GeoStable Tailings Laboratory Mixture Trial

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Abstract

GeoStable Tailings are homogeneous mixtures of tailings and waste rock that are being investigated as an alternative mine waste management solution capable of improving storage efficiency and long-term environmental and closure goals. A laboratory mixing study was conducted to evaluate the influence of tailings type, solids content, mixture ratio, and placement energy on the engineering behavior of GeoStable Tailings. Whole tailings and cycloned underflow tailings were mixed with waste rock at a waste rock mass-to-tailings mass ratio ranging from 0.25 to 2.0. Specimens were prepared at multiple solids contents and placed using loose placement, a drop chute, and Standard Proctor compaction to represent a range of field placement energies. Testing included density, air permeability, penetration resistance, and slump evaluations. Results indicate that both whole tailings and underflow tailings can produce viable GeoStable Tailings mixtures, although performance is strongly dependent on solids content, mixture ratio, and placement method. Dry density generally increased with increasing mixture ratio and placement energy, while penetration resistance and trafficability improved with compaction. Whole tailings exhibited greater sensitivity to water content, with lower solids contents resulting in excessive slump and reduced stability. Underflow tailings displayed more consistent behavior across the range of solids contents evaluated, exhibiting limited slump and a broader range of acceptable mixture ratios. Air permeability was generally low for compacted mixtures but increased in mixtures containing higher solids contents and larger proportions of waste rock due to the development of connected macropores. Results further indicate that the engineering behavior of GeoStable Tailings is governed by the interaction between tailings characteristics, solids content, mixture ratio, and placement energy. The results provide insight into the range of mixture conditions suitable for field-scale evaluation and support the continued development of laboratory-based screening methods for GeoStable Tailings applications.

Introduction

The GeoStable Tailings Consortium (GSTC) is dedicated to advancing the understanding, development,

and implementation of "GeoStable Tailings" to address critical challenges associated with tailings and waste rock (GISTM; Global Industry Standard on Tailings Management, n.d.). The current practice of selecting mixture ratios of GeoStable Tailings for consideration in field trials and full-scale projects is to create mixtures in the laboratory and assess how mixture dry density varies as a function of tailings solids content and mixture ratio.

Commingled tailings and waste rock are homogeneous blends of the two materials that range from tailings-dominated to waste rock-dominated mixtures. For a given tailings solids content and waste rock, an optimum mixture ratio exists at which tailings fill all void space between the waste rock while not compromising waste rock-to-waste rock particle contacts (Wickland et al., 2006). Commingled tailings and waste rock provide a viable alternative for tailings management by incorporating existing materials to maximize storage capacity, reduce acid rock drainage, allow progressive closure, and minimize liquefaction potential (Habte & Bocking, 2017).

A mixing study was performed to inform the selection of an appropriate tailings source, target tailings water content, and mixture ratio of GeoStable Tailings for future field studies. GeoStable Tailings were prepared at different compositions and placed with different levels of compaction energy, and tested for air permeability, penetration resistance, and slump.

Materials and Methods

Colorado State University (CSU) received samples of whole tailings, underflow tailings, and waste rock. The as-received initial water content of the tailings, $w_{tail,i}$, was measured for each sample. All buckets of the same single material (e.g., whole tailings) were combined on tarps, air-dried, and mixed thoroughly.

Waste rock used in all laboratory test work contained a maximum particle size of 25 mm and less than 5% passing the No. 4 sieve (4.75 mm). The small particle size constraint was based on particle size distributions of waste rock, whereas the large particle size constraint was for scaling to all laboratory experiments. These modifications control the amount of finer materials (i.e., sand and fines) in the waste rock such that the finer matrix material in the commingled mixtures is predominantly tailings.

Index Testing

A summary of the geotechnical characteristics for the tested materials is provided in Table 1. Index testing was performed on each material in triplicate, and average values are tabulated. Testing included Atterberg Limits (ASTM D4318-17, 2018), particle size distribution (ASTM D422-63, 2007), specific gravity (Gs) (ASTM D854-23, 2023), and standard compaction (ASTM D698-12, 2021) to define the optimum water content (w_{opt}) and maximum dry density ($\rho_{d\text{-}max}$).

Table 1: Geotechnical Characteristics for Waste Rock (WR), Whole Tailings, and Underflow Tailings

Material	LL (%)	PI (%)	Gravel Content (%)	Sand Content (%)	Fines Content (%)	Clay-Sized Content (%)	G_s	w_{opt} (%)	$\rho_{d\text{-}max}$ (Mg/m^3)
Waste Rock	NM	NM	97	2.8	0.5	NM	NM	NM	NM
Whole	21	NA	0	41.2	49.2	9.6	2.68	14.5	1.82
Underflow	26	NA	0	76.1	21.4	2.4	2.77	17.8	1.62

Note: LL, liquid limit; PI, plasticity index; clay-size content taken as percent particles by mass < 0.002 mm; G_s, specific gravity; w_{opt}, and $\rho_{d\text{-}max}$, maximum dry density and optimum water content, respectively, determined from Standard compaction tests; NA, not applicable; NM, not measured.

Liquid limit was 21 for whole tailings and 26 for underflow tailings; plastic limit could not be determined for either tailings. The specific gravity (G_s) of whole tailings was 2.68, whereas G_s for underflow tailings was 2.77. A G_s of 2.7 was assumed for the waste rock based on previous work.

Mechanical sieving of the waste rock yielded more than 95% gravel fraction, which was anticipated based on modification of waste rock collected from the mine stockpile. Received waste rock was passed through a 25-mm screen, and the passing No. 4 fraction (< 4.75 mm) was limited to < 5% via laboratory processing to coincide with the sand and fines fraction in the stockpile. Whole tailings included 41% sand and 49% fines. Underflow tailings are produced by cycloning the whole tailings, and as anticipated, the underflow tailings contained a higher sand fraction (76%) and lower fines content (21%).

Standard compaction testing (ASTM D698-12, 2021) for whole tailings and underflow tailings yielded w_{opt} = 14.5% and $\rho_{d\text{-}max}$ = 1.82 Mg/m^3 for whole tailings, and w_{opt} = 17.8% and $\rho_{d\text{-}max}$ = 1.62 Mg/m^3 for underflow tailings. Waste rock was omitted from compaction testing.

Zero effective stress settling tests were conducted by thoroughly mixing whole tailings and underflow tailings with water in 1-L beakers to create slurries and allowing them to completely settle without bottom drainage. The supernatant water was removed after settling, and the remaining material was used to determine the solids content at zero effective stress. These settling tests yielded lower bound solids contents of 68.6% for whole tailings and 78.3% for underflow tailings.

Solids contents targeted for testing were set at intervals of approximately 5%, whereby solids contents of 68.6%, 75%, 80%, and 85% were targeted for whole tailings and 78.3%, 80%, and 85% were targeted for underflow tailings. A solids content of 85% was set using the optimum moisture content for both whole and underflow tailings, as defined by standard effort compaction (ASTM D698-12, 2021).

Mixture Trials: Specimen Preparation

An overview of the experimental procedures implemented in this study is depicted in Figure 1. GeoStable

Tailings mixtures were prepared by varying tailings composition (i.e., whole tailings or underflow tailings), tailings solids content, and mixture ratio, and with different placement techniques. Each specimen was evaluated for density, air permeability, penetration resistance, slump, and water content.

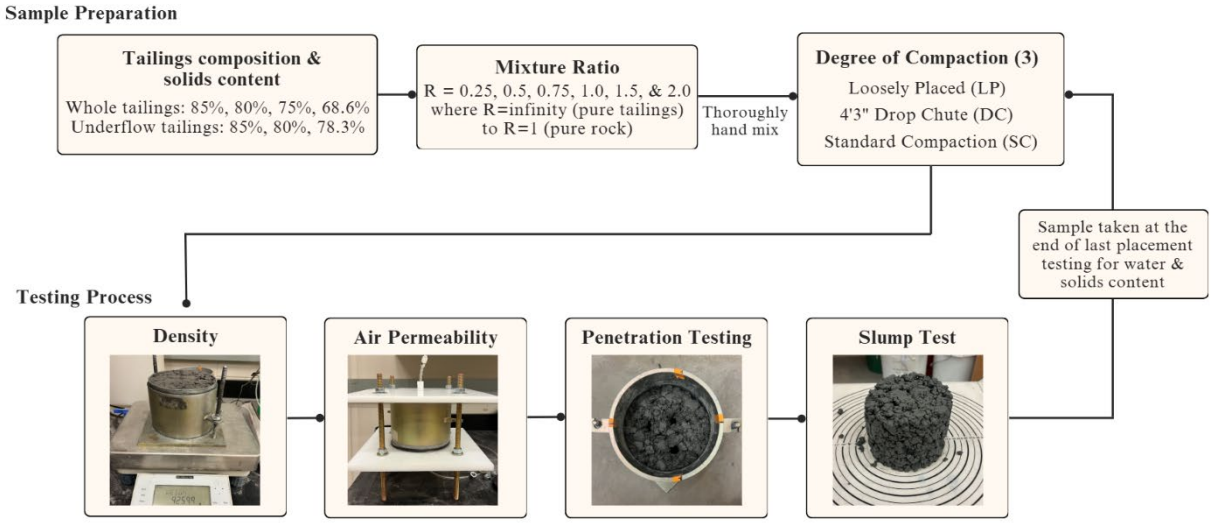

Figure 1: Flowchart of sample preparation and testing procedures conducted

An initial water content of the tailings, $w_{tail,i}$, mixture ratio, R, and target solids content, C_{target}, were selected for each test specimen. The mixture ratios tested in this study are represented as R, which is a ratio of dry waste rock mass to dry tailings mass. Mixture ratios tested included R = 0.25, 0.5, 0.75, 1.0, 1.5, and 2.0 for both whole tailings and underflow tailings at each solids content.

Test specimens were made with three placement techniques: loosely placed (LP), drop chute (DC), and standard compaction (SC). The three methods gave a range of compaction energies. After placing GeoStable Tailings in the compaction mold following either LP, DC, or SC, testing was conducted in the following order: (i) density, (ii) air permeability, (iii) penetration, (iv) slump, and (v) water content.

Placement Techniques

For a given placement technique, GeoStable Tailings were placed in a 152-mm-diameter compaction mold with the collar attached until sufficient material extended above the collar. The collar was then removed, and excess material was scraped off the top to create a flat surface for subsequent testing.

Loose placement was accomplished using a scoop to gently place GeoStable Tailings into the mold. No additional force was applied to the specimen. The drop chute consisted of a 1.3-m-long by 152-mm-diameter PVC pipe through which material was dropped and directed towards the compaction mold. The drop height represented the dump clearance of a CAT 793F mine haul truck (CAT793F Mining Truck Specification, n.d.). The mold with the collar attached was placed below the drop chute and filled until material rested approximately halfway up the collar. No additional compaction was applied to the materials.

This placement technique was developed to create a reproducible method that received higher energy than loose placement, but still less than standard compaction. Standard Proctor effort compaction was used as the upper-bound placement energy and adopted as a method that is reproducible. Placement followed ASTM D698 in a 152-mm diameter mold.

Density

Total density of each GeoStable Tailing specimen placed in a 152-mm diameter compaction mold was determined via mass-volume calculations. Water content was measured at the completion of permeability, penetration resistance, and slump testing, and was used to compute the actual solids content, C_{actual}, bulk gravimetric water content of the sample, w_{GS}, and gravimetric water content of the tailings, w_{tail}. A key assumption in the calculations was that the mixture ratio of tailings and waste rock remained constant after taking the grab sample for water content.

Air Permeability

Air permeability testing was conducted within the compaction mold sandwiched between two plastic plates equipped with O-rings to create air-tight seals between the plates and the mold. An influent port was positioned on the bottom plate and an effluent port positioned on the top plate. Non-woven geotextiles were placed between the plate surface and the test specimen to distribute air across the specimen surface. Once sealed, an air pressure of 10 kPa was applied to the influent side, and a gas bag was attached to the effluent port. Pressure was held constant for 15 s to 5 min to yield a measurable effluent volume, which was then determined by water displacement of the gas bag.

Penetration Testing

A handheld, manual cone penetrometer was used to measure penetration resistance in the GeoStable Tailings specimens. The handheld penetrometer had a cross-sectional area of 6.45 cm^2 (1 in^2) that allowed for multiple penetrations in each specimen. The penetrometer was pushed into a given specimen at three locations on the surface of the specimen. At each surface location, the penetrometer was pushed vertically into the specimen, and a resistance measurement was recorded at 25-mm increments to a maximum depth of 75 mm. The Army Corps of Engineers recommends that the critical cone index be taken within the first 305 mm of soil below the ground surface and that for sandy soils the representative value can be taken within the first 152 mm of penetration from the ground surface (Knight & Army Engineer Waterways Experiment Station, 1961). Due to the specimen size constraints in this study, penetration was only possible to a depth of 75 mm.

Slump Testing

Slump testing can provide a visual comparison of how solids content, mixture ratio, and placement method influence material behavior. In traditional concrete applications, the ASTM C143/C143M-20 standard outlines the procedure for determining the slump of hydraulic-cement concrete, serving as an indicator of workability and flowability (ASTM C143/C143M-20, 2020). This standard involves filling a conical mold with fresh concrete, removing the mold, and measuring the subsidence to assess consistency.

For this study, slump testing was performed with a compaction mold. Slump testing was completed by placing the mold with the specimen upside down onto a silicone mat. The mold was lifted vertically, allowing the specimen to slump vertically and horizontally. The vertical and horizontal displacement was measured per specimen from an initial height of 116 mm and initial width of 152 mm. Top-view and side-view photographs were taken for each specimen after slumping was complete.

Exceptions to this process included some SC specimens, which required an extruder to remove the specimen from the mold. When an extruder was used, the sample was carefully placed onto the silicone mat for photo documentation to ensure consistency in measurement and observation.

Results and Discussion

Density

Relationships of dry density versus mixture ratio for GeoStable Tailings prepared with whole tailings and underflow tailings at a range of solids contents and prepared using SC, DC, and LP are shown in Figure 2. The grey lines in Figure 2 plots are theoretical dry density curves for perfectly mixed materials (Wickland et al., 2006). The peaks of each curve, where a given tailings solids content line intersects the waste rock line for a specified waste rock porosity, represent theoretical optimum mixture ratios where tailings completely fill void spaces between rock particles. The curve to the right of the peak represents waste-dominated mixtures, and the curve to the left of the peak represents tailings-dominated mixtures. Mixture ratios tested in this study (R = 0.25 to 2.0) represent tailings-dominated mixtures.

Waste rock porosities were determined by performing Standard Proctor compaction, drop chute, and loose placement with 100% waste rock. These placement tests yielded a porosity of 0.36 for Standard Proctor compaction, 0.40 for drop chute, and 0.47 for loose placement. As anticipated, waste rock porosity decreased with increasing compaction effort.

The dry density of a given GeoStable Tailings specimen prepared with whole tailings and compacted with SC generally increased with increasing mixture ratio (Figure 2a). Photographs of the GeoStable Tailings specimens prepared with whole tailings and compacted with SC are shown in Figure 3. As mixture ratio increased from 0.25 to 2.0, waste rock particles displaced tailings within the mixtures, which decreased void volume and increased dry density. Although the GeoStable Tailings prepared with tailings at solids

contents of 75% and 80% display a consistent trend of increasing density with mixture ratio, the specimens prepared with tailings at a solids content of 85% show a weaker increase in density with increasing mixture ratio, and ultimately a drop in density at a mixture ratio of 2.0. The clod structure of the higher solids content tailings likely was held together by capillary forces during compaction, resulting in less efficient remolding and densification. This behavior is consistent with decreasing densities achieved for dry-of-optimum compaction of fine-grained soils with decreasing water contents.

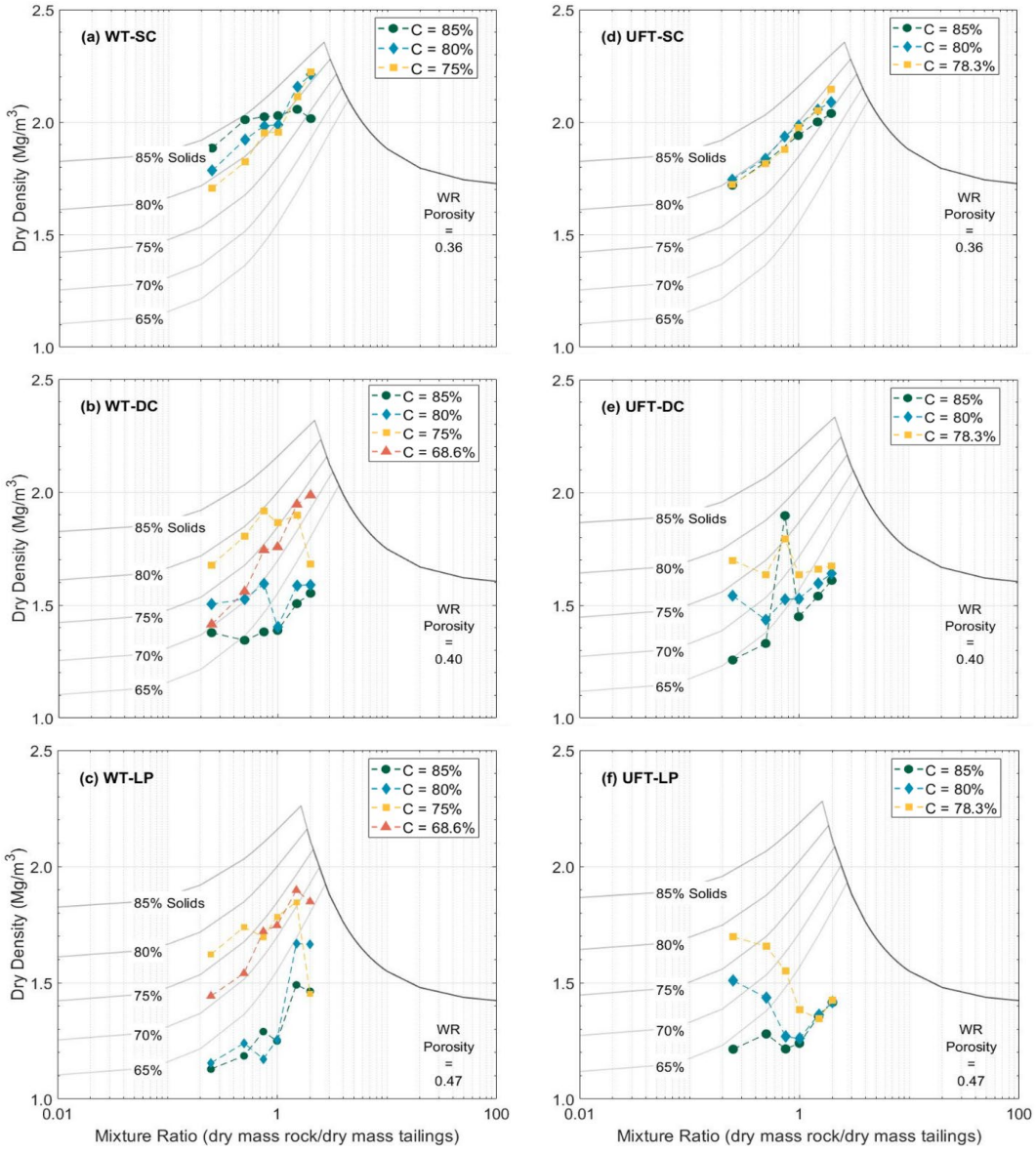

Figure 2: Relationships of dry density versus mixture ratio for whole tailings (WT) prepared via (a) standard compaction (WT-SC), (b) drop chute (WT-DC), and (c) loose placement (WT-LP), as well as underflow tailings (UFT) prepared via (d) Standard compaction (UFT-SC), (e) drop chute (UFT-DC), and (f) loosely placed (UFT-LP). The WT were prepared at solids contents (C) of 85%, 80%, 75%, and 68.6%, whereas UFT were prepared at solids contents of 85%, 80%, 78.3%. Theoretical mixture lines shown in grey include waste rock porosity determined from their respective placement tests

This loss of compaction efficiency at 85% solids content (visible in Figure 3 for R > 0.5) reflects the air-dried waste rock progressively reducing the bulk water content of the mixture as mixture ratio increased.

The GeoStable Tailings specimens prepared with whole tailings at solids content of 80% and 75% exhibited a consistent increase in dry density with increasing mixture ratio (Figure 2a) and reached similar dry densities with increasing mixture ratio. These trends suggest that the tailings were sufficiently wet to minimize capillary forces and not inhibit compaction as waste rock content increased. Photographs of the specimens in Figure 3 support this observation. Nearly all GeoStable Tailings specimens prepared with whole tailings at solids contents of 80% and 75% exhibited a more homogeneous structure with few visible rock particles, clods, and/or macropores. Only the two highest mixture ratios tested (R = 1.5 and 2.0) show the presence of air voids, but still without a connected macroporous structure.

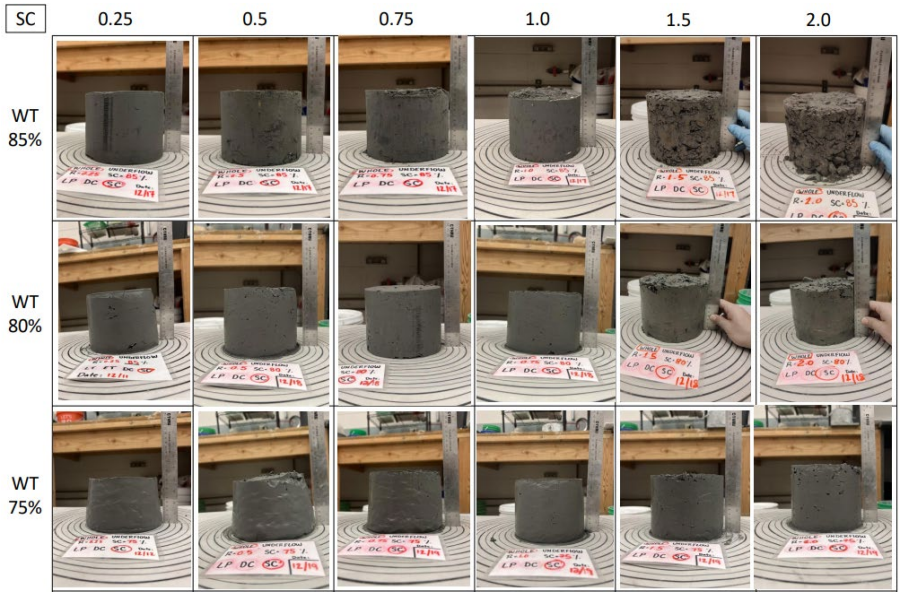

Figure 3: Front view of test specimens with ranging mixture ratios and solids content for whole tailings (WT) placed via Standard compaction (SC)

Dry density of GeoStable Tailings mixtures placed with SC and prepared with underflow tailings increased with increasing mixture ratio as shown in Figure 2d. Minimal differences in dry density were observed as a function of solids content for a given mixture ratio. The underflow tailings were sandier with lower fines content compared to whole tailings (Table 1). Dry density of the compacted underflow tailings mixtures were less sensitive to changes in bulk water content, which agrees with naturally occurring sands and gravel that often exhibit the densest compaction at an air-dried state (Bareither et al., 2008).

In Figure 4, although there are minor cracks and slight macropore structure development for the high mixture ratios, particularly for GeoStable Tailings prepared at 80% solids content, the mixtures show more consistent visible homogeneity compared to whole tailings (Figure 3). This consistency in structure

corroborates the density trends and suggests that the degree of dewatering did not significantly impact dry density of GeoStable Tailings specimens compacted with underflow tailings for a given mixture ratio.

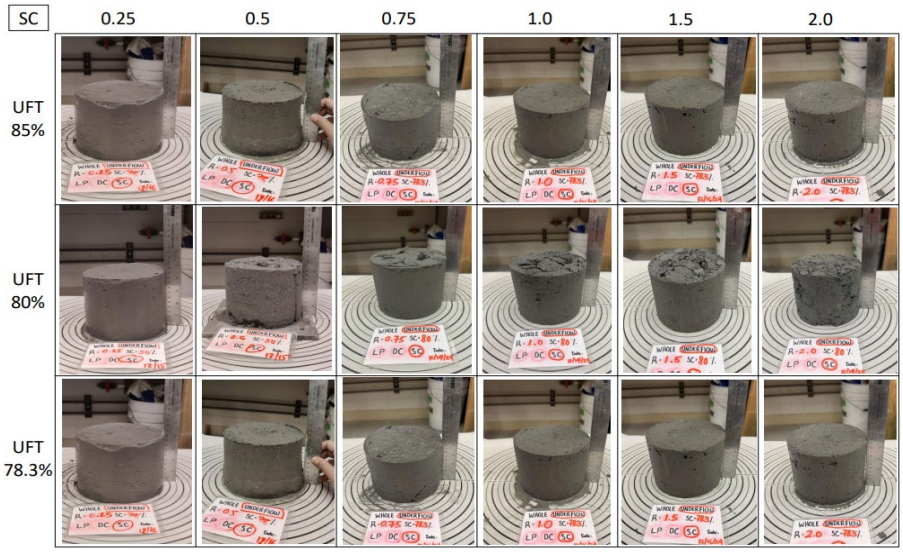

Figure 4: Front view of test specimens with ranging mixture ratios and solids content for underflow tailings (UFT) placed via Standard compaction (SC)

Dry density of GeoStable Tailings prepared via LP with whole tailings are plotted as a function of mixture ratio in Figure 2c. GeoStable Tailings exhibited increasing dry density with increasing mixture ratio from 0.25 to 1.5; variation is observed in the magnitude and trend of dry density as a function of mixture ratio for a given tailings solids content. As mixture ratio increased from 0.25 to 1.5, waste rock replaced tailings, modifying the pore structure and increasing density. The dry density of all specimens prepared at R = 2.0 decreased relative to the mixture prepared at R = 1.5 for the same solids content.

There were notable differences in the GeoStable Tailings structure as a function of solids content and mixture ratio that contributed to variations in dry density (Figure 2c). Whole tailings at a solids content of 68.6% had a slurry consistency, and at a solids content of 75% had a more paste-like consistency. In contrast, whole tailings at 80% and 85% solids content were more soil-like and representative of filtered tailings. The lower solids content specimens (68.6% and 75%) did not exhibit clod formation at R < 1.5, which created a material that could be placed loosely in the compaction mold and deform or flow. This behavior resulted in higher dry density relative to specimens prepared with higher solids content (80% and 85%), which exhibited retained clods and a macroporous structure for all loosely placed specimens.

Dry density of GeoStable Tailings prepared via LP with underflow tailings is plotted as a function of mixture ratio in Figure 2f. Each of the data sets for the three solids contents (78.3%, 80%, and 85%) exhibits an upside-down bell-shaped curve, whereby dry density decreased with increasing mixture ratio above 0.25, reached a minimum dry density, and subsequently increased with additional waste rock content.

Furthermore, dry densities were higher for lower solids content for a given mixture ratio less than about R = 1.0, and then at R = 1.5 and 2.0, dry density was the same regardless of solids content.

At lower mixture ratios (R = 0.25 and 0.5), underflow tailings partially filled voids between waste rock particles, leading to moderate density values. However, at R > 1.0, the mixture became more segregated, and the dominance of the waste rock skeleton limited density increases. At higher solids contents, density was reduced due to insufficient moisture, preventing effective particle arrangement. Unlike whole tailings, which formed distinct clods at lower water contents, underflow tailings exhibited a lower tendency to form and maintain clods at similar solids contents. This behavior was attributed to their higher sand fraction and lower fines content (Table 1), which yielded lower capillary forces. A compilation of photographs from all LP specimens is in Jagerhorn (2025).

Dry density of GeoStable Tailings prepared via DC with whole tailings and underflow tailings are plotted as a function of R in Figure 2b and 2e, respectively. The dry density of GeoStable Tailings prepared using the drop chute exhibited trends that fell between those observed for SC and LP. In general, the additional energy imparted on GeoStable Tailings via the drop chute increased dry density relative to that achieved via LP; however, dry densities were lower than those achieved via SC due to the absence of additional impact forces applied within the compaction mold.

Visual observation of the DC specimens created with whole tailings documents a transition from a more tailings-dominated matrix at lower R and lower solids content to a macroporous and clodded structure at higher R that becomes more evident at higher solids contents. Dry density generally increased with R, but with less efficiency compared to SC. At lower solids contents and mixture ratios, GeoStable Tailings was able to deform during DC placement, similar to LP, which helped to eliminate macropores and led to higher dry density compared to the GeoStable Tailings prepared with higher solids content.

Unlike whole tailings, which exhibited more clod formation at higher solids contents, underflow tailings were more granular. The more granular nature of underflow tailings resulted in a lower tendency to form and maintain clods when unsaturated, leading to lower density for DC specimens compared to SC. Interestingly, the trends of dry density for GeoStable Tailings prepared with underflow tailings are relatively similar between the DC and LP techniques (Figures 2e and 2f).

A compilation of photographs from all SC specimens is in Jagerhorn (2025).

Air Permeability

The goal of the air permeability testing was to establish a permeable versus non-permeable indicator. Measurements near zero flow indicated no measurable air permeability at 10 kPa, whereas measurements of 20 to 60 cm^3/s indicated a permeable macrostructure (Jagerhorn, 2025). Because the upper bound of measurable flow was likely equipment limited, emphasis for testing was placed on the permeable versus

non-permeable distinction rather than the magnitude of flow.

The majority of GeoStable Tailings specimens created with SC were not air permeable. Air flow was largely restricted due to increased density and a more microporous void structure, wherein small pores contained a continuous water phase. However, air-permeable specimens were observed at 85% solids content for both whole and underflow tailings, and both tailings showed an increase in air permeability with increasing R once flow became measurable. These increases in air permeability were attributed to the presence of larger connected voids within the structure as R increased.

GeoStable Tailings prepared with whole tailings at the two lower solids contents (68% and 75%) and at low mixture ratios were not air permeable. As observed for the LP specimens, a more homogeneous structure was present in these specimens that had limited to no visible macropores. In contrast, essentially all whole tailings mixtures prepared with tailings at solids contents of 80% and 85% were air permeable.

GeoStable Tailings prepared via DC with whole tailings transitioned from non-air permeable to air permeable as a function of mixture ratio and solids content. The specimens prepared with a solids content of 68.6% were not air permeable for most mixture ratios except R = 2.0. The change from not air permeable to air permeable occurred at R = 1.0 for solids content = 75%, at R = 0.75 for solids content of 80%, and R = 0.5 for solids content = 85%. This trend likely developed from the additional energy imparted via the drop chute, whereby the efficacy of compaction to eliminate macropores decreased with increasing solids content and mixture ratio.

Overall, the findings suggest that SC effectively reduces airflow except at high tailings solids contents and mixture ratios, whereas DC and LP methods allow for more variable air permeability responses based on mixture ratio and solids content, only yielding low air permeability with the lowest solids content tailings tested. From an operational perspective, the low air permeability observed in compacted mixtures may reduce oxygen ingress into the deposited mixture, thereby supporting one of the principal objectives of commingled waste management: limiting conditions favorable for acid rock drainage. These findings are consistent with previous investigations of commingled waste systems, although long-term field monitoring is necessary to quantify oxygen seepage under in situ conditions (Wickland et al., 2006; Burden & Wilson, 2023). Additional research is also needed to determine the specific threshold at which air permeability collapses in different mixture conditions, as well as how air permeability will shift due to self-weight compaction and consolidation following LP and DC placement conditions.

Penetration

Relationships of penetration resistance versus mixture ratio for GeoStable Tailings prepared with whole tailings and underflow tailings at a range of solids contents and placed via compaction, drop chute, and loose placement are shown in Figure 5. Each data point plotted in Figure 5 represents the average of nine

measurements taken on a GeoStable Tailings specimen, which included penetration measurements at three locations on the surface and at three depths for each location. Penetration resistance testing was conducted to provide an indication of trafficability and structural integrity. Results from penetration testing in test molds cannot be compared to trafficability measurements in the field. However, for reference, penetration values between 20 and 30 psi provide a lower-bound benchmark for minimum trafficability. The handheld penetrometer had an upper measurement limit of 240 psi; values reaching this ceiling are reported as the maximum and reflect a censored upper bound rather than the true resistance.

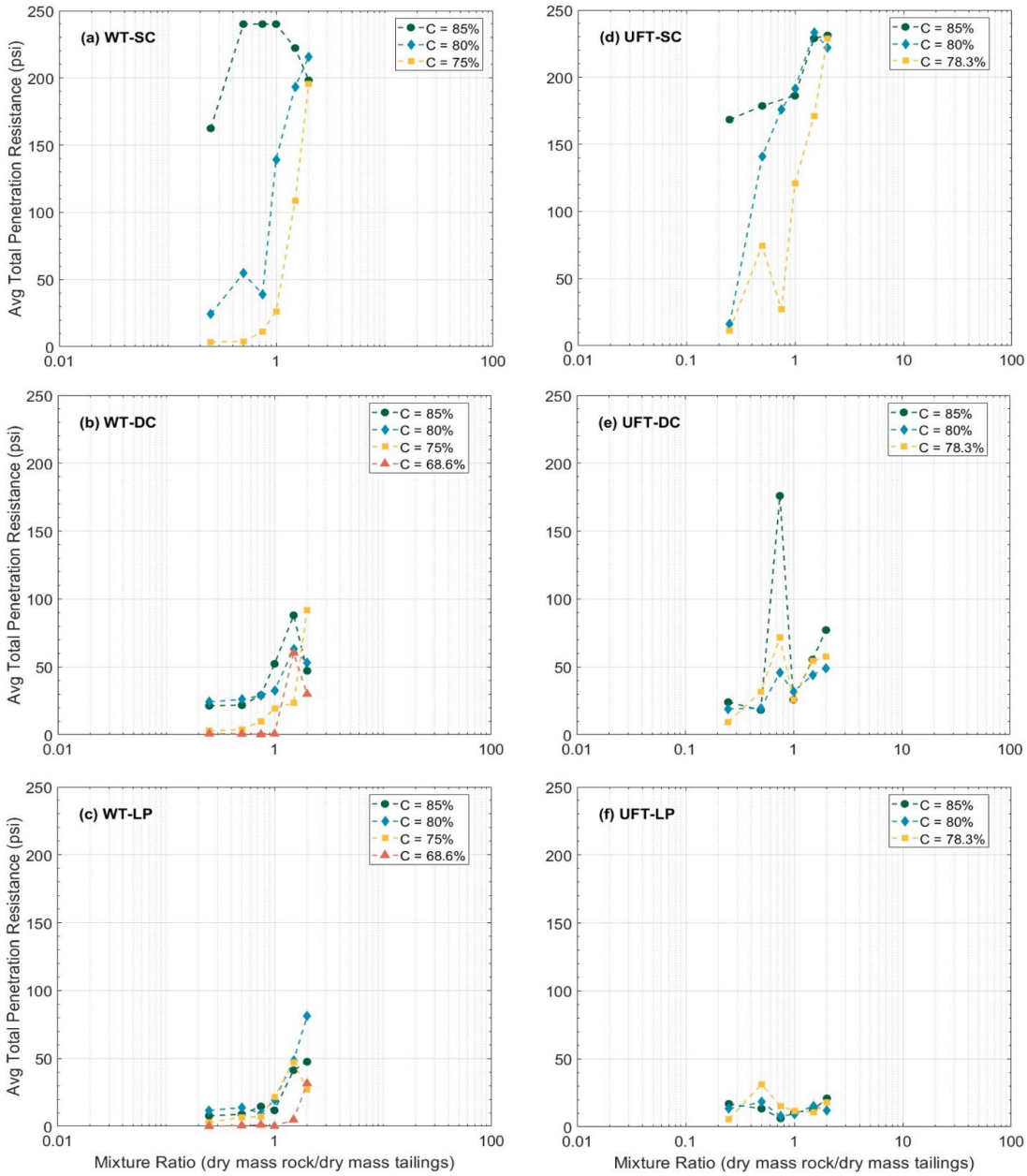

Figure 5: Relationships of average penetration resistance versus mixture ratio for whole tailings (WT) and underflow tailings (UFT) specimens created using standard compaction (SC), drop chute (DC), and loose placement (LP) techniques

Penetration resistance generally increased with increasing solids content and mixture ratio for both whole tailings and underflow tailings. This was expected with SC as denser specimens resulted in a stronger, more resistant structure. Noise in the penetration resistance trends was observed; these variations were attributed to rock interference during penetration, i.e., some penetrations contacted rock with the cone tip while others passed primarily through the inter-rock tailings matrix.

The LP specimens prepared with whole tailings or underflow tailings yielded low penetration resistance. However, there was an observed increase in penetration resistance with whole tailings as the amount of rock increased for the higher mixture ratio. The penetration resistance for underflow tailings was insensitive to mixture ratio, which was attributed to the structure being sufficiently loose that if rock particles were contacted during penetration, they had sufficient void space or loose tailings to displace.

The penetration resistance for the DC-placed specimens prepared with whole tailings was similar to LP; penetration increased with increasing mixture ratio for all solids contents evaluated. A similar trend was observed for underflow tailings. However, this behavior for underflow tailings was different than the relative insensitivity between penetration resistance and mixture ratio observed for the similar specimens prepared with LP. The drop chute imparted more energy during placement and created denser GeoStable Tailings specimens prepared with underflow tailings.

Increased penetration resistance with increasing density and mixture ratio suggests that these mixtures may provide improved mechanical stability during placement and operation. Although liquefaction behavior was not investigated in this study, the observed increases in density and structural integrity are consistent with characteristics generally associated with improved resistance to deformation. Based on penetration testing results, trafficability on GeoStable Tailings will likely require compaction. Field testing will be required to determine if compaction from mine equipment used when placing GeoStable Tailings will be sufficient to ensure trafficability or if additional compaction will be needed. Trafficability issues may arise for whole tailings placed at low solids contents (e.g., 75%) and low mixture ratios (< 1) and underflow tailings at low solids contents (e.g., 80% or less) and low mixture ratios (e.g., 0.25). Without adequate compactive effort, penetration resistance remained low, particularly for low mixture ratio underflow tailings where weak clods limit strength development.

Slump

Slump of GeoStable Tailings prepared with whole tailings was strongly dependent on placement energy, solids content, and mixture ratio (Jagerhorn, 2025). The largest slumps were measured for mixtures prepared with tailings at 68.6% solids content and placed via DC and LP. In both cases, specimens exhibited high slump at low mixture ratio, and a decrease in slump as mixture ratio increased. As solids content increased to 75%, slump was minimal at lower mixture ratios and further decreased with increasing mixture

ratio for specimens prepared via DC and LP. The transition observed for whole tailings mixtures prepared with 68.6% and 75% solids content represented a shift in material behavior, with higher solids content limiting flow-like behavior of the lower solids content mixtures.

Limited vertical slump was measured for all GeoStable Tailings specimens prepared with underflow tailings, even at the lowest solids content evaluated (78.3%) under loose placement. The granular nature of underflow tailings limited slump as excess water was able to freely drain during compaction, resulting in minimal deformation after placement. Thus, underflow tailings remained structurally stable across the tested range of mixture ratios and placement methods.

Horizontal displacement (i.e., spread of the specimen diameter) followed trends similar to vertical slump. For whole tailings, spread was greatest under low placement energies (LP and DC): the 68.6% solids content mixtures spread most at low mixture ratio owing to their slurry-like consistency, with spread diminishing as added waste rock provided support. In contrast, the highest solids content mixtures (85%) showed spread that increased with mixture ratio, attributed to dry clods crumbling and detaching from the top of the specimen after the mold was removed. Horizontal displacement of underflow tailings was minimal across all placement methods, with only minor fragmentation observed for loosely placed specimens. These observations support the use of low slump and low spread together as a constructability indicator for GeoStable Tailings.

Overall, the results indicate that slump in whole tailings was sensitive to solids content and mixture ratio during initially loose placement, with lower solids contents exhibiting greater slump potential. In contrast, underflow tailings maintained structural integrity, regardless of placement conditions, emphasizing their low tendency for slump.

Summary and Conclusion

Results of this laboratory commingling study can be used to inform the selection of tailings and mixture ratios that are best suited for GeoStable Tailings. Both whole tailings and underflow tailings appear to be viable under some, but not all, compositions (i.e., solids contents and mixture ratios).

For whole tailings, we draw the following conclusions from screening tests that incorporated Standard Proctor compaction:

- Solids contents of 80% and 85% provide laboratory indications of viability for stable placement. Slump results suggest that whole tailings with solids contents less than 80% may not be suitable due to excessive slumping (for solids contents between 75-80%) as well as tailings separation and flow (for solids contents < 75%).
- Penetration testing results suggest that whole tailings will be trafficable with mixture ratios of 1.5 and 2.0 for solids contents ranging from 75 to 80%. Mixture ratios < 1.0 at solids contents < 80%

may present challenges with trafficability. Low solids content whole tailings (≤ 75%) may be particularly problematic at mixture ratios of 0.25 to 0.75.

- Air permeability testing suggests whole tailings will (initially) have low air permeability when compacted except for mixtures comprising higher solids content tailings (80-85%) at high mixture ratios (> 1.0 for solids content = 80% and > 1.5 for solids content = 85%).
- Mixture ratios between 1.0 to 2.0 for 75% solids content whole tailings, and a mixture ratio of 1.0 for 80% solids content whole tailings have the highest probability of meeting simultaneous criteria for air-flow minimization, trafficability, and constructability (low slump and spread).

For coarse underflow tailings prepared with Standard Proctor compaction:

- Slump results suggest underflow tailings with solids contents between 78 and 85% at mixture ratios between 0.25 and 2.0 may be viable.
- Penetration testing results suggest that underflow tailings with solids contents between 78 and 85% will be trafficable at mixture ratios ≥ 0.5, and trafficable at mixture ratios ≥ 0.25 with high solids content tailings (85%).
- Air permeability results suggest underflow tailings will (initially) have low air permeability when compacted, except for mixtures comprising higher solids content tailings (85%) at high mixture ratios (> 0.75). Without compaction, underflow tailings demonstrated high air permeability.
- GeoStable Tailings created with underflow tailings at solids contents between 78% and 80% show simultaneous attainment of criteria for air-flow minimization, trafficability, and constructability (low slump and spread) for mixture ratios between 0.25 to 2.0, and with a solids content of 85% for mixture ratios ≤ 0.75.
- GeoStable Tailings created with underflow tailings are likely to have a broader range of acceptable solids contents and mixture ratios than GeoStable Tailings created with whole tailings

A key point of this study was to identify GeoStable Tailings mixtures that have potential for field-scale implementation. Uncertainties remain in how differences in waste rock particle size and gradation at field scale, as well as mixing techniques, will influence GeoStable Tailings mixture ratios, geotechnical characteristics, and hydraulic and mechanical behavior relative to observations from this laboratory study. Coupling the field and lab studies will help establish protocols for laboratory evaluation of GeoStable Tailings that can provide guidance for field-scale implementation.

Beyond constructability considerations, these laboratory mixtures have implications for broader mine waste management objectives. Mixtures that achieve increased density, low air permeability, and adequate trafficability may also reduce oxygen ingress and improve mechanical stability. Although acid rock drainage and liquefaction were not directly evaluated, the observed engineering behavior indicates that these mixtures warrant further investigation during field-scale implementation. Recommended future work

includes reduced- and modified-Proctor compaction on 100% tailings to bound the range of field compactive efforts, identification of the drop height required to achieve Standard Proctor density, determination of the mixture ratio at which air permeability collapses, and evaluation of test repeatability.

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