Novel Experimental Study on Properties of Alkali-Activated Fly Ash, GGBS Slag and Silica Fume based Concrete

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ABSTRACT

Supplementary Cementitious Materials (SCMs) are utilized to partially replace Portland cement in order to enhance both the fresh and hardened properties of concrete. Commonly used SCMs in chloride-exposed environments include C fly ash, F fly ash, Ground Granulated Blast Furnace Slag (GGBFS), and silica fume. SCMs contribute to improved concrete durability, degradation resistance through various mechanisms, and strength development. This study will assess different SCMs using the Pozzolanic Reactivity test and select one for chemical activation. Chemical activation involves applying various chemical agents—such as Ferric Chloride, Potassium Hydroxide, and Sodium Silicate—to alter the physical and chemical properties of SCMs. The performance of the chemically activated SCM in fresh and hardened concrete will be evaluated and compared with standard concrete properties.

Keywords- Experimental Study, Alkali-Activated, GGBS Slag, Silica Fume

1. Introduction

1.1 Supplementary Cementitious Materials (SCMs)

Supplementary Cementitious Materials (SCMs) are increasingly incorporated into concrete either by direct addition during the mixing process or by blending. SCMs, such as fly ash from coal combustion and Ground Granulated Blast Furnace Slag (GGBFS) from iron production, offer a viable alternative to traditional Portland Cement (PC) [1], [2]. These materials help reduce the carbon dioxide emissions associated with cement production because they do not require additional clinkering processes, which are energy-intensive. SCMs contribute to the sustainability of concrete by utilizing industrial by-products and enhancing various concrete properties. Fly ash, with its fine particles, improves workability, long-term strength, and reduces the heat of hydration, while also recycling a manufacturing by-product [3],[4]. GGBFS enhances sulfate resistance, lowers permeability, and improves overall durability [7][8][9]. Silica fume, a by-product from silicon metal and alloy production, fills gaps between cement particles, enhancing strength and mitigating alkali-silica reaction risks. The diverse benefits of SCMs include cost savings, reduced environmental impact, and improved performance, making them crucial for developing sustainable and durable concrete solutions[5][6].

1.2 Activation of SCMs

The activation of SCMs involves treating materials like fly ash, slag, or silica fume with specific chemicals to enhance their reactivity and effectiveness in concrete[10],[11][12][13]. Chemical activation often employs alkali solutions, calcium hydroxide, and other activators, depending on the SCM and desired concrete properties. This process modifies the surface properties of SCM particles, improving their interaction with cementitious materials during hydration. Activated SCMs undergo pozzolanic reactions with calcium hydroxide, forming additional cementitious compounds that refine the concrete's microstructure. This refinement leads to increased strength, reduced permeability, and greater resistance to chemical attacks, thereby extending the lifespan of concrete structures [14][15][16][17]. Research focuses on optimizing activation conditions and agents to maximize SCM reactivity while minimizing potential negative effects on concrete performance. Techniques like thermogravimetric analysis (TGA), X-ray diffraction (XRD), and scanning electron microscopy (SEM) are used to study the microstructural changes induced by activation. Understanding SCM activation is essential for advancing concrete technology and promoting sustainable construction practices.

1.3 Chemical Activation

Chemical activation enhances the reactivity of SCMs in concrete by adding specific chemicals, improving their ability to contribute to the concrete’s strength and durability. This critical aspect of concrete research aims to increase the effectiveness of SCMs, such as fly ash, GGBFS, and silica fume, in sustainable concrete formulations.[18][19] [20][21].. Chemical activation boosts pozzolanic reactions within the concrete matrix, where SCM particles react with calcium hydroxide from cement hydration to form additional cementitious compounds. This process refines the concrete’s microstructure, leading to better mechanical properties, reduced permeability, and increased resistance to chemical degradation[22][23][24]. Chemical activation is not only an academic interest but also has significant practical implications for creating high-performance concrete and advancing sustainable building practices[25][26]. By unlocking the full potential of SCMs, researchers and industry professionals can enhance concrete technology and promote environmentally responsible construction methods, resulting in structures with superior durability and resilience.

Beibei Sun, Yubo Su, Guang Ye, Geert De Schutter (2017): This research focused on a sustainable and cost-effective concrete type, BFS/FA-AAC, made from fly ash and blast furnace slag. The challenge was to clarify the mix design parameters. The study evaluated the impacts of curing times and specific material ratios on the concrete’s properties. It was found that both the mix composition and water content significantly influenced workability and compressive strength. The researchers developed a practical mix design method showing that paste content and mixture composition are crucial for concrete workability. They also identified that a water concentration range of 160 to 195 kg/m³ affects concrete durability. Their strength prediction model proved highly accurate, demonstrating that their mix design not only offers environmental benefits but also performs well in both fresh and hardened states.

Ranjith Dissanayake (2021): This study explored BFS/FA-AAC concrete, incorporating blast furnace slag and fly ash. The aim was to find a cost-effective and eco-friendly concrete mix. The research examined the effects of various factors, including material ratios and curing times, on concrete performance. It was found that the mix composition and water amount significantly impacted practicality and compressive strength. Based on these findings, the researchers developed a mix design method showing that paste content and component ratios affect ease of handling. They also discovered that a water concentration between 160 and 195 kg/m³ influences concrete strength. Their strength prediction technique was highly precise, and the resulting concrete mix demonstrated excellent performance and environmental benefits in both its fresh and hardened states.

Hailong Ye, Le Huang (2021): This study investigated the production of a durable and sustainable cement-like material through alkali activation, using a high volume of fly ash (HVFA). The research explored various activation liquids (water, NaOH, Na2SO4, Na2CO3), the addition of silica fume, and curing times. Na2SO4 was found to be the most effective activator, followed by Na2CO3, NaOH, and water. Alkali addition caused increased shrinkage due to changes in material stiffness and flexibility. NaOH-activated HVFA showed the most shrinkage, with Na2CO3 and Na2SO4 following. The presence of silica fume significantly reduced shrinkage when curing times were extended, although curing time had no impact on shrinkage without silica fume. Regardless of the activator used, silica fume improved material strength while slowing the reaction process.

Gang Xu, Xianming Shi (2019): This research investigated the development of a robust material using specific types of coal fly ash without applying heat. A design approach was used to conduct tests and develop models to understand factors influencing fly ash mixture strength. The study examined surface resistivity and ease of handling (lump flow) after 28 days. Adding two types of fly ash and chemicals to the first batch increased strength and durability. The strength ranged from 2.9 to 20.5 MPa without chemical activation and improved to 16.8 to 33.6 MPa with a single type of fly ash and various chemical activators. Microscopic analysis highlighted the importance of activators in dissolving fly ash particles and forming durable materials through hydration.

Qing-feng Liu, Yuxin Cai, Hui Peng, Zhaozheng Meng, Shishir Mundra, Arnaud Castel (2015): This study explored an eco-friendly alternative to conventional cement, focusing on the durability of alkali-activated fly ash/slag (AAFS) concrete. The research addressed issues such as steel bar corrosion and chloride penetration. An intricate computer model was developed to study chloride movement and potential corrosion onset. The study found that slag content and the water-to-binder ratio are critical factors affecting chloride penetration and steel bar corrosion, as they reduce concrete porosity. The amount of aggregate had a lesser impact compared to these factors. Their methodology provides a means to predict the lifespan of these sustainable concrete structures.

3. Materials

In the crucial phase of material selection for the project, the focus is on choosing supplementary cementitious materials (SCMs) that align with both availability and the specific needs of the project. Key SCMs under consideration include fly ash, slag, and silica fume, each bringing distinct properties that can greatly impact the performance and sustainability of the concrete.

3.1 Fly Ash Class C:

Definition: Class C fly ash is a by-product from coal combustion characterized by a higher calcium oxide content and generally possesses self-cementing properties.

Table 1: Physical Properties of Class C Fly Ash

Sr No.	Physical Tests	ASTM C 618 Limit	Results
1	Fineness	34 Max	16.1
2	Pozzolanic Activity Index	75 Min	79.2
3	Water Requirement	105 Max	89.2
4	Soundness	0.8 Max	0.31
5	Specific Gravity	-	2.58

3.2 Fly Ash Class F:

Definition: Class F fly ash is a byproduct of burning anthracite or bituminous coal. It possesses pozzolanic properties, which means it reacts with calcium hydroxide in the presence of moisture to form compounds that contribute to the strength and durability of concrete.

Table 2: Physical Properties of Class F Fly Ash

Test No.	Test	Unit	IS-3812Part1 Specification	Test Results
1	Fineness- Specific Surface by Blaine's permeability Method (Min.)	m^2/kg	320	382
2	ROS # 500 (25 MIC)	%	Not Specified	-
3	ROS # 350 (45 MIC) Max	%	34	13.24
4	Lime Reactivity (Minimum)	N/mm^2	4.5	5.89
5	Moisture Content (Max)	%	2	0.23
6	Autoclave expansion (Max)	%	0.8	0.026
7	Compressive strength at 28 days Pozzocrete + Cement mortar Plain Cement Mortar	N/mm^2	80% of strength of plain cement mortar cubes (Minimum)	44.5 48.0 92.71 %

3.3 Ground Granulated Blast Furnace Slag (GGBFS):

Ground Granulated Blast Furnace Slag (GGBFS) is a by-product of the iron and steel industry, known for its latent hydraulic properties. Its inclusion in concrete enhances durability and provides significant resistance to sulfate attack. The use of GGBFS is particularly advantageous in regions where it is readily available due to active iron and steel production. Incorporating GGBFS in the concrete mix is a strategic choice aimed at optimizing both the structural integrity and environmental sustainability of the concrete.

Table 3: Physical Properties of GGBFS Slag

Sr No.	Characteristics	Requirements	Test Results
1	Fineness (M/kg)	275 (Min)	390.23
2	Specific Gravity	-	3.08
3	Particle Size (Cumulative %) 45 Micron	-	97.33

3.4 Silica Fume:

Silica fume is a by-product of the production of silicon and ferrosilicon alloys. Its ultrafine particles contribute significantly to enhancing the strength and durability of concrete. While silica fume may not be as readily available as other supplementary cementitious materials (SCMs), its unique properties make it an essential component in projects that require high-performance concrete.

Table 4: Physical Properties of Silica Fume

Sr No.	Characteristics	Test Results
1	Appearance	White colour powder
2	Color	White
3	Pack Density	0.77 gm/cc
4	pH of 5% Solution	6.91
5	Specific Gravity	2.64
6	Moisture	0.055%
7	Oil Absorption	54 ml/100 gms

4. Result/Analysis:

4.1 Normal Test on SCMs

The consistency test on cement assesses the workability or flowability of cement paste, a vital characteristic in the construction industry. This test measures the resistance of the cement paste to deformation, commonly performed using a Vicat apparatus or a flow table. The normal consistency of OPC 53 grade cement was recorded at 32%. It was also noted that increasing the GGBFS content in the mix led to a corresponding increase in the consistency of the cement paste.

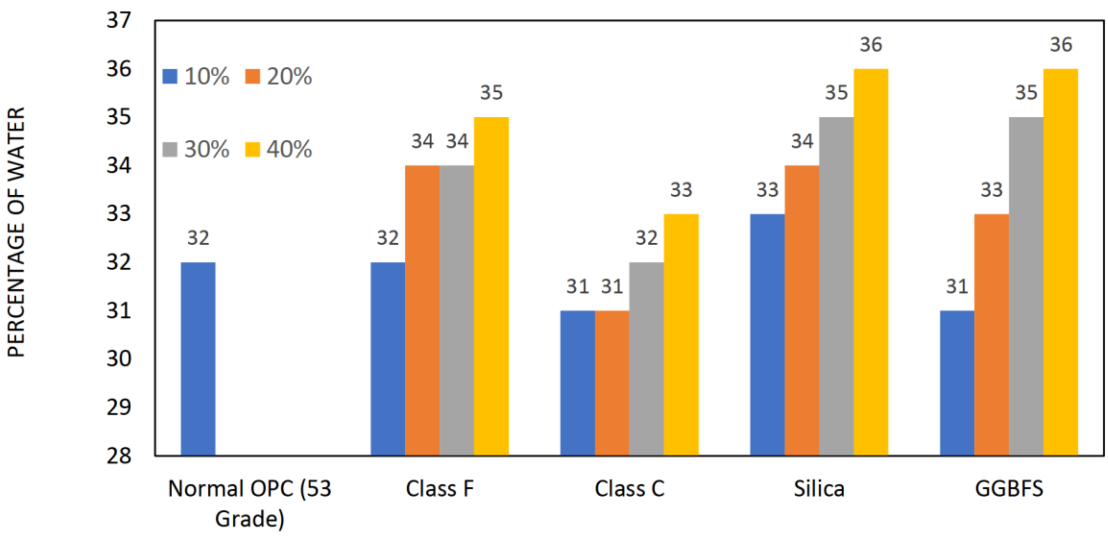

Fig.1 Normal Consistency Result and Analysis

Initial and Final Setting Time:

The initial setting time of ordinary Portland cement (OPC) was observed to be 227 minutes, and the final setting time was 250 minutes. It was noted that the initial setting time increased with the higher replacement percentage of GGBFS, reaching a maximum of 174 minutes at 40% replacement, although this was still less than the setting time of OPC. Additionally, the final setting time also increased with the GGBFS replacement percentage, reaching 197 minutes at a 30% replacement level. However, beyond this 30% replacement level, the final setting time began to decrease.

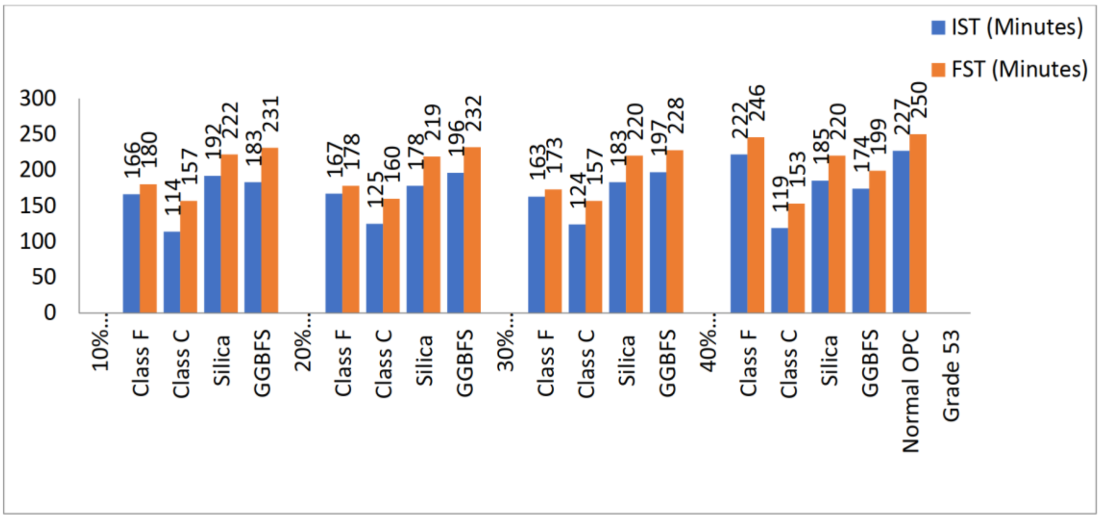

Fig.2 Initial and Final Setting Time Result and Analysis

3. Loss-on-Ignition:

Loss-on-ignition (LOI) is a standard test for supplementary cementitious materials (SCMs) that helps determine the presence of excess moisture and undesirable impurities, such as carbon. This test measures the mass loss in a sample when heated to a maximum of 1,000 °C, where the lost volatile materials typically include 'combined water' and carbon dioxide from carbonates. LOI is often used as a quality control test. The loss on ignition for ground granulated blast furnace slag (GGBFS) was observed to be 0.05%, which is well within the standard limit of 5%, indicating good quality and minimal impurities.

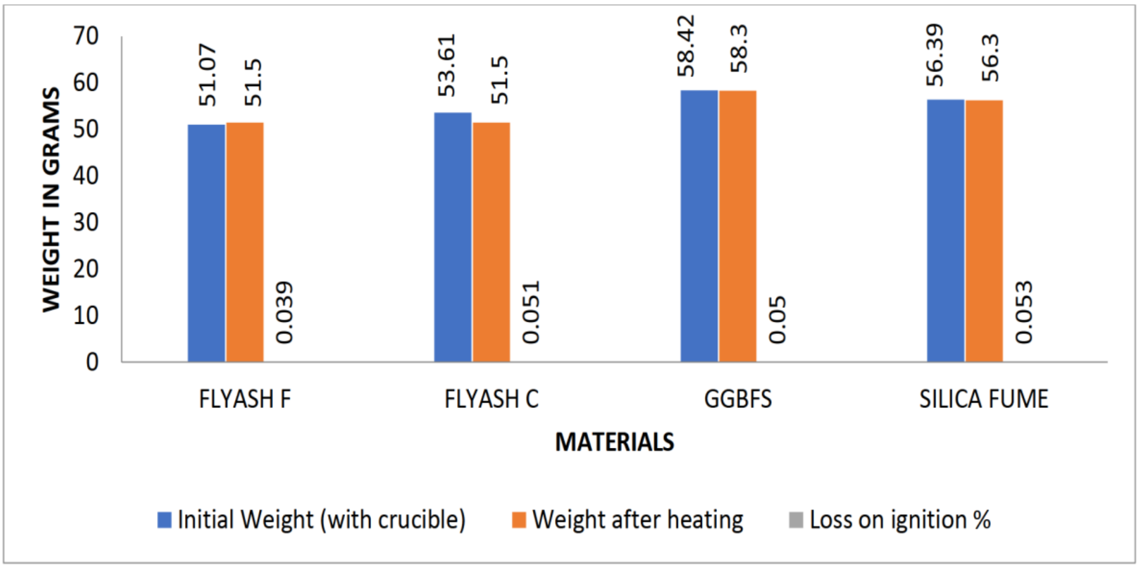

Fig.3 Loss on Ignition Result and Analysis

4. Fineness Test:

The fineness of cement is crucial as it directly affects the rate of hydration, the rate of strength gain, and the rate of heat evolution. Finer cement particles provide a greater surface area for hydration, leading to quicker strength development. The fineness test often involves wet sieving to remove fine particles that may be difficult to sieve before drying and testing the sample. The fineness of ground granulated blast furnace slag (GGBFS) was recorded at 8.6%, which meets the standard criterion of being less than 10%, indicating that the material is sufficiently fine for effective hydration and strength development.

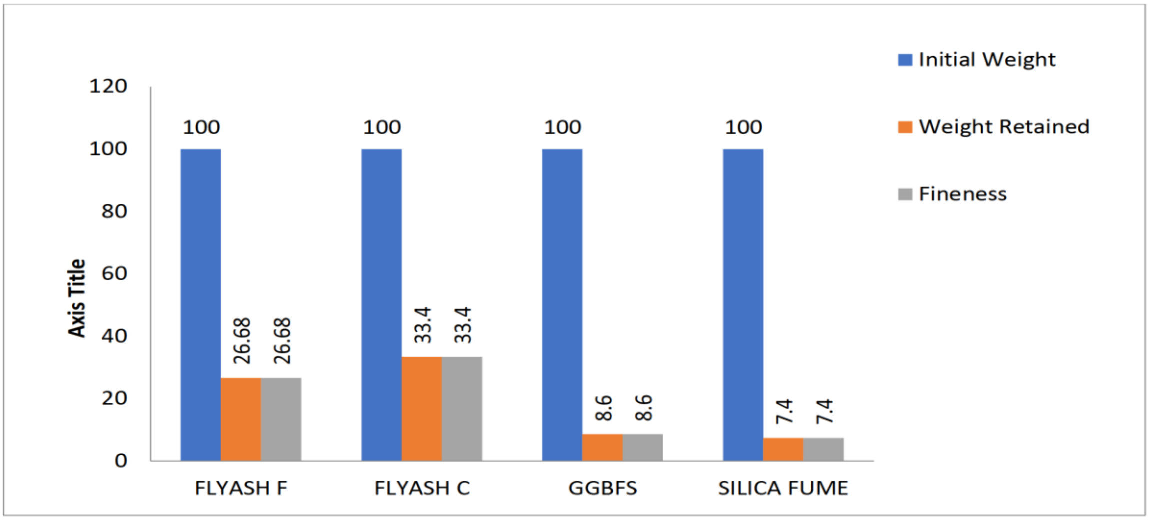

Fig. 4 Fineness Test Result and Analysis

5. Specific Gravity:

The Specific Gravity test measures the ratio of the density of a substance to the density of a reference substance at a fixed temperature. Knowing the specific gravity of a material is essential for its appropriate application in construction, particularly in concrete design. The density of cement is a key parameter in concrete mix design, influencing the volumetric properties of the mix. Specific gravity is a critical factor as it directly affects the overall density and stability of the concrete. For fly ash, the specific gravity typically ranges from 2.1 to 3.0. The specific gravity of ground granulated blast furnace slag (GGBFS) was observed to be 2.86, which falls within the standard range of 2.1 to 3.0, indicating it is suitable for use in concrete mix design.

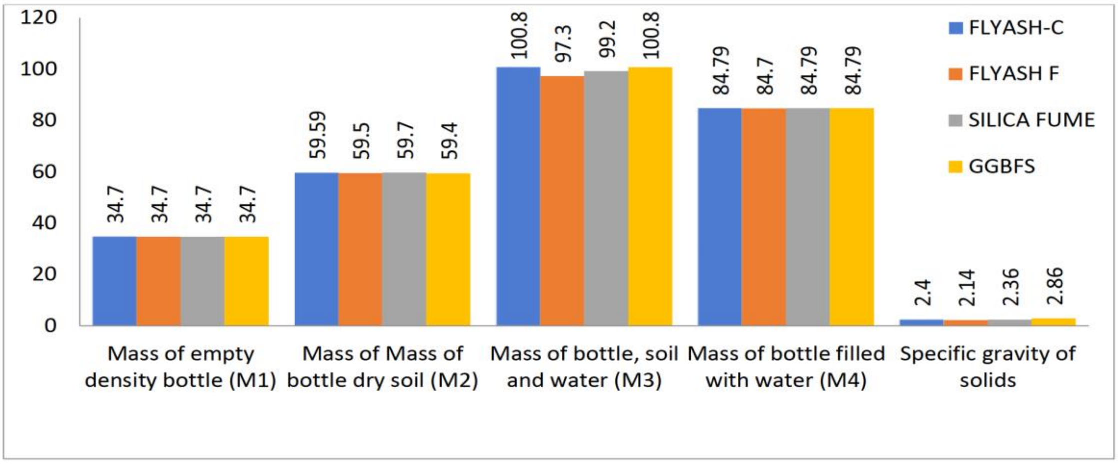

Fig.5 Specific gravity Result and Analysis

6) Strength Activity Index:

The Strength Activity Index (SAI) is a measure of the pozzolanic reactivity of supplementary cementitious materials. The average compressive strength after 7 days for the control specimen was observed to be 5.85 N/mm², while the 7-day strength for Ground Granulated Blast Furnace Slag (GGBFS) was recorded at 10.13 N/mm². This results in a strength activity index of 173.16%, which is significantly above the standard minimum value of 80%. This indicates that the GGBFS exhibits strong pozzolanic reactivity, making it suitable for enhancing the strength of concrete.

4.2 Result

4.2.1 Compressive Strength

A) Normal Cube

Table 5: Compressive Strength of Normal Cube

Sr. No	Specimen Name	7 Day (KN/m2)	7 Day (N/m2)	28 Day (KN/m2)	28 Day (N/m2)	Average (N/m2)
1	1	530.038	23.778			25.318
2	2	514.338	23.078			
3	3	560.038	29.118			
4	4			820.638	36046.238	40.068
5	5			976.938	43.638	
6	6			892.338	39.878	

B). 20% Replacement

I. Cube

Table 6: Compressive Strength 20% Replacement Cube

Sr. No	Specimen Name	7 Day (KN/m2)	7 Day (N/m2)	28 Day (KN/m2)	28 Day (N/m2)	Average (N/m2)
1	1 Cube 20%	495.938	22.268			23.008
2	2 Cube 20%	529.338	23.748			
3	3 Cube 20%	513.138	23.028			
4	4 Cube 20%			949.138	42.408	42.888
5	5 Cube 20%			939.038	41.918	
6	6 Cube 20%			992.738	44.348	

C). 30% Replacement
I. Cube

Table 7: Compressive Strength 30% Replacement Cube

Sr. No	Specimen Name	7 Day (KN/m2)	7 Day (N/m2)	28 Day (KN/m2)	28 Day (N/m2)	Average (N/m2)
1	1 Cube 30%	579.338	25.968			25.488
2	2 Cube 30%	544.238	24.408			
3	3 Cube 30%	582.138	26.098			
4	4 Cube 30%			983.238	43.918	47.518
5	5 Cube 30%			1113.238	49.918	
6	6 Cube 30%			1096.238	48.948	

D). 40% Replacement
I. Cube

Table 8: Compressive Strength 40% Replacement Cube

Sr. No	Specimen Name	7 Day (KN/m2)	7 Day (N/m2)	28 Day (KN/m2)	28 Day (N/m2)	Average (N/m2)
1	1 Cube 40%	544.938	24.438			23.878
2	2 Cube 40%	521.638	23.408			
3	3 Cube 40%	530.238	23.788			
4	4 Cube 40%			1002.238	44.768	47.878
5	5 Cube 40%			1102.238	49.208	
6	6 Cube 40%			1112.238	49.658	

5. Conclusion

The experimental study on the chemical activation of supplementary cementitious materials for concrete production yielded promising results. The activation process significantly enhanced the concrete's strength and durability, suggesting that chemically activated materials could be instrumental in developing more sustainable and efficient construction practices. However, further research and optimization are necessary to facilitate widespread adoption and practical application in the construction industry.

The findings underscore the potential benefits of incorporating chemically activated cementitious materials in concrete production. The observed improvements in mechanical properties and durability indicate a notable enhancement in the overall performance of concrete. Nonetheless, challenges such as understanding the long-term effects and refining activation agents need to be addressed before these techniques can be widely implemented in construction. Overall, this study provides valuable insights into advancing high-performance and sustainable concrete technologies.

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