditional cement (Ordinary Portland Cement) and lime. In industrial applications, geopolymers are produced by reacting aluminosilicate powder with alkali hydroxide or silicate [7]. This material is also referred to as alkali-activated alumina silicate binders. The geopolymerization process, which is responsible for the formation of geopolymers, consists of three distinct processes, outlined as follows: (i) Decomposition, (ii) Poly-condensation, (iii) Transportation/Orientation/Condensation [8].

Fly ash is a byproduct generated from thermal plants through the combustion of coal. It has cementitious properties and is utilized in various industrial applications. More than one hundred years have elapsed since the development of fly ash in the 19th century. It typically substitutes for approximately 20% to 80% of conventional Portland cement.

In thermal stations (power plants), water is heated by combustion of various fossil fuels. The steam generated from the heated water drives a steam turbine, which powers an electric generator. The steam is subsequently recycled following its passage through a condenser, where it undergoes condensation. The designation "Rankine cycle" encompasses the entirety of this cycle. Thermal power plants operating on fossil fuels generate various ashes, including fly ash.

Fly ash is categorized into two primary types: Class C and Class F. High calcium fly ash (class C) are characterized by a carbon fraction of less than 2%, whereas low calcium fly ash (class F) is characterized by a carbon content of less than 5% [11]. The behavior of each type of fly ash is dictated by its physical and chemical properties. Class F fly ash is commonly utilized due to its higher polymerization rate than class C fly ash, which generates calcium silicate hydrate (CSH) and inhibits the polymerization process [12]. The investigation utilizes Class-F type FA. Heat curing is essential for geo-polymerization in fly ash-based geopolymer concrete (GPC). This permits the utilization of fly ash-based GPC exclusively for precast members. Low-class fly ash geopolymer concrete demonstrates enhanced compressive strength compared to traditional concrete (ordinary Portland cement). The results obtained from this form of GPC indicate that heat-cured FA-based GPC exhibits reduced creep and dry shrinkage, along with enhanced resistance to sulfate and acid attack. [15]. According to the research conducted by Shaikh and Hosan in 2016, steel fiber-reinforced fly ash-based geopolymer concrete exhibits enhanced residual mechanical properties when subjected to elevated temperatures of 200 °C, 400 °C, 600 °C, and 800 °C. At 200 and 400 degrees Celsius temperatures, the compressive strength of steel fiber-reinforced geopolymer concrete (GPC) utilizing a sodium-based alkaline solution is approximately 22% and 15%, respectively. The compressive strength decreases by 10% at 600°C and 40% at 800°C as the temperature increases. At 200°C and 400°C, the compressive strength of SF-reinforced cement concrete decreases by 10% and 18%, respectively. This illustrates the distinct behavior of geopolymer compared to OPC concrete when subjected to elevated temperatures.

The splitting tensile strength of steel fiber-reinforced GPC exhibits less heating sensitivity than OPC.

The durability characteristics of GPC, such as permeability, abrasion resistance, chemical attack resistance, freeze-thaw effects, and resistance to chloride ions, were analyzed by Ganesan et al. in 2015. The results indicated that GPC formulated with FA is more durable than concrete produced with conventional cement [17]. Due to the significantly slower reaction of SiO2 and (Al2O3) content in FA, the demolding of FA-based GPC was not feasible even after three days under ambient curing conditions. Silicon and aluminum monomers exhibit a slow dissolution rate in alkaline solutions due to the significant energy required to detach them from the FA particles. Consequently, geo polymerization does not initiate condensation at early stages, and strength progressively develops as the material ages [18]. A review of the literature on slag-based geopolymer concrete indicates that the inclusion of SF resulted in a decrease in the compressive strength of the concrete. The incorporation of steel fibers at 28 days of curing resulted in a notable increase in the split tensile strength and flexural strength of SG-based GPC, rising from 3.75 MPa to 4.64 MPa and from 6.40 MPa to 8.86 MPa, respectively [19]. The compressive strength of slag-based geopolymer is enhanced by curing temperatures and durations up to 150°C [20]. In SG-based GPC, an exothermic reaction involving calcium oxide (CaO) releases heat, thereby accelerating the geopolymerization process. Consequently, earlier ages, such as 3 days, exhibit increased strength development [18].

Nath and Sarker (2014) experimentally demonstrated that the mechanical properties of fly ash-based geopolymer can be enhanced at a young age by incorporating slag up to 30% of the total binder during ambient curing. Elevations in slag content and alkaline solution reduce the workability and setting time of GPC, ultimately compromising the material's compressive strength. The compressive strength decreased from 55 MPa with 30% slag content as the concentration of the alkaline solution increased from 35% to 45% of the total binder. Additionally, the analysis indicated that the compressive strength increased by roughly 10 MPa with each 10% increment in slag content at the specified age in days. The ratio of SS to SH in GPC mixtures was maintained within the range of 1.5 to 2.5. The ACI 318 code results in ambient-cured geopolymer concrete exhibiting tensile strength expectations comparable to conventional cement-based concrete [13].

Glass powder is a byproduct characterized by pozzolanic properties, produced from crushed containers and debris resulting from construction demolition. The composition comprises glass featuring standard particle sizes of 4.65 mm for luminous glass and 11.72 mm for container glass. Before the grinding process, mercury is extracted within a sealed crushing chamber. The findings indicate that waste glass powder (WGP) can replace fly ash, yielding compressive strength results between 34 MPa and 48 MPa when subjected to heat curing for seven days [22]. Furthermore, a published article indicates that the incorporation of 10% glass powder and various additives as a substitute for cement resulted in a 9% increase in the compressive strength of the mortar [23-25].

The primary aim of this study was to develop marble-based geopolymer concrete and investigate its potential as a durable structural material for the construction sector. The investigation results indicated that marble-based geopolymer concrete can be produced, and its mechanical and physical properties functioned effectively. Experiments and a comprehensive test at a large-scale ready-mixed plant have shown that marble-based geopolymer concrete exhibits excellent workability and resistance to temperature fluctuations. The study results suggest that marble-based geopolymer concrete represents a significant future engineering advancement.

The research on geopolymer technology is comprehensive and enhances our knowledge of this innovative building material. The studies improve the comprehension and application of geopolymers by developing novel binder formulations, improving curing conditions, and exploring diverse applications. Geopolymers are poised to emerge as a viable and sustainable option for the construction industry and other sectors, contingent upon ongoing research initiatives that will reveal new opportunities and enhance our comprehension of these materials. The following are the research objectives.

- Develop environmentally friendly concrete.

- Develop geopolymer concrete utilizing fly ash and Marble as primary materials.
- Assess its mechanical properties, including permeability, split tensile, and compressive strength, while maintaining consistent curing conditions.

Material and Method

The final product of preparation resulting in Geo-polymer concrete (GPC), commonly referred to as green concrete, is composed of the following materials:

Binding materials

- Fly Ash, (FA)
- Marble Powder, (MP)

Alkaline solution

- Sodium Silicate (Na_2SiO_3)
- Sodium Hydroxide (NaOH)

Aggregate

- Fine Aggregate (Sand)
- Coarse Aggregate

Water (W)

Fly Ash and Marble Powder

For the preparation of geopolymer concrete (GPC), fly ash (FA) and Marble- powder (MP were both utilized as a binder, which acted as a replacement for cement; for more effective results, fly ash was used for fulfilling the work because it is the preferred source as the rate of polymerization process are being accelerated by it. The microstructure of that geopolymer also tends to improve [1]. FA was acquired from the main campus of UET Lahore. Marble Powder (MP) was collected from Raiwind Road, Lahore.

The chemical composition of FA was determined by the XRF analysis method, depicting the properties listed below in Table 3. 1.

Table 1: Chemical composition of FA

S. No.	Material	Fly Ash (FA)
1	SiO_2	57-65 %
2	Al_2O_3	28-32 %
3	Fe_2O_3	1-4 %
4	CaO	1-2 %
5	MgO	0.50 %
6	SO_3	4 %
7	SiO_2: Al_2O_3	2.03

Table 2: Properties of Fly Ash and Marble Powder

S. No.	Substances	Properties	
		Specific Gravity	Density (kg/m^3)
1	Fly Ash	2.6	925
2	Marble Powder	2.21	1,135

Alkaline Solution

Alkaline activator to binder has a 0.40 ratio. Na_2SiO_3 and NaOH solution combine at room temperature to create alkaline liquids. After combining the solutions, it is best to wait until the alkaline liquid is ready to be employed as a binding agent for around 24 hours. This causes the two solutions to react or polymerize and release significant heat.

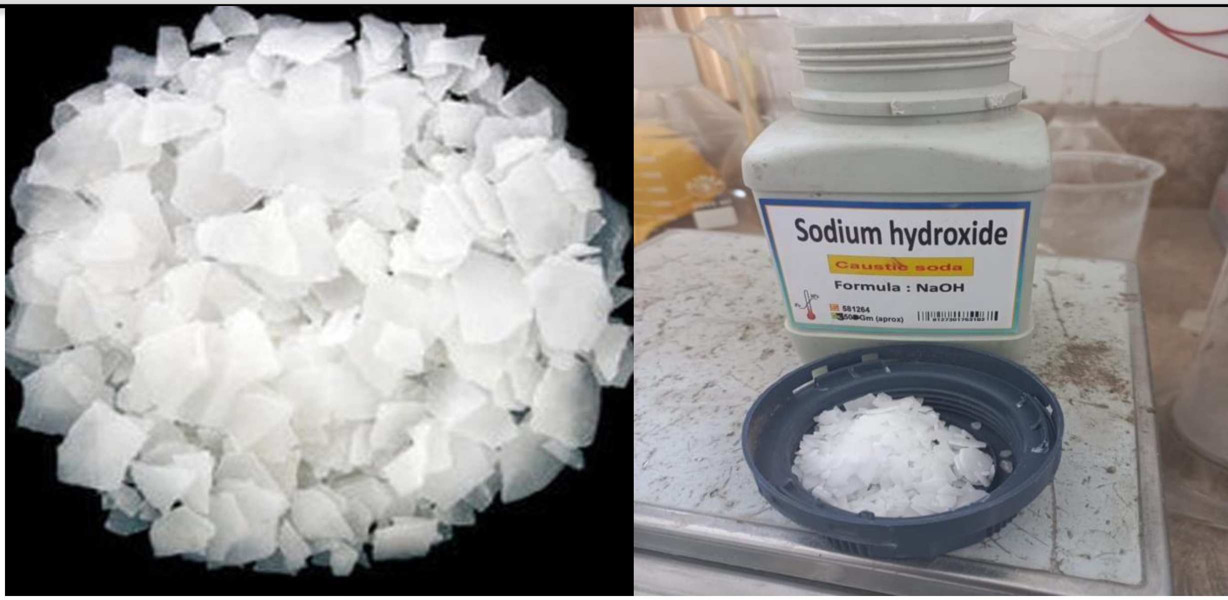

Figure 1: Flakes of NaOH

Figure 2: Solution of (Na_2SiO_3 - NaOH) and Sodium Silicate in liquid form

Aggregate

The aggregates utilized are sourced from Thokar Niaz Baig, Lahore. This investigation used both fine and coarse aggregates. Parameters such as fineness modulus, specific gravity, and density were documented after the determination. Table 3 below presents the density, specific gravity, and fineness modulus for coarse and fine Aggregate.

Table 3: Properties of aggregates

Coarse Aggregate		Fine Aggregate (sand)	
		Fineness modulus	2.59
Density (kg/m^3)	1632	Density (kg/m^3)	1675
Specific gravity	2.6	Specific gravity	2.8

This section provides a detailed explanation of the experimental work conducted with geopolymer concrete. Before outlining the testing procedures, sample preparation and casting are undertaken to determine mixture proportions.

Material Preparation

A program designed for exploratory purposes was developed and managed to meet the exploration objectives. This research examines the effects of curing temperature, duration of curing, and sodium hydroxide molar concentration on the initial strength of geopolymer concrete. To prepare the geopolymer adhesive or paste, sodium hydroxide (NaOH) and sodium silicate (Na2SiO3) were combined to produce the alkaline solution. An alkaline solution was formulated to produce geopolymer glue by mixing NaOH with Na2SiO3.

Mix Proportion preparation

The concrete mixtures were prepared using molds with a diameter of 4 inches and a height of 8 inches, resulting in a volume of 0.0016 m^3. Additionally, cubes with 6x6x6 inches were utilized, with a volume of 0.00354 m^3. The ratio of fly ash, fine Aggregate, and coarse Aggregate utilized is 1:2:4. The percentages of fly ash replaced by marble powder are 25%, 50%, and 75%. Twelve cylinders and 12 cubes were cast, with three samples taken from each shape. Cylinders were used to determine compressive strength, whereas cubes were used to assess permeability. Table 4 presents the percentage of Fly Ash and MP.

Table 4: Mix Designation percentages

S. No.	Alkaline/Binder Ratio	Fly ash %	Marble powder %
1	0.4	100	0
2	0.4	75	25
3	0.4	50	50
4	0.4	25	75

Table 5: Ingredients required for 1m^3 of geopolymer concrete

The ratio of Alkaline Liquid to Fly Ash	Mass of Alkaline Liquid (Kg)	Mass of NaOH Liquid (kg)	Mass of Sodium Silicate Liquid (Kg)	Mass of Fly Ash (Kg)	Fine Aggregate (Kg)	Coarse Aggregate (Kg)
0.40	128.1	36.6	91.5	320.32	640.66	1281.31

Samples preparation and casting

Na2SiO3 and NaOH solutions were prepared 24 hours before mixing, enhancing the solution's reactivity. Fine aggregates (FA) and coarse aggregates (CA) were mixed under saturated surface dry (SSD) conditions. Binders, including FA and MP, were combined with a premixed alkaline activator solution (AAS), which was added gradually. The mixing process lasted for a duration of 3 to 4 minutes.

The molds, designated as cylinders, were subsequently filled with geo-polymer concrete in three distinct layers. Each layer was compacted using a compaction rod and maintained at ambient temperature for 24 hours. The molds were subsequently de-molded and placed in an oven for curing at 80°C for 24 hours. Following this, they were allowed to rest for 7 days in preparation for testing.

Result and Discussions

This section discusses different tests, including the slump test, compressive strength test, and permeability test results.

Slump test

A slump test was conducted on each mix to determine its workability. Workability decreased with an increase in MP. The maximum slump recorded was 90 mm, observed without any replacements. Conversely, the minimum slump was noted at 75 mm, which corresponded to 45 replacements for the same volume of water. A notable decrease in slump is observed when the replacement of MP is increased from 50% to 75%, as illustrated in the figure below.

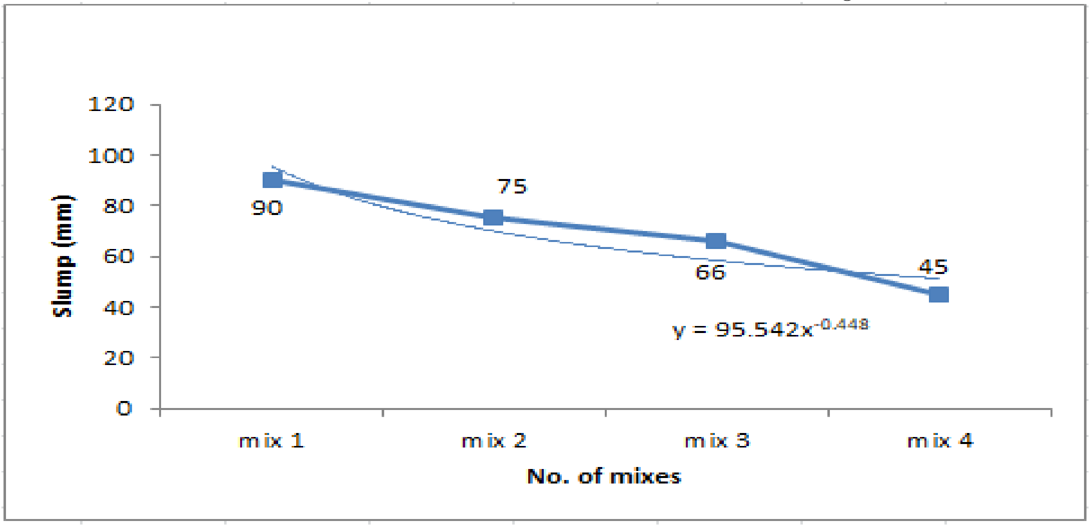

Figure 3: Slump of different mixes

Compressive strength

The compressive strength tests were performed 9 days post-casting. A total of 12 samples were prepared for compressive strength testing, with three samples each incorporating an incremental replacement of fly ash with marble powder at 25% intervals. The results indicated that the compressive strength of the samples improved with the substitution of FA with MP, reaching a maximum enhancement at a replacement level of 50%. The strengths of mix 2, 3, and four have been increased by 7.5%, 52%, and 17.3%, respectively, as indicated in Table 5.

Table 5: Compressive strength with varying percentages of fly ash and marble powder

Mixes	Fly ash content (%)	Marble content (%)	Strength (psi)	Percent increase in strength (compared to control mix)
Mix 1	100%	0%	1185	-
Mix 2	75%	25%	1275	7.5%
Mix 3	50%	50%	1802	52%
Mix 4	25%	75%	1390.6	17.3%

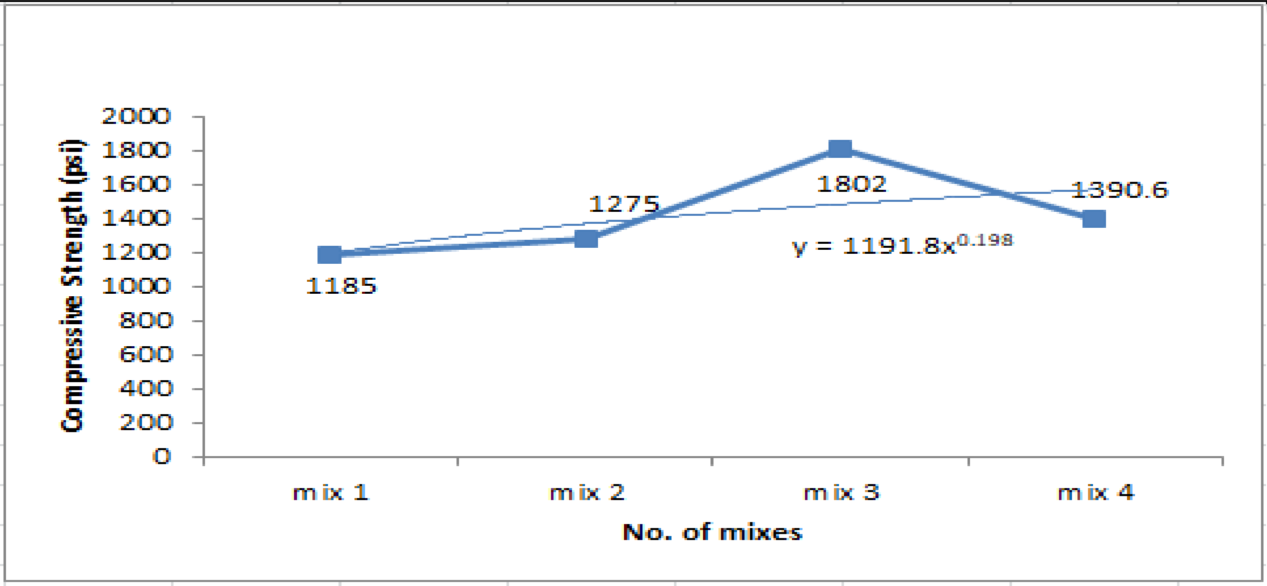

Figure 4: Compressive strength of different mixes

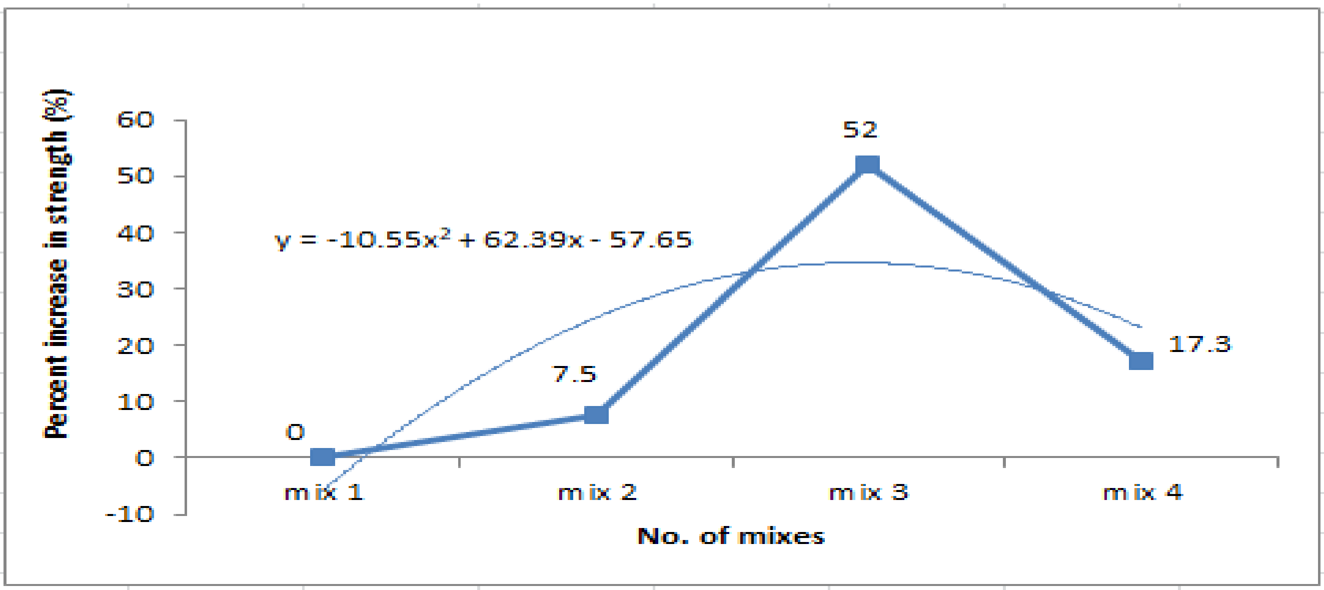

Figure 5: Percent increase in compressive strength of different mixes

Figure 6: Compressive strength specimen

Permeability test

In this investigation, water penetration tests were conducted by DIN-1048, Part 5. Samples with 150 mm x 150 mm x 150 mm were utilized for this purpose. The permeability test was conducted at nine days of age. A cover plate was provided for the surface of the specimens, and they were placed within the permeability cell. The surface of the specimens was exposed to a constant pressure of 5 bar for three days. After three days, the pressure was released, separating the specimens along the path of water penetration, which were subsequently removed from the cell. The penetration depth was measured five to ten minutes later, as illustrated in the table and graphical representations below. The final reported value was derived from the average values obtained from the three specimens

.

Table 6: Depth of penetrations

Mixes	Fly ash content (%)	Marble powder content (%)	Depth of penetration (cm)
Mix 1	100 %	0 %	5.5
Mix 2	75 %	25 %	4.4
Mix 3	50 %	50 %	3.7
Mix 4	25 %	75 %	4.2

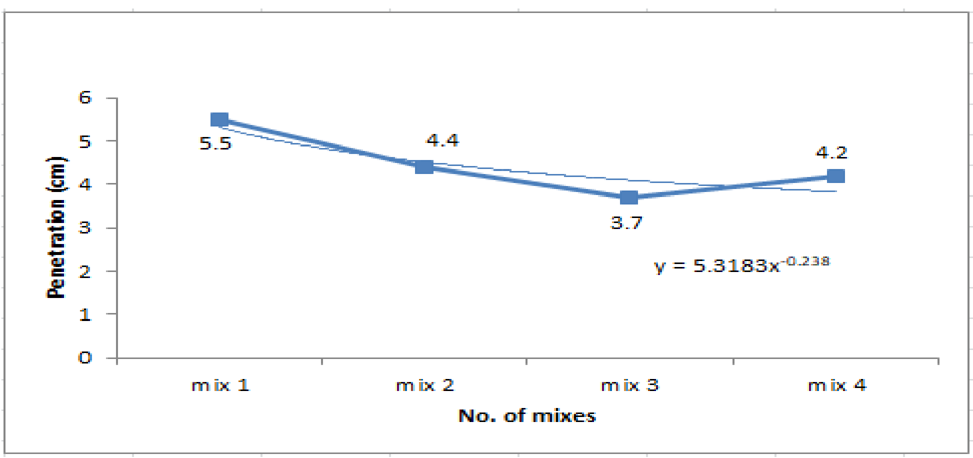

Figure 7: Permeability of different mixes

Permeability Coefficient

The equation used for finding the permeability factor is

$$Permeability\ factor = \left(\frac{CC\ x\ H}{AxTxP}\right) mm/s$$

With an increase in permeability coefficient, the depth of penetration of water also increased and vice versa, which is shown in below Figure 5. 5

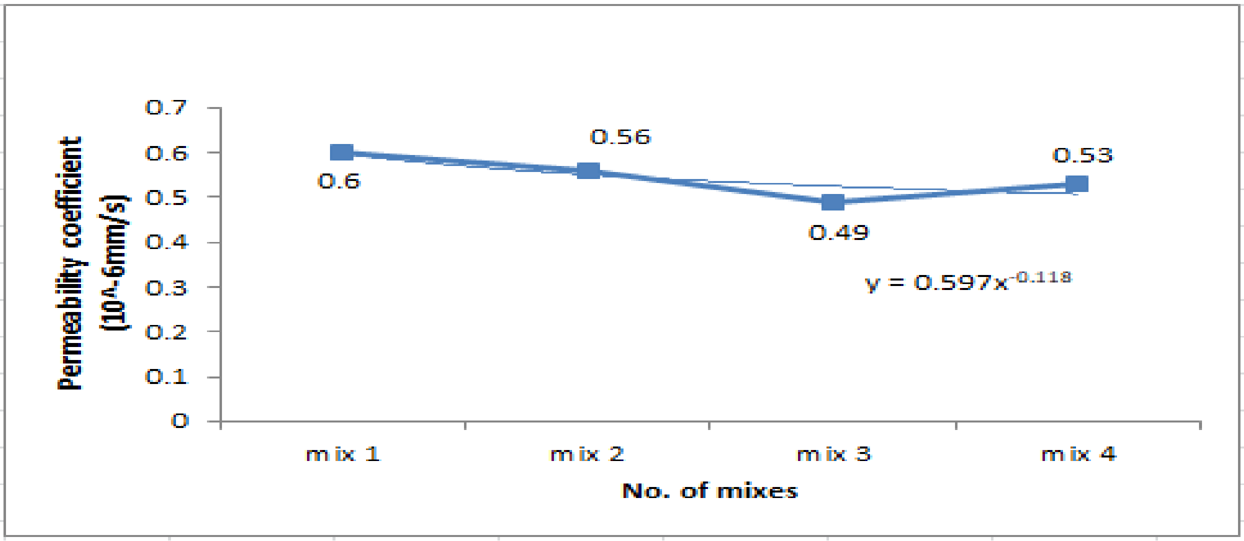

Figure 5: Permeability coefficient of different mixes

Figure 8: Specimens for Permeability Test

Conclusion and Recommendation

Conclusions

Conclusions were derived from experimental tests conducted on various mixtures of geopolymer concrete.

Optimal content of marble powder: The addition of marble powder enhances strength when it constitutes up to 50% of the fly ash content; however, exceeding this Proportion results in a decrease in strength. This provides a range in which the content of marble powder is optimal.

Environmental advantages: Marble powder is a beneficial alternative to sustainable building materials, as it improves strength properties and promotes sustainability in construction practices.

Energy efficiency and carbon reduction: Marble-based geopolymer concrete aligns with the goals of sustainable construction by contributing to a decrease in energy consumption and carbon emissions.

Incorporating a higher percentage of marble powder in concrete enhances its resistance to water damage, effectively reducing water penetration.

Durability considerations: While the incorporation of marble powder enhances the material's resistance to water, excessive water penetration may still adversely affect the longevity of concrete.

Workability issues: Substituting fly ash with marble powder decreases the mixture's workability, complicating the mixing and pouring processes.

Marble powder, a byproduct of marble processing, is a cost-effective alternative to traditional cementitious materials, thereby minimizing the economic impact of construction projects.

Recommendations

The following recommendations are derived from this research.The exothermic reaction and detrimental effects of alkaline solutions on fabrics and human skin present challenges when handling GPC in the field. To enhance the field application of ambient cured GPC, it is essential to utilize solid activators in place of alkaline solutions.

- Further analysis of the economic study of the geopolymer is necessary to determine the effective cost compared to cement concrete manufacturing.
- The mixed Proportion of geopolymer concrete exhibits greater hardness than ordinary Portland cement (OPC). Consequently, the software can be utilized to analyze AI data and predict the compressive strength of geopolymer concrete across different combination proportions.
- Addressing the current economic situation presents significant challenges. One option is to use raw materials rather than fine aggregates in the sodium hydroxide manufacturing process to reduce costs. Alternatively, materials such as crusher dust could be employed. However, it is essential to conduct research on the impact of these materials on the strength of the concrete.
- To enhance workability, the addition of a superplasticizer is recommended.

- Acknowledgment
- We thank Allah for granting us the capability and strength to understand, acquire, and finalize this research article. We express our gratitude to the University of Engineering and Technology, Civil Engineering Department, for allowing us to obtain precise results in our experimental work.

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