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Undrained Shear Behavior of Mixed Waste Rock and Tailings

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SUMMARY: The objective of this study was to evaluate the effect of variability in mixture ratio (R) on shear behavior and shear strength of co-mixed mine waste rock and tailings (WR&T). Crushed granitic gravel was used as a synthetic waste rock, and mixed sand and silt was used as synthetic mine tailings. Co-mixed WR&T specimens were prepared with a mixture ratio varying from coarse-dominated structure to fine-dominated structures, including R_{opt}, where tailings "just fill" the void space of the waste rock. Materials were tested in triaxial compression at effective confining stresses ($\sigma'c$) of approximately 10, 50, and 100 kPa. Undrained triaxial tests were conducted on pure materials and mixed WR&T. The waste rock and WR&T specimens were 150-mm in diameter by 300-mm tall, while tailings specimens were 38-mm in diameter by 76-mm tall. Dilative, strain-hardening behavior was observed for both pure materials. Coarse- and fine-dominated structures exhibited shear behavior similar to the pure materials, with exception of a more contractive, strain-softening behavior observed for the fine-dominated mixture. The mixture prepared at R_{opt} exhibited the largest deviator stress with pronounced strain-hardening behavior. Shear strength parameters of all mixture were larger when compared to the pure materials.

KEYWORDS: Geoenvironmental, Mine Waste, Shear Behavior, Triaxial Test.

1 INTRODUCTION

The Mining, Minerals, and Sustainable Development Project reported in 2002 that approximately 3500 active mine waste facilities exist worldwide (MMSD 2002). Hard rock mining operations, which yield iron, copper-silver, gold, and other metals, generate two predominant waste materials, tailings and waste rock. Tailings are residue generated from ore processing, typically are fine-grained material with high water content (i.e. slurry), and are managed within tailings storage facilities (TSFs). Waste rock primarily consists of coarse-grained particles that are a function of parent rock and mining operations, is generated via excavation of non-economical rock to access ore, and typically is deposited in piles. Tailings and waste rock both require long-term management, which present challenges related to storage capacity, geotechnical stability, and environmental pollution (Bussière 2007).

Mine tailings commonly have low shear strength and high compressibility when deposited as slurry in a TSF, which leads to geotechnical stability concerns. Although shear strength and compressibility are not concerns for waste rock piles, the presence of sulphide minerals can lead to acid rock drainage (ARD), which is a critical environmental issue at mine sites. Mixing waste rock and tailings (WR&T) has been studied as an economical, long-term solution to decrease land disturbance, reduce water consumption, increase stability, and facilitate post closure and reclamation of mine waste facilities (Wickland et al. 2006).

Methods for mixing and co-managing WR&T include (*i*) co-mixing, (*ii*) co-layering, and (*iii*) co-disposal in impoundments (Bussière 2007). Co-layering and co-disposal primarily relate to disposal techniques whereby properties of the mixture are not of critical importance. In contrast, co-mixing implies more control on mix proportion of WR&T to create a material with predictable engineering properties to facilitate reuse in final cover systems for waste containment or as a pseudo-earthen material for earthwork applications.

Studies conducted on co-mixed WR&T have demonstrated that an effectively mixed material has shear strength and compressibility governed by the waste rock and hydraulic conductivity controlled by the tailings-matrix (Wickland et al. 2010; Jehring & Bareither 2016). However, in co-mixing applications, spatial variability of the proportions of tailings and waste rock will exist with a given mixture. Thus, understanding and evaluating the effect of WR&T mixture variability on material properties (e.g., shear strength parameters) is needed for design.

The objective of this study was to evaluate the effect of variability in the ratio of WR&T on the shear behavior and shear strength of mixed WR&T. Consolidated-undrained triaxial tests were used conducted on pure waste rock, pure tailings, and a range of WR&T mixtures. This study is a step towards understanding the shear behavior of different WR&T mixtures such that guidelines and target mixtures can be developed for practical applications.

2 BACKGROUND

2.1 Mixture Theory

Mixtures of coarser- and finer-grained soils have been studied in geotechnical engineering to understand mechanical behavior and evaluate possible applications of such materials (e.g., Thevanayagam 1998, Wickland et al. 2010). A relevant parameter to describe WR&T mixtures is the mixture ratio (R):

$$R = \frac{M_r}{M_f} \tag{1}$$

where M_r = dry mass of waste rock and M_f = dry mass of tailings. The mixture ratio can range from R = 0 for pure tailings to $R = \infty$ for pure waste rock.

Mechanical behavior of mixtures at high R are mainly controlled by the coarse, waste rock, fraction. With decreasing R, a threshold is reached whereupon the coarse-grained particles are no longer in contact with one another. At this threshold, mechanical behavior transitions to be predominately controlled by the finer matrix with influence of coarse-grained material (Thevanayagam 1998; Zuo & Baudet 2015).

Wickland et al. (2006) defined an optimum mixture ratio (R_{opt}), which represents an R when the tailings matrix completely fills void space of the waste rock without compromising particle-to-particle contacts throughout the waste rock skeleton. The R_{opt} can be calculated from a volume-based phase diagram and the following assumptions: (*i*) rock, tailings, and water are incompressible; (*ii*) mass of air is negligible; (*iii*) waste rock void spaces are larger in diameter than the average tailings particles; and (*iv*) a unit waste rock volume. Factoring in these assumptions, R_{opt} is computed as,

$$R_{opt} = \frac{M_c}{M_f} = \frac{\rho_r V_r}{\dfrac{\rho_{slurry} V_{slurry}}{1+w_t}} = \frac{\rho_r V_r}{\dfrac{\rho_{slurry} e_r}{1+w_t}} \tag{2}$$

where e_r is the void ratio of the waste rock, ρ_r is the density of the waste rock, and V_r is the volume of waste rock, assumed V_r=1. For the tailings slurry, ρ_{slurry} is the density of the tailings, V_{slurry} is the volume of the tailings, and w_t is the water content of the tailings slurry. The focus in this study was to vary R bigger and smaller then R_{opt} to assess how transitioning from a coarse- to fine- dominated structure influence shear behavior and shear strength of co-mixed WR&T.

2.2 Undrained Shear Behavior

The potential for undrained shear failure in co-mixed WR&T may develop due to concentrated loading of the tailings fraction in a fine-fraction dominated mixture. Undrained failure has the potential to lead to static liquefaction and dramatic strength loss. In situations where drainage is limited, generation of excess pore water pressure during loading can lead to a corresponding increase or decrease in effective stress, which affects strength of the soil. Positive excess pore pressure during shear is indicative of contractive behavior (i.e., potential to decrease in volume) and negative excess pore pressure is indicative dilative behavior (i.e., potential to increase in volume).

An important outcome from an undrained shear test is defining the steady state (SS). Steady state applies to stress and soil volume conditions that are independent of stress history (Been & Jefferies 1985). Knowledge of steady state allows comparison with the initial state of soil to quantify potential undrained behavior using a state parameter (ψ). A schematic of a theoretical void ratio versus mean effective stress (e-σ'_m) with a steady state line (SS Line) and two initial state condition is shown in Fig. 1. The state parameter is defined as the vertical offset between the initial state of the soil and final position on the SS Line. Materials with positive ψ have a tendency to contract during shear and strain-softening behavior, whereas materials with negative ψ have a tendency to dilate during shear and exhibit strain-hardening behavior. Thus, soils with positive ψ can potentially lead to static liquefaction and rapid strength loss (Bobei et al 2009).

3 METHODS AND MATERIALS

3.1 Materials

One type of synthetic mine tailings (SMT) and one type of synthetic waste rock (SWR) were used in this study. Synthetic mine wastes were created from commercially-available materials to control geotechnical characteristics such that shear behavior could be evaluated more precisely. Synthetic mine tailings were created from silica powder, which primarily contained silt-size quartz minerals (US Silica - Maryland, USA), and angular sand particles passing a #No. 10 sieve from road base material. Synthetic waste rock was created from crushed granite obtained from local quarry (Wyoming, USA).

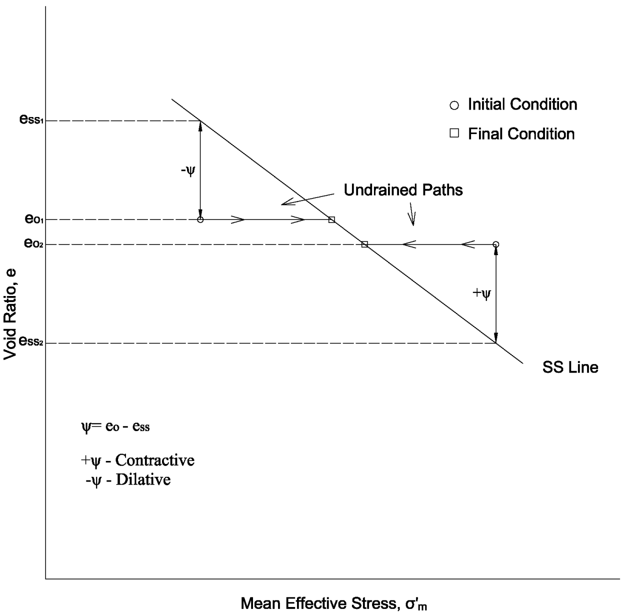

Fig. 1. Schematic showing the relationship between void ratio and mean effective stress with definition of the state parameter (ψ); adapted from Been & Jefferies (1985).

Particle size distributions (PSD) for SMT and SWR are in Fig. 2. The target PSD for both materials was based on literature. Parallel particle gradation theory was applied to SWR to create a material with a maximum particle diameter of 25 mm (Jehring & Bareither 2016).

Synthetic waste rock was classified as poorly graded gravel and SMT classified as low-plasticity silt according to the Unified Soil Classification System. Maximum void ratio (e_{max}) of SWR was determined according to Methods A and B in ASTM D 4254 (2016), and the minimum void ratio (e_{min}) was measured according ASTM D 4253-Method 2A (2016). The e_{max} from Method A was 0.83 and from Method B was 0.88; the e_{min} was 0.65. The specific gravity (G_s) was obtained using the buoyant weight method described in ASTM C 127 (2015), and the G_s of 2.7 refers to an oven-dried specific gravity.

Synthetic mine tailings were composed of a mixture of 20% sand and 80% silica powder by dry mass. The PSD was measured using mechanical sieve and hydrometer testing

(ASTM D422, 2007). Atterberg limits were evaluated following ASTM D4318 (2010); the tailings exhibited non-plastic behavior. The water pycnometer method outlined in ASTM D 854 (2014) was used to determine a G_s = 2.66.

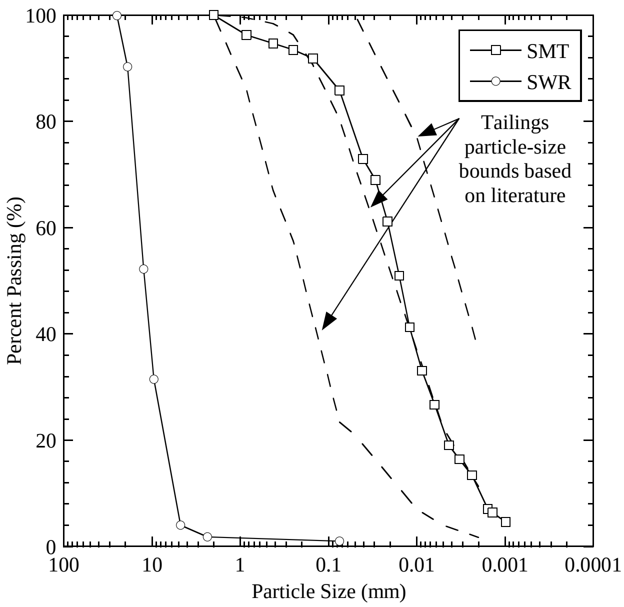

Fig. 2. Particle size distribution for the synthetic mine tailings (SMT) and synthetic waste rock (SWR) developed for this study. Particle size bounds based on a compilation of relevant literature.

3.2 Triaxial Compression Testing

Synthetic waste rock and WR&T mixtures were tested in a large scale triaxial (LSTX) apparatus that included 150-mm-diameter specimens to allow inclusion of particles up to 25 mm in diameter. A conventional 38-mm-diameter triaxial (TX) specimen was used for testing SMT, since d_{max} was ≤ 2.0 mm. Triaxial tests were conducted at target effective confining stresses (σ'_c) of 10, 50, and 100kPa, which represent a range of effective stress that can be anticipated in final cover applications and shallow co-mixed WR&T deposits.

Consolidated undrained (CU) triaxial tests were conducted on all materials in accordance with ASTM D 4767 (2011). Consolidated undrained tests were sheared at an axial strain rate of 5 %/h. Strain rates were selected based on the time required to reach 50% of primary consolidation as described in ASTM D 4767 (2011). All triaxial tests were conducted to an axial strain of at least 20%.

Tailing specimens were prepared as slurry at 40% water content based on modified slump test results (Clayton et al. 2003). This water content was intended to simulate a yield stress that was representative of thickened tailings. The SMT slurry was poured into a 38-mm-diameter by 101-mm-tall split mold lined with a 0.31-mm-thick latex membrane. Due to the low strength of the slurry, a 0.05-mm-thick paper mold was placed on the outside of the latex membrane to keep the specimen intact after removing the split mold and assembling the triaxial cell. Once water was added to the triaxial cell, the paper lost strength and fell apart prior to conducting the triaxial test.

Synthetic waste rock and WR&T mixtures were prepared in a 300-mm-tall by 150-mm-diameter split mold lined with a 5-mm-thick rubber membrane. The membrane thickness was necessary for the LSTX testing to avoid membrane puncture due to the large, angular rock particles. The membrane correction recommended by La Rochelle et al. (1998) was applied to the test data to account for additional strength contributed by the membrane.

Specimen preparation for both pure SWR and WR&T at R_{opt} were intended to achieve a loose waste rock skeleton (i.e., target e_{max}). The WR&T mixture at R_{opt} was prepared following the slurry displacement method in Khalili & Wijewickreme (2008). This method consists of deposition of the rock into slurry tailings such that all void space, to the extent possible, is filled with tailings slurry. Mixture specimens were prepared in six layers, with each layer lightly tamped to achieve a level surface. A variation of this slurry displacement method was used to prepare the SWR via deposition of rock particles in deionized and de-aired water.

An R_{opt} = 2.5 was computed for the SWR and SMT mixture based on SWR prepared at e_{max} and SMT prepared at 40% water content. The other target R ratios were $0.5{\times}R_{opt}$ and $2{\times}R_{opt}$. These ratios were chosen to target fine- and coarse-dominated structures. Specimen preparation procedures for these mixtures included thoroughly mixing the material, evenly depositing the mixture into the mold in six layers, and lightly tamping each layer to achieve a level surface. The actual *R* of each triaxial specimen was measured following testing; samples were taken from the top, middle, and bottom of a given specimen.

Saturation of the all specimens was confirmed via B-check, and B-values > 0.95 were achieved in all tests. Specimens were consolidated via isotropic consolidation for a 24-h period. Changes in specimen height and volume were measured during consolidation to compute density and void ratio of the specimen prior to shearing in accordance with ASTM D 4767 (2011).

4 RESULTS AND DISCUSSION

4.1 Shear Behavior

A summary of the triaxial tests presented in this paper are in Table 1. Tests on pure SWR and pure SMT (i.e., *R* = 0 & *R* = ∞) were conducted as controls for comparison with the WR&T mixtures. Three confining stresses were used for each pure material (10, 50, 100 kPa) to construct a failure envelope and determine relevant shear strength properties.

Table 1. Summary of triaxial tests on synthetic mine tailings (SMT), synthetic waste rock (SWR), and mixtures of waste rock and tailings (WR&T).

Material	Target σ_c' (kPa)	σ_c' (kPa)	Target R	Actual R
AST	10	6.8	R=0	0
	50	49.5	R=0	0
	100	98.7	R=0	0
SWR	10	6.8	R=∞	∞
	50	46.9	R=∞	∞
	100	93.5	R=∞	∞
WR&T	50	45.7	$0.5 \cdot R_{opt} = 1.2$	1.0
	50	46.9	$R_{opt} = 2.5$	2.6
	50	46.9	$2 \cdot R_{opt} = 5.0$	5.0

Relationships of excess pore water pressure (u_e) and deviator stress (Δσ) for the SWR are shown in Fig. 3. Tests on SWR were performed to an axial stress (ε_a) of 25% as this was the physical limit of the triaxial apparatus. The SWR exhibited a tendency to contract on initial loading (+u_e) followed by a tendency to dilate with continued axial deformation (-u_e).

The SWR material exhibited strain-hardening behavior with an increase in Δσ to approximately 20%. The Δσ and u_e were nearly constant for the last 5% of axial strain, which is representative of steady state behavior (i.e., continued shearing under constant stress and volume). The undrained behavior of SWR agrees with that of loosely-prepared coarse-grained material (Lambe & Whitman 1969).

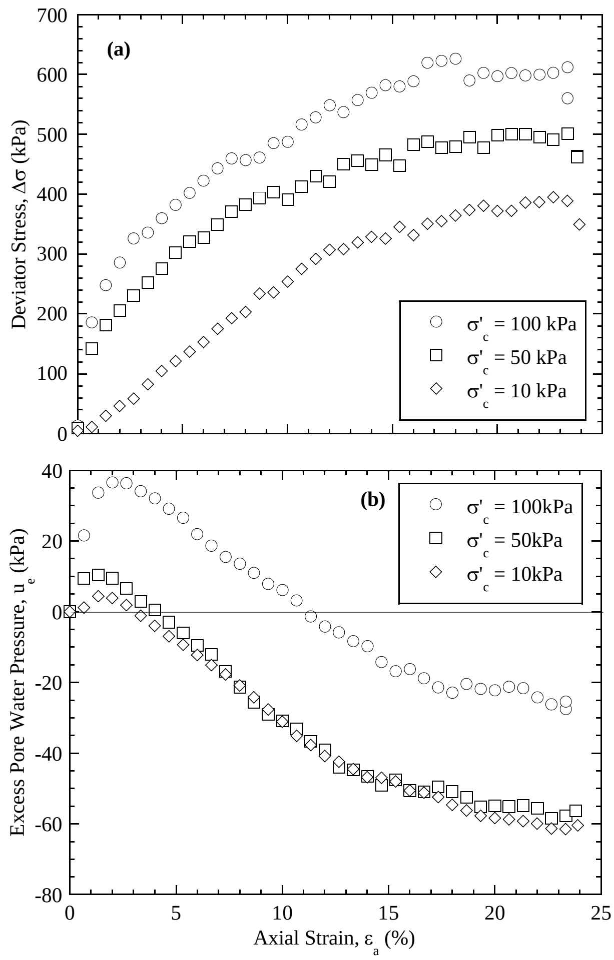

Fig. 3. Relationships of (a) deviator stress and (b) excess pore water pressure versus axial strain for SWR.

Relationships of Δσ and u_e versus ε_a for SMT are shown in Fig. 4. Triaxial tests on SMT were conducted to 30% axial strain with the intent of reaching steady state. The SMT specimen tested at σ'_c = 10 kPa exhibited a very minor tendency to dilate (-u_e) and small Δσ, which were attributed to the high void ratio and slurry-like consistency of this material. An increase in σ'_c to 50 and 100 kPa consolidated the SMT, which led to a greater tendency to dilate and strain-hardening response characterized by continued increase in $\Delta\sigma$. This behavior for a normally consolidated silty material is consistent with behavior of non-plastic silts discussed in Brandon et al. (2006). A pseudo-steady state of the SMT at σ'_c = 50 and 100 kPa could be argued for the end of the experiment and will be assumed herein as steady-state (Fig. 4); however, a true steady-state was not attained in this material.

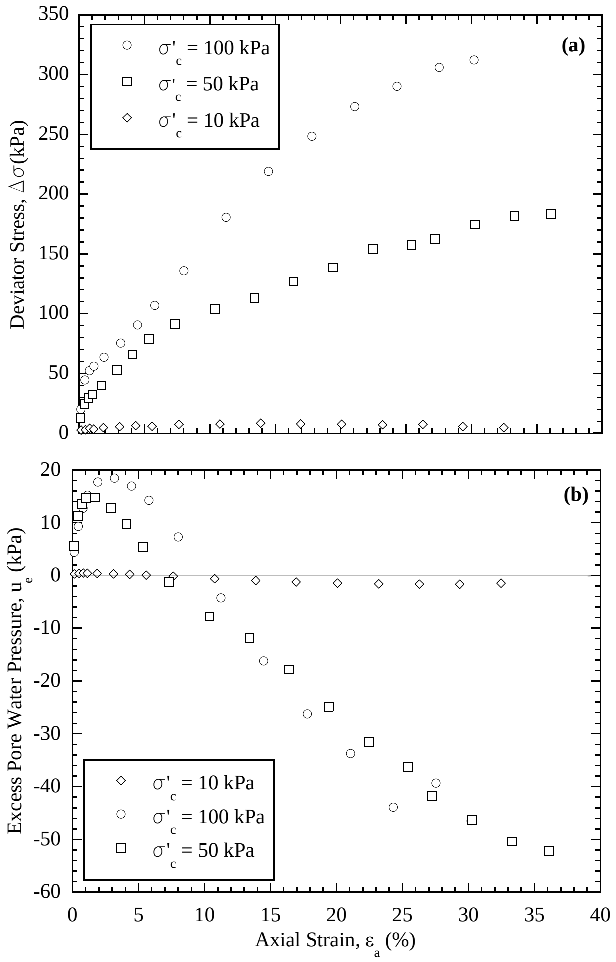

Fig. 4. Relationships of (a) deviator stress and (b) excess pore water pressure versus axial strain for SMT

Triaxial tests on co-mixed WR&T were conducted at σ'_c = 50 kPa to assess the influence of variation in *R* ratio on shear behavior and shear strength. Relationships of u_e and $\Delta\sigma$ versus ε_a for WR&T at R = 1.0, 2.6, and 5.0 are shown in Fig. 5. Data from the SWR and SMT at σ'_c = 50 kPa are also included in Fig. 5 for comparison. The behavior observed supports the hypothesis, where low *R* (i.e. fine-dominated) has behavior similar to SMT and high *R* (i.e. coarse-dominated) has behavior similar to SWR.

The specimen prepared at 0.5×R_{opt} had *R* = 1 and represented a fine-dominated structure. Although this specimen had waste rock particles within the fine matrix that could be perceived as "floating" inclusions, a considerable portion of the total mixture volume was occupied by waste rock. The presence of waste rock supports the modest increase in $\Delta\sigma$ shown in Fig. 5 when compared to pure SMT.

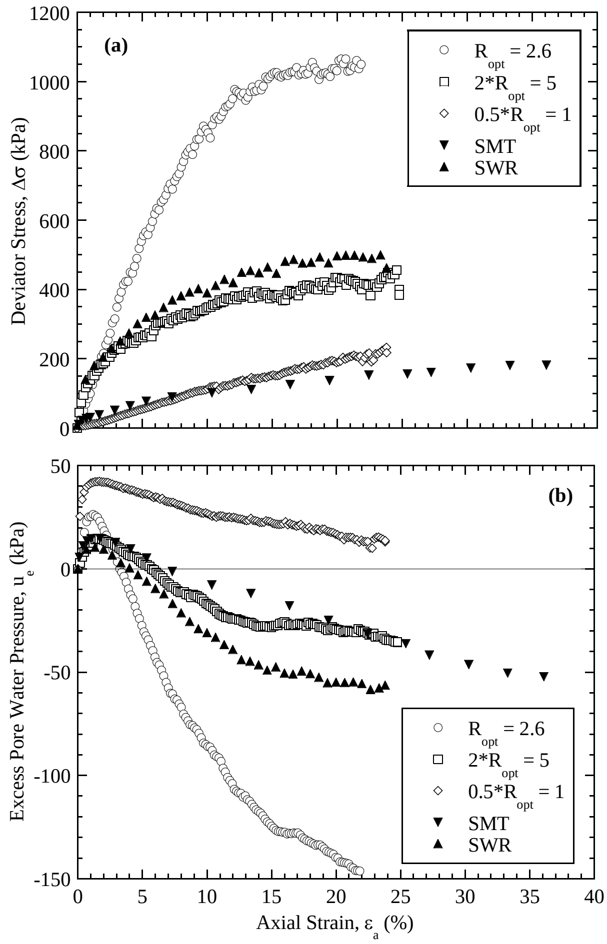

Fig. 5. Relationships of (a) deviator stress and (b) excess pore water pressure versus axial strain for WR&T mixtures at varying R and pure materials at σ'_c = 50 kPa.

The "floating" waste rock inclusions provided increased density and resistance of the mixture, which contributed to an enhanced ability to transfer normal and shear forces through the mixture. This fine-dominated mixture also exhibited a greater tendency to contract relative to the pure SMT (Fig. 5), which may be attributed to the greater amount of tailings within the mixture relative to the small-scale traixial specimen used for the SMT. The axial strain was limited for this test, and that trend shows that u_e decreases with increasing at large strains ε_a.

The WR&T mixture prepared at $2\times R_{opt}$ had a final R = 5. During preparation of this coarse-dominated structure, SMT was observed to coat the SWR particles without generating considerable change in the SWR structure. This particle coating with SMT resulted in a heterogeneous specimen at end of shearing, whereby R varied from the top to bottom of the specimen. Nevertheless, results in Fig. 5 for the $2\times R_{opt}$ mixture show behavior similar to pure SWR. Similar magnitudes of $\Delta\sigma$ and $-u_e$ were observed for both the pure SWR and $2\times R_{opt}$ mixture. These specimens exhibited a tendency to dilate with increasing $\Delta\sigma$ and increasing ε_a.

The WR&T specimen prepared at R_{opt} appeared to represent a state were SWR voids were filled by SMT slurry without noticeable heterogeneity or segregation of fine material throughout the specimen. A considerable increase in $\Delta\sigma$ was observed for R_{opt} relative to all other tests conducted for this study (Fig. 5). This pronounced increase in strength and strain-hardening behavior agrees with tests conducted on actual silty mine tailings and crushed gravel by Jehring & Bareither (2016). An increase in density of the specimens by filling SWR voids with SMT results in a pronounced shear resistance of the mixture when compared to pure SWR or pure SMT. The presence of SMT within the void space of the SMR particles acts as a barrier for rearranging of the SWR particles such that strength is enhanced.

4.2 Shear Strength

An analysis of strength parameters was performed based on Mohr Coulomb failure envelope for pure materials, and stress paths for the mixtures. Thus, a tangent friction angle (φ'_t) was determined for the SWR and SMT, whereas a secant friction angle (φ'_s) was determined for the mixtures.

Stress paths in q-p' space for SWR, SMT, and the three WR&T mixtures tested at σ'_c = 50 kPa are shown in Fig. 6. Stresses in Fig. 6 were computed as $p' = (\sigma_1' + \sigma_3')/2$ and $q = (\sigma_1' - \sigma_3')/2$, where σ_1' and σ_3' are the major and minor principle stresses, respectively. Also included in Fig. 6 is a compilation for relevant friction angles for the five materials. The φ' determined for SMT (27.4°) was the lowest of all the materials, which was anticipated based on the loose, slurry-like nature of the initial material. The φ' of the SWR = 45.2° and a modest increase in φ' was determined for all WR&T mixtures. The largest φ' was determined for the WR&T mixture prepared at R_{opt}, which was attributed to the stiff, dilatant response of the material (Fig. 5). The increase in φ' for mine tailings with addition of waste rock agrees with previous research on co-mixed WR&T (e.g., Wickland et al. 2010; Jehring & Bareither 2016); however, further investigation is needed to assess the coupled effects of tailings composition, σ'_c, and R on shear strength of WR&T mixtures.

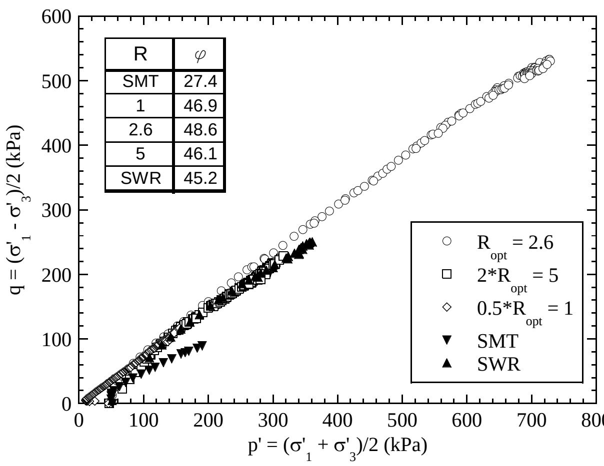

Fig. 6. Stress paths for WR&T mixtures at varying R and pure materials. Friction angles compiled for all materials include tangent friction angles for SWR and SMT and secant friction angles for the WR&T mixtures.

5 CONCLUSION

The effect of varying mixture ratio (*R*) on the shear strength and behavior of co-mixed waste rock and tailings (WR&T) was evaluated with undrained triaxial compression tests. Mixtures of WR&T were created from synthetic waste rock (SWR) and synthetic mine tailings (SMT). The following conclusions were drawn from this study.

- Pure materials exhibited strain-hardening behavior for σ'_c = 10, 50, and 100 kPa: SWR exhibited increasing $\Delta\sigma$ until ε_a = 20% and reached steady-state behavior, whereas SMT exhibited continuously increasing $\Delta\sigma$ with increasing ε_a and a true steady-state was not achieved.
- The fine-dominated WR&T mixture at low R exhibited shear behavior comparable to SMT and the coarse-dominated WR&T mixture at high R exhibited shear behavior comparable to the SWR. Thus, the more predominant mine waste fraction for a given *R* appears to have a strong influence on shear behavior of WR&T mixtures.
- The mixture prepared at R_{opt} exhibited the stiffest and strongest shear behavior with a pronounced dilative response. This enhanced strength was attributed to the SMT that occupied essentially all pore spaces between rock particles and provided an enhanced resistance to shearing stresses.
- Shear strength parameters of all mixtures were higher than the pure materials. However, additional research is needed to better understand coupled effects of tailings composition, σ'_c, and R on shear strength and shear behavior of WR&T mixtures.

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