

# Fly Ash-Based Geopolymerization for Enhancing Clayey Soils in Canal Linings: An Experimental and Numerical Analysis Using SEEP/W

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Received: 19 July 2025 | Revised: 8 September 2025 and | Accepted: 16 September 2025

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## ABSTRACT

Growing environmental concerns and the increasing need for sustainable water infrastructure have stressed the importance of eco-friendly alternatives to conventional canal lining materials. In this study, the potential of Fly Ash (FA)-based geopolymers to improve the impermeability of clayey soils for canal lining applications was examined. Laboratory tests were performed on untreated and geopolymer-treated soils after 7 and 14 days of curing, during which permeability and water flux were measured. The untreated clay soil exhibited a permeability coefficient of  $8.00 \times 10^{-7}$  cm/s. Noticeable improvements were observed after geopolymer treatment. The optimum mixture contained 30% FA activated by the AA/FA1 system, with a ratio of sodium silicate to lime of 0.4. This treatment reduced permeability to  $1.80 \times 10^{-7}$  cm/s, representing a 77.5% decrease, and lowered water flux by approximately 87.93%. In comparison, the AA/FA2 activator, with a ratio of sodium bicarbonate to lime of 0.6 and 30% FA, reduced permeability to  $4.30 \times 10^{-7}$  cm/s, corresponding to a 46.25% reduction. Also, it resulted in an 86.93% decrease in water flux but yielded lower impermeability than the AA/FA1 mixture. The superior performance of AA/FA1 is attributed to its higher alkalinity and the formation of denser geopolymer gels, which refine and stabilize the soil pore structure. The numerical simulations conducted using SEEP/W were closely aligned with the laboratory findings, further validating the proposed treatment approach. Overall, FA-based geopolymer-treated soils demonstrate a promising, durable, and environmentally sustainable method for minimizing seepage in earthen canals and enhancing water conservation.

*Keywords*-fly-ash; geopolymer; canal lining; SEEP/W simulation; soil improvement

## I. INTRODUCTION

Irrigated agriculture represents approximately 20% of the total cultivated land yet contributes nearly 40% of global food production [1]. Consequently, irrigation water is considered a fundamental input for agricultural productivity and a key factor in maintaining food security. Water supply to irrigated fields is predominantly achieved through surface free-flow conveyance in earthen canals [2]. The long-standing use of this method over thousands of years is attributed to its relative simplicity, effectiveness in water conveyance, and low operational cost.

However, substantial water losses occur during transport as water infiltrates downward and laterally from the wetted perimeter of canals into the surrounding soil and rock. Given that irrigation canals often extend for thousands of km within large-scale irrigation networks, these losses pose a persistent challenge for efficient water conveyance. Additionally, water losses typically arise from seepage, evaporation, and improper operation of control structures [3-4]. Among these, seepage usually accounts for the largest proportion of total losses, particularly in unlined earthen canals [5]. Excessive seepage reduces conveyance efficiency, may render low-lying areas

unsuitable for cultivation, and adversely affects the operation and maintenance of canal systems, as a portion of the diverted water fails to reach end-users.

Furthermore, seepage can induce waterlogging, increase uplift pressures, and contribute to structural instability or failure of canals and associated infrastructure [6]. In Iraq, approximately 8 million hectares (Mha) of land are irrigated, while an additional 4 Mha rely on rainfall. In 1997, the total irrigated area was estimated at 3.4 Mha, with 87.5% supplied through irrigation projects, 9.2% by river pumping, 3.1% by wells, and 1.2% by springs [7]. Within this context, seepage and water loss from irrigation canals have become issues of global significance. The current study aims to address these challenges by evaluating innovative alternative materials intended to minimize or prevent seepage in open earthen canals.

## II. TYPES OF CANAL LINING AND SEEPAGE MEASUREMENT

Standard techniques for lining irrigation canals utilize both conventional and non-conventional materials. Traditional lining materials, including various types of concrete, brick masonry, and geomembrane sheets, offer notable advantages, particularly in reducing seepage losses and ensuring long-term structural durability after construction. However, their primary limitation is the relatively high cost associated with material procurement, installation, and subsequent maintenance. As a result, the use of such materials is typically justified only when the anticipated economic benefits exceed the substantial investment required [8].

Increased attention has been directed toward unconventional, cost-effective alternatives for canal lining. One such approach involves the use of compacted or improved soils. Numerous studies have investigated the effectiveness of physical soil compaction in decreasing seepage losses and improving canal durability through both field applications and analytical modeling. Reported results indicate that soil compaction can reduce seepage losses by approximately 80-90% over short time periods [9]. Other studies have examined partial lining strategies, applied either to the canal bed or to the sidewalls, as a means of further minimizing seepage [10].

Regarding the use of improved soils, various studies have focused on soil stabilization using cement. The incorporation of cement has been shown to enhance soil strength and impermeability, thereby improving canal performance and contributing to substantial reductions in seepage losses [11, 12]. Parallel investigations have explored stabilization using polymers, such as polyurethane and anionic polyacrylamides (PAM), including low-cost linear anionic polyacrylamide (LAPAM) and cross-linked ionic variants. These studies indicate that polymer-treated soils can significantly reduce seepage, in some cases achieving notable reductions within a single irrigation season [13, 14].

Multiple approaches are employed for estimating seepage losses, including field experiments, empirical and analytical formulations, and numerical modeling. Among field techniques, ponding and inflow-outflow methods are the most

commonly used, as they yield localized and timely assessments of water loss rates [15, 16]. Numerical modeling has become an increasingly important tool due to its ability to simulate spatial and temporal seepage behavior with high accuracy under various boundary conditions. Models capable of representing saturated and unsaturated flow regimes have been extensively applied to two-dimensional canal cross-sections, including SEEP/W [17, 18].

## III. GEOPOLYMER WITH SOIL AND FLY ASH

Geopolymers are inorganic, amorphous, three-dimensional polymeric networks formed from aluminosilicate materials. These aluminosilicates undergo chemical activation in the presence of an alkaline solution, producing an amorphous inorganic binder commonly referred to as a geopolymer [19]. The formation process primarily depends on the dissolution of aluminosilicate precursors, which is strongly influenced by the type and concentration of the alkaline activator. Considerable research attention has been directed toward geopolymer concrete due to its superior mechanical performance and enhanced durability when compared with Ordinary Portland Cement (OPC) concrete [20].

Geopolymers have emerged as a sustainable and innovative alternative to conventional soil stabilizers such as Portland cement. Alkali-activated binders derived from industrial by-products provide significant environmental and economic benefits, including reductions of approximately 60-80% in CO<sub>2</sub> emissions and about 60% in energy consumption during production, relative to traditional construction materials [21]. Research has therefore focused on developing geopolymeric binders using various industrial waste materials, including FA, Rice Husk Ash (RHA), metakaolin, and Ground Granulated Blast Furnace Slag (GGBFS).

In [22], Alum Sludge (AS) was combined with RHA to produce a geopolymeric binder for stabilizing expansive soils. An optimum mixture containing 15% AS and 6% RHA significantly improved soil performance, increasing the California Bearing Ratio (CBR) to 116.3% and the Unconfined Compressive Strength (UCS) to 1834.5 kPa. Similarly, FA-based geopolymers have been utilized to enhance the engineering characteristics of weak clayey soils, with FA contents ranging from 11% to 19% evaluated over curing periods of 7, 14, and 28 days. The most effective performance was reported at 15% FA, which substantially improved load-bearing capacity and reduced settlement [23]. It has been further demonstrated that geopolymer-treated soils exhibit superior mechanical behavior and durability under alkaline conditions compared with soils stabilized using OPC [24], reinforcing the potential of geopolymer materials as a sustainable and efficient solution for soil improvement.

## IV. MATERIALS AND METHODS

### A. Soil

The clayey soil used in this study was obtained from a site located in southeastern Baghdad, Iraq. Disturbed samples were collected from trial pits excavated at depths ranging between 1.5 and 3.0 m below ground surface. To preserve the natural characteristics of the soil (Table I), the samples were

immediately sealed in airtight plastic bags to minimize moisture loss and were subsequently transported to the Soil Mechanics Laboratory for detailed testing and analysis. Based on the Atterberg limits, the soil is classified as low-plasticity clay (CL) according to the Unified Soil Classification System (USCS).

TABLE I. PHYSICAL PROPERTIES OF CLAY SOILS

Property	Value	Standard
Specific gravity, Gs	2.86	ASTM D 854
Gravel (%)	0	ASTM D 422
Sand (%)	5	ASTM D 422
Silt (%)	35	ASTM D 422
Clay (%)	60	ASTM D 422
Liquid limit (%)	45	ASTM D 4318
Plastic limit (%)	23.8	ASTM D 4318
Plasticity index (%)	21.2	ASTM D 4318
OMC (%)	18	ASTM D 1557
MDD (kN/m <sup>3</sup> )	17.8	ASTM D 1557

### B. Fly Ash

The FA utilized in this study was obtained from local commercial suppliers. Its characteristics conform to the specifications of Class F FA, as defined in ASTM C618.

### C. Alkali Activators

Two alkali activator systems were employed in this investigation. The first system consisted of sodium silicate ( $\text{Na}_2\text{SiO}_3$ ) solution combined with lime ( $\text{CaO}$ ), whereas the second system incorporated solid sodium bicarbonate ( $\text{NaHCO}_3$ ) mixed with lime. Each activator was prepared using a 1:1 mass ratio relative to the weight of FA. These systems were selected due to their low cost, local availability, and practicality, particularly considering the challenges associated with traditional alkaline activators, such as sodium hydroxide, which include high alkalinity, handling difficulties, and safety concerns, therefore contributes to ongoing efforts to identify alternative alkali activators that are environmentally sustainable, safer to use, and more suitable for field implementation.

## V. SAMPLE PREPARATION

The samples were prepared by blending dry soil with predetermined FA percentages by weight (Tables II, III). After weighing the required quantities, the dry components were manually mixed for approximately 3-5 min to ensure uniform distribution. The selected alkaline activator was then gradually added to the dry mixture and manually blended for an additional 5-10 min until a homogeneous and workable mixture with consistent moisture content was achieved.

The Water-to-Geopolymer (W/G) ratio was maintained at 0.35 to promote effective chemical interaction among the binder constituents. The total water content consisted of two components: water equivalent to the Optimum Moisture Content (OMC) of the clay soil, required to achieve Maximum Dry Density (MDD) during compaction, and water corresponding to the geopolymer mixing ratio, necessary to ensure proper cohesion and hardening of the binder. This combination was selected to simultaneously satisfy the

compaction requirements of the soil and the reaction needs of the geopolymer system.

TABLE II. MIX DESIGN PARAMETERS FOR PREPARED SAMPLES

Sample no.	Symbol	FA	Type of activator	AA/FA	W/G ratio
1	Untreated soil	0	0	0	0
2	FAA201	20	AA/FA1	0.4	0.35
3	FAA301	30	AA/FA1	0.4	0.35
4	FAA202	20	AA/FA2	0.6	0.35
5	FAA303	30	AA/FA2	0.6	0.35

TABLE III. WEIGHT OF THE MATERIALS USED

Sample no.	Soil (g)	FA (g)	$\text{Na}_2\text{SiO}_3$ (g)	$\text{NaHCO}_3$ (g)	$\text{CaO}$ (g)	Total water (g)
1	27200	0	0	0	0	4900
2	23940	2720	270	0	270	6041
3	19570	5450	1090	0	1090	7571
4	18480	5450	0	1635	1635	7952
5	14130	8170	0	2450	2450	9475

The specimens were molded in the form of canal-lining sections with dimensions of 1.0 m in length, 0.30 m in width, and 0.05 m in thickness to represent the typical geometry used in field applications. After molding, all specimens were cured at a temperature of 30-38 °C for seven consecutive days to ensure sufficient hardening and the development of the required mechanical and hydraulic properties before testing.

## VI. EXPERIMENTAL SETUP AND SEEP/W MODELING

### A. Channel Setup

The experimental flume used in this study had a rectangular cross-section and was constructed from transparent acrylic to enable direct visual observation of seepage behavior throughout testing. The channel dimensions were 1.0 m in length, 0.30 m in width, and 0.30 m in depth.

To simulate the vertical seepage conditions typically encountered in field canal linings, and to allow downward infiltration through the impermeable acrylic base, the channel floor was perforated with 8 mm diameter holes. These holes were arranged in a uniform grid with 5 cm spacing in both longitudinal and transverse directions, ensuring uniform flow into the soil below.

The inner sidewalls were coated with waterproof silicone sealant to prevent lateral leakage. Before placing any lining materials, the channel was filled with water to confirm complete water tightness along the side boundaries. Because applying linings to vertical surfaces presents practical difficulties, only the bottom surface of the channel was lined.

Two lining configurations were evaluated:

- Natural Soil Lining: A 3 cm thick layer of sand was first placed to promote vertical drainage and replicate the boundary conditions used in the numerical model. Then, a 5 cm thick layer of natural clayey soil was compacted over the sand to achieve the MDD and OMC, as determined

from the ASTM D698 standard Proctor test. The lining was cured for seven days at a temperature of 30-38 °C and covered to minimize moisture loss. This configuration served as the control for comparison with geopolymer-treated linings.

- Geopolymer-Stabilized Soil Lining: A 5 cm thick soil layer treated with an FA-based geopolymer binder was prepared and compacted over a 3 cm thick sand sub-layer. The mixture was compacted to reach its MDD and OMC, and then cured for seven days under controlled laboratory conditions.

#### B. Saturation and Seepage Measurement

After the curing period, the channels were filled with water to begin saturating the lining. Figure 1 shows the lining during this phase. To achieve steady-state saturation, consistent with the conditions assumed in the numerical model (SEEP/W), the water level was kept constant for 14 days, a duration that was considered sufficient to establish hydraulic equilibrium within the soil layer. To reduce evaporation during saturation, the entire channel was covered with a thick polyethene sheet.

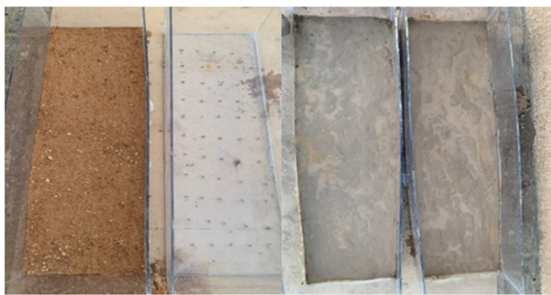


Fig. 1. Experimental canal lining.

Seepage measurements were performed under constant-head conditions. Water loss due to infiltration over a 24-hour period was recorded, and the volumetric seepage flux was calculated by:

$$q = \frac{V}{A \times t} \quad (1)$$

where  $q$  is the volumetric water flux ( $\text{m}^3/\text{s}/\text{m}^2$ ),  $V$  is the infiltrated water volume ( $\text{m}^3$ ),  $A$  is the seepage area ( $\text{m}^2$ ), and  $t$  is the experiment duration (s).

#### C. Numerical Modeling Using SEEP/W

To complement the laboratory experiments, numerical simulations were conducted using the SEEP/W module of the GeoStudio (GeoSlope) software suite, which employs the finite element method to model water flow through porous media.

A rectangular earthen channel embedded within a deep, highly permeable soil domain was modeled to approximate semi-infinite boundary conditions. The boundary conditions involved specifying the total head at the channel bottom and assigning a seepage face along the lower boundary of the domain (Figure 2). The finite element mesh consisted of square and triangular elements with an average element size of 0.5 m.

This discretization achieved stable convergence while keeping computational demands reasonable.

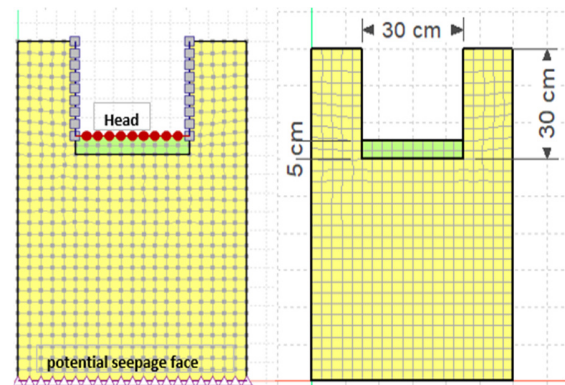


Fig. 2. Finite element mesh size and boundary conditions.

#### D. Permeability Testing

Permeability tests were performed on both untreated soil and geopolymer-treated soil in accordance with ASTM D5084 using the falling-head method. Cylindrical samples were compacted to their MDD and OMC and then cured for seven days to allow stabilization of the chemical reactions in the treated specimens. After curing, the samples were placed in the falling-head permeability apparatus, and the hydraulic conductivity was calculated by:

$$k = \left( \frac{aL}{At} \right) \cdot \ln \left( \frac{h_1}{h_2} \right) \quad (2)$$

where  $k$  is a permeability coefficient (cm/s),  $a$  is the cross-sectional area of the standpipe ( $\text{cm}^2$ ),  $L$  is the length of the soil sample (cm),  $A$  is the cross-sectional area of the soil specimen ( $\text{cm}^2$ ),  $t$  is the time interval (s), and  $h_1$ ,  $h_2$  are the initial and final water head levels in the standpipe (cm).

## VII. RESULTS AND ANALYSIS

#### A. Permeability

Permeability is one of the most important parameters for evaluating the performance of soils used in hydraulic barriers, including canal linings, storage reservoirs, and other water-retaining structures. In this study, the FA inclusion, activated with two different alkaline systems, resulted in a consistent reduction in soil permeability across all treatment mixes, demonstrating substantially better hydraulic performance compared to the untreated soil.

The untreated soil exhibited a relatively high permeability of  $8.00 \times 10^{-7}$  cm/s, confirming that it is unsuitable for hydraulic applications without stabilization. When 20% FA was activated using the AA/FA1 system at a 0.4 ratio, the permeability decreased to  $2.80 \times 10^{-7}$  cm/s, representing a 62.5% reduction (Table IV). This improvement is attributed to pore filling and the early formation of geopolymer gels, which promote densification and enhance soil structure during the initial curing stage [25]. Increasing the FA content to 30% while using the same activator system produced an even greater reduction,

yielding a permeability of  $1.80 \times 10^{-7}$  cm/s, equivalent to a 77.5% decrease relative to the untreated soil.

TABLE IV. PERMEABILITY RESULTS

Sample no.	Symbol	Permeability (cm/s)
1	Soil untreated	$8.00 \times 10^{-7}$
2	FAA201	$2.80 \times 10^{-7}$
3	FAA301	$1.80 \times 10^{-7}$
4	FAA202	$5.50 \times 10^{-7}$
5	FAA303	$4.30 \times 10^{-7}$

In contrast, the AA/FA2 activator system, based on sodium bicarbonate and lime, was less effective. The use of 20% FA with an AA/FA2 ratio of 0.4 achieved only a 31.25% reduction, whereas increasing the FA content to 30% at a 0.6 ratio resulted in an improvement of 46.25%. Despite these reductions, both mixes performed noticeably worse than those activated with the AA/FA1 system. The diminished performance of the AA/FA2 mixtures can be attributed to the lower alkalinity and reduced reactivity of sodium bicarbonate, which slows the geopolymerization process and produces less dense gel matrices. These weaker gels are less efficient at filling voids within the soil, thereby limiting the reduction in hydraulic conductivity.

The findings demonstrate that the chemistry of the activator plays a dominant role in determining the extent of hydraulic improvement (Figure 3). Activators containing sodium silicate promote the rapid formation of reactive silicate species, leading to dense and well-bonded geopolymer gels that effectively block soil pores and enhance impermeability [25, 26]. Conversely, bicarbonate-based activators form more open gel networks and generally require longer curing periods to achieve comparable performance. It has been confirmed that the pH, solubility, and reactivity of the activator govern the kinetics and quality of gel formation during geopolymerization [27]. Overall, the findings exhibit that the activator type and its chemical reactivity have a greater influence on permeability reduction than the FA content alone.

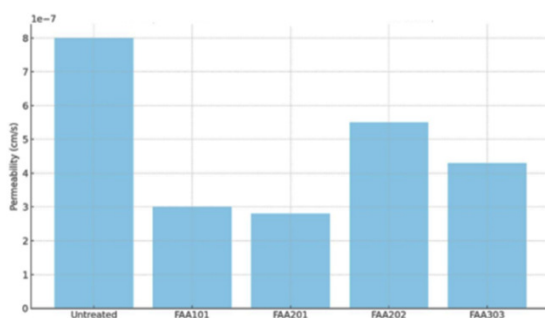


Fig. 3. Comparison of soil permeability.

### B. Water Flux Measurement

Water movement through soil is a key parameter for evaluating the effectiveness of materials used as impermeable liners in irrigation canals. This behavior is expressed as water flux  $q$  ( $\text{m}^3/\text{s}/\text{m}^2$ ) and represents the combined influence of hydraulic conductivity, hydraulic gradient, and the internal

structure of the porous medium. According to Darcy's law, water flux is defined by:

$$q = K \cdot i \quad (3)$$

where  $K$  is the hydraulic conductivity (m/s), and  $i$  is the hydraulic gradient. Equation (3) reflects the combined influence of the soil's hydraulic properties and the physical structure of the porous medium.

The untreated soil exhibited the highest water flux, measured at  $6.80 \times 10^{-4}$   $\text{m}^3/\text{s}/\text{m}^2$  (Table V), reflecting its relatively high permeability. In contrast, all geopolymer-treated soils demonstrated substantial reductions in water flux, with measured values of  $7.84 \times 10^{-5}$ ,  $8.21 \times 10^{-5}$ ,  $8.84 \times 10^{-5}$ , and  $8.89 \times 10^{-5}$   $\text{m}^3/\text{s}/\text{m}^2$  for samples 2-5, corresponding to improvements of 88.47%, 87.93%, 86.99%, and 86.93%, respectively. The close similarity among the treated samples suggests that the improvement approaches a saturation threshold, where additional increases in FA content or activator dosage yield only marginal reductions in water flux. This behavior indicates that, beyond certain limits, the geopolymerization process nearly maximizes pore filling and gel densification.

TABLE V. WATER FLUX RESULTS

Sample no.	Water flux ( $\text{m}^3/\text{sec}/\text{m}^2$ )	Improvement
1	$6.80 \times 10^{-4}$	-
2	$7.84 \times 10^{-5}$	88.47
3	$8.21 \times 10^{-5}$	87.93
4	$8.84 \times 10^{-5}$	86.99
5	$8.89 \times 10^{-5}$	86.93

These observations are consistent with previous findings reporting the effectiveness of FA-based geopolymer systems in reducing permeability and enhancing the hydraulic performance of soil liners [28]. The improvement is primarily attributed to microstructural alterations induced by geopolymerization, including void filling, particle rearrangement, and the formation of a dense binding matrix that restricts water movement. The literature further emphasizes that the type and concentration of alkaline activators significantly influence the strength and durability of the resulting geopolymer gels. However, excessive alkalinity may lead to microcracking and brittleness, which can negatively affect long-term performance [23-30].

### C. Analysis of Variability between Laboratory Experiments and SEEP/W Modeling

Discrepancies were observed between the water-flux values obtained from the laboratory experiments and those predicted by the SEEP/W numerical model (Figure 4). The percentage difference between the two methods was calculated by subtracting the laboratory value from the SEEP/W prediction, dividing by the laboratory measurement, and multiplying by 100. Under this definition, a positive percentage indicates that the SEEP/W model over-predicted the water flux, whereas a negative percentage indicates that it under-predicted the laboratory result.

The untreated soil exhibited the largest positive deviation, equal to 23.4%, which reflects the influence of idealized

assumptions commonly inherent in numerical simulations when compared to the more complex behavior of natural soils. In contrast, the treated soils demonstrated much closer agreement. Sample 4 showed the smallest deviation of 2.94%, indicating that the stabilizing treatment improved both the hydraulic behavior of the soil and the consistency between modeled and measured results.

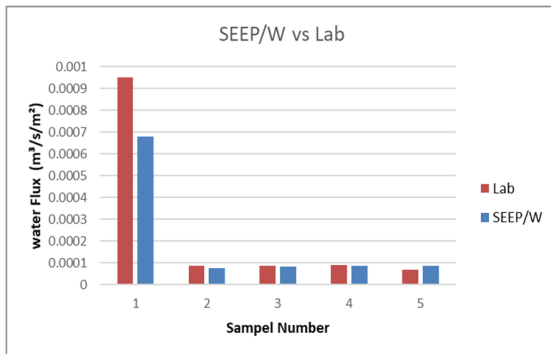


Fig. 4. Comparison of water flux between laboratory tests and SEEP/W.

A negative deviation was observed for sample 5, indicating that the SEEP/W model underestimated the water flux relative to the laboratory measurement. Several factors may explain this discrepancy. Soil heterogeneity, particularly variations in pore size distribution and connectivity, may produce preferential flow paths in the physical specimen that are not fully captured in the model. Moreover, although the boundary conditions in SEEP/W were designed to approximate the experimental setup closely, certain simplifications were unavoidable and may have influenced the accuracy of the predictions. Minor inconsistencies during sample preparation, including variations in compaction or moisture distribution, as well as measurement uncertainties, could also contribute to these differences. Overall, these findings highlight the importance of rigorous calibration and validation when employing numerical models to simulate seepage behavior in soil systems.

### VIII. CONCLUSION

This study demonstrated that Fly Ash (FA)-based geopolymers can significantly enhance the hydraulic barrier performance of clayey soils, making them highly suitable for canal lining applications. The effectiveness of the treatment was found to depend primarily on the FA content as well as the chemical composition and ratio of the alkaline activator. The most effective formulation consisted of 30% FA activated with the AA/FA1 system, of sodium silicate and lime at a 0.4 ratio, which reduced the untreated soil permeability from  $8.00 \times 10^{-7}$  cm/s to  $1.80 \times 10^{-7}$  cm/s. This corresponds to an approximate 77.5% decrease and improved water flux by about 87.93%. These enhancements are attributed to substantial pore refinement and the formation of dense geopolymer gels that restrict water movement.

In comparison, using 30% FA with the AA/FA2 activator of sodium bicarbonate and lime at a 0.6 ratio yielded a permeability of  $4.30 \times 10^{-7}$  cm/s, corresponding to a 46.25% reduction and an 86.93% improvement in water flux, which is

lower than that achieved with AA/FA1. This reduced effectiveness is likely related to the lower alkalinity and slower reaction kinetics of sodium bicarbonate, which generally produce less compact gel structures.

Numerical simulations using SEEP/W showed good agreement with laboratory measurements for treated soils, underscoring the reliability of calibrated modeling in predicting hydraulic behavior. Overall, FA-based geopolymer stabilization represents a promising, durable, and environmentally sustainable method for reducing seepage in earthen canals and similar hydraulic structures. Future work should focus on long-term field validation and cost-benefit assessments to support large-scale implementation.

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