# MOUNTAIN-PLAINS CONSORTIUM

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## Re-Use of Mine Waste Materials Amended with Fly Ash in Transportation Earthworks Projects

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# RE-USE OF MINE WASTE MATERIALS AMENDED WITH FLY ASH IN TRANSPORTATION EARTHWORK PROJECTS

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## ABSTRACT

The objectives of this study were to assess geotechnical properties of mine waste amended with fly ash and evaluate reuse of fly ash amended mine waste as road construction material. Three types of fly ash and one type of cement were used as cementitious binder. Natural and synthetic (i.e., laboratory prepared) mine tailings were used as mine wastes to assess the effects of tailings properties and solids content on hydraulic and mechanical behavior of fly-ash amended materials. The influence of fly ash-amendment on hydraulic conductivity of mine tailings was attributed to (i) molding water content and (ii) plasticity of the mine tailings. Unconfined compressive strength increased with an increase in tailings particle size, solids content, and/or increase in CaO-to-$SiO_2$ ratio of fly ash for amended mine tailings. The compressibility of mine tailings decreased with an increase in fly ash content and an increase in CaO content and CaO-to-$SiO_2$ ratio of fly ash, which resulted in more effective bonding between particles. Fly as-amended mine wastes were shown to have hydraulic and mechanical properties suitable for transportation earthwork applications.

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# EXECUTIVE SUMMARY

The objectives of this study were to evaluate the effect of fly ash amendment on geotechnical properties of mine tailings, and assess applicability of using the amended mine waste as earthwork construction material, such as road subbase and subgrade, unpaved roadways, embankments, and fills. Natural and synthetic (i.e., laboratory prepared) mine tailings were used to assess the effects of tailings particle-size and tailings solids content. Three types of off-specification fly ashes and Type I-II Portland cement were used as cementitious binders. This report was prepared in four sections: (i) Section 1 evaluates hydraulic conductivity of tailings-fly ash mixtures; (ii) Section 2 evaluates unconfined compressive strength of tailings-binder mixtures; (iii) Section 3 evaluates compressibility of tailings-binder mixtures; and (iv) Section 4 summarizes geotechnical properties of tailings-binder mixtures, based on results reported in Sections 1, 2, and 3.

The objective of Section 1 was to evaluate the effect of fly ash addition on hydraulic conductivity ($k$) of mine tailings. Mine tailings used in this section were categorized as synthetic tailings and natural tailings; two synthetic tailings were developed via blending commercially-available soils, and natural tailings were collected from a garnet mine located in the United States. Two fly ashes were used that had sufficient calcium oxide (CaO) content (17% and 18.9%) to generate pozzolanic activity. Hydraulic conductivity was measured on pure tailings and fly ash-amended tailings in flexible-wall permeameters. Fly ash was added to mine tailings to constitute 10% dry mass of the mixture, and specimens were cured for 7 and 28 days. The influence of fly ash-amendment on $k$ of mine tailings was attributed to (i) molding water content and (ii) plasticity of the mine tailings. Tailings that classified as low-plasticity silts with clay contents less than 15% exhibited a decrease in $k$ when amended with fly ash and prepared wet of optimum water content ($w_{opt}$). Tailings classified as low-plasticity clay exhibited a one-order magnitude increase in $k$ with addition of fly ash for materials prepared dry or near $w_{opt}$. The decrease in $k$ for silty tailings was attributed to formation of cementitious bonds that obstructed flow paths, whereas the increase in $k$ for clayey tailings was attributed to agglomeration of clay particles and an overall increase in average pore size. Results also indicated that the effect of curing time on $k$ is more pronounced during the early stages of curing (≤ 7 d), as there was negligible difference between $k$ for 7-d and 28-d cured specimens.

The objectives of Section 2 were to evaluate the effect of binder amendment on the unconfined compression strength (UCS) of mine tailings and assess applicability of using amended materials in earthworks. Natural and synthetic mine tailings were used to assess the effects of tailings particle-size and tailings solids content on UCS. Two types of off-specification fly ashes and Type I-II Portland cement were used as cementitious binders. Tailings and fly ash mixtures were prepared at 70%, 80%, and 90% solids content and amended with 10% or 20% binder. Unconfined compression strength tests were conducted on specimens cured for 7 days. In general, UCS increased with an increase in tailings particle size, solids content, and/or increase in CaO-to-$SiO_2$ ratio of fly ash for amended tailings specimens. A multivariate regression model was developed to predict UCS of tailings amended with fly ash as a function of (i) tailings water content, (ii) water-to-binder ratio, and (iii) CaO-to-$SiO_2$ ratio of fly ash. The model was developed using data from synthetic tailings specimens and validated via tests on natural tailings and data compiled from literature. The model is applicable for estimating the UCS of candidate fly ash-amended hard rock mine tailings and low plasticity soils (i.e., liquid limit < 50). The UCS of high plasticity materials was under-predicted with the model.

The objective of Section 3 was to evaluate the effect of fly ash amendment on the compression behavior of mine tailings. Natural and synthetic mine tailings were used to assess the effects of tailings composition and tailings solids content on compressibility. Three types of off-specification fly ashes and Type I-II Portland cement were used as cementitious binders. Tailings-fly ash mixtures were prepared at solids content of 60% to 75% (water content = 33% to 67%), water-to-binder ratios of 2.5 and 5, and were cured for 0.1 day (2 hours), 7 days, and 28 days. Bi-linear compression curves on semi-log plots were observed in most of the binder-amended tailings specimens. The break in slope on the compression curve was identified as the breaking stress, whereupon cementitious bonds were broken. The breaking stress increased with an increase in fly ash content, which was attributed to a lower water-to-binder ratio and void volume-to-binder volume ratio that produced more effective particle bonding. Breaking stress also increased with an increase in CaO content and CaO-to-$SiO_2$ ratio of fly ash, which resulted in more effective bonding between particles. The effect of curing time on the breaking stress of fly ash amended specimens was characterized by (i) an increase in breaking stress via increase in curing time and cementitious bond formation or (ii) a constant breaking stress with curing time due to competing mechanisms during loading. Specimens cured under a vertical stress showed an increase in breakings stress with applied load water removal prior to cementitious bond formation that reduced the water-to-binder ratio and led to more effective cementation.

# 1. HYDRAULIC CONDUCTIVITY OF FLY ASH-AMENDED MINE TAILINGS[1]

## 1.1 Introduction

Improving roadway construction and initiating new transportation-related construction projects requires a broad array of earthwork construction, such as road subbase and subgrade, unpaved roadways, embankments, and fills. Each of these earthwork projects requires earthen materials (e.g., soil or crushed rock) constructed in a manner to obtain optimal engineering performance. The reuse of industrial waste and by-products, such as mine waste (i.e., mine waste rock and tailings) and coal combustion by-products (CCBs), has the potential to aid transportation-related construction needs, while decreasing energy consumption, raw material use, and greenhouse gas emissions (Hudson-Edwards et al. 2011).

Mine operations produce considerable quantities of waste materials during ore extraction processes. Mine tailings are one of the most ubiquitous mine wastes. These materials typically are fine-grained with high water contents (low solids contents) disposed as slurry in impoundment facilities (Bussière 2007; Blight 2010). The management of mine tailings can require considerable land area, present physical stability challenges related to low shear strength, and environmental contamination challenges related to acid generation (Aubertin et al. 1996; Bussière 2007). There is increasing interest in reusing mine waste amended with cementitious materials (e.g., fly ash or cement) in earthwork construction projects due to challenges facing mine waste disposal (Misra et al. 1996; Godbout et al. 2007).

Amended mine tailings with a cementitious binder have been used as cemented paste backfill (CPB) in underground mining to fill cavities (ranging from 15 to 40 m in lateral extent and up to 100-m tall) to enhance local and global stability. The mechanical, hydraulic, and environmental behavior of CPB has been investigated by numerous researchers (Zou and Li 1999; Belem et al. 2001; Benzaazoua et al. 2004; Fall et al. 2005, 2008; Kesimal et al. 2005; Klein and Simon 2006; Yeheyis et al. 2009; Zhang et al. 2011; Ghirian and Fall 2015). In general, addition of a cementitious binder can increase strength, reduce hydraulic conductivity, increase pH of the effluent, and stabilize heavy metals present in mine tailings.

The other relevant reuse application of mine tailings amended with cementitious binders is in transportation earthworks. Swami et al. (2007) and Qian et al. (2011) both report successful construction and operation of full-scale road subbases with cement-amended mine tailings. Engineering performance of the cement-amended tailings was assessed via mechanical properties (e.g., unconfined compression strength and California bearing ratio); however, these studies did not report on the hydraulic properties of the amended mine tailings. Most research has been focused on understanding factors affecting the mechanical properties of tailings-binder mixtures (e.g., Kesimal et al. 2004; Benzaazoua et al. 2004; Fall et al. 2005; Mahmood and Mulligan 2010; Yilmaz et al. 2011), and only a limited number of studies have focused on understanding factors affecting hydraulic conductivity of tailings-binder mixtures. Recent work has focused on the effects of water-to-binder ratio (Godbout et al. 2007; Fall et al. 2009) and curing time (Belem et al. 2001; Godbout et al. 2007; Fall et al. 2009; El Mkadmi et al. 2013; Ghirian and Fall 2013) on the hydraulic properties of fly ash-amended mine tailings.

Fly ash is a widely used CCB due to the pozzolanic properties of the material and ability to serve as a primary or supplemental cementitious binder. The addition of fly ash to earthen materials has been shown effective in improving mechanical and hydraulic properties for applications in geotechnical engineering (Ferguson 1993; Ghosh and Subbarao 1998; Edil et al. 2002, 2006; Bin-Shafique et al. 2004;

[1] Alhomair, S.A., Gorakhki, M.H., and Bareither, C.A. (2017). Hydraulic conductivity of fly ash-amended mine tailings, *Geotechnical and Geological Engineering*, 35(1), 243-261, DOI 10.1007/s10706-016-0101-z.

Trzebiatowski et al. 2004; Arora and Aydilek 2005; Kim et al. 2005; Senol et al. 2006; Ahmaruzzaman 2010; Amadi 2011; Tastan et al 2011; Phanikumar and Shankar 2016). However, there has been limited research to evaluate the coupled effects of fly ash amendment and physical characteristics of mine tailings on hydraulic conductivity.

The objective of this study was to evaluate the effect of fly ash amendment on hydraulic conductivity of mine tailings. In particular, water content of mine tailings is a critical characteristic to evaluate as most mine tailings are generated at high water contents and subsequent dewatering techniques can be used to modify mine tailings over a broad range of water contents. Understanding how water content influences the mechanical and hydraulic properties of fly ash-amended mine tailings, and coupling this understanding to tailings and fly ash characteristics, will improve reuse potential of these materials in earthwork construction.

## 1.2 Background

Schematics of binder-amended and non-binder amended soil or tailings with coarser and finer particle-sizes are shown in Figure 1.1. The presence of a cementitious binder (e.g., fly ash or cement) results in formation of calcium silicate hydrate and calcium aluminate silicate hydrate gel (i.e., cementitious bonds) between soil or tailings particles (Paulini 1990; Tastan et al. 2011). Total porosity and pore-size distribution are key parameters that control hydraulic conductivity ($k$) of porous materials. In coarser-grained, unamended materials (Figure 1.1a), larger pore spaces (macro-pores) between adjacent particles provide an enhanced ability to convey fluid relative to finer-grained, uncemented materials that have smaller pore sizes (micro-pores).

The formation of cementitious bonds creates new solid material in a binder-amended soil or tailings specimen (Figure 1.1b) with potential to decrease or increase $k$. For fine-grained materials containing clay, the formation of cementation products will agglomerate clay particles into a cluster known as "clay agglomeration." The agglomeration of clay particles increases the average pore size to create a macro-pore structure (Figure 1.1b), which causes an increase in $k$ (Tay and Goh 1991). For coarse-grained materials and non-plastic fines, the formation of cementation products will bind solid particles, which can decrease the average pore size and develop additional micro-pore structure (Figure 1.1b) that decreases $k$ (Quang and Chai 2015). Key factors shown to influence $k$ of tailings-binder mixtures include (i) water-to-binder ($W/B$) ratio, (ii) binder content, and (iii) curing time.

Bin-Shafique et al. (2004) investigated the effect of water content on reactivity of fly ash-amended silty soils and reported the highest cementitious activity and strength gain for specimens compacted at optimum water content ($w_{opt}$) with no delay in hydration and 1% wet of $w_{opt}$ for specimens compacted 2 hours after hydration. Excess water present in the fly ash-amended soils that does not participate in cementitious bond formation was reported to increase porosity and create a larger pore-size network that increased $k$. Similarly, Fall et al. (2009) conducted experiments on silty tailings-cement mixtures with three $W/B$s (i.e., cement content = 5% and water contents = 23%, 34%, and 45%) and reported that excess available water can increase $k$ by approximately one order of magnitude. Cementitious binders can be non-reactive in clayey specimens compacted dry of $w_{opt}$, because most of the water adsorbs to clay particles and leaves limited available water to react and generate cementitious bonds.

Godbout et al. (2007) evaluated the effect of different binder contents (1% and 4.5%) on $k$ of mine tailings (82% silt) prepared at a constant water content ($w$ = 32%). A larger reduction in $k$ was measured for the higher binder content, which was attributed to enhanced microstructure development with formation of cementitious bonds that reduced void volume and obstructed the flow paths. Xenidis et al. (2002) also investigated the effect of varying fly ash addition (10%, 18%, 31%, and 63%, by dry mass) on *k* of sulfate-rich tailings prepared at constant water content. Hydraulic conductivity decreased three orders of magnitude with an increase in fly ash content from 0% to 63%, due to more cementitious bonding that enhanced blockage of flow paths through the amended specimens.

In contrast, Goh and Tay (1993) reported that an increase in binder content mixed with soft marine clay (primarily kaolin) increased *k* by three orders of magnitude. In a similar study, Deb and Pal (2014) reported that *k* of silty clay soil increased up to 20 times with an increase in fly ash content from 0% to 30% when prepared $w_{opt}$. Similar effects of binder addition on *k* of marine clay have also been reported by Show et al. (2003). These studies attributed the increase in *k* of fly ash-amended clayey soils to (i) agglomeration of clay particles, (ii) binder hydration and cementation on the overall soil structure, and (iii) an increase in overall particle size due to adding rounded, silt-size fly ash particles. Results in Goh and Tay (1993) suggest that clay agglomeration is the dominant mechanism contributing to an increase in *k*.

The effect of curing time has been evaluated by Belem et al. (2001), Godbout et al. (2007), and Fall et al. (2009). These researchers used a broad range of materials and binders to evaluate whether longer binder hydration times led to changes in *k*. All researchers reported that *k* changed relative to the unamended materials during the first seven days of hydration and subsequent increases in hydration time yielded negligible effect on *k* due to near complete binder hydration within seven days.

## 1.3 Materials and Methods

### 1.3.1 Materials

#### 1.3.1.1 Mine Tailings

Two types of tailings were used in this study: (i) one type of natural mine tailings and (ii) two synthetic tailings. Natural and synthetic tailings were used to develop comparisons with literature on fly ash-amended tailings and soils that are used beneficially in earthwork construction applications. Commercially-available soils were used to create two synthetic mine tailings that represent typical particle-size distributions (PSDs) and plasticity of actual hard-rock mine tailings. Natural tailings were collected from a garnet mine located in the state of New York. Garnet tailings were separated into fine and coarse fractions at the mine using a hydrocyclone for subsequent reuse in mine site earthworks (e.g., tailings dams). The fine fraction (i.e., fine-garnet) of the bulk mine tailings was used in this study. A compilation of relevant characteristics for the tailings is in Table 1.1. Geotechnical characterization of synthetic tailings included mechanical sieve and hydrometer (ASTM D422, ASTM 2007), Atterberg limits (ASTM D4318, ASTM 2014a), specific gravity (ASTM D854, ASTM 2014b), and standard-effort compaction (ASTM D698, ASTM 2014c). Physical characterization of natural (fine garnet) tailings was adopted from Jehring and Bareither (2016), with exception of compaction parameters.

The average, upper-bound, and lower-bound PSDs based on a compilation of eight hard-rock mine tailings from literature are shown in Figure 1.2. Two types of synthetic tailings were used in this study: (i) fine synthetic tailings – created to represent the upper-bound PSD and (ii) average synthetic tailings – created to represent the average PSD (Figure 1.2). The PSDs in Figure 1.2 indicate that close replication was achieved for both synthetic mine tailings. These synthetic tailings were created via mixing angular sand from road base material with a maximum particle diameter of 2 mm, silica silt (US silica, USA), and kaolin (Thiele Kaolin Company, USA). The use of synthetic mine tailings was to control material variability (e.g., mineralogy, pore fluid chemistry, angularity) and capture a range in geotechnical characteristics.

#### 1.3.1.2 Fly Ash

Two types of fly ash were used in this study. Fly ash A (FA-A) was collected from Stanton Station, which is a 190-MW power plant in Stanton, North Dakota, and fly ash B (FA-B) was obtained from Platte River Power Authority, which operates a 280-MW power plant near Fort Collins, Colorado. Chemical compositions of the fly ashes were measured with x-ray fluorescence (XRF) and the results are listed in Table 1.2. The XRF analysis of FA-A was performed with a Philips 1600/10 Simultaneous Wavelength Dispersive Unit by Mineralogy-INC (Tulsa, Oklahoma), whereas XRF information for FA-B was obtained from the power plant. Fly ashes were classified based on ASTM C618 (ASTM 2015) and Tastan et al. (2011), and both classified as off-specification (off-spec) fly ash. The off-spec designation only means that the fly ashes do not formally classify as either Class C or Class F, and off-spec fly ashes can yield effective self-cementing behavior. Lime (CaO), which is a primary component responsible for cementitious reactions, accounted for 17% of FA-A and 18.9% of FA-B (Table 1.2).

Janz and Johansson (2002) introduced the CaO-to-$SiO_2$ ratio as a potential indicator for cementitious bond formation, where an increase in this ratio corresponds to a material with enhanced cementitious potential. For FA-A, the CaO-to-$SiO_2$ ratio was 0.86, which was higher than the CaO-to-$SiO_2$ ratio (0.41) in FA-B. Tastan et al. (2011) reported that the highest pozzolanic behavior of fly ashes used in their study was observed for CaO-to-$SiO_2$ ratios between 0.5 and 1.0. Thus, the potential to form cementitious bonds for FA-A was anticipated to be more pronounced relative to FA-B based on the CaO-to-$SiO_2$ ratio.

#### 1.3.1.3 Mixtures of Tailings and Fly Ash

Tailings typically are generated at low solids content (*SC* = solid mass / total mass) ranging from 25-45% as a function of ore processing. These low *SC* tailings can be dewatered to reclaim water for subsequent ore processing and create materials that are more geotechnically stable for final disposal in tailing impoundments or for use in earthwork construction applications. Bussière (2007) identified three ranges of *SC*s that correspond to different levels of tailings dewatering: (i) thickened tailings – *SC* ranging from 50-70%, (ii) paste tailings – *SC* ranging from 70-85%, and (iii) filtered tailings – *SC* greater than 85%.

Synthetic and natural tailings were mixed with tap water to create mixtures with target *SC*s of 70%, 80%, and 90%, which corresponded to approximate initial water contents ($w_i$) of 40%, 25%, and 11%, respectively. Chemical characteristics of the tap water used in all mixtures were pH = 6.9 and electrical conductivity (*EC*) = 13 mS/m. The *SC*s used in this study were selected to provide a range of potential dewatering levels at a given mine as progressive dewatering from thickened to paste to filtered tailings requires additional time, energy, and economic investment. Fly ash-amended natural and synthetic tailings were created with fly ash contents of 10% on a dry mass basis. This fly ash content was adopted based on Edil et al. (2002) who report that 10% fly ash amendments are common in field-construction. Thus, the range of *SC*s selected for this study combined with a single, relevant percent fly ash amendment yielded target *W/B* ratios of 1, 2.5, and 4. This variability in specimen properties was selected to evaluate the effect of tailings dewatering levels and tailings composition on hydraulic conductivity of fly ash-amended materials.

All pure tailings and fly ash-amended hydraulic conductivity specimens were prepared initially from dry tailings. Synthetic tailings were prepared to the target PSD (Figure 1.2) in a dry state and natural tailings were air-dried and ground with a rubber pestle to break all clods. Fly ash-amended tailings mixtures were first mixed dry with the appropriate percent contribution of fly ash and then mixed with tap water (Senol et al. 2006) in a 20-liter bucket and allowed to hydrate for 2 hours. This procedure was used to simulate a typical duration between hydration and compaction in field-scale construction (Edil et al. 2006; Senol et al. 2006). Additionally, ACAA (2003) specifies a maximum elapsed time of 2 hours between moistening a soil-fly ash mixture and compaction. Following compaction or placement of fly ash-amended tailings in the PVC molds, the entire mold and specimen were sealed in polyethylene bags and allowed to cure for seven or 28 days prior to testing. Curing was completed in a room with 100% relative humidity and temperature of 21℃ in accordance with prior research (Mohamed et al. 2002; Bin Shafique et al. 2006; Edil et al. 2006; Senol et al. 2006; Godbout et al. 2007).

### 1.3.2 Compaction Tests

Compaction tests were completed on all three tailings in accordance with standard-effort compaction procedures in 101.6-mm-diameter compaction molds (Method B in ASTM D698, ASTM 2014c). The maximum dry unit weight ($\gamma_{dmax}$) and optimum water content ($w_{opt}$) for each unamended tailings are in Table 1.1. These properties were determined via fitting a third-order polynomial to the compaction curves in accordance with Howell et al. (1997). Compaction characteristics for the unamended tailings exhibit anticipated effects of material composition on $\gamma_{dmax}$ and $w_{opt}$, where an increase in sand and silt content and corresponding decrease in plasticity shifted compaction curves to higher $\gamma_{dmax}$ and lower $w_{opt}$ (Holtz et al. 2011). The higher $\gamma_{dmax}$ for natural tailings relative to both synthetic tailings was also due to a higher $G_s$ (Table 1.1).

A series of compaction tests using the natural tailings was completed with varying fly ash amendment of FA-A to assess how fly ash amendment influences $\gamma_{dmax}$ and $w_{opt}$. Compaction curves for natural tailings and natural tailings amended with 5%, 10%, and 15% FA-A (based on dry mass) are shown in Figure 1.3. Compaction curves for the fly ash-amended natural tailings all plot slightly to the right of the pure natural tailings (Figure 1.3), suggesting that a modest increase in $w_{opt}$ may be anticipated with addition of fly ash. However, there was no clear trend between increasing fly ash content and $\gamma_{dmax}$ or $w_{opt}$.

### 1.3.3 Hydraulic Conductivity Experiments

Hydraulic conductivity tests were done on pure tailings and fly ash-amended tailings. Hydraulic conductivity was measured in flexible-wall permeameters using a constant head method (Method A) in accordance with ASTM D 5084 (ASTM 2010). A schematic of a hydraulic conductivity setup is shown in Figure 1.4. Each experimental setup consisted of a permeameter, headwater (influent) accumulator, tailwater (effluent) accumulator, and an elevated water reservoir to control cell pressure. A manifold was connected to the elevated reservoir so multiple permeameters could be pressurized with the same cell pressure.

Cell pressure was controlled via the water level in the reservoir (Figure 1.4) and set at a target pressure of 15 kPa to simulate anticipated near surface field conditions in transportation earthwork projects (Ghosh and Subbaro 1998; Bin-Shafique et al. 2006). Headwater and tailwater accumulators used for measuring influent and effluent volumes consisted of 38-mm inner diameter clear acrylic tubes with platens and O-rings at each end. Constant head loss across a given specimen was maintained via a Mariotte tube in the headwater accumulator and an elevated exit tube in the tailwater accumulator (Figure 1.4). The hydraulic gradient was approximately 10 (head loss ≈ 1.3 m) in all experiments. This hydraulic gradient was in agreement with ASTM D5084 (ASTM 2010) based on an assumed $k$ of $10^{-7}$ to $10^{-9}$ m/s for the pure tailings. The hydraulic gradient in transportation earthwork applications is expected to be approximately one; however, a larger hydraulic gradient was used to decrease test duration.

Hydraulic conductivity tests on tailings and tailings amended with fly ash were performed in 101.6-mm-diameter flexible-wall permeameters. Tap water ($EC$ = 13 mS/m and pH = 6.9) was used within the permeameters to apply cell pressure and in the permeant fluid to represent field conditions (Ghosh and Subbarao 1998; Fall et al. 2009). Environmental compatibility of leachate from mine tailings and fly ash mixtures was also evaluated on the effluent water (Alhomair 2016), but is not included here. Visible air bubbles were flushed from the drainage tubes prior to testing, and permeation was conducted upward through the specimen to aid in removing entrapped air bubbles. Backpressure was not applied to represent field conditions (Benson and Daniel 1990), but final saturation was computed following completion of all tests. Filter paper and porous stones were placed on the top and bottom of a specimen. All porous stones were soaked in tap water and all specimens were separated from the cell pressure fluid via conventional latex membranes sealed with O-rings.

Permeation of a given hydraulic conductivity specimen was executed until the following termination criteria were achieved for at least four consecutive measurements (ASTM D 5084; Daniel 1994): (i) ratio of effluent volume to influent volume ($V_{out}/V_{in}$) was between 0.75 and 1.25 and (ii) $k$ was within ± 25% of the geometric mean $k$ for $k \geq 1 \times 10^{-10}$ m/s. The majority of specimens were permeated until net outflow equated at least three pore volumes of flow (*PVF*), with exception of specimens prepared with fine synthetic tailings that necessitated longer testing times due to lower hydraulic conductivity ($< 1\text{x}10^{-9}$ m/s) of the kaolin clay. The pore volume of a given specimen was determined with respect to the porosity achieved during specimen preparation. Testing times were extended after meeting ASTM termination criteria to evaluate if temporal trends existed for $k$. After terminating a given experiment, final water content measurements were conducted. The computed final degree of saturation ($S_f$) was between 90% and 99% for the majority of the test specimens. In certain cases, saturation criteria were not met (i.e., some specimens yielded $S_f$ < 95% or $S_f$ > 105%). However, all experiments were conducted in the same manner and all specimens are considered sufficiently saturated to yield representative hydraulic conductivity values.

Hydraulic conductivity specimens consisting of tailings alone and fly ash-tailings mixtures were prepared in 101.6-mm-diameter by 116.4-mm-tall PVC molds. All materials were prehydrated and then either compacted or poured into the PVC molds, depending on consistency of the material; lower *SC* specimens were slurry materials and were poured into the molds, whereas higher *SC* specimens were soil-like and were compacted with standard-effort energy (ASTM D698, ASTM 2014c). The PVC molds containing slurry materials were vibrated following deposition of the slurry to promote air removal and increase specimen density. The inner sidewall of the PVC molds was lubricated with Vaseline® prior to specimen preparation to reduce friction and help facilitate extrusion of the specimens following curing (Jiang et al. 2016). All specimens had height-to-diameter ratios (*H*/*D*) of approximately 1.0, which was in agreement with hydraulic conductivity testing recommendations in Daniel (1994).

Pure tailings specimens at low solids contents (i.e., average synthetic and natural tailings at *SC* = 80% and 70%, and fine synthetic tailings at *SC* = 70%) exhibited slurry consistency and were not possible to test in flexible-wall permeameters because the slurried specimens slumped following removal of a split mold. Therefore, a technique was adopted from Malusis et al. (2009) whereby an acrylic cylinder was placed on the outside of the flexible membrane to avoid slumping of the slurried specimens via providing rigid lateral support for the soft material. A smaller flexible-wall specimen, with length and diameter = 71.1 mm, was used to accommodate the acrylic mold. A small annulus between the inside of the acrylic mold and latex membrane of the test specimen allowed pressurized water to be in direct contact with the flexible membrane encasing the test specimen such that these slurried specimens were subjected to the same 15 kPa confining pressure as the conventional flexible-wall specimens.

A check on $k$ measured with this alternative technique was conducted using average synthetic tailings at a *SC* = 90%. The $k$ measured in the 101.6-mm-diameter flexible-wall permeameter was $5.6\text{x}10^{-8}$ m/s and $k$ measured in the 71.1-mm-diameter flexible-wall apparatus with external acrylic mold was $5.7\text{x}10^{-8}$ m/s. Thus, $k$ determined with this alternative hydraulic conductivity measurement technique was assumed equivalent to $k$ measured in the larger diameter flexible-wall permeameters and are compared directly to each other in this study.

## 1.4 Results

The results of all hydraulic conductivity tests conducted on unamended and fly ash-amended average synthetic, fine synthetic, and natural tailings are in Table 1.3. The initial and final void ratios ($e_i$ and $e_f$), water contents ($w_i$ and $w_f$), and degree of saturations ($S_i$ and $S_f$) are provided for all test specimens. In some cases, $S_f$ was greater than 100%, which is not reasonable. These high values of $S_f$ resulted from difficulty in accurately measuring total volume of some specimens after disassembling the test cells. However, specimens with $S_f$ > 100 % were assumed fully saturated. A compilation of all experimental data from the hydraulic conductivity tests as well as effluent leachate chemistry is in Alhomair (2016).

### 1.4.1 Hydraulic Conductivity Testing

Temporal trends of *k* and $V_{out}/V_{in}$ for unamended average synthetic, fine synthetic, and natural tailings prepared at a *SC* ≈ 90% ($w_i$ ≈ 11%) are shown in Figure 1.5. Minor fluctuations in *k* and $V_{out}/V_{in}$ were observed in the early stages of testing, and both parameters subsequently stabilized. All specimens met ASTM D5084 termination criteria and were subsequently permeated several additional *PVF*s to evaluate any temporal trends in hydraulic behavior. The *k* for each tailings specimen reported in Table 1.3 are representative of the last four consecutive *k* measurements for a given experiment. As shown in Figure 1.5, ASTM termination criteria were met prior to terminating a given experiment and evaluation of a final average *k*. In all experiments, the difference between the final average *k* and *k* based on ASTM termination criteria was less than ± $1x10^{-9}$ m/s, and equal to $1x10^{-10}$ m/s (10%), on average. The final average *k* of each experiment was adopted here as the representative *k* for each material tested in this study.

### 1.4.2 Hydraulic Conductivity of Fly Ash-Amended Tailings

The hydraulic conductivity of synthetic and natural tailings-fly ash mixtures was evaluated using three *SC*s to represent three levels of tailings dewatering (i.e., *SC* ≈ 70%, 80%, and 90%, which coincided approximately with target $w_i$ ≈ 40%, 25%, and 11%, respectively) and all were amended with 10% fly ash, based on dry mass. These test specifications resulted in target *W/B*s of 1, 2.5, and 4. Compilations of *k* versus initial molding water content ($w_i$) for average synthetic, fine synthetic, and natural tailings are shown in Figure 1.6. The $w_{opt}$ identified in Figure 1.6 are representative of unamended tailings (Table 1.1). Bin-Shafique et al. (2004) and Deb and Pal (2014) reported no difference in $w_{opt}$ between binder-amended and non-binder amended silty clay soils, and Lee et al. (2014) reported a modest decrease in $\gamma_{dmax}$ and $w_{opt}$ with addition of fly ash to silty tailings. Thus, for practical purposes, $w_{opt}$ from unamended tailings and were taken as approximate $w_{opt}$ for the fly ash-amended tailings based on literature and the compaction evaluation in Figure 1.3. Data in Figure 1.6 include tailings amended with FA-A and FA-B and specimens cured for 7 days and 28 days.

The *k* versus $w_i$ of all unamended tailings (synthetic and natural) exhibited anticipated behavior relative to $w_{opt}$. Hydraulic conductivity of the average synthetic tailings (Figure 1.6a) and fine synthetic tailings (Figure 1.6b) decreased when transitioning from a dry to wet of $w_{opt}$ condition, which is consistent with an enhanced ability to remold clods with an increase in water content (Mitchell et al. 1965; Benson and Daniel 1990; Daniel and Benson 1990). This remolding results in a more micro-pore dominated structure with increased tortuosity (Shackelford and Moore 2013) that decreases *k*. Subsequent increase in $w_i$ for average and fine synthetic tailings from 25% to 40% increased void ratio of the tailings and increased *k* (Table 1.3).

A similar effect of increasing $k$ with continuous increase in $w_i$ and $e_i$ can be observed for natural tailings in Figure 1.6c. The low water content, unamended natural tailings specimen ($w_i \approx 11\%$) was compacted slightly wet of $w_{opt}$, which yielded the lowest $k$. Subsequent increases in $w_i$ increased $e_i$ from 0.57 to 0.63 and 0.65 (Table 1.3) and yielded a corresponding increase in $k$. Thus, variability in $k$ of the unamended tailings can be explained via anticipated effects of molding water content on hydraulic conductivity.

The effect of fly ash-amendment on $k$ of mine tailings was dependent on (i) the initial molding water content of the mixture ($w_i$) and (ii) solid particle composition of the tailings. The first mechanism is identical to the effect of $w_i$ on $k$ described for the unamended tailings. The range of $w_i$ for the fly ash-amended tailings coincided with mixtures that were prepared dry of $w_{opt}$, near $w_{opt}$, or wet of $w_{opt}$. The effect of $w_i$ relative to $w_{opt}$ on $k$ differed between tailings that were low-plasticity silts (i.e., average synthetic tailings and natural tailings) and tailings that classified as a low-plasticity clay (i.e., fine synthetic tailings). Mechanistic effects on $k$ were evaluated via these two factors and the $W/B$ of the as-prepared tailings-fly ash mixture.

#### 1.4.2.1 Low-Plasticity Silt Tailings

The $k$ versus $w_i$ relationships for the four different fly ash-amended average synthetic tailings are shown in Figure 1.6a. These four fly ash treatments corresponded to two different types of fly ash (FA-A and FA-B) and two curing times (7 days and 28 days). In general, the $k$ versus $w_i$ trends for all four fly ash treatments exhibited a similar trend to the unamended tailings. Hydraulic conductivity decreased when water content increased from dry to wet of optimum, and subsequent increase in water content increased $k$. Additionally, there were no distinct differences between trends or magnitude of $k$ for the four different fly ash treatments.

The $k$ versus $w_i$ relationships for the four different fly ash-amended natural tailings are shown in Figure 1.6c. All four fly ash-amended specimens at $w_i \approx 11\%$ can be assumed compacted near to $w_{opt,}$ based on $w_{opt}$ of unamended natural tailings of 10% and modest increase in $w_{opt}$ for natural tailings amended with 10% fly ash (Figure 1.3). The two higher $w_i$ (≈ 25 and 40%) corresponded to conditions considerably wet of $w_{opt}$. Similar to the unamended tailings, all $k$ measurements for the fly ash-amended natural tailings were lowest for specimens compacted near $w_{opt}$ and $k$ increased with increasing water content (Figure 1.6c).

The synthetic average tailings included 13% clay-sized particles, but exhibited no plasticity (Table 1.1). The natural tailings had a lower clay content (6.6%) and negligible plasticity. Thus, in the average synthetic tailings and natural tailings the clay-sized particles were primarily non-clay minerals and both can be referred to as silty tailings. The effect of fly ash amendment on $k$ was similar for the average synthetic tailings and natural tailings, which was attributed to similarity in tailings particle characterization.

A relationship between $k$ of the fly ash-amended tailings ($k_B$) normalized to the $k$ of unamended tailings ($k_0$) versus $W/B$ for all experiments conducted in this study is shown in Figure 1.7a. The normalized $k$ (i.e., $k_B/k_0$) for the average synthetic and natural tailings (i.e., silty tailings) exhibit scatter about $k_B/k_0 \approx 1.0$ for $W/B \approx 1$ and $k_B/k_0$ were all less than 1.0 for $W/B \approx 2.5$ and 4 (Figure 1.7a). The average synthetic tailings prepared at $w_i \approx 11\%$ ($SC \approx 90\%$; $W/B \approx 1$) were prepared approximately 5% dry of $w_{opt}$ and natural tailings prepared at the same initial conditions were approximately at $w_{opt}$. The limited influence of fly ash on $k$ of the average synthetic and natural tailings at $w_i \approx 11\%$ was attributed to the low-reactivity of fly ash hydration to generate cementitious bonds as both tailings and fly ash particles competed for the limited available water (Bin-Shafique et al. 2004). The one outlier in Figure 1.7a is for the average synthetic tailings prepared at $W/B \approx 1$, amended with FA-A, and cured for 7 days.

Average synthetic tailings and natural tailings prepared at $w_i \approx 25\%$ and 40% exhibited a reduction in $k$ with addition of fly ash relative to the unamended condition (Figures 1.6a and 1.6c). Additionally, in both tailings $k$ reduced more for specimens prepared at $w_i \approx 25\%$ ($W/B \approx 2.5$) compared to specimens prepared at $w_i \approx 40\%$ ($W/B \approx 4$). Hydraulic conductivity of the fly ash-amended average synthetic tailings decreased, on average, by a factor of 3.0 for specimens prepared at $W/B \approx 2.5$ and by a factor of 1.8 for $W/B \approx 4$ (Figure 1.7a). Larger reductions of approximately 5.0 and 2.0 were observed for natural tailings prepared at $W/B \approx 2.5$ and 4, respectively (Figure 1.7a). This reduction in $k$ was attributed to development of cementitious bonds that likely decreased the pore size distribution and/or increased tortuosity. The smaller reduction in $k$ for the average synthetic and natural tailings at $W/B \approx 4$ (i.e., highest $w_i \approx 40\%$) was attributed to reduced effectiveness in cementitious bond formation due to an increase in available water and increase in spacing between the particles (i.e., higher $e_i$).

A compilation of $k_B/k_0$ versus $W/B$ for fly ash-amended materials from literature are shown in Figure 1.7b. Data compiled from literature were separated with respect to silty and clayey materials (i.e., tailings or soil) identified in this study. Similar trends in the effect of fly ash-amendment on $k$ of low-plasticity silty materials are observed in data from Godbout et al. (2007) and Fall et al. (2009), where the addition of fly ash typically decreased $k$.

The development of cementitious bonds for the aforementioned fly ash-amended synthetic average tailings and natural tailings specimens was qualitatively confirmed via the ability to extrude intact specimens following curing, whereas the unamended tailings were slurry and non-self-supporting. An increased stiffness of the fly ash-amended specimens via cementitious bond formation was also supported by the relative change in void ratio of the unamended and amended specimens as shown in Figure 1.8. The change in void ratio ($-\Delta e$) was computed as the difference between final void ratio at the end of a given hydraulic conductivity test ($e_f$) and initial void ratio for the as-prepared specimens ($e_i$). The $-\Delta e$ increased for all silty tailings specimens with an increase in $w_i$. The $-\Delta e$ for the unamended average synthetic (Figure 1.8a) and natural tailings (Figure 1.8c) decreased with addition of fly ash for all specimens prepared at $w_i \approx 25\%$. This reduction in $-\Delta e$ was attributed to increased specimen stiffness due to cementitious bond formation.

The reduction in $-\Delta e$ for both unamended silty tailings specimens prepared at $w_i \approx 40\%$ was more pronounced for specimens amended with FA-A versus FA-B (Figures 1.8a and 1.8c). Fly ash A had a larger $CaO/SiO_2$ ratio and was anticipated to have more pozzolanic potential and be more effective in development of cementitious bonds. This enhanced pozzolanic potential of FA-A versus FA-B is supported by the lower $-\Delta e$ at higher $w_i$ of the silty tailings.

#### 1.4.2.2 Low Plasticity Clay Tailings

The relationships between $k$ versus $w_i$ for the four different fly ash-amended fine synthetic tailings are shown in Figure 1.6b. These $k$ versus $w_i$ relationships exhibit similar trends to the unamended tailings, where a reduction in $k$ was observed for all fly ash treatments when $w_i$ increased from 11% to 25%. This reduction was attributed to more effective remolding of tailings and fly ash clods as water content shifted from a dry of $w_{opt}$ to wet of $w_{opt}$ condition (Mitchell et al. 1965; Benson and Daniel 1990; Daniel and Benson 1990). A subsequent increase in $k$ from $w_i \approx 25\%$ to $w_i \approx 40\%$ was observed for all fly ash treatments except FA-A cured for 28 days. This increase in $k$ was attributed to an increase in overall specimen void ratio with an increase in molding water content (Table 1.3). The continued decrease in $k$ for the fine synthetic tailings specimen amended with FA-A and cured for 28 days may be due to more effective development of cementitious bonds with additional curing time. However, a definitive reason for this trend relative to the other fly ash-amended materials was not identified.

All $k_B/k_0$ for the fly ash-amended fine synthetic tailings were greater than 1.0 and indicate that the addition of fly ash to clayey tailings resulted in an increase in $k$ relative to an unamended condition (Figure 1.7a). This effect of fly ash amendment on $k$ of clayey tailings was attributed to agglomeration of clay particles via addition of a cementitious binder that likely decreased tortuosity and increased $k$. The ratio of $k_B/k_0$ was approximately 10 for $w_i \approx 11\%$ and 25%, and reduced to 3.4, on average, with an increase in $w_i$ to 40%. The one exception was for the fine synthetic tailings at $W/B \approx 1$, amended with FA-A, and cured for 28 days, which did not exhibit as a pronounced increase in $k$ as the other tailings with addition of fly ash. Thus, the effect of fly ash-amendment on $k$ of clay-rich tailings diminished with an increase in water content wet of $w_{opt}$. This behavior is similar to that observed for silty tailings, and can be attributed to larger void ratios and larger pore spaces with additional water present that reduced effectiveness of cementitious bonds to reduce $k$ relative to an unamended condition. Similar observations on the effects of cementitious binder addition and agglomeration of clay particles have been reported in literature as shown in Figure 1.7b.

The development of cementitious bonds in the fine synthetic tailings was qualitatively supported by the ability to extrude intact, fly ash-amended specimens for mixtures prepared at $w_i \approx 40\%$, whereas, the unamended material was slurry and non-self-supporting. The reduction in $-\Delta e$ of the fine synthetic tailings was negligible for all amended and unamended specimens prepared at $w_i \approx 11\%$ and 25% (Figure 1.8b). The absence of volume change following application of a 15 kPa confining pressure was due to specimen preparation dry and near $w_{opt}$, which corresponds to molding water contents that typically yield high strength (e.g., Mitchell et al. 1965). However, the $-\Delta e$ for fine synthetic tailings specimens prepared at $w_i \approx 40\%$ was lower for specimens amended with fly ash relative to the unamended tailings (Figure 1.8b). Additionally, for a given curing time (7 days or 28 days) specimens amended with FA-A yielded lower $-\Delta e$ relative to specimens amended with FA-B, which agrees with observations made for silty tailings and further supports that FA-A was more effective in generating cementitious bonds relative to FA-B.

### 1.4.3 Evaluation of Curing Time and Fly Ash Type

A comparison between $k$ of fly ash-amended tailings cured for 28 days versus 7 days is shown in Figure 1.9a and a comparison between $k$ of tailings amended with FA-B versus FA-A is shown in Figure 1.9b. These 1:1 plots include both synthetic and natural tailings. In general, all data points in Figures 1.9a and 1.9b plot near the 1:1 lines and there is no discernable impact of either curing time or fly ash type on $k$ of the fly ash-amended tailings evaluated in this study.

The negligible effect of an increase in curing time from 7-28 days on $k$ of fly ash-amended tailings was anticipated, based on findings reported in literature (Belem et al. 2001; Godbout et al. 2007; Fall et al. 2009). The limited influence of curing time was attributed to the majority of cementitious bond formation occurring within the first 7 days following hydration. Subsequent increases in curing time yielded limited further development of cementitious bonds, and thus, limited change in hydraulic conductivity.

The negligible effect of fly ash type on $k$ was not anticipated, as past research has demonstrated a greater reduction in $k$ of binder-amended materials via enhanced development of cementitious bonds (e.g., Godbout et al. 2007). A comparison between $CaO/SiO_2$ for FA-A (0.86) versus FA-B (0.41) suggests that FA-A was a more effective cementitious binder based on observed pozzolanic activity by Tastan et al. (2011) for fly ash with $CaO/SiO_2$ between 0.5 and 1.0. Additionally, less volume change occurred for high water content specimens following application of the 15 kPa confining pressure for tailings amended with FA-A (Figure 1.8). Although FA-A had more favorable cementitious characteristics and was observed to lead to stiffer specimens, there was no distinguishable effect of fly ash type on $k$ of the amended tailings.

### 1.4.4 Practical Implications

Soil-binder mixtures can be used in a variety of applications including flowable fill for earthwork applications and underground mining, embankments, and road base and subbase materials. Soils amended with binders should meet specific mechanical, hydraulic, and in some cases environmental criteria, for each application. A summary of hydraulic criteria (i.e., required hydraulic conductivity) for earthwork applications is in Table 1.4. The hydraulic conductivity of synthetic and natural tailings amended with fly ash ranged between $10^{-9}$ to $10^{-7}$ m/s. Thus, in general, the hydraulic conductivity measured on the fly ash-amended synthetic and natural tailings meet acceptability criteria for earthwork construction applications.

Binder amendment to silty tailings caused a decrease in *k* when sufficient water was available to facilitate cementation reactions. In contrast, binder amendment to clayey tailings caused an increase in *k*. Neither of these effects on *k* is detrimental to the applicability of fly ash-amended tailings in earthwork applications. In addition, factoring in the increase in stiffness with fly ash amendment for higher initial water content, the ability to gain strength and have sufficient *k* to fit within the hydraulic criteria compiled in Table 1.5 are beneficial attributes.

**Table 1.1** Summary of synthetic and natural tailings physical characteristics and classification

| Material | *LL* (%) | *PI* (%) | USCS | $d_{max}$ (mm) | Sand Content (%) | Fines Content (%) | Clay Content (%) | $G_s$ | $w_{opt}$ (%) | $\gamma_{dmax}$ (KN/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Fine Synthetic | 37 | 15 | CL | 0.05 | 0.0 | 100.0 | 40.0 | 2.63 | 23.0 | 14.9 |
| Average Synthetic | NA | NA | ML | 2.00 | 14.2 | 85.8 | 13.0 | 2.66 | 17.6 | 16.5 |
| Natural | 18.8 | 0.4 | ML | 2.00 | 36.7 | 63.3 | 6.6 | 3.07 | 9.7 | 18.6 |

Note: *LL* = liquid limit; *PI* = plasticity index (ASTM D4318); USCS = Unified Soil Classification System (ASTM D2487); $d_{max}$ = maximum particle size (ASTM D422); $G_s$ = specific gravity (ASTM D854); $w_{opt}$ = optimum water content and $\gamma_{dmax}$ = maximum dry unit weight (ASTM D698); NA = not applicable.

**Table 1.2** Chemical composition of fly ashes by percent dry mass, based on x-ray fluorescence analysis

| Component | Chemical Formula | Fly Ash A (FA-A) (%) | Fly Ash B (FA-B) (%) |
|---|---|---|---|
| Sodium oxide | $Na_2O$ | 11.6 | 1.1 |
| Magnesium oxide | $MgO$ | 2.4 | 3.9 |
| Aluminum oxide | $Al_2O_3$ | 12.2 | 16.5 |
| Silicon dioxide | $SiO_2$ | 19.8 | 46.1 |
| Phosphorous Pentoxide | $P_2O_5$ | 0.28 | 1.1 |
| Sulfur Trioxide | $SO_3$ | 15.8 | 4.9 |
| Potassium oxide | $K_2O$ | 1.2 | 0.64 |
| Calcium oxide | $CaO$ | 17.0 | 18.9 |
| Iron(III) oxide | $Fe_2O_3$ | 3.6 | 4.9 |

Note: balance of chemical composition to 100% includes additional constituents not listed as components.

**Table 1.3** Initial and final specimen properties and average final hydraulic conductivity for experiments conducted on average synthetic tailings, fine synthetic tailings, and natural tailings with and without fly ash

| Material | Target W/B | Fly Ash | Curing Time (d) | Initial Properties | | | Final Properties | | | $k_{ave}$ (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $e_i$ | $w_i$ (%) | $S_i$ (%) | $e_f$ | $w_f$ (%) | $S_f$ (%) | |
| Average Synthetic Tailings | — | — | — | 0.71 | 11.2 | 41.8 | 0.71 | 26.4 | 98.6 | $5.7 \times 10^{-8}$ |
| | 1 | B | 7 | 0.69 | 11.7 | 44.2 | 0.69 | 26.4 | 99.2 | $6.7 \times 10^{-8}$ |
| | 1 | B | 28 | 0.69 | 11.2 | 42.6 | 0.69 | 25.9 | 98.8 | $6.5 \times 10^{-8}$ |
| | 1 | A | 7 | 0.73 | 11.3 | 40.5 | 0.73 | 29.7 | 106.8 | $2.2 \times 10^{-7}$ |
| | 1 | A | 28 | 0.76 | 9.4 | 32.6 | 0.76 | 28.3 | 98.0 | $5.6 \times 10^{-8}$ |
| | — | — | — | 0.80 | 25.3 | 84.1 | 0.70 | 24.2 | 90.7 | $3.5 \times 10^{-8}$ |
| | 2.5 | B | 7 | 0.66 | 25.0 | 98.8 | 0.66 | 22.8 | 90.1 | $1.5 \times 10^{-8}$ |
| | 2.5 | B | 28 | 0.63 | 23.3 | 96.0 | 0.63 | 22.5 | 92.7 | $1.4 \times 10^{-8}$ |
| | 2.5 | A | 7 | 0.73 | 24.5 | 88.6 | 0.73 | 26.1 | 94.5 | $9.2 \times 10^{-9}$ |
| | 2.5 | A | 28 | 0.70 | 23.7 | 89.0 | 0.70 | 26.3 | 98.6 | $1.0 \times 10^{-8}$ |
| | — | — | — | 1.13 | 38.8 | 90.6 | 0.78 | 29.7 | 100.4 | $8.0 \times 10^{-8}$ |
| | 4 | B | 7 | 0.87 | 38.0 | 96.4 | 0.60 | 24.4 | 105.3 | $4.0 \times 10^{-8}$ |
| | 4 | B | 28 | 0.79 | 39.0 | 96.5 | 0.68 | 25.1 | 103.0 | $2.8 \times 10^{-8}$ |
| | 4 | A | 7 | 1.03 | 38.0 | 94.3 | 0.90 | 37.0 | 104.4 | $4.5 \times 10^{-8}$ |
| | 4 | A | 28 | 1.04 | 38.6 | 97.8 | 0.94 | 37.8 | 106.6 | $6.8 \times 10^{-8}$ |
| Fine Synthetic Tailings | — | — | — | 0.87 | 11.4 | 34.4 | 0.87 | 33.1 | 99.7 | $5.5 \times 10^{-9}$ |
| | 1 | B | 7 | 0.88 | 12.6 | 37.1 | 0.88 | 34.2 | 99.9 | $5.2 \times 10^{-8}$ |
| | 1 | B | 28 | 0.86 | 11.6 | 34.8 | 0.86 | 32.9 | 98.7 | $4.9 \times 10^{-8}$ |
| | 1 | A | 7 | 0.85 | 9.6 | 29.9 | 0.85 | 34.8 | 107.5 | $5.8 \times 10^{-8}$ |
| | 1 | A | 28 | 0.78 | 10.3 | 34.5 | 0.83 | 35.4 | 112.0 | $1.4 \times 10^{-8}$ |
| | — | — | — | 0.72 | 24.4 | 81.4 | 0.72 | 25.8 | 93.3 | $2.3 \times 10^{-10}$ |
| | 2.5 | B | 7 | 0.74 | 25.0 | 87.0 | 0.74 | 26.8 | 93.0 | $1.9 \times 10^{-9}$ |
| | 2.5 | B | 28 | 0.75 | 24.9 | 86.4 | 0.75 | 26.5 | 91.9 | $1.8 \times 10^{-9}$ |
| | 2.5 | A | 7 | 0.72 | 24.8 | 86.5 | 0.72 | 28.3 | 102.7 | $9.8 \times 10^{-10}$ |
| | 2.5 | A | 28 | 0.73 | 24.8 | 85.9 | 0.73 | 29.4 | 105.6 | $2.0 \times 10^{-9}$ |
| | — | — | — | 1.13 | 41.1 | 95.8 | 1.00 | 38.7 | 99.6 | $7.3 \times 10^{-10}$ |
| | 4 | B | 7 | 1.13 | 39.4 | 90.1 | 0.97 | 36.8 | 98.7 | $2.8 \times 10^{-9}$ |
| | 4 | B | 28 | 1.09 | 39.1 | 92.3 | 1.02 | 36.4 | 97.8 | $2.4 \times 10^{-9}$ |
| | 4 | A | 7 | 1.17 | 41.7 | 93.5 | 1.09 | 42.3 | 102.1 | $3.7 \times 10^{-9}$ |
| | 4 | A | 28 | 1.17 | 41.9 | 93.7 | 1.17 | 43.0 | 97.3 | $1.3 \times 10^{-9}$ |

Notes: subscript *i* identifies initial conditions after preparation of unamended specimen and after curing for amended specimen; subscript *f* identifies final conditions after hydraulic conductivity testing; *W/B* = water-to-binder ratio; *e* = void ratio; *w* = water content; *S* = degree of saturation; $k_{ave}$ = arithmetic average of the last four hydraulic conductivity measurements.

**Table 1.4** Initial and final specimen properties and average final hydraulic conductivity for experiments conducted on average synthetic tailings, fine synthetic tailings, and natural tailings with and without fly ash (continued)

| Material | Target W/B | Fly Ash | Curing Time (d) | Initial Properties | | | Final Properties | | | $k_{ave}$ (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $e_i$ | $w_i$ (%) | $S_i$ (%) | $e_f$ | $w_f$ (%) | $S_f$ (%) | |
| Natural Tailings | — | — | — | 0.57 | 12.1 | 65.1 | 0.57 | 16.8 | 90.1 | $3.0 \times 10^{-8}$ |
| | 1 | B | 7 | 0.62 | 11.8 | 56.6 | 0.62 | 18.6 | 89.0 | $3.1 \times 10^{-8}$ |
| | 1 | B | 28 | 0.61 | 11.8 | 57.5 | 0.61 | 18.6 | 90.0 | $4.5 \times 10^{-8}$ |
| | 1 | A | 7 | 0.61 | 10.9 | 53.6 | 0.61 | 19.9 | 97.5 | $1.8 \times 10^{-8}$ |
| | 1 | A | 28 | 0.60 | 10.9 | 54.3 | 0.60 | 19.7 | 97.7 | $1.3 \times 10^{-8}$ |
| | — | — | — | 1.03 | 27.1 | 80.7 | 0.63 | 20.5 | 99.8 | $1.1 \times 10^{-7}$ |
| | 2.5 | B | 7 | 0.65 | 21.6 | 99.0 | 0.55 | 19.5 | 104.7 | $5.7 \times 10^{-8}$ |
| | 2.5 | B | 28 | 0.66 | 21.6 | 97.8 | 0.55 | 19.6 | 106.3 | $5.5 \times 10^{-8}$ |
| | 2.5 | A | 7 | 0.79 | 23.2 | 88.1 | 0.79 | 25.0 | 95.1 | $5.4 \times 10^{-8}$ |
| | 2.5 | A | 28 | 0.78 | 23.2 | 88.8 | 0.78 | 24.9 | 95.4 | $5.5 \times 10^{-8}$ |
| | — | — | — | 1.18 | 36.4 | 94.7 | 0.64 | 22.2 | 105.7 | $2.4 \times 10^{-7}$ |
| | 4 | B | 7 | 1.12 | 36.1 | 95.4 | 0.66 | 23.4 | 105.0 | $1.4 \times 10^{-7}$ |
| | 4 | B | 28 | 1.14 | 37.5 | 97.8 | 0.68 | 23.6 | 103.6 | $1.5 \times 10^{-7}$ |
| | 4 | A | 7 | 1.09 | 35.7 | 98.4 | 0.97 | 31.8 | 98.5 | $1.5 \times 10^{-7}$ |
| | 4 | A | 28 | 1.09 | 36.3 | 99.9 | 0.97 | 32.1 | 99.1 | $1.3 \times 10^{-7}$ |

Notes: subscript *i* identifies initial conditions after preparation of unamended specimen and after curing for amended specimen; subscript *f* identifies final conditions after hydraulic conductivity testing; *W/B* = water-to-binder ratio; *e* = void ratio; *w* = water content; *S* = degree of saturation; $k_{ave}$ = arithmetic average of the last four hydraulic conductivity measurements.

**Table 1.5** Hydraulic conductivity (*k*) criteria for acceptability of earthen materials in earthwork construction applications

| Application | Reference | *k* (m/s) |
|---|---|---|
| Base Layer | FHWA (1997); Kalinski and Yerra (2006) | $10^{-8}$ - $10^{-7}$ |
| Sub-base road construction | Tuncan et al. (2000) | $10^{-10}$ - $10^{-6}$ |
| Flowable Fill | FHWA (1997); Deng and Tikalsky (2008) | $10^{-9}$ - $10^{-8}$ |
| Embankment or structural fill | FHWA (1997) | $10^{-8}$ - $10^{-6}$ |
| Stabilized waste for land disposal | US EPA (1989) | $\leq 1 \times 10^{-7}$ |
| Standard solidified waste | US EPA (1989) | $< 10^{-7}$ |
| Typical stabilized wastes | Tuncan et al. (2000); Mohamed et al. (2002) | $10^{-10}$ - $10^{-6}$ |

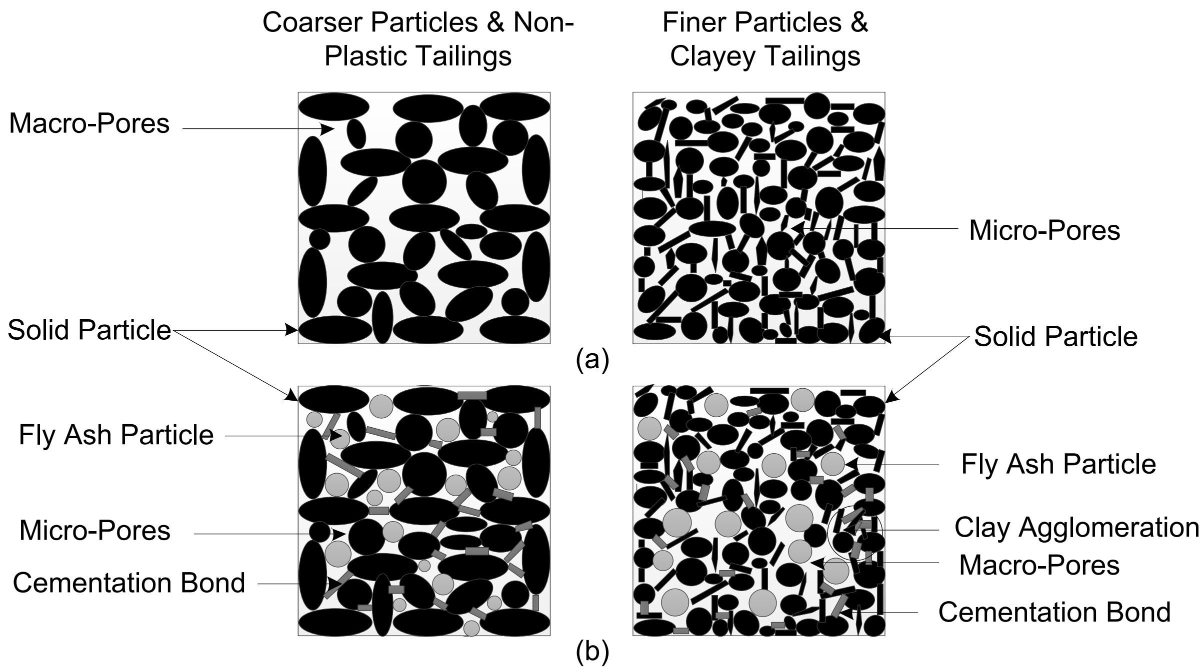



**Figure 1.1** Schematics of (a) unamended and (b) binder-amended tailings (or soils) based on a soil matrix that is either coarser-grained and/or non-plastic or finer-grained and containing clay particles (i.e., exhibits some plasticity).

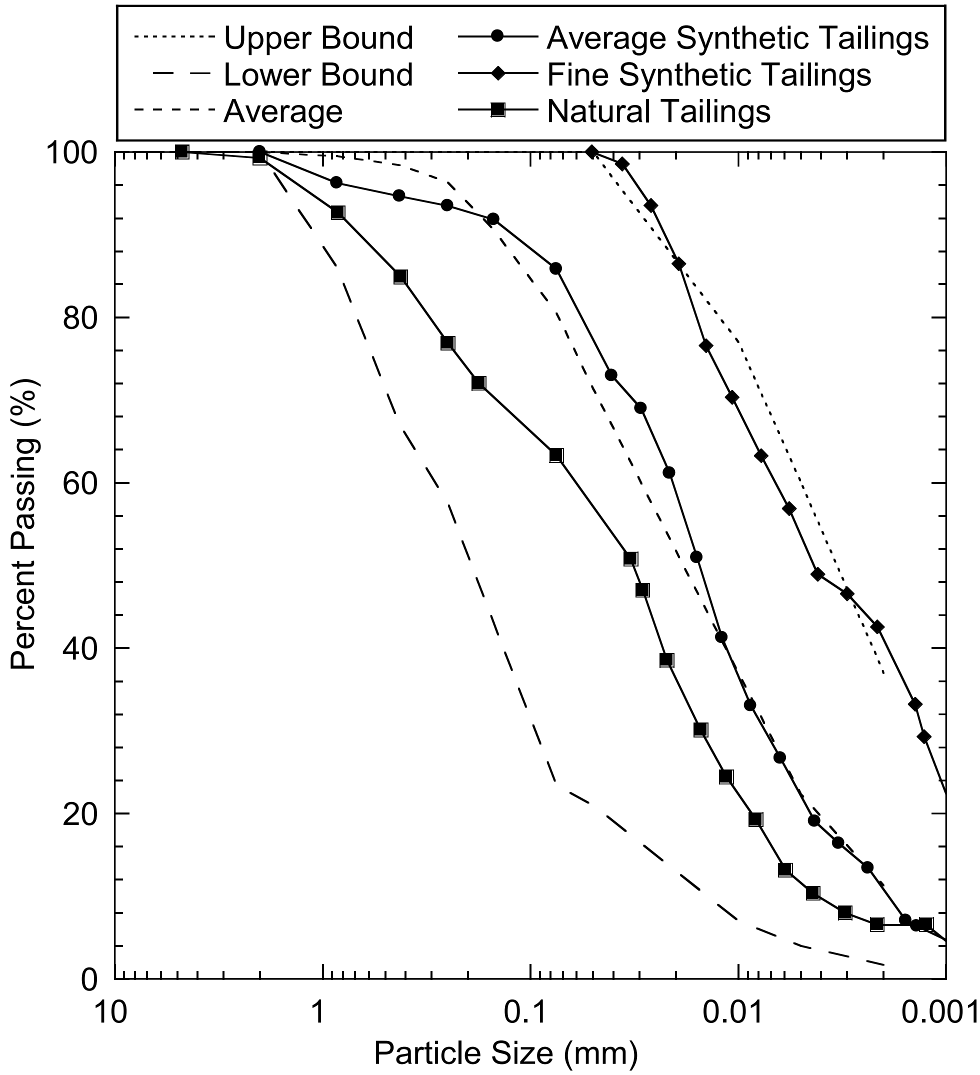



**Figure 1.2** Particle-size distribution for natural tailings, average synthetic tailings, fine synthetic tailings, and the upper-bound, lower-bound, and average from compiled mine tailings particle-size distributions (Qiu and Sego 2001; Morris and Williams 2005; Khalili et al. 2005; Wickland

and Wilson 2005; Wickland et al. 2006; Bussière 2007; Khalili et al. 2010; Wickland et al. 2010).

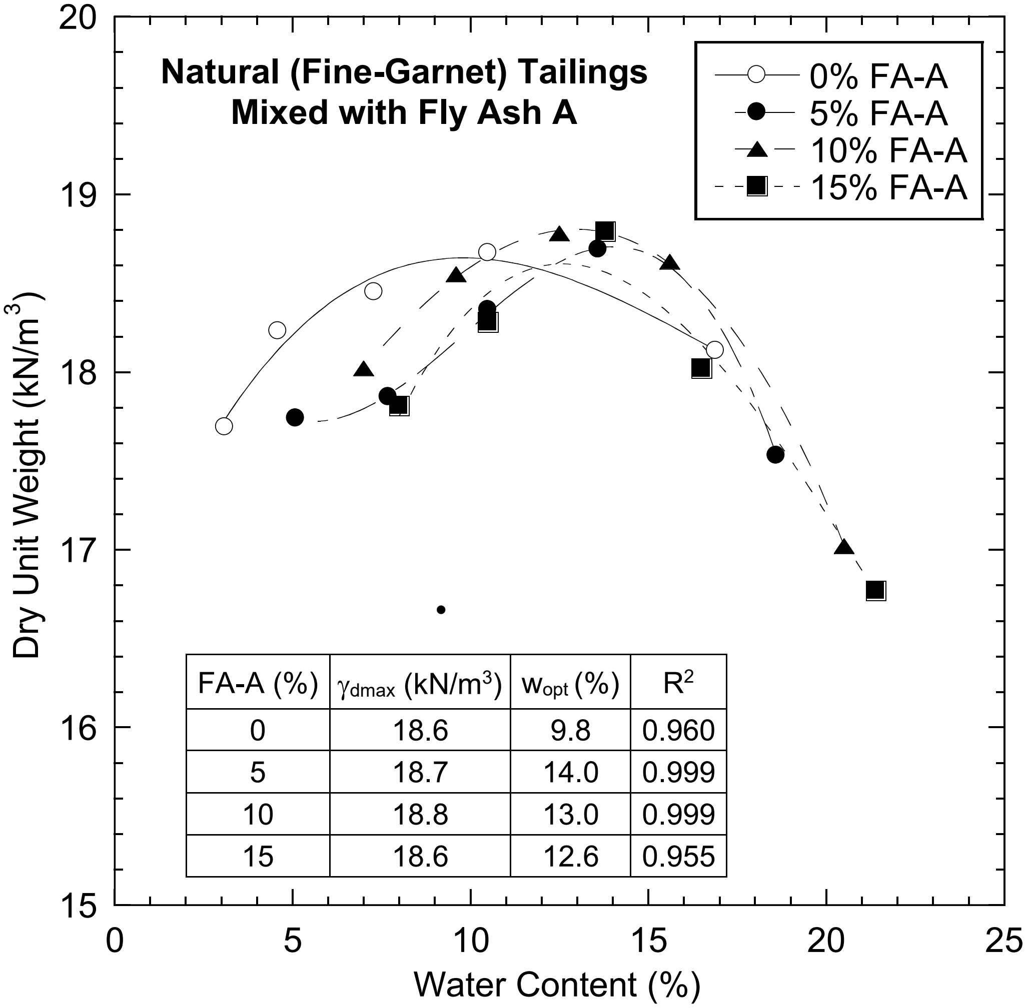



**Figure 1.3** Compaction curves of unamended natural tailings and fly ash-amended natural tailings with 5%, 10%, and 15% addition of Fly ash A (FA-A), based on dry mass. Compaction curves were fitted with a third-order polynomial, based on Howell et al. (1997). The coefficient of determination ($R^2$) represents the fit of the polynomial to compaction data.

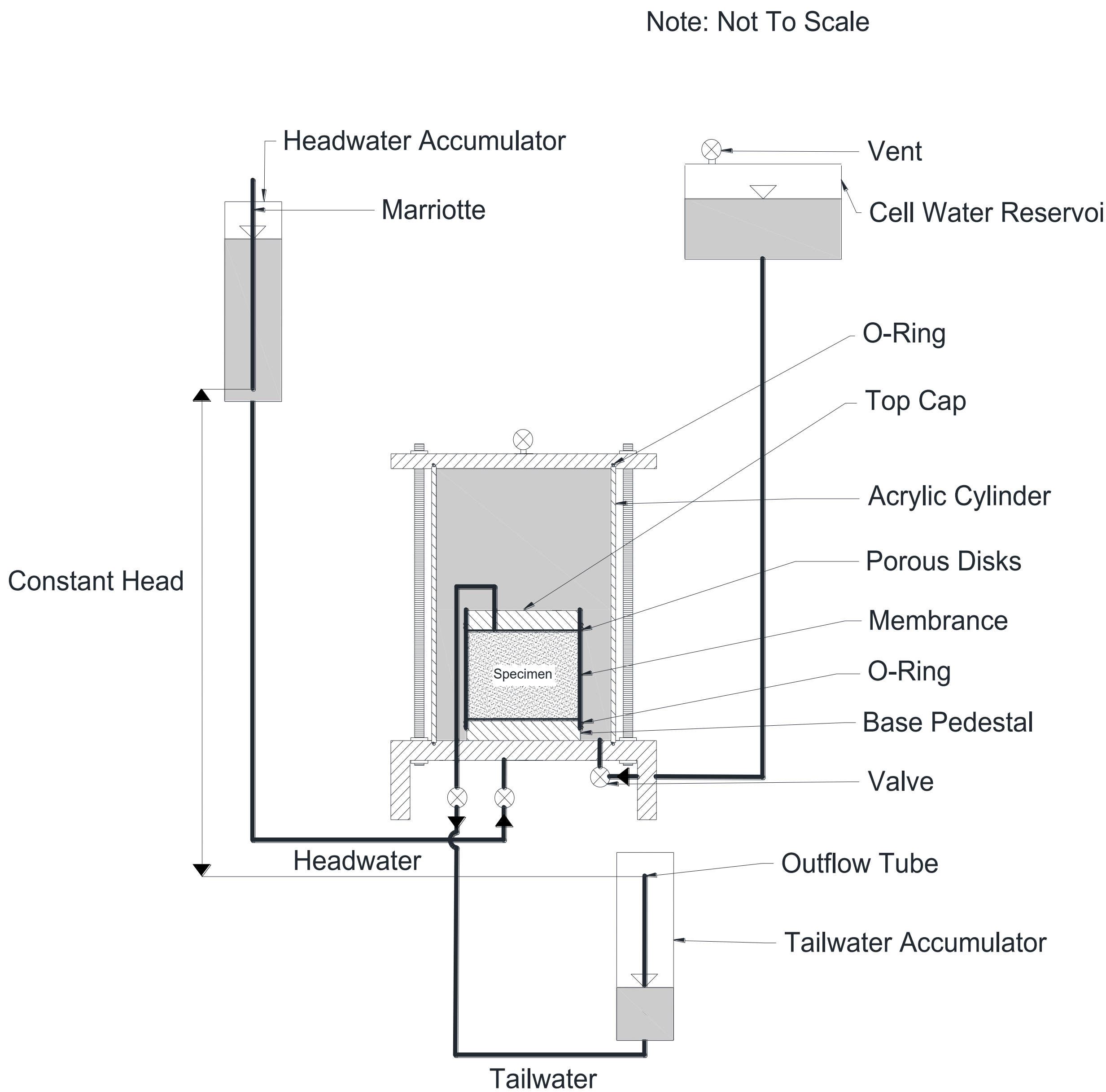



**Figure 1.4** Schematic of the hydraulic conductivity test setup

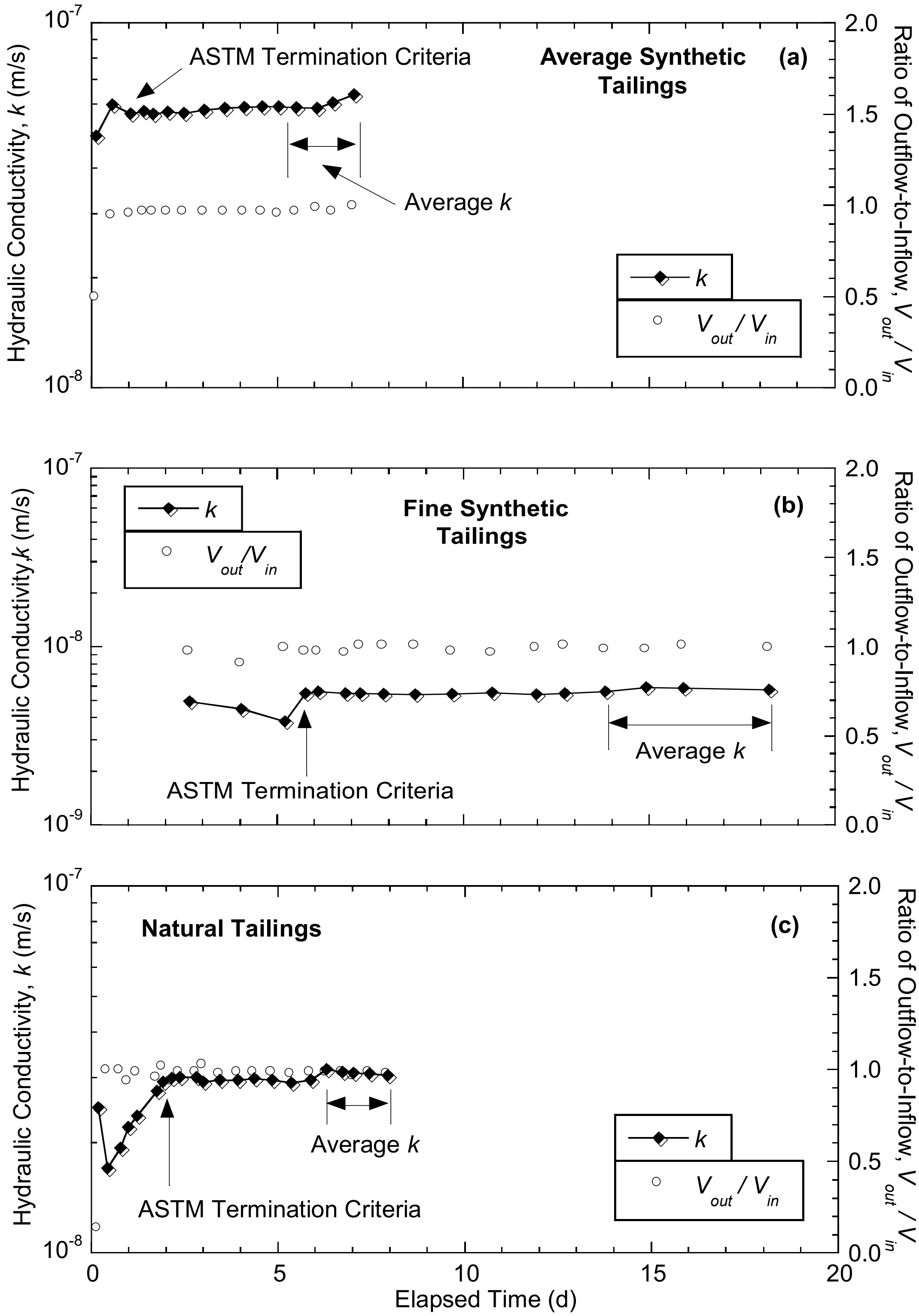



**Figure 1.5** Temporal relationships of hydraulic conductivity and ratio of outflow-to-inflow for unamended (a) average synthetic tailings, (b) fine synthetic tailings, and (c) natural tailings prepared at an initial target water content of 11%.

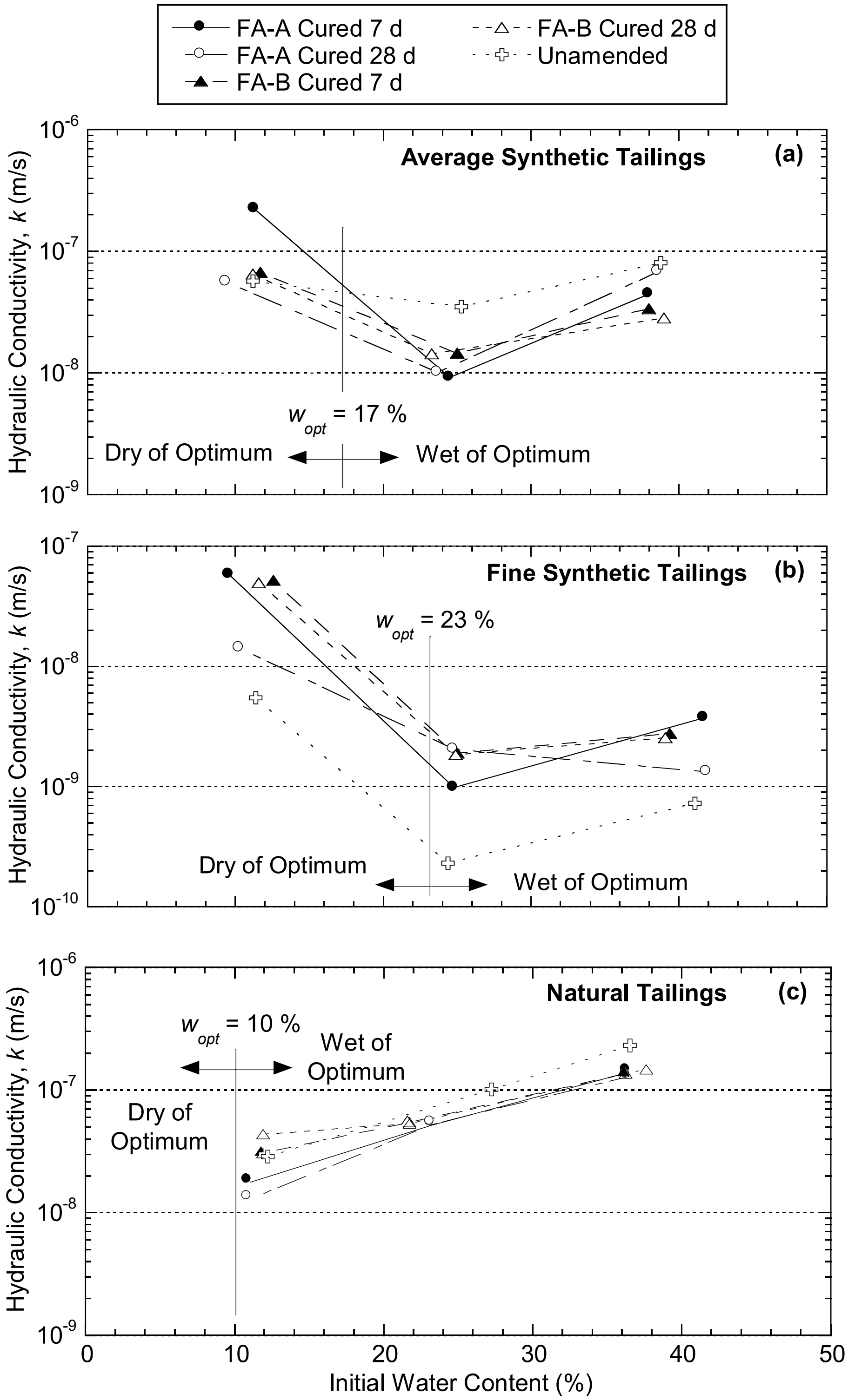
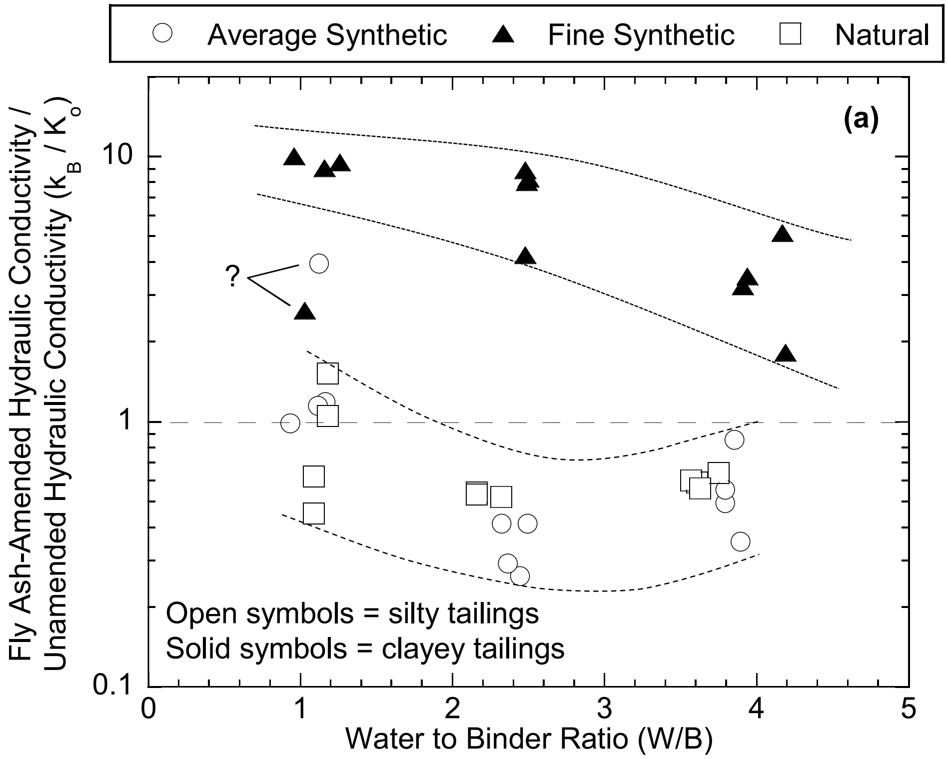



**Figure 1.6** Relationship between hydraulic conductivity ($k$) and initial molding water content ($w_i$) for unamended and all fly ash-amended (a) average synthetic tailings, (b) fine synthetic tailings, and (c) natural tailings. Fly ash-amended tailings include materials mixed with Fly Ash A (FA-A) or Fly Ash B (FA-B) and cured for either 7 days or 28 days.



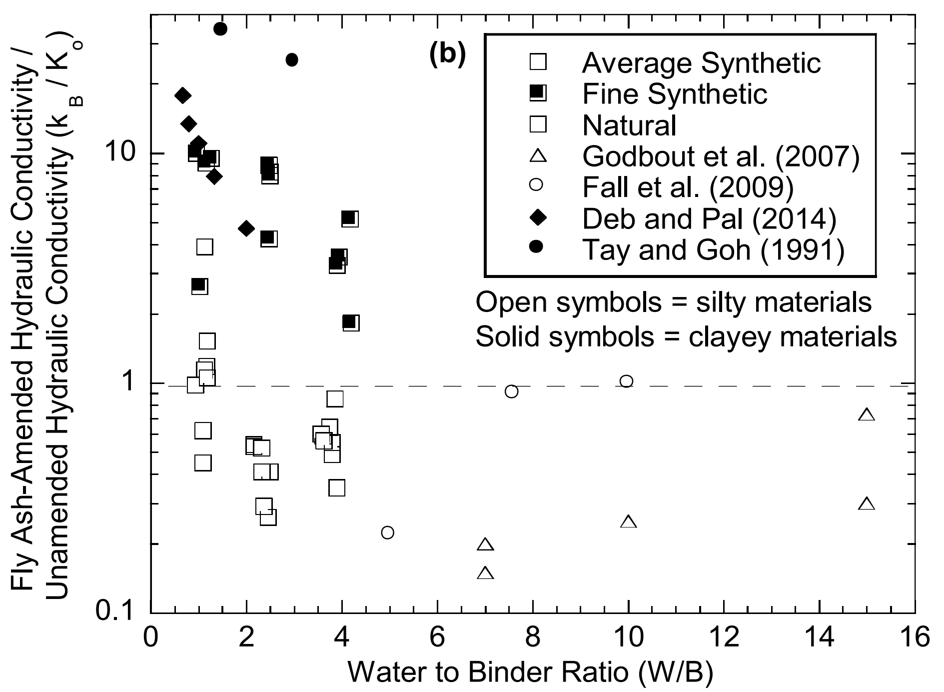




**Figure 1.7** Relationships between (a) normalized hydraulic conductivity ($k_B/k_0$) and water to binder ratio (*W/B*) for all fly ash-amended tailings specimens evaluated in this study, and (b) $k_B/k_0$ versus *W/B* for tests conducted as part of this study and data compiled from literature. Dashed lines capture general trends in $k_B/k_0$ versus *W/B* relationships and the question mark (?) designates outliers in the data.

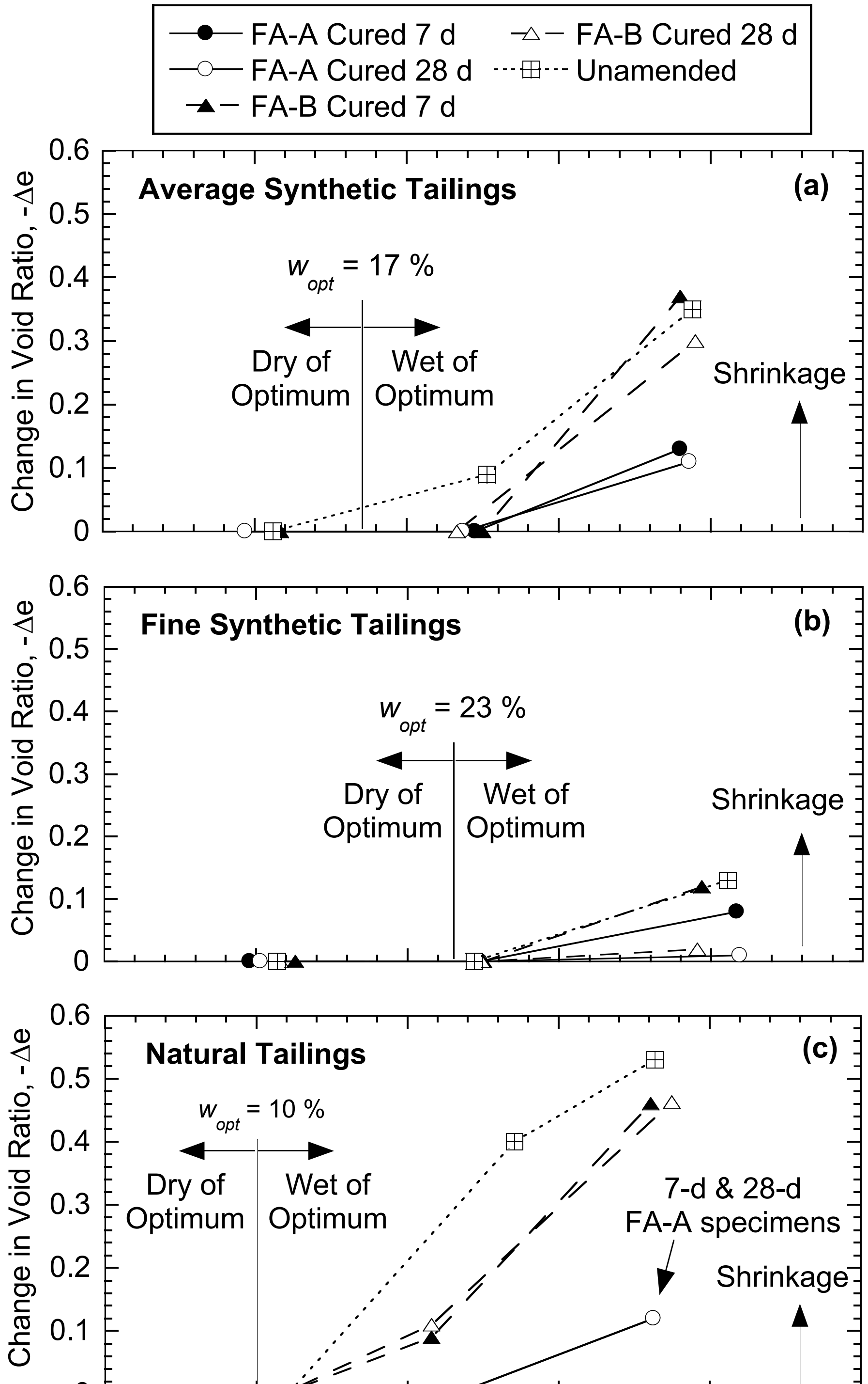



**Figure 1.8** Relationships between the change in void ratio and initial molding water content for (a) average synthetic tailings, (b) fine synthetic tailings, and (c) natural tailings. Change in void ratio computed as the difference between final and initial void ratios [$-\Delta e = -(e_f - e_i)$].

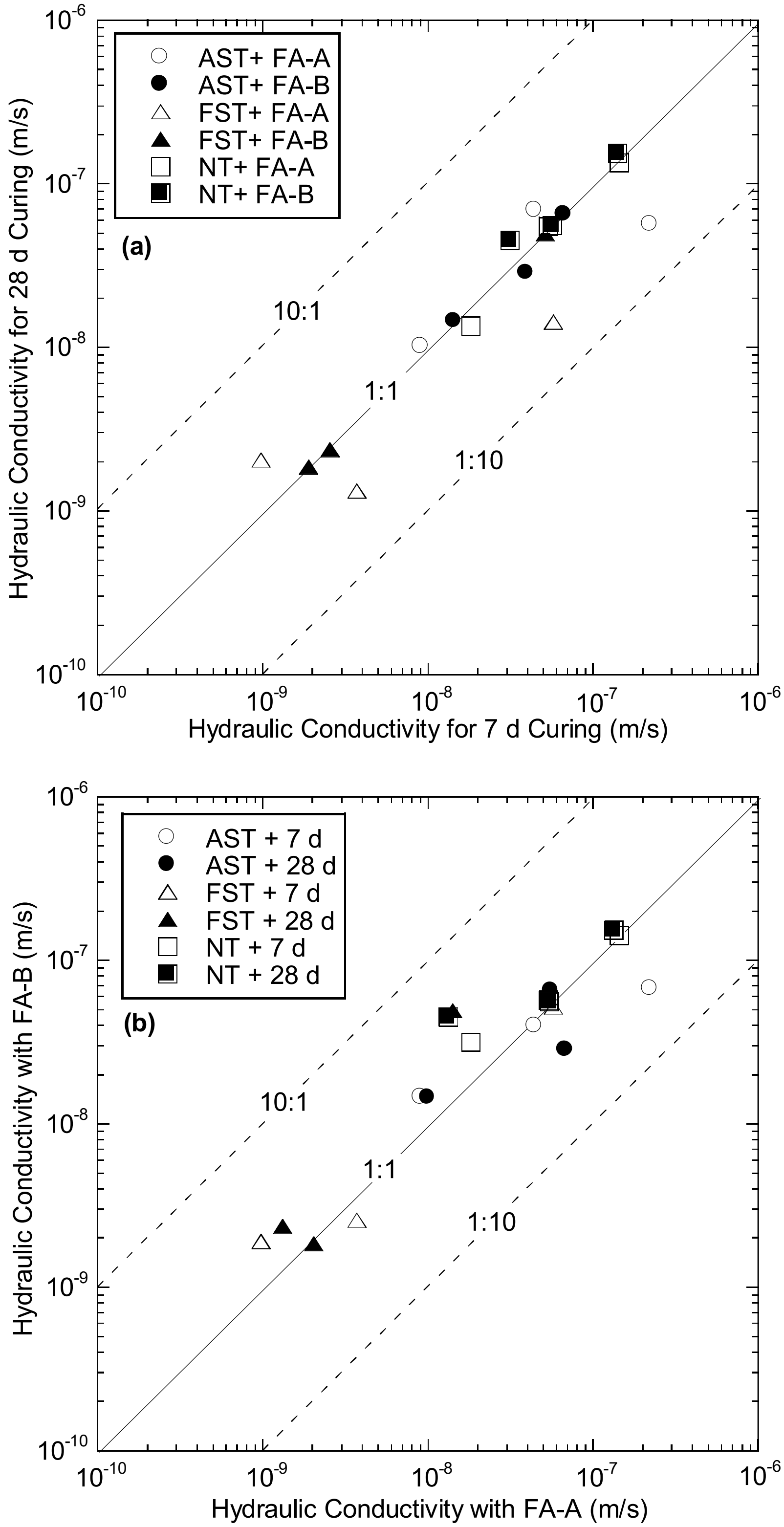



**Figure 1.9** One-to-one plots of hydraulic conductivity of amended tailings (a) cured for 28 days versus those cured for 7 days, and (b) that were cured with Fly ash B (FA-B) versus those cured with Fly ash A (FA-A).

# 2. UNCONFINED COMPRESSIVE STRENGTH OF SYNTHETIC AND NATURAL MINE TAILINGS AMENDED WITH FLY ASH AND CEMENT[2]

## 2.1 Introduction

Improving roadways and initiating new transportation-related projects includes a broad array of earthworks, such as road subbase and subgrade, unpaved roadways, embankments, and fills. Each of these earthworks requires earthen materials (e.g., soil, crushed rock, etc.) that are incorporated into the design to obtain the desired engineering performance. The Federal Highway Administration (FHWA) has identified that the use of recycled materials, such as coal combustion by-products (CCBs), mine waste (mine waste rock and tailings), blast furnace slag, municipal solid waste combustion ash, reclaimed concrete pavement, and scrap tires, has potential to aid transportation-related construction needs (Schroeder 1994; Chesner et al. 1998). Reusing industrial wastes and byproducts can decrease energy consumption, raw material use, and greenhouse gas emissions (Hudson-Edwards et al. 2011).

Mining operations produce considerable volumes of waste materials during ore extraction processes. The two predominant waste materials that require short- and long-term management are tailings and waste rock (e.g., Bussière 2007; Blight 2010). Tailings typically are fine grained and have high water contents (low solids contents), whereas waste rock generally is gravel- to cobble-sized material with some sand and fines. Management of mine tailings in impoundment facilities can be challenging due to variability in physical and chemical properties of the tailings (Bussière 2007). There is increasing interest in reusing mine waste amended with cementitious materials (e.g., fly ash or cement) in earth construction projects due to challenges accompanying mine waste disposal (Misra and Mehta 1996; Godbout et al. 2007).

Amending mine tailings with a cementitious binder has been used as cemented paste backfill (CPB) in underground mining to fill cavities (ranging from 15 to 40 m in lateral extent and up to 100-m tall) and enhance local and global stability. The mechanical, hydraulic, and environmental behavior of CPB has been investigated by numerous researchers (Zou and Li 1999; Belem et al. 2000; Fall et al. 2005; Kesimal et al. 2005; Klein and Simon 2006; Ouellet et al. 2006; Ouellet et al. 2007; Benzaazoua et al. 2008; Ercikidi et al. 2009; Yeheyis et al. 2009; Nasir and Fall 2010; Zhang et al. 2011; Ercikidi et al. 2013). In general, addition of a cementitious binder to mine tailings has been shown to increase strength, reduce hydraulic conductivity, increase pH of effluent, and stabilize heavy metals.

The use of mine tailings amended with binders in the construction of roadways has been investigated by Swami et al. (2007), Mahmood and Mulligan (2010), and Qian et al. (2011). Mahmood and Mulligan (2010) investigated the unconfined compressive strength (UCS) of six mine tailings mixed with Type I Portland cement. Specimens were prepared at different water contents and a constant cement content to evaluate the effect of water-to-binder (*W/B*) ratio. Unconfined compressive strength of the cement-modified tailings ranged from 0.5 to 9.6 MPa for *W/B* ranging between 0.3 and 1.1. The authors did not report a unique correlation between UCS and *W/B*, which suggests that compositional differences between the six mine tailing may have contributed to variability in the UCS measurements.

Qian et al. (2011) evaluated the mechanical performance of cement-stabilized granite tailings and cement-stabilized crushed stone as road subbase material. The UCS of tailings increased with an increase in cement addition and was 5.8 MPa for 6% cement amendment (by dry mass). Split tensile strength (i.e.,

[2] Gorakhki, M.H. and Bareither, C.A. (2017). Unconfined compressive strength of mine tailings amended with fly ash, *Journal of Geotechnical and Geoenvironmental Engineering*, 143(7), 1-14, 10.1061/(ASCE)GT.1943-5606.0001678.

cylindrical specimens loaded along the diameter to measure tensile strength), UCS, and static and dynamic moduli were comparable for cement-stabilized crushed stone and cement-stabilized tailings, which implied that cement-stabilized tailings had suitable strength for road subbase application. Qian et al. (2011) also reported that the physical performance (e.g., UCS, compaction, smoothness, number of cracks, etc.) of a 20.4-km-long highway subbase in China that was constructed with 4%-cement amended tailings was comparable to subbases constructed with traditional materials, and also met roadway specifications immediately following and 2-yr after construction.

Swami et al. (2007) investigated the potential use of cement-amended kimberlite tailings as road construction materials in India. Mixtures of cement-amended tailings met the UCS and California Bearing Ratio requirements for base and subbase material according to construction standards. A 1-km field test section of base course constructed with the cement-amended kimberlite tailings met standard requirements for durability 0.5 yr and 1 yr after construction.

These past studies demonstrated that cement-amended tailings can be suitable for road construction. However, the effect of tailings characteristics and water content on the UCS of tailings amended with different binders (e.g., fly ash) has received little attention. In particular, fly ash is an attractive binder as fly ash is a common CCB used in geotechnical applications in the U.S. due to pozzolanic properties and high availability from coal combustion (ACAA 2015; Park et al. 2014). The use of cementitious binders as a soil-amendment has been evaluated by numerous researchers (e.g., Trzebniatowski et al. 2004; Arora and Aydilek 2005; Edil et al. 2006; Consoli et al. 2007; Consoli et al. 2009; Tastan et al. 2011; Vizcarra et al. 2011; Bose 2012; Senol et al. 2012; Rosa et al. 2016), and this collection of work was used as a baseline to assess the applicability of creating and using binder-amended mine tailings in earthworks.

The objectives of this study were to (i) assess the effect of mine tailings properties (e.g., particle size and water content) and fly ash addition on the UCS of fly ash-amended mine tailings and (ii) assess applicability of the mixtures for use as earth construction materials. The first objective was completed using three synthetic mine tailings prepared from laboratory-controlled materials to more effectively isolate material differences between tailings. The second objective was evaluated via comparison to UCS requirements for different earth construction materials. Additionally, an empirical equation was developed from a multivariate regression analysis to predict UCS of fly ash-amended tailings. This equation was validated via UCS tests conducted on natural tailings as well as relevant data compiled from literature.

## 2.2 Materials and Methods

### 2.2.1 Materials

#### 2.2.1.1 Mine Tailings

Two types of mine tailings were used in this study: (i) synthetic tailings and (ii) natural tailings. Synthetic tailings were created from laboratory-controlled materials [i.e., angular sand from road base material, silica flour (US silica, USA), and kaolin clay (Thiele Kaolin Company, USA)] to capture a range in geotechnical characteristics of mine tailings. Natural tailings were collected from a copper mine in Arizona, USA and a garnet mine in New York, USA. Two fractions of garnet tailings were collected as a hydrocyclone is used at the garnet mine to segregate tailings for subsequent reuse in mine site earthworks (e.g., tailings dams). Geotechnical characterization of all tailings included mechanical sieve and hydrometer (ASTM D422, ASTM 2007), Atterberg limits (ASTM D4318, ASTM 2014a), specific gravity (ASTM D854, ASTM 2014b), and standard-effort compaction (ASTM D698, ASTM 2014c).

The average, upper-bound, and lower-bound particle-size distributions (PSD) of eight different hard rock mine tailings are shown in Figures 2.1a and 2.1b along with the synthetic (Figure 2.1a) and natural (Figure 2.1b) tailings used in this study. Synthetic tailings were created to approximate the average, upper-bound, and lower-bound PSDs in Figure 2.1a, and close replication was achieved in all three cases. The PSDs shown in Figure 2.1b indicate that the natural tailings ranged between average and coarse synthetic tailings (Figure 2.1b).

A summary of geotechnical characteristics for the synthetic and natural tailings is in Table 2.1. Hard rock mine tailings typically classify as low plasticity silts (liquid limit, $LL < 50$ %) (Aubertin et al. 1996; Wickland and Wilson 2005; Bussière 2007; Daliri et al. 2014). The LL of all synthetic and natural tailings in this study was ≤ 37, which compares well to literature. The Unified Soil Classification of the synthetic and natural tailings all differ from one another (Table 2.1), which indicates that a range of material characteristics representative of hard rock mine tailings was captured in this study. Compaction tests were completed primarily to identify the optimum water content ($w_{opt}$), which was used as a reference point to assess the effect of molding water content on water availability during formation of cementitious bonds.

#### 2.2.1.2 Cementitious Binders

Two types of fly ash and one type of cement were used as binders. Fly Ash A (FA-A) was obtained from Stanton Station, which is a 190-MW power plant in North Dakota, USA. Fly Ash B (FA-B) was obtained from Platte River Power Authority power plant, which is a 280-MW power plant in Colorado, USA. Type I-II Portland cement was used as this material was readily available to the researchers; this cement had basic properties of Type I and Type II cements.

The chemical composition of fly ash and cement was measured with x-ray fluorescence (XRF) and results are listed in Table 2.2. The XRF analysis of FA-A was performed with a Philips 1600/10 Simultaneous Wavelength Dispersive Unit by Mineralogy-INC (Tulsa, Oklahoma, USA), whereas XRF information for FA-B and cement were obtained from the power plant and cement producer, respectively. Fly ash was classified based on ASTM C618 (ASTM 2015a) and Tastan et al. (2011), and both FA-A and FA-B classified as off-specification (i.e., off-spec). The off-spec designation only indicates that the fly ashes do not formally classify as Class C or F, and does not infer cementitious behavior. Lime (CaO), which is the main component required for cementitious bond formation, accounted for 17% of FA-A and 18.9% of FA-B.

The relative composition of $CaO + MgO$, $SiO_2$, and $Al_2O_3 + Fe_2O_3$ for the two fly ashes and cement used in this study are shown in the ternary plot in Figure 2.2. Janz and Johansson (2002) introduced the CaO-to-$SiO_2$ ratio as an indicator for potential pozzolanic reaction and Odadjima et al. (1995) introduced CaO-to-[$Al_2O_3$+$SiO_2$] ratio as an indicator for potential to form cementitious bonds. In FA-A, CaO-to-$SiO_2$ ratio (0.86) and CaO-to-[$Al_2O_3$+$SiO_2$] (0.53) were higher than CaO-to-$SiO_2$ ratio (0.41) and CaO-to-[$Al_2O_3$+$SiO_2$] (0.30) in FA-B. Fly Ash A had a more favorable relative composition of the key chemical compounds required for cementitious bond formation compared to FA-B, which suggested that the cementitious behavior of FA-A should be more effective compared to FA-B. Thus, regardless of the larger percent by dry mass composition of all chemical components required for cementitious behavior in FA-B compared to FA-A, the relative makeup of the cementitious constituents in FA-A was higher. The cement used in this study plots within the anticipated range of cements and has higher cementitious properties in comparison with FA-A and FA-B (Figure 2.2).

### 2.2.2 Slump Tests

Mine tailings generated at ore processing plants typically contain low solids content (*SC*) and high water content (*w*) due to ore extraction processes (Bussière 2007). Dewatering of mine tailings often is conducted to reclaim water for subsequent ore processing, and Bussière (2007) reported the following levels of dewatered tailings: (i) thickened tailings = *SC* from 50 – 70% and *w* from 43 to 100%, (ii) paste tailings = *SC* from 70 – 85% and *w* from 18 to 43%, and (iii) filtered tailings = *SC* > 85% and *w* < 8%. Natural tailings typically are dewatered for use in earthwork applications. Thus, both synthetic and natural tailings were prepared to *SC*s of 70%, 80%, and 90% in this study to represent a range of dewatering from thickened to filtered tailings. These *SC*s also yielded a range of *W/B* ratios for a given percent binder amendment.

Slump cone tests were conducted on fine, average, and coarse synthetic tailings prepared to three target *SC*s (70%, 80%, and 90%) following ASTM C143 (ASTM 2015b). Each slump cone specimen was prepared in three layers of equal volume and each layer was tamped 25 times. Relationships between slump and solids content for the three synthetic tailings are shown in Figure 2.3. All three synthetic tailings tested at *SC* = 90% yielded a slump of zero, which corresponds to a specimen that remained completely intact with no vertical deformation (Figure 2.3). In contrast, coarse and average synthetic tailings were slurries at *SC* = 70% and deformed completely to yield a slump of 300 mm. An increase in slump corresponds to a more slurried material that has lower strength to remain erect once the external slump cone used to form the specimen is removed. Slump values were higher (i.e., more vertical deformation under self-weight) for specimens with larger particle-size prepared at the same *SC*. This trend in slump for synthetic tailings was attributed to an increase in soil suction with a decrease in particle size for materials prepared to the same water content (e.g., Lu and Likos 2004; Fredlund et al. 2012). A higher soil suction corresponds to a higher effective stress that enables a specimen to remain intact and yield a lower slump.

### 2.2.3 Unconfined Compression Strength Tests

Unconfined compression strength tests were conducted on tailings alone and on binder-amended tailings in accordance with ASTM D5102 (ASTM 2009). All UCS specimens were prepared in 102-mm-diameter by 203-mm-tall PVC split molds. Mixtures were compacted or poured into the PVC molds depending on material consistency; i.e., lower *SC* (higher *w*) specimens were slurry-like and were poured into the molds, whereas higher *SC* (lower *w*) specimens were soil-like and were compacted with standard effort. PVC molds containing slurried materials were vibrated to promote air removal and increase specimen density. Following specimen preparation within the PVC molds, the entire specimen including the mold was wrapped in plastic to prevent evaporation and allowed to cure for 7 days at a temperature of 25 °C and relative humidity of approximately 100% as recommended by Senol et al. (2006).

Unconfined compressive strength tests were conducted at an axial strain rate of 1 %/min (ASTM D5102, ASTM 2009) using a Geotest S5760 load frame with axial load capacity of 20 kN. A 25-kN S-type load cell (25 ± 0.005 kN; ELE Int., Bedfordshire, UK) with external signal conditioner (CCT 100; Omega Engr. Inc., Stamford, CT, USA) was used to measure axial force and a linear position transducer (76.2 ± 0.02 mm; GeoTac, Houston, TX, USA) was used to measure axial displacement. Force and displacement transducers were monitored via a National Instruments data acquisition board (UCS-6009) controlled with LabVIEW software.

In-situ fly ash- and cement-amended soils typically are compacted 1-2 hours after preparing the mixture and moistening the material (Edil et al. 2006). A delay between hydrating a binder-amended mixture and compaction can decrease strength of the mixture due to breakage of cementitious bonds during compaction. ACAA (2003) specifies a maximum delay of two hours between moistening the soil-fly ash mixture and compaction. Based on these recommendations, compaction of the UCS specimens prepared in this study was performed two hours after adding binder to a specimen and hydrating to simulate field conditions.

## 2.3 Results

### 2.3.1 Unconfined Compressive Strength

A summary of all UCS tests conducted on synthetic tailings, with and without binder amendment, is in Table 2.3. All percent binder amendments listed in Table 2.3, and those referenced throughout this paper, are based on dry mass. Examples of stress-strain relationships for unamended and amended coarse synthetic tailings prepared at a *SC* = 90% are shown in Figure 2.4. The UCS was selected as the maximum axial stress applied to a given specimen. The fly ash-amended specimens (10% FA-A and 10% FA-B) exhibited an initial stiffer response to loading and attainment of a larger UCS relative to the unamended specimen. Additionally, the specimen modified with FA-A exhibited a much more pronounced strength gain relative to FA-B, which is an artifact of more effective cementitious bonds formed via FA-A relative to FA-B (described subsequently). Both the amended and unamended data sets in Figure 2.4 exhibit strain-softening behavior following attainment of a maximum axial stress. Stress-strain behavior shown in Figure 2.4 is representative of the UCS experiments conducted as part of this study.

#### 2.3.1.1 Unconfined Compressive Strength of Pure Synthetic Tailings

The relationship between UCS of pure synthetic tailings specimens (i.e., no binder amendment) as a function of *SC* and water content is shown in Figure 2.5. Data in Figure 2.5 support a trend of increasing UCS with increasing *SC* or decreasing water content. A decrease in water content (increase in *SC*) can increase soil suction and correspondingly increase effective stress as long as water menisci remain connected between adjacent particles (e.g., Lu and Likos 2004; Fredlund et al. 2012). The largest UCS of the unamended synthetic tailings was measured for *SC* = 90% for all three synthetic tailings (Figure 2.5). Although moisture retention properties of the synthetic tailings were not measured, UCS data suggest that the progressive increase in *SC* from 70% to 90% corresponded to an increase in soil suction and effective stress that increased UCS (Figure 2.5). Similarly, the increase in *SC* from 80% to 90% for the average and coarse synthetic tailings resulted in the development of effective stress such that the UCS was measurable (Figure 2.5).

Fine synthetic tailings prepared at *SC* = 70% and average and coarse synthetic tailings prepared at *SC* = 70% and 80% yielded no measurable UCS (Figure 2.5). The non-self-supporting behavior of these specimens agrees with slump tests conducted on the synthetic tailings (Figure 2.3) whereby slumps > 10 mm coincided with specimens that yielded a UCS of essentially zero.

#### 2.3.1.2 Unconfined Compressive Strength of Fly Ash-Amended Synthetic Tailings

The UCS of fly ash-amended synthetic tailings is shown in Figure 2.6 as a function of *SC* and type of synthetic tailings. The UCS of unamended tailings is included in Figure 2.6 for comparison. The UCS of fly ash-amended synthetic tailings can be explained via three mechanisms: (i) the availability of water to react with fly ash and generate cementitious bonds; (ii) replacement of angular tailings particles with rounded fly ash particles; and (iii) chemical composition of the binder and overall potential to generate cementitious bonds. The first mechanism is primarily related to the impact of tailings particle size on the availability of free water to react with fly ash and form cementitious bonds that can lead to enhanced

UCS. This mechanism is discussed via relationships to optimum water content ($w_{opt}$) of the pure synthetic tailings and *W/B* ratios. The second mechanism of material replacement relates to the addition of rounded fly ash particles that can reduce interlocking between angular tailings particles. This mechanism was observed to decrease UCS. The third mechanism is related to the difference in chemical composition of the binders, whereby the enhancement of UCS relative to a no-binder condition corresponded to cementitious potential of a binder, which is related to chemical composition.

#### 2.3.1.2.1 Water Availability

Specimens were prepared to target *SC*s. Fly ash was added to more appropriately simulate anticipated field operations. As a result, water initially adsorbed to tailings particles may result in limited water available to participate in cementitious reactions (Bin-Shafique et al. 2004). Powers and Brownyard (1948) and Jensen and Hansen (2001) report that water present in soil-cement mixtures can be classified into three groups: (i) capillary water, which is free water within the pore space; (ii) gel water, which is physically-bonded water; and (iii) chemically-bonded water, which is water incorporated in cementitious bonds. Physically and chemically bonded water are a function of chemical composition of the binder. Free water is mobile water retained in the void space of the specimen. The ideal water content of a binder-amended specimen is the sum of chemically- and physically-bonded water, where no free water exists. However, the optimum *W/B* is not only a function of chemical composition of the binder, but also a function of water available to react with the binder.

Bin-Shafique et al. (2004) investigated the effect of molding water content on UCS of fly ash-amended soils and reported that the highest UCS were obtained for specimens compacted at $w_{opt}$ with no delay in hydration and 1% wet of $w_{opt}$ for specimens compacted 2-h after hydration. Synthetic tailings specimens prepared at *SC* = 90% coincided with water contents that were 12% dry of $w_{opt}$ for fine synthetic tailings, 6.5% dry of $w_{opt}$ for average synthetic tailings, and 2.5% wet of $w_{opt}$ for coarse synthetic tailings. These comparisons are based on an assumption that the $w_{opt}$ of fly ash-amended low-plasticity material does not differ considerably from $w_{opt}$ of unamended low plasticity soil (Senol et al. 2006; Deb and Pal 2014). Accounting for this assumption, available water to react with fly ash in the 90% *SC* specimens was low in fine synthetic tailings, whereas more water was available in the average and coarse synthetic tailings. The formation of cementitious bonds and increase in UCS was evident in coarse and average synthetic tailings at *SC* = 90% that were amended with FA-A (Figure 2.6a). However, the addition of FA-B did not yield a consistent trend of enhanced UCS, which was attributed to chemical characteristics of the fly ash (described subsequently).

The increase in water content for average and coarse synthetic tailings prepared at a *SC* = 80% and 70% relative to *SC* = 90% resulted in no measureable UCS for unamended specimens (Figure 2.5, and Figures 2.6b and 2.6c). However, the addition of FA-A to average and coarse synthetic tailings generated cementitious bonds and resulted in measureable UCS for these two low *SC*s. The UCS of average and coarse synthetic tailings amended with FA-B was measureable for a *SC* = 80%, which indicates that FA-B had some cementitious potential to enhance UCS relative to an unamended condition (Figure 2.6b). The increase in water content to a *SC* = 70% resulted in complete strength loss in both the average and coarse synthetic tailings amended with FA-B. However, formation of cementitious bonds in the fine synthetic tailings at *SC* = 70% is supported by the measurable UCS of all fly ash-amended specimens relative to zero UCS for unamended fine synthetic tailings (Figure 2.6c).

The relationship between UCS of fly ash-amended synthetic tailings as a function of *W/B* is shown in Figure 2.7a. Data plotted in Figure 2.7a include all UCS experiments conducted on fly ash-amended synthetic tailings (Table 2.3) and support a trend of decreasing UCS with increasing *W/B*. Data in Figure 2.7a are segregated into two groups: (i) synthetic tailings specimens amended either completely or partially with FA-A and (ii) synthetic tailings specimens amended completely with FA-B. Logarithmic regression lines included for each group in Figure 2.7a are statistically significant and indicate similar trends of decreasing UCS with increasing *W/B*. The enhanced UCS for specimens amended with FA-A relative to FA-B was consistent among materials evaluated in this study and was attributed to the difference in chemical composition of the two fly ashes (discussed subsequently).

A decrease in *W/B* for tests conducted in this study corresponded to either an increase in *SC* and corresponding decrease in *w*, or an increase in percentage of fly ash (Table 2.3). The decrease in *w* was shown to increase UCS of unamended synthetic tailings (Figure 2.5) and similarly increase the UCS on fly ash-amended specimens (e.g., increase in UCS for a given synthetic tailings and percent fly ash amendment in Figure 2.6). The increase in fly ash from 10% to 20% for a given synthetic tailings and *SC* generally corresponded to an increase in UCS (Figure 2.6). However, this trend likely would have been strengthened with experiments that included 20% FA-A, which was not possible due to limitations on the mass of available material. Regardless, data collected in this study support the general trend of increasing UCS with increasing percent fly ash amendment that has been demonstrated by others (e.g., Bin-Shafique et al. 2004; Edil et al. 2006; Senol et al. 2006; Tastan et al. 2011).

The relationship between UCS of fly ash-amended synthetic tailings and the ratio of porosity to volumetric binder content ($n/B_v$) is shown in Figure 2.7b. The $n/B_v$ parameter is representative of the ratio of void volume to binder volume in a given specimen and has been evaluated as a predictor of binder-amended UCS (e.g., Consoli et al. 2007; Consoli et al. 2009). Trendlines included for both FA-A and FA-B data sets in Figure 2.7b are statistically significant and indicate that UCS decreases with increasing $n/B_v$. An increase in $n/B_v$ corresponds to either an increase in porosity for a constant binder volume or a decrease in binder volume for a given soil porosity. In both cases, the fraction of void volume filled with cementitious binder decreases as $n/B_v$ increases, which supports the decreasing trend with UCS. The trendlines included in Figures 2.7a and 2.7b show similar trends of UCS as a function of *W/B* and $n/B_v$. The increase in statistical significance for the UCS- $n/B_v$ relationship was attributed to a broader range in the magnitude of $n/B_v$ (~ 0-12) versus *W/B* (~ 0-5), and both relationships are effective in explaining variability in UCS of binder-amended mine tailings as a function of material properties.

**2.3.1.2.2 Material Replacement**

The UCS of all fine synthetic tailings specimens prepared at *SC* = 90% and amended with FA-A and FA-B were approximately the same (Figure 2.6a). This similarity in UCS was attributed to the low amount of available water, considering the as-prepared water content coincided with 12% dry of $w_{opt}$, which limited water available to generate cementitious bonds. The modest reduction in UCS for the fly ash-amended specimens was attributed to reduced particle interlocking as rounded fly ash particles replaced a fraction of the angular tailings particles. Similar, but more pronounced effects of this mechanism of strength reduction via material replacement were observed for fine synthetic tailings prepared at *SC* = 80% (Figure 2.6b). The UCS of all fly ash-amended fine synthetic tailings at *SC* = 80% were less than the UCS of the unamended specimen. Considering that the fine synthetic specimens at *SC* = 80% were prepared 2% dry of $w_{opt}$ and sufficient water was likely not available for pozzolanic reactions, the reduced UCS of the fly ash-amended specimens was attributed to the replacement of tailings particles with rounded fly ash particles.

This same mechanism of strength loss due to material replacement supports the modest reduction in UCS for average synthetic tailings prepared at SC = 90% and amended with FA-B (Figure 2.6a). The unamended average synthetic tailings specimen was prepared at 6.5% dry of $w_{opt}$, which suggests there may be a limitation on available water to generate cementitious bonds. The increase in UCS for average tailings amended with FA-A indicates that some water was available for the pozzolanic reactions to generate cementation. However, considering the weakly cementing behavior of FA-B, the inclusion of rounded fly ash particles to average synthetic tailings at SC = 90% had more potential to decrease UCS via material replacement versus enhancing strength via cementation. These competing mechanisms are supported by the decrease in UCS, as the percent contribution of FA-B was increased from 10% to 20%, which led to a more pronounced reduction in UCS via increased material replacement.

#### 2.3.1.2.3 Fly Ash Chemical Composition

Comparisons between the UCS of fine, average, and coarse synthetic tailings amended with 10% FA-B and 10% FA-A are shown in Figure 2.8a. Comparisons between the UCS of fine, average, and coarse synthetic tailings amended with 20% FA-B and 10% FA-A plus 10% FA-B (i.e., 20% total fly ash amendment) are shown in Figure 2.8b. Data points in Figure 2.8 are differentiated based on tailings type (fine, average, and coarse) as well as *SC* (70, 80, and 90%). All data in Figure 2.8a plot below the 1:1 line. Similarly, all data in Figure 2.8b plot below the 1:1 line with the exception of fine synthetic tailings at SC = 90%. These comparisons indicate that the UCS of synthetic tailings amended with FA-A was greater than the UCS of synthetic tailings amended with FA-B. The one exception was discussed previously in regards to the lack of available water in fine synthetic tailings prepared to a SC = 90%, which actually resulted in reduced UCS relative to the unamended material (Figure 2.6a).

The two fly ashes used in this study had comparable CaO contents (FA-A = 17 % and FA-B = 18.9 %). However, the $CaO/SiO_2$ ratio was 0.86 for FA-A and 0.41 for FA-B. Tastan et al. (2011) investigated the UCS of three organic soils amended with six different fly ashes and reported higher UCS for specimens amended with fly ash that had $CaO/SiO_2$ ratios between 0.5 and 1.0 as compared to lower ratios. The higher $CaO/SiO_2$ ratio for FA-A yielded more pronounced pozzolanic activity and resulted in higher UCS via cementitious bond formation relative to FA-B. This observation was consistent for both the 10% fly ash (Figure 2.8a) and 20% fly ash (Figure 2.8b) amendment comparisons.

The UCS of synthetic tailings specimens prepared at SC = 80% and 10% Portland cement amendment are listed in Table 2.3. The UCS of cement-amended synthetic tailings ranged between approximately 1810 kPa and 2190 kPa. This increase in UCS relative to unamended specimens was considerably larger compared to specimens amended with fly ash. This enhanced UCS was anticipated based on the $CaO/SiO_2$ ratio of the cement (Figure 2.2) and these UCSs agree with UCS of cement-amended mine tailings reported in previous studies (e.g., Swami et al. 2007; Mahmood and Mulligan 2010).

## 2.3.2 Multivariate Regression Analysis

### 2.3.2.1 Model Development

A multivariate regression analysis was used to develop an empirical relationship to predict UCS, based on relevant physical characteristics of tailings and fly ash. Regression analysis was preferred relative to other prediction methods due to the simplicity with which a regression equation can be applied, the ability to ensure statistical significance of each independent variable, and the clarity with which physical significance between dependent and independent variables can be evaluated. Forward, backward, and stepwise regressions were performed. Forward stepwise regression begins with no independent variables and sequentially adds variables to a model in order of their significance in predicting the dependent variable. Backward stepwise regression begins with all independent variables and sequentially removes variables from a model that are least significant in predicting the dependent variable. A general stepwise regression is a modified version of forward regression, where a backward step follows each forward step. Independent variables are added (forward and stepwise model selections) or removed (backward and stepwise model selections) until only those variables that are statistically significant remain in the model. All regression analyses were conducted in SAS® University Edition (SAS Institute Inc., Cary, NC, USA) and a significance level of 0.05 was used to evaluate statistical significance of each independent variable.

Regression analyses were performed with UCS as the dependent variable and the following independent variables: $D_{10}$ (particle diameter at 10 % passing on a PSD); $D_{50}$ (particle diameter at 50% passing on a PSD); $C_u$ (coefficient of uniformity); $C_c$ (coefficient of curvature); $f_c$ (fines content; percent of particles < 0.075 mm); *c* (clay content; percent of particles < 0.002 mm); *w* (water content of tailings); $w$-$w_{opt}$ (difference between water content and optimum water content of tailings); $UCS_0$ (UCS of tailings without fly ash amendment); *fa* (fly ash content by dry mass); *W/B* (water to binder ratio); and $CaO/SiO_2$ (ratio of calcium oxide over silicon oxide of the fly ash). The chemical composition of fly ash was included as an independent variable via the $CaO/SiO_2$ ratio as this parameter is more descriptive in the propensity to induce cementitious bonds relative to other parameters (e.g., CaO) (Tastan et al. 2011). The $n/B_v$ parameter was not included in the regression analysis since most studies did not provide volumetric binder fraction or binder particle density, which limited calculation of $n/B_v$ for model validation.

The empirical relationship in Eq. 3.1 was obtained via the regression analysis.

$$UCS = 270.7 - 697.7 \cdot w + 288.7 \cdot \frac{CaO}{SiO_2} - 34.1 \cdot \frac{W}{B} \quad (3.1)$$

This model was obtained via both backward and stepwise model selection procedures. All three independent variables (*w*, $CaO/SiO_2$, and *W/B*) can be readily measured via standardized laboratory procedures and have physical significance. The negative coefficients on *w* and *W/B* indicate that an increase in either of these parameters will decrease UCS, which was shown in Figure 2.5 and Figure 2.7a. The positive coefficient on $CaO/SiO_2$ indicates that an increase in this ratio will increase UCS of fly ash-amended materials. This relationship was documented via comparison of FA-A and FB-B (Figure 2.8) as well as in the relationship shown in Figure 2.2.

The forward regression analysis resulted in a similar model as Eq. 3.1, but with inclusion of two additional independent variables (i.e., clay content and UCS of unamended material). A modest improvement in the coefficient of determination ($R^2$) was achieved for the forward regression ($R^2 = 0.80$) relative to the backward and stepwise model in Eq. 3.1 ($R^2 = 0.79$). However, the modest improvement in statistical significance could not be justified via inclusion of two additional independent variables. Also, including UCS of unamended material would require an additional experiment to be conducted to predict UCS of an amended material. Thus, the forward regression model was not selected.

A comparison between predicted UCS via Eq. 3.1 and measured UCS of synthetic tailings is shown in Figure 2.9. The regression model predicted UCS within 100 kPa for nearly all specimens. Six predictions for specimens with low measured UCS yielded a negative predicted UCS based on Eq. 3.1. These negative predicted UCSs were plotted as zero in Fig 3.9.

### 2.3.2.2 Validation of the Prediction Model

The UCS of three natural tailings prepared at *SC* = 70% and 80% and amended with 10% FA-A, FA-B, or cement are shown in Figure 2.10. The UCS of pure tailings at both solids contents (SC = 70% and 80%) were not measured as all natural tailings at these *SC*s exhibited slurry behavior. Similar to the observations from UCS tests on synthetic tailings, FA-A yielded higher UCS relative to FA-B at both *SC*s (Figure 2.10). Natural tailings specimens amended with FA-B at *SC* = 70% did not have any strength, which was attributed to the high *w* and *W/B* that inhibited development of cementitious bonds. However, FA-B was effective in strengthening natural tailings prepared at *SC* = 80% (Figure 2.10b). The UCS of cement-amended natural tailings was an order of magnitude larger relative to fly ash-amended specimens, which agreed with the strength enhancement observed for synthetic tailings.

Comparisons of predicted UCS versus measured UCS for natural tailings evaluated in this study and data compiled from literature are in Figures 2.11 and 2.12. All UCS predictions were made via Eq. 3.1. Data compiled from Senol et al. (2002), Trzebniatowski et al. (2004), Tastan et al. (2011), Bose (2012), and Senol et al. (2012) are based on fly ash-amended soils. Data included in Figure 2.11 are for low plasticity soils and tailings that have LL < 50, whereas data included in Figure 2.12 are for high plasticity soils with LL > 50. Additionally, data compiled from literature only were included that had UCS < 400 kPa to coincide with the UCS range based on the synthetic tailings experiments used to generate the regression equation.

The regression model in Eq. 3.1 predicted UCS within 100 kPa for nearly all low plasticity specimens compiled from literature and this study (≈ 90% of measured UCS are within ± 100 kPa of predicted UCS in Figure 2.11). The average bias for UCS predicted with Eq. 3.1 for data compiled in Figure 2.11 was -6.3 kPa (bias computed as predicted minus measured UCS). The narrower range of predicted UCS for natural tailings from this study (± 85 kPa) compared with data compiled from literature (± 175 kPa) was attributed to using the same fly ash and UCS procedures as used to create the prediction model. The model in Eq. 3.1 is applicable for assessing a potential range of UCS for candidate low plasticity mine tailings and fly ashes in earthwork constructions. However, additional testing and analysis is needed to refine the model, and direct prediction of UCS via Eq. 3.1 should be completed with engineering judgement.

In general, the UCS of high plasticity materials was under-estimated by nearly 100 kPa with the regression model (i.e., average bias = - 92.3 kPa in Figure 2.12). This underestimation primarily was attributed to higher as-prepared *w* for high plasticity soils that led to a reduction in predicted UCS due to the large negative coefficient on *w* in Eq. 3.1. The regression model in Eq. 3.1 was created based on low plasticity materials with $w_{opt}$ ranging from approximately 9% to 23% (synthetic tailings). The $w_{opt}$ of materials in Figure 2.11 (low plasticity soils) ranged between 0% and 28%, whereas $w_{opt}$ of materials in Figure 2.12 (high plasticity soils) ranged between 21% and 48%; as a result, low plasticity soils are wet of optimum or slurry in the $w_{opt}$ range of high plasticity soils. This water content constraint with the model underestimated UCS of high plasticity soils.

Tastan et al. (2011) developed the following model for UCS of fly ash-amended soils:

$$UCS = -320 + 795\left(\frac{CaO}{SiO_2}\right) - 573\left(\frac{CaO}{SiO_2}\right)^2 - 125{,}673\left(e^{-OC}\right) + 6\left(f_a\right) + 25\left(UCS_0\right) - 33\left(pH_{mix}\right) \qquad (3.2)$$

where *OC* is organic content of soil, $pH_{mix}$ is pH of soil-fly ash mixture, and all other parameters are as defined previously. This model was developed based on UCS measured on three soils with *OC* ranging between 5% and 27% and clay content ranging from 15% to 55%. Specimens were prepared with 10%, 20%, and 30% amendment of six different fly ashes with $CaO/SiO_2$ ranging from 0.09 to 1.15. Eq. 3.2 was used to predict UCS of synthetic tailings amended with fly ash in this study considering *OC* = 0. The UCS of mixtures prepared at *SC* = 90% for all synthetic tailings and *SC* = 80% for fine synthetic tailings was over-estimated by one order of magnitude, whereas UCS of mixtures prepared at *SC* = 70% for all synthetic tailings and 80% for average and coarse synthetic tailings yielded negative values. These inaccurate UCS predictions were attributed to the inclusion of $UCS_0$, which was substantial for all synthetic tailings at *SC* = 90% and fine synthetic tailings at *SC* = 80%, whereas $UCS_0$ was near zero for most synthetic tailings prepared at *SC* = 70% and 80% (Figure 2.6).

The inaccurate prediction of fly ash-amended specimens in this study via Eq. 3.2 and under-prediction of high plasticity soils compiled from literature via Eq. 3.1 (Figure 2.12) suggests that two models may be needed to predict UCS of fly ash-amended specimens; i.e., one model for low plasticity materials and another model for high plasticity materials. Further investigation is needed to develop a model to predict the UCS of fly ash-amended high plasticity tailings and/or evaluate the feasibility of developing a single, holistic UCS prediction model for the broad range of plasticity encountered in soils, mine tailings, and other geomaterials.

### 2.3.3 Practical Implications

The focus of this study was to evaluate the UCS of hard rock mine tailings amended with fly ash. Hard rock mine tailings generally classify as low plasticity with *LL* ranging between 15 and 35% (Aubertin et al. 1996; Wickland and Wilson 2005; Daliri et al. 2014). The empirical model developed using synthetic mine tailings (Eq. 3.1) encompassed the range of plasticity and particle size anticipated in most hard rock mining operations and was shown applicable to provide preliminary estimates of the UCS of natural mine tailings and low plasticity soils compiled from literature (Figure 2.11). The model is applicable for estimating the UCS of candidate fly ash-amended hard rock mine tailings and fly ash-amended low plasticity soils. However, engineering judgement should be used when extrapolating the model beyond the parameter ranges used for development and additional testing should be considered to quantify the UCS of actual materials to be used in design.

A schematic of transportation earthworks and the corresponding UCS ranges required for earthen materials used in these earthworks is shown in Figure 2.13. Also listed in Figure 2.13 are UCS criteria for relevant applications of mine tailings in cemented paste backfill. Earthen materials amended with binders generally are required to meet specific mechanical, hydraulic, and in some cases environmental criteria for each application. These requirements often differ from one application to the other (Figure 2.13). The UCS of synthetic and natural tailings amended with fly ash ranged between 0 to 590 kPa and the UCS of tailings amended with cement ranged between 1050 to 2190 kPa. The UCS of tailings amended with fly ash did not meet UCS requirements for base or sub-base of roadways. However, the UCS of tailings amended with Portland cement in SC = 80% was sufficient for road sub-base construction. Tailings prepared at a *SC* = 90% and amended with FA-A, and specimens prepared with Portland cement at all SCs met the UCS requirements for use in flowable fill and cemented paste backfill. Thus, there are varieties of earthwork applications in which fly ash amended mine tailings are suitable, and further modification of the SC, fly ash content, and/or other relevant parameters may render them suitable for additional applications.

Creating a sustainable geomaterial from two waste materials (e.g., mine waste and fly ash) for use in earthwork construction should not have negative impacts on the natural environment. A companion study (Alhomair 2016; Alhomair et al. 2016) was conducted to assess hydraulic conductivity and effluent leachate chemistry on a broad range of the fly ash-amended synthetic and natural tailings discussed herein. Leachate chemistry was evaluated to quantify the concentration of heavy metals (e.g., chromium, copper, cadmium, silver), and peak measured concentrations were compared to maximum contaminant levels (U.S. EPA 1993) and toxicity limits (U.S. EPA 1986) for drinking water. All heavy metal concentrations were below the toxicity limits with exception of chromium and copper for some tailings specimens amended with FA-A. No universal relationships were observed between exceedance of metal concentration levels for drinking water among the different mine tailings and fly ashes used in this study. Thus, there may be environmental constraints on reusing certain mine tailings and/or fly ashes in earthwork construction and specific environmental tests should be completed on candidate materials.

**Table 2.1** Summary of synthetic and natural tailings physical characteristics and classification

| Material | *LL* (%) | *PI* (%) | USCS | $d_{max}$ (mm) | Sand Content (%) | Fines Content (%) | Clay Content (%) | As-Collected Water Content (%) | $G_s$ | $w_{opt}$ (%) | $\gamma_{max}$ (KN/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Fine Synthetic | 37 | 15 | CL | 0.05 | 0.0 | 100.0 | 40.0 | NA | 2.63 | 23 | 14.9 |
| Average Synthetic | NA | NA | ML | 2.00 | 14.2 | 85.8 | 13.0 | NA | 2.66 | 17.6 | 16.5 |
| Coarse Synthetic | NA | NA | SM | 2.00 | 70.3 | 29.7 | 5.5 | NA | 2.69 | 8.6 | 19.9 |
| Copper | 25.2 | 13.7 | SC | 0.85 | 54.7 | 45.3 | 7.0 | 238.0 | 2.72 | 13.3 | 16.7 |
| Fine Garnet | 18.8 | 0.4 | ML | 2.00 | 36.7 | 63.3 | 6.6 | 13.1 | 3.07 | 9.7 | 18.6 |
| Coarse Garnet | NA | NA | SP | 2.00 | 89.9 | 10.1 | - | 3.2 | 2.99 | 0.0 | 19.3 |

Note: *LL* = liquid limit; *PI* = plasticity index; USCS = Unified Soil Classification System; $d_{max}$ = maximum particle size; $G_s$ = specific gravity; and NA = not applicable.

**Table 2.2** Chemical composition of fly ashes and cement by percent dry mass based on x-ray fluorescence analysis

| Component | Chemical Formula | Fly Ash A (FA-A) (%) | Fly Ash B (FA-B) (%) | Cement (%) |
|---|---|---|---|---|
| Sodium oxide | $Na_2O$ | 11.6 | 1.1 | - |
| Magnesium oxide | $MgO$ | 2.4 | 3.9 | 1.4 |
| Aluminum oxide | $Al_2O_3$ | 12.2 | 16.5 | 4.7 |
| Silicon dioxide | $SiO_2$ | 19.8 | 46.1 | 19.9 |
| Phosphorous Pentoxide | $P_2O_5$ | 0.28 | 1.1 | - |
| Sulfur Trioxide | $SO_3$ | 15.8 | 4.9 | 3.3 |
| Potassium oxide | $K_2O$ | 1.2 | 0.64 | - |
| Calcium oxide | $CaO$ | 17.0 | 18.9 | 63.2 |
| Iron(III) oxide | $Fe_2O_3$ | 3.6 | 4.9 | 3.2 |

Note: balance of chemical composition to 100% includes additional constituents not listed in Components.

**Table 2.3** Summary of unconfined compressive strength (UCS) tests conducted on synthetic tailings specimens amended with fly ash or cement

| Name | Tailings | Solids Content (%) | Saturation (%) | Porosity | Binder Type | Binder Content (%) | Water-to-Binder Ratio | UCS (kPa) |
|---|---|---|---|---|---|---|---|---|
| SF-90-N | F | 90 | 34 | 0.46 | - | 0 | - | 303 |
| SA-90-N | A | 90 | 42 | 0.41 | - | 0 | - | 298 |
| SC-90-N | C | 90 | 83 | 0.26 | - | 0 | - | 209 |
| SF-80-N | F | 80 | 81 | 0.45 | - | 0 | - | 214 |
| SA-80-N | A | 80 | 94 | 0.41 | - | 0 | - | 0 |
| SC-80-N | C | 80 | 96 | 0.41 | - | 0 | - | 0 |
| SF-70-N | F | 70 | 98 | 0.53 | - | 0 | - | 0 |
| SA-70-N | A | 70 | 94 | 0.55 | - | 0 | - | 0 |
| SC-70-N | C | 70 | 97 | 0.54 | - | 0 | - | 0 |
| SF-90-FA-A10 | F | 90 | 39 | 0.43 | FA-A | 10 | 1.1 | 276 |
| SA-90-FA-A10 | A | 90 | 36 | 0.45 | FA-A | 10 | 1.1 | 371 |
| SC-90-FA-A10 | C | 90 | 89 | 0.25 | FA-A | 10 | 1.1 | 553 |
| SF-80-FA-A10 | F | 80 | 86 | 0.43 | FA-A | 10 | 2.5 | 180 |
| SA-80-FA-A10 | A | 80 | 93 | 0.42 | FA-A | 10 | 2.5 | 304 |
| SC-80-FA-A10 | C | 80 | 98 | 0.41 | FA-A | 10 | 2.5 | 315 |
| SF-70-FA-A10 | F | 70 | 93 | 0.55 | FA-A | 10 | 4.3 | 93 |
| SA-70-FA-A10 | A | 70 | 96 | 0.54 | FA-A | 10 | 4.3 | 123 |
| SC-70-FA-A10 | C | 70 | 100 | 0.54 | FA-A | 10 | 4.3 | 112 |
| SF-90-FA-B10 | F | 90 | 35 | 0.45 | FA-B | 10 | 1.1 | 260 |
| SA-90-FA-B10 | A | 90 | 45 | 0.39 | FA-B | 10 | 1.1 | 272 |
| SC-90-FA-B10 | C | 90 | 79 | 0.27 | FA-B | 10 | 1.1 | 228 |
| SF-80-FA-B10 | F | 80 | 84 | 0.44 | FA-B | 10 | 2.5 | 59 |
| SA-80-FA-B10 | A | 80 | 95 | 0.41 | FA-B | 10 | 2.5 | 72 |
| SC-80-FA-B10 | C | 80 | 100 | 0.40 | FA-B | 10 | 2.5 | 72 |
| SF-70-FA-B10 | F | 70 | 95 | 0.54 | FA-B | 10 | 4.3 | 15 |
| SA-70-FA-B10 | A | 70 | 95 | 0.54 | FA-B | 10 | 4.3 | 0 |
| SC-70-FA-B10 | C | 70 | 99 | 0.54 | FA-B | 10 | 4.3 | 0 |
| SF-90-FA-B20 | F | 90 | 37 | 0.43 | FA-B | 20 | 0.55 | 275 |
| SA-90-FA-B20 | A | 90 | 47 | 0.38 | FA-B | 20 | 0.55 | 250 |
| SC-90-FA-B20 | C | 90 | 83 | 0.26 | FA-B | 20 | 0.55 | 333 |
| SF-80-FA-B20 | F | 80 | 81 | 0.44 | FA-B | 20 | 1.25 | 89 |
| SA-80-FA-B20 | A | 80 | 95 | 0.41 | FA-B | 20 | 1.25 | 112 |
| SC-80-FA-B20 | C | 80 | 96 | 0.41 | FA-B | 20 | 1.25 | 78 |
| SF-70-FA-B20 | F | 70 | 97 | 0.53 | FA-B | 20 | 2.15 | 18 |
| SA-70-FA-B20 | A | 70 | 98 | 0.53 | FA-B | 20 | 2.15 | 0 |
| SC-70-FA-B20 | C | 70 | 100 | 0.53 | FA-B | 20 | 2.15 | 0 |
| SF-90-FA-A10+B10 | F | 90 | 38 | 0.43 | FA-A&B | 20 | 0.55 | 281 |
| SA-90-FA-A10+B10 | A | 90 | 47 | 0.38 | FA-A&B | 20 | 0.55 | 460 |
| SC-90-FA-A10+B10 | C | 90 | 87 | 0.25 | FA-A&B | 20 | 0.55 | 590 |
| SF-80-FA-A10+B10 | F | 80 | 80 | 0.45 | FA-A&B | 20 | 1.25 | 165 |
| SA-80-FA-A10+B10 | A | 80 | 95 | 0.41 | FA-A&B | 20 | 1.25 | 269 |
| SC-80-FA-A10+B10 | C | 80 | 94 | 0.41 | FA-A&B | 20 | 1.25 | 290 |
| SF-70-FA-A10+B10 | F | 70 | 96 | 0.54 | FA-A&B | 20 | 2.15 | 116 |
| SA-70-FA-A10+B10 | A | 70 | 98 | 0.54 | FA-A&B | 20 | 2.15 | 110 |
| SC-70-FA-A10+B10 | C | 70 | 100 | 0.53 | FA-A&B | 20 | 2.15 | 120 |
| SF-80-CEM10 | F | 80 | 84 | 0.26 | CEM | 10 | 2.5 | 1812 |
| SA-80-CEM10 | A | 80 | 100 | 0.23 | CEM | 10 | 2.5 | 2187 |
| SC-80-CEM10 | C | 80 | 99 | 0.23 | CEM | 10 | 2.5 | 2112 |

Specimen nomenclature: S = synthetic; F = fine; A = average; C = coarse; 70, 80, and 90 = solids contents; FA-A = fly ash A; FA-B = fly ash B; CEM = cement; 10 and 20 are binder content.

**Table 2.4** Summary of unconfined compressive strength (UCS) tests conducted on natural tailings amended with fly ash or cement

| Name | Tailings | Solids Content (%) | Saturation (%) | Porosity | Binder Type | Binder Content (%) | Water-to-Binder Ratio | UCS (kPa) |
|---|---|---|---|---|---|---|---|---|
| NCu-80-FA-A10 | Cu | 80 | 92 | 0.42 | FA-A | 10 | 2.5 | 212 |
| NCG-80-FA-A10 | CG | 80 | 95 | 0.44 | FA-A | 10 | 2.5 | 178 |
| NFG-80-FA-A10 | FG | 80 | 100 | 0.43 | FA-A | 10 | 2.5 | 196 |
| NCu-70-FA-A10 | Cu | 70 | 98 | 0.54 | FA-A | 10 | 4.3 | 135 |
| NCG-70-FA-A10 | CG | 70 | 98 | 0.57 | FA-A | 10 | 4.3 | 141 |
| NFG-70-FA-A10 | FG | 70 | 99 | 0.56 | FA-A | 10 | 4.3 | 121 |
| NCu-80-FA-B10 | Cu | 80 | 92 | 0.44 | FA-B | 10 | 2.5 | 139 |
| NCG-80-FA-B10 | CG | 80 | 95 | 0.42 | FA-B | 10 | 2.5 | 20 |
| NFG-80-FA-B10 | FG | 80 | 100 | 0.42 | FA-B | 10 | 2.5 | 106 |
| NCu-70-FA-B10 | Cu | 70 | 100 | 0.54 | FA-B | 10 | 4.3 | 0 |
| NCG-70-FA-B10 | CG | 70 | 100 | 0.56 | FA-B | 10 | 4.3 | 0 |
| NFG-70-FA-B10 | FG | 70 | — | — | FA-B | 10 | 4.3 | 0 |
| NCu-80-CEM10 | Cu | 80 | — | — | CEM | 10 | 2.5 | 1540 |
| NCG-80-CEM10 | CG | 80 | 91 | 0.46 | CEM | 10 | 2.5 | 1438 |
| NFG-80-CEM10 | FG | 80 | 100 | 0.43 | CEM | 10 | 2.5 | 1800 |
| NCu-70-CEM10 | Cu | 70 | — | — | CEM | 10 | 4.3 | 1105 |
| NCG-70-CEM10 | CG | 70 | 100 | 0.57 | CEM | 10 | 4.3 | 1250 |
| NFG-70-CEM10 | FG | 70 | 100 | 0.56 | CEM | 10 | 4.3 | 1061 |

Specimen nomenclature: N = natural; Cu = copper; CG = coarse garnet; FG = fine garnet; 70 and 80 = solids contents; FA-A = fly ash A; FA-B = fly ash B; CEM = cement; and 10 = percent my mass binder content
Note: — = calculations not possible due to measurement errors

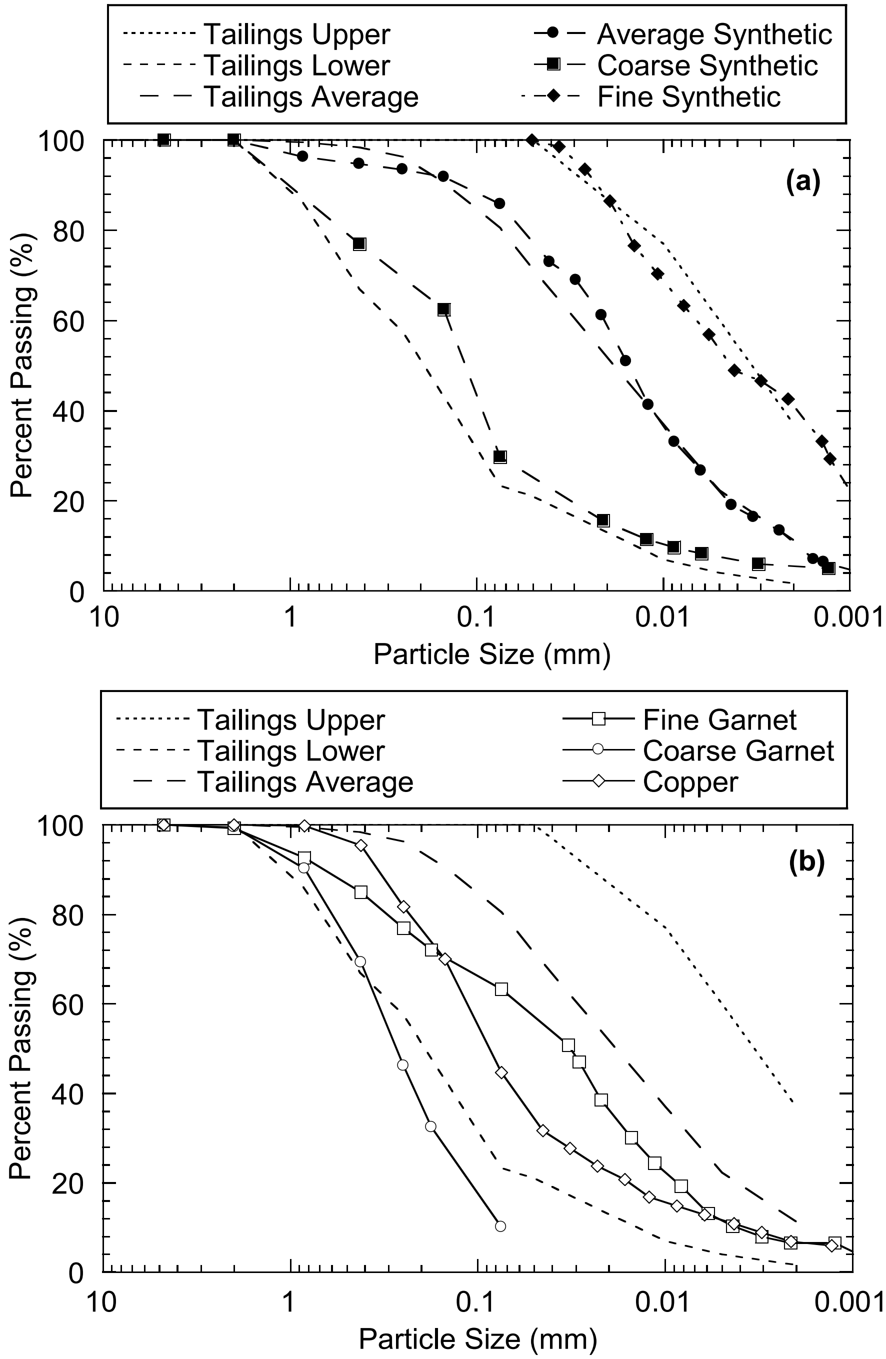
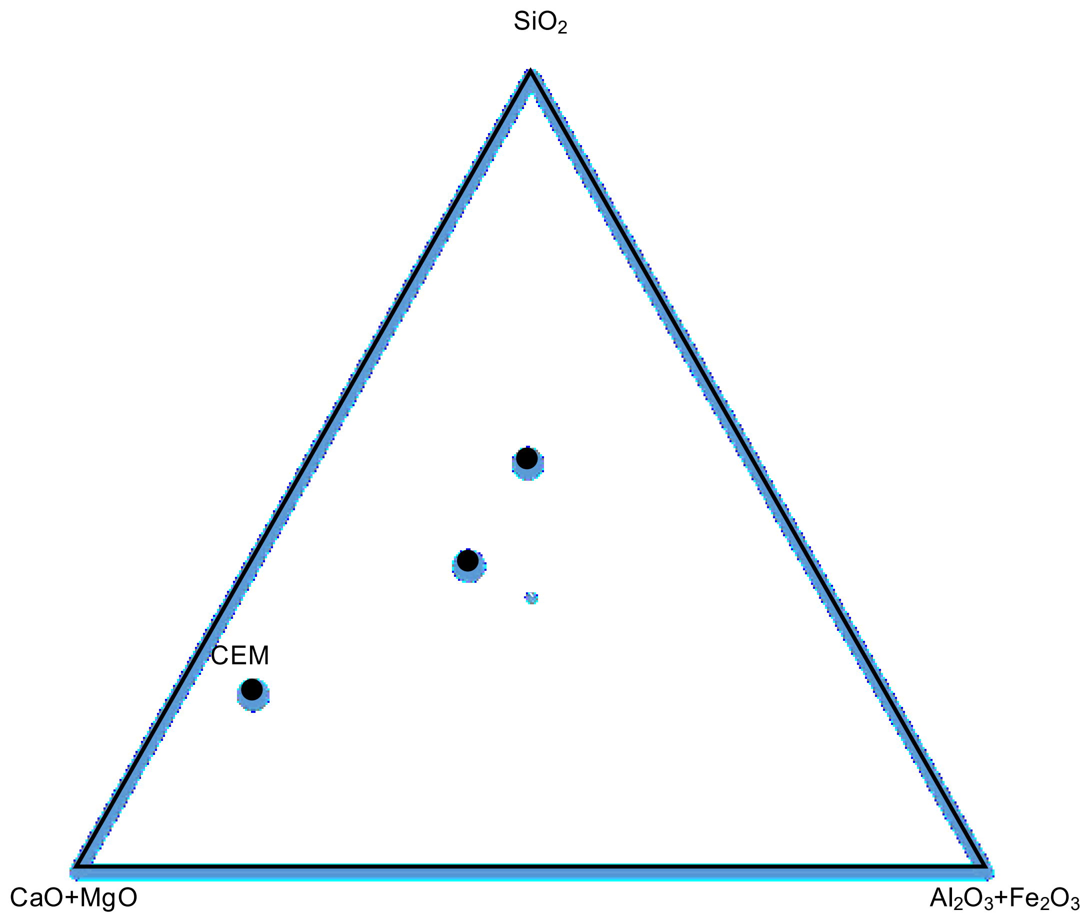



**Figure 2.1** Particle-size distributions for (a) average, coarse, and fine synthetic mine tailings prepared for this study and (b) fine garnet, coarse garnet, and copper natural tailings. The upper, lower, and average tailings particle-size distributions shown in both plots are based on a compilation from literature (Qiu and Sego 2001; Morris and Williams 2005; Khalili and Wijewickreme 2008; Wickland and Wilson 2005; Wickland et al. 2006; Bussière 2007; Khalili et al. 2010; Wickland et al. 2010).




| Binder | Total Mass Fraction of $SiO_2$ + MgO + CaO + $Fe_2O_3$ + $Al_2O_3$ (%) | Percent Contribution of $SiO_2$ in Modified Total (%) | Percent Contribution of MgO + CaO in Modified Total (%) | Percent Contribution of $Fe_2O_3$ + $Al_2O_3$ in Modified Total (%) | Ratio of CaO to $SiO_2$ |
|---|---|---|---|---|---|
| FA-A | 55 | 36 | 35 | 29 | 0.86 |
| FA-B | 90 | 51 | 25 | 24 | 0.41 |
| Cement | 91 | 22 | 69 | 9 | 3.18 |

**Figure 2.2** Ternary phase diagram of chemical composition of common binders (Popovics 1970; Tariq 2012) and fly ash A (FA-A), fly ash B (FA-B), and cement (CEM) used in this study. Tabulated values represent the total mass fraction of chemical components of the fly ashes and cement used in the ternary diagram, percent of each constituent plotted in the diagram, and calcium oxide to silica ratio ($CaO/SiO_2$).

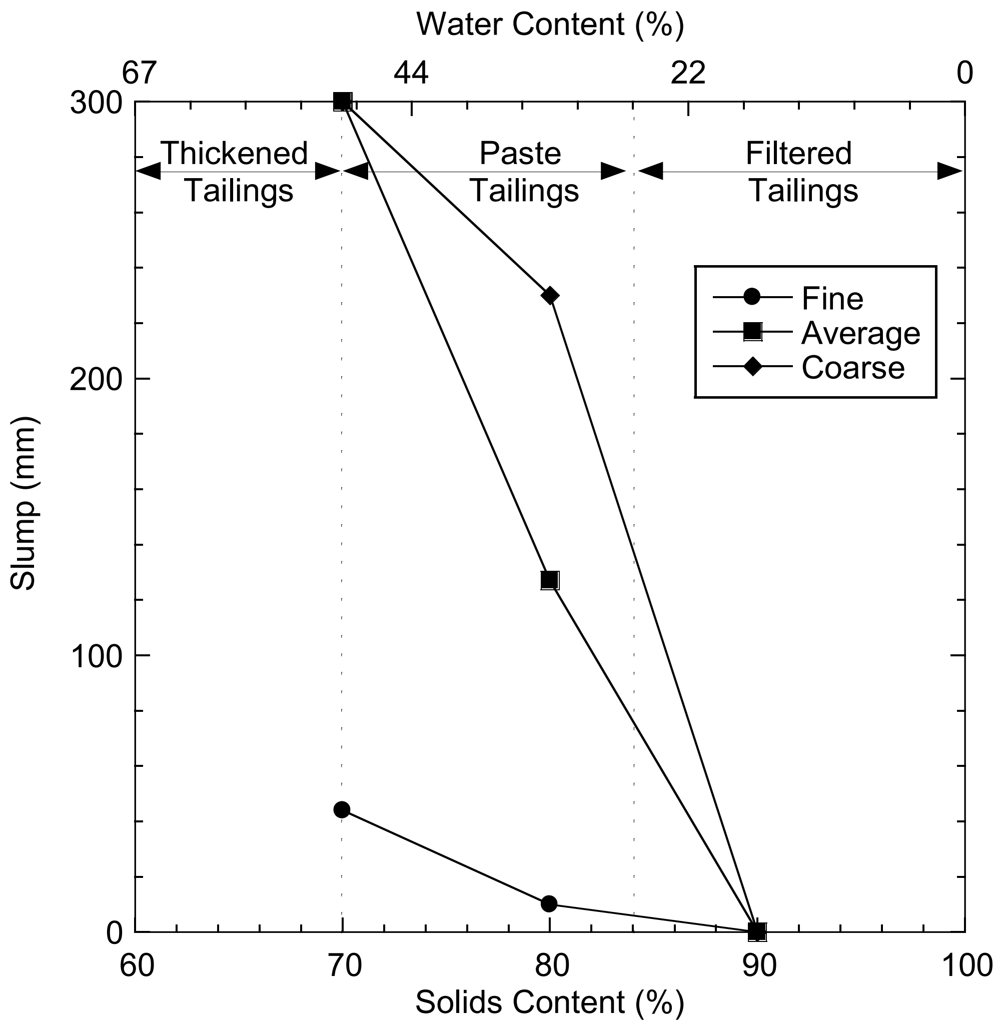



**Figure 2.3** Relationship between slump and solids content (SC) or water content for synthetic tailings prepared to different levels of dewatering: thickened tailings – SC < 70%; paste tailings – 70% < SC < 85%; filtered tailings – SC > 85%.

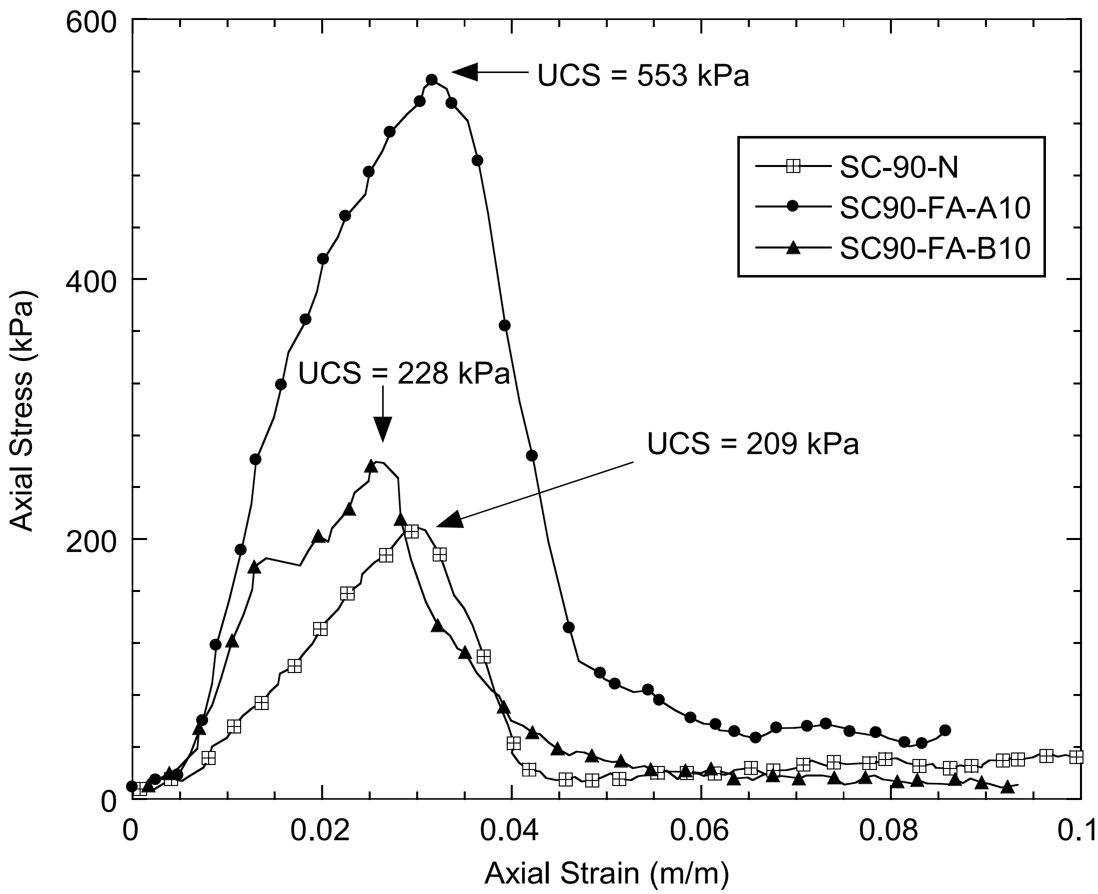



**Figure 2.4** Relationship between axial stress and axial strain for unconfined compression strength tests non-fly ash amended (SC-90-N) and fly ash amended (SC-90-FA-A10 and SC-90-FA-B10) synthetic mine tailings.

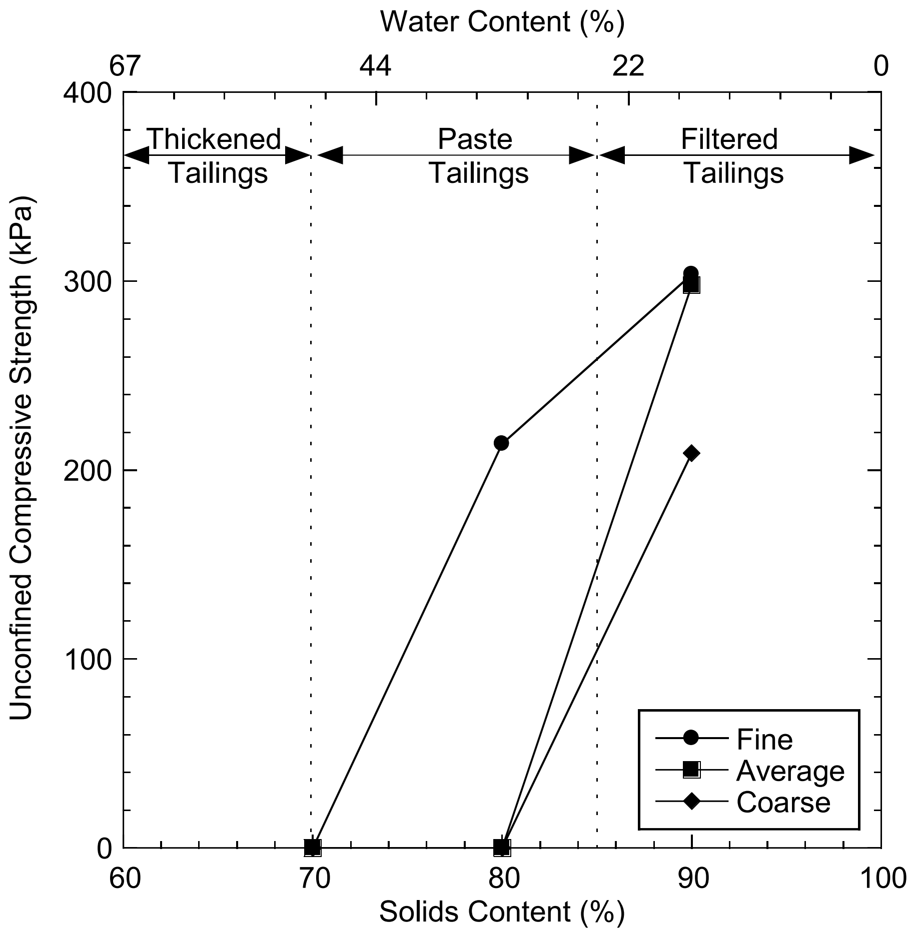



**Figure 2.5** Relationship between unconfined compressive strength (UCS) and solids content or water content for non-amended synthetic tailings specimens. Note: UCS = 0 kPa corresponds to slurry materials that were not self-supporting and had no capacity to carry an axial load.

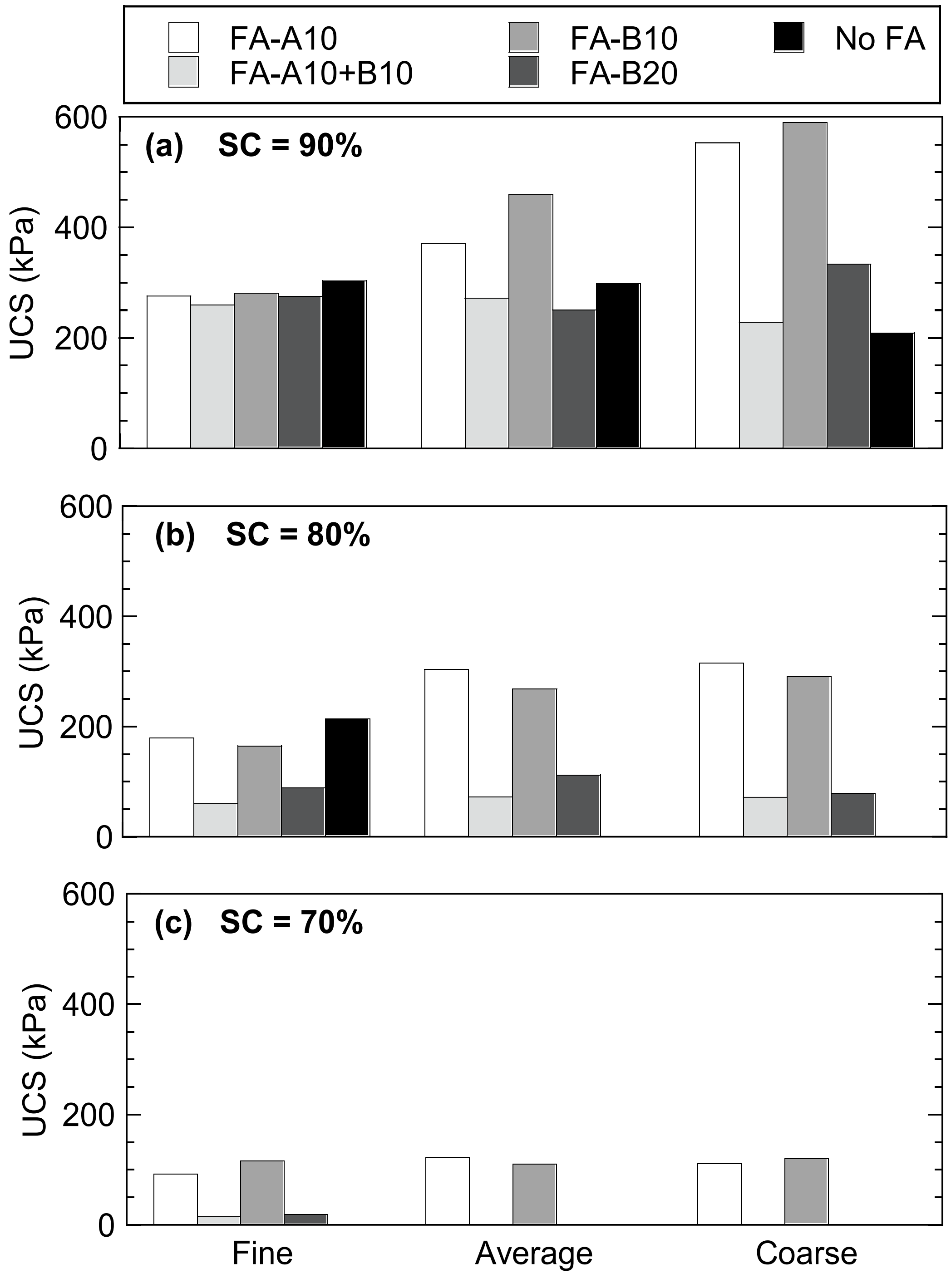



**Figure 2.6** Unconfined compressive strength (UCS) of fine, average, and coarse synthetic tailings with no fly ash (No FA) and amended with 10% Fly Ash A (FA-A10), 10% Fly Ash B (FA-B10), a mixture of 10% Fly Ash A and 10% FA-B (FA-A10+B10) and 20% Fly Ash B (FA-B20). Unconfined compressive strengths are show for synthetic tailings prepared to solids contents (SC) of (a) 90%, (b) 80%, and (c) 70%.

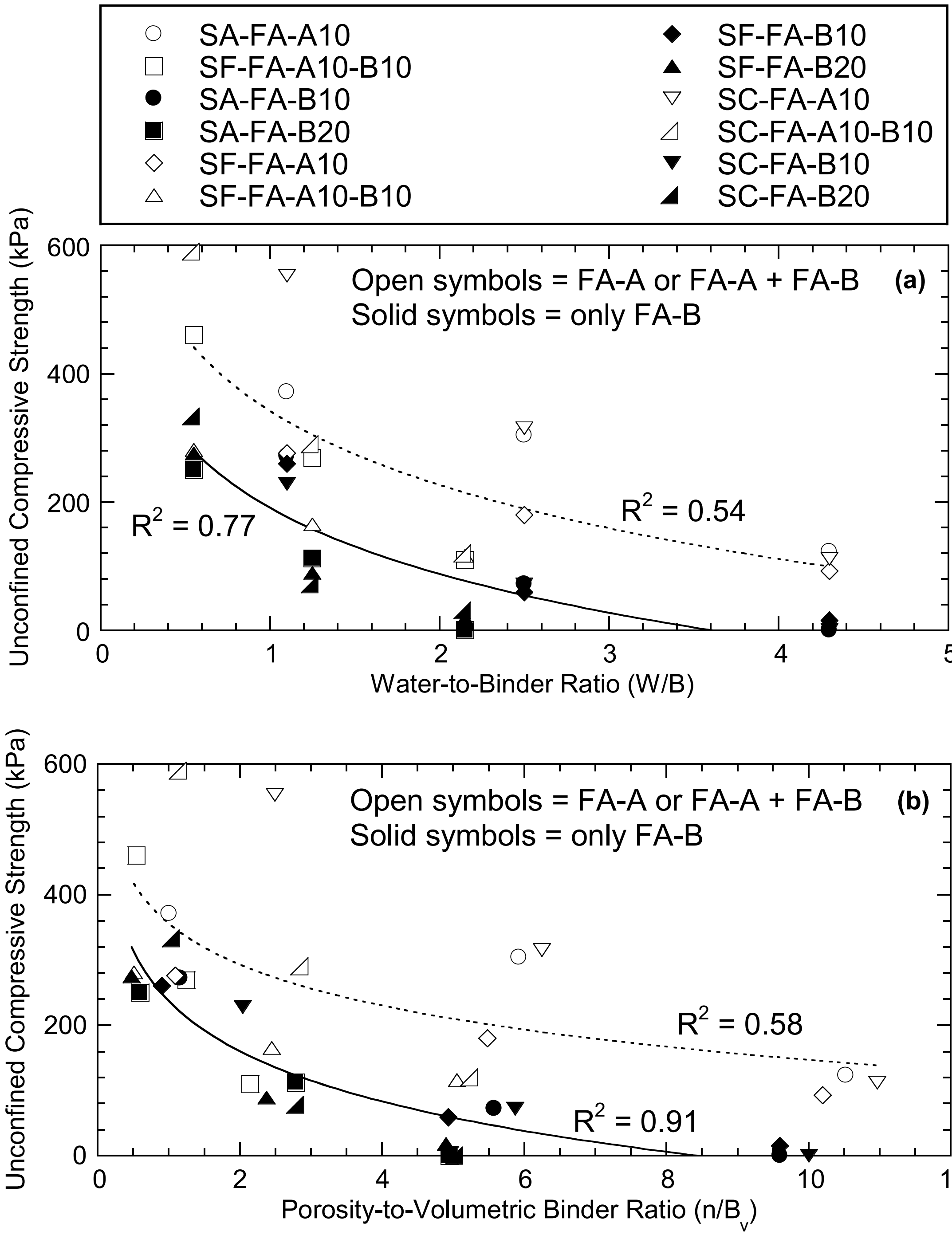



**Figure 2.7** Relationships between unconfined compressive strength and (a) water-to-binder ratio (*W/B*) and (b) porosity-to-volumetric portion of binder ($n/B_v$) for fly ash-amended synthetic tailings specimens. Nomenclature notes: SA = average synthetic tailings; SF = fine synthetic tailings; SC = coarse synthetic tailings; FA-A = Fly Ash A; FA-B = Fly Ash B; 10 and 20 are percent fly ash amendments by dry mass.

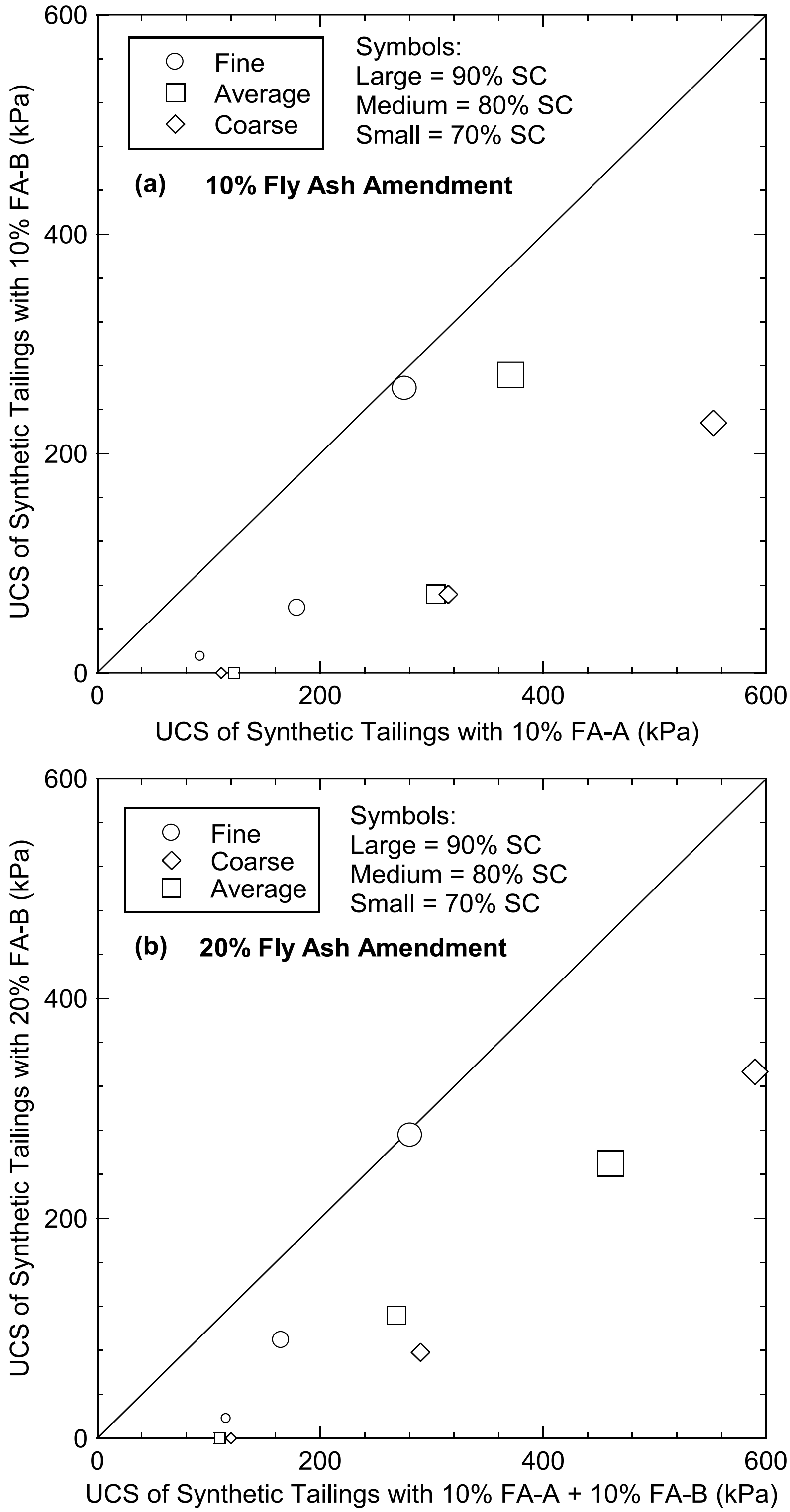



**Figure 2.8** Comparison of unconfined compressive strength (UCS) of fine, average, and coarse synthetic tailings amended with Fly Ash B (FA-B) versus UCS of fine, average, and coarse synthetic tailings amended with Fly Ash A (FA-A): (a) 10% FA-B versus 10% FA-A and (b) 20% FA-B versus 10% FA-A plus 10% FA-B.

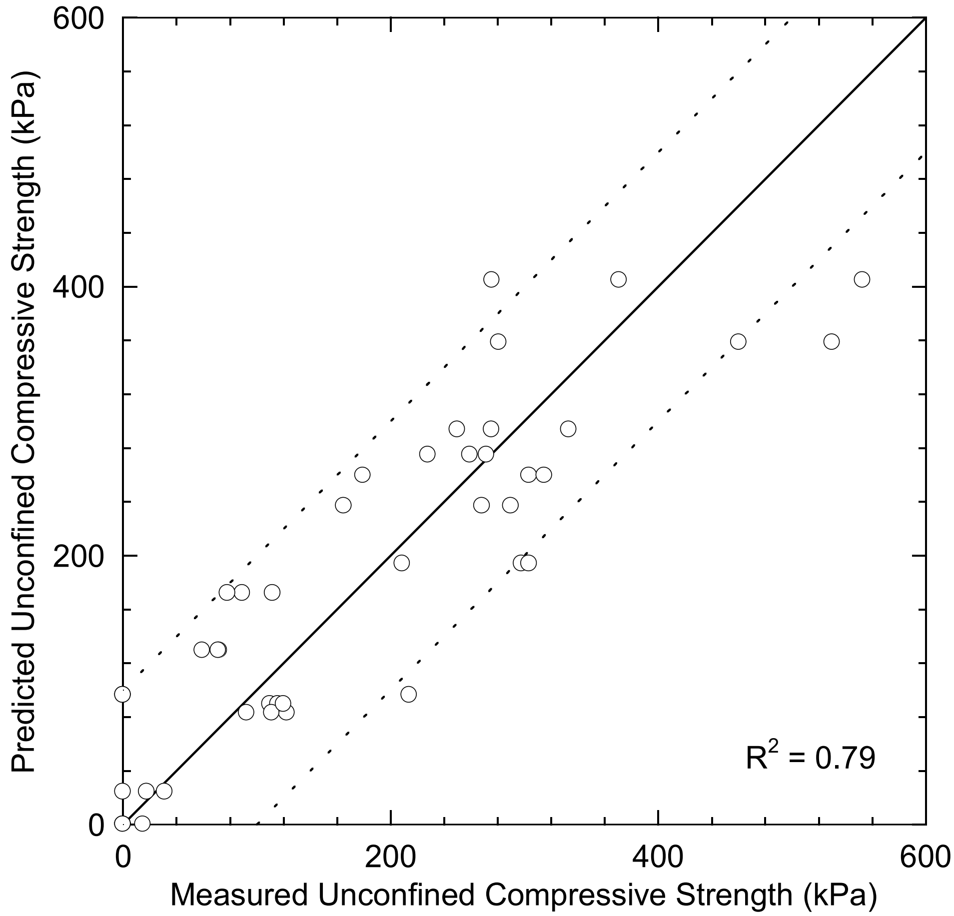



**Figure 2.9** Comparison between unconfined compressive strength predicted using the regression model developed based on the synthetic tailings experiments (Eq. 3.1) and unconfined compressive strength measured on the synthetic tailings.

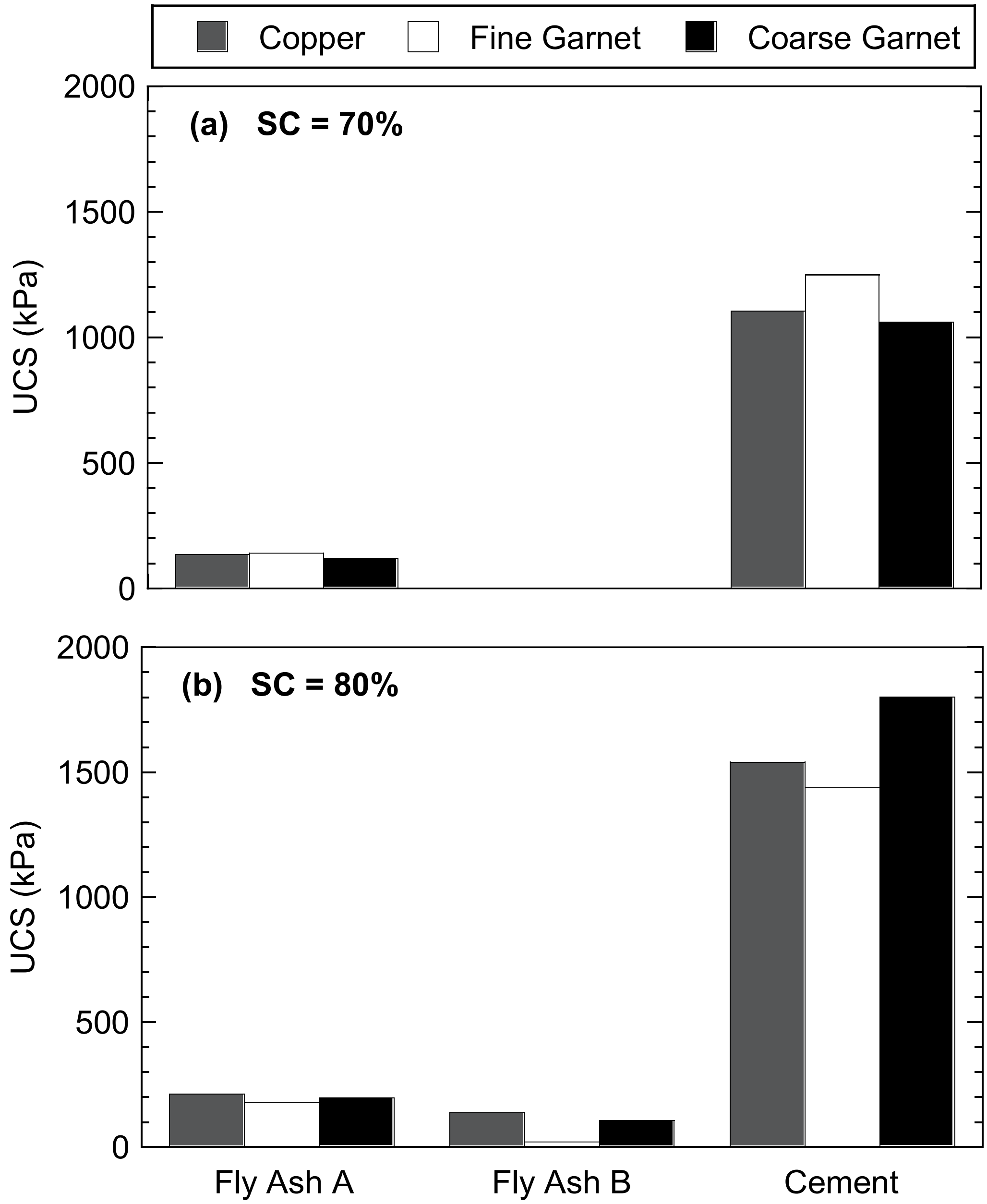



**Figure 2.10** Unconfined compressive strength (UCS) of natural tailings prepared to solids contents (SC) of (a) 70% and (b) 80% and amended with 10% of Fly Ash A, 10% of Fly Ash B, and 10% cement.

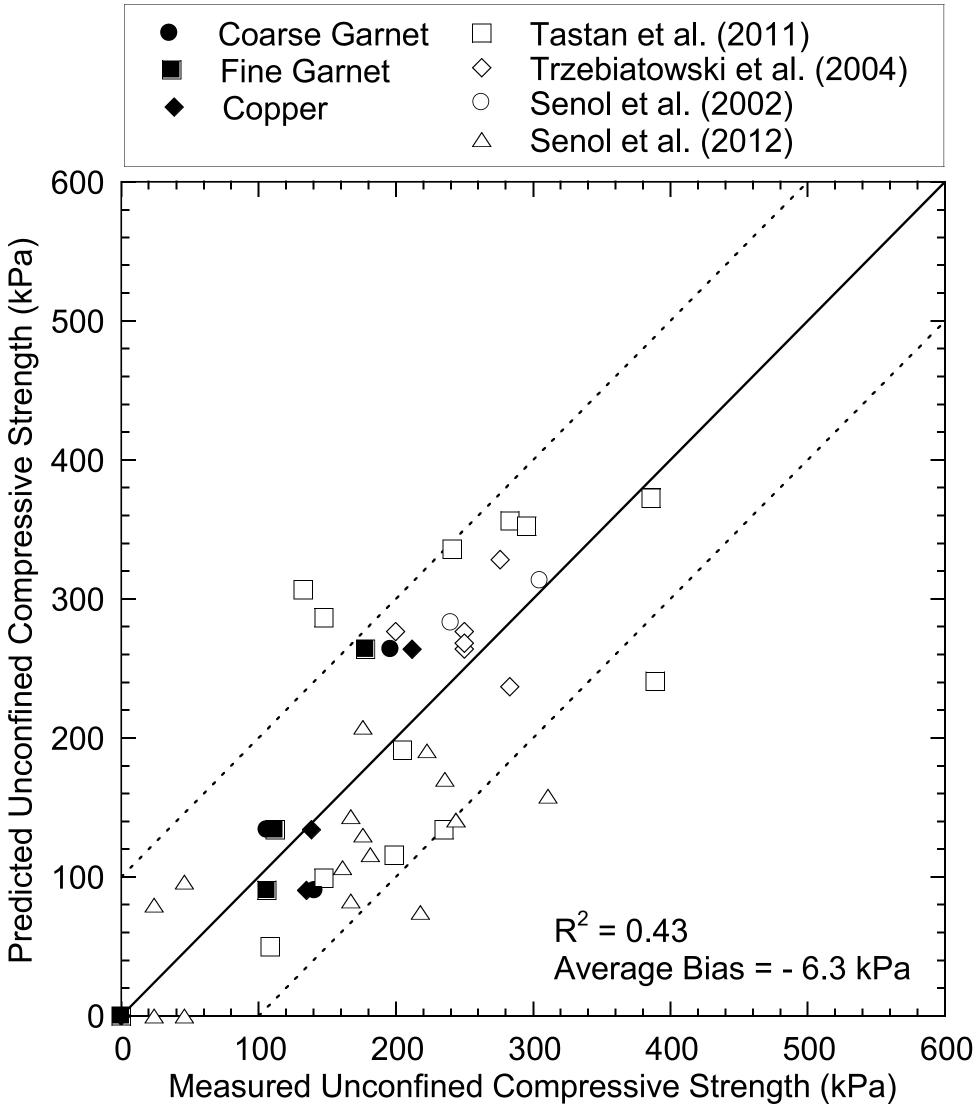



**Figure 2.11** Comparison between unconfined compressive strength (UCS) predicted using the regression model developed in this study, based on the synthetic tailings experiments (Eq. 3.1) and UCS measured on natural tailings in this study as well as low plasticity soils (i.e., liquid limit < 50%) compiled from literature [note: Theresa Soil plotted from Tastan et al. (2011) and CL soil plotted from Senol et al. (2012)]. Average bias was computed as the arithmetic average of predicted minus measured.

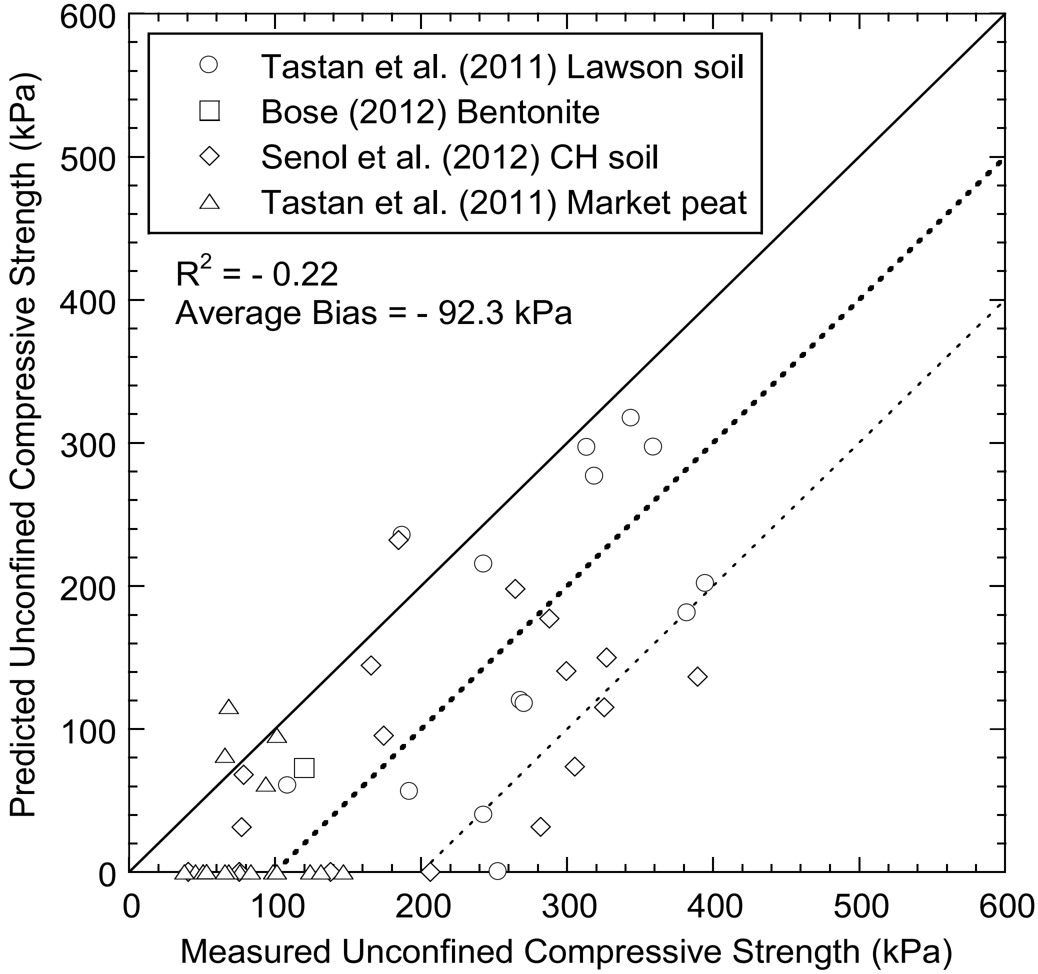
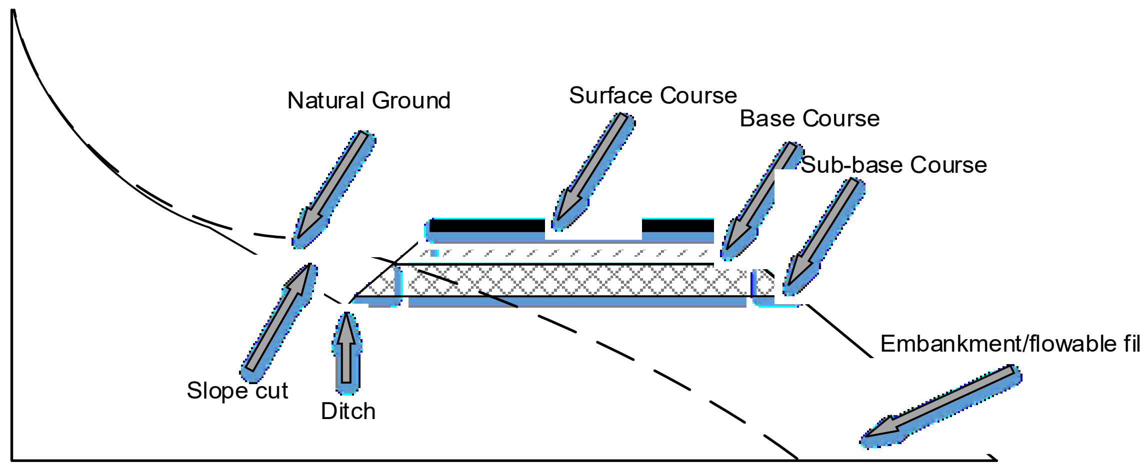



**Figure 2.12** Comparison between unconfined compressive strength (UCS) predicted using the regression model developed in this study based on the synthetic tailings experiments (Eq. 3.1) and UCS for high plasticity soils (i.e., liquid limit ≥ 50%) compiled from literature. Average bias was computed as the arithmetic average of predicted minus measured.




| Application | Reference | UCS (kPa) |
|---|---|---|
| Base Course | AASHTO MEPDG (ARA 2004) | > 5200 |
| Sub-base Course | AASHTO MEPDG (ARA 2004) | > 1700 |
| Base Layer | ACAA (2003) | > 2760 |
| Flowable Fill | FHWA (2003) | 345-8300 |
| Pavement Subsealing | FHWA (2003) | > 4100 |
| Cemented Paste Backfill (eliminating liquefaction) | Bloss 2002; Tariq 2012 | 150-300 |
| Cemented Paste Backfill (surface disposal application) | US EPA (1998) | > 345 |
| Cemented Paste Backfill (roof support) | Grice 1998; Tariq 2012 | > 4000 |

**Figure 2.13** Schematic of a typical roadway cross-section with common earthworks identified and tabulated mechanical criteria for road construction materials and cemented paste backfill used in mining applications.

# 3. COMPRESSION BEHAVIOR OF MINE TAILINGS AMENDED WITH CEMENTITIOUS BINDERS[3]

## 3.1 Introduction

Earthwork construction, such as roads, embankments, and fills, requires earthen materials (e.g., soil, crushed rock, etc.) designed for specific engineering performance. The Federal Highway Administration has identified that the use of recycled materials, such as coal combustion by-products (CCBs), mine waste (mine waste rock and tailings), blast furnace slag, municipal solid waste combustion ash, reclaimed concrete pavement, and scrap tires, has potential to aid earth construction needs (Schroeder 1994; Chesner et al. 1998). Reuse of industrial waste and byproducts is particularly attractive to decrease energy consumption, raw material use, and greenhouse gas emissions (Hudson-Edwards et al. 2011).

Mining is an industry that generates considerable volumes of waste materials during ore extraction processes. The two predominant waste materials that require short- and long-term management are tailings and waste rock (e.g., Bussière 2007; Blight 2010). Tailings typically are fine grained and have high water contents (low solids contents); waste rock generally is gravel- to cobble-sized material with some sand and fines. Disposal and management of mine tailings can be challenging due to variability in physical and chemical properties of the tailings, potential release of contamination to surface and ground water (Bussière 2007), and failure of tailings dams (Davies 2002; Bowker et al. 2015). The risks associated with tailings storage and long-term management in impoundment facilities highlights the importance of finding alternative methods for mine tailings management.

Mine tailings dewatering is commonly done to improve the mechanical properties of tailings. There are three common levels of dewatered tailings: (i) thickened tailings, which increases solids content (*SC*) to 50-70%; (ii) paste tailings, which increases *SC* to 70-85%; and (iii) filtered tailings, which increases *SC* above 85% (Bussière 2007). Progressive dewatering from thickened to paste to filtered tailings requires additional time, energy, and financial investment. Thickened and paste tailings contain sufficient water that can prolong consolidation and limit strength gain within reasonable timeframes for earthwork construction. The addition of cementitious binder has been shown to improve the mechanical properties of mine tailings and fine-grained soils.

Incorporating mine tailings in earthwork applications provides an alternative to circumvent disposal and long-term management. There is increasing interest in reusing dewatered mine tailings amended with cementitious binders (e.g., fly ash or cement) in earthwork construction projects (e.g., Misra et al. 1996; Godbout et al. 2007). The potential to reuse mine tailings in earthwork construction with fly ash, a prevalent industrial by-product with self-cementing behavior, promotes sustainable management of industrial wastes.

Amending dewatered mine tailings with cementitious binders has been used as cemented paste backfill (CPB) in underground mining to fill cavities (ranging from 15 to 40 m in lateral extent and up to 100-m tall) and enhance local and global stability. The mechanical, hydraulic, and environmental behavior of CPB has been investigated by numerous researchers (Zou and Li 1999; Belem et al. 2000; Fall et al. 2005; Kesimal et al. 2005; Klein and Simon 2006; Ouellet et al. 2006; Ouellet et al. 2007; Benzaazoua et al. 2008; Ercikidi et al. 2009; Yeheyis et al. 2009; Nasir and Fall 2010; Zhang et al. 2011; Ercikidi et al. 2013). In general, addition of a cementitious binder has been shown to increase strength, reduce hydraulic conductivity, increase pH of effluent, and stabilize heavy metals present in mine tailings.

[3] Gorakhki, M.H. and Bareither, C.A. Compression behavior of mine tailings amended with cementitious binders, *Geotechnical and Geological Engineering*, online 13 July 2017, 10.1007/s10706-017-0299-4.

Compressibility of high water content soils and tailings amended with a cementitious binder has been the focus of recent studies (e.g., Nalbantoglu and Tuncer 2001; Horpibulsuk et al. 2005; Duraisamy et al. 2009; Yilmaz et al. 2010; Bobet et al. 2011; Fahey et al. 2011; Federico et al. 2015; Yilmaz et al. 2015). Horpibulsuk et al. (2005) investigated the effect of cement addition on compression of soft clay (liquid limit = 120%) at water contents ranging from 150% to 250%. They reported limited vertical deformation with increasing vertical stress followed by a transition to larger deformations after reaching a certain stress level. This transition in compression was linked to a threshold stress level referred to as the breaking stress ($\sigma'_B$), which coincided with breakage of cementitious bonds in the cement-amended clay.

Bobet et al. (2011) evaluated compressibility of a highly organic soil (organic content = 40% to 60%, by dry mass) amended with cement in constant rate-of-strain and traditional consolidation tests. They reported that settlement decreased with an increase in cement content due to an increase in $\sigma'_B$. However, they reported an approximately equal compression index ($C_c$) for cement-amended soil and natural soil under vertical stress > $\sigma'_B$. Federico et al. (2015) evaluated compressibility of a high plasticity clay (*LL* = 55%) amended with cement and cement-lime mixture. They reported that $\sigma'_B$ was approximately 1.5 times the unconfined compressive strength (UCS) for similarly prepared mixtures. Federico et al. (2015) reported the binder content was the most important parameter that affected compressibility of highly compressible soils.

Yilmaz et al. (2015) evaluated the efficacy of three binders (slag; Portland cement; and mixture of slag and Portland cement) on reducing compressibility of mine tailings for specimens cured under stress (SC = 81%; fines content ≈ 70%). Secimens were cured for 0, 1, 3, and 7 daysunder stresses up to 400 kPa. Reduction in $C_c$ was reported with an increase in binder content and/or curing time. Rotta et al. (2003) reported similar positive correspondence between $\sigma'_B$, cement content, and stress applied during curing for non-plastic silty sand mixed with cement.

These past studies have demonstrated that the addition of Portland cement and lime can decrease compression of mine tailings and highly compressible soils at high water contents. However, the effects of cementitious by-products (e.g., fly ash), material characteristics (e.g., particle-size and plasticity), and water content on the compression behavior of mine tailings has received limited attention. These factors are important to enhancing a mechanistic understanding of tailings-fly ash mixtures to promote beneficial reuse of these waste by-products in earthwork projects. The objectives of this study were to (i) assess the coupled effects of tailings properties, tailings water content, fly ash addition, and curing time on the compression behavior of fly ash-amended mine tailings and (ii) assess the effect of applied stress during curing on compressibility. The second objective was included to expand the relevance of this study to fly ash-amended mine tailings in CPB applications.

## 3.2 Materials and Methods

### 3.2.1 Materials

#### 3.2.1.1 Mine Tailings

Two types of mine tailings were used in this study—synthetic tailings and natural tailings. A compilation of geotechnical characteristics of these materials is in Table 3.1. Synthetic tailings were created from laboratory-controlled materials (i.e., angular sand from road base material, silica flour (US silica, USA), and kaolin clay (Thiele Kaolin Company, USA)] to capture a range in geotechnical characteristics of mine tailings. Natural tailings were collected from a (i) copper mine in Arizona, (ii) soda ash mine in Wyoming, and (iii) garnet mine in New York. Two fractions of garnet tailings were collected as a hydrocyclone is used at the garnet mine to segregate tailings for subsequent reuse in mine site earthworks (e.g., tailings dams). The finer fraction of the garnet tailings (fine-garnet tailings), which represents overflow material from the hydrocyclone, was used in this study. A portion of the fine-garnet tailings was processed via wet sieving through a No. 200 sieve to produce a tailings material with a finer-grained particle distribution; this laboratory-processed material is referred to as $NP_{200}G$. Geotechnical characterization of all tailings included mechanical sieve and hydrometer (ASTM D422, ASTM 2007), Atterberg limits (ASTM D4318, ASTM 2014), and specific gravity (ASTM D854, ASTM 2014).

The average, upper-bound, and lower-bound particle-size distributions (PSD) of eight different hard rock mine tailings are shown in Figures 3.1a and 3.1b along with the synthetic tailings (Figure 3.1a) and natural tailings (Figure 3.1b). Synthetic tailings were created to approximate the average and upper-bound PSDs in Figure 3.1a. Particle-size distributions of the fine and average synthetic tailings are also shown in Figure 3.1a and close replication was achieved in both cases. Synthetic mine tailings representative of the lower-bound PSD in Figure 3.1a classified predominantly as sand and were not evaluated in this study as the focus was on compression behavior of finer-grained materials.

Particle-size distributions of the natural tailings are shown in Figure 3.1b. The compilation of PSDs from literature indicates that the copper and fine-garnet mine tailings ranged between the average and lower-bound. Soda ash and $NP_{200}G$ ranged between the average and upper-bound PSDs (Figure 3.1b). The liquid limits (*LL*) of synthetic and natural tailings ranged between 0 to 37% (Table 3.1), which was in the typical range of hard rock mine tailings (0 to 40%) (e.g., Aubertin et al. 1996; Qiu and Sego 2001; Wickland and Wilson 2005; Daliri et al. 2014).

#### 3.2.1.2 Cementitious Binders

Three types of fly ash and one type of cement were used as cementitious binders. Fly Ash A (FA-A) was obtained from Stanton Station, North Dakota, which operates a 190-MW power plant. Fly Ash B (FA-B) was obtained from Platte River Power Authority, Colorado, which operates a 280-MW power plant. Fly Ash C (FA-C) was obtained from Coal Creek Station, North Dakota, which operates an 1100-MW power plant. Type I-II Portland cement was made available for this study and had basic properties of Type I and Type II cements (Day et al. 2013).

Chemical composition of the fly ashes and cement are listed in Table 3.2. Chemical composition of FA-A and FA-C were measured via x-ray fluorescence with a Philips 1600/10 Simultaneous Wavelength Dispersive Unit by Mineralogy-INC (Tulsa, Oklahoma, USA), whereas chemical composition of cement and FA-B were obtained from the cement producer and power plant, respectively. Fly ashes were classified based on ASTM C618 (ASTM 2003) and Tastan et al. (2011), and all three fly ashes classified as off-specification (off-spec). The off-spec designation only implies that the fly ashes did not formally classify as Class C or F. Off-spec fly ashes can yield self-cementing behavior, and lime (i.e., calcium oxide, CaO), which is the main component responsible for cementitious reactions, accounted for 17% of FA-A, 12% of FA-C, and 18.9% of FA-B (Table 3.2).

The relative composition of calcium oxide plus magnesium oxide (CaO + MgO), silicon dioxide ($SiO_2$), and aluminum oxide plus ferric oxide ($Al_2O_3 + Fe_2O_3$) for the fly ashes and cement are shown in the ternary plot in Figure 3.2. Janz and Johansson (2002) introduced the CaO-to-$SiO_2$ ratio ($CaO/SiO_2$) as an indicator for pozzolanic reaction of binders. In FA-A, the $CaO/SiO_2$ (0.86) was higher than the $CaO/SiO_2$ (0.41) in FA-B. Fly Ash C had the lowest $CaO/SiO_2$ (0.25) in comparison with the other two fly ashes. Fly Ash A had a more favorable relative composition of the key chemical compounds required for formation of cementitious products (i.e., calcium silicate hydrate and calcium aluminate silicate hydrate) compared to FA-B and FA-C, which implied that FA-A would be more effective as a cementitious binder. The cement plotted in the ternary plot in Figure 3.2 in the anticipated range of cements and had high cementitious properties in comparison with fly ashes.

### 3.2.2 Compression Testing

One-dimensional compression tests were performed in conventional fixed-ring consolidation cells on unamended tailings and fly ash-amended tailings in accordance with ASTM D2435 (ASTM 2014). All specimens were prepared via initially mixing tailings with de-aired water and then adding the required binder quantity (if applicable) to the slurried tailings. Water-to-binder ratios (*W/B*) of 2.5 and 5 were targeted for tailings prepared to different *SC*s as these *W/B*s are common for CPBs (Kesimal et al. 2005). Fine synthetic tailings were prepared to target *SC*s of 60% and 70% (w = 67% and 43%, respectively) to create a slurry that approximated dewatering levels in thickened tailings (*SC* = 60 %) and paste tailings (*SC* = 70%). Average synthetic tailings and natural mine tailings were prepared to target *SC*s of 70% (*w* = 43%) and 75% (*w* = 33%). These tailings were not prepared at a lower *SC* as a decrease in *SC* (increase in *w*) resulted in segregation of solids and water.

All unamended tailings, tailings-fly ash mixtures, and tailings-cement mixtures were tested in consolidation rings with an inside diameter of 63.5 mm and height of 25.4 mm. All initial specimens were in slurry form and poured into the consolidation rings. Following deposition of the slurried materials, all consolidation rings were vibrated to promote air removal. Water content measurements were conducted on remaining slurried material and were used in conjunction with final specimen dimensions and total mass to determine initial dry density, void ratio, and saturation. All specimens within the consolidation rings were sealed in polyethylene bags to prevent evaporation and allowed to cure for 0.1 day (2 hours), 7 days, and 28 days at a temperature of 25°C and relative humidity of approximately 100% as recommended by Senol et al. (2006).

Consolidation rings containing the specimens were placed in oedometers after curing and low-weight porous disks were placed on top of the specimens. The porous disks were machined from a single piece of polyethylene and had a mass of 30-50 g that resulted in a low vertical stress ($\sigma < 0.16$ kPa) applied to the specimen. These porous disks were effective for evaluating compression behavior of slurried materials. Vertical deformation was recorded for all specimens and pore water pressure was measured for select specimens. Vertical loads were applied incrementally every 24 hours following Method A in ASTM D2435 (ASTM 2014).

An additional consolidation test series was performed to evaluate the effect of applied vertical effective stress ($\sigma'_v$) during curing on the compression behavior of fly ash-amended tailings. These tests were used to simulate actual conditions that exist in CPB. Cemented-paste backfill is injected into mine cavities in slurry form such that water expulsion due to loading and pozzolanic reactions that generate cementitious bonds occur simultaneously.

Specimens prepared to evaluate the effect of $\sigma'_v$ during curing on compression behavior were prepared identical to the previously described specimens. However, no lag time was allowed between specimen preparation and application of $\sigma'_v$. Applied vertical effective stresses of 10, 60, and 100 kPa were achieved via an initial 10 kPa load applied immediately after specimen preparation and subsequent loads approximately doubled every 15 min to allow excess pore water pressure dissipation. Thus, final $\sigma'_v$ = 60 kPa and 100 kPa were achieved in 45 and 60 minutes, respectively, following addition of binder to the tailings slurry. The cementitious bonds generated from pozzolanic reactions initiate within 1 hr to 1 d at standard temperature and pressure (Kurtis 2007; Pacheco-Torgal et al. 2014). Thus, all vertical loading in this test series was targeted before cementitious bond formation initiated.

The applied loads were left in-place for 7 days and then all specimens were unloaded. Specimens subsequently were loaded incrementally. Environmental conditions of temperature and humidity were approximately similar between specimens cured with and without an applied $\sigma'_v$. Specimens cured under an applied $\sigma'_v$ were inundated during loading and temperature of the laboratory was equivalent to temperature of the humidity-controlled room.

## 3.3 Results

A summary of compression tests conducted on synthetic tailings with and without binder amendment and no applied vertical stress is in Table 3.3. A summary of the compression tests on fly ash-amended specimens cured under an applied vertical stress is in Table 3.4. The summaries in Tables 4.3 and 4.4 include binder content by dry mass, *W/B*, $\sigma'_B$, and $C_c$. Additionally, the initial specimen porosity (n), ratio of porosity to volumetric fraction of binder ($n/B_v$), and curing time ($t_c$) are tabulated in Table 3.3. The $C_c$s in Tables 4.3 and 4.4 were either (i) determined for the entire compression curve for unamended specimens or specimens with negligible cementitious bond formation or (ii) determined for the linear portion of the compression curve for $\sigma'_v > \sigma'_B$ for fly ash-amended specimens that exhibited cementitious bonding.

An example of temporal compression behavior for fine synthetic tailings prepared at *SC* = 70%, FA-A = 8.5%, and $t_c$ = 7 days is shown in Figure 3.3a for $\Delta\sigma'_v$ = 50 kPa and a final $\sigma'_v$ = 83 kPa. The temporal compression behavior in Figure 3.3a is representative of all specimens tested in this study, where primary and secondary compression were separated via the logarithm-of-time curve-fitting procedure. The decrease in void ratio between the end-of-primary compression and 24 h (i.e., secondary compression) was considered negligible such that the void ratio at 24 h was used as the end-of-primary compression in all tests.

The relationship between *e* at 24 h and $\sigma'_v$ for the same fly ash-amended specimen (fine synthetic tailings, *SC* = 70%, FA-A = 8.5%, and $t_c$ = 7 d) is shown in Figure 3.3b. A change in slope of the compression curve was apparent for most binder-amended specimens evaluated in this study. This change in slope was attributed to breakage of cementitious bonds and the presence of a $\sigma'_B$, which has been observed by Horpibulsuk et al. (2005). The shape of compression curves for binder-amended specimens were analogous to overconsolidated soils, and thus, the Casagrande method for determining a pre-consolidation stress was applied to determine $\sigma'_B$ for all binder-amended specimens. The *e*-$\sigma'_v$ relationship in Figure 3.3b is representative of all binder-amended specimens evaluated in this study that exhibited cementitious behavior.

### 3.3.1 Compression Behavior of Specimens Cured with No Applied Vertical Stress

Temporal trends of *e* and excess pore water pressure ($\Delta u$) for compression tests on fine synthetic tailings prepared at *SC* = 70% with no binder addition, 8.5% FA-A, and 8.5% cement ($t_c$ = 7 days) are shown in Figure 3.4. Compression behavior of the unamended specimen is representative of other unamended tailings specimens tested in this study. Compression behavior of the fly ash- and cement-amended specimens are representative of binder-amended specimens evaluated. Excess pore water pressure was monitored during incremental loading; however, the measured $\Delta u$ was lower than $\Delta\sigma_v$ for all loading steps for all specimens. Yilmaz et al. (2010) reported $\Delta u$ between 0% and 96% of $\Delta\sigma_v$ for 203-mm-thick specimens consisting of comparable materials tested.  hey reported that only a portion of $\Delta u$ could be measured when drainage valve(s) remain open. The top drainage boundary for consolidation tests was open to the atmosphere, and when combined with the thin specimens (≈ 25.4-mm thick), $\Delta u$ dissipated rapidly following loading and only a fraction of the $\Delta u$ was measured. Thus, trends in the development of $\Delta u$ as a function of loading were compared between unamended and amended specimens, and the actual magnitude of $\Delta u$ was given little consideration.

Excess pore water pressure increased following load application and subsequently decreased concurrently with an increase in settlement in the unamended fine synthetic tailings (Figure 3.4a). Larger contributions of Δu were measured in the unamended tailings during initial stress increments when the material was softer and applied loads were more effectively transferred to the pore water fraction. In contrast, initial load increments for the fly ash- and cement-amended tailings yielded small settlements and negligible Δu (Figures 3.4b and 3.4c). Formation of cementitious bonds between adjacent particles inhibited vertical deformation and transfer of applied stress to the pore water fraction in the binder-amended specimens.

Horpibulsuk et al. (2005) reported that effective stress in granular materials with cementitious bonds can be carried via particle-to-particle contacts and cementitious bonds. The cementitious bonds can carry nearly all applied load when $\sigma'_v$ is less than $\sigma'_B$. A transition in compression behavior of the fly ash- and cement-amended tailings was observed as $\sigma'_v$ exceeded $\sigma'_B$; settlement magnitudes increased and larger fractions of Δu were measured (Figures 3.4b and 3.4c). This behavior was attributed to breakage of cementitious bonds and transfer of applied load to the more deformable soil skeleton.

The influence of binder amendment on compression curves ($e$-$\sigma'_v$) of fine synthetic tailings prepared at $SC$ = 70% is shown in Figure 3.5. In general, the slope of the $e$-$\sigma'_v$ curve for binder-amended tailings was lower compared to unamended tailings for $\sigma'_v < \sigma'_B$. An increase in slope of the $e$-$\sigma'_v$ curve was observed for all binder-amended tailings specimens at $\sigma'_v > \sigma'_B$. Unamended tailings exhibited compression behavior characteristic of normally consolidated soils, which was anticipated, since all unamended tailings specimens were prepared from slurries. Compression behavior of binder-amended tailings was analogous to overconsolidated soils, and the magnitude of $\sigma'_B$ was a function of cementitious properties of the binders. Compression curves in Figure 3.5 indicate that cement amendment yielded the largest $\sigma'_B$, and that FA-A yielded a larger $\sigma'_B$ compared to FA-C.

### 3.3.1.1 Effect of Physical Properties

Relationships between $\sigma'_B$ and $C_c$ versus fly ash content for fine synthetic tailings and average synthetic tailings amended with FA-A are shown in Figure 3.6. Data in Figure 3.6 include fine synthetic tailings prepared at SC = 60% and 70% and cured for 0.1, 7, and 28 d, and average synthetic tailings prepared at SC = 70% and cured for 0.1, 7, and 28 days. In general, $\sigma'_B$ increased with an increase in fly ash content for fine and average synthetic tailings, regardless of SC or $t_c$ (Figures 3.6a and 3.6b). An increase in fly ash content led to more pronounced development of cementitious bonds between adjacent particles that were capable of supporting larger applied loads and corresponded to higher $\sigma'_B$.

There was no clear trend between $C_c$ determined for $\sigma'_v > \sigma'_B$ and fly ash content for fine synthetic tailings or average synthetic tailings (Figures 3.6c and 3.6d). This observation regarding the compressibility of cementitious binder-amended soils and tailings is in agreement with past research (e.g., Horpibulsuk et al. 2005; Bobet et al. 2011; Federico et al. 2015), and suggests that compression behavior of binder-amended materials is predominantly controlled by the soil or tailings matrix for $\sigma'_v > \sigma'_B$. However, Nalbantoglu and Tuncer (2001) reported a decrease in $C_c$ with an increase in binder content (e.g., lime and fly ash) in a high plasticity soil, which was attributed to flocculation and aggregation of soil particles that decreased compressibility. Thus, soil plasticity likely influences the compressibility of binder-amended materials for $\sigma'_v > \sigma'_B$. Soil plasticity has been observed to influence the hydraulic and strength properties of binder-amended soils and mine tailings (e.g., Alhomair et al. 2016; Gorakhki and Bareither 2017).

A hypothesis evaluated in this study was that the $C_c$ in binder-amended tailings for $\sigma'_v > \sigma'_B$ increases with an increase in $\sigma'_B$. This hypothesis implies that materials with strong cementitious bonding and high $\sigma'_B$ experience collapsible behavior as $\sigma'_v$ exceeds $\sigma'_B$. The relationship between $C_c$ and $\sigma'_B$ is shown in Figure 3.7, which includes data from fine synthetic tailings amended with FA-A, FA-C, and cement and average synthetic tailings amended with FA-A and cement. In general, $C_c$ increases with increasing $\sigma'_B$ for both fine and average synthetic tailings. Linear trend lines for the $C_c$-$\sigma'_B$ relationships yielded coefficients of determination ($R^2$) of 0.74 for fine synthetic tailings and 0.48 for average synthetic tailings. Although some scatter exists in fine and average synthetic tailings data sets in Figure 3.7, both data compilations support the hypothesis that $C_c$ increases with increasing $\sigma'_B$ for cementitious binder-amended tailings. The relationships are dependent on incorporation of a broad range of $\sigma'_B$ developed from different types of cementitious binders and specimens prepared with different percent binder amendments. The $C_c$-$\sigma'_B$ relationships suggest that although a stiff material with high $\sigma'_B$ can be created via the addition of cementitious binders with higher pozzolanic potential, there is a concern of increasing collapse potential (i.e., high $C_c$) when $\sigma'_v$ exceeds $\sigma'_B$.

The relationship between $\sigma'_B$ of fly ash-amended synthetic tailings and $n/B_v$ is shown in Figure 3.8. The $n/B_v$ parameter represents the fraction of void volume that is composed of binder since $B_v$ equals the ratio of binder volume to total volume. The $n/B_v$ parameter has been evaluated as a predictive parameter for mechanical behavior (e.g., shear strength and compressibility) of cement-amended soils (Consoli et al. 2004, 2007, 2009), and decreasing $n/B_v$ correlates with stiffer and stronger materials. Specimens in this study were prepared at $W/B$ = 2.5 and 5, which corresponded to $n/B_v$ ranging from approximately 6-7 and 12-13, respectively. Data in Figure 3.8 suggest a trend of decreasing $\sigma'_B$ with increasing $n/B_v$. An increase in $n/B_v$ corresponds to either an increase in void volume with constant binder volume or a decrease in binder volume with constant void volume. Consoli et al. (2009) reported a decrease in UCS of cement-amended soils with increase in $n/B_v$, and Federico et al. (2015) reported an empirical relationship between UCS and $\sigma'_B$. Thus, the $n/B_v$ can be an effective parameter to evaluate compressibility and $\sigma'_B$ of cementitious binder-amended materials.

A comparison between $\sigma'_B$ of fine synthetic and average synthetic tailings amended with FA-A is shown in Figure 3.9. Data points in Figure 3.9 are differentiated based on $W/B$ (2.5 and 5) and curing time ($t_c$ = 0.1 d, 7 d, and 28 d). All data in Figure 3.9 plot above the 1:1 line, which implies that $\sigma'_B$ of average synthetic tailings are larger than fine synthetic tailings when prepared similarly (i.e., same SC, FA content, $W/B$, and $t_c$). Larger $\sigma'_B$ for coarser-grained materials agrees with findings in literature (e.g., Fall et al. 2005; Fall et al. 2008). Fall et al. (2005) evaluated the effect of finer particles in tailings (i.e., particles with diameter < 0.020 mm) on the UCS of tailings-binder mixtures and reported a decrease in UCS via increase in finer particles for all curing times and binder types evaluated in their study. Federico et al. (2015) reported a linear relationship between UCS and $\sigma'_B$, which suggests that material parameters affecting UCS have similar influence on $\sigma'_B$. The larger-sized particles in average synthetic tailings compared with fine synthetic tailings (Table 3.1) correspond to larger UCS in cementitious-binder amended materials (Federico et al. 2015), which in turn correspond to larger $\sigma'_B$.

### 3.3.1.2 Effect of Curing Time

Relationships between $\sigma'_B$ and $t_c$ for fine synthetic and average synthetic tailings amended with FA-A and FA-C at different fly ash contents are shown in Figures 3.10a and 3.10b. Negligible influence of $t_c$ on $\sigma'_B$ was observed for specimens amended with FA-C. This behavior was due to the limited effectiveness of FA-C in generating cementitious bonds (discussed subsequently). Two general trends between $t_c$ and $\sigma'_B$ were observed for fine and average synthetic tailings amended with FA-A: (i) for fine synthetic tailings, $\sigma'_B$ increased with an increase in $t_c$ from 0.1 dayto 7 daysand then remained approximately constant for $t_c$ = 7 days and 28 days; and (ii) for average synthetic tailings, $\sigma'_B$ was approximately constant and independent of $t_c$.

Nearly all fine synthetic and average synthetic tailings specimens cured for $t_c$ = 7 days and 28 days yielded negligible difference in $\sigma'_B$. This consistency in $\sigma'_B$ was anticipated and attributed to the pronounced development of cementitious products in the first few days following binder hydration for non-sulfidic mine tailings (Yilmaz et al. 2014). However, the more confounded effect of increasing $t_c$ from 0.1 day to 7 days on $\sigma'_B$ was due to the following competing mechanisms that occurred simultaneously: (i) binder hydration to generate cementitious products; (ii) breakage of cementitious bonds via incremental loading; and (iii) reduction in $n/B_v$ via discharge of water following loading. The first mechanism is inherently time dependent (e.g., Tastan et al. 2011), whereas the second and third mechanisms are artifacts of incremental loading that affect specimens with $t_c$ = 0.1 d. The breakage of cementitious bonds during the process of cementitious bond formation acts to decrease $\sigma'_B$ and the discharge of water (i.e., reduction in pore volume) acts to decrease $n/B_v$ and increase $\sigma'_B$.

A comparison of compression behavior between average synthetic tailings and fine synthetic tailings amended with FA-A at $W/B$ = 5 and $t_c$ = 0.1 day, 7 days, and 28 days is shown in Figure 3.11. Average synthetic tailings at $t_c$ = 0.1 day had approximately the same $\sigma'_B$ as specimens cured for 7 days and 28 days ($\sigma'_B$ = 110 to 115 kPa, Table 3.3 and Figure 3.11a). However, fine synthetic tailings cured for 0.1 day yielded a smaller $\sigma'_B$ (15 kPa) compared to specimens cured for 7 days and 28 days (55 and 60 kPa, Table 3.3 and Figure 3.11b). The difference in development of $\sigma'_B$ between $t_c$ = 0.1 day and 7 days for fine synthetic and average synthetic tailings amended with FA-A was attributed to differences in compression behavior prior to breakage ($\sigma'_v < \sigma'_B$) (Figure 3.11).

Cementitious products generated from the pozzolanic reactions form at different reaction times, whereby calcium silicate hydrate gel (CSH) begins to form 1-2 hours after hydration under standard temperature and pressure (STP) and calcium aluminate silicate hydrate gel (CASH) begins to form 1 day after hydration at STP (Kurtis 2007; Pacheco-Torgal et al. 2014). Thus, CSH bonds develop after applying the first load and CASH bonds develop after applying the second load for binder-amended specimens with $t_c$ = 0.1 day. During these initial loading steps, water can simultaneously (i) react with fly ash to generate CSH and CASH products and (ii) discharge from the specimen due to consolidation. Hydraulic conductivity of fine synthetic tailings was lower than average synthetic tailings (Alhomair et al. 2016). This difference resulted in a tendency for water to be retained in the fine synthetic tailings during initial incremental loads, which led to cementitious bond formation at larger $n/B_v$. Development of cementitious bonds at higher $n/B_v$ yields lower $\sigma'_B$ (Figure 3.8). Cementitious bonding in the fine synthetic tailings developed under comparable specimen porosities for $t_c$ = 0.1 day, 7 days, and 28 days, which led to an anticipated increase in $\sigma'_B$ from $t_c$ = 0.1 day to $t_c$ = 7 days and comparable $\sigma'_B$ for $t_c$ = 7 days and 28 days (Figures. 3.10a and 3.11b).

In contrast, the larger hydraulic conductivity of average synthetic tailings was advantageous to rapid consolidation (i.e., rapid discharge of water) during initial loading for specimens with $t_c$ = 0.1 day. The $e$-$\sigma'_v$ relationships for average synthetic tailings in Figure 3.11a show a reduction in $e$ with initial loading for the $t_c$ = 0.1-day specimen, which was followed by comparable compression to specimens cured for 7 days and 28 days. This initial reduction in e corresponded to a decrease in $n/B_v$ that likely contributed to increasing $\sigma'_B$ larger than initially anticipated for a short duration curing time. Although speculative, a lower $n/B_v$ corresponds to conditions that are more conducive to cementitious bond formation and development of $\sigma'_B$ (e.g., Figure 3.8). The discharge of water during initial consolidation and subsequent development of cementitious bonds for the average synthetic tailings specimens cured at $t_c$ = 0.1 day resulted in approximately the same $\sigma'_B$ for specimens cured at $t_c$ = 0.1 day, 7 days, and 28 days.

Relationships between $C_c$ and $t_c$ for fine and average synthetic tailings are shown in Figures 3.10c and 3.10d, respectively. In general, two different behaviors between $C_c$ and $t_c$ were observed: (i) an increase in $C_c$ with an increase in $t_c$ for fine synthetic tailings specimens amended with FA-A; and (ii) no trend between $C_c$ and $t_c$ for fine synthetic tailings specimens amended with FA-C and for average synthetic tailings specimens. These trends correspond to the behavior discussed in regards to Figures 3.7 and 3.11a. An increase in $\sigma'_B$ correlated with an increase in $C_c$ (Figure 3.7). Fine synthetic tailings specimens that exhibited an increase in $\sigma'_B$ with increase in $t_c$ exhibit comparable trends of increasing $C_c$ with increasing $t_c$. In contrast, fine synthetic tailings amended with FA-C exhibited negligible development of $\sigma'_B$ (Figure 3.10a), and correspondingly, $C_c$ was comparable for different curing times. The influence of $t_c$ on $\sigma'_B$ was confounded by competing mechanisms of specimen consolidation and binder hydration (discussed previously); no definitive trends between $C_c$ and $t_c$ were observed for average synthetic tailings (Figure 3.11b). Further investigation is needed to evaluate the effect of curing time on compressibility behavior of mine tailings, particularly for $\sigma'_v > \sigma'_B$.

#### 3.3.1.3 Effect of Fly Ash Chemical Composition

Comparison between $\sigma'_B$ for fine and average synthetic tailings amended with FA-A and FA-C are shown in Figure 3.12a. Data in Figure 3.12 are differentiated based on *W/B* (2.5 and 5) and curing time (0.1 day, 7 days, and 28 days). Fine and average synthetic tailings prepared at SC = 60% and amended with FA-C did not exhibit a $\sigma'_B$, which is why the majority of data in Figure 3.12a plot along the x-axis. Although some synthetic tailings specimens prepared at SC = 70% and amended with FA-C exhibited a $\sigma'_B$, all data in Figure 3.12a plot below the 1:1 line. This contrast in $\sigma'_B$ between FA-A and FA-C was attributed to greater pozzolanic potential of FA-A, which was observed in regard to the position of each fly ash in the ternary plot in Figure 3.2. FA-A plotted between Portland cement and typical fly ash, whereas FA-C plotted in the range of typical fly ash. The higher CaO and larger $CaO/SiO_2$ of FA-A in comparison with FA-C resulted in more pronounced generation of cementitious bonds. This pozzolanic behavior has been observed in previous research (e.g., Janz and Johnson 2002; Tastan et al. 2011).

The effect of fly ash type on $C_c$ of fine and average synthetic tailings specimens prepared with similar initial conditions is shown in Figure 3.12b. Although the majority of the data plot close to 1:1 line, the data indicate that $C_c$ for tailings amended with FA-A were larger than $C_c$ for tailings amended with FA-C. This observation is attributed to more favorable pozzolanic potential of FA-A that led to larger $\sigma'_B$ and subsequently larger $C_c$ for $\sigma'_v > \sigma'_B$. The data points that plot furthest from the 1:1 line are for fine synthetic tailings amended with 27% fly ash and cured for 7 days and 28 days. These two specimens yielded high $\sigma'_B$ when amended with FA-A ($\sigma'_B$ = 90 and 100 kPa) and $\sigma'_B$ = 0 kPa when amended with FA-C.

### 3.3.2 Compression Behavior for Specimens Cured Under Applied Vertical Stress

The compression analysis for fly ash-amended materials cured under an applied vertical load included both fine and average synthetic tailings (Table 3.4). The fine synthetic tailings specimens were prepared at *SC* = 60%, amended with 13% FA-A (*W/B* = 5), and cured under $\sigma'_v$ = 0, 10, 60, and 100 kPa (Table 3.4). This range of $\sigma'_v$ is representative of tailings-fly ash mixtures at depths between 0 m to 18 m in a saturated tailings deposit. The average synthetic tailings specimens were prepared at *SC* = 70%, amended with 17 % FA-A (*W/B* = 2.5), and cured under $\sigma_v$ = 0, 10, and 60 kPa (Table 3.4). This range of $\sigma'_v$ is representative of tailings-fly ash mixtures at depths between 0 m to 9 m within a saturated tailings deposit.

The $e$-$\sigma'_v$ relationships for fine synthetic tailings and average synthetic tailings cured for $t_c$ = 7 days under different $\sigma'_v$ are shown in Figures 3.13a and 3.13b. The initial $e$ plotted in Figures 3.13a and 3.13b for the lowest $\sigma'_v$ correspond to the $e$ after curing for 7 days and subsequently unloading the specimens. Vertical stress was applied on each specimen within 1 hour following mixing and preparation of the specimens. This short duration of loading was achieved prior to formation of cementitious bonds and resulted in compression and expulsion of pore water. As expected, all specimens compressed under an applied $\sigma'_v$ such that the initial $e$ after curing decreased with increase in $\sigma'_v$. Limited compression was observed for all fine and average synthetic tailings specimens for the first load increment, which supports the development of $\sigma'_B$ in all specimens.

The relationships between $\sigma'_B$ and $\sigma'_v$ during curing for fine and average synthetic tailings are shown in Figure 3.14a. Linear trend lines were fit to both data sets in Figure 3.14a and indicate that $\sigma'_B$ increased with an increase in $\sigma'_v$ during curing. Compression of the fine and synthetic tailings specimens during initial application of $\sigma'_v$ resulted in lower water contents for these specimens during curing. Lower water contents during cementitious bond formation resulted in lower *W/B* and $n/B_v$. A decrease in *W/B* or $n/B_v$ for mixtures prepared with the same fly ash content (Table 3.4) corresponded to an increase in cementitious products relative to void volume. This greater abundance of cementitious products in the fabric of a given tailings specimen resulted in a stiffer and stronger amended material (e.g., Zhu et al. 1995; Yilmaz et al. 2009, 2010).

The relationships between $C_c$ and $\sigma'_v$ during curing for fine and average synthetic tailings are shown in Figure 3.14b. An increase in $C_c$ was observed with an increase in $\sigma'_v$ during curing for both synthetic tailings. This behavior was anticipated based on the increase in $\sigma'_B$ with increasing $\sigma'_v$ and the positive relationship observed previously between $C_c$ and $\sigma'_B$ (Figure 3.7). The final void ratios of the fine synthetic tailings specimens at $\sigma'_v$ = 1200 kPa were similar and ranged between 0.73 and 0.83 (Figure 3.13a). Similarly, the final void ratios of the average synthetic tailings specimens at $\sigma'_v$ = 1200 kPa were in a close range (0.79 to 0.88, Figure 3.13b). Thus, although an increase in compression was observed as $\sigma'_v$ exceeds $\sigma'_B$ for synthetic tailings specimens cured under an applied $\sigma'_v$, the specimens ultimately approached similar void ratios (i.e., density) with continued increase in $\sigma'_v$.

### 3.3.3 Natural Tailings

A summary of compression tests conducted on natural tailings with and without binder amendment is in Table 3.5. The suite of experiments conducted on natural tailings was to (i) validate observed behavior from the synthetic tailings analysis and (ii) assess if these general observations translate across fly ashes and mine tailings with different compositions. To this extent, four actual (i.e., natural) mine tailings and an additional fly ash were included in this analysis. The natural mine tailings (Table 3.5) included soda ash tailings (NSA), fine garnet tailings (NFG), fine garnet tailings passing a No. 200 sieve ($NP_{200}G$), and copper tailings (NCu). In general, similar compression behavior was observed in experiments on natural tailings as those observed and described for synthetic tailings: (i) bi-linear compression curves were observed in all fly ash-amended natural tailings; (ii) $\sigma'_B$ decreased with an increase in *W/B* or $n/B_v$; and (ii) $\sigma'_B$ increased with an increase in cementitious potential of fly ash (i.e., $CaO/SiO_2$).

The relationship between $\sigma'_B$ of fly ash-amended natural tailings as a function of $n/B_v$ for different fly ash types is shown in Figure 3.15. The $\sigma'_B$ of fly ash-amended synthetic tailings at $t_c$ = 7 days are included in Figure 3.15 for comparison. Data in Figure 3.15 suggest a trend of decreasing $\sigma'_B$ with increasing $n/B_v$. The trend of decreasing $\sigma'_B$ with increase in $n/B_v$ is more apparent in specimens amended with FA-A. Reduction in $\sigma'_B$ with an increase in $n/B_v$ was small for tailings amended with either FA-B or FA-C. These trends were attributed to the higher cementitious properties of FA-A in comparison with FA-B and FA-C. The general relationship between $\sigma'_B$ and $n/B_v$ for natural tailings is in agreement with findings from the experiments on synthetic tailings and literature (Consoli et al. 2004, 2007, 2009;).

Fly Ash B (FA-B) was used to evaluate conclusions drawn on the effect of fly ash chemical composition on the compression behavior of fly ash-amended mine tailings. This fly ash plotted between FA-A and FA-C in the ternary plot in Figure 3.2. The $CaO/SiO_2$ of FA-A, FA-B, and FA-C were 0.86, 0.41, and 0.25 respectively. The chemical composition and position of FA-B in Figure 3.2 suggests that FA-B has lower cementitious potential compared to FA-A, but slightly better cementitious compared to FA-C. Compression tests conducted on $NP_{200}G$ prepared at SC = 70%, amended with the three different fly ashes at 17%, and cured for 7 days support an increase in $\sigma'_B$ with increasing pozzolanic potential of fly ash (Table 3.5). The $\sigma'_B$ for $NP_{200}G$ amended with FA-A was 205 kPa and reduced to 33 kPa for FA-B and 12 kPa for FA-C.

The effect of tailings composition (e.g., PSD, plasticity) on σ'$_B$ was adequately addressed due to the limited number of experiments conducted on a given natural tailings combined with multiple confounding factors (e.g., percent binder amendment, *SC*, etc.). However, the σ'$_B$ plotted in Figure 3.15 for compression tests conducted on tailings amended with FA-A suggest that non-plastic tailings can be expected to yield higher σ'$_B$ compared to tailings that exhibit plasticity. The largest two σ'$_B$ plotted in Figure 3.15 for $n/B_v \approx$ 6-7 are for $NP_{200}G$ and average synthetic tailings, which are followed by soda ash tailings (NSA) and fine synthetic tailings. The $NP_{200}G$ and average synthetic tailings classified as non-plastic silts (Table 3.1) and yielded larger σ'$_B$ relative to NSA and fine synthetic tailings that classified as low-plasticity clays (Table 3.1). Higher σ'$_B$ were measured for both non-plastic silts compared to the low-plasticity clays when all other specimen preparation conditions were identical (i.e., *SC*, *W/B*, and $t_c$). Plasticity properties of a given tailings must be considered in assessing compressibility of binder-amended tailings and is a topic in need of additional research.

**Table 3.1** Summary of waste rock and tailings physical characteristics and classification

| Material | *LL* (%) | *PI* (%) | USCS | $d_{max}$ (mm) | $D_{50}$ (μm) | Sand Content (%) | Fines Content (%) | Clay Content (%) | As-Collected Water Content (%) | $G_s$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Fine Synthetic | 37 | 15 | CL | 0.05 | 2.7 | 0.0 | 100.0 | 40.0 | NA | 2.63 |
| Average Synthetic | NA | NA | ML | 2.00 | 15.8 | 14.2 | 85.8 | 13.0 | NA | 2.66 |
| Copper | 25.2 | 13.7 | SC | 0.85 | 80.0 | 54.7 | 45.3 | 7.0 | 238.0 | 2.72 |
| Soda Ash | 33.5 | 16.1 | CL | 2.00 | 11.1 | 16.5 | 73.5 | 24.0 | 124.0 | 2.55 |
| $P_{200}$ Garnet | NM | NM | ML | 0.075 | 18.0 | 0.0 | 100.0 | 10.4 | NA | NM |
| Fine Garnet | 18.8 | 0.4 | ML | 2.00 | 32.8 | 36.7 | 63.3 | 6.6 | 13.1 | 3.07 |

Note: *LL* = liquid limit; *PI* = plasticity index; USCS = Unified Soil Classification System; $d_{max}$ = maximum particle size; $D_{50}$ = average particle diameter; $G_s$ = specific gravity; NA = not applicable; and NM = not measured.

**Table 3.2** Chemical composition by percent (%) mass for fly ash and cement based on X-ray fluorescence analysis

| Component | Chemical Formula | Fly Ash A (%) | Fly Ash B (%) | Fly Ash C (%) | Cement (%) |
|---|---|---|---|---|---|
| Sodium oxide | $Na_2O$ | 11.62 | 1.13 | 1.87 | - |
| Magnesium oxide | $MgO$ | 2.36 | 3.88 | 2.52 | 1.4 |
| Aluminum oxide | $Al_2O_3$ | 12.24 | 16.53 | 13.67 | 4.7 |
| Silicon dioxide | $SiO_2$ | 19.76 | 46.08 | 47.86 | 19.9 |
| Phosphorous Pentoxide | $P_2O_5$ | 0.28 | 1.09 | 0.26 | - |
| Sulfur Trioxide | $SO_3$ | 15.76 | 4.91 | 0.79 | 3.3 |
| Potassium oxide | $K_2O$ | 1.15 | 0.64 | 2.59 | - |
| Calcium oxide | $CaO$ | 17.00 | 18.90 | 12.13 | 63.2 |
| Iron(III) oxide | $Fe_2O_3$ | 3.62 | 4.89 | 5.64 | 3.2 |

Note: balance of chemical composition to equal 100% includes additional constituents not listed under Components.

**Table 3.3** Summary of specimen properties and compression parameters of synthetic and natural tailings with and without binder amendment

| Name | SC (%) | Binder Type | FA (%) | W/B | n | n/Bv | Curing Time (d) | Breaking Stress (kPa) | Cc |
|---|---|---|---|---|---|---|---|---|---|
| FS0 | 60 | - | 0 | 0 | 0.64 | - | - | 0 | 0.48 |
| FS1 | 60 | FA-A | 13.3 | 5 | 0.63 | 13.2 | 0.1 | 18 | 0.44 |
| FS2 | 60 | FA-A | 13.3 | 5 | 0.64 | 13.4 | 7 | 9 | 0.37 |
| FS3 | 60 | FA-A | 13.3 | 5 | 0.63 | 13.2 | 28 | 55 | 0.39 |
| FS4 | 60 | FA-C | 13.3 | 5 | 0.63 | 12.6 | 0.1 | 0 | 0.41 |
| FS5 | 60 | FA-C | 13.3 | 5 | 0.66 | 13.2 | 7 | 0 | 0.32 |
| FS6 | 60 | FA-C | 13.3 | 5 | 0.67 | 13.4 | 28 | 0 | 0.32 |
| FS7 | 60 | CEM | 13.3 | 5 | 0.64 | 13.8 | 7 | 150 | 0.67 |
| FS8 | 60 | FA-A | 26.7 | 2.5 | 0.65 | 6.8 | 0.1 | 25 | 0.35 |
| FS9 | 60 | FA-A | 26.7 | 2.5 | 0.64 | 6.7 | 7 | 100 | 0.46 |
| FS10 | 60 | FA-A | 26.7 | 2.5 | 0.65 | 6.8 | 28 | 90 | 0.51 |
| FS11 | 60 | FA-C | 26.7 | 2.5 | 0.62 | 6.2 | 0.1 | 0 | 0.30 |
| FS12 | 60 | FA-C | 26.7 | 2.5 | 0.62 | 6.2 | 7 | 0 | 0.28 |
| FS13 | 60 | FA-C | 26.7 | 2.5 | 0.61 | 6.1 | 28 | 0 | 0.25 |
| FS14 | 60 | CEM | 26.7 | 2.5 | 0.64 | 7.2 | 7 | 200 | 0.48 |
| FS15 | 70 | - | 0 | 0 | 0.54 | - | - | 0 | 0.26 |
| FS16 | 70 | FA-A | 8.5 | 5 | 0.53 | 13.4 | 0.1 | 15 | 0.30 |
| FS17 | 70 | FA-A | 8.5 | 5 | 0.54 | 13.7 | 7 | 55 | 0.46 |
| FS18 | 70 | FA-A | 8.5 | 5 | 0.53 | 13.4 | 28 | 60 | 0.39 |
| FS19 | 70 | FA-C | 8.5 | 5 | 0.51 | 12.3 | 0.1 | 0 | 0.25 |
| FS20 | 70 | FA-C | 8.5 | 5 | 0.52 | 12.7 | 7 | 0 | 0.35 |
| FS21 | 70 | FA-C | 8.5 | 5 | 0.53 | 12.8 | 28 | 21 | 0.28 |
| FS22 | 70 | CEM | 8.5 | 5 | 0.52 | 15.4 | 7 | 250 | 0.76 |
| FS23 | 70 | FA-A | 17 | 2.5 | 0.52 | 6.5 | 0.1 | 30 | 0.32 |
| FS24 | 70 | FA-A | 17 | 2.5 | 0.54 | 6.9 | 7 | 75 | 0.30 |
| FS25 | 70 | FA-A | 17 | 2.5 | 0.54 | 6.8 | 28 | 75 | 0.37 |
| FS26 | 70 | FA-C | 17 | 2.5 | 0.54 | 6.5 | 0.1 | 15 | 0.30 |
| FS27 | 70 | FA-C | 17 | 2.5 | 0.54 | 6.5 | 7 | 18 | 0.21 |
| FS28 | 70 | FA-C | 17 | 2.5 | 0.51 | 6.1 | 28 | 15 | 0.32 |
| FS29 | 70 | CEM | 17 | 2.5 | 0.53 | 7.9 | 7 | 210 | 0.64 |
| AS0 | 70 | - | 0 | - | 0.52 | - | - | 0 | 0.26 |
| AS1 | 70 | FA-A | 8.5 | 5 | 0.51 | 13.0 | 0.1 | 115 | 0.33 |
| AS2 | 70 | FA-A | 8.5 | 5 | 0.53 | 13.4 | 7 | 110 | 0.36 |
| AS3 | 70 | FA-A | 8.5 | 5 | 0.55 | 13.9 | 28 | 115 | 0.35 |
| AS4 | 70 | CEM | 8.5 | 5 | 0.53 | 15.4 | 7 | 250 | 0.39 |
| AS5 | 70 | FA-A | 17 | 2.5 | 0.56 | 7.1 | 0.1 | 175 | 0.46 |
| AS6 | 70 | FA-A | 17 | 2.5 | 0.51 | 6.5 | 7 | 180 | 0.36 |
| AS7 | 70 | FA-A | 17 | 2.5 | 0.57 | 7.2 | 28 | 180 | 0.30 |
| AS8 | 70 | CEM | 17 | 2.5 | 0.53 | 7.9 | 7 | 750 | 0.48 |

Notes: SC = solids content; FA = fly ash addition by dry mass; W/B = water-to-binder ratio; n = porosity; $n/B_v$ = porosity-to-binder volume ratio; $C_c$ = compression index; FS = fine synthetic tailings; AS = average synthetic tailings; FA-A = fly ash A; FA-C = fly ash C; CEM = cement.

**Table 3.4** Summary of specimen properties and compression parameters of synthetic and natural tailings amended with binder and cured under an applied vertical stress

| Name | SC (%) | Stress During Curing (kPa) | FA-A (%) | W/B | Breaking Stress (kPa) | $C_c$ |
|---|---|---|---|---|---|---|
| FS-CUS-0 | 60 | 0 | 13.3 | 5 | 9 | 0.37 |
| FS-CUS-1 | 60 | 10 | 13.3 | 5 | 55 | 0.53 |
| FS-CUS-2 | 60 | 60 | 13.3 | 5 | 200 | 0.76 |
| FS-CUS-3 | 60 | 100 | 13.3 | 5 | 350 | 0.99 |
| AS-CUS-4 | 70 | 0 | 17 | 2.5 | 55 | 0.27 |
| AS-CUS-5 | 70 | 10 | 17 | 2.5 | 25 | 0.45 |
| AS-CUS-6 | 70 | 60 | 17 | 2.5 | 75 | —[a] |

Notes: SC = solids content; FA-A = fly ash A; W/B = water-to-binder ratio; $C_c$ = compression index; FS = fine synthetic tailings; AS = average synthetic tailings; CUS = curing under stress.
[a] Post breakage compression behavior was not adequately defined to determine $C_c$.

**Table 3.5** Summary of specimen properties and compression parameters of synthetic and natural tailings amended with fly ash

| Name | SC (%) | Binder Type | FA (%) | W/B | n | $n/B_v$ | Curing Time (d) | Breaking Stress (kPa) | $C_c$ |
|---|---|---|---|---|---|---|---|---|---|
| NSA0 | 70 | — | 0 | — | 0.50 | — | — | 0 | 0.21 |
| NSA1 | 70 | FA-A | 17 | 2.5 | 0.49 | 6.26 | 7 | 140 | 0.23 |
| NFG-0 | 75 | — | 0 | — | 0.48 | — | — | 0 | 0.16 |
| NFG1 | 75 | FA-A | 6.7 | 5 | 0.49 | 12.92 | 7 | 50 | 0.23 |
| $NP_{200}G1$ | 70 | FA-A | 17 | 2.5 | 0.56 | 6.64 | 7 | 205 | 0.28 |
| $NP_{200}G2$ | 70 | FA-C | 17 | 2.5 | 0.58 | 6.55 | 7 | 12 | 0.16 |
| $NP_{200}G3$ | 70 | FA-B | 17 | 2.5 | 0.56 | 5.85 | 7 | 33 | 0.16 |
| $NP_{200}G4$ | 70 | FA-C | 8.5 | 5 | 0.54 | 12.32 | 7 | 16 | 0.25 |
| $NP_{200}G5$ | 70 | FA-B | 8.5 | 5 | 0.58 | 12.08 | 7 | 17 | 0.16 |
| NCu0 | 75 | — | 0 | — | 0.48 | — | — | 0 | 0.12 |
| NCu1 | 75 | FA-A | 6.7 | 5 | 0.47 | 13.13 | 7 | 75 | 0.12 |

Notes: SC = solids content; FA = fly ash addition by dry mass; W/B = water-to-binder ratio; n = porosity; $n/B_v$ = porosity-to-binder volume ratio; $C_c$ = compression index; NSA = natural soda ash tailings; NFG = natural fine garnet tailings; $NP_{200}G$ = natural fine garnet tailings passing a No. 200 sieve; NCu = natural copper tailings; FA-A = fly ash A; FA-B = fly ash B FA-C = fly ash C; — = not applicable

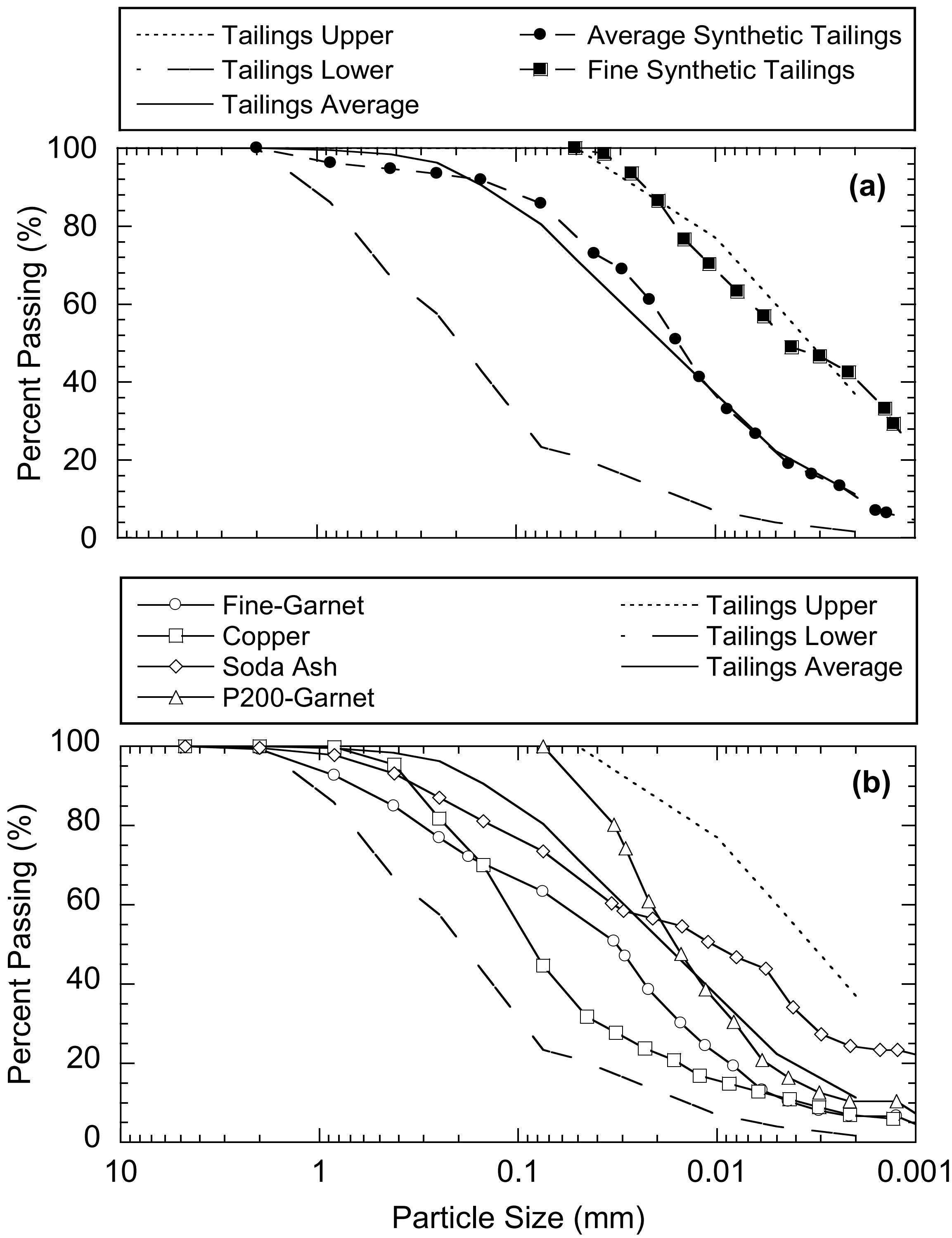
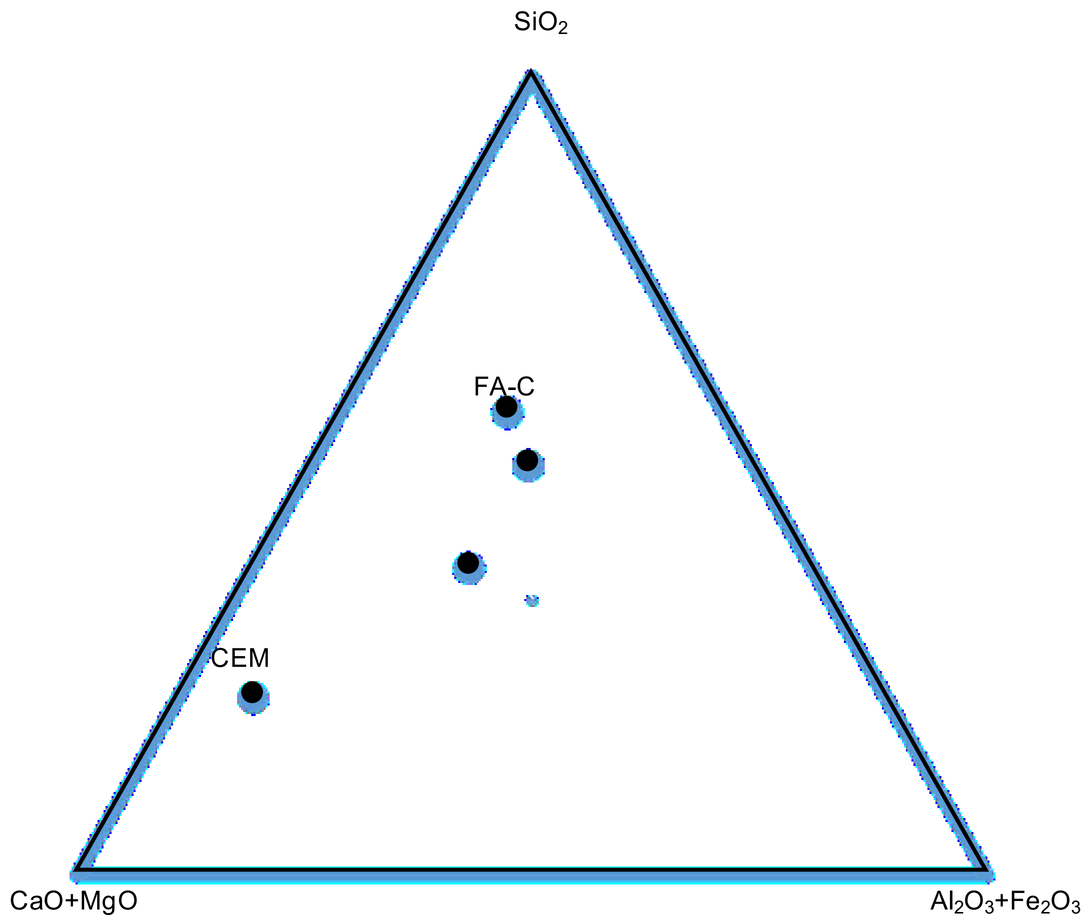



**Figure 3.1** Particle-size-distribution of compiled range and average particle-size distributions for mine tailings compiled from Qiu and Sego (2001), Morris and Williams (2005), Khalili et al. (2005), Wickland and Wilson (2005), Wickland et al. (2006) Bussière (2007), Khalili et al. (2010), and Wickland et al. (2011), (a) synthetic tailings, and (b) natural tailings.




| Binder | Total (%) ($SiO_2$+MgO+CaO+$Fe_2O_3$+$Al_2O_3$) | $SiO_2$ / Total | (MgO+CaO) / Total | ( $Fe_2O_3$+$Al_2O_3$) / Total | CaO / $SiO_2$ |
|---|---|---|---|---|---|
| FA-A | 55 | 0.36 | 0.35 | 0.29 | 0.86 |
| FA-B | 90 | 0.51 | 0.25 | 0.24 | 0.41 |
| FA-C | 82 | 0.58 | 0.18 | 0.24 | 0.25 |
| Cement | 91 | 22 | 69 | 0.09 | 3.18 |

**Figure 3.2** Ternary phase diagram of chemical composition of common binders and composition table of cement and fly ashes used in this study (Popovics 1970; Conner 1990; Tariq 2012) and binder used in this study.

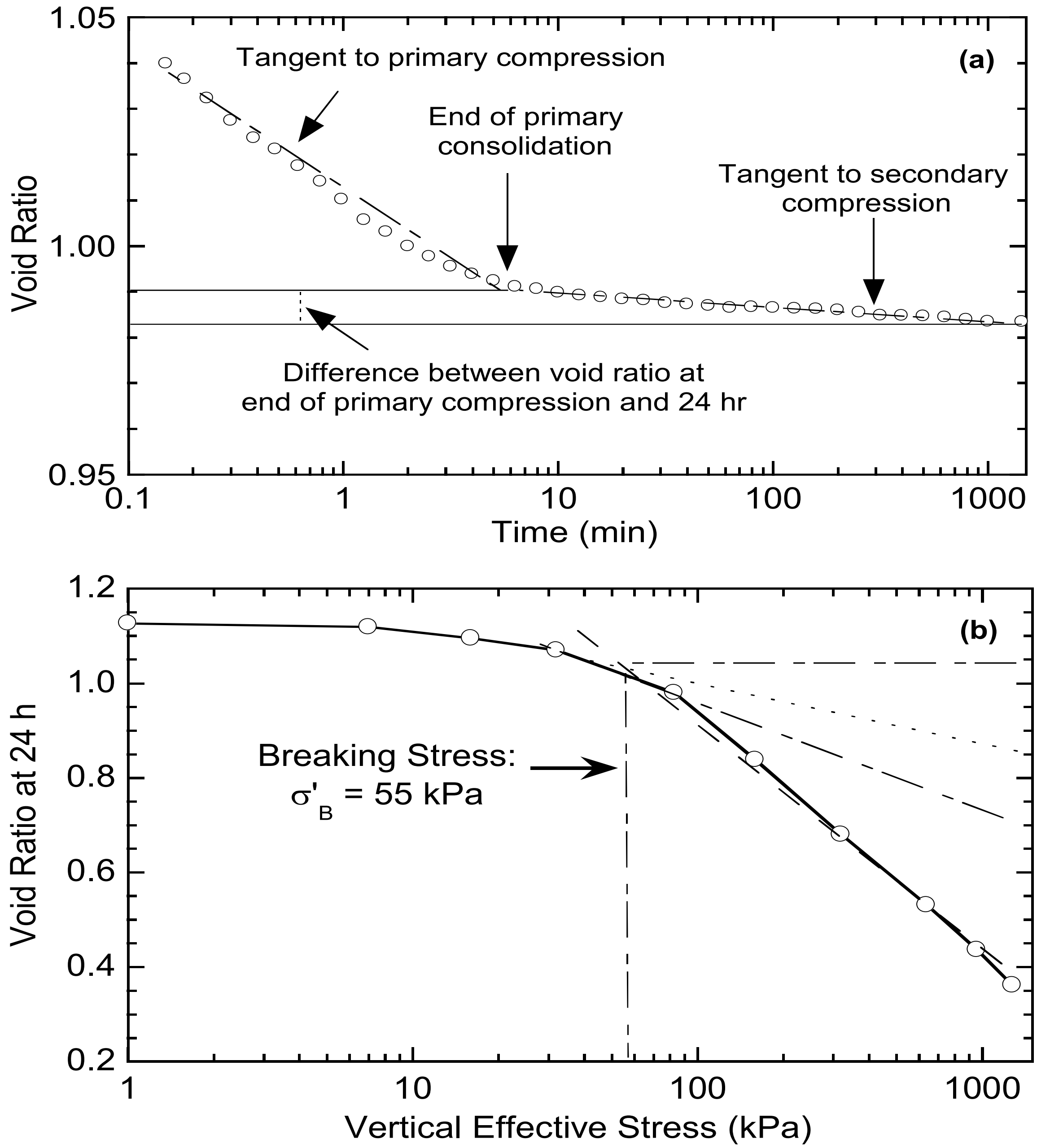



**Figure 3.3** Relationships of (a) void ratio versus time and (b) void ratio at 24-h versus vertical effective stress for specimen fine synthetic tailings prepared at a solids content of 70%, Fly Ash A amendment of 8.5%, and curing time = 7 days (FS17). Data in (a) are for a vertical stress increase of 50 kPa and final vertical effective stress = 83 kPa. Identification of the breaking stress was based on the Casagrande method for pre-consolidation stress.

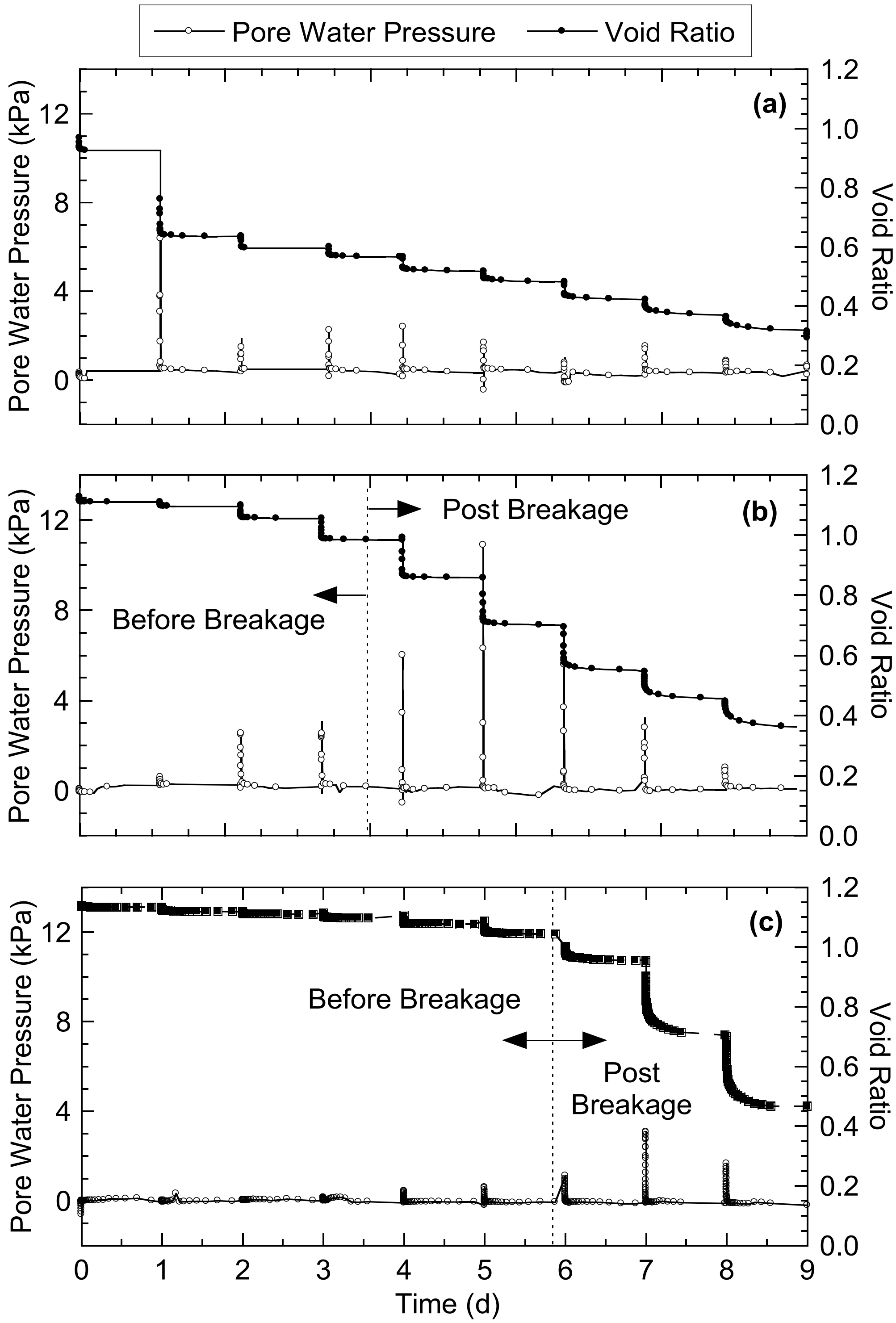



**Figure 3.4** Temporal trends of void ratio and pore water pressure in fine synthetic tailings specimens prepared at 70% solids contents with (a) no binder amendment (FS15), (b) 8.5% Fly Ash A amendment (FS17), and (c) 8.5% cement amendment (FS22).

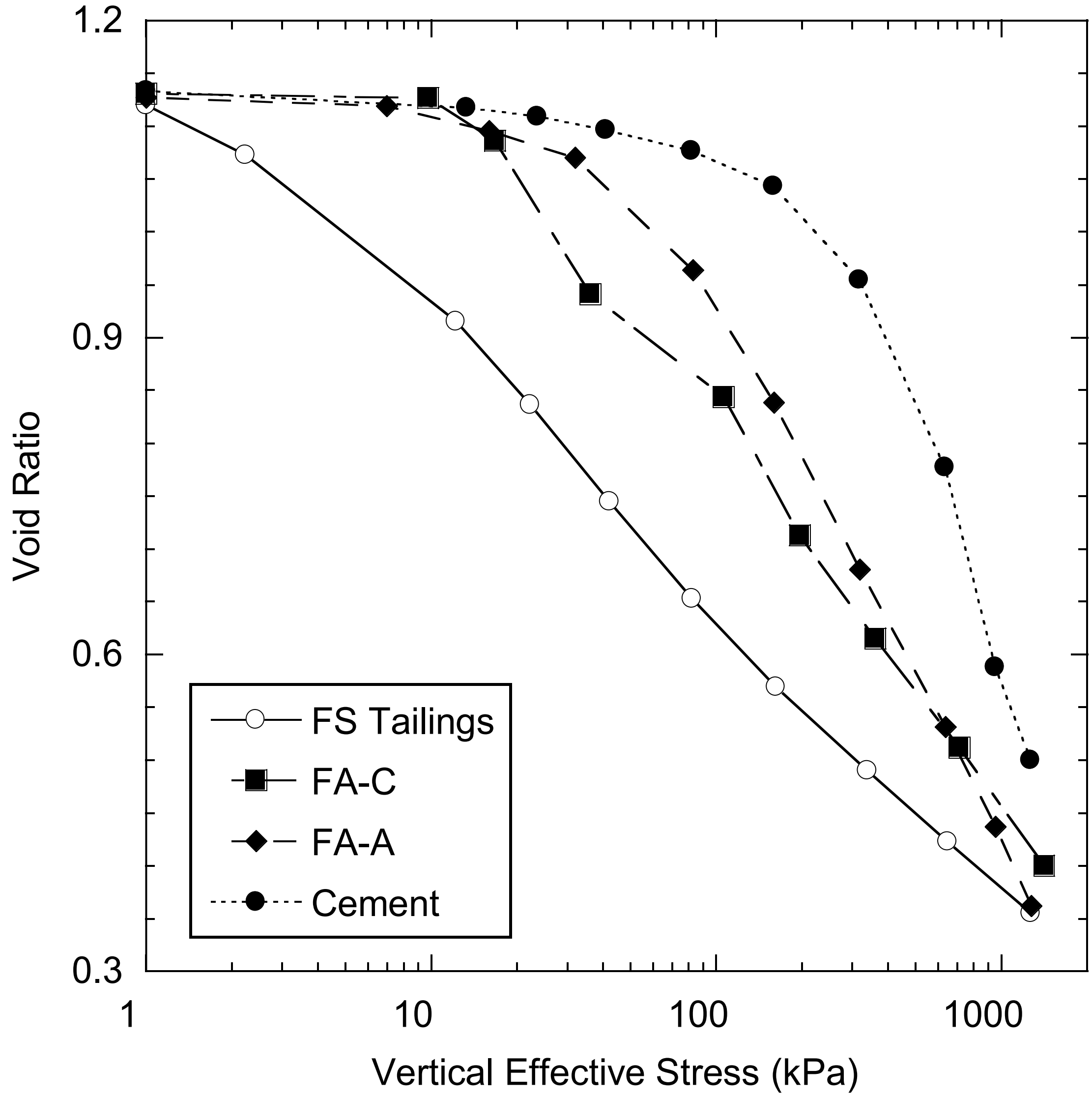



**Figure 3.5** Void ratio at the end of 24 hours versus vertical effective stress relationships for fine synthetic tailings prepared at 70% solids content with 8.5% Fly Ash A (FA-A) (FS17), 8.5% Fly Ash C (FA-C) (FS20), 8.5% cement (FS29), and no binder addition (FS Tailings) (FS15).

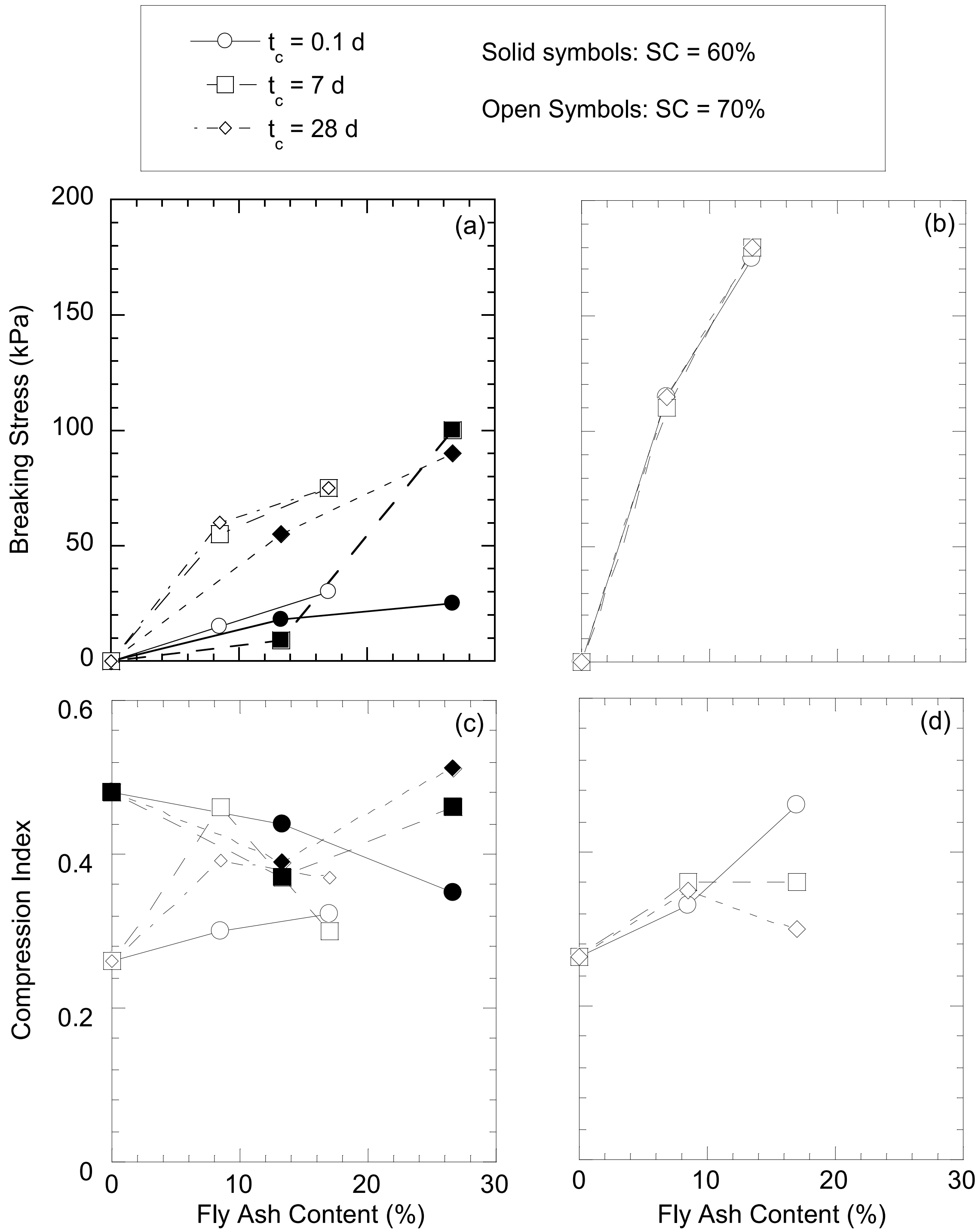



**Figure 3.6** Effect of fly ash content on compression behavior of mine tailings amended with fly ash (a) effect of fly ash content on breaking stress of fine synthetic tailings; (b) effect of fly ash content on breaking stress of average synthetic tailings; (c) effect of fly ash content on compression index of fine synthetic tailings; and (d) effect of fly ash content on compression index of average synthetic tailings.

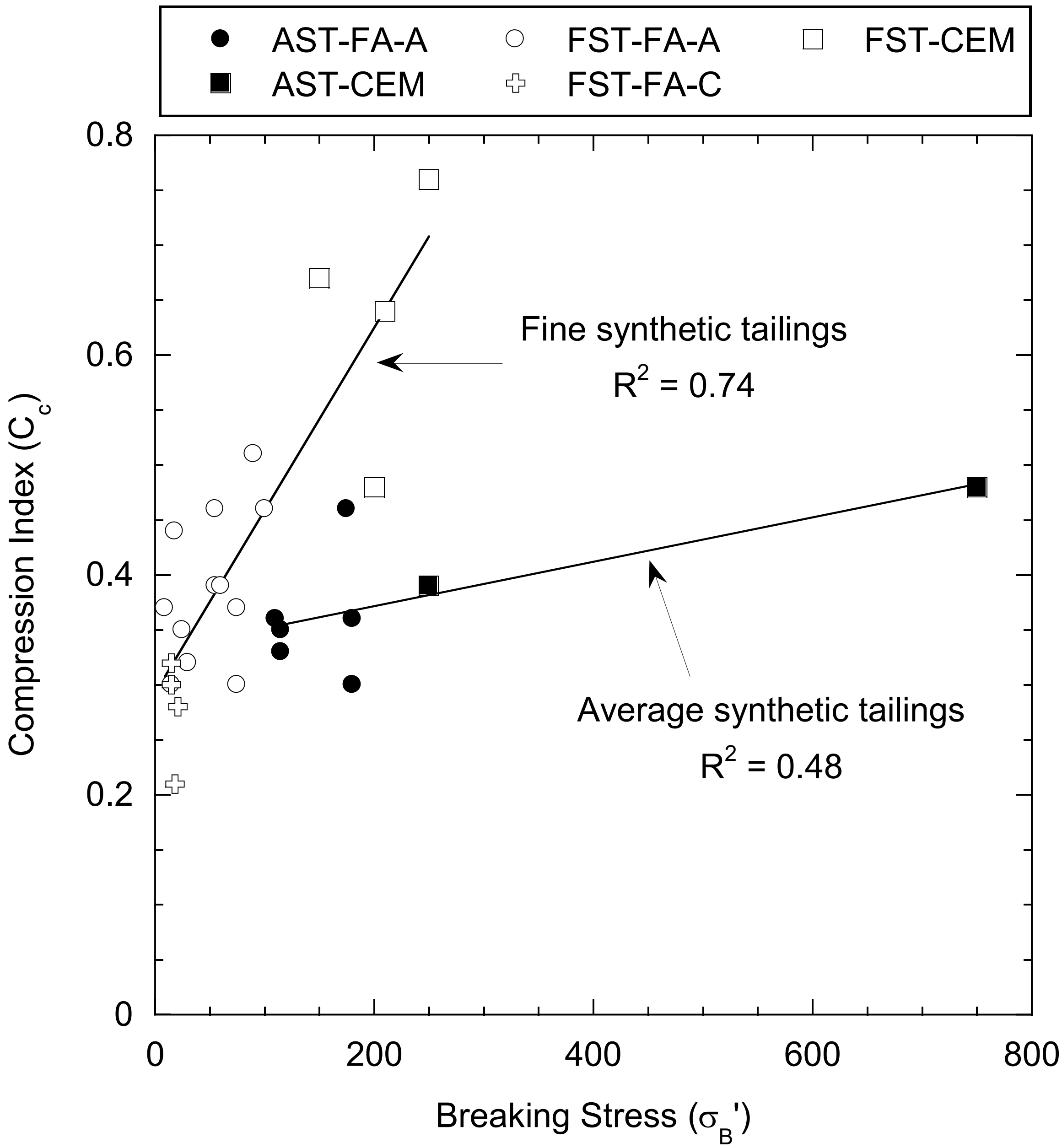



**Figure 3.7** Relationship between compression index ($C_c$) and breaking stress ($\sigma'_B$) for average synthetic tailings (AST) and fine synthetic tailings (FST) amended with fly ash A (FA-A), fly ash C (FA-C), and cement (CEM).

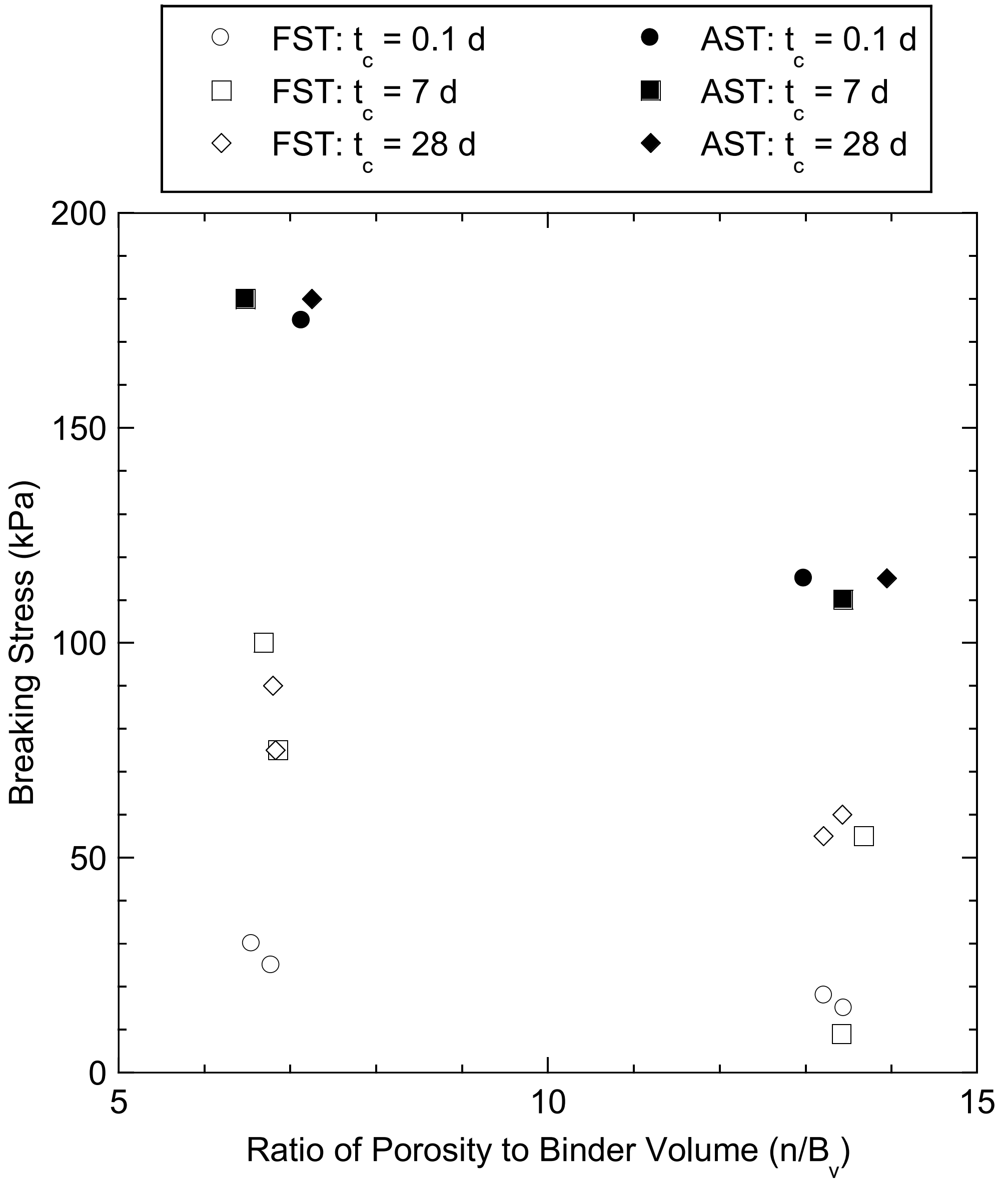



**Figure 3.8** Relationship between breaking stress ($\sigma'_B$) and porosity-to-volumetric portion of binder ($n/B_v$) for synthetic tailings specimens amended with FA-A. Nomenclature notes: AST = average synthetic tailings; FST = fine synthetic tailings; t = curing time.

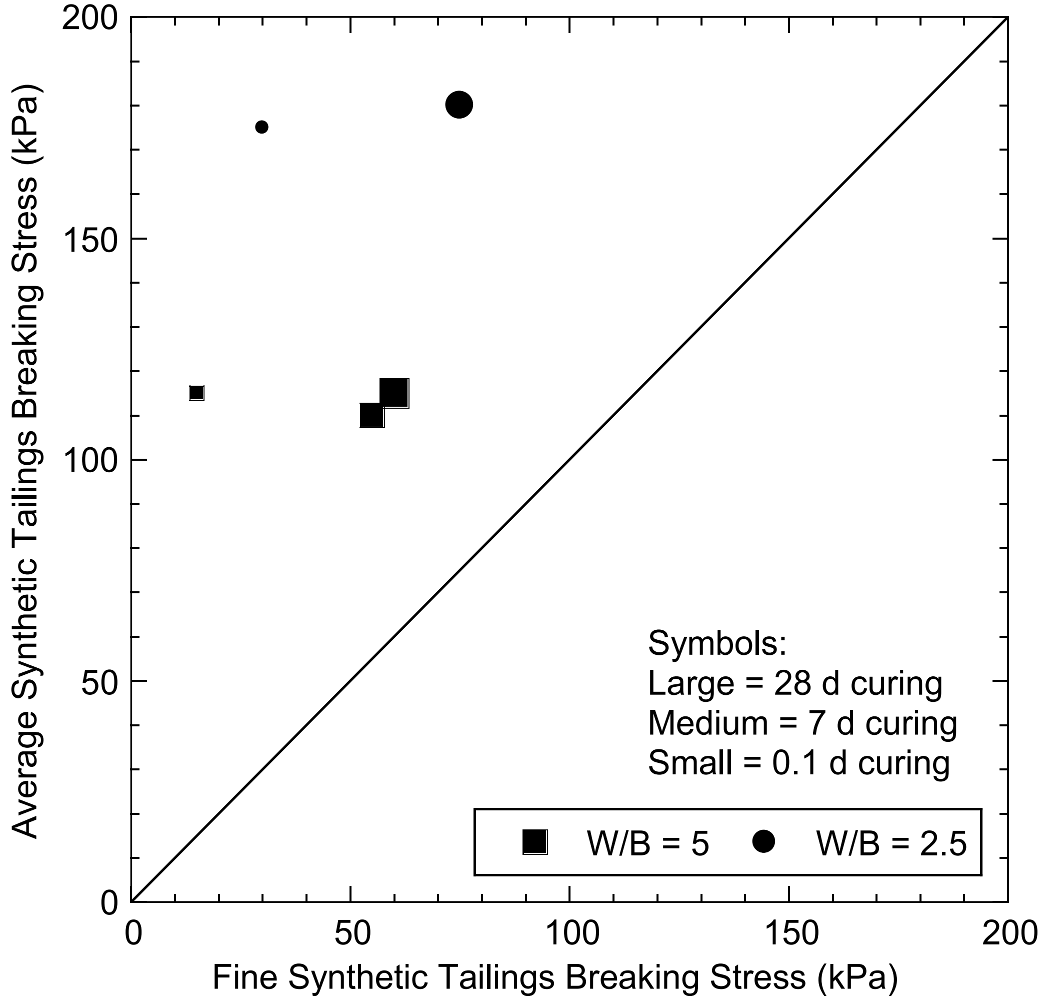



**Figure 3.9** Comparison between breaking stress determined for average synthetic tailings and breaking stress determined for fine synthetic and average synthetic tailings for specimens prepared at similar solids contents, water-to-binder ratios (W/B), and curing times.

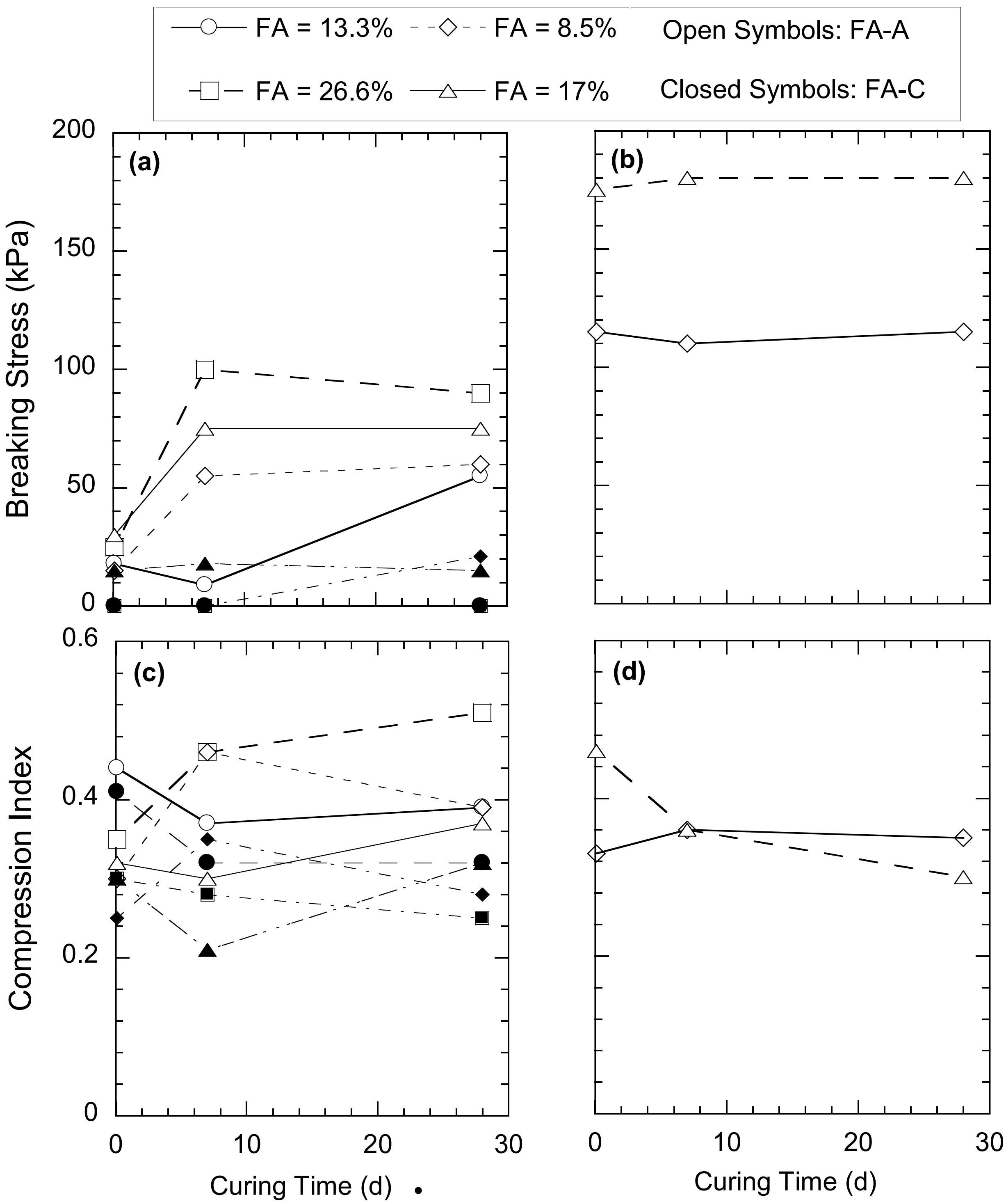



**Figure 3.10** Effect of curing time on compression behavior of mine tailings amended with fly ash (a) effect of curing time on breaking stress of fine synthetic tailings; (b) effect of curing time on breaking stress of average synthetic tailings; (c) effect of curing time on compression index of fine synthetic tailings; and (d) effect of curing time on compression index of average synthetic tailings.

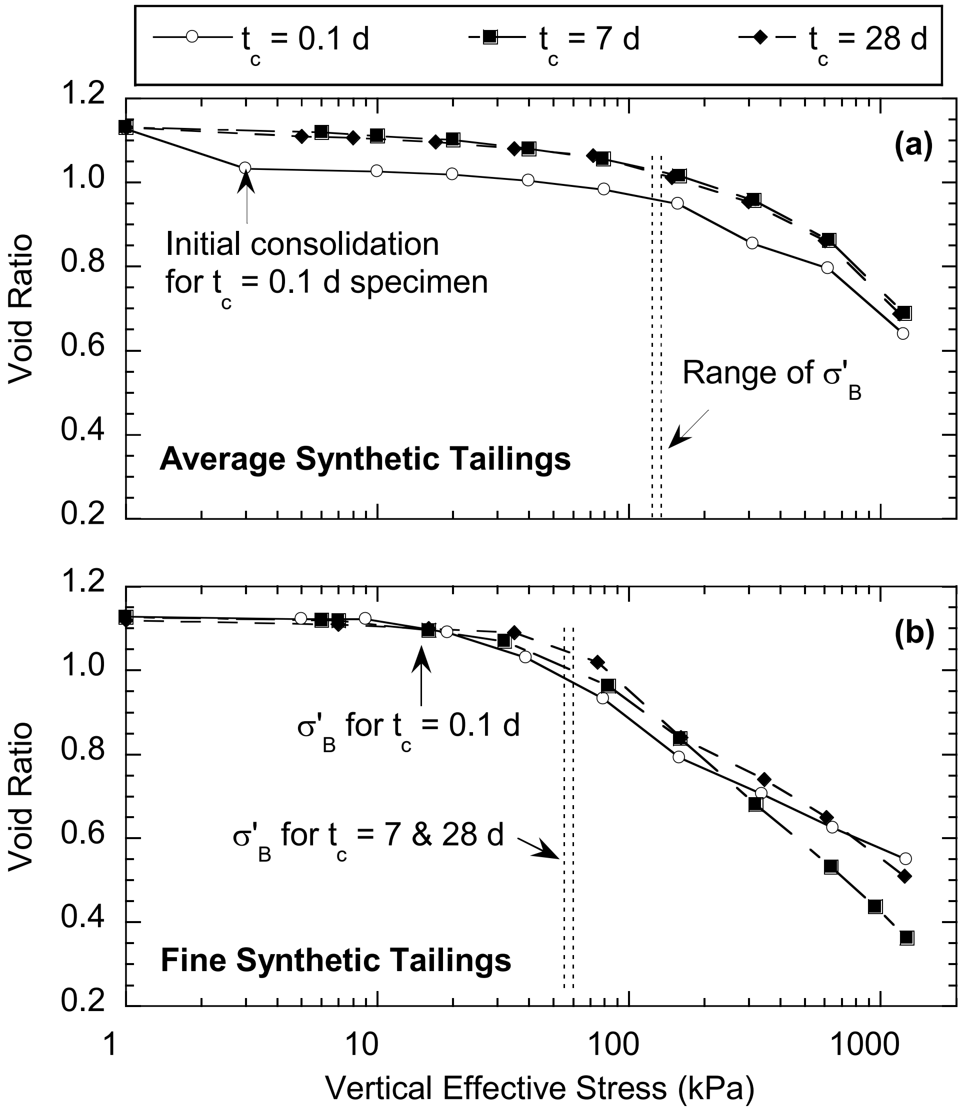
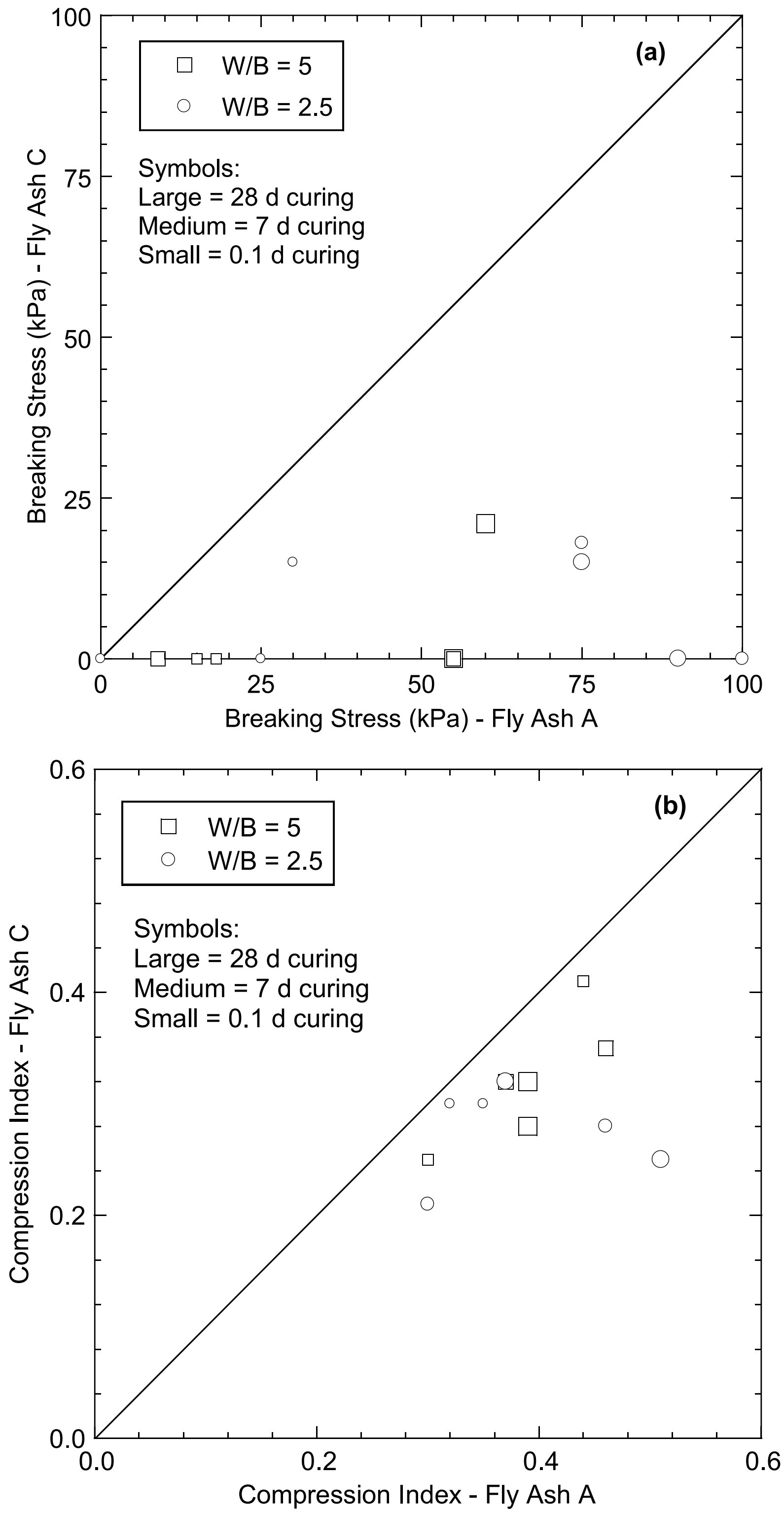



**Figure 3.11** Comparison of compression behavior for (a) average synthetic tailings and (b) fine synthetic tailings for specimens amended with Fly Ash A, and prepared at a solids content = 70%, water-to-binder ratio = 5, and at cured for $t_c$ = 0.1 day, 7 days, and 28 days.




**FIigure 3.12** Comparisons of (a) breaking stress and (b) compression index for average and synthetic tailings amended with Fly Ash C and Fly Ash B and prepared to different water-to-binder ratios (W/B) and curing for 0.1 day, 7 days, and 28 days.

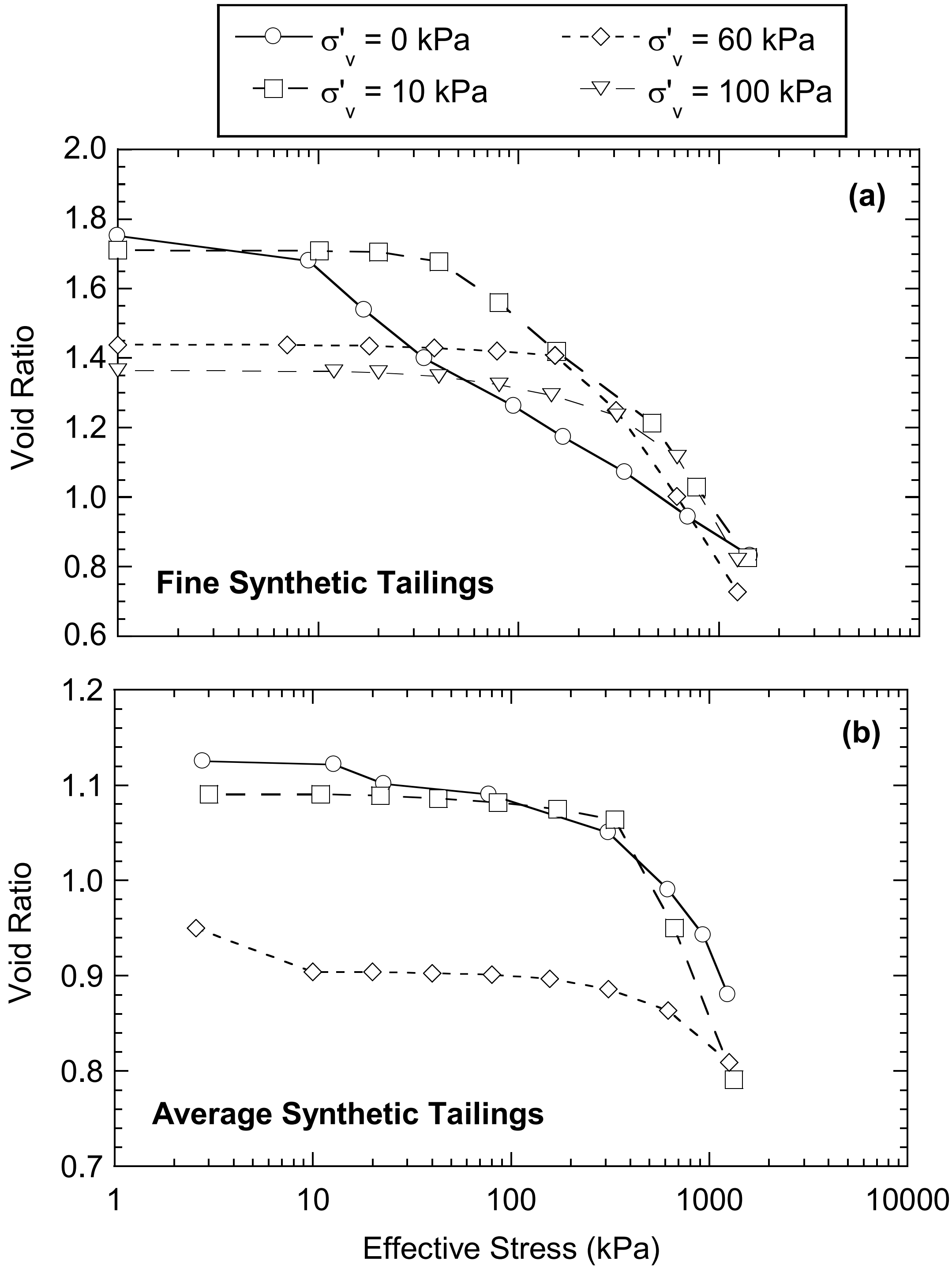



**Figure 3.13** Relationships between void ratio and vertical effective stress (σ'$_v$) for (a) fine synthetic tailings and (b) average synthetic tailings cured under σ'$_v$ ranging from 0 to 100 kPa. All specimens were amended with Fly Ash A and cured for 7 days under the applied stress (Table 3.4).

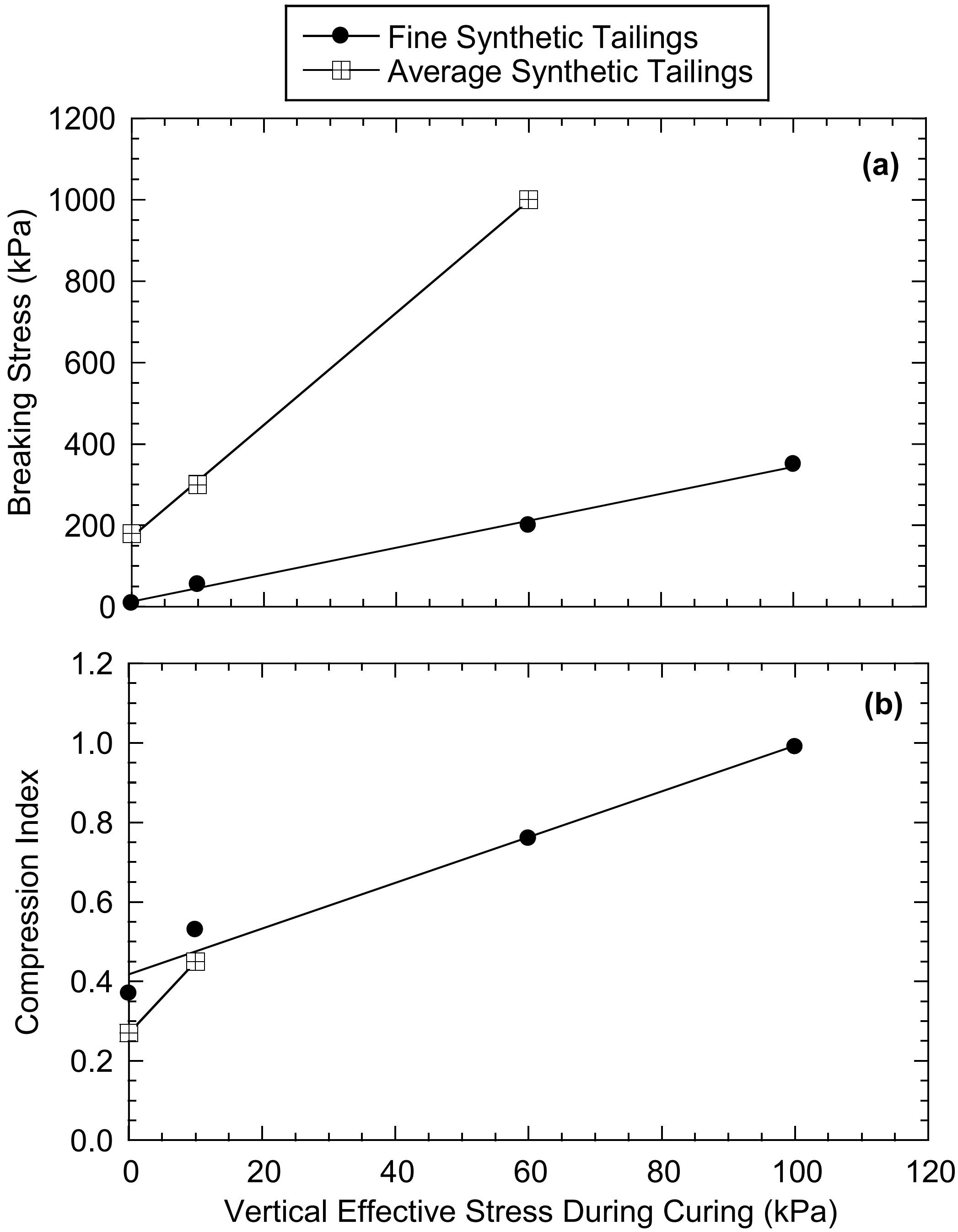



**Figure 3.14** Relationships between (a) breaking stress and (b) compression index versus applied vertical effective stress during curing for fine synthetic tailings and average synthetic tailings.

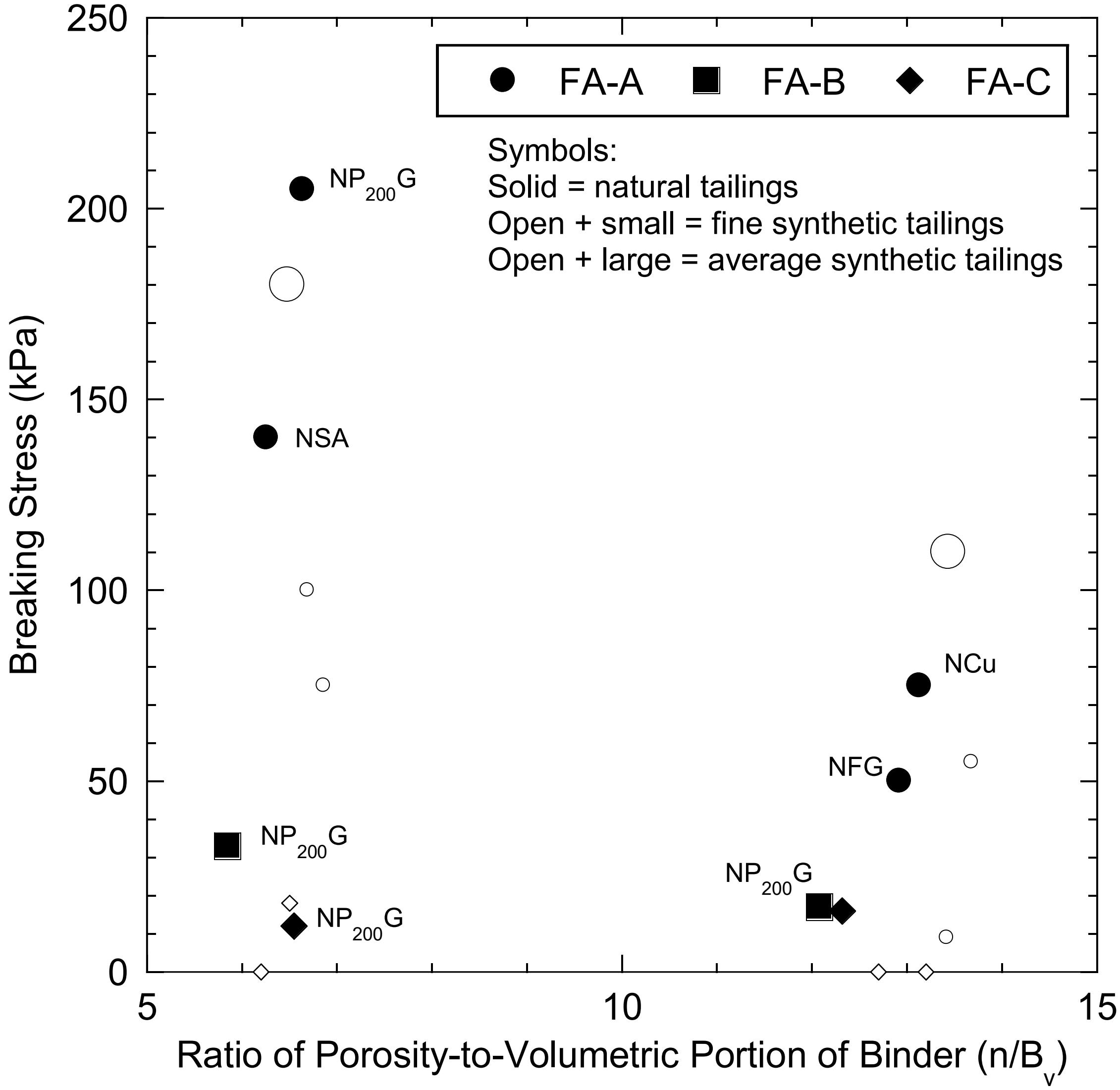



**Figure 3.15** Relationship between breaking stress ($\sigma'_B$) and ratio porosity-to-volumetric portion of binder ($n/B_v$) for fly ash-amended natural tailings specimens and fly ash-amended synthetic tailings that were cured for 7 days. Nomenclature notes: NSA = natural soda ash tailings; NFG = natural fine garnet tailings; $NP_{200}G$ = natural fine garnet tailings passing a No. 200 sieve; NCu = natural copper tailings; FA-A = Fly Ash A; FA-B = Fly Ash B; and FA-C = Fly Ash C.

# 4. SUMMARY AND CONCLUSION

Hydraulic conductivity, unconfined compressive strength, and compressibility tests were performed on mixtures of mine tailings and cementitious binder, and the following conclusions were drawn from this study:

## 4.1 Hydraulic Conductivity

Hydraulic conductivity ($k$) tests were conducted on synthetic and natural mine tailings amended with fly ash to evaluate the effect of fly ash addition on hydraulic conductivity of mine tailings. Hydraulic conductivity tests were conducted on (i) pure tailings and (ii) fly ash-amended tailings in flexible-wall permeameters. Experimental results of fly ash-amended tailings were evaluated in regard to $k$ to identify potential reuse applications in transportation-related earthwork projects and other geotechnical engineering projects.

- Hydraulic conductivity of all unamended and fly ash-amended mine tailings exhibited anticipated trends with initial molding water content ($w_i$). A decrease in $k$ was observed with an increase in $w_i$ for conditions dry of optimum water content ($w_{opt}$), whereas $k$ increased with an increase in $w_i$ wet of $w_{opt}$.
- The $k$ of fly ash-amended average synthetic and natural tailings (i.e., low-plasticity silts) decreased two to five times relative to unamended tailings for specimens wet of $w_{opt}$, whereas $k$ of amended tailings was approximately equal to $k$ of unamended tailings when specimens were prepared dry or near $w_{opt}$. The reduction in $k$ was attributed to the formation of cementitious bonds and decreased average pore size.
- The $k$ of amended fine synthetic tailings (i.e., low-plasticity clay) increased approximately 10 times the $k$ of unamended tailings when prepared dry or near $w_{opt}$. This increase in $k$ reduced with an increase in $w_i$ wet of $w_{opt}$. The increase in $k$ was attributed to agglomeration of clay particles and increased average pore size.
- The $k$ of fly ash-amended tailings cured for 7 days and 28 days were approximately equal, and agree with past research that indicates there is negligible influence on k of fly ash-amended tailings and soils with an increase in hydration time from 7 days to 28 days.
- There was negligible influence of type of fly ash on $k$ of amended-tailings. However, tailings amended with FA-A exhibited lower total volume change during application of a 15-kPa confining stress, which suggests that FA-A yielded a stiffer material and was more effective in generation of cementitious bonds.
- The $k$ of low-plasticity silt tailings-fly ash mixtures at all *W/Bs* met hydraulic criteria for reuse as a base layer, sub-base layer, and embankment fill. The $k$ of low-plasticity clay tailings-fly ash mixtures at $W/B \approx 2.5$ and 4 met hydraulic criteria for reuse in a sub-base layer, and for flowable fill at $W/B \approx 1$.

## 4.2 Unconfined Compressive Strength

Unconfined compressive strength tests were conducted on synthetic and natural mine tailings amended with fly ash and cement to assess effects of tailings solids content, tailings particle-size distribution, and binder type on UCS of binder-amended mine tailings. The following observations and conclusions were drawn from this study.

- The effect of fly ash addition on UCS was attributed to three mechanisms: (i) availability of water to generate cementitious bonds; (ii) replacement of angular tailings particles with rounded fly ash particles; and (iii) cementitious bond potential of fly ash.

- The UCS of unamended tailings and fly ash-amended tailings decreased with a decrease in solids content (i.e., increase in water content). The UCS of non-fly ash amended synthetic tailings at 70 and 80% solids content were zero because specimens were slurry. The UCS of fly ash-amended synthetic tailings decreased with an increase in the water-to-binder ratio and increase in ratio of porosity to volumetric binder content.
- A reduction in UCS was observed for fine and average synthetic tailings amended with fly ash that were prepared dry of optimum water content. In these specimens, fly ash exhibited negligible cementitious potential due to low water availability or low reactivity. The reduction in UCS was attributed to reduced particle-to-particle interlocking due to the replacement of angular tailings particles with spherical fly ash particles.
- A more pronounced increase in UCS was observed for tailings amended with higher $CaO/SiO_2$ fly ash. The more reactive fly ash in this study, FA-A, had lower total mass contribution of cementitious reagents relative to FA-B; however, FA-A had a more favorable balance of chemical constituents (e.g., higher $CaO/SiO_2$) that led to the more pronounced cementitious potential and UCS enhancement.
- A multivariate regression model was developed to predict UCS of tailings amended with fly ash as a function of tailings water content, water-to-binder ratio, and $CaO/SiO_2$ ratio of fly ash. The model yielded an $R^2 = 0.43$ when used to predict UCS of low plasticity (LL < 50%) natural tailings and fly ash-amended soil data compiled from literature. This model is applicable to estimate the UCS of candidate fly ash-mine tailings mixtures; however, engineering judgment should accompany use of the prediction tool in practice.
- The multivariate regression model under-estimated the UCS of high plasticity soils by 100 kPa. Thus, the model is not applicable to high plasticity soils and further investigation is needed to develop a universal UCS model both low- and high-plasticity geomaterials amended with fly ash.
- High solids content mine tailings (*SC* = 80% to 90%) amended with higher pozzolanic potential fly ash (FA-A) yielded UCS that supported reuse applicability as flowable fill and cemented paste backfill. The UCS of cement-amended tailings support reuse of these materials as road subbase materials.

## 4.3 Compressibility

One-dimensional compression tests were conducted on synthetic and natural mine tailings amended with cementitious binders (fly ash or cement) to assess the effect of binder amendment on tailings compressibility. Experiments were conducted with synthetic tailings to assess compression behavior with and without an applied vertical stress during curing and on natural tailings, to assess similarity in compression behavior between synthetic and natural mine tailings. The following conclusions were drawn from this study.

- The breaking stress ($\sigma'_B$), identified as the change in slope of the compression curve at which cementitious bonds are broken, increased with increasing cementitious binder potential. The slope of the compression curve ($C_c$) for vertical effective stress ($\sigma'_v$) > $\sigma'_B$ increased with increasing $\sigma'_B$, and positive correlations between $\sigma'_B$ and $C_c$ were identified for both average and fine synthetic tailings for the range of cementitious binders used in this study.
- A more pronounced increase in $\sigma'_B$ with increasing fly ash content was observed for tailings amended with fly ash characterized by higher $CaO/SiO_2$. Additionally, all tailings and fly ashes used in this study supported a trend of increasing $\sigma'_B$ with decreasing ratio of porosity to volumetric fraction of binder ($n/B_v$). The $n/B_v$ ratio decreased with an increase in solids content (i.e., lower porosity) or increase in the percent binder amendment by dry mass.
- The effect of curing time on development of $\sigma'_B$ differed between the average and fine synthetic tailings amended with FA-A. An increase in $\sigma'_B$ with an increase in curing time was observed for fine synthetic tailings, whereas a constant $\sigma'_B$ was measured regardless of curing time for average

synthetic tailings. This behavior was attributed to water removal during the early stages of loading for average synthetic tailings that decreased $n/B_v$ and led to more effective cementation.

- Breaking stress increased with an increase in applied $\sigma'_v$ during curing for fine and average synthetic tailings. These positive correlations were also attributed to water removal and reduction in $n/B_v$ that enhanced cementitious bond formation. The $C_c$ increased with an increase in $\sigma'_v$ during curing, which was due to an increase in $\sigma'_B$ and relatively high void ratio of a given specimen at the time of breakage.
- Soil plasticity was observed to influence the $\sigma'_B$ such that larger $\sigma'_B$ were measured for synthetic and natural tailings that classified as non-plastic silts as compared to those tailings that classified as low-plasticity clays.

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