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# BENTONITE-AMENDED GEO-POLYMERISED FLY ASH-GGBS MIXTURE FOR WASTE CONTAINMENT APPLICATIONS

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***ABSTRACT*****:** The reuse of Fly Ash (FA) with the optimum amount of Ground Granulated Blast Furnace Slag (GGBS) polymerized with an alkali solution for the construction of barriers for waste containment and vertical cutoff walls for the contaminated ground is explored in this study. For this, detailed strength and permeability tests have been conducted on different ratios of FA and GGBS compacted and cured for up to 28 days. Compacted samples of FA and GGBS mixtures, at an optimal ratio of 40:60, were polymerized with sodium hydroxide alkali solution up to 5 molar concentration, as the effectiveness of polymerization varies with alkali concentration. The significant increase in compressive strength is attributed to pozzolanic reactions, whereas the increase in tensile strength is due to the polymerization of the components of the mixtures. Geopolymerisation is done through the incorporation of alkali and is known to enhance pozzolanic activity by converting part of silica to reactive silica, producing more pozzolanic compounds and part modification of pozzolanic reaction compounds. To optimize the increase in compressive strength and the percent reduction in tensile strength, the maximum concentration of alkali is restricted to 5 M. To reduce the permeability for their application in the construction of the barrier, a 5% bentonite, in addition to the optimum FA-GGBS mixture, is considered, as its high specific surface and negative charges can retain ionic contaminants such as heavy metals. Both compressive and tensile strength increased over curing, and permeability decreased. The retention capacity of selected heavy metal (lead and nickel) ions is due to their precipitation in the voids of the barrier materials.

***ABSTRAK*****:** Penggunaan semula Abu Terbang (FA) dengan jumlah optimum Lebihan Pasir Kisar Relau Bagas (GGBS) yang dipolimerkan dengan larutan alkali bagi pembinaan penghalang pembendungan sisa dan dinding titik potong menegak bagi tanah tercemar diterokai dalam kajian ini. Bagi tujuan ini, ujian kekuatan dan kebolehtelapan terperinci telah dijalankan pada nisbah berbeza FA dan GGBS yang dipadatkan dan diawet selama 28 hari. Sampel padat campuran FA dan GGBS, pada nisbah optimum 40:60, digeopolimerkan dengan larutan alkali natrium hidroksida sehingga 5 kepekatan molar, kerana keberkesanan pempolimeran berbeza dengan kepekatan alkali. Peningkatan ketara dalam kekuatan mampatan adalah disebabkan oleh tindak balas pozzolanik, manakala peningkatan dalam kekuatan tegangan adalah disebabkan oleh pempolimeran komponen campuran. Geopolimerisasi adalah melalui penggabungan alkali dan diketahui dapat meningkatkan aktiviti pozzolanik melalui penukaran sebahagian silika kepada silika reaktif, menghasilkan lebih banyak sebatian pozzolanik dan sebahagian pengubahsuaian sebatian tindak balas pozzolanik. Bagi mengoptimumkan peningkatan kekuatan mampatan dan pengurangan peratus kekuatan tegangan, kepekatan maksimum alkali dihadkan kepada 5 M. Bagi mengurangkan kebolehtelapan penggunaannya dalam pembinaan halangan, bentonit 5% sebagai tambahan kepada campuran optimum FA-GGBS dipertimbangkan, kerana permukaan spesifiknya yang tinggi dan cas negatif boleh mengekalkan bahan cemar ionik seperti logam berat. Kedua-dua kekuatan mampatan dan tegangan meningkat berbanding pengawetan, dan kebolehtelapan berkurangan. Kapasiti pengekalan ion logam berat (plumbum dan nikel) terpilih adalah disebabkan oleh pemendakannya di dalam lompang bahan penghalang.

***KEYWORDS:*** *alkali, bentonite, fly ash, ground granulated blast furnace slag, permeability*

# 1. INTRODUCTION

To meet the increasing energy demand worldwide, coal is combusted in thermal power plants to generate electricity. Fly ash (FA) is a by-product generated from these plants, and its characteristics and properties vary depending on the type of coal and combustion conditions. Class C fly ash is generated by combusting lignite or sub-bituminous coal, whereas anthracite or bituminous coal combustion generates Class F fly ash. Most FA in India is Class F due to the abundance of bituminous coal reserves. FA is utilized in various applications such as concrete production, the construction industry, soil stabilization, roads, and embankments to a limited extent, and excess FA is generally disposed of, which consumes cost, land, and environmental hazards [1]. Studies have shown that Class F fly ash alone as a source material results in less strength over curing at ambient temperature due to its reduced pozzolanic nature [2]. Utilization of Class F fly ash is highly desirable as it is considered a negative-cost material. ASTM C618-22 classified fly ashes mainly based on their calcium content. Class C fly ash with a higher amount of calcium is pozzolanic in nature besides being cementitious, whereas Class F fly ash with a lower amount of calcium is less pozzolanic or not pozzolanic but can become sufficiently pozzolanic if it contains reactive silica or more silica becoming soluble in the presence of alkali.

The restricted suitability of class F FA is due to its slow early strength gain, longer setting time, and higher water absorption. Materials rich in calcium (Ca) can be added to FA to enhance the mechanical properties. In the present work, Ground Granulated Blast Furnace Slag (GGBS) is added to increase the efficiency of FA. In addition, FA alone produced cementitious compounds by lime and reactive silica if available or becomes available in the presence of alkali. This pozzolanic reaction is time-dependent, and strength development can be slow. GGBS with higher reactive silica can react fast and produce cementitious materials to develop strength. Improper combination can also lead to decreased efficiency, and the optimum proportions of the mixture need to be evaluated [3]. Therefore, FA is amended to match the right proportion of GGBS.

Another approach for mobilizing the strength of the FA and GGBS is through alkaline polymerization. Geopolymers are gaining attention as they offer various benefits like high early and long-term compressive strength, high tensile strength, sorption capacity, sufficient durability, low $CO_2$ emissions, and limited drying shrinkage, which make them sustainable as landfill liner materials [4]. The eco-friendly construction materials are formed by activating source materials rich in silica ($SiO_2$) and alumina ($Al_2O_3$) like FA, GGBS, kaolinite, metakaolin, etc. with alkaline activators like sodium hydroxide, sodium silicate, and a combination of both [5]. Studies on the effect of alkaline activators in the polymerization process revealed that sodium hydroxide is preferred to sodium silicate as an activator as it leaves a smaller carbon footprint, and the precursors can be activated with NaOH solution without resorting to alkali silicate. Earlier studies have noticed an effective polymerization with sodium hydroxide and without sodium silicate [6]. The use of an appropriate amount of alkali needs to be determined through laboratory testing.

One of the promising uses for alkali polymerized FA-GGBS mixtures is as a component of barriers for landfills and in constructing vertical cut-off walls to protect adjacent sites and groundwater from potential sources of pollution. Besides forming pozzolanic compounds, polymerization enhances tensile strength, a major advantage in the present application [7]. Generally, pozzolanic compounds bind particles, which can increase mostly UCS only. The enhancement in the tensile strength is only through polymerization. This is the major advantage of polymerization of the material with alkali. However, alkali inclusion also enhances pozzolanic reactions by dissolving crystalline silica and partially modifying pozzolanic compounds to N-A-S-H and C-S-H [8].

The desirable properties of any barrier materials and impoundments are good strength, low permeability, adsorption, and/or retention of contaminants contained in the leachate generated [9]. These properties also become important for constructing cut-off walls for contaminated grounds to isolate them from the surrounding environment. Relatively high strength is required for cut-off walls compared to constructing barriers for landfills, and lower permeability is more desirable for landfills than for cut-off walls. The upper limit of permeability of vertical cut-off walls is 10-6 cm/s, whereas the same is 10-7 cm/s for bottom liners [10] since cut-off walls are not constructed for hazardous waste landfills to minimize contaminant migration. The pozzolanic materials have low settlement and shrinkage properties. Being highly alkaline, they can precipitate most metal ions and make them immobile [11].

Initial tests have shown that fly ash with 60% GGBS develops optimum strength. Later, FA-GGBS mixtures were polymerized with different concentrations of sodium hydroxides in the range of 1 to 5 molar (M), which further improved their properties, particularly their applications in barriers. To further improve the tensile strength, lower hydraulic conductivity, and enhance the sorption of contaminants in the migrating leachates, the addition of about 5% calcium bentonite is considered [12]. Bentonite is known to swell on hydration in the presence of water and block the voids, reducing the hydraulic conductivity. Bentonite with high negative surface charges can also absorb ionic species present in the system, which will be an added advantage in retaining ionic contaminants such as heavy metals when they are trying to migrate through the barrier system. This swelling and blocking of the pores will be maximum when the ionic species is monovalent sodium. The initial divalent cation ions, such as calcium, are used for pozzolanic reactions, and bentonite will tend to become increasingly monovalent sodium bentonite. The alkaline conditions of the material precipitate any ionic metal ions, making them immobile and trapping them within the barrier system, apart from reducing the effective void ratio for the conduction of the contaminated leachate generated in the landfill disposal or contaminated grounds [13].

## 2. MATERIALS AND METHODS

### 2.1. Materials Used

Pozzolanic materials used in the production of geopolymers include FA and GGBS. Polymerization of these admixtures was attempted using sodium hydroxide as an alkali activator. Bentonite (B) is added to enhance cohesiveness and reduce permeability. FA was collected from the Raichur thermal power plant in Karnataka. Commercially available GGBS, bentonite, and sodium hydroxide pellets were used in the study.

The materials used in the study were characterized for specific gravity as per ASTM D792, grain size distribution (ASTM, 2007a), and compaction characteristics (including the maximum dry unit weight and optimum moisture content; ASTM, 2007b). The details are given in Table 1. Grain size distribution shows that FA and GGBS are sand and silt-sized particles, with coarse sand-sized particles being more common in FA and silt-sized particles being more prevalent in GGBS. Additionally, bentonite contains almost equal amounts of silt and clay-sized particles. Thus, a mixture of FA-GGBS amended with bentonite results in a well-packed composite with fewer voids.

Table 1. Physical properties of materials

| **Properties** | **FA** | **GGBS** | **B** |
|---|---|---|---|
| Specific Gravity (G) | 2.14 | 2.80 | 2.70 |
| Grain Size distribution (%) | | | |
| Coarse sand (4.75- 0.075mm) | 58.55 | 25.51 | 0.90 |
| Silt size (0.075- 0.002mm) | 39.82 | 70.49 | 57.80 |
| Clay size (<0.002mm) | 0.63 | 4.00 | 41.30 |
| Liquid Limit. % | 27 | 30 | 233 |
| Compaction parameters | | | |
| MDD (kN/m$^3$) | 14.00 | 15.90 | - |
| OMC (%) | 15.60 | 22.70 | - |

The oxide compositions of $SiO_2$, $Al_2O_3$, and CaO of FA, GGBS, and bentonite are obtained through Figure 1. Based on the oxide composition, FA can be categorized as Class F fly ash, a low-calcium precursor, as the calcium content of FA is less than 18%, according to ASTM C618-22 [14].

The ternary diagram shows that FA, GGBS, and bentonite used in the study contain silicon, aluminum, and CaO oxides. A mixture of FA and GGBS is advantageous for optimally utilizing both available reactive silica and CaO. It was found that FA and GGBS, in a ratio of 40:60, can achieve optimal amounts of cementitious compounds and possess better strength.

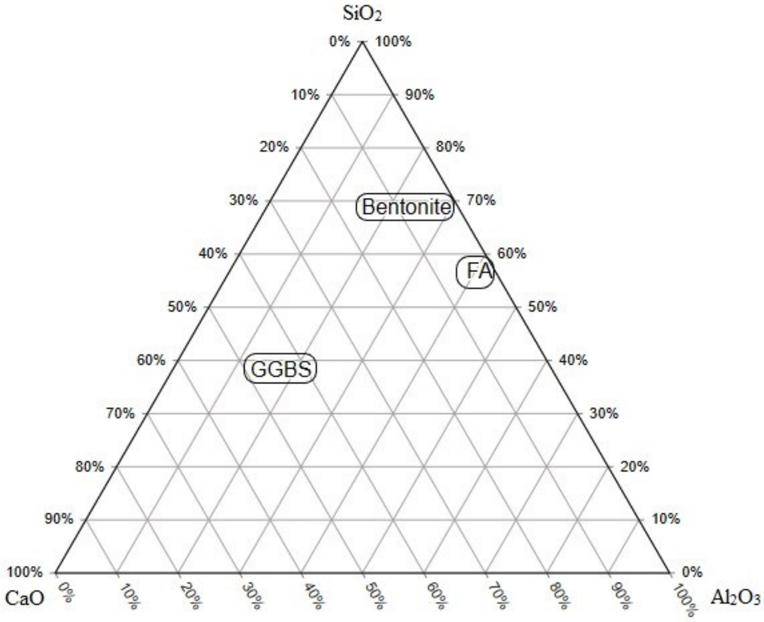


Figure 1. Composition of major FA, GGBS, and Bentonite oxides in a ternary diagram.

### 2.2. Alkali Activator

As an alkali, sodium hydroxide (NaOH) is dissolved in a calculated amount of distilled water, depending upon the required concentration as per IS 10262-2009 standards. For example, the alkaline activator was prepared by dissolving 40 g of sodium hydroxide pellets in 1 liter of water to make a 1 molar concentration solution [15].

### 2.3. Preparation of Solution with Heavy Metal Ions

The required amount of lead nitrate was dissolved in 1 liter of distilled water to make a 1000-ppm lead solution. Similarly, the required quantity of nickel nitrate is dissolved in 1000 ml of distilled water to get a 1000 ppm solution. 50 ppm solutions of lead and nickel were obtained by diluting the stock solutions.

### 2.4. Test Methods

Compaction parameters for the following four FA: GGBS mixtures were evaluated by a minicompaction test apparatus [16]. i) 20 FA:80 GGBS; ii) 40 FA:60 GGBS; iii) 60 FA:40 GGBS; and iv) 80 FA:20 GGBS. FA and GGBS were dry mixed initially until a homogeneous mixture was obtained, and then, depending on the molar concentration, sodium hydroxide solution was added as an activator. The influence of bentonite on FA-GGBS-based geopolymers with respect to strength and permeability has been investigated in the present study.

### 2.5. Preparation of Test Specimen

The mixtures were prepared on a dry-weight basis by adding the requisite quantity of water. Compacted samples of standard size (3.8 cm x 7.6 cm) for Unconfined Compressive Strength (UCS) were prepared so that the same impact energy is maintained per unit volume for each sample. Then, the extruded samples were sealed in airtight bags, and the effect of time was investigated by curing the samples in a desiccator while maintaining 100% relative humidity at room temperature for 3, 14, and 28 days [16]. During their respective curing periods, the samples were unwrapped from polythene bags and tested per ASTM-D5102 standards. The effect of the curing period and concentration of sodium hydroxide on different combinations of FA and GGBS mixtures was studied. Later, the influence of bentonite on the optimized FA-GGBS mixture in terms of strength is examined. The percentage addition of 5% bentonite was selected from the literature [17].

The optimized FA-GGBS mixture with the highest compressive strength is considered for tensile strength analysis. Specimens were cast and cured for 28 days by adding 5% bentonite to the optimized FA-GGBS mixture, with dimensions of 100 mm in diameter and 200 mm in height under molar concentrations of 1 to 5. The stiffness or tensile strength is studied by testing the specimens using a digital compression testing machine per IS 5816 (1999) standards.

Cubic specimens of 100 mm size were cast and cured for 28 days. Then, they were permeated with water and tested for permeability in terms of penetration depth as per IS 516-Part 2-Sec1.

Batch equilibrium experiments were performed by adding 5% Bentonite to a polymerized 40% FA- 60% GGBS mixture. 50 ppm of lead (Pb) and nickel (Ni) solutions were used in batch equilibrium studies. 10 grams of adsorbent collected from the tested UCS samples were added to 100 ml of solution and kept in a rotary shaker, maintaining a contact time of 8 hours. Later, the samples were filtered and tested for heavy metals using Atomic Absorption Spectroscopy (AAS).

A representative sample from the tested specimens was collected to analyze the microstructural studies using SEM. Moisture in the collected powdered sample is eliminated by oven drying it for 24 hours and maintaining a temperature of less than 40°C [18].

# 3. RESULTS AND DISCUSSION

## 3.1. UCS of FA-GGBS Mixtures After Curing for Different Periods

Figure 2 presents the variation in UCS of FA-GGBS mixtures after curing for different periods. An increase in UCS with curing is observed in all FA-GGBS mixtures, where the strength increment is greater from 3 to 14 days when compared to the increment observed between 14 and 28 days of curing.

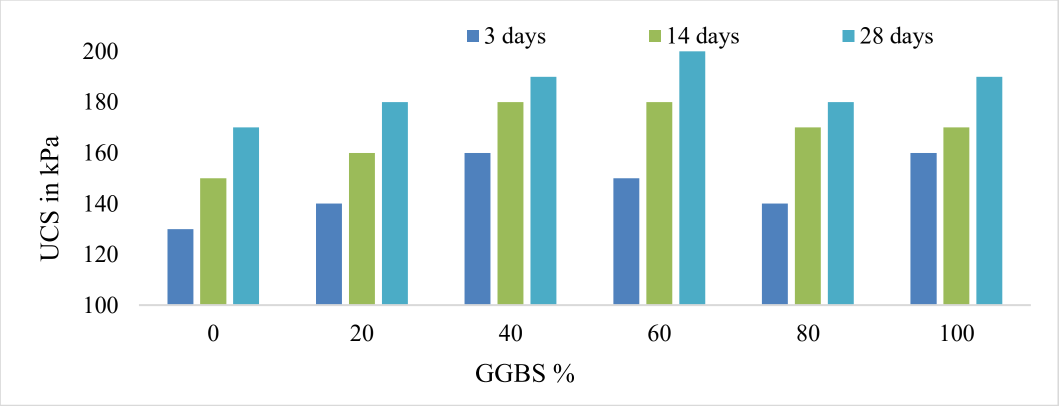


Figure 2. Influence of curing on UCS of FA-GGBS mixtures.

Among all the mixtures, the mix with 80% GGBS gave the lowest UCS after curing for 3 days but increased with further curing. Interestingly, mixtures with a GGBS content of 40 to 60% showed higher compressive strength at any curing period. It is seen from Figure 1 that GGBS has a higher calcium content compared to FA. Cementitious compounds such as CSH are produced better when calcium and silica (reactive) are in the desired proportion. This ideal ratio is achieved with 40% FA and 60% GGBS. The formation of pozzolanic reaction compounds increased gradually over time and probably reached their maximum after 28 days of curing. At the optimum percentage, a calcium-to-reactive silica ratio reaches the ideal proportion for maximum production of calcium silicate hydrates, as evident from earlier studies [19].

## 3.2. Compaction Behavior

From the unconfined compressive strength studies of different FA-GGBS mixtures compacted at their respective OMC and MDD and cured for 28 days, a mixture of 40% FA and 60% GGBS exhibited the highest strength at all molar concentrations at the 28-day curing time. So, this is considered the optimized mix in the present work. 5% bentonite is added to the optimized mixture, and its OMC and MDD were calculated using a mini-compaction test apparatus, as shown in Figure 3.

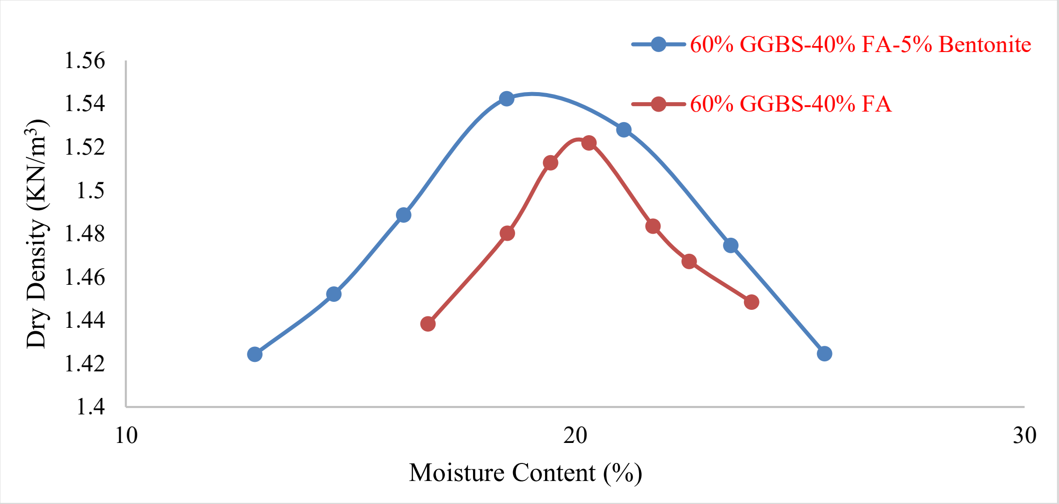


Figure 3. Compaction behavior of FA-GGBS-Bentonite mixtures.

It is known that bentonite is a highly swelling clay, and a decrease in MDD and a higher OMC are expected due to its high water-holding capacity. On the contrary, it is observed that the addition of 5% bentonite to the optimized FA-GGBS mixture resulted in an increase in MDD and a decrease in OMC. This reversal effect of bentonite on compaction behavior might be due to a reduction in swell capacity and water adsorption capacity in the presence of FA and GGBS due to the higher calcium content, which reduces its ability to swell. With the reduced swell capacity of bentonite, its finer particles get accommodated within the voids of the FA-GGBS matrix, increasing its density and decreasing its ability to hold water.

### 3.3. UCS of 40% FA-60% GGBS Mixture with 5% Bentonite After Curing

When FA or GGBS is in higher proportions, the formation of pozzolanic compounds is not ideal. Thus, the effect of adding alkali and bentonite to this combination is considered.

The mixture with 40% FA and 60% GGBS is considered an optimized mix (O) as it gave the highest compressive strength after 28 days of curing at all molar concentrations. To this, 5% bentonite is added, and the specimens are compacted for standard dimensions of UCS at their respective OMC and MDD, cured for different aging periods, and then tested.

Figure 4 shows that when 5% bentonite is added to the optimized mix with varying alkali concentrations, a gradual increase in UCS is observed with both an increase in curing and also the alkali concentration. At any alkali concentration, the strength increase is considerable after 3 days of curing, which further increases with 4 to 5 M concentrations. The increase in compressive strength with the curing period shows that the enhanced strength is mainly due to pozzolanic activity by reactions between calcium from GGBS and FA.

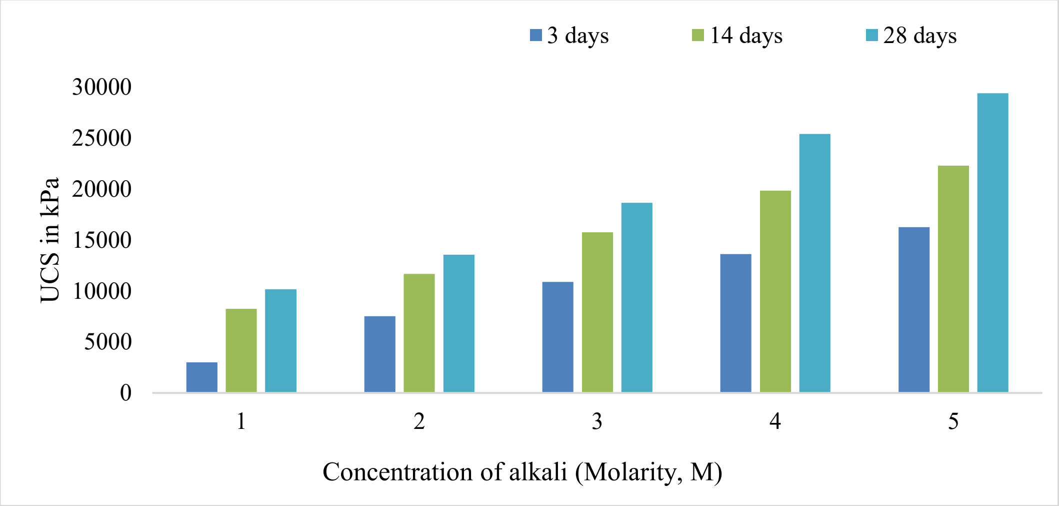


Figure 4. Effect of alkali concentration on 5% Bentonite on 40% FA-60% GGBS mixture

Apart from FA and GGBS, the added bentonite also participates in pozzolanic reactions with the available calcium hydroxide. If it were only due to polymerization, there would not have been such a significant increase in strength with an alkali solution. However, the increase in strength with increasing concentrations of alkali might also be due to the modification of the pozzolanic compounds of FA and GGBS, which produce more voluminous calcium aluminate silicate hydrate (C-A-S-H) than calcium silicate hydrate (C-S-H) alone. The effect of polymerization with alkali may not be substantial on compressive strength. This is seen more clearly by comparing the strength of the material with and without bentonite after curing for 28 days in Figure 5.

The increase in strength of FA and GGBS mixtures is low up to 3M alkali concentration when cured beyond 14 days. However, the strength is significantly higher up to 28 days of curing with a higher alkali concentration of 4 and 5 M. This will ensure that the strength reduction will not occur with higher concentrations. The UCS achieved is about 13 MPa with 4 M, which further increases with 5 M to 16 MPa after curing for 3 days. In practice, the strength required for most landfills of more than 20 feet in height is about 200 kPa. The strength achieved with the 4 or 5 M solution is more than adequate for their use as components of any barrier systems, even at lower curing periods. Thus, for these mixtures, alkali activation is sufficient with 3 to 4M alkali concentrations for enhancing the compressive strength.

### 3.4. Comparison of UCS in FA-GGBS Mixtures with the Effect of Bentonite

A comparison is made between the UCS of the 40% FA-60% GGBS mixture under varying molar concentrations with and without 5% bentonite after 28 days of curing. Figure 5 shows that at all curing periods, the 40% FA-60% GGBS mixture with 5% bentonite gave a higher compressive strength than the normal 40% FA-60% GGBS mixture. It is noticed that until 3 molar concentration, the increase in UCS for the mix having 5% bentonite is less when compared with the increase in UCS beyond 3 M alkali. This can be because of the presence of bentonite in the pozzolanic reaction with free lime to increase strength.

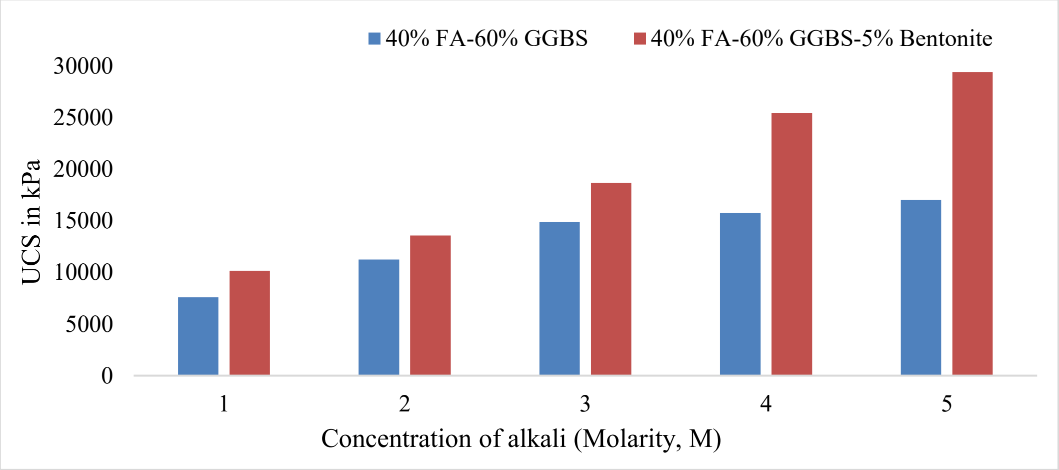


Figure 5. UCS of 40% FA-60% GGBS mixture with 5% Bentonite at 28 days curing.

### 3.5. Effect of Bentonite on Tensile Strength of FA-GGBS Mixtures at Different Alkali Concentrations

After 28 days of curing, a study was conducted on the 40% FA-60% GGBS mixture with 5% Bentonite for tensile strength. Figure 6 shows that the tensile strength is gradually increasing with an increase in alkali concentration after 28 days of curing. However, the 40% FA-60% GGBS mixture with a 5% Bentonite addition exhibited less tensile strength when compared to the optimized mixture (40% FA-60% GGBS). This contrasts the trend obtained in UCS, where mixtures with bentonite exhibited more UCS than the normal FA-GGBS mixture. The increase in tensile strength concerning alkali is due to the polymerization effect. In contrast, the reason behind the reduction in tensile strength compared to mixtures without bentonite is the dominance of pozzolanic compounds over polymerization. Additionally, bentonite possesses sufficient tensile strength due to its cohesive nature in its unreacted part.

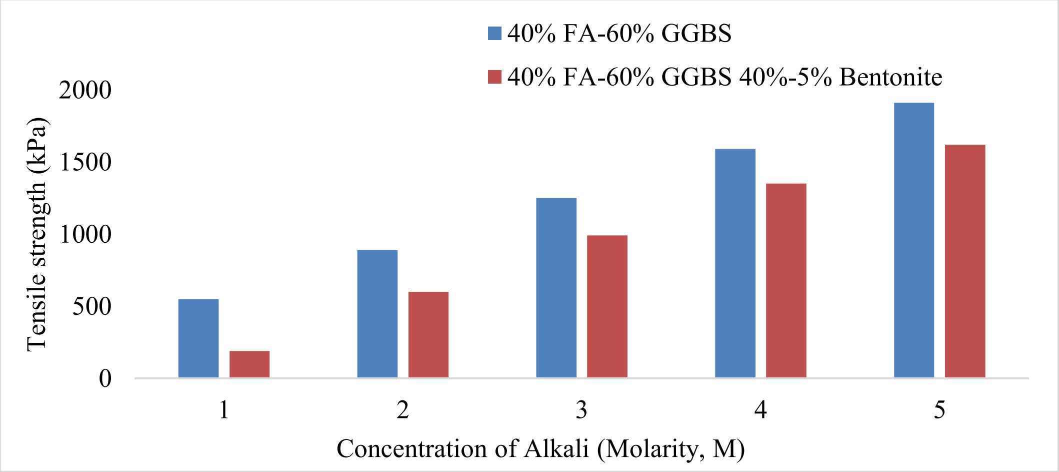


Figure 6. Effect of alkali on Tensile strength of 40%FA-60%GGBS mixture with Bentonite.

Also, bentonite is an ultrafine material with a large specific surface and adsorption capacity, which might favorably affect the development of tensile strength. Thus, bentonite can have higher cohesion than higher friction resistance, contributing more to the tensile strength. Other researchers have observed similar behaviour.

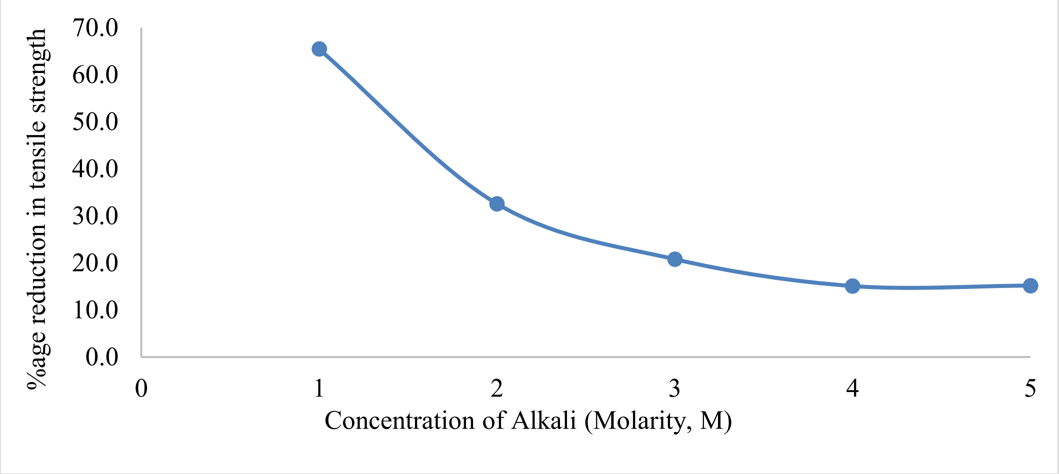


Figure 7. Reduction in tensile strength in 40% FA-60% GGBS due to Bentonite.

From Figure 7, it is evident that the percent reduction in the tensile strength gradually reduces with an increase in the alkali concentration up to 4M and remains unaffected with a further increase in the alkali concentration. This confirms that the initial effect of the presence of alkali is to reduce tensile strength. Still, with effective polymerization and increased alkali concentration, the reduction is countered by polymeric bonding. It is evident that the reduction in tensile strength is lowest with a concentration of alkali greater than 3 M. Thus, the concentration of alkali is restricted to 5 M. Higher concentrations of alkali may cause very high compressive strength, leading to brittleness, which in some cases leads to unnecessary complications.

### 3.6. Permeability

As shown in Figure 8, the permeability of the mixture of 40% FA and 60% GGBS cured for 28 days meets the criteria of a hazardous waste landfill, which should be less than $1\times10^{-7}$ cm/s.

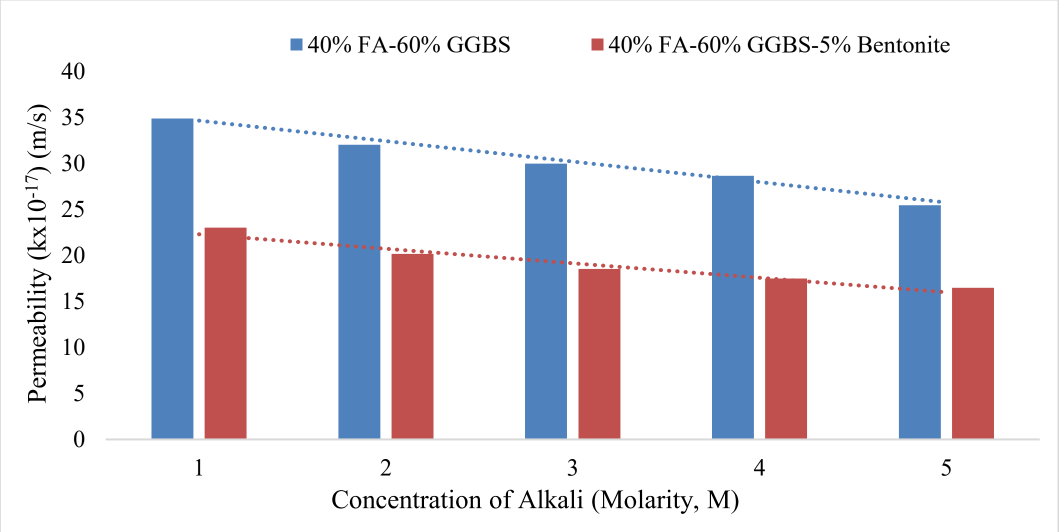


Figure 8. Effect of Bentonite on the permeability of 40% FA-60% GGBS mixture with alkali concentration.

The addition of 5% bentonite further reduced the hydraulic conductivity by about 30 to 40%, irrespective of the alkali concentration. The decrease is almost linear with the concentration of alkali. This is due to the formation of more cementitious compounds with the addition of bentonite, which blocks the voids in FA-GGBS mixtures. Thus, an increase in alkali concentration may further reduce the permeability. From the overall consideration of strength and permeability, the concentration is restricted to 5 molars. Thus, this impermeable material overcomes the situation where leachate interaction might increase the permeability and adversely affect its long-term performance.

### 3.7. Batch adsorption investigation

Batch adsorption experiments were performed by adding an optimized FA-GGBS mixture with 5% bentonite as an adsorbent to a synthetic solution prepared in a laboratory at a known initial concentration of 50 ppm. Lead (Pb) and nickel (Ni) were the selected heavy metals for these studies. 10 grams of adsorbent are added to 100 ml of synthetic solution and kept in a rotary shaker, maintaining a contact time of 8 hours. Later, the samples were filtered and tested for heavy metals using Atomic Absorption Spectroscopy (AAS), as shown in Table 2.

Table 2. Heavy metal analysis

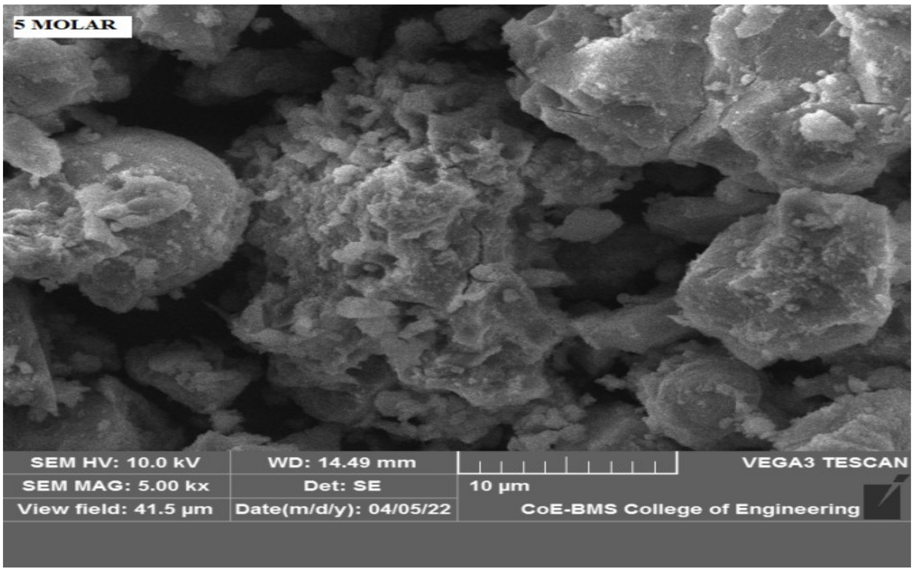
| Concentration of alkali | Lead (Pb), mg/l | Nickel (Ni), mg/l |
|---|---|---|
| 1M | BDL | 1.4 |
| 2M | BDL | BDL |
| 3M | BDL | BDL |
| 4M | BDL | BDL |
| 5M | 0.2 | BDL |

The concentration of Pb and Ni was very low or not detectable in the filtered solution, confirming good removal or retention efficiency of heavy metals in the barrier material. The concentration of Pb in the leachate/filtrate was Below Detectable Level (BDL) at all alkali concentrations of 1 to 4 M. In contrast, it was slightly observed when a 5 M solution was used. However, in the case of Ni, a very low concentration is observed with 1 M concentration but not detectable at all other concentrations of Ni used. This confirms that Ni is completely precipitated at a higher concentration of alkali.

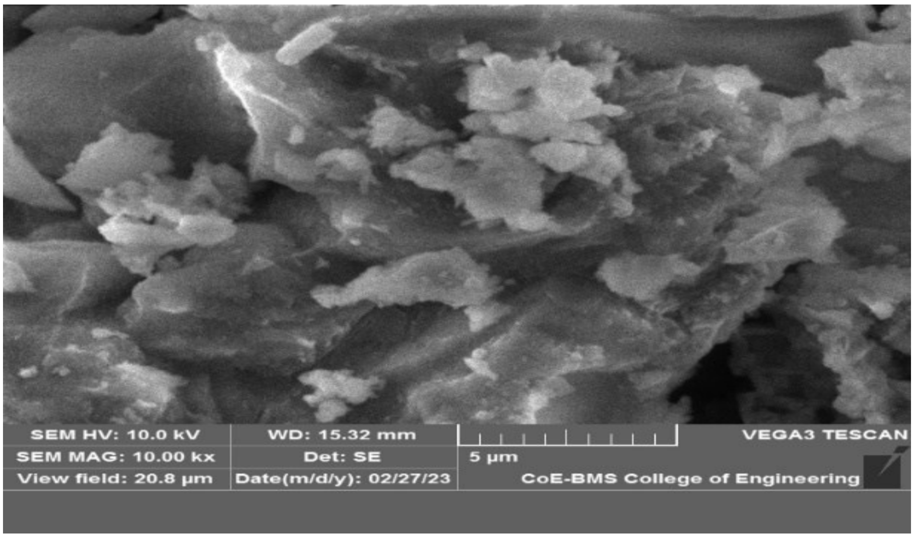
### 3.8. Micro Structural Investigations

An attempt is made to support the above comparative study's findings regarding variations in UCS and tensile strength with varying GGBS content, bentonite content, and alkali concentration.

A noticeable alteration in the FA-GGBS structure is evidenced after geopolymerization and is studied through microstructural studies using scanning electron microscopy. Imposed changes in FA-GGBS mixtures due to polymerization were detected. Evaluation of surface morphology using SEM images of FA-GGBS mixtures at 28 days of curing on the optimized mix with and without 5% bentonite at 5M of alkali concentration shows that a major percentage of FA and GGBS particles reacted and resulted in gel formation. While the role of bentonite in gel formation is limited, the predominant mechanism is silica reactions with lime of FA and GGBS. At an alkali concentration of 5 molars, when a comparison is made between the optimized mixture (60% GGBS-40% FA) and the optimized mixture with 5% bentonite (60% GGBS-40% FA-5% B), the SEM images reveal the formation of more cementitious compounds in bentonite mixtures, which results in more compressive strength and also makes the specimen more flexible. The mineralogical formation is shown in Figure 9.



(a) Without Bentonite



(b) With Bentonite

Figure 9. SEM image for 60% GGBS- 40% FA at 5 M concentration cured for 28 days

## 4. MECHANISM PROPOSED FOR THE STRENGTH AND PERMEABILITY OF THE IMPROVED POLYMERIZED MIXTURES

Based on the available literature on the studies by various investigators and the data presented in this paper, as explained above, the summary of the mechanism proposed for variations in the strength forms and permeability has been illustrated.

### 4.1. Pozzolanic Reactions

The main pozzolanic reaction between reactive silica and lime of FA and GGBS is described as:

$$Ca^{++} + 2\,(OH)^{-} + SiO_2 \rightarrow CSH \qquad (1)$$

These reactions, which produce CSH gel, are mainly responsible for binding particles and developing strength, particularly compressive strength.

### *4.1.1. Enhancement of pozzolanic reaction in the presence of alkali*

Alkali presence can enhance the available silica for pozzolanic reactions by dissolving reactive silica, producing more pozzolanic compounds. Also, it is possible that modification of pozzolanic reaction compounds could enhance the cementation of the barrier material.

### *4.1.2. Modification of the pozzolanic reactions*

With various combinations of FA and GGBS, the amount of reactive silica and lime varies, producing maximum pozzolanic reaction compounds at an optimum ratio of FA and GGBS.

$$\text{Ca++} + \text{Na+} + 2\ \text{(OH)-} + \text{SiO2} \rightarrow \text{NCSH} \qquad (2)$$

Part conversion/formation of CSH to more voluminous NCSH can also enhance the strength.

### *4.1.3. Polymerization of FA and GGBS*

Both FA and GGBS can get polymerized as per the general equation or formula:

$$\text{Nan}\{\text{—(SiO2)r—AlO2—}\}\text{n} \qquad (3)$$

where Na is a sodium ion, n is the degree of polycondensation, and r is the Si/Al ratio [20]. $SiO_2$ and $AlO_2$ are from FA and GGBS. This polymerization can enhance the tensile strength of the FA-GGBS mixture.

### *4.1.4. Role of Bentonite*

Bentonite is a fine, swelling, cohesive material that swells in the presence of water and blocks the voids of the barrier system, effectively reducing the voids and hydraulic conductivity. It can also absorb ionic contaminants, leading to the adsorption and retention of the contaminants.

### *4.1.5. Precipitation of Heavy Metals in the Presence of Alkaline Barriers*

Heavy metals such as Pb and Ni can precipitate and get trapped, making them immobile and also reducing the void ratio, leading to lower hydraulic conductivity.

## 5. CONCLUSIONS

This study has clearly shown that the properties of the FA-GGBS mixture in the presence of alkali and bentonite were improved in terms of increased strength and reduced permeability, along with the retention of heavy metal ions, making it a good barrier material for landfills and cut-off walls.

The detailed conclusions include:

- The compacted FA and GGBS mixture in the proportion of 40:60 develops good strength, which further increases with the incorporation of an alkali solution in the range of 1 to 5 M. The increase in strength with alkali solution has been attributed to enhanced pozzolanic reactions in compressive strength and polymerization in tensile strength. While a lower alkali concentration, up to 3 M, does not significantly increase the strength beyond 14 days, a higher concentration of alkali, 4 or 5 M, increases the strength beyond 14 days. Further, the reduction in percent tensile strength becomes negligible with a higher concentration of 5M alkali solution, and the alkali concentration is restricted to a maximum of 5M. Thus, an alkali solution effectively enhances the pozzolanic reaction and polymerization effect.

- Incorporating 5% bentonite steeply reduces the permeability of the compacted FA-GGBS mixture. This is due to the occupation of bentonite particles within the polymerized FA-GGBS mixture, confirmed through SEM.
- Batch equilibrium studies revealed effective retention of ionic metal contaminants by precipitation at high alkaline conditions prevailing in the barrier system.

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