Experimental Study On Ambient Cured Alkali Activated Geopolymer Concrete Using Metakaolin And Copper Slag As Sustainable Cementitious Binders

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Abstract- *The global demand for cement is rising exponentially to meet the rapid development of infrastructure. However, the production of Ordinary Portland Cement (OPC) is highly carbon-intensive, contributing significantly to global greenhouse gas emissions and environmental degradation. Consequently, researchers are under substantial pressure to find sustainable, alternative binders that can minimize this carbon footprint. Geopolymers have gained significant traction as novel, eco-friendly binders emerging as a viable alternative to OPC. The superior performance of geopolymer binders particularly regarding fire and corrosion resistance—is largely attributed to the distinct absence of water and calcium-rich phases within their cross-linked network compared to traditional cement hydrates.*

To further enhance sustainability, industrial by-products can be upcycled as supplementary cementitious materials. Metakaolin (MK), Metakaolin is a highly reactive supplementary cementitious material (SCM), primarily used in concrete technology as a partial replacement for Ordinary Portland Cement (OPC).. Its high silica and alumina content plays a crucial role in achieving superior mechanical strength and durability in concrete. Similarly, copper slag is a massive by-product generated during the smelting and refining of copper. The current disposal methods for both Metakaolin and copper slag pose severe environmental and spatial challenges around industrial sectors. Incorporating these industrial wastes into geopolymer concrete serves a dual purpose: it mitigates the environmental impact of cement production and provides an effective waste-management solution. While many geopolymer systems require elevated heat curing to achieve optimal properties, this study focuses on ambient-cured systems to maximize practical field applicability. This paper presents an experimental investigation into the acid resistance of ambient-cured alkali-activated Metakaolin and copper slag concrete. Additionally, it provides a comprehensive review of existing literature evaluating the performance and degradation mechanisms of geopolymer concrete when exposed to various acidic media over extended periods.

Keywords: Copper slag (CS), Metakaolin (MK), Sodium Hydroxide (NaOH), Sodium Silicate (Na2SiO3), Compressive strength, split tensile strength test, Acid immersion.

I. INTRODUCTION

Cement Concrete is the structural backbone of modern civilization, a composite material consisting essentially of water, aggregates, and a binder. As global infrastructure needs escalate, the construction industry faces a two-fold ecological crisis: the high carbon footprint associated with Ordinary Portland Cement (OPC) production and the environmental degradation caused by the extraction of natural fine aggregates. Sustainable development in civil engineering now necessitates a paradigm shift toward circular economy models, where industrial and municipal waste are upcycled to mitigate these impacts.

The production of Portland cement is a significant contributor to global CO2 emissions, posing a severe threat to both environmental stability and long-term construction feasibility. Simultaneously, the aggressive dredging of natural river sand—traditionally preferred for its morphology and grading—has triggered ecological collapse in riverbeds, groundwater depletion, and structural risks to infrastructure

The impact of carbon dioxide emission due to production of portland cement can be reduced with supplementary cementitious materials. Copper slag and Metakaolin (MK) are the waste materials comprising pozzolanic properties but their disposal is causing impact on the environment. The utilization of industrial waste product in concrete has been a major step on waste reduction. Metakaolin and copper slag can be effectively used in concrete as a cementitious material because of their high content of silica and pozzolanic properties which plays an important role in achieving high strength and durability in concrete. To Substitute the cement we can utilize copper slagand MK that is accessible as a waste material delivered by steel enterprises separately.

Copper slag is an individual by product material produce by copper smetting and refining processes. Copper slag is a by-product materialproduced from the process of manufacturing copper.The disposal of this material is already inflicting environmental issues round factories.As the emission of carbon dioxide during the production of cement is more and thus causes serious problems to degradation of environment. In view of this, there is a significant expectation on the researchers to reduce CO2 emission. In order to reduce the usage of ordinary Portland cement, there is a need to find the alt

ernate material to the cement.

The primary reasons for the development of concrete that uses copper slag and Metakaolin as a partial replacement for cement are as follows

1. To ensure that natural resources such as lime stone, coal, fuel, and gypsum are preserved for future generations.
2. Using an alkali activating solution to improve the reactivity of copper slag and Metakaolin powder.
3. For the safe and efficient disposal of copper slag and Metakaolin.
4. The use of copper slag and Metakaolin as a partial replacement for cement in concrete is cost-effective and environmentally sustainable
5. The concrete with mineral admixtures provides lower permeability and reduces heat of hydration, making it more durable.

II. REVIEW OF LITERATURE

Geopolymer concrete serves as an innovative, low-carbon alternative to OPC-based binders. By activating aluminosilicate-rich industrial wastes such as fly ash, metakaolin (MK), and copper slag with alkaline solutions (e.g., sodium silicate and sodium hydroxide), high-strength structural components can be engineered without the environmental burden of cement production. To meet its goal, sustainable development must provide that these three components remain healthy and balanced. Furthermore, it must do so simultaneously and throughout the entire planet, both now and in the future. At the moment, the environment is probably the most important component, and an engineer or architect uses sustainability to mean having no net negative impact on the environment.

Junaid, M. T., Kayali, O., Khennane, A., and Black, J. (2015) In this paper he decided the mix proportions geopolymer concrete (GPC) by utilizing Calcium Class F Flay Ash and Alkaline solutions of sodium silicates and sodium hydroxide. For the distinctive mix plans he discovered ideal substance of alkaline fluid to fly ash (AL/FA) proportion, water to geopolymer concrete (W/GPS) proportion and Alkaline to water (AL/W) proportion.

Sangeetha,P.S.Joanna (2014) studied the structural behavior of RC beams with MK concrete. The results obtained from experiments states that the ultimate moment capacity of MK was less than the controlled beam when tested at 28 days, but it increases by 21% at 56 day. The measured crack width at service load ranged between 0.17 to 0.20mm and is within the limits (IS456-2000).

Anas Shahid Multani, A K Nigam (2017) Investigated on Partial Replacement of Cement with Metakaolin in Association with Super Plasticizer. Metakaolin seems to be an auspicious additional cementitious material for superior cement. Properties of cement with metakaolin are for the most part favoured added substances in superior cement. The metakaolin consolidations increment the quality of the concrete specimens. In this work, the impact of various contents of Metakaolin included to concrete containing super plasticizer its compressive quality strength and workability has been contemplated. Samples with 0%, 5%, 10%, 15%, 20% and 25% content of metakaolin replacing the cement have been evaluated for M30 grade. The outcomes have been contrasted and those for the control test and practicality of adding metakaolin to concrete has been examined. It was watched that up to 15% of concrete can be supplanted with metakaolin blended with superplasticizer.15% substitution is the ideal rate at which expanded quality of test sample is seen from the base sample test.

Saxena, S. K., Kumar, M., & Singh, N. B. (2018) compared the results of geopolymer cement with opc interms of compressive strength , durability test by using sulphuric acid. The geopolymer cement was made by using fly ash , Alkaline Solution (14M NaOH) and Silicate solution (Sodium silicate solution) And also he used alccofine powder which has have similar properties of silica fume. Finally he concluded that compared to OPC this designed mix (geopolymer mix) giving better reliable results than OPC in terms of durability, Compressive strength.

III. MATERIALS AND METHODS

The experimental investigation work is started with various tests on the constituent materials. The constituent materials are given below.

1. Cement
2. Coarse aggregate

3. Water
4. Copper Slag
5. Metakaolin.
6. Super plasticizer

I. Cement

Ordinary Portland Cement (OPC) was used in the experimental work which is conforming to I.S 4031-1988.The O.P.C is classified into three grades, those are 33grade, 43grade and 53 grade, depending upon the strength of the cement in this experiment 43grade cement is used.

II. Fine Aggregate

Fractions from 4.75 mm to 150 microns are termed as fine aggregate. Locally available river sand passed through 4.75mm IS sieve is applied as fine aggregate conforming to the requirements of IS 383:1970.

III. Coarse Aggregate

The crushed aggregates used were of 20mm nominal maximum size.Aggregate most of which is retained on 4.75-mmIS Sieve and containing only so much finer material as is permitted for the various types described in this standard.

IV. Copper Slag

Copper slag is an individual by product material produce by copper smetting and refining processes. Copper slag is a by-product material produced from the process of manufacturing copper. The disposal of this material is already inflicting environmental issues round factories.

V. Metakaolin

Metakaolin (MK) Metakaolin (MK) is a thermally activated aluminosilicate material, white in colour with a dull luster, obtained by calcining kaolin clay within the temperature range 6500-80000C. In the present investigation, Metakaolin marketed by Jeetmull Jaichandlall Pvt. Ltd. Chennai, Tamilnadu was used.

VI. Superplasticizer

Naphthalene based super plasticizer namely Fosroc Conplast SP430 is a chloride free, super plasticizing admixture based on sulphonated naphthalene polymer is used to upgrade or boost the workability as well as strength of geopolymer concrete. The dosage is raging from 1.00 to 3.00 litres per 100 kg of cementitious material such as fly ash, MK and alccofine etc.

IV. MIX DESIGN

The process of selecting suitable ingredients of concrete and determining their relative amounts with the objective of producing a concrete of the required, strength, durability, and workability as economically as possible, is termed the concrete mix design. If the plastic concrete is not workable, it cannot be properly placed and compacted. The property of workability, therefore, becomes of vital importance. Percentage dosage of super plasticizer was fixed as per the mix design method described in IS 10262- 2009. Mix proportion was arrived through various trial mixes. The grade of concrete prepared for the experimental study was M30.

V. TESTS ON FRESH CONCRETE

5.1 WORKABILITY OF CONCRETE

Workability of conventional and geopolymer concrete with variable proportions is determined utilizing slump cone. It is seen that decline in the slump an incentive as expansion in both molarity of alkaline solution and proportion of MK and copper slag are flaky in nature and high molar solution has greater viscosity when contrasted with water. Naphthalene based synthetic admixture i.e., super plasticizer is vital for redesign workability of GPC while mixing the various ingredients. Slump test was carried out to measure the workability of various mixes. The workability of various mixes was assessed as per the IS 1199:1959 specification.

TABLE 5.1 shows the Variation of Slump Values

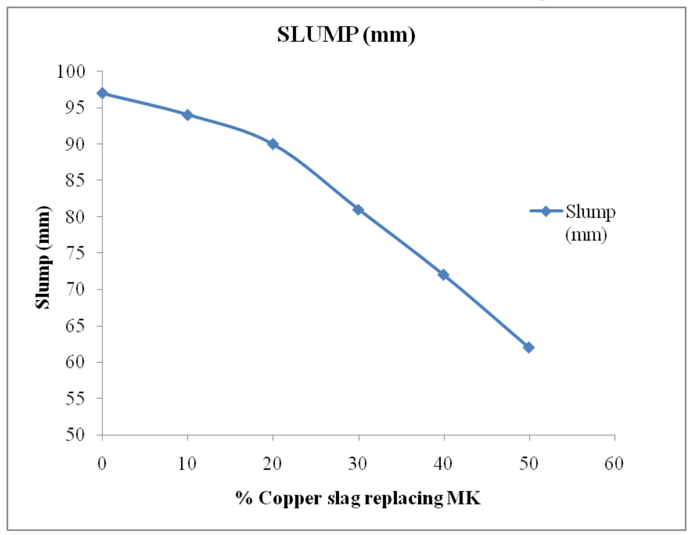
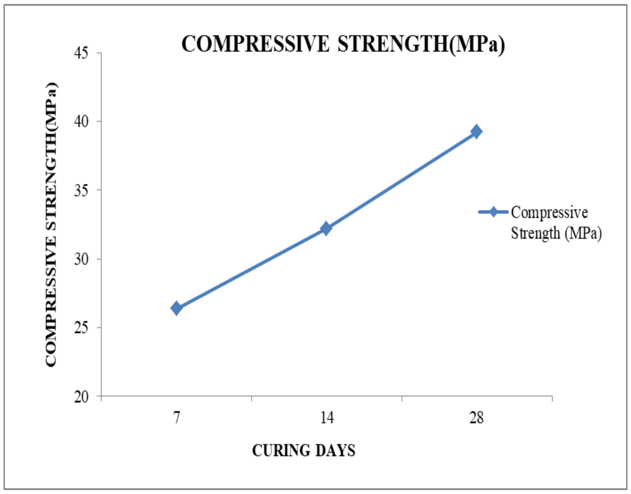


Fig 5.1: Plot shows the Variation of Slump Values for different proportions of Copper Slag + MK

VI. TESTS ON HARDENED CONCRETE

6.1 COMPRESSIVE STRENGTH OF CONVENTIONAL CONCRETE

To find the compressive strength of conventional concrete 150x150x150 mm size mould is used for the casting of compressive test specimen, after the 24 hours of casting of specimens remove the cubes from moulds and the cubes are placed in curing tank up to one day before the testing. The specimen's ultimate load is defined as the load at which it fails. At the ages of seven and twenty-eight days, this test was conducted. The average load of three specimens is used to calculate strength for each mix.



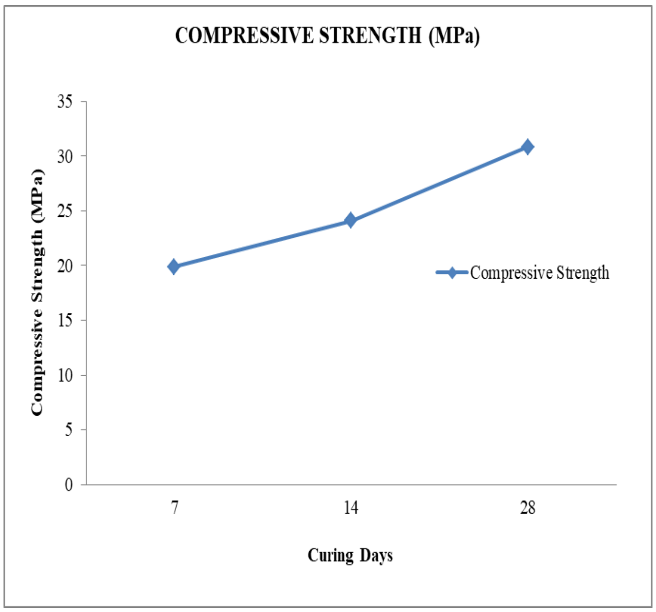


Fig 6.1: Plot shows the Variation of Compressive strength of conventional concrete

6.1.1 COMPRESSIVE STRENGTH OF GEOPOLYMER CONCRETE

This test is the important to direct and the relative investigations have done consolidating MK and copper slag. It is noticed that Na2SiO3/NaOH proportion of 2.5 the outcomes acquired are generally more.

Cube specimens of size 150mm were cast for compressive strength as per Indian standard specifications BIS: 516-1959. Immediately after finishing, the specimens were covered with sheets to minimize the moisture loss from them. Specimens were demoulded after 24-hours at approximately room temperature till testing. Compressive strength tests for cubes were carried out at 7, 14 and 28 days.

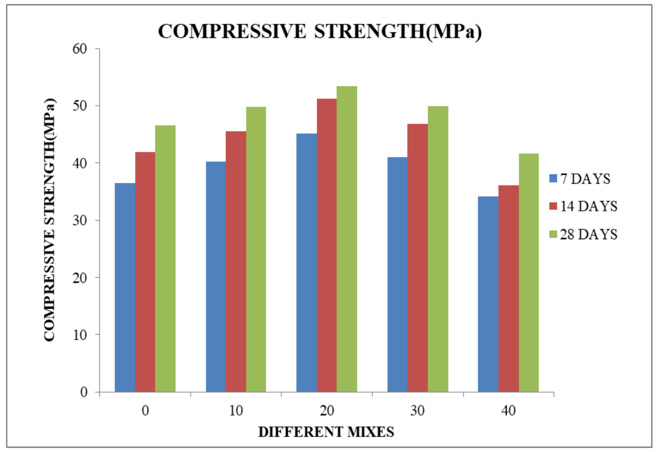
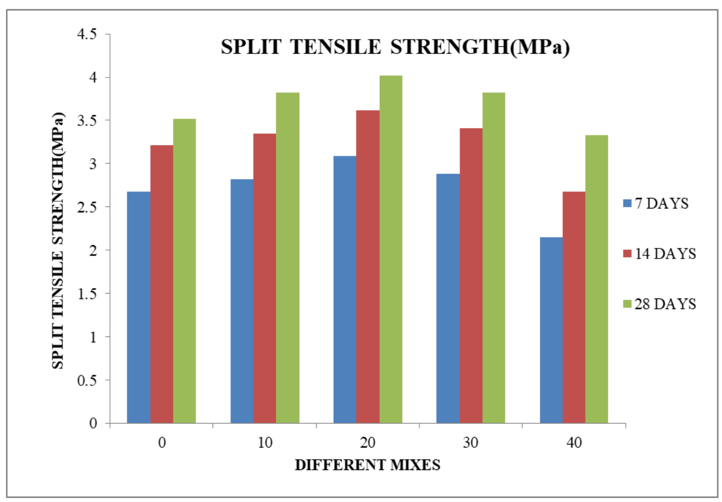


Fig 6.2: Plot shows the Variation in compressive strength for different proportions of CS+MK

6.2 SPLIT TENSILE STRENGTH OF GEOPOLYMER CONCRETE

Split tensile test is also used to determine the tensile stress in concrete; this method is also called as Brazilin test. In this we place the cylindrical specimen of size 300 mm height and 150 mm diameter is placed in horizontal between the loading surfaces of compression test machine and load is applied until the failure of the specimen along the vertical diameter. This test is performed as per IS: 5816 code.

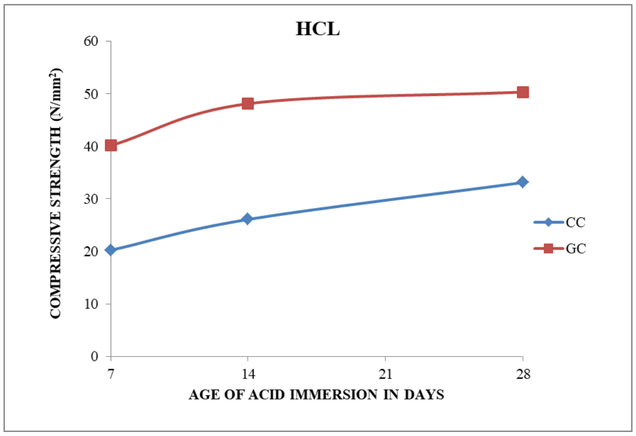


Graph 6.13: Plot shows the Variation in split tensile strength for different proportions of CS+MK at ambient curing

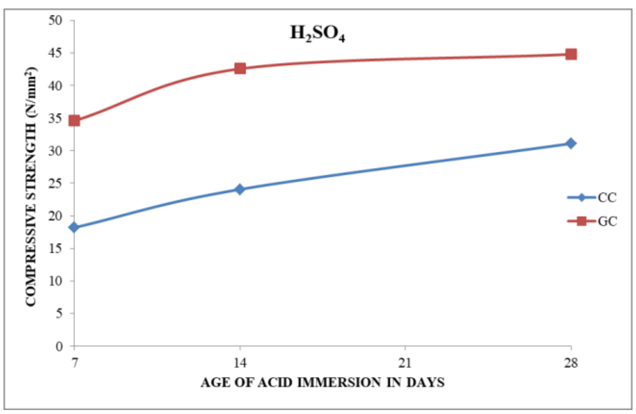
6.3 COMPRESSIVE STRENGTH ON ACID IMMERSION

Based on the compressive strength results of geopolymer concrete it is observed that at 20% replacement of copper slag the compressive strength is more pronounced. These mix cubes were cured under ambient curing for 7 days, 14 days and 28 days. These specimens were immersed in 5% of acid solutions i.e HCL, H2SO4, MgSO4 solutions for a period of 7 days, 14 days and 28 days. After completion of immersion period, concrete specimens were taken out and allowed for drying for a period of 1 day and weight of concrete cubes were determined.

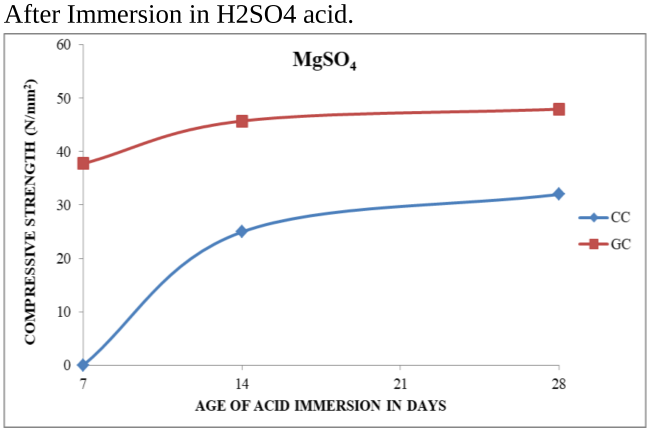
And also, the compressive strength of concrete cubes after acid immersion was determined by using U.T.M. Residual compressive strength and percentage weight loss of geopolymer and conventional concrete cubes after acid immersion have been studied and compared.



Plot shows the variation of Compressive Strength of Conventional concrete (CC) and Geopolymer Concrete (GC) - After Immersion in HCL acid



Plot shows the variation of Compressive Strength of Conventional concrete (CC) and Geopolymer Concrete (GC) - After Immersion in H2SO4 acid.



: Plot shows the variation of Compressive Strength of Conventional concrete (CC) and Geopolymer Concrete (GC) - After Immersion in MgSO4 acid.

Geopolymer concrete cubes and conventional concrete cubes were immersed in 5% of acid solutions i.e HCL, H2SO4, MgSO4 solutions and tested. From the results drawn graphs, based on the graphs it is observed that compared to conventional concrete, geopolymer concrete mixes resisted acid attack more. When compared to all the solutions, among all H2SO4 attack is more on concrete cubes.

S.No	Curing	HCL		H_2SO_4		$MgSO_4$	
		CC	GC	CC	GC	CC	GC
1	7 Days	23.23	11.1	30.92	23.34	27.51	16.34
2	14 Days	19.1	6.09	25.31	16.92	22.49	10.76
3	28 Days	15.6	5.84	20.77	16.22	18.47	10.31

Table 6.7 shows variation of split tensile Strength (N/mm2) of Conventional concrete (CC) and Geopolymer Concrete (GC) (N/mm2)-After Immersion in acids.

S.No	Curing	HCL		H_2SO_4		$MgSO_4$	
		CC	GC	CC	GC	CC	GC
1	7 Days	1.53	2.72	1.28	2.38	1.38	2.55
2	14 Days	2.11	3.23	1.81	2.92	1.91	3.18
3	28 Days	2.65	3.61	2.45	3.31	2.56	3.48

It is noted from the above graphs that when compared to conventional concrete, the slag based alkali activated concrete resisted the attack in a better way both in compressive strength point of view and tensile strength point of view. It is observed that the strength of concrete dependents on quantities of various oxides in the cementitious material, viz, cements and copper slag and Metakaolin.

It is observed With increasing in percentage of copper slag in MK with alkaline solution there is an increase in compressive strength up to 20% replacement of copper slag and 80% replacement of MK further replacement leads to decrease in strength and optimum found to be 20% + 80% replacement of copper slag and Metakaolin.

VII. CONCLUSIONS

Based on the document provided, the experimental research on Geopolymer Concrete (GC) using Metakaolin (MK) and Copper Slag (CS) as partial replacements for cement yields the following primary conclusions:

1. Optimal Replacement Ratios

• Compressive Strength: The experimental results indicate that the optimal performance for Geopolymer Concrete is achieved at 20% replacement of copper slag and 80% replacement of metakaolin. Beyond this ratio, compressive strength begins to decrease.

• Mechanical Efficiency: The use of copper slag and metakaolin in these proportions significantly enhances both the compressive and split tensile strength of the concrete matrix compared to control mixes.

2. Durability and Chemical Resistance

Acid Resistance: Geopolymer concrete (slag-based, alkali-activated) exhibits superior resistance to chemical attacks (HCl, H2SO4 and MgSO4) compared to conventional Ordinary Portland Cement (OPC) concrete.

• Percentage Loss: The study reports a lower percentage loss in both compressive and split tensile strength for GC specimens after acid immersion compared to conventional concrete (CC), confirming the durability benefits of the geopolymer matrix in aggressive environments.

3. Structural and Rheological Benefits

Sustainability: The study confirms that replacing cement with industrial waste (Metakaolin and Copper Slag) is a viable path toward reducing the carbon footprint of construction.

Waste Valorization: Utilizing these steel industry by-products helps minimize the space required for waste disposal while simultaneously improving the concrete's strength and chemical durability.

4. Summary Table of Key Findings (Acid Resistance)

The following table summarizes the performance improvement regarding tensile strength loss after acid exposure:

Curing Period	**Acid Type**	**Conventional Concrete (% Loss)**	**Geopolymer Concrete (% Loss)**
7 Days	HCL	14.52	12.62
14 Days	HCL	11.21	10.77
28 Days	HCL	10.78	9.71

Conclusion: The slag and Metakaolin based alkali-activated concrete demonstrated better resilience to acid exposure, confirming that the chemical composition (specifically the silicate and alumina oxides) derived from the waste materials plays a critical role in resisting degradation.

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