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Influence of cracking conditions on seepage performance of alkali-activated geopolymer linings in earthen canals

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Abstract

Water seepage from earthen canals severely reduces irrigation efficiency. This study evaluates an alkali-activated fine-ash geopolymer as a canal lining material and investigates how lining cracks affect seepage. Laboratory tests assessed soil hydraulic conductivity across varying fine-ash contents and curing periods, while SEEP/W finite element modeling simulated seepage performance under different configurations, water levels, and crack conditions. Results show that higher fine-ash content and longer curing periods significantly decrease hydraulic conductivity. The optimal mixture (30% fine ash, 28-day curing) reduced hydraulic conductivity from 1.0×10-6 m/s to 2.91×10-8 m/s, yielding a 97% reduction in seepage losses. Full geopolymer lining decreased seepage discharge from 1.2 m3/day/m (an 89.9% reduction), whereas bed-only lining reduced it by 62.5%, indicating the bed accounts for roughly 70% of losses. Numerical analysis further demonstrated that seepage increases with higher water heads and greater crack dimensions, with bed cracks causing the most severe losses. Ultimately, alkali-activated fine-ash geopolymer emerges as a highly effective material for controlling canal seepage.

Keywords: Geopolymer, Earthen canals, Cracking influence, Water losses, Seepage discharge

1. Introduction

Population growth and climate change pose major challenges in scientific research today [1], [2]. The increasing water demand is one of the most prominent of these challenges [3], [4], especially irrigation water needed for agriculture, which is the foundation of human life [5]. However, irrigation necessarily requires conveying water from its sources to farms [6]. Earthen canals are among the oldest and most common methods of conveying irrigation water because they are economical and practical [7]. Despite these advantages, earthen canals suffer from water losses due to seepage from the bed and side slopes [8]. These losses greatly reduce the efficiency of the irrigation conveyance system [9]. Therefore, seepage control is considered vital to sustainability [10], which, in turn, has become an urgent requirement across all fields [11], [12], especially in the domain of civil engineering [13], [14]. Several techniques are available to reduce seepage losses, such as lining with concrete or asphaltic slabs, asphaltic materials, geomembranes, clay liners, compaction, and chemical stabilization [8]. However, these techniques have several disadvantages, including high cost, impracticality, inefficiency, short lifespan, aging, and the need for periodic maintenance [15], [16].

Therefore, there is a crucial need to find an effective alternative. Geopolymers can meet this need [17]. Alkali-activated fly ash is a commonly used material in this domain [18]. Unfortunately, fly ash has become scarce and is declining significantly these days for two reasons. Firstly, this material is a byproduct of coal-fired power plants, most of which have closed. Secondly, it is required for use in several industries [19], [20], [21]. Therefore, finding a similar or better alternative is essential. To find such an alternative, an extensive literature review was conducted in the domain of canal lining. Several studies were conducted in the domain of lining. Afterward, the review focused on papers specializing in literature reviews, as they cover a large number of studies within the field. Among these papers, two recent papers (published in 2024) were within the core of this area [22], [23], [24]. However, no study suggested a revolutionary alternative that exposes a clear gap in this domain.

Therefore, this study aims to use fine ash as an alternative to fly ash to fill the knowledge gap in this field. This material was selected for two reasons. First, geopolymers produced from fine ash are widely used in various construction fields [25], [26]. Second, it is widely available in large quantities in Iraq, as it is a by-product of brick plants. To the best of the authors' knowledge, no prior study has used this material as a geopolymer to line earthen canals, underscoring the significance and novelty of this study.

However, geopolymer lining can be damaged by cracking, reducing its functional efficiency. Therefore, this study was expanded to examine the influence of cracking on the efficiency of seepage reduction. This part enhances the study's scientific value, opens a new avenue for research in this area, and confirms its novelty. To achieve the study's aim, a two-phase approach was adopted.

First, the study examined the influence of varying fine-ash contents on soil hydraulic conductivity using standard laboratory testing methods. Second, finite element analysis was utilized to investigate the influence of hydraulic conductivity, lining configuration, water level, and lining cracking on seepage performance. The fourth parameter (lining cracking) comprises three sub-parameters: cracking extent (the cracked area as a percentage of the lining area), crack width, and crack depth. To implement the second phase, effective software is required because computing makes problem-solving easier, increases the effectiveness and accuracy of solutions, and reduces the time and effort spent in finding solutions [27]. Therefore, this study adopted the SEEP/W software for its effectiveness and accuracy in simulating domain problems [28], [29].

2. Method

This paper investigates the influence of lining cracks on seepage discharge in earthen canals lined with alkali-activated geopolymer. The framework includes two phases. First, the laboratory phase, which involves investigating the influence of varying alkali-activated fine-ash contents on soil hydraulic conductivity. To achieve this objective, sufficient soil was collected from Maysan city in southern Iraq. It is an agricultural area famous for rice cultivation, a crop that requires large quantities of water for irrigation, which is usually supplied through traditional earthen canals.

The collected soil was divided into separate parts. The first part was used to produce the control samples. The other parts were used to produce treated samples at five alkali-activated fine ash percentages: 5%, 10%, 15%, 20%, and 30%. Afterward, the properties of the soil samples were examined in the laboratory. In addition to the basic properties of the samples, the hydraulic conductivity of the control and soil treated with different contents was investigated. Second, a numerical phase was conducted using SEEP/W finite-element software to simulate seepage performance and investigate the influence of cracking geometry on canal seepage losses.

3. Materials used

3.1. Soil

The properties of the soil used were determined through laboratory testing in accordance with standard procedures, as shown in Table 1. The test results indicate that the soil can be classified as CL based on the Unified Soil Classification System (USCS). This soil has a high clay content, which results in a high plasticity index, indicating swelling properties and low permeability.

Table 1. Soil properties

Property		Result	Standard
Particles sizes	Coarser than 4.75 mm	0%	ASTM D6913
	Within the range 0.075–4.75 mm	15%	
	Finer than 0.075 mm (75 µm)	85%	
Specific gravity (Gs)		2.66	ASTM D854
Liquid limit (LL)		47%	ASTM D4318
Plastic limit (PL)		26%	
Plasticity index (PI)		21%	Calculation
Soil class		CL (low plasticity clay/ sandy lean clay)	USCS
Optimum moisture content (OMC)		15%	ASTM D1557
Maximum dry density (MDD)		1690 kg/m^3	
Saturated hydraulic conductivity (K)		1×10^{-6} m/s	ASTM D5084

3.1.1. Fine-ash

Sufficient quantities of fine ash were collected from local brick plants in Maysan city. The collected quantity was sieved on sieve number 200 before any test. The physical properties and chemical composition of this material were determined using standard testing procedures. The results are illustrated in Table 2. The results in Table 2 show that all particles are finer than 75 µm in size as a result of sieving on sieve No. 200. The specific gravity was found to be 2.21, which is within the common range. The chemical composition of the material consists mainly of silica and alumina, with minor amounts of other oxides, including Fe_2O_3, CaO, MgO, K_2O, and Na_2O. This composition (high contents of silica and alumina) reflects its potential for geopolymerization via alkaline activation.

3.1.2. Alkaline activator

To activate the fine ash, an alkaline solution consisting of NaOH and Na_2SiO_3 was used. Table 3 abstracts the properties of the activator. NaOH is the main material in the chemical reaction, whereas Na_2SiO_3 assists in the dissolution of $Al_2O_3 \cdot 2SiO_2$. This reaction produces geopolymer gel. Equation (1)illustrates the reaction.

$$Al_2O_3 \cdot 2SiO_2 + NaOH/Na_2SiO_3 \rightarrow N-A-S-H\ gel \quad (1)$$

Table 2. Physical properties and chemical composition of fine ash used

Physical properties		
Property	Result	Standard
Color	light gray	Visually
Specific gravity	2.21	ASTM C188
Fineness	All particles < 75 µm	ASTM C43
Chemical composition		
SiO_2: 50–65%	59%	ASTM C114
Al_2O_3: 15–25%	25%	
Fe_2O_3: 5–10%	8%	

Physical properties		
Property	Result	Standard
CaO: 3–8%	4%	
Other oxides (MgO, K_2O, Na_2O)	4%	

Table 3. Properties of the activator

Sodium Hydroxide (NaOH)		
Purity	99%	ASTM E291
Density	1.05 g/cm³	ASTM D891
Sodium Silicate (Na_2SiO_3 solution)		
SiO_2/Na_2O ratio	2.9	ASTM C114
Density	1.45 g/cm³	ASTM D891
Combined Activator Solution		
Na_2SiO_3 / NaOH ratio	2	N/A
pH	14	ASTM E70

3.2. Geopolymer soil preparation

To prepare the geopolymer soil, the dry mixing method was adopted. This method includes four steps. First, drying the pure soil completely; second, mixing the preselected doses of fine ash with the soil; third, gradually adding the activator to the mixture to ensure homogeneity; and fourth, adding water to the optimum content, as previously mentioned in Table 1. The mixture was divided and converted into separate specimens using the standard Proctor method (ASTM D1557). These specimens were carefully sealed to prevent water loss and ensure effective curing. The curing process was continued for three periods: 7, 14, and 28 days to study the effect of the geopolymer reaction under different curing periods.

3.3. Hydraulic conductivity testing

The standard method specified in ASTM D5084 was used to determine the K values of the control soil sample and soil samples treated with the preselected geopolymer doses. Afterward, the ratio of lining hydraulic conductivity (KL) to that of control soil (K) was calculated as (KL/K) to evaluate the seepage reduction efficiency.

3.4. Modeling

To analyze steady-state seepage in earthen canals, a 2D FEM was implemented using SEEP/W. Typical irrigation canal geometry (height, width, side slopes, flow depth) was adopted in this step. Several boundary conditions were adopted in this modeling. First, at the surface, the head of water is constant. Second, at the downstream boundary, the pressure head is equal to zero. Third, to ensure high accuracy, the soil range is discretized into finite elements, with a finer mesh near the lining area. Fourth, the geometry of the canal was assumed to have a trapezoidal shape with a total depth of 3.8 m, 2 m for bed width, 13.4 m for top canal width, and a side slope of 1V:1.5H. Fifth, the lining thickness was assumed to be 50 mm for all cases.

The lining was considered a thin layer, 50 mm thick, with KL values obtained from testing as previously described in subsection 2.3. Different KL/K ratios represent different geopolymer contents.

However, several parameters were considered to assess their influence on seepage discharge. First, the KL/K ratio comprises five ratios, each corresponding to a specific fine-ash content (5%, 10%, 15%, 20%, and 30%) and one of three curing periods (7 days, 14 days, or 28 days), for a total of 15 ratios. This parameter exposes the influence of fine-ash geopolymer on seepage losses compared to the control soil. Second, the lining configuration includes three cases: full lining, bed-only, and side-slope-only. This parameter exposes a major source of seepage losses. Third, the influence of water level was examined at four levels: 1.5 m, 2.2 m, 3.0 m, and 3.8 m. This parameter exposes the influence of water head (hydraulic pressure) on seepage discharge. Anyway, the reference case includes two selected constants.

First, the KL/K ratio is related to 30% fine ash under 28 days of curing. Second, the water depth is 3 m. These were assumed to be constant when other parameters changed to control the influence. SEEP/W considers these parameters using a fine mesh to ensure a sensitive analysis and accurate results. It simulates seepage in a real earthen canal and provides discharge for each related case. In all cases, the discharge values are given for one unit length of the canal (per 1 m of length). Figure 1 illustrates the simulation of the unlined canal case as an example.

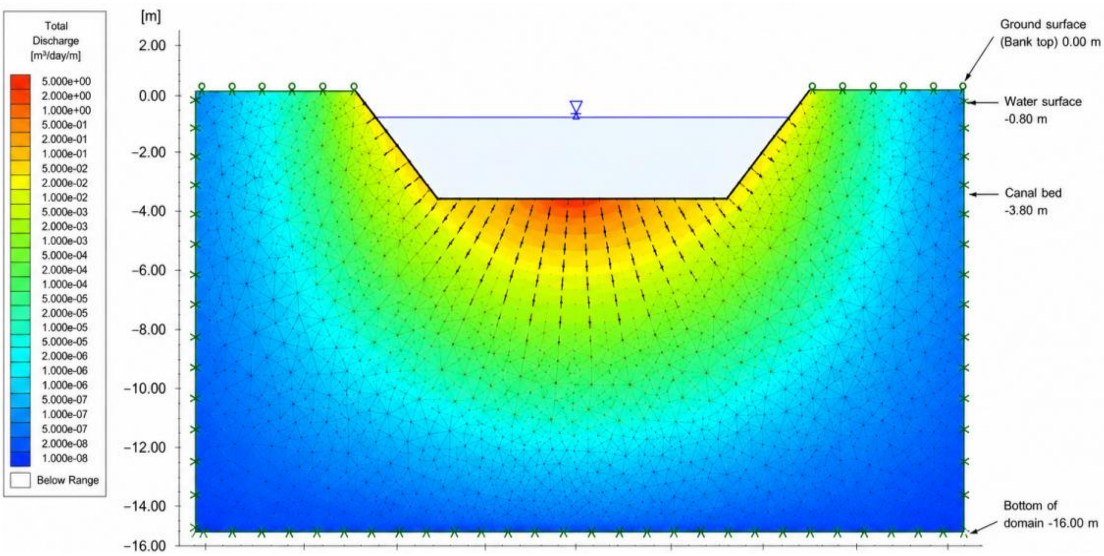

Figure 1. Simulation of unlined canal case (example)

3.5. Crack modeling

This step was adopted to model the cracking of the lining layer. SEEP/W was also used to simulate cracking cases, using the previously mentioned reference case in subsection 2.4. The reference case includes the constants mentioned in subsection 2.4. However, three parameters were considered to study the influence of cracking in the lining layer on seepage discharge.

First, crack width, including four different widths: 0.5 mm, 1.0 mm, 2.0 mm, and 5.0 mm. Second, crack depth, including three different depths: 15 mm, 30 mm, and 50 mm. Third, crack location, including three different locations: side slope, bed-side junction, and canal bed center. Figure 2 illustrates the simulation of a fully lined canal with a 5% cracked area of 2 mm in width and 50 mm in depth located at the bed as an example.

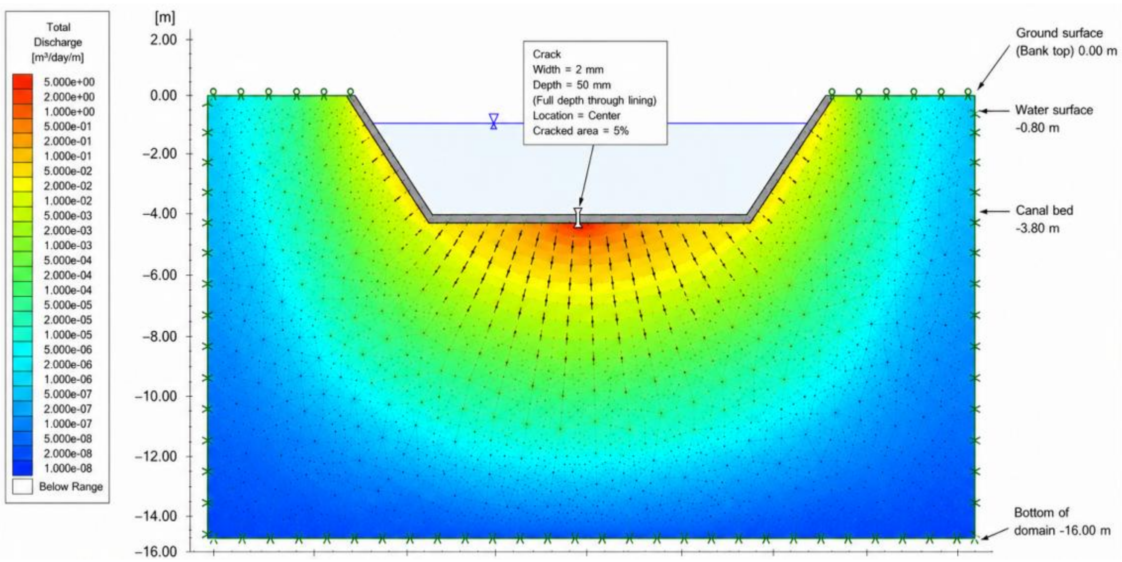

Figure 2. Simulation of a fully lined canal with a 5% cracked area of 2 mm in width and 50 mm in depth located at the bed (example)

4. Results and discussion

4.1. Influence of fine-ash content on hydraulic conductivity

Table 4 presents the K values for the control soil sample and for soil samples treated with different contents of fine ash under different curing periods. The results show that an increase in fine-ash content reduces K values. To understand the effect of different fine-ash contents on K values in treated soils relative to the control soil, the KL/K ratio can be useful, as shown in Table 5. This Table shows that the ratio decreases from 1 for untreated soils to 0.03 for soil treated with 30% fine ash and cured for 28 days. This decrease is significant, as it dramatically reduces seepage.

To visualize the trend, Figure 1 illustrates the relationship between fine-ash content and the percentage decrease in hydraulic conductivity across different curing periods. For example, when adding 30% fine ash with 28 days of curing (the best case), the increase in hydraulic conductivity was 97%, a substantial increase. Furthermore, as shown in Figure 3, the enhancement in samples treated with high contents of fine ash (20% and 30%) becomes similar across different curing periods. However, there are noticeable differences at low contents (5% and 10%). This can be attributed to the saturation of soil voids with fine ash at high ash contents, despite the ash's increased reactivity. Anyway, the trends show an increase in enhancement in all cases, as shown in Figure 1. The reduction in hydraulic conductivity can be attributed to several factors.

First, the fine particles of the fine ash fill the gaps in the soil, thereby cutting off the continuous pathways of water within the soil. Second, the geopolymer gel resulting from alkaline activation (which consists mainly of an aluminosilicate matrix) forms bonds between soil particles and prevents water migration. Third, geopolymer products work by converting large, interconnected voids into smaller, less interconnected voids, thereby reducing permeability. Fourth, due to its cementitious properties, the geopolymer acts as a binder, bonding the particles into an intact, homogeneous structure. This dense structure reduces the permeability. Fifth, the presence of geopolymers within the soil structure creates a winding path, which limits movement and reduces permeability. Sixth, geopolymer products work by sealing small cracks and blocking capillary channels, thereby reducing permeability. Consequently, an increase in fine-ash content enhances the aforementioned effects on soil structure. To explain the decrease in permeability with increasing curing period, it can be said that longer wetting durations increase the reactions. Therefore, the reaction products close more gaps and cracks and cut more pathways within the soil structure, thus reducing permeability.

Table 4. Hydraulic conductivity values for soil with fine-ash content and curing time

Fine Ash Content (%)	K values under different curing periods (m/s)		
	7 days	14 days	28 days
0% (control soil)	1.00×10^{-6}	1.00×10^{-6}	1.00×10^{-6}
5%	9.12×10^{-7}	8.34×10^{-7}	7.63×10^{-7}
10%	6.18×10^{-7}	5.06×10^{-7}	4.28×10^{-7}
15%	2.48×10^{-7}	1.93×10^{-7}	1.67×10^{-7}
20%	8.46×10^{-8}	6.72×10^{-8}	5.84×10^{-8}
30%	4.26×10^{-8}	3.51×10^{-8}	2.91×10^{-8}

Table 5. KL/K ratio for soils treated with different fine-ash contents after different curing periods

Fine Ash Content (%)	KL/K ratio after different curing periods		
	7 days	14 days	28 days
0% (control soil)	1.00	1.00	1.00
5%	0.91	0.83	0.76
10%	0.62	0.51	0.43
15%	0.25	0.19	0.17
20%	0.08	0.07	0.06
30%	0.04	0.04	0.03

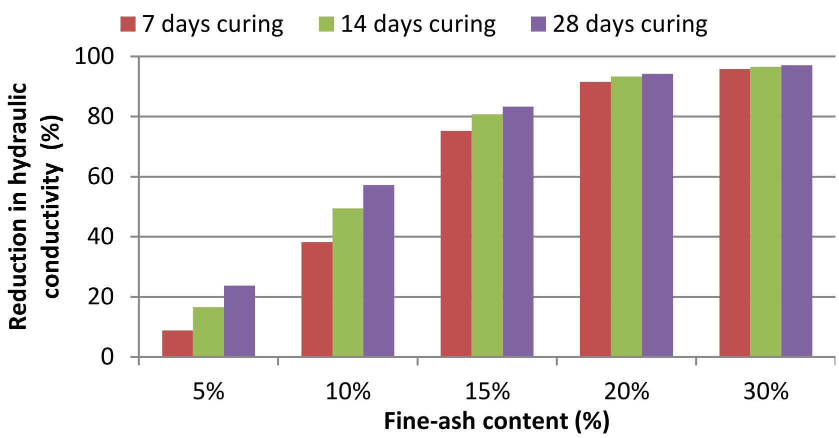

Figure 3. Reduction in hydraulic conductivity compared with control soil (%)

4.2. Seepage discharge results

This subsection presents the results of seepage discharge under various hydraulic conditions and lining configurations for the intact lining layer (no cracking).

4.2.1. Influence of KL/K ratios on seepage

Table 6 presents the effect of KL/K ratio on the seepage discharge values. The discharge values decrease with decreasing KL/K ratio, as a lower ratio indicates enhanced seepage reduction, as previously mentioned. Figure 4 illustrates the Reduction efficiency. The reduction efficiency was calculated by Equation 2. The trend in Figure 4 agrees with that shown in Figure 3. This agreement is expected, as a decrease in hydraulic conductivity reduces seepage.

$$\text{Reduction Efficiency} = 1 - \frac{Q}{Q0} \times 100 \quad (2)$$

Where: Q is the seepage discharge of the lined canal under any condition, and Q_0 is the seepage discharge of the unlined canal.

Table 6. Effect of KL/K ratios on seepage discharge

Fine Ash Content (%)	KL/K Ratio	Seepage discharge (m³/day/m)
0 (control soil)	1.00	1.200
5	0.76	0.915
10	0.43	0.560
15	0.17	0.280
20	0.06	0.165
30	0.03	0.125

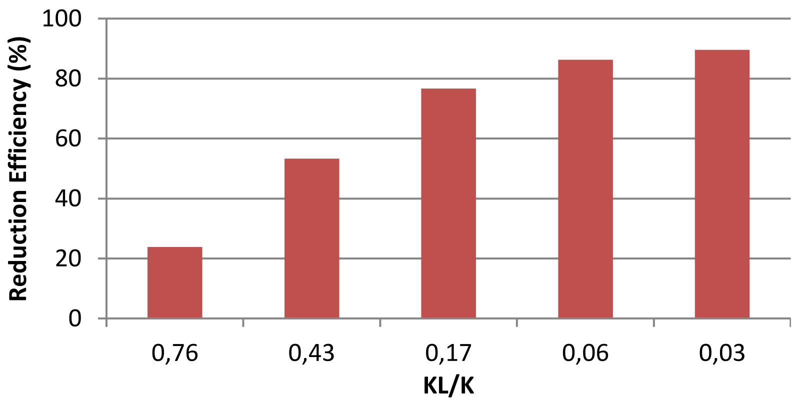

Figure 4. Seepage reduction efficiency vs KL/K values

4.2.2. Influence of lining configuration on seepage discharge

Table 7 presents the seepage discharge value for three different configurations: unlined canal, bed lining only, and full lining. It is clear that the greater the extent of lining, the less the seepage. The values were 1.20 m^3/day/m, 0.45 m^3/day/m, and 0.125 m^3/day/m for the unlined canal, bed lining only, and full lining, respectively. Full lining with soil treated with 30% fine ash, cured for 28 days, gives the best results, with seepage reduction up to 89.6%, which is an effective achievement. These results reflect the efficiency of Alkali-activated fine-ash geopolymer for adoption as a lining material due to its low hydraulic conductivity. Lining the bed only provides a 62.5% reduction in seepage.

This means that the bed is responsible for about (62.5/0.896 = 70%) of seepage. This indicates that the canal bed is the primary source of seepage, rather than the sides. This is due to the dominance of hydraulic pressure at the base of the canal compared to the lower pressure on its sides, thereby reducing the permeability of the base; lining it controls more seepage. These results are in line with those stated by El-Molla and El-Molla [30] and Salmasi and Abraham [29].

Table 7. Seepage discharge of various lining configurations

Lining Configuration	KL/K Ratio	Seepage Discharge (m^3/day/m)	Reduction vs. Unlined (%)
Unlined canal	1.00	1.20	0.0
Bed lining only	0.03	0.45	62.5
Full lining	0.03	0.125	89.6

4.2.3. Influence of water level on seepage

To understand the influence of water level on seepage, various water depths were considered: 1.5 m, 2.2 m, 3.0 m, and 3.8 m. Table 8 shows that the related seepage discharge values are 0.055 m^3/day/m, 0.087 m^3/day/m, 0.125 m^3/day/m, and 0.195 m^3/day/m. An increase in hydraulic head increases the seepage discharge. This can be attributed to the combined effects of increased hydraulic head, which increases the hydraulic gradient, and increased wetted perimeter, which enlarges the effective seepage area.

Table 8. Seepage discharge under different water levels

Hydraulic Head (m)	Seepage Discharge (m^3/day/m)
1.5	0.055
2.2	0.087
3.0	0.125
3.8	0.195

4.3. Influence of lining cracking on seepage discharge

This subsection investigates the influence of four parameters related to cracking in the lining layer on seepage losses, including crack width, depth, location, and extent (the cracked area as a percentage of the lining layer's total area).

4.3.1. Influence of crack width and extent

Table 9 presents a matrix connecting two parameters with seepage discharge: cracked area (extent of cracking) and crack width. It is clear that an increase in cracked area and an increase in crack width increase seepage discharge. Figure 3 simplifies the content of Table 9 and provides a good configuration. The worst case can be captured at a combination of a crack width of 5 mm and a crack area of 5%, with a seepage discharge value of 0.88 m^3/day/m. Compared to that of an unlined canal (1.20 m^3/day/m), it represents about 73%. This high percentage indicates that cracking significantly reduces the lining's efficiency. Water can easily penetrate through the cracks. Therefore, an increase in crack width and cracked area increases seepage discharge. Figure 5 illustrates the combined influence of cracking extent and crack width on seepage discharge.

Table 9. Influence of cracking extent and crack width on seepage discharge

Crack Width (mm)	Intact (0%)	0.5% Damage	1.0% Damage	3.0% Damage	5.0% Damage
0 (intact)	0.125	—	—	—	—
0.5	—	0.155	0.18	0.22	0.27
1.0	—	0.185	0.245	0.32	0.4
2.0	—	0.24	0.38	0.52	0.65
5.0	—	0.36	0.55	0.75	0.88

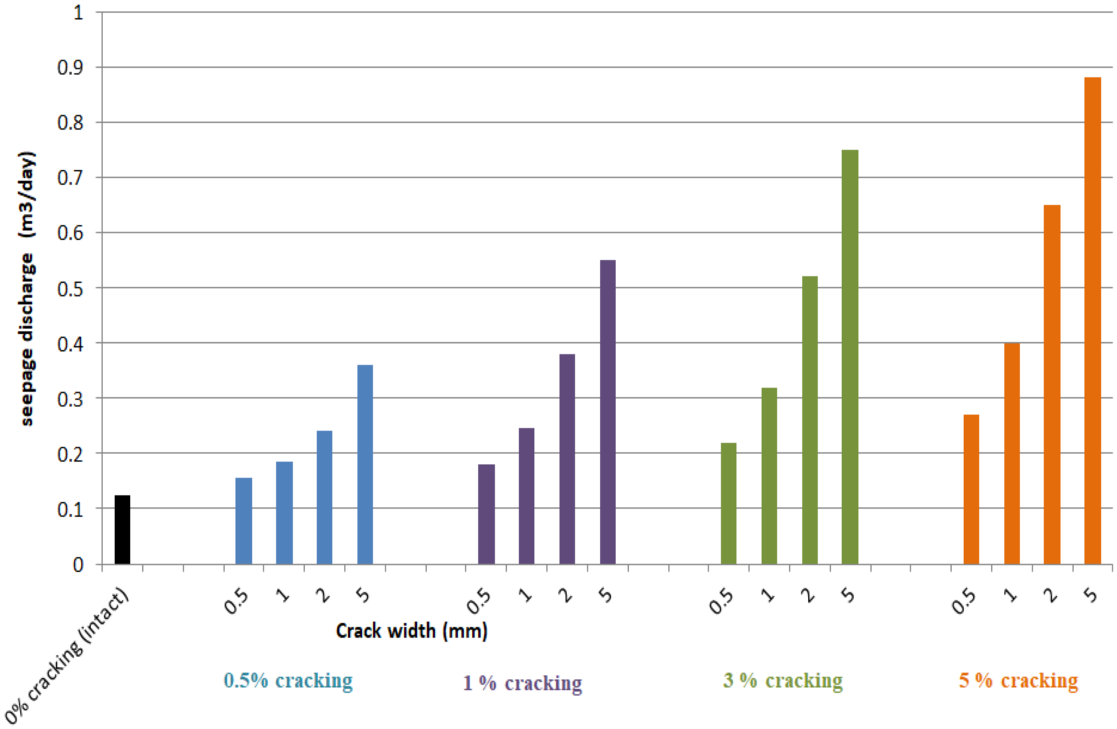

Figure 5. Combined influence of cracking extent and crack width on seepage discharge

4.3.2. Influence of crack depth

Similar to Table 9, Table 10 presents a matrix connecting two parameters that affect the seepage discharge: cracking extent and crack depth. The results show that the seepage discharge increases with increasing crack depth. In the case of a 5% cracked area with a full-depth crack, the seepage discharge increased to 0.65 m^3/day/m, compared with the reference discharge (no cracking) of 0.125 m^3/day/m. This means seepage increased by more than 5-fold, indicating a significant reduction in lining efficiency. An increase in crack depth facilitates the direct transport of water through the lining layer. Figure 6 simplifies the configuration of the results.

Table 10. Influence of cracking extent and crack depth on seepage discharge

Crack Depth	0.5% Damage	1.0% Damage	3.0% Damage	5.0% Damage
15 mm (30%)	0.170	0.250	0.350	0.450
30 mm (60%)	0.210	0.320	0.440	0.560
50 mm (100%)	0.240	0.380	0.520	0.650

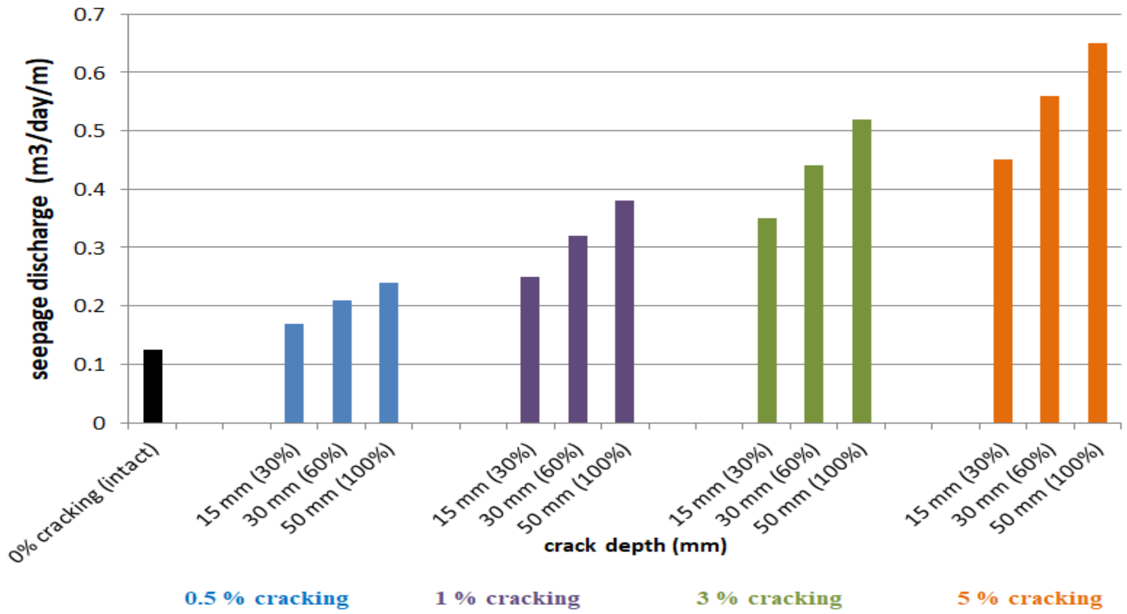

Figure 6. Combined influence of cracking extent and crack depth on seepage discharge

4.3.3. Influence of crack location

Table 11 presents the influence of crack location on the seepage discharge in the canal. The worst case (the highest seepage discharge occurs when the cracks are located at the bed center. This trend may be due to the high-water pressure on the bed, given that the water head is highest there, as previously described. In the case of the bed-side junction, the values of seepage discharge are close to those of the bed center case. This can be attributed to the similarity of the conditions, especially the water head. Figure 7 simplifies the configuration of the results.

Table 11. Influence of cracking extent and crack location on seepage discharge

Crack Location	0.5% Damage	1.0% Damage	3.0% Damage	5.0% Damage
Side slope	0.180	0.290	0.400	0.500
Bedside junction	0.230	0.370	0.510	0.630
Canal bed center	0.240	0.380	0.520	0.650

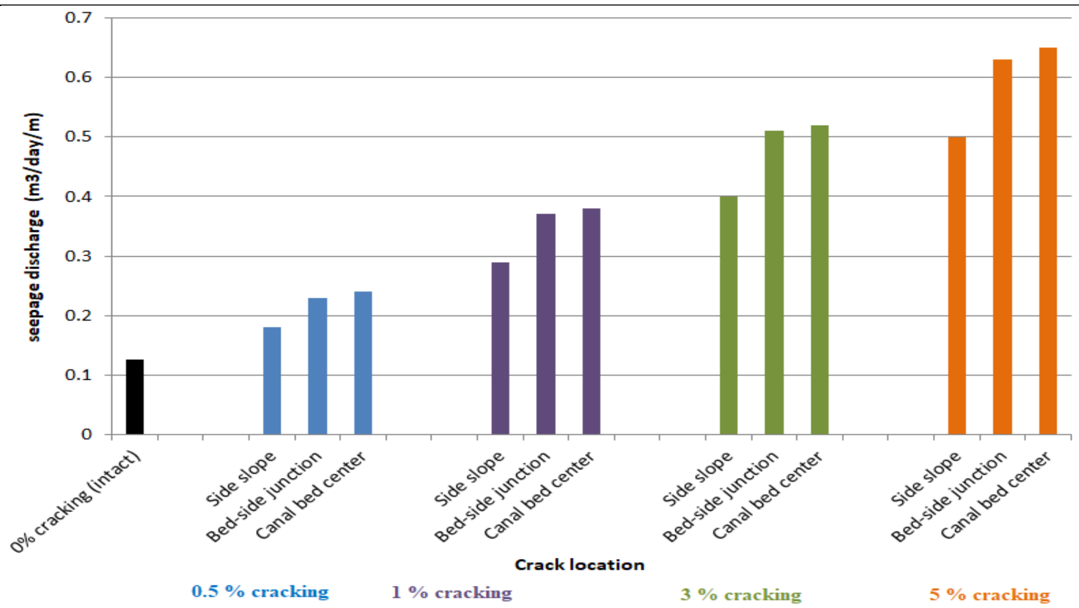

Figure 7. Combined influence of cracking extent and crack location on seepage discharge

5. Conclusions

The present study evaluated the efficiency of an alkali-activated geopolymer as a lining layer in earthen canals to control water seepage losses, considering both non-cracked and cracked conditions. Tests were conducted to explore the effects of varying fine-ash contents and curing periods on the hydraulic conductivity of the treated soil. Afterward, SEEP/W software was adopted to simulate the influences of hydraulic conductivity, lining configuration, water level, and crack geometry on water seepage discharge. Based on the research findings, the following conclusions were drawn:

1. Adding alkali-activated fine ash greatly decreases the hydraulic conductivity of the treated soil. The best results were obtained by adding 30% fine ash and curing with water for 28 days, as this mixture reduces the hydraulic conductivity from 1.0×10^{-6} m/s in untreated soil to 2.91×10^{-8} m/s. This led to a 97% reduction in seepage losses.
2. A decrease in hydraulic conductivity significantly enhances seepage performance. Under the best-case conditions, the value of seepage discharge reduced from 1.2 m^3/day/m in an unlined canal to 0.125 m^3/day/m in the case of a fully lined canal. This represents an 89.9% reduction in seepage.
3. Lining configuration greatly affects seepage losses. Full lining results in the highest reduction in seepage. However, lining the bed reduces seepage to 0.450 m^3/day/m, which is 62.5% less than an unlined canal. This means that the canal bed accounts for about 70% of the losses.
4. Water head noticeability influences the seepage discharge. An increase in water depth from 1.50m to 3.80m increases the seepage discharge from 0.055 m^3/day/m to 0.195 m^3/day/m, indicating that a greater hydraulic gradient results in greater losses.
5. Crack width and cracking extent significantly influence lining performance; their increase increases the seepage losses. The worst case can be captured at a 5mm crack width and a 5% crack area. This case results in a seepage discharge of 0.88 m^3/day/m, which represents about 73% of the losses from the unlined canal. This indicates a significant reduction in lining performance.
6. Crack depth has a significant effect on seepage losses. Considering a 5% cracked area, increasing crack depth from 15mm to 50mm increases seepage discharge from 0.45 m^3/day/m to 0.65 m^3/day/m, indicating that deeper cracks considerably reduce lining performance.
7. The location of the cracks affects the seepage losses. Cracks in the canal bed cause the greatest losses.
8. The outcomes of this study showed that alkali-activated fine-ash geopolymer can be considered an effective material if used in the lining of earthen canals, as it significantly reduces the seepage losses. Nevertheless, its performance depends greatly on the integrity of the lining, as cracking significantly reduces it.

Declaration of competing interests

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: A. Taher: study conception and design; A. Mosa, L. Abdulrahman: data collection and laboratory testing; A. Taher, A. Mosa: modeling; L. Abdulrahman, I, Jawad: analysis and interpretation of results; A. Taher: draft preparation. All authors approved the final version of the manuscript.

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