Effect of hydraulic gradient on internal stability of coal discard filters

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ABSTRACT: Internal stability is an important factor to consider in the design and performance of granular filters, as it prevents particle migration and erosion. This study investigates the effect of hydraulic gradient on the internal stability of coal discard and its potential use as a filter material. Coal discard is a byproduct of coal mining which can serve as a sustainable alternative to conventional filter materials. Recycling coal discard as a filter material may reduce mining waste stockpiles and lessen its environmental impact. To evaluate the internal stability of coal discard, a series of laboratory tests were conducted using a specialised upward seepage permeameter focusing on particle migration under varying hydraulic gradients. Seepage tests were conducted across hydraulic gradients ranging from 0.1 to 1.2. According to Kenney and Lau, an internally stable material should maintain a shape curve ratio greater than or equal to 1. From the results obtained, at hydraulic gradients less than 1.0, there were no particle migration and the shape curve ratio obtained was 1.94. Overall, this study presents coal discard as a viable filter material.

1 INTRODUCTION

Internal stability is the ability of a granular material to prevent the loss of its fine particles when acted upon by external forces such as seepage or vibration. Internal instability occurs when fine particles are lost from a matrix of coarse soil under seepage flow or vibration potentially altering the geotechnical properties of the soil (Zhou et al. 2017). Internal instability can occur as suffosion or suffusion. Suffosion is the migration and loss of fine particles from the soil matrix resulting in a reduction in the total volume of the soil. On the other hand, suffusion is the redistribution and selective removal of finer fractions from within the coarser fraction without any change in the total volume of the soil (Moffat et al. 2011). While suffusion maintains the total volume of the soil, it affects geotechnical properties such as permeability, hydraulic conductivity and strength, thereby diminishing the effectiveness of the soil as a filter material. As a result, internal stability is an important factor to consider in the design of granular filters for embankment dams. Internal instability in granular soils is influenced by the particle size distribution (PSD) and the prevailing hydromechanical conditions (Kenney & Lau 1985, Li & Fannin 2008, Ke & Takahashi 2012, Zhou et al. 2017).

South Africa's extensive mining activities have resulted in a large number of tailings storage facilities across the country. Over time, some of these structures may be susceptible to internal erosion caused by seepage. Internal erosion occurs when soil particles are removed from the main structure due to mechanical or chemical interactions with fluid flow (Ke & Takahashi 2012). Internal erosion progressively weakens the dam structure, posing a significant risk of failure. Seepage-induced internal erosion is a primary contributor to tailings dam failures globally (Flores-Berrones & Lopez-Acosta 2011). To mitigate internal erosion, filters are incorporated into dam design. Filters play a crucial role in managing seepage by allowing water to exit freely, while preventing the migration of fine particles from the dam body (Das 2008, Knappett 2012). However, the high cost of conventional filter materials poses a challenge to balancing safety, constructability and cost efficiency.

South Africa generates approximately 60 million tons of coal discard annually, adding to a cumulative stockpile of approximately 1.5 billion tons (Department of Energy 2001). Coal discard is a waste by-product of coal mining, composed of fine- and coarse-grained particles, rock fragments and silt-sized particles. Coal discard poses significant environmental hazard as it can contribute to acid mine drainage and undergo instantaneous combustion (Fred et al. 2012, Zhang et al. 2024), particularly in South Africa's arid climate, releasing greenhouse gases and contributing to environmental pollution.

Given its abundance, if coal discard meets filter material requirements, it could address two pressing issues simultaneously: reducing its environmental impact and offering a cost-effective alternative to conventional granular filters.

This study investigates the geotechnical properties of coal discard, focusing on its internal stability as a filter for co-disposal coal discard dams.

2 ASSESSMENT OF INTERNAL STABILITY

Internal stability can be assessed using three primary approaches: empirical, theoretical and experimental methods. These methods can be used individually or in combination. Three empirical criteria have been established in the evaluation of internal instability namely the Kezdi criterion (1979), the Sherard criterion (1979) and the Kenney and Lau criterion (1985, 1986). These approaches evaluate the potential for instability of granular soil by analysing the particle size distribution (PSD) curve.

2.1 *Empirical methods for evaluating internal instability.*

2.1.1 *The Kezdi Criterion*

Kezdi (1979) proposed an empirical ratio derived from the PSD curve which divides the material into coarse and fine fractions. The ratio is calculated using D_{15} (the particle size at 15% finer of the coarse fraction) and d_{85} (the particle size at 85% finer of the fine fraction). Internal stability is indicated if the ratio satisfies the following condition:

$$D_{15}/d_{85} \leq 4 \tag{1}$$

This criterion aligns with Terzaghi's filter rule. Skempton and Brogan (1994) further elaborate that for a loosely packed soil, this ratio is less than 4 while for a densely packed soil, the ratio is greater than 4.

2.1.2 *The Sherard Criterion*

Sherard (1979) approach is very similar to Kezdi's. Sherard introduced the stability index defined as:

$$I_r = D_{15}/d_{85} \leq 5 \tag{2}$$

This criterion was developed for broadly graded and gap-graded soils. The threshold value of 5 distinguishes stable materials from those susceptible to internal instability.

2.1.3 *The Kenney and Lau Criteria (1985, 1986)*

Kenney and Lau developed a method for evaluating internal instability based on the H:F ratio, where: F is the mass fraction smaller than a given particle size D, and H is the incremental mass fraction measured between particle sizes D and 4D. F is less than 20% for what is defined as widely graded primary fabric and less than 30% for a narrowly graded primary fabric.

Two conditions determine instability:

For loosely packed soils (Kenney & Lau 1985):

$$H/F < 1.3 \tag{3}$$

For well-compacted soils (Kenney & Lau 1986):

$$H/F < 1 \tag{4}$$

The Kenney and Lau method was developed for widely graded sand and gravel. This method has been found to better predict the instability of granular soils for widely graded soils compared to Kezdi and Sherard's methods (Moffat 2003, Fannin & Moffat 2006, Li & Fannin 2008, Zhou et al. 2017).

3 METHODOLOGY

3.1 *Experimental setup*

A permeameter setup was used to conduct laboratory tests to evaluate the internal stability of coal discard under upward seepage flow. The permeameter was made from a polycarbonate tube with an internal diameter of 194 mm and an external diameter of 200 mm which was fabricated in three sections, i.e. the top, middle and bottom sections. The top and bottom sections, each 300 mm in length, had a 40 mm diameter opening at the base to facilitate water inflow and outflow. The middle section measured 240 mm in length. The three parts were joined together using 10 mm diameter tie rods and a rubber gasket between each section to prevent leakage. Medium-coarse gravel (with particle size ranging from 1 mm to 13.2 mm) was placed in both the top and bottom sections of the permeameter. The gravel at the top served as a surcharge, stabilising the setup and the gravel at the bottom facilitated the uniform distribution of water into the discard.

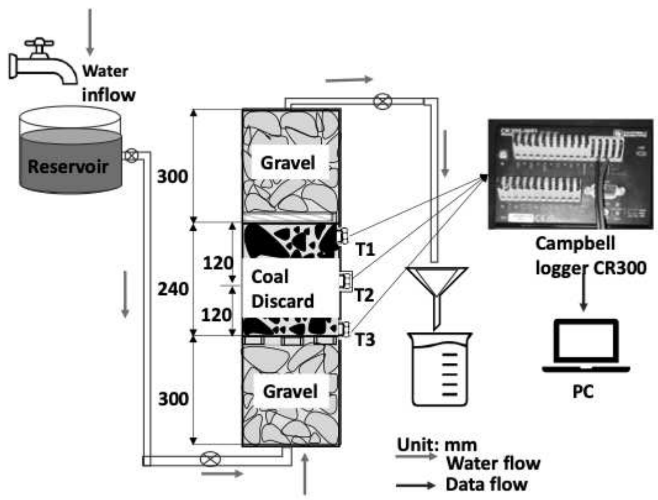

Figure 1. Experimental setup.

The coal discard was regraded to include particle sizes ranging from 75 µm to 19 mm. The discard was prepared at a void ratio of 0.5 and 0.8 and uniformly compacted into the middle section of the permeameter in five layers of 48 mm, resulting in a total height of 240 mm. Piezometers were installed at the top, middle and bottom of the coal discard to measure pore pressures. A non-woven needle-punched geotextile was placed between the bottom gravel filter and the coal discard to prevent washing of discard particles into the gravel and a wire mesh with 0.52 mm opening size was placed between the discard and the top gravel to allow for the passage of fines during seepage flow. Water was introduced from a constant head reservoir with an upward flow through the permeameter as shown in Figure 1 above. The outflow water was collected in a measuring cylinder where filter paper was used to collect any washed-out fines. During testing, the permeameter was lightly tapped at the sides using a rubber hammer to introduce vibration to aid the mobilisation of fines. This was done in an effort to ensure conservative results, i.e. without vibration internal erosion was less likely.

4 TEST RESULTS

Table 1 presents the geotechnical properties of the coal discard tested in the laboratory. The specific gravity of the coal discard is in line with those obtained by Fred et al. (2012). The seepage test was carried out at hydraulic gradients of 0.1 to 1.2. A total of 11 tests were conducted each 100-minute duration from the time the tap was opened. It was observed that particle wash-out only occurred in the first 20 minutes of each test.

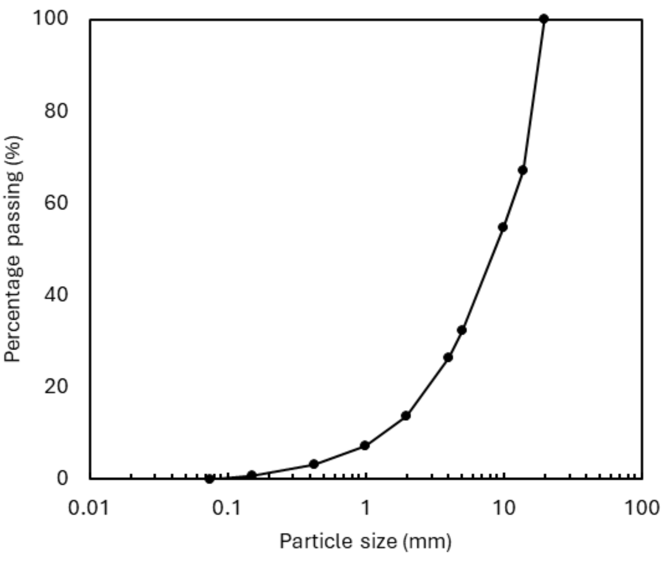

Figure 2. Grain size distribution curve of the coal discard.

Table 3. Geotechnical properties of Coal Discard

Properties	Values
Specific gravity	2.08
Permeability k (m/s)	1.44×10^{-3}
Initial moisture content (%)	5.73
Gravel-sized particles (%)	74
Sand-sized particles (%)	25.8
Silt-sized particles (%)	0.2
D_{10} (mm)	1.43
D_{30} (mm)	4.61
D_{60} (mm)	11.70
C_u	8.18
C_c	1.27
Max. void ratio	0.853
Min. void ratio	0.468
Friction angle (∘)	38
Cohesion (kPa)	0

The PSD curve in Figure 2 shows that the coal discard is a well-graded gravel with sand. The Kenney and Lau criteria can be used to empirically analyse widely graded upward concave grading curve.

Figure 3 illustrates the variation of total head and hydraulic gradient over time. For the first 50 min, the system was allowed to saturate and stabilize. Upon opening the tap, the total head increased and eventually reached equilibrium for the duration of the test, after which the tap was closed. The discard can be divided into three sections top, middle and bottom. Pore pressure was measured with piezometers labelled T1, T2 and T3, installed at the top, middle and bottom of the coal discard section respectively (see Figure 1). The hydraulic gradient across the coal discard sample was calculated from the measured total head using the equation:

$$i_{av} = \frac{\Delta h}{l} = \frac{h_3 - h_1}{l} \quad (5)$$

Where i is the hydraulic gradient, Δh is the head difference across the section (m), l is the length between the top and bottom piezometers (m).

The total head distribution over time (Fig. 3) highlights distinct behaviours at different depths within the sample. The top layer (T1) consistently shows lower head values, indicative of a freer drainage path. In contrast, the middle (T2) and bottom layers (T3) exhibit higher total heads, which stabilize after initial fluctuations indicative of flow resistance, likely influenced by finer particle accumulation and structural changes within the discard. These observations suggest that the coal discard's permeability decreases with depth, potentially due to compaction of the sample.

The average permeability of the coal discard was estimated using Equation 6:

$$k_{av} = \frac{Q}{A.i.t} \quad (6)$$

Where k is the permeability (m/s), Q is the volume of water flow from the discard (ml) over a period t, A is the cross-sectional area (m^2) and t is the time in sec.

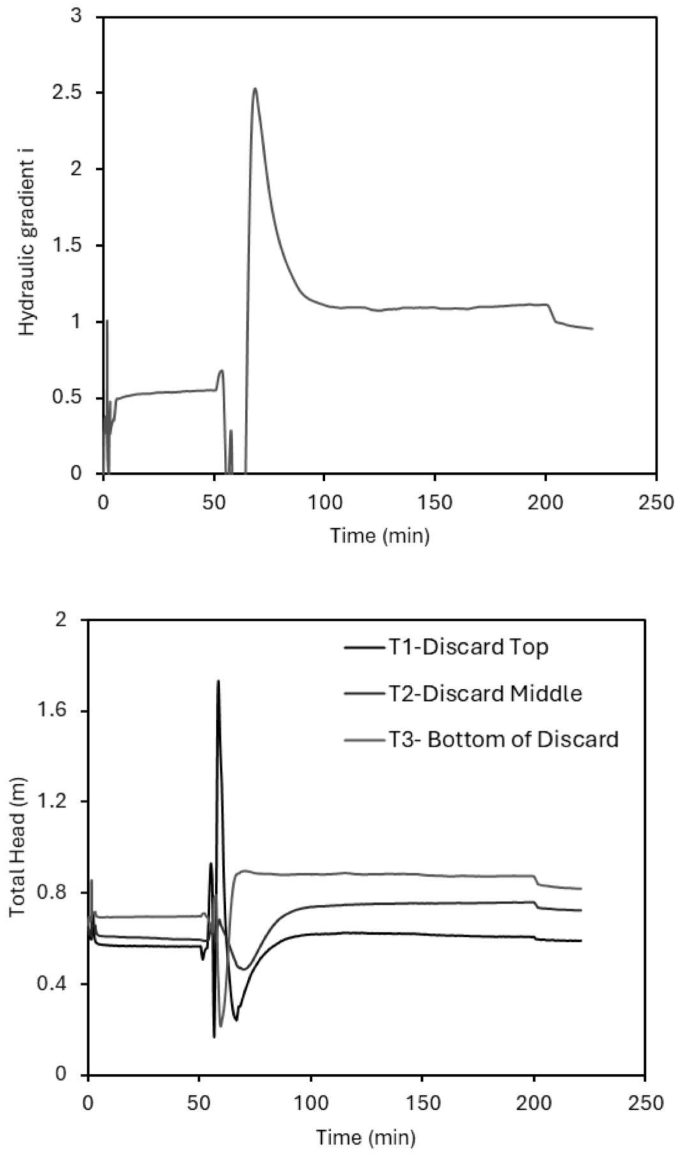

Figure 3. Total head and hydraulic gradient variation over time at i = 1.053.

4.1 *Test results for void ratio of 0.5*

At hydraulic gradient i_{av} of 0.11, the calculated permeability k_{av} was 2.74 x 10^{-3} m/s, with no particle loss observed. At $i_{av} = 0.326$ there was a reduction in the value of k_{av} to 1.06 x 10^{-3} m/s.

When the gradient was increased to 0.512 and 0.815, slight decreases in permeability ($k_{av} = 9.20$ x 10^{-4} m/s and 8.23 x 10^{-4} m/s respectively) were observed, but no particle loss occurred.

At $i_{av} = 1.053$, permeability further reduced to 7.06 x 10^{-4} m/s, and no particle loss was observed. Finally, at $i_{av} = 1.24$, very small particle loss (0.0375%) was recorded during the first 20 minutes and the permeability slightly increased to 8.72 x 10^{-4} m/s.

4.2 *Test results for void ratio of 0.8*

At hydraulic gradient i_{av} of 0.11, the calculated permeability k_{av} was 1.9 x 10^{-3} m/s, with no particle loss observed. At $i_{av} = 0.326$ there was a reduction in the value of k_{av} to 1.75 x 10^{-3} m/s and 0.0131% particle loss was recorded.

When the gradient was increased to 0.512, k_{av} slightly increased to 1.81 x 10^{-3} m/s and a loss of 0.0293 % was recorded. As the hydraulic gradient further increased to 0.815, k_{av} reduced to 1.62 x 10^{-3} m/s with particle loss of 0.0855%.

At $i_{av} = 1.053$, permeability further reduced to 1.44 x 10^{-3} m/s, and particle loss of 0.190% was recorded.

A summary of the test results for void ratios of 0.5 and 0.8 are presented in Table 2.

The reduction in permeability with an increased hydraulic gradient for both void ratios can be attributed to the structural changes occurring within the discard as water flows through it. The higher hydraulic gradients cause particle rearrangement within the sample, altering the pore structure and reducing the flow paths available for water. Additionally, the vibrations introduced by tapping the sides of the permeameter contribute to further densification of the sample, compacting the soil particles and decreasing its permeability.

Table 2. Summary of the test results for void ratios of 0.5 and 0.8

Hydraulic gradient i_{av}	e = 0.5		e = 0.8	
	Permeability k_{av} (m/s)	Particle Loss (%)	Permeability k_{av} (m/s)	Particle Loss (%)
0.11	2.74 x 10^{-3}	0.000	1.9 x 10^{-3}	0.000
0.326	1.06 x 10^{-3}	0.000	1.75 x 10^{-3}	0.0131
0.512	9.20 x 10^{-3}	0.000	1.81 x 10^{-3}	0.0293
0.815	8.23 x 10^{-4}	0.000	1.62 x 10^{-3}	0.0855
1.053	7.06 x 10^{-4}	0.000	1.44 x 10^{-3}	0.190
1.24	8.72 x 10^{-4}	0.0375	-	-

Figure 4 depicts the relationship between particle loss and hydraulic gradient. For a void ratio of 0.5, no particle migration was observed at lower hydraulic gradients. However, at an increased gradient of 1.24, the coal discard began to show the first signs of internal instability with a small loss of fines which occurred over the first 20 minutes of testing. For a void ratio of 0.8, at low hydraulic gradients of 0.11, there was no particle loss, but as the gradients gradually increased, particle losses were observed. The plot of cumulative particle loss with time (Figs 5, 6) indicates that there was a rapid initial particle loss that occurred within the first 15-20 minutes after which the curve flattens indicating stabilisation (void ratio of 0.5). For a void ratio of 0.8, the amount of particle loss increased with increasing hydraulic gradient, with a hydraulic gradient of 1.052 having the highest cumulative particle loss of 0.190%. At lower gradients of 0.326 and 0.512, particle loss is minimal and stabilises at approximately 0.005-0.015%, indicating internal stability even at a high void ratio. Most of the particle loss occurred within the first 15-20 minutes after which the curve stabilises.

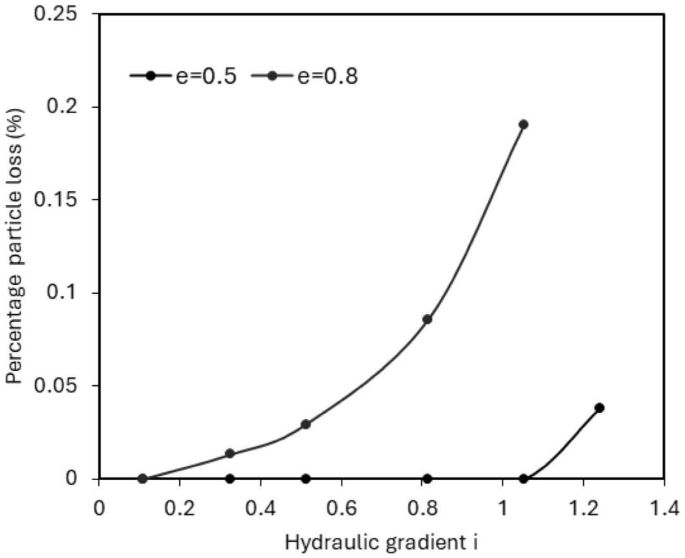

Figure 4. Plot of Hydraulic gradient and Percentage particle loss.

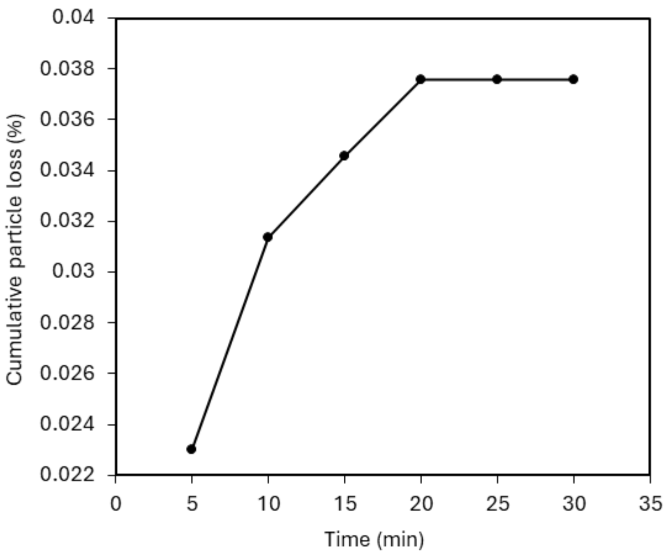

Figure 5. Cumulative particle loss with time for void ratio of 0.5.

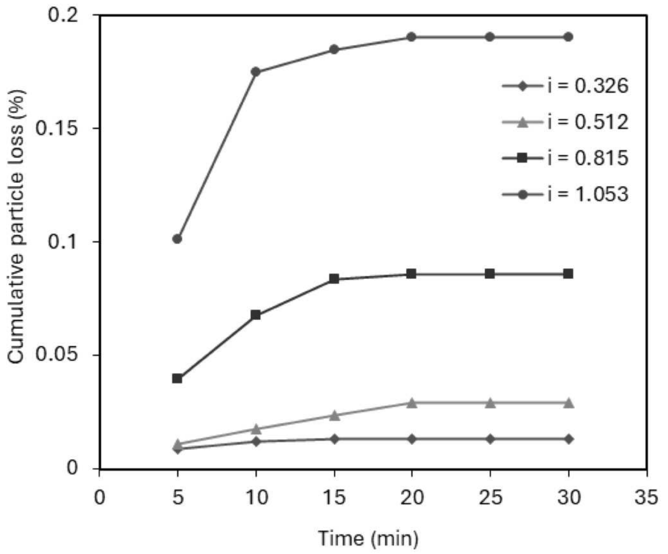

Figure 6. Cumulative particle loss with time for void ratio of 0.8.

The PSD curve was further analysed using the Kenney and Lau criteria, as shown in Figure 7. The criteria evaluated the coal discard as stable with a $(H/F)_{min}$ value of 1.94 within the widely graded boundary of 0.2 exceeds the threshold value of 1.0 (indicated in blue), indicating internal stability for a well-compacted soil. This result aligns with the negligible fine loss observed during testing and the minimal change in permeability.

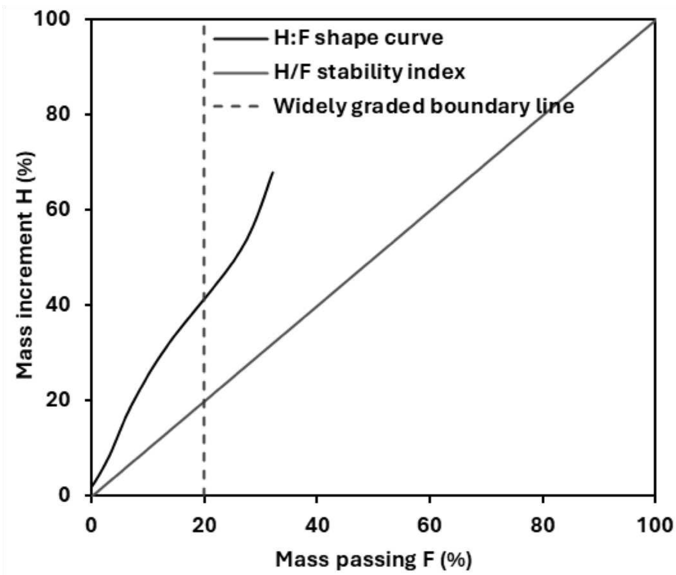

Figure 7. Kenney and Lau analysis.

5 CONCLUSION

The results indicate that the coal discard demonstrated internal stability across hydraulic gradients ranging from 0.11 to 1.053 for a void ratio of 0.5, even when subjected to disturbances from tapping with a hammer. However, at a hydraulic gradient of 1.24, only a negligible amount of particle loss occurred accompanied by a small change in permeability. At a higher void ratio of 0.8, the coal discard maintained internal stability for hydraulic gradients below 0.326. Particle migration was noted at gradients exceeding this threshold. Despite these migrations, the overall particle loss remained minimal, at a gradient of 1.052, the total particle loss was less than 0.5%. The empirical analysis using the Kenney and Lau method also agrees with the experimental result obtained. This obtained an H/F value higher than the threshold value for well-compacted and loosely packed soils.

Based on these findings, coal discard shows promise as a filter material for co-disposal coal discard facilities, subject to further evaluation under varying hydraulic conditions. However, it is crucial to note that the void ratio of the coal discard has a significant impact on internal stability. At a lower void ratio, there is more resistance to particle loss under high hydraulic gradients compared to a higher void ratio. Also, at higher hydraulic gradients, the material may approach a threshold beyond which internal stability could be compromised, leading to accelerated particle migration.

Finally, using coal discards in seepage control can mitigate the environmental challenge of their disposal, thus serving as a cheaper alternative to conventional filter materials.

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