

A Study on the Utilization of Industrial and Agricultural Waste in Geopolymer Matrix Development

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Abstract - In today's world, industries and agriculture produce a lot of waste materials like slag, fly ash, rice husk ash (RHA), and red mud. These wastes create serious environmental problems when dumped. A new method called geopolymerization can help use these waste materials in a useful way by turning them into strong building materials using sodium hydroxide (NaOH).

In this study, four waste materials slag, fly ash, RHA, and red mud were mixed with different amounts of NaOH (5%, 10%, and 15%). Tests were done to find out how much water and how tightly these mixtures can be packed. Then, cylindrical samples were made and kept at room temperature for 0, 7, and 28 days. Their strength was checked using a compressive strength test, and the chemical changes were studied using an X-ray test (XRD).

Results showed that slag and fly ash became much stronger when mixed with NaOH especially slag with 10% NaOH, which reached around 27 MPa strength in just 7 days. Fly ash also showed good strength after 28 days. RHA had lower strength at first, but improved after 28 days. Red mud gave better results only at 5% NaOH; higher NaOH made it weaker. The X-ray test confirmed that a special bonding material was formed, which helped improve the strength. This study shows that using waste materials with NaOH can create eco-friendly and low-cost construction materials, helping reduce pollution and save natural resources.

Keywords: Geopolymer, Industrial waste, Agricultural waste, Sodium hydroxide, Strength test, X-ray analysis.

I. INTRODUCTION

1.1 General

With the rapid growth of industries and agriculture, a huge amount of waste materials is being produced every year. Some of the major waste products include coal ash (fly ash), red mud, blast furnace slag, and rice husk ash (RHA). The biggest problem with these wastes is disposal, as they require a lot of land and can cause serious pollution. Fine particles from these wastes can pollute the air, and harmful chemicals

can leach into the soil and water, making the land unfit for use.

To solve this issue, scientists and engineers are working on ways to reuse these wastes in construction, so that they don't harm the environment. One promising way is to use them in making geopolymers, a type of building material that is strong, durable, and eco-friendly. However, even today, we are not able to use 100% of these waste products effectively.

Some of the commonly studied wastes are:

- Blast furnace slag – This is a by-product of steel industries and is rich in silica and alumina. It can replace cement in concrete.
- Fly ash – Produced in thermal power plants when coal is burnt. India generates over 163 million tons of fly ash every year, but only about 61% of it is being used. The rest is dumped in ash ponds, which pollutes land and water.
- Red mud – Comes from aluminium industries during the processing of bauxite. Globally, over 3 billion tons of red mud has been produced, and this number is increasing every year.
- Rice husk ash (RHA) – A waste from rice mills when rice husk is burnt as fuel. It contains high amounts of silica. India, being a large rice-producing country, generates around 20 million tons of RHA every year. Improper disposal of RHA creates serious land and air pollution.

Instead of dumping these wastes, we can use them to make geopolymers. Geopolymer is a cement-like material formed by reacting these silica and alumina-rich wastes with an alkaline solution like sodium hydroxide. This process is called geopolymerization, first introduced by scientist Joseph Davidovits in the 1970s.

II. REVIEW OF LITERATURE

2.1 Introduction

Inorganic polymers can be produced by geopolymerization; a progressive technology that can alter various

aluminosilicate by-products into beneficial construction materials. Geo-polymerization consists of a diverse chemical reaction between aluminosilicate sources and alkali metal ions at highly alkaline conditions and mild temperatures, resulting glassy to semi-crystalline polymeric structures, which consist of Si-O-Al and Si-O-Si bonds [Davidovits, 1999]. Even though mechanism of geo-polymerization is not fully understood, the most common method comprises three parallel steps:

- Dissolution of solid aluminosilicate materials in alkaline sodium silicate solution
- Oligomerization of Si and/or Si-Al in aqueous phase
- Solidification of the oligomeric species.

According to Davidovits (1991) geo-polymers are comprised of several fundamental poly (sialates) units as shown Fig. 2.1.

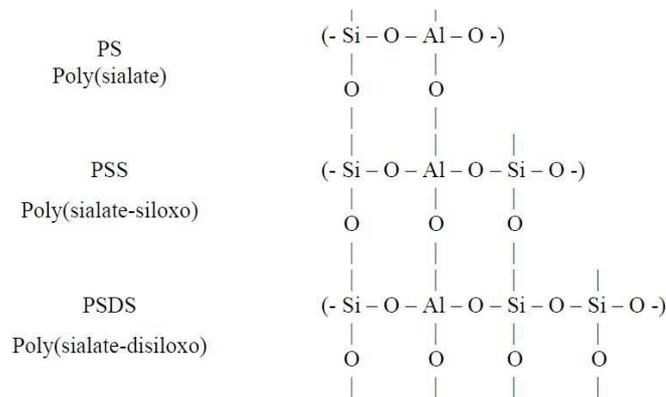


Figure 2.1: Geo-polymeric Molecular Networks

Mustafa et al. (2011) experimented on fly ash based geopolymer samples. They chose mixture of sodium silicate and sodium hydroxide as alkaline activator. Various temperatures (room temperature, 50oC, 60oC 70oC, 80oC) were chosen for curing with the duration of 24 hour. The 7th day strength revealed that maximum compressive strength of 67.04MPa is found for the samples cured at temperature of 60oC.

Arioz et al. (2012) took fly ash based geo polymer for the research work. They investigated mechanical and micro structural properties of the prepared materials which were activated by 4M, 8M and 12M of sodium hydroxide and sodium silicate solutions. All the specimens were cured at 80oC for 15hours. On 7th day and 28th day, strength tests were carried out. The microstructure of the samples was examined by Scanning Electron Microscope, EDX, X-Ray Diffraction and FTIR. They concluded that with the increase in concentration of sodium hydroxide solution the compressive strength and degree of reaction increases.

Zhang et al. (2013) examined the viability of geo polymer in stabilizing lean clay. Metakaolin based geo polymer was used for the stabilization lean clay with varying concentration at OMC. The concentration ranges from 3 to 15 weight percentage of unstabilized soil. Specimens are characterized for compressive strength tests, Scanning Electron Microscope, EDX, FTIR, X-Ray Diffraction, volume change during curing.

Puertas et al. (2000) showed that increasing slag content in fly ash slag blends enhanced strength.

Cheng and Chiu (2003) demonstrated that slag-based geopolymers exhibit excellent fire resistance and early strength development.

Dimas et al. (2009) developed red mud-based geopolymers by mixing red mud with metakaolin and alkaline solutions, achieving good mechanical properties.

He et al. (2013) explored red mud and RHA mixtures, showing potential for use in geopolymer binders.

Rahim et al. (2014) found that RHA-based geopolymers developed acceptable strength with sufficient alkali activation.

Prabhu et al. (2014) reviewed the mechanical properties of RHA-based geopolymers and noted the influence of carbon content on reactivity.

Arioz et al. (2012) concluded that 8-12M NaOH produces better compressive strength than lower concentrations.

The research work available on the effects of using NaOH alone as the alkali activator for the development of geo polymer materials is limited. The present research aims to explore the activation of by-products with different percentages of NaOH. Strength characteristics of the activated materials were observed by unconfined compressive test (UCS test). XRD analysis was carried out to find out the minerals produced after the alkali activation.

III. MATERIAL AND METHODOLOGY

3.1 Materials Used

3.1.1 Ground Granulated Blast Furnace Slag:

Ground Granulated Blast Furnace Slag (GGBFS) is a by-product of the iron and steel industry. It is formed when molten slag, produced during the manufacturing of iron in a blast furnace, is rapidly cooled using water or steam. This rapid cooling process turns the slag into a glassy, non-crystalline (amorphous) material that contains useful compounds like calcium silicates, alumina (Al₂O₃), silica

(SiO₂), and magnesia (MgO). Because GGBFS contains a high amount of silica and alumina, it can be used as an important raw material in the geopolymerization process. It reacts well with alkaline solutions (like sodium hydroxide) to form strong, cement-like materials. The amorphous nature of GGBFS makes it highly reactive compared to traditional materials.

For this project work, GGBFS was collected from Bhilai Steel Plant. The material was first dried in an oven to remove moisture. Then, to increase its fineness and surface area, the material was ground in a ball mill. After grinding, the powder was passed through a 75-micron sieve to ensure a uniform particle size for better reactivity during geopolymer formation.

Table 3.1: Typical Chemical Composition of GGBFS

Mineral Name	Calcium oxide	Silica	Alumina	Magnesia
Percentage	40%	35%	13%	8%

3.1.2 Fly Ash

Fly ash is a fine powder that is produced as a waste material when coal is burned in thermal power plants. It is collected from the flue gases using electrostatic precipitators. Fly ash is rich in silica (SiO₂), alumina (Al₂O₃), and calcium oxide (CaO), which makes it a good aluminosilicate material for use in geopolymers. For this project, fly ash was collected from Godawari Power & Ispat Ltd., Raipur. After collection, the fly ash was dried in an oven to remove any moisture. The dried material was then stored carefully to prevent contamination and to keep it ready for further experiments.

3.1.3 Rice Husk Ash

RHA contains a very high amount of silica content and is found to be amorphous in nature. The amorphous silica contained in RHA can react with cementitious binders to perform pozzolanic activity. Locally available rice husk ash was used to carry out the research work. In this research work, dry RHA were sieved to remove residual bran and clay particles and kept in oven at 105°C-110°C for 24 hours before sample preparation.

3.1.4 Red Mud

Red Mud is the insoluble product after bauxite digestion with sodium hydroxide at higher temperature and pressure. It is a combination of minerals initially available in the raw ore, bauxite, and of compounds introduced during the Bayer cycle. Wet disposal of red mud is mostly preferred by preparing slurry with 10-30% of solid concentration. The pH of red mud is generally in the range of 11-13. The amount of red mud generated gets influenced by the quality of bauxite ore and it varies from 55-65% of the treated bauxite. Alkalinity of red mud in spite of high water content is high because of the

existence of an extreme amount of dissolved sodium hydroxide. Moreover, constituents of red mud comprise generally iron oxides, alumina, and silica. Red mud was collected from KJ Engineering works, Raipur. The material was oven dried and the fineness of the material was increased by putting it in a ball mill. The red mud use in this project work had pH of 11.2.

3.1.5 Sodium Hydroxide

Sodium hydroxide was used for the alkali activation of the raw materials (i.e. Slag, fly ash, rice husk ash, red mud). The sodium hydroxide pellets used for this project were Fisher Scientific brand with 98% purity. The NaOH solution was prepared before 24 hours to ensure proper dissolution of the sodium hydroxide pellets.

3.2 Methodology

3.2.1 Specific Gravity

The specific gravity of fly ash was determined according to IS: 2720 (Part-III, section-1) 1980 by using pycnometer with distilled water as the solvent. The values are shown in Table 3.2.

Table 3.2 Specific Gravity of the Raw Materials

Material	Specific Gravity
Slag	2.75
Fly ash	2.59
Rice husk ash	2.01
Red mud	3.13

3.2.2 Moisture Content-Dry Density Relationship

The compaction characteristics of the materials were determined as per IS 2720 (Part VII) 1980. Four materials were activated by varying percentage of NaOH (i.e. 5%, 10%, 15%) of its drying weight. The sodium hydroxide solution was prepared with the starting percentage of water to be added to dry sample for standard proctor test. The solution was kept for 24 hrs. to dissolve the sodium hydroxide pallets properly. As per IS: 2720 (Part II) 1973 the moisture content of the compacted mixture was determined. From the dry density and moisture content relationship, optimum moisture content (OMC) and maximum dry density (MDD) were determined.

3.2.3 Unconfined Compressive Strength

For determination of strength of alkali activated raw material at different curing days (0day, 7days and 28 days), 100mm height and 50 mm diameter samples are prepared at OMC and MDD by adding varying percentage of NaOH with oven dried raw material. Unconfined compressive strength

tests were conducted as per IS 2720 (Part X) 1991. The samples were coated with wax and kept for curing at ambient temperature. The UCS tests were conducted on the prefixed curing days. Curing periods for the project work were 0 day, 7 days and 28 days. UCS tests for the determination of immediate strength were conducted within 2hrs after mixing the raw material with alkaline solution.

3.2.4 XRD Analysis

The X-ray diffraction (XRD) tests were used for the determination of the crystalline phase of the minerals present in the raw materials and activated samples. XRD test is performed by using Philips X' PERT System X-Ray diffractometer. After prefixed curing period, samples were collected and soaked in acetone to discontinue the ongoing reaction. Samples were made finer than 75 μm before taking it for XRD analysis. The specimen was positioned in the diffractometer and scanned using Cu $K\alpha$ radiation, a step size of 0.02° with range 10° to 70° at a rate of $10^\circ/\text{min}$. XRD Pattern of all the four by-products are shown in fig. (2)-(5). From XRD analysis, it was observed that quartz (SiO_2) is present in all raw materials. A hump between 2 theta ($20^\circ - 40^\circ$) is observed from XRD pattern of GGBFS which represents the glassy structure of GGBFS. From XRD analysis of fly ash, the crystalline peaks are found to be hematite (Fe_2O_3) and quartz (SiO_2). From fig 4, we can conclude that hematite, magnetite, quartz and aluminum oxide are the minerals present in red mud. The RHA contains silica and cristobalite and the halo in the range of $10^\circ - 30^\circ$ represents the amorphous structure of RHA.

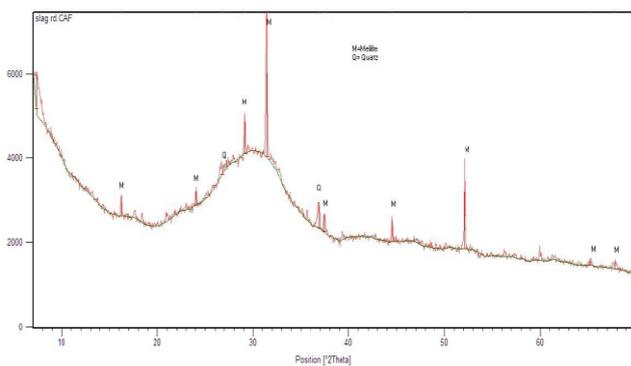


Figure 3.1: XRD Pattern of GGBFS

IV. RESULTS AND DISCUSSIONS

4.1 Light Compaction Test

The Fig. (1)- Fig (4) represent the compaction characteristics of slag, fly ash, red mud and rice husk ash with different percentage of NaOH (i.e. 0%, 5%, 10%, 15%) respectively. With increase in percentage of NaOH added to

raw material, optimum moisture content (OMC) decreases and maximum dry density (MDD) increases.

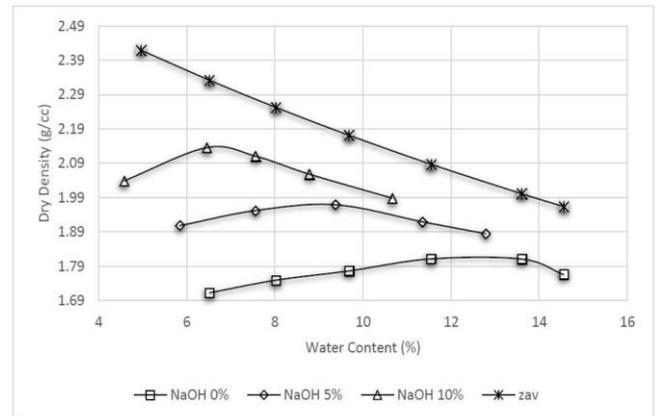


Figure 4.1: Moisture Content-Dry Density Relationships for Slag with Different % of Alkali Content

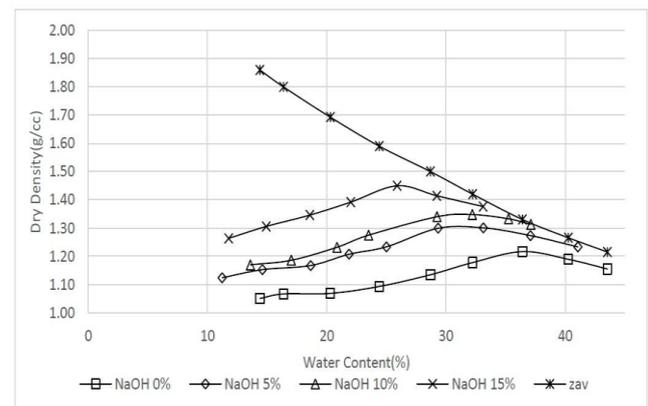


Figure 4.2: Moisture Content- Dry Density Relationship of Fly Ash at Different Alkali Content

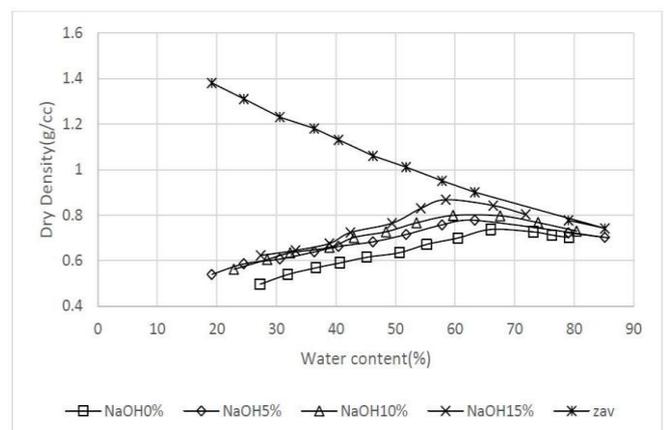


Figure 4.3: Moisture Content- Dry Density Relationship for Rice Husk Ash with Different % of Alkali Content

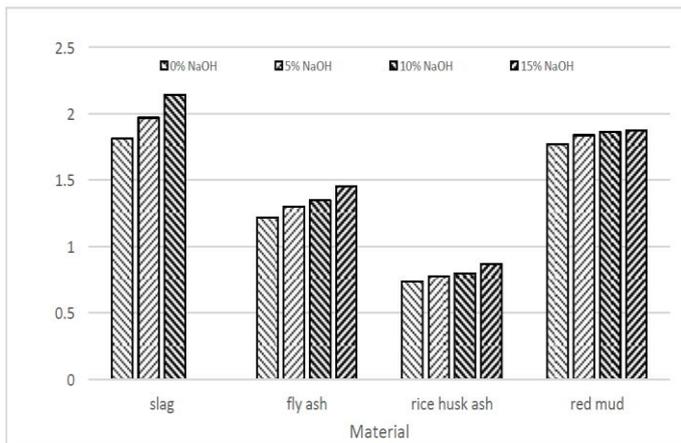


Figure 4.4: Variation of MDD with Different Percentages of NaOH

Table 4.1 OMC and MDD of Raw Materials with Varying NaOH %

Description	Optimum Moisture Content (%)	Maximum Dry Density (g/cc)
Fly ash	36	1.216
Fly ash+5% NaOH	33	1.301
Fly ash+10% NaOH	32	1.347
Fly ash+15% NaOH	26	1.45
Slag	13	1.811
Slag+5% NaOH	9	1.969
Slag+ 10% NaOH	7	2.14
Red mud	24	1.768
Red mud+5% NaOH	22	1.837
Red mud+10% NaOH	21	1.86
Red mud+15% NaOH	20	1.876
RHA	66	0.737
RHA+ 5% NaOH	63	0.777
RHA+ 10% NaOH	59	0.798
RHA+ 15% NaOH	58	0.867

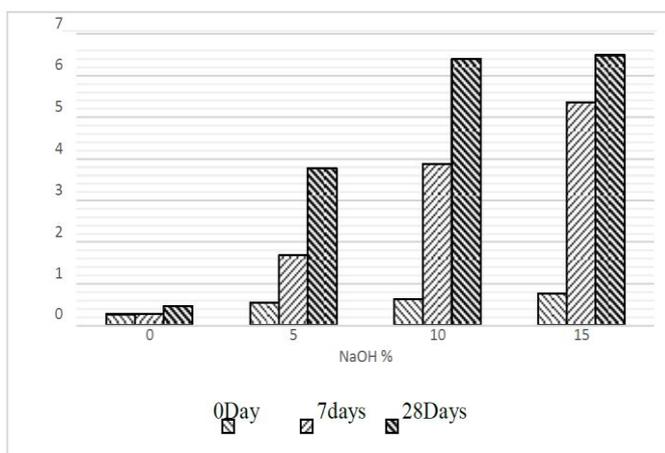


Figure 4.5: Comparison of Strength of Fly Ash at Different Curing Periods

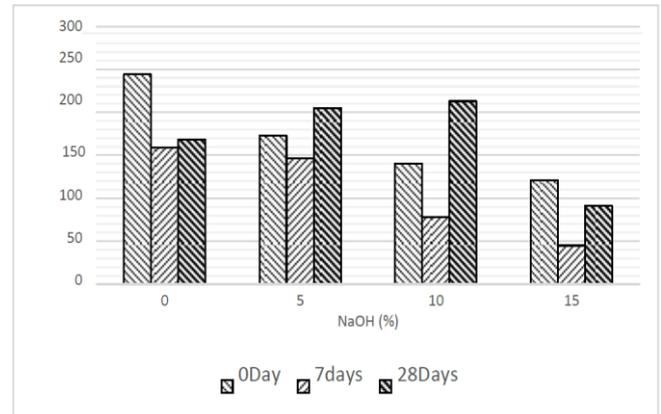


Figure 4.6: Comparison of Strength of Rice Husk Ash at Different Curing Periods

The change in strength of the alkali-activated rice husk ash (RHA) samples with different curing periods is shown in Fig 4.18. On the 7th day of curing, the strength of the samples decreases compared to the initial (0 day) strength, but by the 28th day, there is a slight increase in strength. However, with an increase in the percentage of NaOH, the overall strength tends to decrease. This may be due to the presence of unburnt carbon in RHA, which interferes with the geopolymerization process. Also, higher alkali content can lead to excess pore water and poor bonding, resulting in reduced strength development.

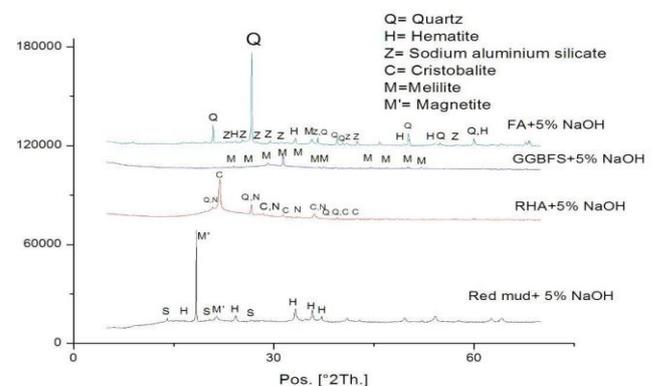


Figure 4.7: Comparison of XRD Analysis of Activated Materials

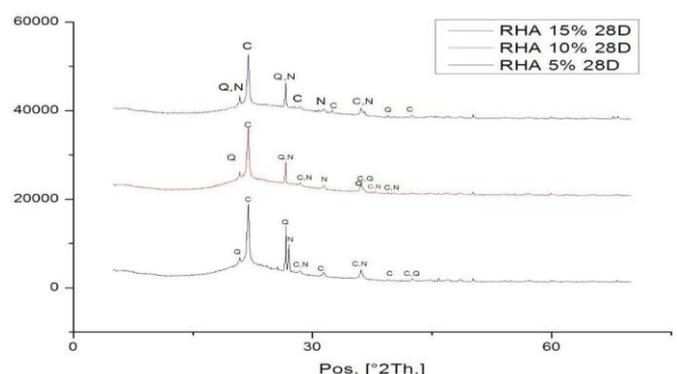


Figure 4.8: XRD Pattern of Activated RHA at 28 Days

V. CONCLUSIONS

5.1 Summary

In this project, three main tests were carried out on four different waste materials slag, fly ash, rice husk ash (RHA), and red mud. These tests included the light compaction test, unconfined compressive strength (UCS) test, and X-ray diffraction (XRD) analysis. After studying the basic properties of these raw materials, they were stabilized using sodium hydroxide (NaOH) in different percentages (5%, 10%, and 15%) to observe how the alkaline activator affects their behavior.

5.2 Conclusion

This work investigates how four solid wastes ground granulated blast furnace slag (GGBFS), fly ash, rice husk ash (RHA), and red mud behave when transformed into geopolymer binders with different doses of sodium hydroxide (NaOH: 0%, 5%, 10%, 15%). Light compaction tests established optimum moisture content (OMC) and maximum dry density (MDD), unconfined compressive strength (UCS) tests tracked mechanical performance at 0, 7, and 28 days, and X-ray diffraction (XRD) identified reaction products.

Key findings are as follows:

Increasing NaOH lowers OMC and raises MDD for all wastes because the NaOH gel lubricates the mix. At 15% NaOH, slag paste becomes supersaturated and cannot be mixed.

Slag shows the fastest reaction: UCS rises $2.9 \times$ and $7.6 \times$ at 5% and 10% NaOH, reaching ≈ 27.5 MPa by day 28 with little gain beyond day 7; failures are brittle.

Fly ash gains early strength (0.55 MPa at 5% NaOH, $\approx 2 \times$ the raw value) and reaches $\approx 20 \times$ the untreated strength after 28 days; 10% and 15% NaOH give similar long term results.

RHA loses strength immediately when NaOH is added, drops further at day 7, but rebounds slightly by day 28; higher alkali makes specimens bulge, and $\sim 10\%$ residual carbon slows the reaction.

Red mud benefits only from 5% NaOH (UCS ≈ 1.08 MPa at day 7); higher dosages and longer curing reduce strength because its crystalline phases limit geopolymer formation.

Overall, NaOH reacts most rapidly with slag and slowest with RHA.

XRD confirms the disappearance of quartz peaks and growth of sodium aluminosilicate hydrate (N-A-S-H) gel in slag and fly ash matrices, while sodium silicate phases dominate in RHA systems.

These results show that moderate alkali activation (5-10% NaOH) can convert selected industrial and agricultural wastes into strong, low carbon binders, but each precursor demands its own optimum alkali dose and curing regime.

5.3 Scope of Future Work

Based on the findings of the present study, there exists significant potential for further research in the field of alkali-activated geopolymer matrix development using industrial and agricultural wastes. Future investigations can focus on a detailed microstructural analysis of the alkali-activated products using advanced characterization techniques such as Scanning Electron Microscopy (SEM), Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and Nuclear Magnetic Resonance (NMR) to better understand the reaction mechanisms and gel formation. Since the current study was limited to ambient temperature curing, the influence of elevated curing temperatures (e.g., 40°C to 80°C) on setting time, strength development, and polymerization efficiency should be explored. Additionally, the use of alternative or mixed activators such as sodium silicate, potassium hydroxide, or combined systems may improve the mechanical and durability properties of the binders. Further studies should also evaluate the long-term durability of the developed materials under aggressive environments, including sulphate attack, acid exposure, freeze-thaw cycles, and water absorption. Beyond unconfined compressive strength (UCS), other mechanical properties such as flexural strength, tensile strength, and modulus of elasticity should be assessed. Optimization of the mix design parameters, including the solid-to-liquid ratio, alkali concentration, and water-to-binder ratio, can help in achieving better performance and consistency. Moreover, conducting life cycle assessments (LCA) and cost-benefit analyses will provide insights into the environmental and economic viability of using geopolymer binders in practical applications. To validate laboratory findings, pilot-scale field applications, such as in pavement sub-bases or masonry units, should be undertaken. Incorporating fibrous reinforcements like jute, polypropylene, or glass fibers may enhance toughness and reduce brittleness. Finally, the exploration of other industrial by-products such as metakaolin, waste glass powder, or cement kiln dust for creating hybrid geopolymer systems represents a promising direction for future research.

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Citation of this Article:

Vishwa Ranjan Kumar, & Prof. R.R.L. Birali. (2025). A Study on the Utilization of Industrial and Agricultural Waste in Geopolymer Matrix Development. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 9(6), 212-219. Article DOI <https://doi.org/10.47001/IRJIET/2025.906028>
