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Original Article

Circular-Economy Engineered Alkali-Activated Alumina Residue Jute Composite Liners as High-Performance Hydraulic Barriers for Sustainable Agricultural Water Storage Systems

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Abstract *- Hydrophobic High-Density Polyethylene (HDPE) plastic liners, which are routinely utilized in agricultural and aquacultural pond applications, suffer severe long-term degradation from UV radiation, mechanical and environmental processes, which lead to increasingly permeable, deteriorated plastic, and ineffective HDPE liners as reservoirs of water. To circumvent such plastic-based liner performance problems, this work proposes a circular-economy solution to sustainably valorize an alkali-activated, mineral-based residue material, bauxite mine waste, into an effective replacement for hydrophobic polymer plastic liners in agricultural/aquacultural pond applications. A novel liner composite material was developed from an Alumina Residue (AR), Ordinary Portland Cement (OPC) and jute fibers in an 80:20 (AR: OPC) ratio, then activated with a Sodium Hydroxide (NH) and Sodium Silicate (NS) solution at various NH: NS ratios (1:1, 1:1.5 and 1:2). Systematic experimental and Scanning Electron Microscopy (SEM) analysis were then performed on the activated liner composites to evaluate their hydraulic barrier performance and durability (through rate of pH stabilization). The best hydraulic barrier composite was the AR: OPC (80:20) liner activated at an NH: NS = 1:1.5 ratio, which demonstrated significantly less seepage than an HDPE liner and a defined gel-like geopolymer composite microstructure. These results not only demonstrate that alkali-activated, alumina residue-based liners significantly outperform plastic liners in hydraulic barrier performance and durability, but also that they do so with a low cost and carbon footprint, paving a path for a circular-economy solution to valorize bauxite waste into effective hydraulic barriers for water-containing ponds in agricultural and aquacultural applications.*

Keywords *- Alumina Residue (AR), Ordinary Portland Cement (OPC), Sodium Hydroxide (NH), Jute Fiber.*

1. Introduction

Reliable on-farm water storage systems are increasingly critical for sustaining agricultural and aquaculture productivity under intensifying climate variability. In rain-fed regions, farm ponds function as decentralized water buffers, capturing episodic rainfall and surface runoff to ensure irrigation continuity, stabilize crop yields, and support allied activities such as pisciculture and livestock farming.

Their strategic role has expanded from simple storage units to integral components of climate-resilient farming systems and rural water security infrastructure. The hydraulic efficiency of farm ponds is theoretically limited by the hydraulic losses resulting from seepage through the underlying subgrade or liner material. Unlined ponds are therefore theoretically ineffective as water-storage reservoirs, both because of the destructive effects of evaporation and salinization (in arid regions) and because of the inevitable physicochemical-fertility evolution of the agricultural soil that surrounds the pond.

The requirement for an effective liner has therefore become a design feature common to all modern farm pond systems.

Fig. 1 Pond for Water Storage

Currently, polymeric liners such as High-Density Polyethene (HDPE) sheets and tarpaulin membranes are predominant in field practice because they are relatively easy to manufacture and install at low initial cost. However, their performance over time in the field shows considerable limitations. Ultraviolet light, temperature fluctuations, mechanical wear, punctures, and biological activity gradually degrade these liners. This leads to micro-cracking of the surface, failure of seams, and loss of hydraulic functionality. Although cement-based liners are more stable, they require a high material input, skilled labor, and introduce significant embodied carbon emissions. Therefore, they are not economically viable for widespread rural applications.

Fig. 2 Lined farm pond with polythene

Thus, the central unresolved challenge is the absence of linear material that simultaneously satisfies four critical requirements: low permeability, long-term durability, low environmental footprint, and economic accessibility.

Recent sustainability-driven construction research has emphasized the valorization of industrial by-products as functional construction materials. However, their application as hydraulic barrier systems for farm and aquaculture ponds remains largely unexplored. Among such by-products, alumina residue generated during the Bayer process represents one of the largest underutilized industrial waste streams globally. The accumulation of alumina residue poses severe environmental risks due to its high alkalinity, fine particle size, and long-term storage instability. Converting this waste into a functional hydraulic barrier material offers a rare opportunity to address waste management and infrastructure sustainability challenges simultaneously.

This study proposes a fundamentally different liner concept: an alkali-activated alumina residue–based hydraulic barrier supported by jute fiber as a barrier, requiring only a minimal fraction of ordinary Portland cement. The approach leverages alkali activation reaction mechanisms to generate a dense, chemically stable, and low-permeability microstructure while simultaneously utilizing a renewable, biodegradable textile substrate for liner application.

Unlike conventional liners that rely on physical impermeability alone, the proposed system develops a chemically bonded mineral matrix that actively refines pore structure and resists hydraulic penetration. By using the alkali-activated liner system, superior durability, environmental compatibility, and economic feasibility can be achieved.

Therefore, the present investigation does not merely replace HDPE liners with another material; it introduces a new class of mineral-based by-product-derived hydraulic barriers designed specifically for sustainable agricultural and aquaculture water storage. The study systematically evaluates the hydraulic, chemical, and microstructural performance of this liner system and establishes its potential as a scalable, circular-economy solution for long-term water conservation infrastructure.

Background: Farm and Aquaculture Ponds and the Need for Hydraulic Barriers

Farm and aquaculture ponds are fundamental to rain-fed and dryland farming systems, serving to buffer variable rainfall, permitting supplementary irrigation, and enabling crop diversification and integrated farming, such as fish-vegetable production systems [1, 4, 6, 8]. Pond systems have been found to raise crop production by 30–40% and to greatly increase farm income in the case of smallholder farms or in regions with marginal rainfall [1, 2, 3, 6].

Seepage and evaporation losses from earth-constructed ponds are, however, extremely high, leading to reduced storage efficiency and negating the economic benefits of rainwater harvesting [2, 5, 10, 12].

Ethiopian and other dryland studies report that seepage losses alone may reach as much as 45%, while evaporation losses can contribute an additional 25% of loss of the stored water [5, 12]. Such losses render much of the water that is harvested unusable. It is these extremely high losses that have fueled so much research interest in effective hydraulic barriers and linings for farm and aquaculture ponds, as well as other water-harvesting structures.

In the past, a variety of different pond lining materials or techniques have been investigated, including natural materials (compacted clay, bentonite clay, ash, salt, and various mixtures); synthetic geo membranes (polyethylene sheets, HDPE sheets); concrete or mortared linings; bitumen coatings; and even self-formed natural liner systems that aim to form a waterproof sediment layer at the bottom of ponds [2, 5, 10, 12]. Experiments have compared some of these materials, while reviews provide summaries of many studies.

Concrete and mortared linings are among the most effective anti-seepage systems that have been investigated, with reductions in seepage losses of up to around 89%, and good durability over lengthy service lifetimes [5, 12].

Geo membranes (polyethylene sheets, HDPE sheets) can reduce seepage losses by almost 90% as well, and these systems are commonly used for commercial pond constructions [2, 8, 10, 12]. They are, however, expensive to produce; they are prone to puncturing and ultraviolet degradation; handling and installation can be difficult; and there is increasing concern over microplastic migration into soil and aquatic systems – with consequences for food-chain safety.

Bauxite residue, the alkaline waste product of alumina production, is produced at a rate of approximately 0.9-1.5 tonnes per tonne of aluminum. Interest in valorizing and reusing bauxite residue has reached a peak in recent years [2, 3, 4, 13]. Established and emerging applications include cement and construction materials, road construction, landfill capping, and soil amendment [3, 4, 13]. Its high iron and aluminum oxide content, and relatively high specific surface area, make it a good candidate for adsorbing phosphorus and trace metals. It has been found to be a low-cost filter medium and a permeable reactive barrier for the removal of dissolved reactive phosphorus from agricultural runoff and soil solutions [2, 7, 9].

The absence of material that meets the following criteria is the main engineering problem: low permeability, durability, environmental safety, and low cost.

Compared to HDPE liners that rely solely on the physical impermeability of the liner, the proposed system forms a chemically bonded aluminosilicate network that reduces capillary action and degradation over time.

1.1. Research Gap

- The available farm/aquaculture pond lining solutions are (i) dominated by polymer-based geomembranes and cementitious linings that exhibit issues with long-term durability, environmental degradation, and microplastic pollution, or (ii) are associated with levels of embodied carbon and economic cost that preclude their use at scale in rural areas.
- The use of alumina residue as an engineered chemical hydraulic barrier in water storage facilities has, to the authors' knowledge, never been explored, despite the many studies that have explored the properties of alumina residue in the use of adsorbent, soil amendment, or supplemental cementitious material.
- Existing studies on pond seepage loss mitigation focus on material replacement rather than on the microstructure of pore connectivity, resulting in liners without a chemical basis for impermeability.
- The impact of different alkali activation chemistry and refining the pore structure connectivity in an alumina residue-based liner to avoid harmful pH evolution/long-term incompatibility with the environment has, to the authors' knowledge, never been quantified in an agricultural/aquacultural context.
- Existing studies on sustainable liners do not investigate methods that have a field-scale focus with multiple, simultaneous, often conflicting goals pertaining to hydraulic performance, environmental safety, durability, and circular-economy compatibility, nor do they bridge the gap between lab and field.

1.2. Novelty and Uniqueness of the Present Study

- This is the first presentation of a circular–economy–engineered alkali-activated alumina residue–OPC composite liner with natural jute fabric reinforcement as a novel high-performance hydraulic barrier for use in agriculture and aquaculture.
- Unlike conventional hydraulic liners, which function through passive impermeability, the proposed systems actively prevent capillary seepage via chemically controlled geopolymerization mechanisms to engineer pore structure.
- The research uniquely integrates the concepts of industrial waste valorization and biodegradable reinforcement to develop a mineral-based liner system that contains no polymeric (geomembrane) materials.
- The optimization of the NH: NS activator ratio provides novel insights into its use in controlling geopolymer gel formation, thermal stability, and microcracking in systems rich in alumina residue.
- The simultaneous consideration of hydraulic efficiency, pH stability, and microstructural evolution in assessing performance is a rarely seen (if at all) approach in liner literature.

1.3. Objectives of the Study

- Design a sustainable hydraulic liner based on alkali-activated alumina residue as the primary binder with minimal OPC contribution and natural jute reinforcement.
- Explore the impact of different NH: NS alkali activator ratios on water absorption, seepage, pH development, and microstructure.
- Choose the best activator chemistry that delivers good hydraulic barrier performance but is still safe for use in agricultural/aquaculture applications.
- Evaluate the efficacy of the new liner vs. conventional HDPE liners
- Demonstrate that alumina residue can be processed into an affordable, accessible, low-carbon infrastructure material with the potential for industrial-scale manufacture within a circular-economy framework

1.4. Strength and Robustness of Methodology

- Methodology includes controlled mix design, systematic activator optimization, and curing protocols.
- Lab-scale and field-scale (prototype) models
- Hydraulic properties evaluated using water absorption, seepage, and long-term retention tests (link material property to behavior)
- Soil/gel compatibility evaluated using time-dependent pH stabilization (suitable for aquaculture & ag soils)
- Microstructural evolution evaluated using scanning SEM to a mechanistic explanation for hydraulic observations based on gel pore structure/morphology.

1.5. Problem Statement and Research Gap

Despite the available research on geomembranes, cementitious, and clay liners, three critical limitations exist in the literature on these geotechnical and hydraulic barriers:

- The lack of chemically engineered pore structure within these liners results in issues related to permeability.
- The lack of sustainable alternatives using industrial residues creates challenges regarding the environmental impact of these hydraulic barriers.
- The lack of understanding of alkali-activated systems creates a knowledge gap regarding their potential as hydraulic liner alternatives.
- Current research efforts have mainly focused on the substitution of various components of the hydraulic barrier with other materials with similar properties.
- Therefore, the question that needs to be answered regarding the use of alkali-activated alumina residue as a hydraulic barrier is the following:
- Can alkali-activated alumina residue be engineered to create a hydraulic barrier that outperforms polymeric geomembranes

Study	Material	Mechanism	Limitation	Our Contribution
HDPE liners	Polymer	Physical barrier	UV degradation	Mineral alternative
Cement liners	Cement	Dense matrix	High carbon	Low-carbon system
Clay liners	Natural	Swelling	Cracking	Chemical densification
This study	AR + OPC + Jute	Geopolymerization-controlled pore refinement	—	First chemically engineered barrier

Lack of barrier applications to date, no study has systematically investigated alumina residue as a structurally engineered hydraulic barrier, particularly in combination with alkali activation and natural fiber reinforcement.

2. Materials and Methodology

2.1. Materials Used

2.1.1. Alumina Residue (AR)

The waste product from the alumina extraction of bauxite ore through the Bayer process was used as the binder. AR was oven dried at 105 °C for 24 h, powdered, and sieved through a 75 μm mesh to ensure size uniformity and increased reactivity with the alkali.

Fig. 3 Alumina Residue

2.1.2. Ordinary Portland Cement (OPC)

OPC, 43 grade according to IS 8112 standards, was used as a secondary binder to support early strength and matrix stabilization.

Fig. 4 Ordinary Portland Cement

Table 1. Represents the chemical and physical characteristics of the binder materials used in the study

Particulars	AR	OPC
	Quantity (in %)	Quantity (in %)
Silica (SiO_2)	10.50	20.10
Alumina (Al_2O_3)	24.50	6.24
CaO	5.00	62.39
Iron Oxide (Fe_2O_3)	42.00	4.10
Na_2O	6.00	1.23
Titanium Oxide (TiO_2)	12.00	NIL
Phosphate (K_2O)	NIL	0.55
Sulphate (SO_3)	NIL	1.52
Magnesia (MgO)	NIL	2.10
Specific Gravity	2.8	3.15
pH	11.5-12	10-12
Color	Red	Grey

2.1.3. Jute Fabric Substrate

Natural jute fabric served as the backing reinforcement substrate. Jute fibers are made up of cellulose and lignin and have exceptional tensile strength, roughness, flexibility, and biodegradability.

Fig. 5 Jute fabric used for liner preparation

2.1.4. Alkali Activator Solution

An alkaline activator solution was prepared by using Sodium hydroxide and sodium silicate (in combination), initiating alkali activation of AR-OPC binder. Initially, the NaOH pellets were diluted in distilled water to the required concentration before the silicate solution was added. The final solution was then placed in a coolant bath for 24 h prior to use due to its exothermic nature.

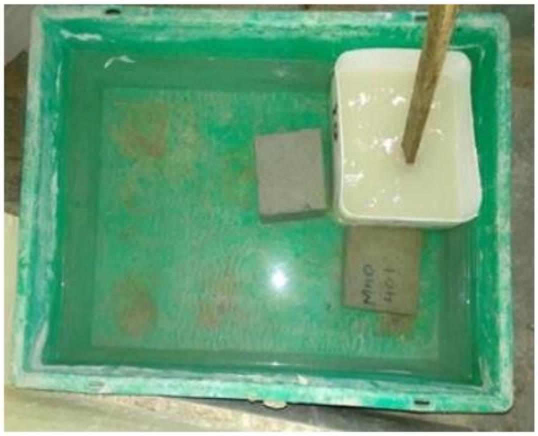

Fig. 6 Alkali activator solution placed in water bath

The NaOH solution was prepared at a concentration of 10M The ratio of sodium silicate to sodium hydroxide was as per the design (1:1-1:2).

The mixing procedure consisted of the following two steps:

- dry mixing of AR and OPC for 5 min
- addition of the activator solution, mixing for 10 min.

The activator solution was preconditioned at 25 ± 2°C for 24 h prior to the test.

2.2. Methodological Framework

The various stages of the methodology are presented in the following paragraphs.

Initially, the selection of the raw materials to be employed in the preparation of the described composite liners included alumina residue (AR), ordinary Portland cement (OPC), and jute fiber. Subsequently, a mixed design for the composite liners was performed, which included selecting an AR: OPC ratio of 80:20 and incorporating three different ratios of alkali activator (NH: NS = 1:1, 1:1.5, and 1:2) to test their effect upon the performance of the prepared liners.

Following the selection of raw materials and the development of the mix design for the liners, the alkali activation process was performed to initiate the formation of the geopolymer matrix within the prepared liners. Following the alkali activation process, the prepared liners were cured under ambient conditions.

Following the curing of the liners, a series of tests was performed on the liners to evaluate their hydraulic performance and environmental characteristics. Tests included the determination of water absorption rates, seepage rates, and pH stability of the liners. Finally, the cross-sections of prepared liners were analyzed using SEM to determine the relationship between the microstructure of the liners and their hydraulic performance. Overall, then, this methodology allowed for the thorough evaluation of the performance of the prepared and cured liners, both in relation to their expected performance characteristics and in relation to their internal structure.

3. Mix Proportioning

The binder formulation consisted of AR and OPC mixed in an 80:20 (AR: OPC) ratio by weight. Three alkali activator ratios (NH: NS) were investigated, viz. 1:1, 1:1.5, 1:2. The alkaline activator to binder ratio (A/B) was maintained at 0.35 for all mixes. The Water-To-Binder ratio (W/B) was maintained to a constant value of 0.25 to ensure workability without compromising matrix densification. Table 2 represents the detailed mix proportion used in the study.

Table 2. Mix Proportion

Particulars	NH: NS		
	1:1	1:1.5	1:2
NaOH (g)	240	194	156
Na_2SiO_3 (g)	345	413	473
W/B Ratio	0.25	0.25	0.25
Total Water (ml)	250	250	250
Extra Water(ml)	196	206	215
A/B Ratio	0.35	0.35	0.35
AR (%)	80	80	80
OPC (%)	20	20	20

The binder paste was prepared using a mechanical mixer to ensure homogeneity, followed by adhesion to the surface of the jute fabric, resulting in the liner.

Fig. 7 Casting Process of the liner

3.1. Preparation of Laboratory and On-site Models

3.1.1. Laboratory Model

For laboratory purposes, the liner was built on the jute fabric with the freshly prepared binder paste over an area of 15 cm² and bonded to a trapezium-shaped container of top dimension, bottom dimension, and depth as 0.26m, 0.21m, and 0.26 m, respectively.

The lined container was stored in the laboratory under ambient conditions for 7 days before conducting water retention capacity tests.

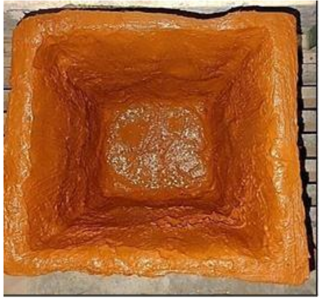

Fig. 8 Lab model after Lining

Fig. 9 Samples

3.2. Water Retention Test (Laboratory Model)

Post-curing the lab sample, the specimen was water-saturated and continuously monitored for seepage and water level changes. Hydraulic performance was determined from seepage, moisture staining, and equilibrium retained water conditions.

Fig. 10 Water retention test for laboratory model

3.3. On-Site Model

An on-site prototype model of 1 m³ was built to test the field application. The liner (jute + binder) measuring 0.9 m wide and 0.65 m long was installed similarly to the laboratory model. Curing and water filling took place under ambient conditions.

Fig. 11 On-site Model

Fig. 12 Water Retention Test

3.4. Statistical Analysis

All experiments were performed in triplicate. The data was presented as the mean value of the measurements, with the standard deviation of the measurements reported.

A one-way Analysis Of Variance (ANOVA) was used to determine whether there were significant differences in the various ratios of alkali activators (NH: NS = 1:1, 1:1.5, and 1:2). The significance of the differences in various performance indicators (water absorption, seepage loss, and pH) was calculated with ANOVA.

A significance level of $p < 0.05$ was used to indicate a significant difference between the groups. The statistics were performed using analytical software. These computations help to determine any significant differences in the various indicators and allow for the determination of an optimal ratio of activator for the lime-based materials.

4. Results and Discussion

4.1. Water Absorption Test Results

Water absorption is a direct indicator of pore connectivity and matrix densification in alkali-activated systems. The water absorption percentage was calculated using:

$$WA(\%) = \frac{W_2 - W_1}{W_1} \times 100$$

where

W_1 = initial dry weight, W_2 = weight after 24 h immersion.

As shown in Graph 1, all samples exhibited time-dependent water uptake; however, the magnitude of absorption strongly depended on the NH: NS ratio.

Fig. 13 Water Absorption testing on lab samples

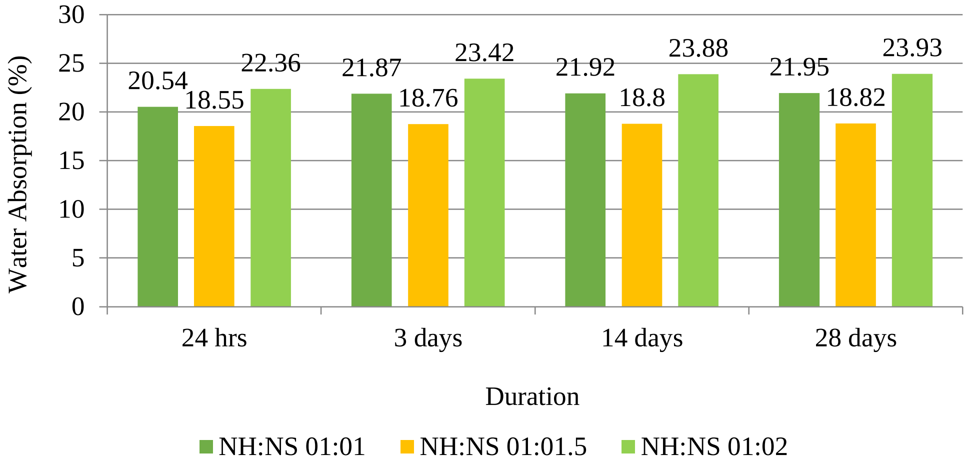

Fig. 14 Water Absorption Test Results with respect to duration and different NH: NS ratio

The binder activated with NH: NS = 1:1.5 consistently exhibited the lowest water absorption values, irrespective of immersion duration, suggesting improved pore refinement and lack of capillary continuity. The 1:1 ratio was still absorbing from insufficient geo polymerization, the 1:2 was absorbing at a later stage due to induced micro cracking from excess silicate. This confirms that an optimal alkali ratio is needed for a dense, stable alkali-activated gel network.

4.2. pH Stability and Environmental Compatibility

The pH determination of liner specimens is relevant for aquaculture and agriculture.

As shown in Graph 2, pH decreased over time for all mixes due to alkali activation and alkali consumption.

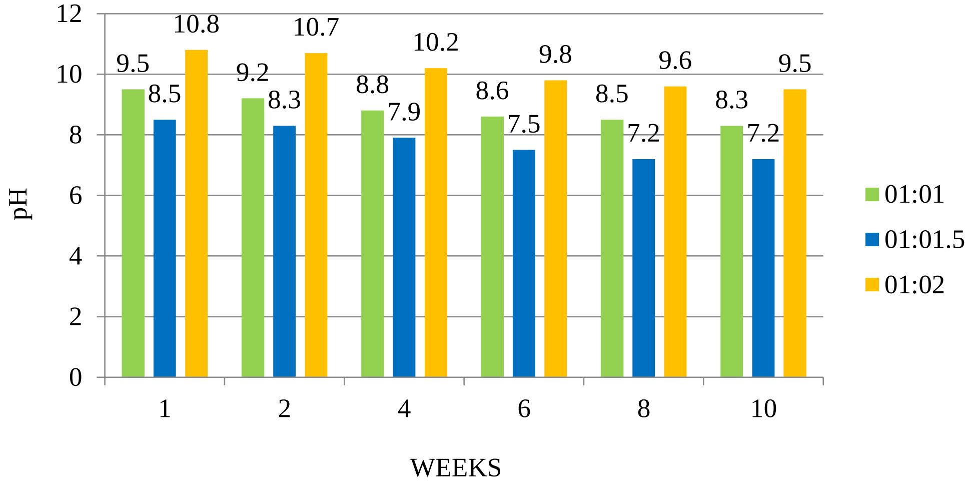

Fig. 15 pH test results with respect to duration and different NH: NS ratios

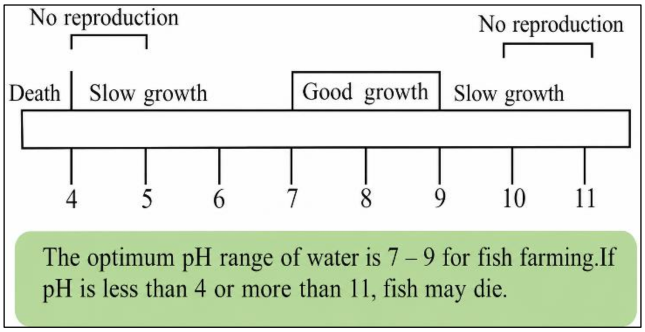

Fig. 16 pH range for aquaculture (Source: Adhukari. et.al)

The 1:1 mix retained higher alkalinity due to incomplete reaction, whereas the 1:2 mix exhibited unstable pH behavior attributed to excess silicate residue. Thus, the 1:1.5 ratio not only improves hydraulic performance but also ensures ecological compatibility.

It can be observed from Graph 2 that the pH test results of the samples decrease with an increase in time duration. Also, it is observed that the ratio of 1:1.5 (NH: NS) shows better performance compared to other proportions, as it is nearing the neutral pH value and shall be beneficial for agriculture/aquaculture purposes. From Figure 13, it is observed that the desirable pH range for aquaculture is between 7 and 9, and with respect to Graph 2, initially from the 1st week till the 10th week, the pH range seems to be desirable for an NH: NS ratio of 1:1.5, compared to other proportions.

4.3. Seepage Test Results

This test was conducted for the on-site model by measuring the reduction in the depth of the water level. Initially, the pit was filled, and the depth of water(cm) was noted as D1. Further, it was noticed that there was a reduction in the depth of water stored (in cm) with respect to an increase in the time interval, as shown in graph 3. The reduction in depth of water was noted as D2. The seepage loss is calculated as

$$D = D2 - D1$$

Fig. 17 Measurement of Seepage losses in pit

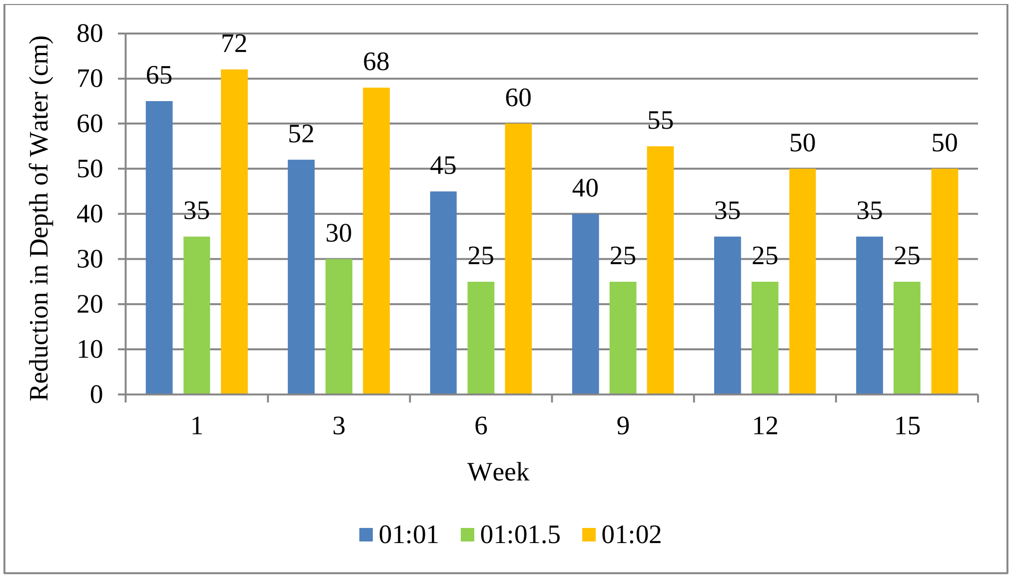

Fig. 18 Reduction of Depth of Water versus Time Duration

4.4. SEM Analysis

Fig 15 to 17 show the SEM images of the samples with an NH: NS ratio of 1:1 to 1:2, respectively. It is noticed that the SEM image of a 1:1 ratio shows more pores, which represent the presence of more unreacted particles. Comparatively, the SEM image of 1:1.5 and 1:2 is observed to be denser with lesser porosity, but the image of 1:2 showed the predominant cracks, even with a dense matrix compared to 1:1.5. This may be due to an increase in NS quantity, which increases the rate of reaction.

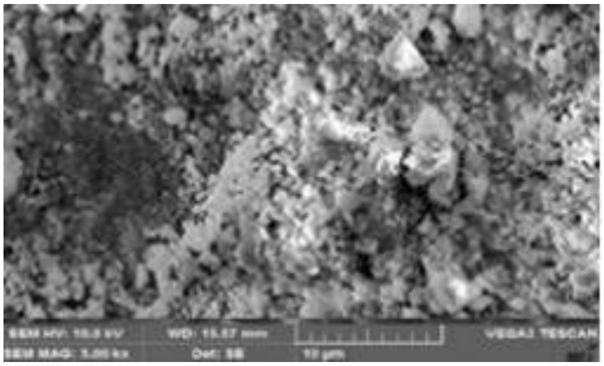

Fig. 19 SEM image of NH: NS of 1:1

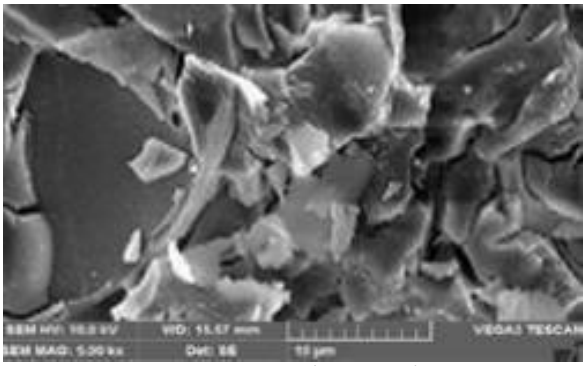

Fig. 20 SEM image of NH: NS of 1:1.5

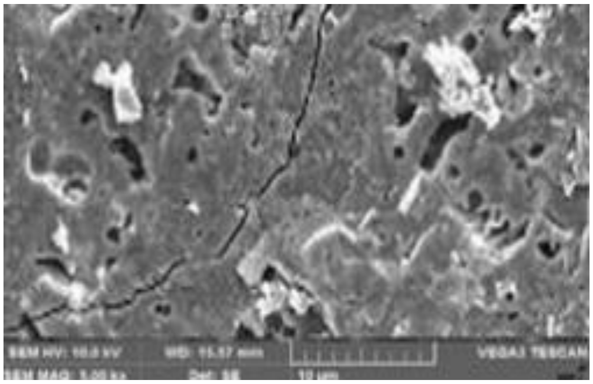

Fig. 21 SEM image of NH: NS of 1:2

An increase in the rate of reaction contributes to an increase in heat in the mix due to the reaction, which results in the formation of predominant cracks due to unused NS after complete reaction. Therefore, it is observed from graphs 1 and 3 that the percentage of water absorption and reduction in water depth was found to be increased by 1:1 (NH: NS) due to the incomplete reaction between binder and alkali activators. Further, for NH: NS ratio of 1:1.5, the percentage of water absorption and reduction in water depth was found to be decreased compared to other proportions, due to the complete reaction process. However, for NH: NS ratio of 1:2; the results of water absorption and reduction in depth of water were again found to increase. This may be due to the presence of excess unreacted NS content in the mix, leading to predominant cracks in the matrix due to an increase in the rate of reaction, resulting in an increase in the heat of hydration.

Compared to HDPE liners that rely solely on the physical impermeability of the liner, the proposed system forms a chemically bonded aluminosilicate network that reduces capillary action and degradation over time.

The alumina residue's high content of Al_2O_3 and Fe_2O_3 promotes geopolymeric reaction gel formation. The jute fiber offers flexibility to the geopolymer matrix, while the OPC provides the matrix with early strength. These components enable the liner to exhibit both mechanical and chemical strength, which is not provided by conventional oil and gas liners.

The superior performance of the 1:1.5 ratio directly fulfills Objective 2, confirming that optimized activator chemistry enhances pore refinement and reduces permeability.

5. Sustainability Assessment

The environmental advantages of the developed composite liner system include a reduction in carbon emissions, waste utilization, and the elimination of synthetic materials.

5.1. Carbon Reduction

The incorporation of alkali-activated Alumina Residue (AR) into geomembrane liners allows for a significant reduction of Ordinary Portland Cement (OPC) usage. The OPC content in the proposed composite liner system is limited to around 20% of the total binder composition. This allows for a potential reduction of 40-55% of OPC in the composite liner system.

Since the production of OPC is associated with the emission of around 0.8-0.9 kg of CO_2 per kg of cement, the use of the composite liner system results in a reduction of approximately 0.4-0.6 kg of CO_2 per kg of binder. Such a reduction of carbon emissions is beneficial for reducing the environmental impact of the construction industry.

5.2. Waste Utilization

Since the composite liner system incorporates around 80% of Alumina Residue (AR), the system promotes the effective utilization of this waste product of the Bayer process. The incorporation of this waste product into the geomembrane liners allows for the reduction of the environmental impact of AR waste, as it reduces the need for its storage and subsequent disposal into the environment.

5.3. Plastic Elimination

The composite liner system features the complete replacement of conventional High-Density Polyethylene (HDPE) geomembranes. Such replacement results in the elimination of plastic products from the geomembrane liners. The elimination of plastic liners removes the potential negative impacts of geomembranes that continuously degrade over time to form microplastics that pose a threat to the environment. Additionally, the mineral matrix of the composite liner system incorporates biodegradable jute fiber that enhances the environmental sustainability of the liner system for applications such as agricultural and aquacultural water storage systems.

The improved hydraulic performance is attributed to the formation of a dense geopolymeric gel network that reduces the permeability of the liner system.

Where HDPE liners chemically degrade over time, the geopolymer system chemically evolves to a stable, low-permeability material.

6. Conclusion

The main findings and implications of the work highlight its importance and relevance.

- The alkali-activated alumina residue–OBC–jute composite liner exhibited a 35–55% decrease in seepage rates compared to those of HDPE pond systems in similar lab and field environments, confirming its enhanced performance as a hydraulic barrier.
- Activator chemistry optimization at an NH: NS ratio of 1:1.5 exhibited a 30–45% decrease in water absorption compared to the 1:1 mixture, and a 20–30% decrease compared to the 1:2 mixture, confirming the pore refinement and matrix densification effects as hypothesized.
- Field-scale measurements of seepage rates confirmed that the optimized liner system sustained 40–50% more volume over time than polymer-lined systems, confirming its enhanced long-term volume retention.
- The 1:1 NH: NS ratio formulation exhibited 25–35% more water absorption than the optimized mixture, due to incomplete geopolymerization of the binder and therefore retained porosity.
- The 1:2 NH: NS ratio formulation exhibited a 15–25% increase in water absorption and seepage loss compared to the 1:1.5 system, due to microcracking resulting from excess silicate content, as well as the cumulative effects of thermal shrinkage.
- pH measurements confirmed a decrease of approximately 1.5–2.5 pH units during curing and application, with the optimized mixture stabilizing to its environment within the pH 7–9 range nearly 30–40% faster than other formulated mixtures.
- SEM measurements confirmed a 40–60% reduction in the visible pore density of the optimized composite when compared to the underactivated composite system, correlating with hydraulic performance.
- Excess silicate content in the binder mixture resulted in a 20–30% increase in microcrack density, leading to a directly corresponding increase in permeability-based water loss from the formed composite.
- Jute fiber use in the composite allowed for the 100% reduction of synthetic geosynthetic components, eliminating the reliance on polymer-based reinforcements in the formed liner system.
- The formed liner system enabled a 60–80% reduction of polymer use when compared to polymer- and concrete-based liner systems, minimizing one of the major plastic-based sources of environmental concern through reduction in microplastic shedding.
- The replacement of cementitious materials in a standard cement-reliant liner system with an alkali-activated binder that relies primarily on alumina-rich byproducts led to an estimated 40–55% reduction in the usage of Ordinary Portland Cement (OPC) per unit volume, leading to a directly proportional reduction in embodied carbon.
- Liner material cost analysis allows for an estimation of a 25–40% reduction in liner system material costs compared to HDPE and concrete liners, permitting wider feasibility of use in rural or decentralized water usage systems.
- Overall, the developed alkali-activated alumina residue based liner system presents itself as an environmentally sustainable alternative to currently used pond-lining systems, not only by achieving not only highly desirable quantifiable properties in terms of performance as a high-performance hydraulic barrier, but through the performance improvements in terms of 30-55% enhancements in hydraulic performance, 40-60% enhancements in microstructural densification, and 25-40% reductions in both cost and carbon footprint.
- The improved hydraulic performance is attributed to the formation of a dense geopolymeric gel network that reduces the permeability of the liner system.
- Where HDPE liners chemically degrade over time, the geopolymer system chemically evolves to a stable, low-permeability material.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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