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Experimental Investigation of Mine Tailings Migration Through Waste Rock in Co-disposal Structures

Florian Behlke, Polytechnique Montréal, Montreal, Quebec, Canada
Carlos Ovalle, Polytechnique Montréal, Montreal, Quebec, Canada
Li Li, Polytechnique Montréal, Montreal, Quebec, Canada

Abstract

Co-disposal of waste rock and tailings (WR&T) represents a promising alternative to conventional mine waste management, by depositing both materials in a single storage facility. This alternative reduces the required storage space and improves the properties of the waste materials, leading to safer and less environmentally hazardous facilities. The interaction between WR&T is crucial for efficient construction and operation, including the potential migration of tailings into the pores of waste rock. Since most past studies have focused on mixtures, co-disposal interactions between WR&T are seldom studied. This study presents a laboratory investigation of the migration of tailings into dry waste rock, once both materials are in direct contact. Multiple simple migration column tests were performed, varying the particle size distributions of the waste rock and the solids content of the slurry tailings. The adopted methodology was elaborated through consideration of existing empirical filter criteria. The results show that the grading of waste rock and the tailings' water content significantly influence tailings migration. The results will contribute to establishing criteria for evaluating the mixing of both types of mine waste in co-disposal facilities.

Introduction

The production of mine waste is continuously increasing due to the rising demand for minerals and the extraction of lower-grade ores (Reichl et al., 2014). Mine waste is categorized into waste rock and tailings (WR&T), and is traditionally deposited in separate facilities (Blight, 2010; Vick, 1990), both of which are associated with environmental and geotechnical risks (Aubertin et al., 2002; Bussière & Guittonny, 2020; Davies, 2002). Co-disposal presents a promising alternative to conventional practices by allowing the deposition of WR&T in a single facility. This approach requires a lower footprint and enhances the geotechnical properties of the waste materials, resulting in safer facilities (Behlke et al., 2025; Gowan et al., 2010; James, 2009; James & Aubertin, 2009; Leduc & Smith, 2003; Ouellet et al., 2021; Wickland et al., 2006; Wilson et al., 2000). The significant variances in the characteristics of WR&T, such as grain size distribution and water content, lead to interactions between the two types of materials. Mechanisms such as drainage and the migration of tailings into the waste rock are crucial for the effective design and operation of these facilities. Recent studies on co-disposal have primarily focused on mixtures of WR&T (Jehring & Bareither, 2016; Khalili et al., 2010; Wickland et al., 2006; Zhang et al., 2020). However, the interactions associated with drainage and particle migration are rarely explored (Essayad, 2021; Essayad et al., 2018; García-Torres et al., 2023). For instance, field and laboratory tests by Essayad (2021) on waste rock inclusions showed limited tailings migration into the inclusions and a moderate reduction in hydraulic conductivity. Garcia-Torres et al.'s (2023) laboratory tests also confirmed limited tailings retention and decreased permeability, while drainage conditions remained adequate in all cases.

Existing filter criteria in geotechnics are typically established to protect large hydraulic structures, such as dams. A properly designed soil filter in such structures consists of a granular medium with pore size openings that are sufficiently small to prevent the migration of the finer base soil. Moreover, the filter material should possess adequate permeability to ensure proper water flow (FEMA, 2011). The first proposed criterion for filter design to prevent migration was suggested by Terzaghi (1922), who established the criterion for the filter ratio $d_{15\_filter}/d_{85\_base} \leq 4$. Since then, various researchers have examined particle migration, proposing protective filter criteria primarily based on empirical data (Bertram, 1940; Foster & Fell, 2001; Locke & Indraratna, 2002; Sherard & Dunnigan, 1989). Other studies have focused on the internal stability of granular materials, which is the ability of granular materials to retain finer particles in pore spaces formed by coarser particles under hydraulic gradients, without causing particle migration, segregation, or piping (Chapuis, 1992; Kenney & Lau, 1985, 1986; Shire & O'Sullivan, 2013). It is a crucial characteristic of granular filters and essential to ensure filter quality and stable drainage structures. The current state-of-the-art on filter criteria continues to advocate for the use of d_{15_filter} and d_{85_base}; however, different filter ratios are recommended depending on the characteristics of the base material (Fell, 2005; ICOLD, 2001).

In the context of mine waste co-disposal, hydrogeological conditions and material characteristics show significant differences depending on the applied method and mine site characteristics. In general, the particle size distribution of the base (tailings) and filter (waste rock) materials can vary significantly based on site-specific geologies, extraction methods, and crushing processes. Thus, waste rock is often highly heterogeneous with considerable variations in particle sizes, ranging from clay-sized to boulder-sized particles. Additionally, grain shapes are typically angular and often elongated. Thus, commonly used criteria to prevent migration may not be representative.

This study presents a laboratory investigation on the migration of tailings into dry waste rock. The main objective is to enhance the understanding of tailings migration in co-disposal structures, promoting more sustainable waste management practices and their design. A series of migration column tests was conducted, varying the particle size distribution of the waste rock and the solids content of the slurry tailings. The methodology was developed by considering existing empirical filter criteria.

Methodology

Material Characterization

The particle size distributions (PSD) of the waste rock and tailings used in this study are presented in Figure 1a. The tailings are non-reactive and mainly composed of silt and fine sand, with a small fraction of clay-sized particles. d10-tailings is 5.6 µm and d60-tailings is 37 µm, corresponding to a coefficient of uniformity (Cu = d60/d10) of 6.6. According to the Unified Soil Classification System (USCS) (ASTM International, 2017), the tailings are classified as low plasticity silts (ML). The initial solids content of the tailings in the presented migration tests ranges from 45% (slurry) to 62% (thickened).

The waste rock also originates from the same mine, and its gradation has been altered to comply with the sizes of the tested specimens. The different PSDs used in this investigation are presented in Figure 1a, with a minimum particle size of 250 µm. Additionally, the samples are distinguished by their $d_{15\text{-}wr}$ values with 0.85, 1.4, and 2 mm, respectively. The minimum particle size of the waste rock samples is chosen to ensure that it does not overlap with the maximum particle size of the tailings, allowing for clear differentiation after sieving mixtures of both materials. For each $d_{15\text{-}wr}$, multiple samples were prepared with varying C_u ranging from 10 to 25, mainly depending on the coarse fraction (d_{60}), since the fine fraction (d_{10}) did not change significantly.

As shown in Figure 1b and Table 1, the internal stability of the waste rock gradations was assessed using the method after Kenney and Lau (1985, 1986), based on the material's PSD presented in Fig.1a. The method checks if the ratio of particles between sizes d and 4d (H) to those finer than 4d (F) is at least 1. This is based on the assumption that the voids between large particles (approximately four times larger) control whether smaller particles can pass through; if they can, the material may be internally unstable.

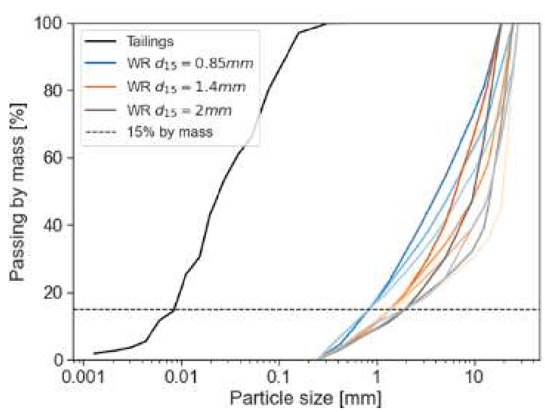

Figure 1: (a) PSD of tailings and waste rock (after Kenney & Lau, 1985, 1986)

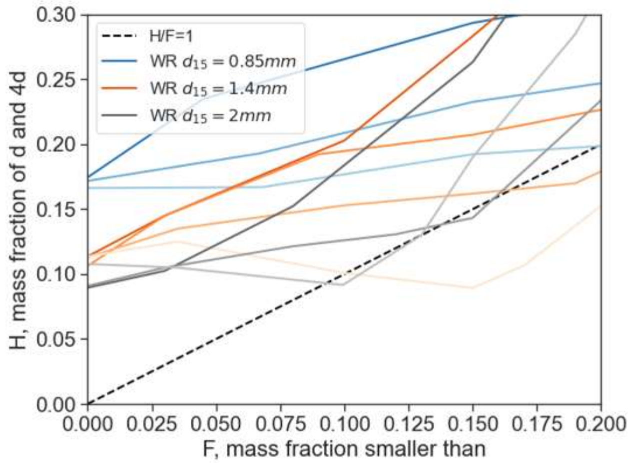

Figure 1: (b) Internal stability of each PSD (after Kenney & Lau, 1985, 1986)

Testing Procedure

The migration test consists of a rigid column filled with dry waste rock, where slurry tailings are deposited on top and allowed to migrate into the waste rock column. The column has a diameter of 300 mm and a height of 600 mm. The waste rock for each test is prepared separately according to the predetermined PSD. As presented in Figure 2, four equal portions by mass are prepared, with each portion forming a layer in the column specimen. The material is placed loosely into the column, and measurements are taken after each portion to identify the average thickness of each waste rock layer (4.5–5.5 cm). Then, the tailings are prepared to meet the required solids content. Migration is then initiated by pumping the tailings into the column. Tailings were kept in a mixture while being pumped into the column with an average pumping speed of 4 l/min. The deposited dry mass of tailings in each test is approximately 6.5 kg, which corresponds to about 10.6 litres of tailings with 45% solids content and 6.5 litres for 62%, respectively. Water and tailings that migrate through the entire specimen are collected at the outlet (bottom of the column). Once the water drainage stops, after a period varying from a few hours to a day, the sample is dismantled. The layers are sampled based on the specified heights.

First, the covering tailings that did not migrate into the waste rock are removed (see Figure 2b). Then, each layer is sampled and separated into two portions: one representing the inner core (center) and the other representing the outer rim (rim), as shown in Figures 2a and 2c. In the column of 300 mm in diameter, the inner core sample consists of the material within a diameter of 10–12 cm, while the rim consists of the leftover material between the inner core sample and the inner wall of the column. Every layer is sampled accordingly. The sampling method is proposed due to the container wall effect, which results from the large, rigid surface of the column. This effect depends on the diameter of the column (D_{column}) and could generate a heterogeneous void ratio within the waste rock specimen. Thus, this methodology is based on the hypothesis that particle migration in the center of the specimen is unaffected by the wall effect, making it more representative. After the migration tests, the samples are sieved to obtain the PSD for each layer and location, either the center or the rim. The obtained information on the particle distribution is used to describe the migration through retained tailings per layer and the alteration of the initial waste rock void ratio compared to the WR&T mixture after migration. In addition, the particles that migrated through the entire waste rock column specimen are collected at the bottom outlet.

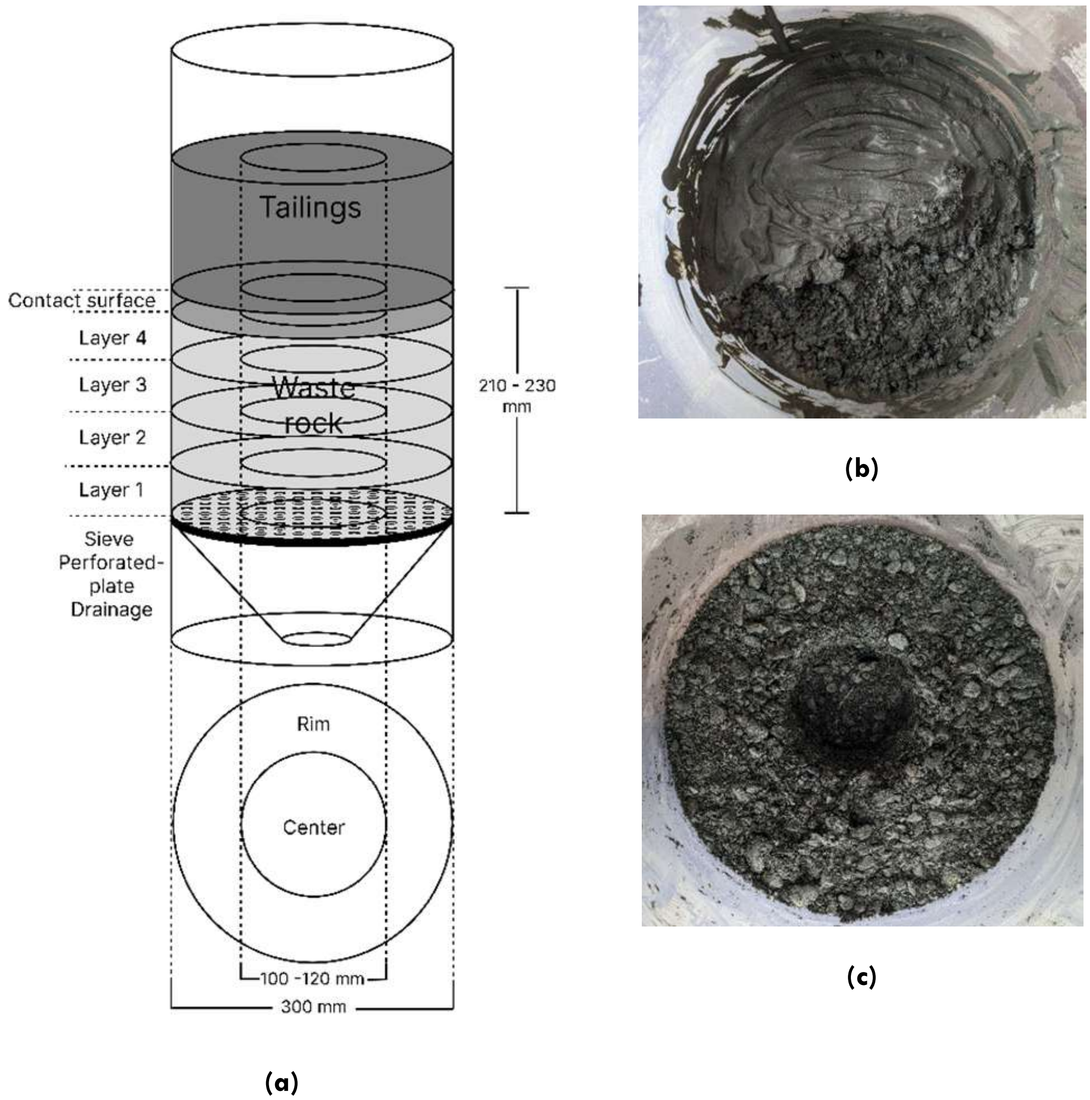

Figure 2: (a) Physical model of the column migration test; (b) removal of the contact surface; (c) sampling of a specimen center

Testing Program

The testing program consists of 12 tests. The tests are listed in Table 1, which includes the tailings solids content, the filter ratio (with a constant $d_{85\text{-tailings}} = 0.1$ mm), and key characteristics of the waste rock samples.

Table 1: Testing Program with Initial Material Characteristics

Solids content [%]	$d_{15\text{-wr}}/d_{85\text{-tailings}}$ [-]	C_u [-]	e [-]	Internally stable	Well graded
45	8.5	10	0.31	x	
		15	0.28	x	
		20	0.27	x	
	14	10	0.35	x	x
		15	0.29	x	x
		20	0.28		x
		25	0.31		
	20	10	0.34	x	x
		15	0.33		
62	14	25	0.30		
	20	15	0.33		
		20	0.29		

Results

Tailings Migration

Filter Ratio $d_{15\text{-wr}}/d_{85\text{-tailings}} = 8.5$

Figure 3 shows the results of using a filter ratio of 8.5 with waste rock samples containing C_u = 10, 15, and 20. The retained tailings by mass for each layer are presented in Figure 3a, indicating only a minor difference between core and rim samples; this suggests a slight wall effect. In the 3 tests with $d_{15\text{-wr}}/d_{85\text{-tailings}}$ = 8.5, less than 10% of the deposited tailings migrated into the sample, and less than 5 g of tailings were captured at the outlet. As shown in Figure 3b, the initial void ratio decreased in the tests with higher C_u (15 and 20). However, the difference in the void ratio between initial and post-migration remains nearly constant. The results reveal only a minor degree of migration with low tailings retention and a slight change in void ratio.

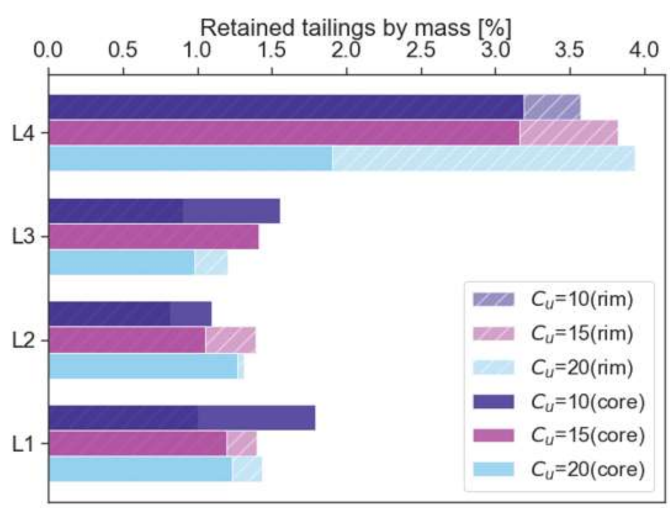

Figure 3 (a): Results for a filter ratio ($d_{15\text{-wr}}/d_{85\text{-tailings}}$) = 8.5 with an initial tailings solids content of 45%: retained tailings per layer

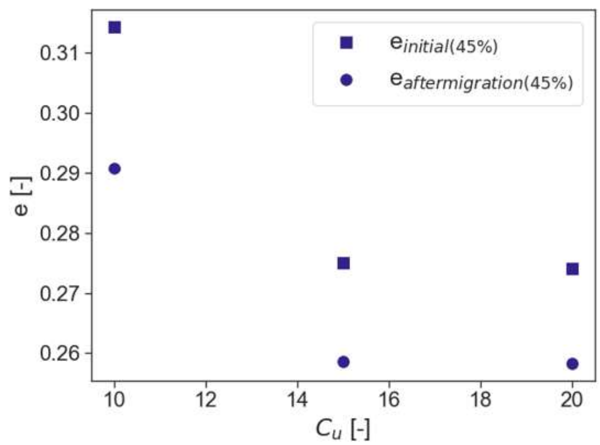

Figure 3 (b): Results for a filter ratio ($d_{15\text{-}wr}/d_{85\text{-}tailings}$) = 8.5 with an initial tailings solids content of 45%: initial and post-migration void ratio

Filter Ratio $d_{15\text{-}wr}/d_{85\text{-}tailings}$ = 14

Figure 4 shows the results of the migration tests using a filter ratio of 14, for tests with 45% and 62% tailings solids contents, respectively. With the tailings having an initial solids content of 45%, Figure 4a demonstrates a strong effect of C_u on the retained tailings per layer. The retained tailings with C_u of 20 and 25 are up to three times more than the retained tailings with C_u of 10 and 15 in the bottom layers L1 and L2. In all cases, the wall effect becomes more pronounced. With the waste rock having an initial C_u of 10 and 15, less than 20% of tailings migrated, with 20 and 4g collected at the outlet. For the coarser waste rock specimens with C_u = 20 and 25, 40 to 50% of tailings migrated, with 85 and 11g collected at the outlet.

Only one test was conducted with tailings at 62% solids content, replicating the test with the highest observed migration from the test series using 45% solids content. The results for the test with C_u = 25, presented in Figure 4b, show a significant reduction in retained particles per layer for the center samples. It is also important to note the substantial difference in retained tailings between core and rim, implying a strong impact of the wall effect. In this case, less than 35% of the deposited tailings migrated, and 288g of tailings were caught at the outlet, likely related to the preferential pathways due to the wall effect.

The trend illustrated for particle retention is also observable in Figure 4c, presenting the initial and post-migration void ratio of each test. The results show a reduction of the initial void ratio as the value of C_u increases from 10 to 20, followed by an increase for a further rise in the value of C_u to 25. The difference between initial and post-migration is nearly the same for C_u = 10 and 15, while there is a strong reduction for tests using C_u = 20 and 25. In the case of the test using 62% tailings solids content, the void ratio difference is greatly reduced compared to the test with 45%.

In the tests where the initial tailings solids content was 45%, only minor migration was observed for waste rock specimens with C_u = 10 and 15. In tests using coarser waste rock with C_u = 20 and 25, migration was higher. However, a large portion of tailings was still retained from migrating into the waste rock in both tests. When using a higher solids content of 62% with a $C_u = 25$, the migration was minor and greatly reduced compared to the test using a solids content of 45%.

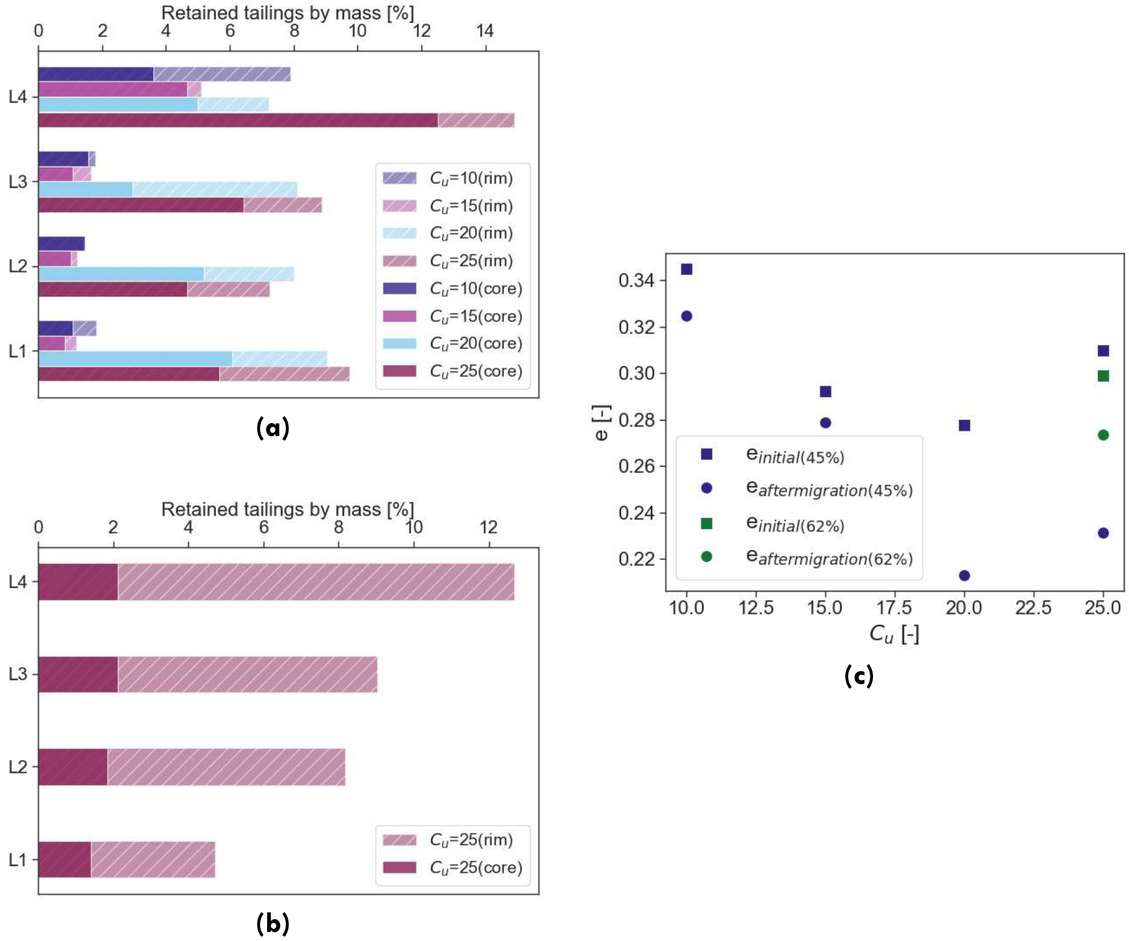

Figure 4: Results for a filter ratio = 14:(a) retained tailings per layer for qn initial solids content of 45%; (b) retained tailings per layer for an initial solids content of 62% (c), initial and post-migration void ratio

Filter Ratio $d_{15\text{-}wr}/d_{85\text{-}tailings} = 20$

The results using a tailings solids content of 45% and 62% are presented in Figure 5. With 45% solids content, the waste rock specimen with $C_u = 10$ shows a significant decrease in retained tailings with depth in Figure 4a, reaching a mass of 3.6% in layer 2. In layer 1, tailings have accumulated, increasing the retained tailings by mass to 7.5%. For $C_u = 15$, the decrease in retained tailings with depth is not noticeable from layers 3 to 1, with more than 5% retained in each layer. In the test with $C_u = 10$, over 50% migrated into the waste rock, and 370g of tailings were collected. In the test using $C_u = 15$, all the tailings migrated, and 50% (3229 g) of the deposited tailings were captured at the outlet.

The tests using a solids content of 62% show a notable wall effect and a trend of decreasing retained tailings particles with depth. However, the reduction in retained particles is more significant for the waste rock specimen with $C_u = 20$. In the test using $C_u = 15$, the mass of retained tailings ranges from 5% in the first three layers to 2% in the last layer. In the tests with an initial solids content of 62%, less than 30% migrated for both tests, with only a small amount of tailings (16g) collected at the outlet for the test using $C_u = 15$ and none for $C_u = 20$.

The initial and post-migration void ratios for each test are presented in Figure 5c, which demonstrates that the initial void ratio decreases as the C_u of the waste rock increases, particularly from $C_u = 15$ to 20. The difference in void ratios is significantly higher for the tests using tailings at 45%, whereas the test results using 62% reflect a noticeable reduction in the void ratio when comparing the results for $C_u = 15$. The smallest difference is observed in the test with $C_u = 20$.

The results of the migration tests, conducted with an initial tailings solids content of 45%, indicate high migration. In the case of $C_u = 20$, all tailings migrated in or through the waste rock specimen. The test results using a tailings content of 62% show low migration, specifically for the test with an initial $C_u = 20$.

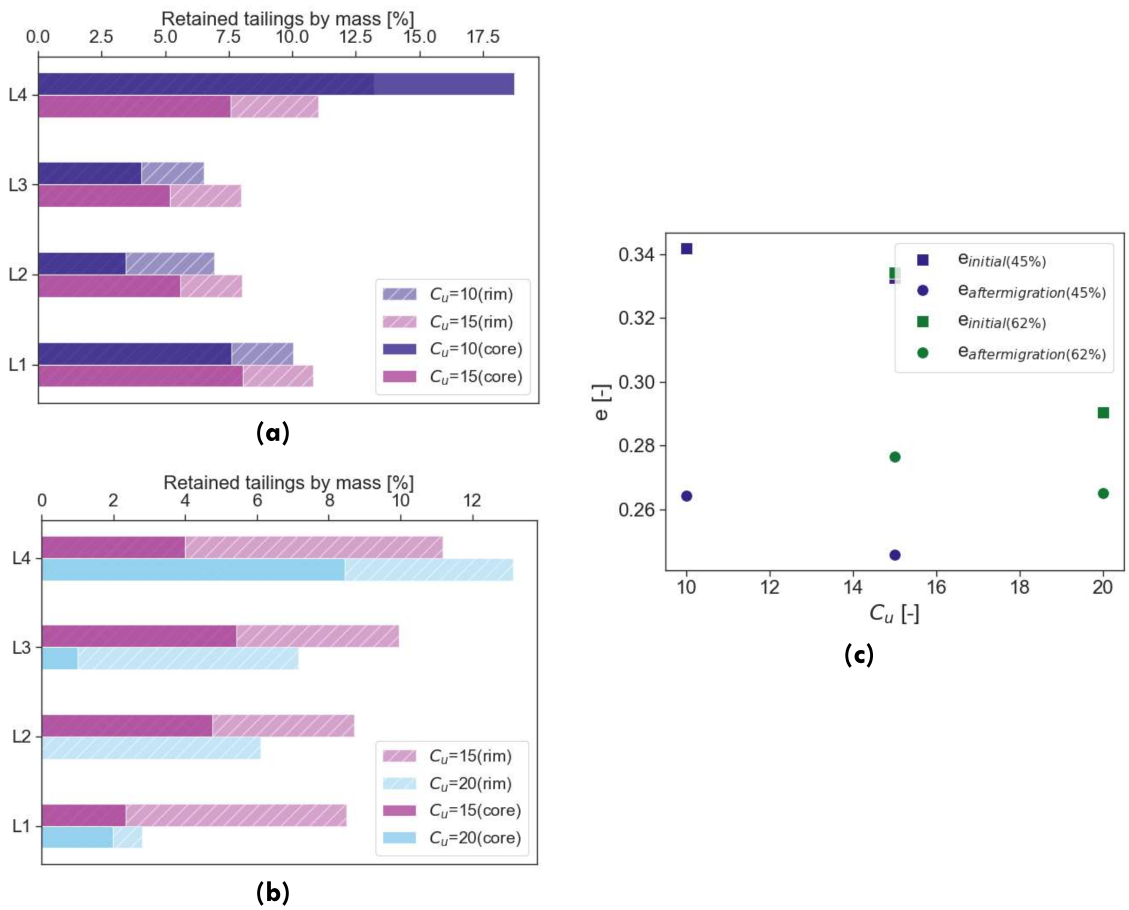

Figure 5: Results for a filter ratio = 20: (a) retained tailings per layer for an initial solids content of 45%; (b) retained tailings per layer for an initial solids content of 62%; (c) initial and post-migration void ratio

Discussion

The migration of tailings was characterized by the retention of tailings within the waste rock specimens, the change in void ratio due to retained tailings into the waste rock voids, and whether tailings would be retained on top of the waste rock or migrate through the whole column. In the case of surface clogging, particle retention should decrease with depth. However, the wall effect resulted in more substantial migration in coarser specimens. As a result, particles may have migrated along preferential pathways through the column, which contradicts observations of migration based on retained particles from the center samples. Another observed phenomenon is that, in some tests, the amount of retained tailings increases in the bottom layer for both center and rim samples. This effect arises from the accumulation of tailings that could not drain through the bottom mesh due to clogging or insufficient water to flush them through. Consequently, the last sample is less representative as the wall effect also influences the center sample.

The void ratio of the samples before and after migration serves as a good indicator for observing and comparing the potential of multiple tests to prevent migration. The initial void ratio, along with the particle size distribution, is a crucial characteristic that controls migration potential. In practice, granular filters are always sufficiently compacted; however, in the context of waste rock deposition on mining sites, this is not the case, since the void ratio primarily depends on the gradation, segregation, and packing of particles in a loose state.

The internal stability, a crucial characteristic of granular materials for retaining the finer fraction necessary for effective filtering potential, is assessed according to the method proposed by Kenney and Lau (1985, 1986). However, previous empirical tests validating this method were conducted using rounded to sub-rounded filter materials (Kenney & Lau, 1985; Skempton & Brogan, 1994), rather than angular and elongated coarser materials. This difference may affect internal stability through factors such as packing, void shapes, and particle interlocking; however, previous studies on migration in waste rock have shown that the method of Kenney and Lau yields accurate results (Essayad, 2021).

This study has several limitations. The materials used, specifically tailings and waste rock, are limited in variety, and the results may not apply to other materials with different granular properties. Additionally, the effects of higher hydraulic gradients and potential mechanical loading were not examined, and these factors could significantly influence particle migration behavior.

Conclusion

Several migration tests were conducted to investigate the migration of tailings into waste rock column specimens when deposited in direct contact. The effects of filter ratio, coarse fraction, and solid content were examined. The retained tailings particles per layer and the alteration of the waste rocks' void ratio before and after migration were used to describe the degree of migration in each test. As a result of the migration or prevention, some tailings would migrate through the sample or be kept from entering the waste rock.

The results demonstrate that, for tailings deposited with an initial solids content of 45%, a filter ratio of 8.5 resulted in minimal tailings migration, with less than 2% of tailings retained in each test. Similar outcomes were observed for a filter ratio of 14 in samples exhibiting internal stability with a C_u of 10 and 15. A marked increase in both tailings migration and retention was evident in samples possessing a larger coarse fraction and thus higher C_u (20 and 25), where up to 6% of tailings were retained. At a filter ratio of 20, a comparable trend in tailings retention was noted; however, in the case of a C_u of 20, a significant proportion of tailings migrated throughout the entire sample and was collected at the outlet. Tests conducted with a higher solids content of 62% indicated reduced migration and tailings retention across all tests, with less than 2% of tailings retained in the final layer.

The results underline the importance of the d_{15} and the internal stability to characterize the migration potential. Internal instability makes the material more prone to preferential pathways and may affect the migration potential. A higher coefficient of uniformity in the material can also have an effect by improving packing and reducing void ratio, thus reducing migration.

In the future, additional tests will be conducted to enhance certainty regarding the boundaries of material characteristics, such as gradation and filter ratio, to develop simple criteria for preventing or estimating the migration of tailings with varying solids content. The results of this study will contribute to the design of co-disposal facilities, promoting innovative alternatives to conventional waste disposal methods.

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