THESIS

HYDRAULIC CONDUCTIVITY OF FLY ASH-AMENDED MINE TAILINGS

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2016

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ABSTRACT

HYDRAULIC CONDUCTIVITY OF FLY ASH-AMENDED MINE TAILINGS

The objective of this study was to evaluate the effect of fly ash addition on hydraulic conductivity (*k*) of mine tailings. Fly ash-amended mine tailings have potential application as construction materials in active mines, transportation earthworks, and other geotechnical engineering projects. Addition of cementitious binder (fly ash) to mine tailings has the potential to reduce hydraulic conductivity and enhance contaminant sequestration to be feasible in earthwork projects. Mine tailings used in this study were categorized as synthetic tailings and natural tailings. Natural tailings were collected from a garnet mine located in the U.S. Two synthetic mine tailings were developed via blending commercially-available soils to create typical particle-size distributions and plasticity characteristics of actual mine tailings. The two types of fly ash used classified as off-specification, but had sufficient calcium oxide (CaO) content (17% and 18.9%) for pozzolanic activity.

Hydraulic conductivity (*k*) was measured on pure tailings and fly ash-amended tailings in flexible-wall permeameters. All experiments were conducted following a constant head technique (Method A in ASTM D 5084). Fly ash was added to mine tailings to constitute 10% dry mass of the mixture, and specimens were cured for 7 and 28 d inside a constant humidity and temperature room (100% humidity and 21℃) prior to hydraulic conductivity testing. Effluent from the experiments was measured for pH, electrical conductivity, and the presence of heavy metals to assess leaching potential of the tailings and fly ash-amended tailings mixtures. Chromium (Cr), copper (Cu), cadmium (Cd), and silver (Ag) concentrations were evaluated based on common heavy metals associated with fly ash and then compared with drinking water standards and toxicity limits.

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, or presence of clay particles. Average synthetic tailings that represent typical average particle-size distribution of tailings and natural tailings both classified as low-plasticity silts (ML) with clay contents less than 15%. Hydraulic conductivity of these fly ash-amended tailings were approximately equal to unamended tailings when prepared dry or near optimum water content (w_{opt}), and two to five times lower than unamended tailings when prepared wet of w_{opt}. Fine synthetic tailings that represent typical fine particle-size distribution of tailings classified as low-plasticity clay (CL) and contained 42% clay-sized particles, comprising primarily kaolin. The k of fine synthetic tailings increased approximately one order of magnitude with addition of fly ash for materials prepared dry or near w_{opt}. This increase in k reduced to 3.4 times that of unamended tailings for material prepared wet of w_{opt}. The increase in k with addition of fly ash for the clayey tailings was attributed to agglomeration of clay particles and an overall increase in average pore size to conduct flow. The decrease in k for silty tailings was attributed to formation of cementitious bonds between tailings particles that obstructed flow paths and decreased average pore size.

The 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- and 28-d cured specimens. The propensity to form cementitious bonds was evaluated via the CaO-to-SiO_2 ratio, whereby fly ash with a higher CaO-to-SiO_2 ratio was anticipated to yield lower k due to more cementitious bond formation. There was no distinguishable difference in the impact on k between the two fly ashes used in this study.

Chemical constituents in the effluent of all hydraulic conductivity specimens were compared with literature on tailings-fly ash and soil-fly ash that have been used in geoengineering applications. Concentrations of Ag and Cd for all amended tailings were below the drinking water maximum contaminant levels (MCLs) and toxicity limits. This result was attributed to low solubility of Ag and Cd in alkaline environments (i.e., pH ≥ 7) combined with the propensity for Ag and Cd to sorb to solid particles. Concentrations of Cr and Cu for amended tailings with fly ash A (FA-A) exceeded drinking water MCLs and toxicity limits, which was attributed to low solubility and high mobility of Cr and Cu in alkaline environments. Thus, tailings amended with FA-A have potential use in transportation-related earthwork projects, but high initial concentrations of Cr and Cu must be evaluated. All tailings amended with fly ash A (FA-B) are an environmental-friendly option and can be safely used in transportation-related earthwork projects from an environmental perspective.

ACKNOWLEDGEMENTS

I would first like to thank and express my sincere gratitude to my advisor, Dr. Christopher Bareither for advising, guiding, supporting and assisting me throughout my Master's program generally and on my thesis particularly. Also, I would like to thank Professor Charles Shackelford and Professor Kenneth Barbarick for serving as committee members.

I would like to thank my research colleagues at Colorado State University for their assistance with my laboratory work and their contribution to understand the needed concept in the entire research including Mohammad H. Gorakhki, Shahin Ghazizadeh, and Matteus Hamade. Additionally, I would also like to thank Shan and Amara for their assistance during hydraulic conductivity testing.

Last, but not least, I would like to thank in special my wife, Wafa, for taking care of the family and supporting and encouraging me throughout the whole effort in my entire academic career. I would also like to thank my two beautiful daughters, Danah and Ghadah, for their love. My wife and my daughters mean the entire world and everything to me.

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AST	average synthetic tailings	*H:D*	specimen height-to-diameter ratio
A	specimen cross sectional area	G_s	specific gravity
B	binder content	*k*	hydraulic conductivity
d_{max}	maximum particle size	k_B	hydraulic conductivity of a binder-amended specimen
e	void ratio	k_0	hydraulic conductivity of a unamended specimen
e_i	initial void ratio	k_{avg}	average hydraulic conductivity
e_f	final void ratio	*LL*	liquid limit
Δe	change in void ratio	*NT*	natural tailings
EC	electrical conductivity	ρ_w	density of water
I	ionic strength	ρ_d	dry density
FST	fine synthetic tailings	S_i	initial degree of saturation
PI	plasticity index	S_f	final degree of saturation
γ_{dmax}	maximum dry unit weight	SC	solid content
V_{out}/V_{in}	volumetric outflow-to-inflow	*t*	curing time
w_{opt}	optimum water content	UCS_t	unconfined compressive strength at given time
w	water content	UCS_{max}	maximum unconfined compressive strength
w_i	initial water content	*PVF*	pore volume of flow
w_f	final water content	W/B	water to binder ratio

CHAPTER 1: INTRODUCTION

1.1 Problem Statement

Environmental sustainability and land stewardship are challenging but laudable goals for all infrastructure development in the United States. The Colorado Department of Transportation (CDOT) has identified (i) the maintenance and improvement of roadways and (ii) increased construction of local road systems as strategic goals in Colorado's statewide transportation plan (CDOT 2008). These infrastructure development goals support an overarching objective in Colorado to enhance transportation safety while meeting future needs of increased transportation capacity.

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) that are 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. The total quantity of mine waste requiring management can be expected to increase in the future due to increased consumption of raw materials with population growth and exploitation of lower grade ore bodies. Two types of mine waste that require short- and long-term management are tailings and waste rock (Bussière 2007; Blight 2010). Tailings typically are fine-grained particles with high water contents (low solids contents) that usually are disposed as slurry in impoundment facilities. Waste rock generally is gravel- to cobble-sized material with some sand and fines (Bussière 2007). In particular, 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).

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 reuse applications in geotechnical engineering projects (Edil et al. 1992; Ferguson 1993; Ghosh and Subbarao 1998; Edil et al 2002; 2006; Acosta et al. 2002; Bin-Shafique et al. 2004; 2006; Trzebiatowski et al. 2004; Arora and Aydilek 2005; Kim et al. 2005; Shang and Wang 2005; Senol et al. 2006; Ahmaruzzaman 2010; Tastan et al 2011; ACAA 2012).

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 (Landriault et al. 1997; Zou and Li 1999; Belem et al. 2000; Belem et al. 2001; Benzaazoua et al. 2004; Fall et al. 2005, 2008; 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 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, California bearing ratio); however, these studies did not report on the hydraulic properties or environmental compatibility of the amended mine tailings. The majority of research has been focused on understanding factors affecting the mechanical properties of tailings-binder mixtures (e.g., Landriault, 1995; Belem et al. 2000; Kesimal et al. 2004; Benzaazua et al. 2004; Fall et al. 2005, 2007; 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 (Jones et al. 2001; Godbout et al. 2007; Fall et al. 2009) and curing time (Belem et al. 2001; Godbout et al. 2007; Celestin et al. 2008; Fall et al. 2009; EL Mkadmi et al. 2013; Ghirian and Fall 2013) on the hydraulic properties of fly ash-amended mine tailings.

There has been limited work conducted to evaluate the effects of physical characteristics of mine tailings on hydraulic conductivity of fly ash-amended 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 to aid earthwork construction needs. The potential to reuse these waste materials in transportation earthwork projects can decrease energy consumption, decreased the quantity of raw earthen materials required on a given project, and reduce greenhouse gas emissions. Additionally, the beneficial reuse of mine waste can reduce the final mine waste volume for disposal and long-term management (Wilson et al. 2003; Wilson et al. 2009).

1.2 Objective of Research

The objectives of this study were to evaluate (i) the effect of fly ash amendment on hydraulic conductivity of mine tailings and (ii) environmental compatibility of leachate generated from mine tailings and fly ash mixtures. The following materials were used in this study: (i) one type of natural mine tailings, (ii) two synthetic tailings, and (iii) two types of fly ash. The natural mine tailings were collected from a garnet mine located in the U.S and used herein as a case study to represent actual mine tailings. The two synthetic tailings were laboratory-prepared mixtures composed of commercially-available soils to represent the typical particle-size distributions and plasticity characteristics of actual mine tailings and to isolate material variability between tailings. Natural and synthetic tailings were used to develop comparisons with literature on fly ash- and cement-amended tailings and soils to be used beneficially in earthwork construction applications. These comparisons provided support for the laboratory methods used in this study and establish a baseline for comparison with actual mine tailings. Two off-specification fly ashes with self-cementing characteristics (i.e., contain sufficient calcium oxide (CaO) content to promote pozzolanic activity) were used for all fly-ash amended specimens.

The following research tasks were completed as part of this study:

1. Created two synthetic tailings from laboratory-controlled materials to simulate particle-size distributions of hard rock mine tailings compiled from literature;
2. Conducted hydraulic conductivity tests in flexible-wall permeameters on synthetic tailings, natural tailings, and mixtures of fly ash-amended tailings;
3. Developed specimen preparation procedures for fly ash-tailings mixtures at high water content (25% and 40%) to assess the reuse potential of slurried waste;
4. Measured chemical characteristics of effluent leachate, including pH, electrical conductivity, and cation concentrations, for pure tailings and fly ash-amended tailings to assess environmental compliance; and

5. Developed recommendations for potential reuse applications based on comparisons between laboratory-measured hydraulic properties and required engineering properties.

Experimental results were evaluated with regard to hydraulic conductivity of the materials and associated effluent chemistry from solid-liquid interactions to identify potential reuse applications in transportation-related earthwork projects (e.g., road base, subbase, backfill). However, results also may be relevant to other geoengineering applications (e.g., cemented paste backfill) where hydraulic properties and solid-liquid interactions are important

CHAPTER 2: BACKGROUND

This study focused on the hydraulic behavior and chemical characteristics of the effluent of hard rock mine tailings mixed with fly ash. The following reuse applications were considered to develop a sound basis for the state-of-art and state-of-practice of fly ash-amended mine tailings: (i) transportation earthwork construction material, (ii) cemented paste backfill, and (iii) tailings-fly ash co-disposal. Transportation earthworks include a broad range of applications, such as road base, road sub-base and subgrade, un-paved roadways, and embankment fill. Cemented paste backfill and tailings-fly ash co-disposal are relevant to enhance sustainability of mine waste management and aid in mine site closure via improving mechanical and hydraulic performance of mine tailings (e.g., Landriault 1995; Fall et al. 2009). These mining applications were included to broaden results of this study.

2.1 Cementitious Binders

Binders are defined as adhesive substances that create solid bonds between adjacent materials. In the case of cement and fly ash, solid bonds form via the following chemical reactions with water (Paulini 1990; Tastan et al. 2011):

$$CaO + H_2O \rightarrow Ca(OH)_2 \tag{2.1}$$

$$Ca(OH)_2 \rightarrow Ca^{2+} + 2[OH]^- \tag{2.2}$$

$$Ca^{2+} + 2[OH]^- + SiO_2 \rightarrow CSH \tag{2.3}$$

$$Ca^{2+} + 2[OH]^- + Al_2O_3 \rightarrow CASH \tag{2.4}$$

where calcium silicate hydrate gel (CSH) and calcium aluminate silicate hydrate gel (CASH) are cementitious solid end-products. The required reagents are calcium oxide (CaO), calcium hydroxide [$Ca(OH)_2$], silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3). The cementitious bonds, CSH and CASH, form at different reaction rates, whereby CSH begins to form in 1-2 h at standard temperature and pressure (STP) and CASH begins to form in 1 d at STP (Kurtis 2007; Pacheco-Torgal et al. 2014). Thus, high CaO and SiO_2 leads to more rapid cementation via CSH formation, whereas high CaO and Al_2O_3 leads to more prolonged cementation via CASH formation.

In the U.S., coal-fired power plants account for more than 1/3 of annual electrical power generation (EIA 2014). This process leads to the generation of approximately 110 Mg of coal-combustion by-products (CCBs) annually (ACAA 2012; Park et al. 2014). Fly ash accounts for 39% of CCBs and bottom ash (10%), boiler slag (2%), and flue gas desulphurization (37%) constitute the majority of the remaining CCBs (ACAA 2014). Chemical properties of CCBs depend on parent coal composition, storage condition, combustion process, and emission control (Park et al. 2014). Bottom ash and blast furnace slag are coarse-grained materials that accumulate in the bottom of the furnace, whereas fly ash and flue gas desulphurization are separated from off-gas via electrostatic precipitators (Park et al. 2014). The American Coal Ash Association (ACAA) reported 48% of all CCBs generated in 2014 were reused and 21% of all CCBs generated in 2014 were reused in geo-related applications (ACAA 2014).

A ternary plot of common cementitious binders used in geotechnical applications is shown in Fig. 2.1. Lime is the main cementing agent that is added to form cement with other additives to increase SiO_2 and Al_2O_3 to generate CSH and CASH bonds (Eq. 2.1-2.4). Binders with higher CaO and SiO_2 content (e.g., fly ash and natural pozzolans) lead to the formation of CSH bonds, whereas binders with higher CaO-MgO and Al_2O_3-Fe_2O_3 contents (e.g., Portland cement, lime, high alumina cement) lead to CASH bond formation. The CaO-to-SiO_2 ratio has been used as an indicator parameter to evaluate the pozzolanic potential of binders (Janz and

Johansson 2002; Tastan et al. 2011). An increase in CaO-to-SiO_2 ratio generally corresponds to more effective cementitious binders (Janz and Johansson 2002; Tastan et al. 2011).

Fly ash classifies as Class C, Class F, and off specification based on chemical composition and physical properties (ASTM C618, ASTM 2012). Class C fly ash usually is generated from burning anthracite or bituminous coal (ASTM C618, ASTM 2012), and has CaO content > 20% and Al_2O_3 + Fe_2O_3 + SiO_2 content > 50 % (by dry mass) (Tastan et al. 2011). These chemical properties yield CSH and CASH cementitious bonds that have self-cementing behavior. Class F fly ash usually is generated from burning anthracite or bituminous coal and contains CaO content < 10%. Thus, Class C fly ash is preferred in geotechnical engineering due to self-cementing behavior, whereas Class F fly ash requires an active reagent high in CaO (e.g., lime, Fig. 2.1) to assist in cementitious behavior (ASTM C618, ASTM 2012; Tastan et al. 2011).

2.2 Factors Affecting Hydraulic Conductivity of Binder-Amended Materials

Factors that have been shown to influence hydraulic conductivity (k) of tailings-binder mixtures include (i) water-to-binder (*W/B*) ratio, (ii) binder content, and (iii) curing time. There are other parameters that influence k, including chemical composition (e.g., pyrite content) and pore-water chemistry of mine tailings, which were not investigated in this study.

Schematics of binder-amended and non-binder amended soil or tailings with coarser- and finer-grained particle-size distributions are shown in Fig. 2.2. The presence of a cementitious binder (e.g., fly ash or cement) results in formation of CSH and CASH gel surrounding the soil or tailings particles (Fig. 2.2b). Total porosity and pore-size distribution are key parameters that control k of amended and unamended materials. In coarser-grained, unamended materials (Fig. 2.2a), 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 (i.e., CSH and CASH) creates new solid material within a binder-amended soil or tailings specimen (Fig. 2.2) that has the potential to decrease or increase *k*. For the 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 (Fig. 2.2b), 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 together, which can decrease the average pore size and develop additional micro-pore structure (Fig. 2.2b) that decreases *k* (Quang and Chai 2015).

2.2.1 Water-to-Binder Ratio

Powers and Brownyard (1948) and Jensen and Hansen (2001) report that water present in soil-cement (e.g., concrete) mixtures can be classified into three groups: (i) capillary water = free water within the pore space; (ii) gel water = physically bonded water; and (iii) chemically bonded water = water incorporated within the cementitious bonds. Physically and chemically bonded water are a function of binder type as the amount of water that reacts with a binder depends on binder composition. For example, Powers and Brownyard (1948) report that 0.23 g of water can chemically bond to 1 g of cement (chemically bonded water) and that physically bonded water adsorbed as a surface gel accounts for approximately 19% by mass. Free water is mobile water retained within the void space of the specimen. Thus, the ideal water content of a binder-amended specimen is the summation off chemically and physically bonded where no free water exists. The optimum *W/B* ratio 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 reactivity of fly ash-amended silty soils and reported the highest cementitious activity and strength gain were obtained for specimens compacted at optimum water content (w_{opt}) with no delay in hydration and 1% wet of w_{opt} for specimens compacted 2-h after hydration. Also, they explained that excess water present in fly ash-amended soils that does not participate in cementitious bond formation increases porosity or decreases the contact areas for bonding among soil particles, leading to a larger pore-size network and higher *k*. Edil et al. (2002) found the maximum unconfined compressive strength (UCS) of silty and clayey soil-fly ash mixtures occurred at 1% wet of w_{opt}, which is indicative of the highest cementitious activity and strength gain.

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 the excess available water can increase *k* by approximately one order of magnitude. In general, fly ash can be non-reactive in specimens compacted dry of w_{opt}, because most of the water adsorbs to clayey soil particles, leaving limited water available to react with fly ash and generate cementitious bonds (Bin-Shafique et al. 2002).

2.2.2 Binder Content

Godbout et al. (2007) studied the effect of binder content on *k* of mine tailings (82% silt) at constant water content (*w* = 32%). Two different fly ash contents (1% and 4.5%) were evaluated and a larger reduction in *k* was measured for the higher binder content. The difference in reduction of *k* was attributed to microstructure development with formation of cementitious bonds that reduced *k* of silt-dominated mine tailings. This microstructure reduced void volume and obstructed the flow paths.

Xenidis et al. (2002) investigated the effect of fly ash addition on *k* of sulfate-rich tailings. Test specimens were prepared with constant water content and mixed with Class C fly ash at 10%, 18%, 31%, and 63% contents by dry weight. Hydraulic conductivity decreased three orders of magnitude with an increase in fly ash content from 0% to 63%. The higher fly ash content produced more cementitious bonds, which enhanced blockage of flow paths through the amended specimen. In contrast, Goh and Tay (1993) reported that an increase in fly ash content mixed with soft marine clay (primarily kaolin clay) increased *k* by three orders of magnitude. This behavior was attributed to (i) agglomeration of clay particles and (ii) the effect of binder hydration and cementation on the overall soil structure. Results in Goh and Tay (1993) suggest that the first mechanism dominates the second mechanism in clay based soils. Tay and Goh (1991) reported that soft marine clay mixed with 10% of fly ash content increased *k* by one order of magnitude due to the flocculation or agglomeration of ash particles that enhanced flow.

Deb and Pal (2014) investigated the effect of fly ash addition on *k* of silty clay soil. Test specimens were prepared at w_{opt} and mixed with 10% to 30% fly ash on a dry mass basis. The *k* increased up to two orders of magnitude with an increase in fly ash content from 0% to 30%. Deb and Paul (2014) reported that the increase in *k* of silty clay soil when mixed with fly ash was due to a combination of (i) the effect of adding rounded, silt-size fly ash that resulted in a coarser mixture and (ii) agglomeration of the clay particles that enhanced flow. Similar trends also were reported by Show et al. (2003) regarding the effect of fly ash addition on the *k* of marine clay consisted primarily of kaolinite.

2.2.3 Curing Time

Binder hydration progresses with an increase in curing time such that the strength and durability of tailings-binder mixtures increases as more cementitious bonds form. Fall et al. (2009) suggested that the effect of binder hydration time on *k* can be related to the relationship between binder hydration time and UCS. The following empirical model was proposed by Fall et al. (2009):

$$k_B = Q \cdot k_0 \cdot \alpha^R \tag{2.5}$$

where k_B is hydraulic conductivity of a binder-amended specimen, k_0 is hydraulic conductivity of a unamended specimen, *Q* and *R* are dimensionless fitting parameters determined for each tailings-binder mixture, and α is related to UCS. The parameter α and be computed as:

$$\alpha = \frac{UCS_t}{UCS_{\max}} \tag{2.6}$$

where UCS_t is unconfined compressive strength of the tailings-binder mixture for a given curing time and UCS_{max} is the maximum UCS of the tailings-binder mixture. Fall et al. (2009) evaluated Eq. 2.5 with data reported by Godbout (2005), Adrien (2008), Celestin (2008), and Mukesh (2008) and reported good agreement between the model and published data. Also, they reported that binder hydration can be separated into two time periods: (1) 0 - 7 d and (2) > 7 d. Fall et al. (2009) reported that *k* decreased nearly one order of magnitude during the first 7 d and only a slight decrease was observed for hydration > 7 d. This behavior was explained by the fact that the majority of cementitious bond formation occurs during the first 7 d following binder hydration.

Belem et al. (2001) investigated the effect of curing time on *k* of tailings mixed with 80% slag + 20% cement binder and reported that *k* decreased one order of magnitude with an increase in curing time from 0 to 7 d. Subsequent curing after 7 d was reported to have negligible effect on *k*, which was due to near complete binder hydration within 7 d. Also, Belem et al. (2001) suggested the following exponential relationship between *k* of unamended tailings and *k* of tailings-binder mixtures with different curing times:

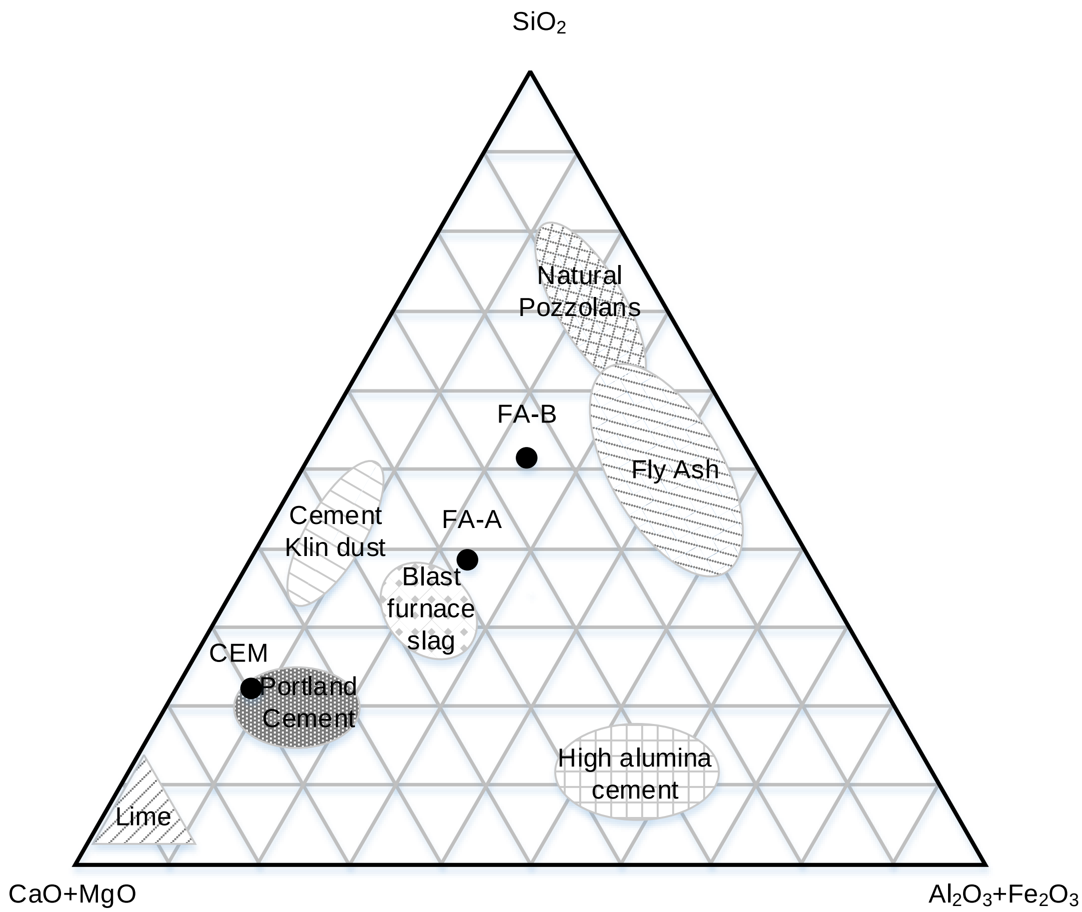
$$k_B = k_0 \cdot e^{(-s \cdot t)} \tag{2.7}$$

where *s* is a function of binder type, binder content, and tailings properties, and *t* is curing time in days. Eq. 2.7 has been reported to provide accurate estimations of k_B for varying curing times (e.g., Belem et al. 2001; Jones et al. 2001).

Godbout et al. (2007) evaluated *k* of tailings-binder mixtures as a function of curing time and proportion and type of binder. They developed the following empirical relationship:

$$k_B = k_0 \cdot t^{-(\beta \cdot \ln(\mathrm{B}) + \chi)} \tag{2.8}$$

where *t* is curing time (1 < *t* < 28 d), *B* is binder content, and *β* and *χ* are fitting parameters. The relationship developed by Godbout et al. (2007) has the potential to yield predictions of k_B for different binder contents and curing times. Also, they reported that *k* of tailings-fly ash mixtures decreased one order of magnitude with an increase in curing time from 0 to 7 d, and after 7 d, *k* stabilized. Thus, findings reported in the aforementioned literature related to the effect of curing time on *k* of binder-amended tailings indicate that there is negligible effect of an increase in curing time on *k* beyond 7 d.



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

Fig. 2.1. Ternary phase diagram of chemical composition of common binders (Popovics 1970; Conner 1990; Tariq 2012). Fly ashes used in this study are shown as FA-A = Fly ash A and FA-B = Fly ash B.

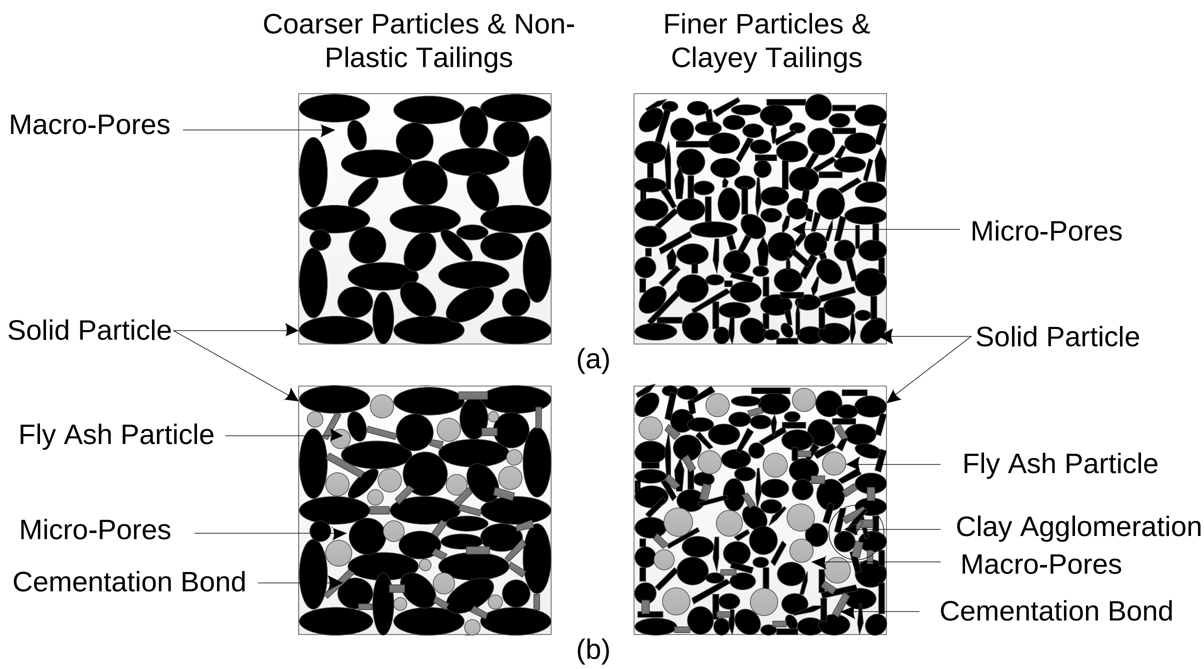


Fig. 2.2. Schematics of (a) unamended and (b) binder-amended tailings (or soils) with based on a soil matrix that is either coarser-grained and/or non-plastics or finer-grained and containing clay particles (i.e., exhibits some plasticity).

CHAPTER 3: METHODS AND MATERIALS

Materials used in this study included synthetic tailings, natural tailings, and two types of fly ash. Hydraulic conductivity tests were conducted on each unamended tailings as well as on fly ash-amended tailings to evaluate the influence of fly ash-amendment on hydraulic conductivity. Effluent was collected from the hydraulic conductivity experiments to characterize and quantify leached heavy metals and to evaluate environmental compliance.

3.1 Materials

3.1.1 Mine Tailings

Commercially-available soils were used to create two synthetic mine tailings that represent typical particle-size distributions and plasticity of actual mine tailings. Natural tailings were collected from a garnet mine located in New York, USA. 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 geotechnical characteristics for the mine tailings is given in Table 3.1. Geotechnical characterization of synthetic tailings included mechanical sieve and hydrometer tests (ASTM D422, ASTM 2007), Atterberg limits (ASTM D4318, ASTM 2014), specific gravity (ASTM D854, ASTM 2014), and standard-effort compaction (ASTM D698, ASTM 2014). Physical characterization of natural (fine garnet) tailings were adapted from Jehring and Bareither (2016), with exception of the compaction parameters.

The average, upper-bound, and lower-bound particle-size distributions (PSDs) based on a compilation of eight hard rock mine tailings from literature are shown in Fig. 3.1. 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

(Fig. 3.1). The PSD comparison in Fig. 3.1 indicates 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.

Average synthetic tailings contained 86% fines (particle diameter < 0.075 mm) with 75% silt-sized particles (0.005 mm < particle diameter < 0.075 mm), and classified as low-plasticity silt based on the Unified Soil Classification System (USCS) as in ASTM D2487. Fine synthetic tailings contained 100% fines content with 42% clay, which was predominantly kaolin, and classified as low-plasticity clay (CL) based on the USCS. The PSD of natural (fine-garnet) tailings is also shown in Fig. 3.1. The natural tailings were slightly coarser than the average synthetic tailings and included the highest sand content (37%) and lowest clay content (7%) of the tailings evaluated in this study. The natural tailings classified as low-plasticity silt with sand (ML), with a liquid limit (*LL*) = 18.8 and plasticity index (*PI*) = 0.4 (Table 3.1). Hard-rock mine tailings typically classify as low plasticity (*LL* < 50) with *LL* ranging between 15 and 35 (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 were in the same range (Table 3.1).

3.1.2 Fly Ashes

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, USA, and Fly ash B (FA-B) was obtained from Platte River Power Authority power plant, which is a 280 MW power plant in For Collins, Colorado, USA. Chemical compositions of the fly ashes were measured with x-ray fluorescence (XRF) and the results are listed in Table 3.2. The XRF analysis was performed with a Philips 1600/10 Simultaneous Wavelength Dispersive Unit by Mineralogy-INC

(Tulsa, Oklahoma, USA). Fly ashes were classified based on ASTM C618 (ASTM 2003), and both classified as off-specification (off-spec) fly ash. The off-spec designation only means that the two 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 3.2).

The relative composition of CaO + MgO, SiO_2, and Al_2O_3 + Fe_2O_3 for the two fly ashes used in this study is shown in the ternary plot in Fig. 2.1. Fly ash A had a relative composition of the key constituents required for CSH and CASH that plotted more towards stronger cementitious binders in compared to FA-B (Fig. 2.1). Thus, regardless of the larger percentage by dry mass composition of all chemical components required for cementitious behavior for FA-B compared to FA-A, the relative composition of the chemical constituents in FA-A indicate more favorable cementitious behavior.

Janz and Johansson (2002) introduced the CaO-to-SiO_2 ratio as potential for pozzolanic reaction of binders and Odadjima et al. (1995) introduced CaO-to-[Al_2O_3+SiO_2] ratio as potential to form CSH and CASH gel. For FA-A, the CaO-to-SiO_2 ratio was 0.86 and the CaO-to-Al_2O_3+SiO_2 ratio was 0.53, which were both higher than the CaO-to-SiO_2 ratio (0.41) and CaO-to-Al_2O_3+SiO_2 ratio (0.30) in FA-B. Also, 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 pozzolanic activity of FA-A was anticipated to be more effective relative to FA-B based on CaO-to-SiO_2 ratio and the relative position of the fly ashes in the ternary plot shown in Fig 2.1.

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

Synthetic and natural tailings were mixed with tap water to create mixtures with *SC*s of 70%, 80%, and 90%, which corresponded to initial target water contents (*w*) of 40%, 25%, and 11%, respectively. Influent chemical characteristics of the tap water used in all tests was *EC* = 13 mS/m and pH = 6.9. These *SC*s 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. The fly ash content of 10% was adopted based on Edil et al. (2002) who report that 10% fly ash amendments are commonly used in field-construction. Thus, the range of *SC*s selected for this study combined with a single, relevant percent fly ash amendment yielded *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.

The *EC* and pH of the three tailings and two fly ashes used in this study are given in Table 3.3. pH and *EC* were measured via a pH probe (Ross Ultra Triode, Thermo Scientific Orion, Waltham, MA) and EC probe (150 A+ Conductivity Meter, Thermo Orion, Beverly, MA) connected to a Thermo Scientific Orion Versa Star multi-function meter (Waltham, MA). The *EC* of all tailings and fly ashes were measured following the 1:5 method, whereby 1 part dry soil is mixed with 5 parts of de-ionized (DI) water by mass (Page et al. 1983; Gorakhki and Bareither 2015). Mixtures were placed in a sealed container and then shaken for 1 min every 30 min over a 2 h period. Electrical conductivity was measured on the supernatant liquid at the end of 2-h.

pH of all materials was measured following procedures in ASTM D4972 (ASTM 2013). These pH and *EC* measurements were used to establish a baseline to compare effluent chemical measurements from the pure tailings and fly ash-amended tailings hydraulic conductivity test specimens.

3.2 Methods

3.2.1 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 2014). Compaction curves for the synthetic and natural tailings are shown in Fig 3.2. A 3rd order polynomial was fit to all compaction curves following Howell et al. (1997) to determine the maximum dry unit weight (γ_{dmax}) and w_{opt} (Table 1). Compaction curves shown in Fig. 3.2 exhibit anticipated effects of material composition on γ_{dmax} and w_{opt}, whereby an increase in sand and silt content and corresponding decrease in plasticity shifted compaction curves to higher γ_{dmax} and lower w_{opt} (Holtz et al. 2011). The higher γ_{dmax} for the natural tailings relative to both synthetic tailings was also attributed to higher G_s (Table 3.1).

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 γ_{dmax} and w_{opt}. Compaction curves for natural tailings and natural tailings amended with 5%, 10%, and 15% FA-A are shown in Fig. 3.3. Compaction curves for the fly ash-amended natural tailings all plot slightly to the right of the pure natural tailings (Fig. 3.3), suggesting that a modest increase in w_{opt} of approximately 3% may be anticipated with addition of fly ash. However, there was no clear trend between increasing fly ash content and γ_{dmax} or w_{opt}.

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. Lee et al. (2014) reported a minor effect on compaction curve between unamended silty tailings and amended silty tailings with fly ash, whereby both γ_{dmax} and w_{opt} slightly decreased. Thus, for practical purposes w_{opt} from unamended tailings can be assumed representative of w_{opt} for fly ash-amended tailings based on the assessment on natural tailings (Fig. 3.3) and reported effects of fly ash on w_{opt} in literature. This assumption has been used to assess the influence of molding water content relative to w_{opt} of unamended and amended tailings on the measured hydraulic conductivity.

3.2.2 Hydraulic Conductivity Experiments

Hydraulic conductivity tests were conducted 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. A schematic of a hydraulic conductivity setup is shown in Fig. 3.4. Each experimental setup consisted of a permeameter, headwater (influent) accumulator, tailwater (effluent) accumulator, and an elevated water reservoir used to control cell pressure. A manifold was connected to the elevated reservoir for cell pressure such that multiple permeameters could be pressurized from the same reservoir.

Cell pressure was controlled via the water level within the reservoir (Fig. 3.4) 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 (Fig. 3.4). The hydraulic gradient was approximately 10 (head loss ≈ 1.3 m) in all hydraulic conductivity experiments. This hydraulic gradient was in agreement with ASTM D5084 based on an assumed hydraulic conductivity (*k*) of 10^{-3} to 10^{-5} m/s for the pure mine tailings. The hydraulic gradient in transportation earthwork applications is expected to be approximately 1; 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 as well as in the accumulator system as the permeant fluid to represent field conditions (Ghosh and Subbarao 1998; Fall et al. 2009). 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 in the hydraulic conductivity tests to represent field conditions (Benson et al. 1990), but final saturation was computed following completion of all tests. Filter paper and porous stones were placed on the top and bottom of the specimen. All porous stones were soaked in tap water prior to placement within the permeameter. 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 $k \geq 1 \times 10^{-6}$ m/s. The majority of the 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 long testing times due to lower hydraulic conductivity (< 1×10^{-5} 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 and to evaluate chemical compatibility. 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 majority hydraulic conductivity 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 (described subsequently) 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 2014). 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 between mold and specimens to 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).

All pure tailings and fly ash-amended hydraulic conductivity specimens were prepared initially from dry tailings. Synthetic tailings were prepared to the target PSD (Fig. 3.1) in a dry state and natural tailings (fine-garnet) 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) at *W/B* = 1, 2.5, and 4 in a 20-L bucket in six layers and allowed to hydrate for 2-h. 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 (2009) specifies a maximum elapsed time of 2-h 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 was wrapped and sealed in polyethylene bags to prevent desiccation and allowed to cure for 7 or 28 d prior to hydraulic conductivity 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; Soleimanbeigi et al. 2013).

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 and 71.1-mm-diameter flexible-wall apparatus with external acrylic mold were approximately equal; *k* for a 101.6-mm-diameter specimen = 5.6×10^{-4} m/s and *k* for a 71.1-mm-diameter specimen = 5.7×10^{-4} m/s. Thus, *k* values determined with this alternative hydraulic conductivity measurement technique were equivalent to those measured in the larger diameter flexible-wall permeameters and are compared directly to each other in this study.

3.2.3 Leachate Chemistry Analysis

Effluent from the hydraulic conductivity tests was monitored for pH, *EC*, and concentration of cations (i.e., heavy metals). This analysis was conducted to assess potential environmental impacts of reusing mine tailings and fly ash-amended mine tailings in earthwork projects. Leachate samples were collected routinely during specimen permeation to assess pH and *EC*. However, only single samples were collected and processed to measure cation concentrations. Single samples to assess cation concentration were collected from the initial effluent to capture the highest potential concentration (Creek and Shackelford 1992; Edil et al. 1992; Bin-Shafique et al. 2002, 2006). All effluent samples were collected in clean, inert plastic bottles that were sealed to prevent evaporation.

Cation concentrations were measured via inductively coupled plasma-atomic emission spectrometry, or ICP-AES, (IRIS® Advantage/1000 ICAP Spectrometer, Thermo Jarrel Ash Co., Franklin, MA) by the Soil, Water, and Plant Testing Laboratory at Colorado State University (Fort Collins, CO), and no charge was provided as multiple cation species constitute a given metal concentration. Effluent samples were diluted with different dilution factors based on the following correlation between ionic strength (*I*) and EC (Griffin and Jurinak 1973; Shackelford 1994):

$$I = 0.013 \cdot EC \tag{3.1}$$

where *EC* is in mS/cm and *I* is mol/L. The ionic strength of a given solution is a function of the concentration of all ions in solution. Thus, *I* of the effluent was estimated for each specimen based on peak *EC* (Eq. 3.1), since the initial concentration of the given solution was unknown. For ICP analysis, the as-collected effluent was diluted to fit within the detection limits of the ICP-AES instrument: maximum concentration ≤ 60 mg/L and minimum detection = 0.1 mg/L. The target ionic strength for the different dilutions was as follows: (i) $I \leq 0.002$ mol/L – the solution was not diluted; (ii) 0.002 mol/L < *I* < 0.15 mol/L – the solution was diluted 1:20 and 1:40; (iii) 0.15 mol/L ≤ *I* < 1 mol/L – the solution was diluted 1:100, 1:200, and 1:500; and (iv) *I* ≥ 1 mol/L – the solution was diluted to 1:1000. Multiple dilutions for the same sample were used to capture all target cation concentrations within the detection range.

A compilation of studies associated with the applicability of using fly ash for field application is in Table 3.4. Leaching of heavy metals is one of the main environmental concerns related to the reuse of mine tailings and fly ash. Table 3.4 includes target cations compiled from different references, standards used for assessing field application, and recommendations for reuse in practice. Chromium (Cr), copper (Cu), cadmium (Cd), and silver (Ag) were selected as target cations in this study based on total elemental analyses of the fly ashes and corresponding deleterious effects on human health and the environmental. These target cations were considered to investigate if the tailings-fly ash mixtures provide reasonable chemical-compatibility to be used in earthwork projects such that there are no negative impacts on human health or the environment.

Table 3.1. Physical characteristics and classification of natural and synthetic tailings.

Material	*LL* (%)	*PI* (%)	USCS	d_{max} (mm)	Sand Content (%)	Fines Content (%)	Clay Content (%)	As-Collected Water Content (%)	G_s	w_{opt} (%)	γ_{dmax} (kN/m^3)
Fine Synthetic	37	15	CL	0.05	0.0	100.0	42.0	NA	2.63	23	14.9
Average Synthetic	NA	NA	ML-CL	2.00	14.2	85.8	13.0	NA	2.66	17	16.5
Natural (Fine Garnet)	18.8	0.4	ML	2.00	36.7	63.3	6.6	13.1	3.07	10	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 γ_{dmax} = maximum dry unit weight (ASTM D698); NA = not applicable; and NM = not measured.

Table 3.2. Chemical compositions by percent (%) mass for two type of fly ash 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

Table 3.3. Summary of pH and electrical conductivity (EC) for individual mine tailings and fly ash.

Material	pH	EC (mS/m)
Fine-garnet (natural) tailings	8.2	81
Average synthetic tailings	7.2	27.8
Fine synthetic tailings	6.6	52.9
Fly Ash A (FA-A)	11.5	3700
Fly Ash B (FA-B)	9.5	2130

Table 3.4. Compilation of target metals, criteria for field application, and recommended use of fly ash-amended materials in earthwork applications.

References	Target metals	Criteria for field application	Recommendation for use
Creek and Shackelford (1992)	Al, Ca, Cd, Cr, Cu, Fe, Mn, Mo, Pb, Sr, Zn	(1) Drinking water standard, EPA 1986	Yes, with caution. Some metals exceed limits for first flow and other metals show delayed leaching.
Ghosh and Subbarao (1998)	Cu, As, Cr, Cd, Fe, Hg, Mg, Ni, Pb, Zn	(1) Concentration ≤ allowable limits based on WHO (1984), U.S. EPA (1986) and GCDEQ (1979); (2) concentration ≤ threshold limits, which = 100 times allowable limit.	Yes. Concentrations below limits.
Sauer et al. (2012)	Cd, Cr, Se, Ag	(1) "Beneficial Use of Industrial Byproducts" via Wisconsin Administrative Code, NR 538; (2) U.S. EPA MCLs for drinking water standards	Yes. Concentrations below limits.
Becker et al. (2013)	Cu, As, Cr	(1) Federal EPA drinking water maximum contaminant levels (MCLs) for Cr and As; (2) Maryland aquatic toxicity chronic limits for Cu.	Yes, with caution. Some metals exceed limits during early stages of leaching.

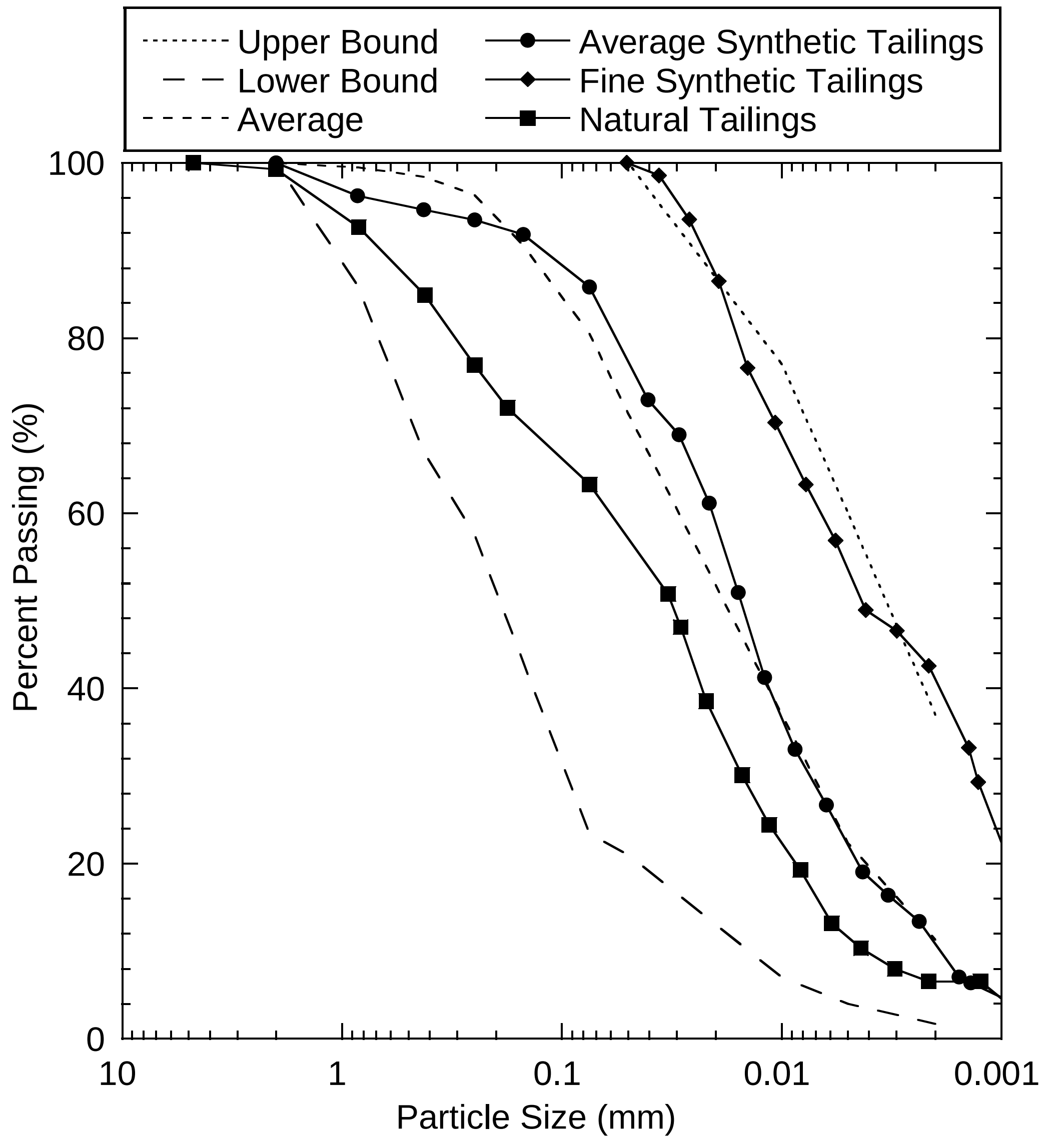


Fig. 3.1. Particle-size distribution for natural (fine-garnet) tailings, average synthetic tailings, fine synthetic tailings, and the upper-bound, lower-bound, and average from compiled mine tailings particle-size distributions (Qiu and Sego 2001; Morris and Williams 2005; Khalili et al. 2005; Wickland and Wilson 2005; Wickland et al. 2006; Bussière 2007; Khalili et al. 2010; Wickland et al. 2011).

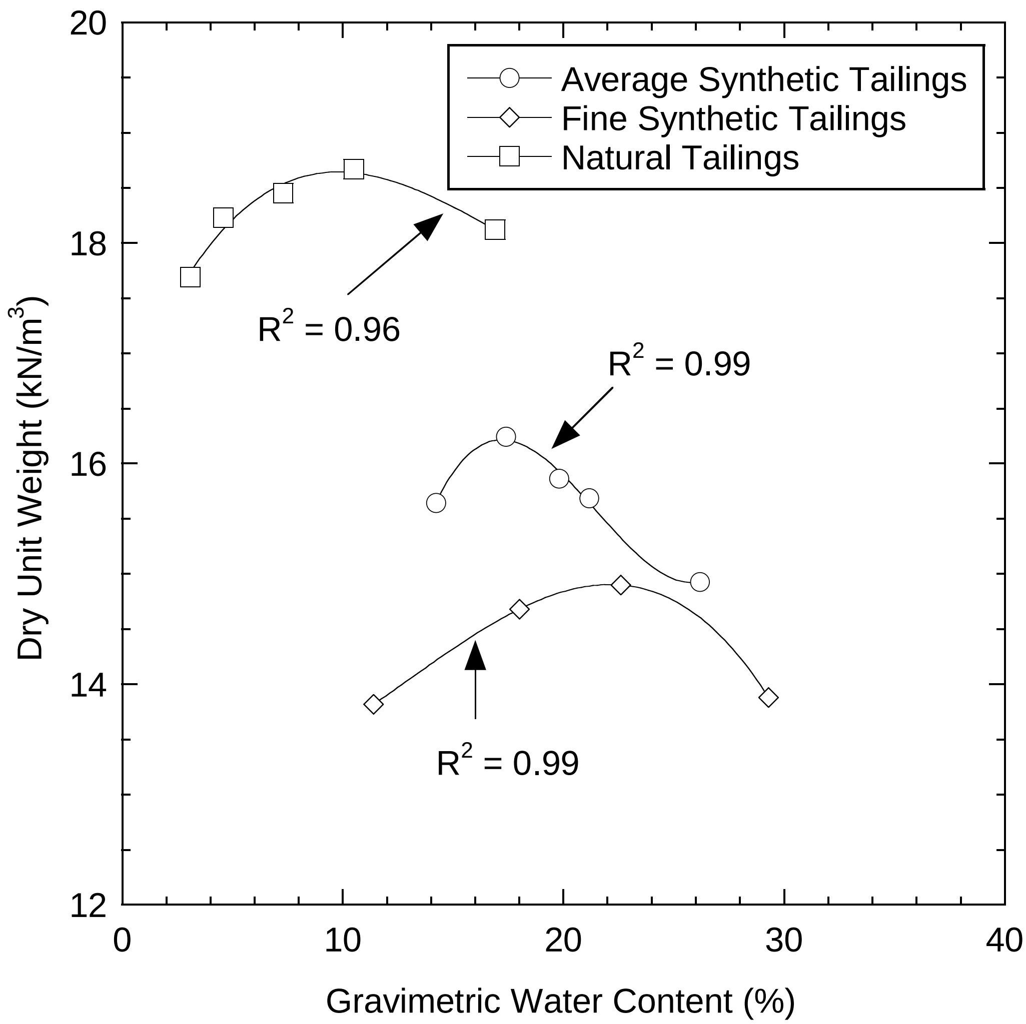
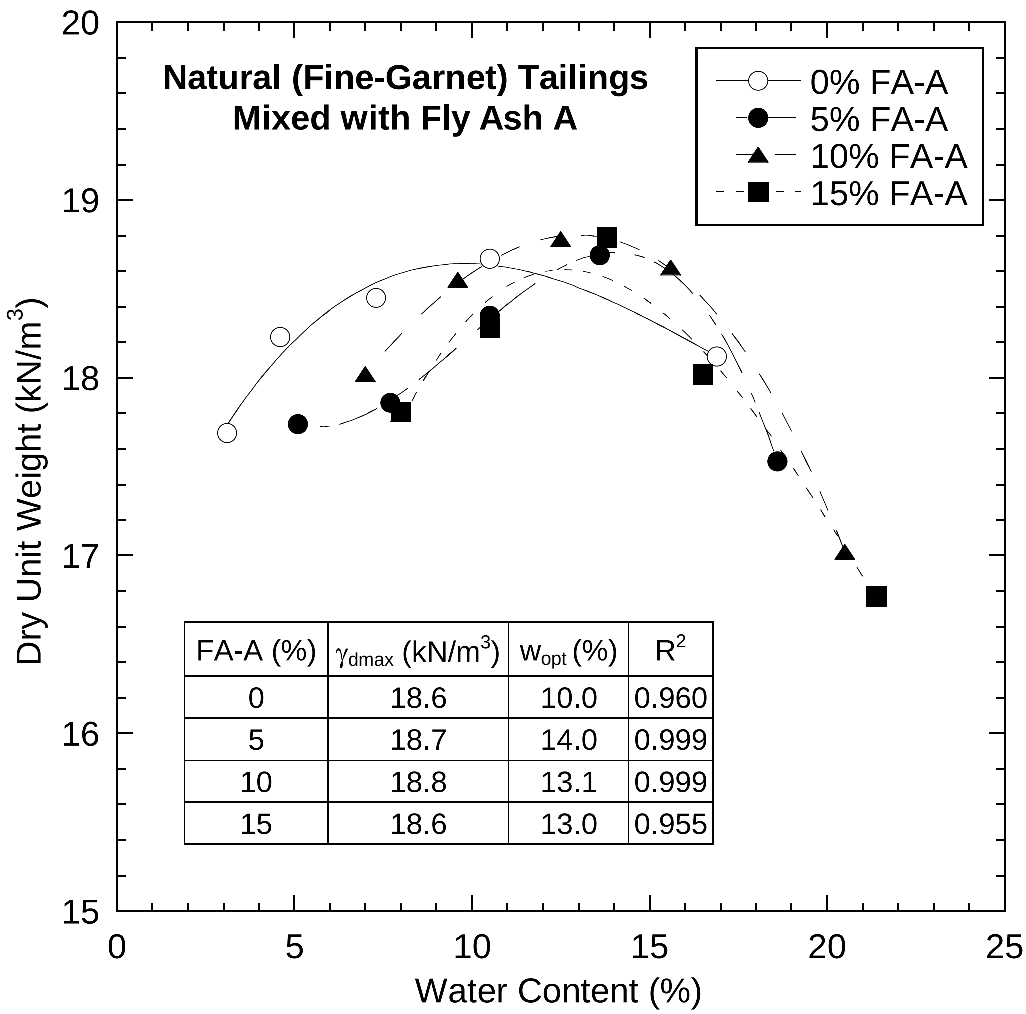


Fig. 3.2. Compaction curves unamended average and fine synthetic tailings and natural (fine-garnet) tailings. Compaction curves were fitted with a 3rd-order polynomial based on Howell et al. (1997), and the coefficient of determination (R^2) represents the fit of the polynomial to the compaction data.



FA-A (%)	γ_{dmax} (kN/m^3)	w_{opt} (%)	R^2
0	18.6	10.0	0.960
5	18.7	14.0	0.999
10	18.8	13.1	0.999
15	18.6	13.0	0.955

Fig. 3.3. Compaction curves unamended natural (fine-garnet) 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 3rd-order polynomial based on Howell et al. (1997), and the coefficient of determination (R^2) represents the fit of the polynomial to the compaction data.

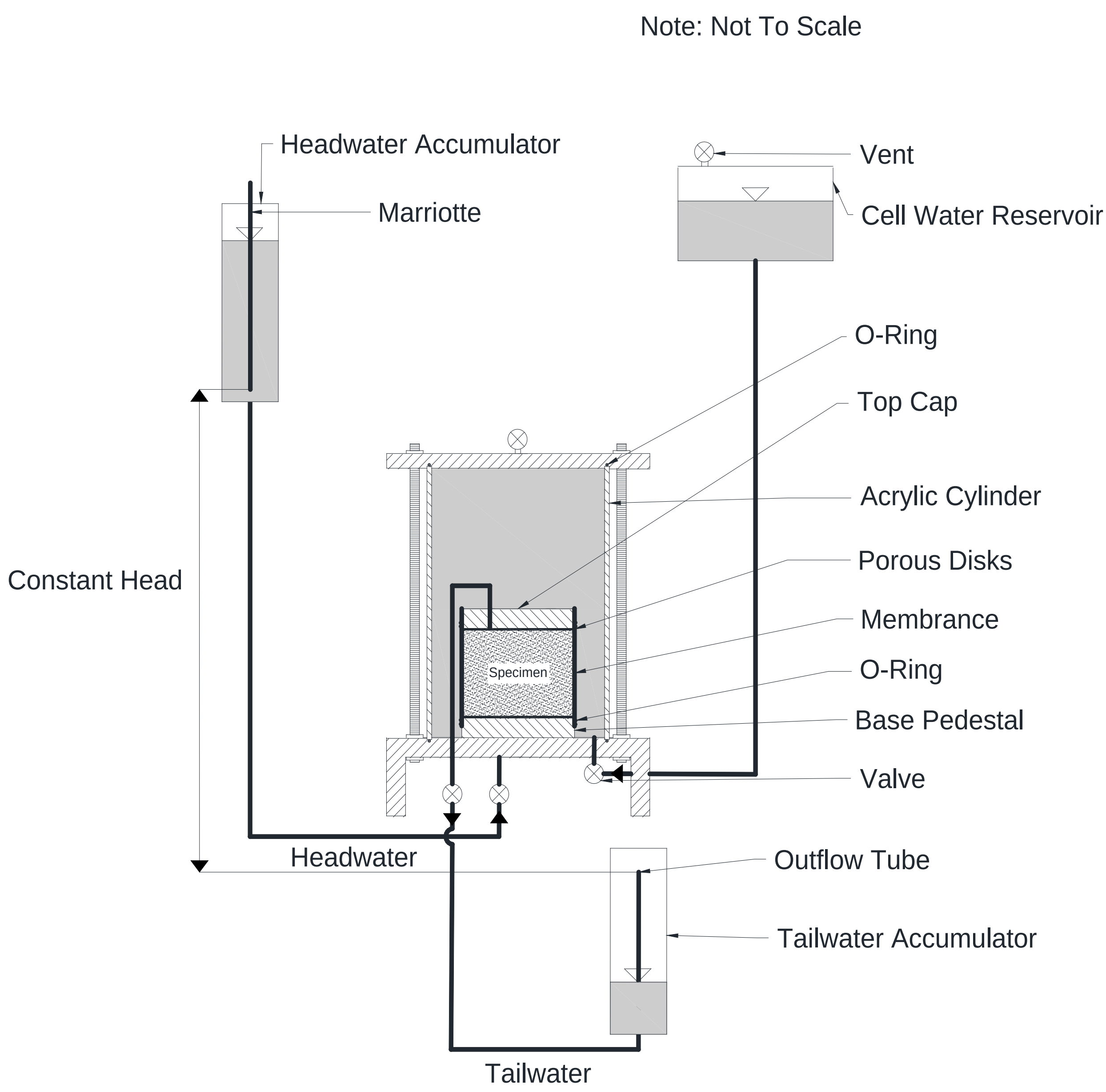


Fig. 3.4. Schematic of the hydraulic conductivity test setup.

CHAPTER 4: RESULTS AND DISCUSSION

The results of all hydraulic conductivity tests conducted on pure tailings and fly ash-amended average synthetic, fine synthetic, and natural (fine-garnet) tailings are summarized in Tables 4.1, 4.2, and 4.3. The initial and final void ratio (e_i and e_f), water content (w_i and w_f), and degree of water saturation (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 % can be assumed fully saturated at the time of experiment termination. A compilation of experimental data from hydraulic conductivity tests on all materials is in Appendix B, which includes relationships of hydraulic conductivity versus elapsed time and *PVF*, ratio of volumetric outflow-to-inflow (V_{out}/V_{in}) versus elapsed time and *PVF*, and pH and EC of the effluent leachate versus time.

4.1 Hydraulic Conductivity Testing

The temporal trends of k and V_{out}/V_{in} for unamended average synthetic tailings, fine synthetic tailings, and natural tailings prepared at a *SC* = 90% (w_i = 11%) are shown in Fig. 4.1, Fig. 4.2, and Fig. 4.3, respectively. Minor temporal fluctuations in k and V_{out}/V_{in} were observed in the early stages of testing, and both parameters subsequently stabilized for the duration of testing. All specimens met ASTM D5084 termination criteria (i.e., $0.75 \leq V_{out}/V_{in} \leq 1.25$; $k = \pm 0.25 \cdot k_{ave}$, where k_{ave} is the average k for four sequential measurements when $k_{ave} \geq 1 \times 10^{-8}$ cm/s) and were subsequently permeated several additional *PVF*s to assess the presence of any temporal trends in hydraulic behavior or chemical characteristics in the leachate. The k for each tailings specimen reported in Tables 4.1 through 4.3 are representative of the last four consecutive k measurements for a given experiment. As can be seen in Figs. 4.1 through 4.3, 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^{-5} m/s, and equal to 1x10^{-6} m/s (10%), on average. Thus, the final average *k* of each experiment was adopted herein as the representative *k* for each material tested in this study.

4.2 Hydraulic Conductivity of Fly Ash-Amended Tailings

The hydraulic conductivity of synthetic and natural tailings-fly ash mixtures were evaluated using three *SC*s to represent three levels of tailings dewatering (i.e., *SC* = 70%, 80%, and 90%, which coincided 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 initial *W/B*s of 1, 2.5, and 4. Compilations of *k* versus initial molding water content (w_i) for average synthetic tailings, fine synthetic tailings, and natural (fine-garnet) tailings are shown in Figs. 4.4, 4.5, and 4.6, respectively. The w_{opt} identified in Figs. 4.4 through 4.6 are representative of unamended tailings (Table 3.1) and are taken as approximate w_{opt} for the fly ash amended tailings specimens based on the compaction evaluation in Sec. 3.2.1. Data in Figs. 4.4 through 4.6 include tailings amended with FA-A and FA-B as well as specimens cured for 7 and 28 d.

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 (Fig. 4.4) and fine synthetic tailings (Fig. 4.6) 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; Daniel 1994). 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* (Tables 4.1 and 4.2).

A similar effect of increasing *k* with continuous increase in w_i and e_i can be observed for natural tailings in Fig. 4.6. The low water content, unamended natural tailings specimen (w_i = 12%) was compacted 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 4.3) 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 the two tailings that were low-plasticity silts (i.e., average synthetic tailings and natural tailings) and the one tailings that classified as a low-plasticity clay (i.e., fine synthetic tailings). Mechanistic effects on *k* can be explained via these two factors as well as the *W/B* of the as-prepared tailings-fly ash mixture.

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 Fig. 4.4. These four fly ash treatments corresponded to two different types of fly ash (FA-A and FA-B) and two curing times (7 d and 28 d). In general, the *k* versus w_i trends for all four fly ash treatments exhibit 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 are no distinct differences between the relative 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 Fig. 4.6. All four fly ash-amended specimens at $w_i \approx 12\%$ can be assumed compacted very 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 (Fig. 3.3). 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 (Fig. 4.6).

The synthetic average tailings included 13% clay-sized particles but exhibited no plasticity (Table 3.1). The natural tailings had a lower clay content (6.6%) and also 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 composition.

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 Fig. 4.7. 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 = 1.0 for *W/B* = 1.0 and k_B/k_0 were all less than 1.0 for *W/B* = 2.5 and 4.0 (Fig. 4.7). The average synthetic tailings prepared at w_i = 11% (*SC* = 90%; *W/B* = 1.0) were prepared approximately 5% dry of w_{opt} (Fig. 4.4) and natural tailings prepared at the same initial conditions were approximately at w_{opt}. The limited influence of fly ash amendment on *k* of the average synthetic and natural tailings at w_i = 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 Fig. 4.7 is for the average synthetic tailings prepared at a *W/B* = 1.0, amended with FA-A, and cured for 7 d.

Average synthetic tailings and natural tailings prepared at w_i = 25% and 40% exhibited a reduction in *k* with addition of fly ash relative to the unamended condition (Figs. 4.4 and 4.6). Also, in both tailings *k* reduced more for specimens prepared at w_i = 25% (*W/B* = 2.5) compared to specimens prepared at w_i = 40% (*W/B* = 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* = 2.5 and by a factor of 1.8 for *W/B* = 4 (Fig. 4.7). Larger reductions of approximately 5.0 and 2.0 were observed for natural tailings prepared at *W/B* = 2.5 and 4.0, respectively (Fig. 4.7). 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* = 4.0 (i.e., highest w_i = 40%) was attributed to reduced effectiveness in cementitious bond formation due to 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 Fig. 4.8. Data compiled from literature are separated with respect to the silty versus clayey tailings identified in this study. Similar trends in the effect of fly ash-amendment on *k* of low-plasticity silty materials are observed in the compiled data from Godbout et al. (2007) and Fall et al. (2009), whereby the addition of fly ash typically decreases *k*.

The development of cementitious bonds for these aforementioned fly ash-amended 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 Fig. 4.9. The change in void ratio ($-\Delta e$) was computed as the difference between the final void ratio computed at the end of a given hydraulic conductivity test (e_f) and the initial void ratio for the as-prepared specimens (e_i). The $-\Delta e$ increased for all silty tailings specimens with an increase in initial molding water content. The magnitude of $-\Delta e$ for the unamended average synthetic (Fig. 4.9a) and natural tailings (Fig. 4.9c) decreased with addition of fly ash for all specimens prepared at w_i = 25%. This reduction in $-\Delta e$ was attributed to increase specimen stiffness due to cementitious bond formation.

The reduction in -Δe for both unamended silty tailings specimens prepared at w_i = 40% was more pronounced for specimens amended with FA-A versus FA-B (Fig. 4.9). Fly Ash A had a larger CaO/SiO_2 ratio (Fig. 2.1) 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 -Δe at high water contents of the silty tailings.

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 Fig. 4.5. These *k* versus w_i relationships exhibit similar trends to the unamended tailings, whereby 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; Daniel 1994). A subsequent increase in *k* from w_i = 25% to w_i = 40% was observed for all fly ash treatments except FA-A cured for 28 d. This increase in *k* was attributed to an increase in overall specimen void ratio with an increase in molding water content (Table 4.2). The continued decrease in *k* for the fine synthetic tailings specimen amended with FA-A and cured for 28 d 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 (Fig. 4.7). This effect of fly ash amendment on *k* of clay-rich tailings was attributed to agglomeration of tailings particles via addition of a cementitious binder that led to high tortuosity that increased *k*. Similar observations on the effects of cementitious binder addition and agglomeration of clay particles has been reported in literature (e.g., Tay and Goh 1991; Deb and Pal 2014) as shown in Fig 4.8. The ratio of k_B/k_0 was approximately 10 for w_i = 12% 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* = 1.0 and amended with FA-A and cured for 28 d, 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 most likely 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.

The development of cementitious bonds in the fine synthetic tailings was qualitatively supported by the ability to extract intact, fly ash-amended specimens for mixtures prepared at w_i = 40%, whereas the unamended material was slurry and non-self-supporting. The reduction in -Δe of the fine synthetic tailings was negligible for all amended and unamended specimens prepared at w_i = 12% and 25% (Fig. 4.9b). The absence of volume change following application of a 15 kPa confining pressure to these specimens 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 -Δe for fine synthetic tailings specimens prepared at w_i = 40% was lower for specimens amended with fly ash relative to the unamended tailings (Fig. 4.9b). Additionally, for a given curing time (7 d or 28 d) specimens amended with FA-A yielded lower -Δe 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.

4.3 Evaluation of Curing Time and Fly Ash Type

A comparison between *k* of fly ash-amended tailings cured for 28 d versus 7 d is shown in Fig. 4.10a and a comparison between *k* of tailings amended with FA-B versus FA-A is shown in Fig. 4.10b. These 1:1 plots include both synthetic and natural tailings. In general, all data points in Figs. 10a and 10b 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 to 28 d on *k* of fly ash-amended tailings was anticipated based on findings reported in literature (Jones et al. 2001; Belem et al. 2001; Godbout et al. 2007; Fall et al. 2009). The limited influence of curing time is attributed to the majority of cementitious bond formation occurring within the first 7 d following hydration. Subsequent increases in curing time yield 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 soils and tailings with more pronounced 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 is 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 (Fig. 4.9). Although FA-A had more chemically-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.

4.4 Leachate Chemistry Evaluation

Temporal trends in pH and *EC* for effluent leachates representative of fly-ash amended tailings are shown in Fig. 4.11. Two leaching patterns were observed in the hydraulic conductivity experiments: (i) first flush, FF, and (ii) lagged response, LR. Differentiation of these two leaching patterns was based on *EC* measurements since *EC* was taken as an indicator parameter of the abundance of ions in solution. The FF-leach behavior in Fig. 4.11a exhibits a high *EC* measurement for the first effluent sample collected, which is followed by a continuous decrease in *EC*. The LR-leach behavior in Fig. 4.11b exhibits an increase in *EC* during the early stages of leaching that is followed by attainment of a maximum *EC* and subsequent reduction. Effluent samples collected and analyzed for metal concentrations were representative of the peak *EC* identified in the FF- or LR-leaching behavior.

Chemical characteristics of the effluent samples collected from average synthetic tailings, fine synthetic tailings, and natural tailings are summarized in Table 4.5, 4.6, and 4.7, respectively. pH and metal concentrations tabulated in Tables 4.5 through 4.7 are representative of the peak *EC* identified via the FF or LR leaching pattern. The *PVF* at peak identifies that amount of liquid that passed through a given specimen at which a peak concentration was measured (Tables 4.5 - 4.7). Chromium (Cr), copper (Cu), cadmium (Cd), and silver (Ag) were selected for evaluation of heavy metal concentration and potential environmental contamination based common heavy metals associated with fly ash-amended earthworks (Table 3.4). Peak metal concentrations were compared to the maximum contaminant levels (MCLs) for drinking water (U.S. EPA 1993) and toxicity limits (U.S. EPA 1986). Bolded concentrations in Tables 4.5 through 4.7 designate effluent concentrations that exceeded both the MCL for drinking water and toxicity limit.

Concentrations of Ag and Cd for all amended and unamended tailings were below the drinking water MCLs and toxicity limits specified by US EPA. These low Ag and Cd concentrations were attributed to low solubility of Ag and Cd at high pH (Tables 4.5, 4.6, and

4.7) as well as the tendency for Ag and Cd to sorb to solid particles (Smith 2007; Kosson et al. 2009; Sauer et al. 2012). Concentrations of Cr and Cu exceeded drinking water MCLs and toxicity limits for nearly all tailings specimens amended with FA-A that were prepared at w_i = 12% and 25% (*W/B* = 1.0 and 2.5). Exceedance of the drinking water MCLs and toxicity limits for specimens amended with FA-B were only observed for Cu in the natural tailings.

The concentration of Cr for all tailings amended with FA-A were above the drinking water MCL and toxicity limit, with the exception of the fine synthetic tailings and natural tailings prepared at w_i = 40% (*W/B* = 4). Chromium is both soluble and mobile at pH ≥ 7 (Sauer et al. 2012; Cetin et al. 2014), which led to high concentrations in nearly all effluent samples. The concentration of Cr decreased with an increase in molding water content due to increased dilution (Tables 4.5 – 4.7), and this dilution led to concentrations below the toxicity limit for fine synthetic and natural tailings at w_i = 40% (*W/B* = 4). Concentrations of Cr above the toxicity limit were not measured in any tailings specimens amended with FA-B; and thus, all high Cr concentrations observed in this study were linked to fly ash amendment with FA-A.

The concentrations of Cu exhibited variability in measured concentration for a given tailings and fly ash amendment as well as with molding water content. Concentrations of Cu for the average synthetic tailings exceeded the drinking water MCL only for specimens amended with FA-A at w_i = 12% and 25% (*W/B* = 1 and 2.5), and the Cu concentration decreased with increase in w_i. The low Cu concentration for the average synthetic tailings specimen amended with FA-A and cured for 28 d appears low and is assumed not representative of the actual concentration. The concentrations of Cu for fine synthetic tailings also only exceeded the drinking water MCL for specimens amended with FA-A and prepared at the lower two water contents (W/B = 1 and 2.5). In contrast, the Cu concentrations for most of the fly ash-amended natural tailings exceeded the MCL of drinking water (Table 4.7). No clear trend between Cu concentration and molding water content exists for the amended natural tailings, and both FA-A and FA-B yield concentrations that can be perceived as threatening to human health and the environment.

4.5 Practical Implications

Soil-binder mixtures can be used in 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., hydraulic conductivity) for each application is listed in Table 4.7. The hydraulic conductivity of synthetic and natural tailings amended with fly ash ranged between 10^{-6} to 10^{-3} 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 the hydration reactions. In contract, 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 constructions. Also, factoring in the observed and quantified 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 4.7 is beneficial.

From an environmental standpoint, all tailings types amended with FA-B can be safely used in earthwork applications since the majority of heavy metals in the effluent were below the toxicity limits. In contrast, all tailings type amended with FA-A should be used with caution since the Cr and Cu concentrations were above the toxicity limits. A decrease in metal concentrations with FA-A were observed for specimens prepared at higher initial water content and W/B = 4; however, high water contents may not be suitable for reuse from a strength perspective and all criteria need to be evaluated prior to reuse in earthwork applications. Higher initial molding water contents for tailings, and in particular on the wet side of w_{opt}, are favorable to reduce leachate generation (Ghosh and Subbarao 1998).

Additionally, the leachability of Cr and Cu can be decreased with the increase in the pH as shown by Mofarrh et al. 2012. All amended tailings specimen from Table 4.4, 4.5, and 4.6 showed the range of pH from 8.5 to 13.5. Besides, using fly ash can generate an alkaline environment remained alkaline even more than 12 *PVF*, thus immobilize migration of heavy metals (Shang and Wang 2005). However, the EPA recommends that public water systems maintain pH levels of between 6.5 and 8.5. Drinking water with a pH level above 8.5 indicates that a high level of alkalinity minerals is present and does not pose a health risk.

Table 4.1. Specimen properties and average final hydraulic conductivity for experiments conducted on average synthetic tailings (AST) with and without fly ash.

Test No.	Material	W/B	Fly Ash	Curing Time (d)	Initial Properties				Final Properties			
					ρ_{di} (g/cm^3)	e_i	w_i (%)	S_i (%)	e_f	w_f (%)	S_f (%)	k_{ave} (m/s)
1	AST	-	-	-	1.55	0.71	11.2	41.8	0.71	26.4	98.6	5.7×10^{-4}
2	AST	1	B	7	1.55	0.69	11.7	44.2	0.69	26.4	99.2	6.7×10^{-4}
3	AST	1	B	28	1.55	0.69	11.2	42.6	0.69	25.9	98.8	6.5×10^{-4}
4	AST	1	A	7	1.52	0.73	11.3	40.5	0.73	29.7	106.8	2.2×10^{-3}
5	AST	1	A	28	1.50	0.76	9.4	32.6	0.76	28.3	98.0	5.6×10^{-4}
6	AST	-	-	-	1.48	0.80	25.3	84.1	0.70	24.2	90.7	3.5×10^{-4}
7	AST	2.5	B	7	1.58	0.66	25.0	98.8	0.66	22.8	90.1	1.5×10^{-4}
8	AST	2.5	B	28	1.60	0.63	23.3	96.0	0.63	22.5	92.7	1.4×10^{-4}
9	AST	2.5	A	7	1.53	0.73	24.5	88.6	0.73	26.1	94.5	9.2×10^{-5}
10	AST	2.5	A	28	1.55	0.70	23.7	89.0	0.70	26.3	98.6	1.0×10^{-4}
11	AST	-	-	-	1.24	1.13	38.8	90.6	0.78	29.7	100.4	8.0×10^{-4}
12	AST	4	B	7	1.40	0.87	38.0	96.4	0.60	24.4	105.3	4.0×10^{-4}
13	AST	4	B	28	1.46	0.79	39.0	96.5	0.68	25.1	103.0	2.8×10^{-4}
14	AST	4	A	7	1.31	1.03	38.0	94.3	0.90	37.0	104.4	4.5×10^{-4}
15	AST	4	A	28	1.30	1.04	38.6	97.8	0.94	37.8	106.6	6.8×10^{-4}

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

Table 4.2. Specimen properties and mean of final consecutive hydraulic conductivity measurements for fine synthetic tailings (FST) with and without fly ash.

Test No.	Material	W/B	Fly ash	Curing time (d)	Initial Properties				Final Properties			
					ρ_d (g/cm^3)	e_i	w_i (%)	S_i (%)	e_f	w_f (%)	S_f (%)	k_{ave} (m/s)
1	FST	-	-	-	1.41	0.87	11.4	34.4	0.87	33.1	99.7	5.5×10^{-5}
2	FST	1	B	7	1.38	0.88	12.6	37.1	0.88	34.2	99.9	5.2×10^{-4}
3	FST	1	B	28	1.39	0.86	11.6	34.8	0.86	32.9	98.7	4.9×10^{-4}
4	FST	1	A	7	1.42	0.85	9.6	29.9	0.85	34.8	107.5	5.8×10^{-4}
5	FST	1	A	28	1.47	0.78	10.3	34.5	0.83	35.4	112.0	1.4×10^{-4}
6	FST	-	-	-	1.52	0.72	24.4	81.4	0.72	25.8	93.3	2.3×10^{-6}
7	FST	2.5	B	7	1.49	0.74	25.0	87.0	0.74	26.8	93.0	1.9×10^{-5}
8	FST	2.5	B	28	1.48	0.75	24.9	86.4	0.75	26.5	91.9	1.8×10^{-5}
9	FST	2.5	A	7	1.52	0.72	24.8	86.5	0.72	28.3	102.7	9.8×10^{-6}
10	FST	2.5	A	28	1.52	0.73	24.8	85.9	0.73	29.4	105.6	2.0×10^{-5}
11	FST	-	-	-	1.23	1.13	41.1	95.8	1.00	38.7	99.6	7.3×10^{-6}
12	FST	4	B	7	1.25	1.13	39.4	90.1	0.97	36.8	98.7	2.6×10^{-5}
13	FST	4	B	28	1.27	1.09	39.1	92.3	1.02	36.4	97.8	2.4×10^{-5}
14	FST	4	A	7	1.21	1.17	41.7	93.5	1.09	42.3	102.1	3.7×10^{-5}
15	FST	4	A	28	1.21	1.17	41.9	93.7	1.17	43.0	97.3	1.3×10^{-5}

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

Table 4.3. Specimen properties and mean of final consecutive hydraulic conductivity measurements for natural tailings (NT) with and without fly ash.

Test No.	Material	W/B	Fly ash	Curing time (d)	Initial Properties				Final Properties			
					ρ_d (g/cm^3)	e_i	w_i (%)	S_i (%)	e_f	w_f (%)	S_f (%)	k_{ave} (m/s)
1	NT	-	-	-	1.95	0.57	12.1	65.1	0.57	16.8	90.1	3.0×10^{-4}
2	NT	1	B	7	1.83	0.62	11.8	56.6	0.62	18.6	89.0	3.1×10^{-4}
3	NT	1	B	28	1.84	0.61	11.8	57.5	0.61	18.6	90.0	4.5×10^{-4}
4	NT	1	A	7	1.87	0.61	10.9	53.6	0.61	19.9	97.5	1.8×10^{-4}
5	NT	1	A	28	1.88	0.60	10.9	54.3	0.60	19.7	97.7	1.3×10^{-4}
6	NT	-	-	-	1.51	1.03	27.1	80.7	0.63	20.5	99.8	1.1×10^{-3}
7	NT	2.5	B	7	1.8	0.65	21.6	99.0	0.55	19.5	104.7	5.7×10^{-4}
8	NT	2.5	B	28	1.79	0.66	21.6	97.8	0.55	19.6	106.3	5.5×10^{-4}
9	NT	2.5	A	7	1.68	0.79	23.2	88.1	0.79	25.0	95.1	5.4×10^{-4}
10	NT	2.5	A	28	1.69	0.78	23.2	88.8	0.78	24.9	95.4	5.5×10^{-4}
11	NT	-	-	-	1.41	1.18	36.4	94.7	0.64	22.2	105.7	2.4×10^{-3}
12	NT	4	B	7	1.40	1.12	36.1	95.4	0.66	23.4	105.0	1.4×10^{-3}
13	NT	4	B	28	1.39	1.14	37.5	97.8	0.68	23.6	103.6	1.5×10^{-3}
14	NT	4	A	7	1.44	1.09	35.7	98.4	0.97	31.8	98.5	1.5×10^{-3}
15	NT	4	A	28	1.44	1.09	36.3	99.9	0.97	32.1	99.1	1.3×10^{-3}

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

Table 4.4. Leachate characteristics and metal concentrations for unamended and fly ash-amended average synthetic tailings.

Tailings	W/B	Fly Ash	Curing Time (d)	pH	Leaching Pattern	PVF at Peak	Peak Concentration (mg/L)			
							Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Silver (Ag)
AST	-	-	-	7.2	FF	0.6	< 0.1	< 0.1	< 0.1	< 0.1
	1	A	7	13.5	FF	0.2	< 0.1	**59.1**	**18**	< 0.1
			28	13.4	FF	0.8	< 0.1	**6.8**	0.5	< 0.1
		B	7	9.7	FF	0.2	< 0.1	< 0.1	0.2	< 0.1
			28	9.8	FF	0.2	< 0.1	< 0.1	0.3	< 0.1
	2.5	A	7	13.1	LR	0.6	0.2	**8.4**	**3.1**	< 0.1
			28	13.5	LR	0.5	0.1	**7.0**	**4.1**	< 0.1
		B	7	10.5	LR	1.7	< 0.1	0.4	0.4	< 0.1
			28	10.4	LR	0.7	< 0.1	0.4	0.4	< 0.1
	4	A	7	13.1	LR	0.6	< 0.1	**5.7**	1.1	< 0.1
			28	13.5	LR	1	0.7	**5.1**	1.2	< 0.1
		B	7	9.2	FF	0.6	< 0.1	0.4	0.6	< 0.1
			28	9.5	FF	0.5	< 0.1	0.4	0.6	< 0.1
Maximum U.S. EPA DWS							0.005	0.1	1.3	0.05
Toxicity Limits							1	5	-	-

Note: Concentrations exceeding drinking water standards and maximum toxicity limits are in bold font; FF = First flush; LR = Lagged response.

Table 4.5. Leachate characteristics and metal concentrations for unamended and fly ash-amended fine synthetic tailings.

Tailings	W/B	Fly Ash	Curing Time (d)	pH	Leaching Pattern	PVF at Peak	Peak Concentration (mg/L)			
							Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Silver (Ag)
FST	-	-	-	6.6	FF	0.3	< 0.1	< 0.1	< 0.1	< 0.1
	1	A	7	13.1	FF	0.7	< 0.1	**9.5**	**1.5**	< 0.1
			28	13.3	FF	0.2	< 0.1	**9.9**	**2.1**	< 0.1
		B	7	9.4	FF	0.4	< 0.1	0.8	0.5	< 0.1
			28	9.3	FF	0.8	< 0.1	0.8	0.5	< 0.1
	2.5	A	7	13.3	LR	0.4	< 0.1	**7.2**	**3.3**	< 0.1
			28	13.3	FF	0.3	< 0.1	**5.6**	**2.4**	< 0.1
		B	7	8.7	LR	0.5	< 0.1	0.5	0.9	< 0.1
			28	8.8	LR	0.6	< 0.1	0.5	0.9	< 0.1
	4	A	7	13.1	LR	0.3	< 0.1	4.4	1.0	< 0.1
			28	13.1	LR	0.4	< 0.1	4.0	0.8	< 0.1
		B	7	8.5	LR	0.4	< 0.1	0.3	0.8	< 0.1
			28	8.6	LR	0.4	< 0.1	0.3	0.8	< 0.1
Maximum U.S. EPA DWS							0.005	0.1	1.3	0.05
Toxicity Limits							1	5	-	-

Note: Concentrations exceeding drinking water standards and maximum toxicity limits are in bold font; FF = First flush; LR = Lagged response.

Table 4.6. Leachate characteristics and metal concentrations for unamended and fly ash-amended natural tailings.

Tailings	W/B	Fly Ash	Curing Time (d)	pH	Leaching Pattern	PVF at Peak	Peak Concentration (mg/L)			
							Cadmium (Cd)	Chromium (Cr)	Copper (Cu)	Silver (Ag)
NT	-	-	-	7.2	FF	0.4	< 0.1	< 0.1	0.1	< 0.1
	1	A	7	13.4	LR	0.5	< 0.1	**8.4**	**2.1**	< 0.1
			28	13.4	LR	0.6	< 0.1	**8.8**	**2.5**	< 0.1
		B	7	9.2	FF	0.3	< 0.1	1.0	1.1	< 0.1
			28	9.8	FF	0.6	< 0.1	0.6	**1.4**	< 0.1
	2.5	A	7	13.2	LR	0.8	< 0.1	**6.2**	1.0	< 0.1
			28	13.3	LR	0.8	< 0.1	**7.2**	**2.5**	< 0.1
		B	7	10.8	LR	1.5	< 0.1	0.3	**1.3**	< 0.1
			28	10.7	LR	1.7	< 0.1	0.3	**3.0**	< 0.1
	4	A	7	13.0	LR	0.7	< 0.1	4.1	1.0	< 0.1
			28	13.0	LR	0.7	< 0.1	3.6	**2.23**	< 0.1
		B	7	10.4	FF	1.1	< 0.1	0.3	**1.64**	< 0.1
			28	10.3	FF	0.9	< 0.1	0.3	**1.64**	< 0.1
Maximum U.S. EPA DWS							0.005	0.1	1.3	0.05
Toxicity Limits							1	5	-	-

Note: Concentrations exceeding drinking water standards and maximum toxicity limits are in bold font; FF = First flush; LR = Lagged response.

Table 4.7. Hydraulic conductivity (*k*) criteria for acceptability of earthen materials in road construction applications.

Application	Reference	*k* (m/s)
Base Layer	FHWA 1997; Kalinski and Yerra 2006	$10^{-4} – 10^{-3}$
Sub-base road construction	Tuncan et al. 2000	$10^{-6} – 10^{-2}$
Flowable Fill	FHWA 1997; Deng and Tikalsky 2008	$10^{-5} - 10^{-4}$
Embankment or structural fill	FHWA 1997	$10^{-4} – 10^{-2}$
Stabilized waste for land disposal	US EPA (1986); Cullinane and Jones (1990)	$\leq 1x10^{-3}$
Standard solidified waste	US EPA (1989)	$<10^{-3}$
Typical stabilized wastes	Tuncan et al. 2000; Mohamed et al. 2002	$10^{-6} – 10^{-2}$

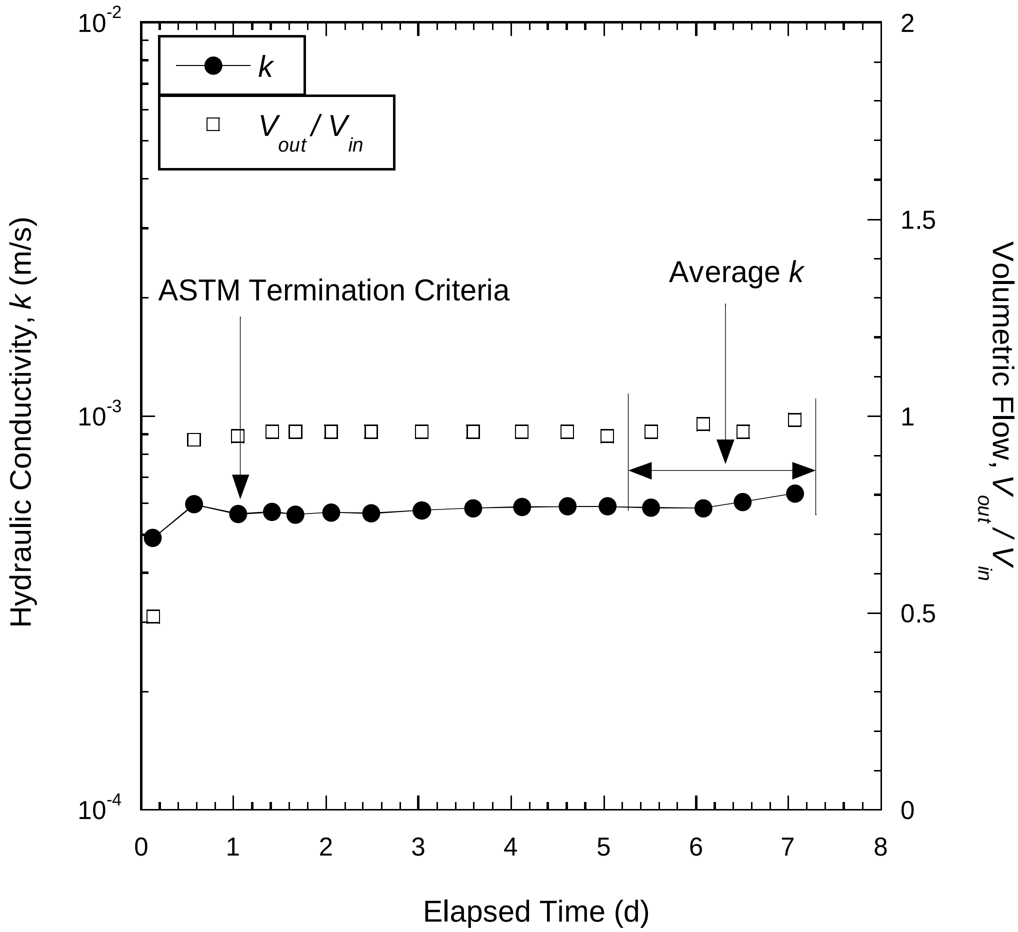


Fig. 4.1. Temporal relationships of hydraulic conductivity and ratio of volumetric outflow-to-inflow for unamended average synthetic tailings prepared at an initial water content = 11%.

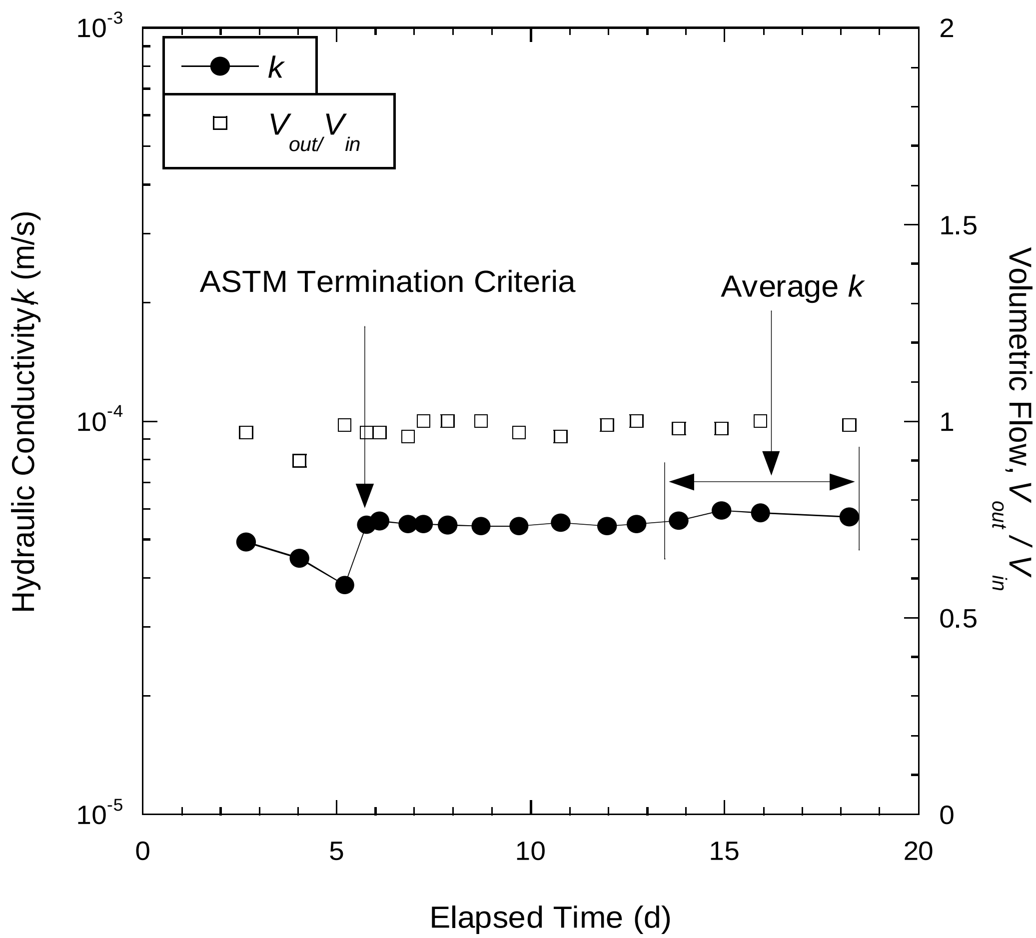


Fig. 4.2. Temporal relationships of hydraulic conductivity and ratio of volumetric outflow-to-inflow for unamended fine synthetic tailings prepared at an initial water content = 11%.

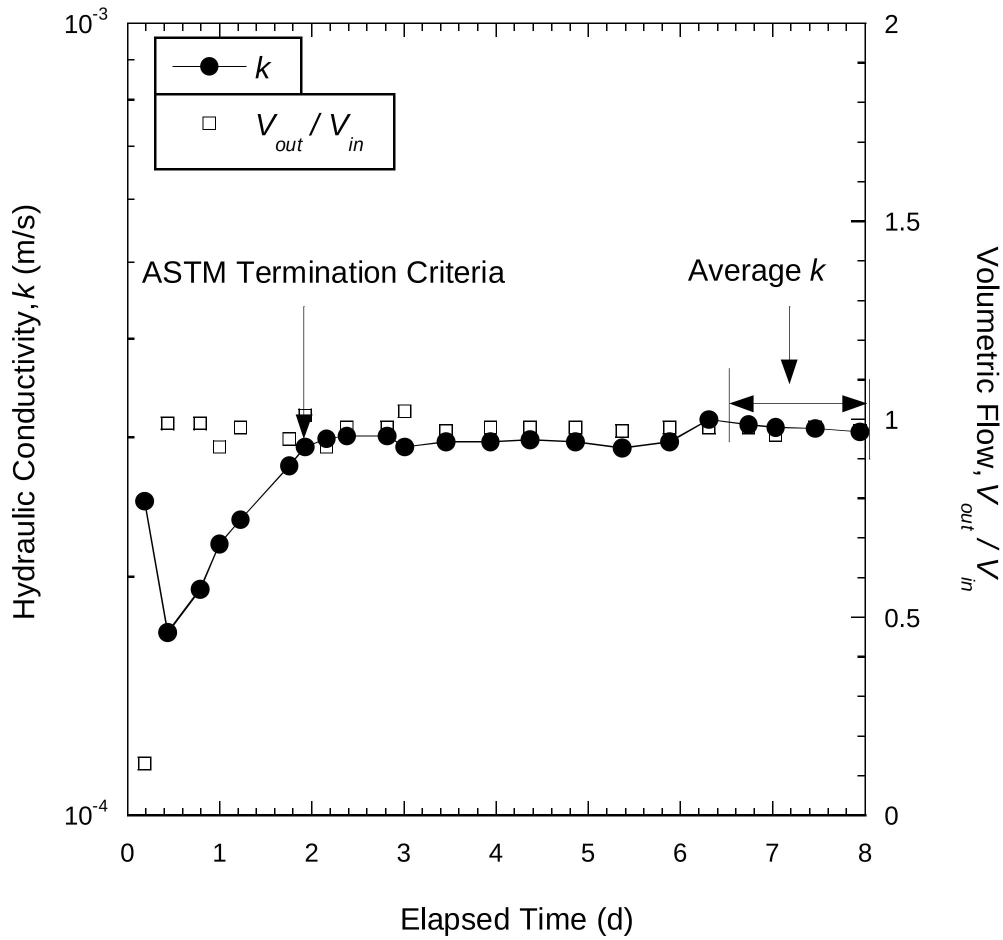


Fig. 4.3. Temporal relationships of hydraulic conductivity and ratio of volumetric outflow-to-inflow for unamended natural tailings prepared at an initial water content = 11%.

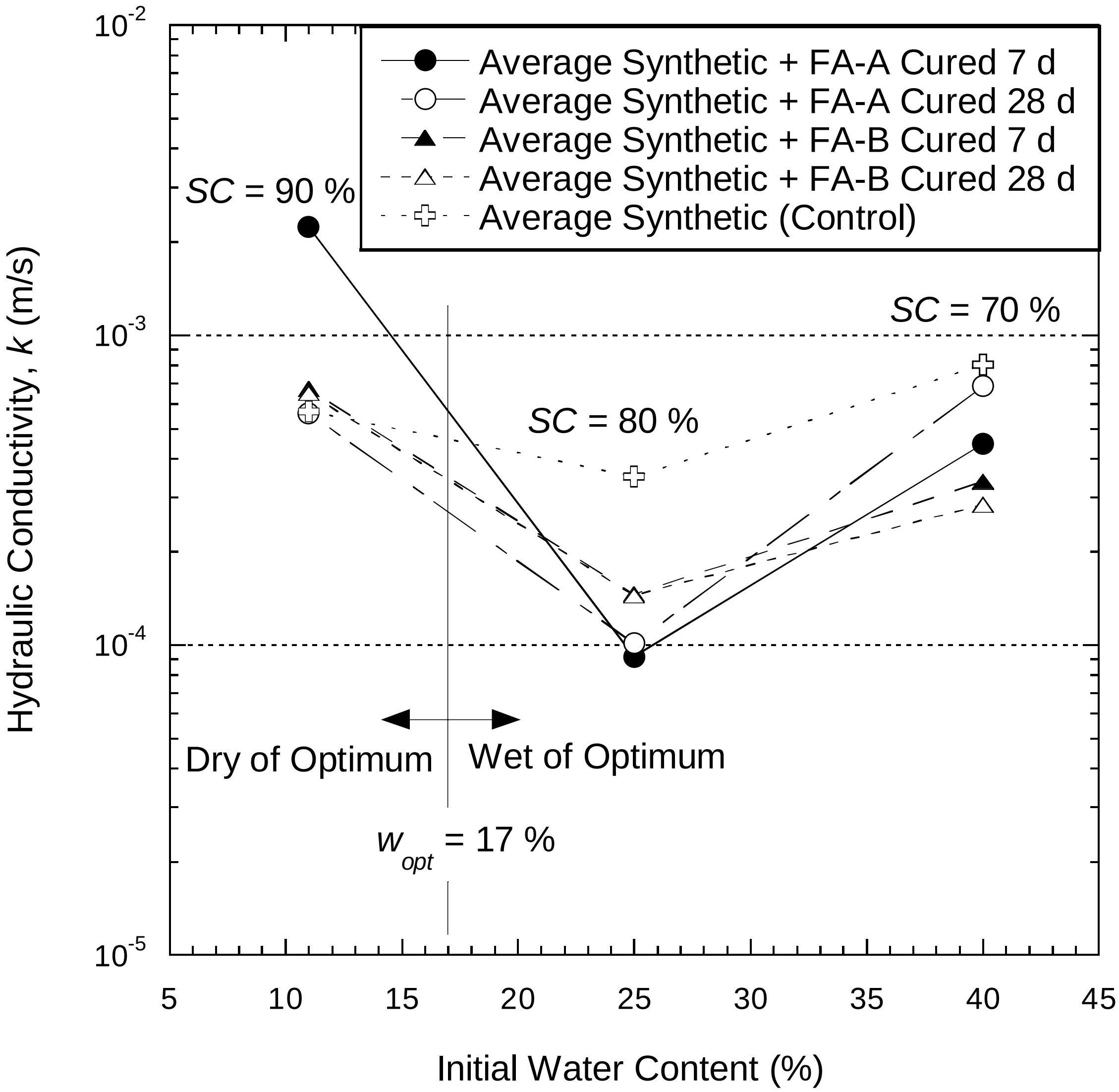


Fig. 4.4. Relationship between hydraulic conductivity (*k*) and initial molding water content (w_i) for unamended average synthetic tailings and all fly ash-amended average synthetic tailings mixed with Fly Ash A (FA-A) or Fly Ash B (FA-B).

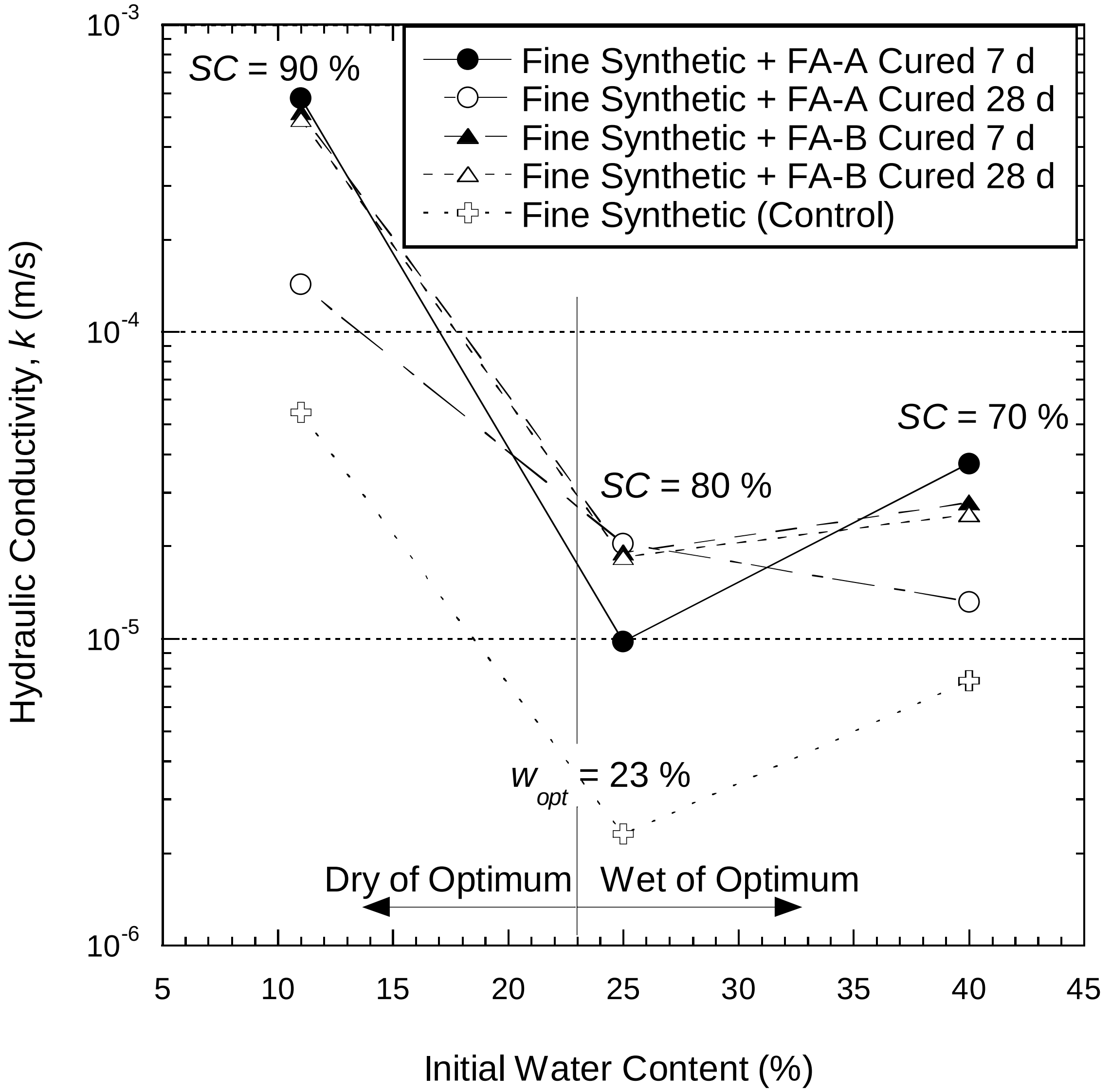


Fig. 4.5. Relationship between hydraulic conductivity (k) and initial molding water content (w_i) for unamended fine synthetic tailings and all fly ash-amended fine synthetic tailings mixed with Fly Ash A (FA-A) or Fly Ash B (FA-B).

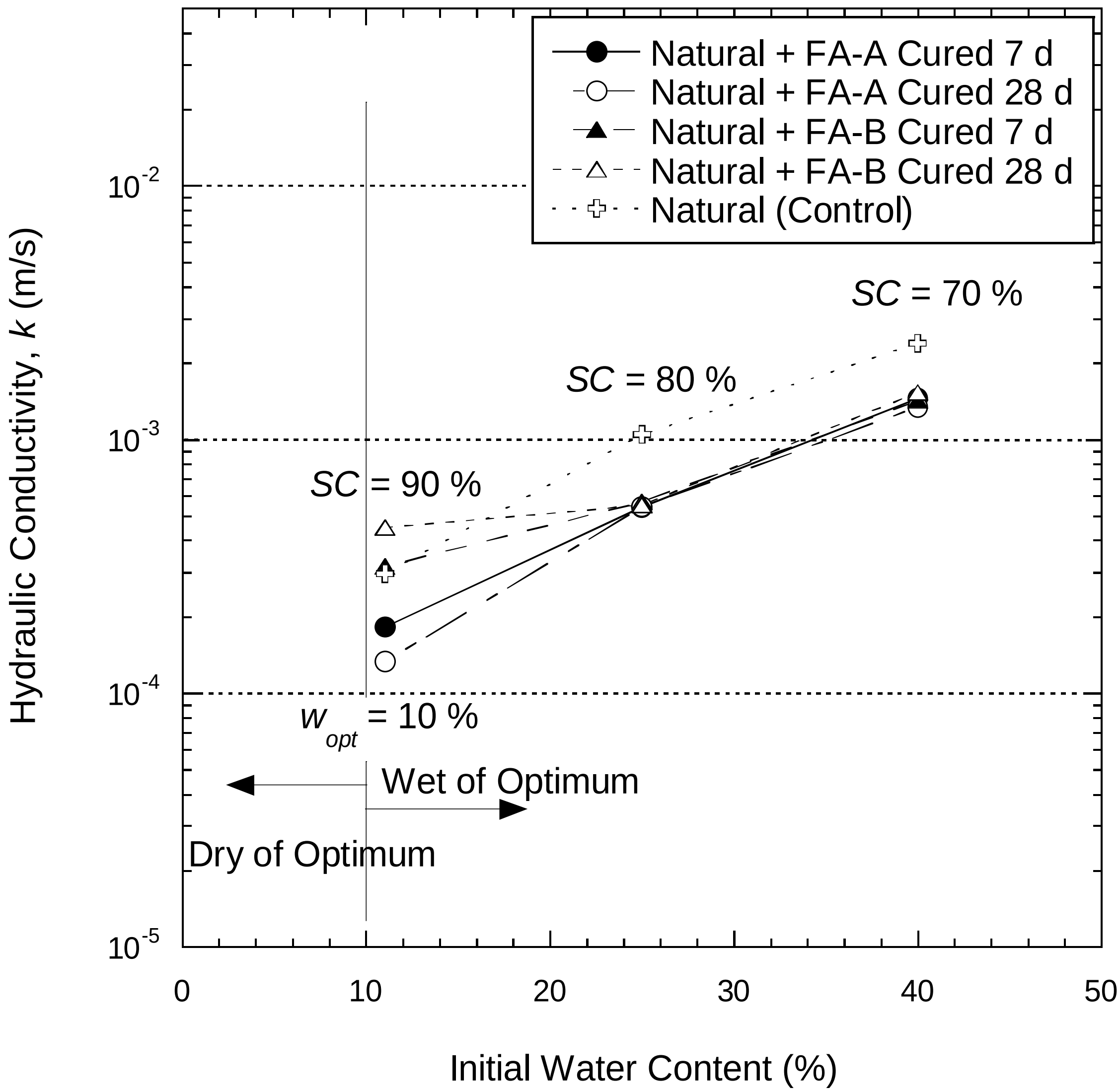


Fig. 4.6. Relationship between hydraulic conductivity (k) and initial molding water content (w_i) for unamended natural (fine-garnet) tailings and all fly ash-amended natural (fine-garnet) tailings mixed with Fly Ash A (FA-A) or Fly Ash B (FA-B).

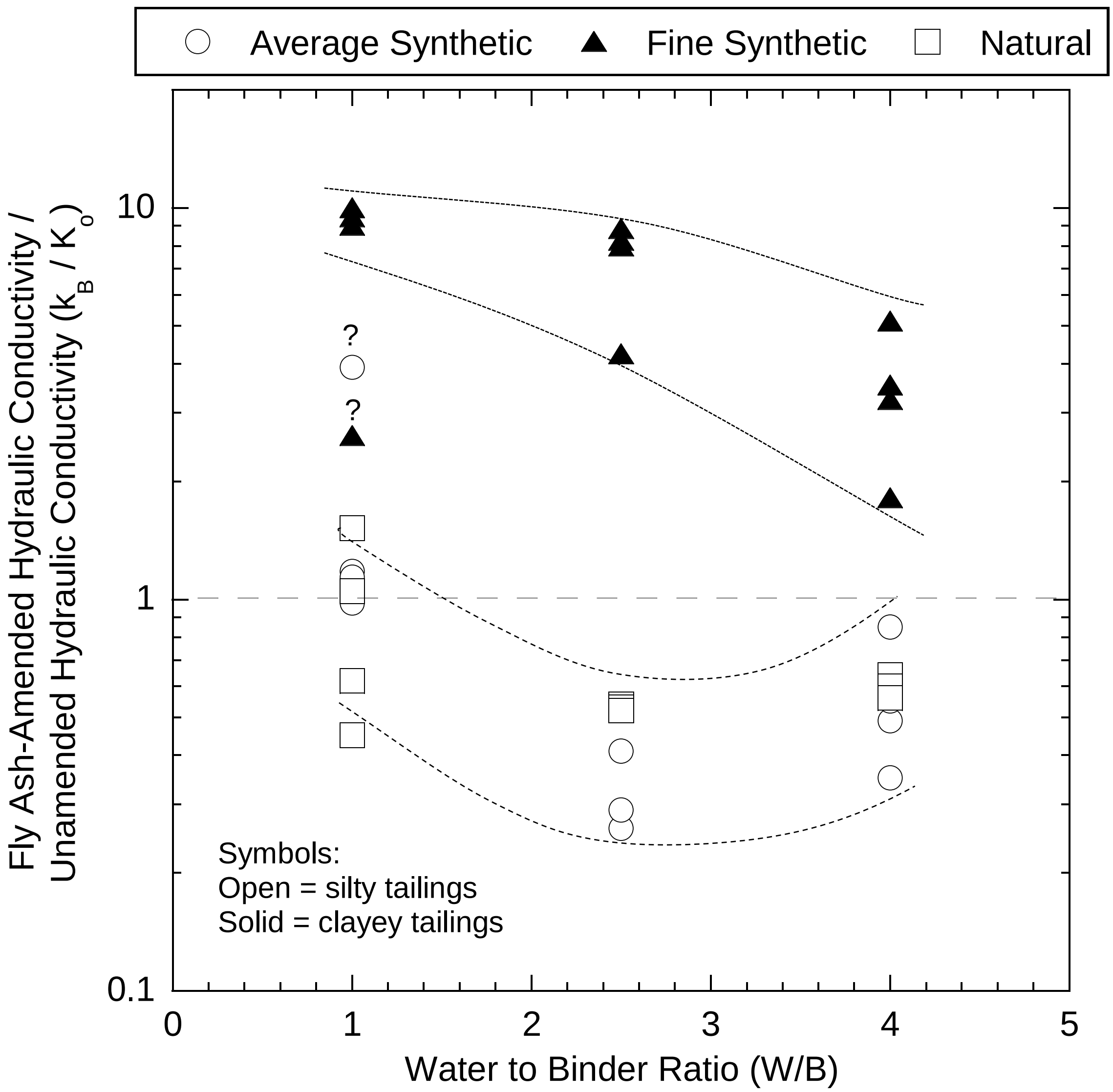


Fig. 4.7. Relationship between normalized hydraulic conductivity (k_B/k_0) and water to binder ratio (*W/B*) for all fly ash-amended tailings specimens evaluated in this study. Dashed lines capture general trends in the effect of *W/B* on k_B/k_0 for silty and clayey tailings and the question mark (?) designates outliers in the data.

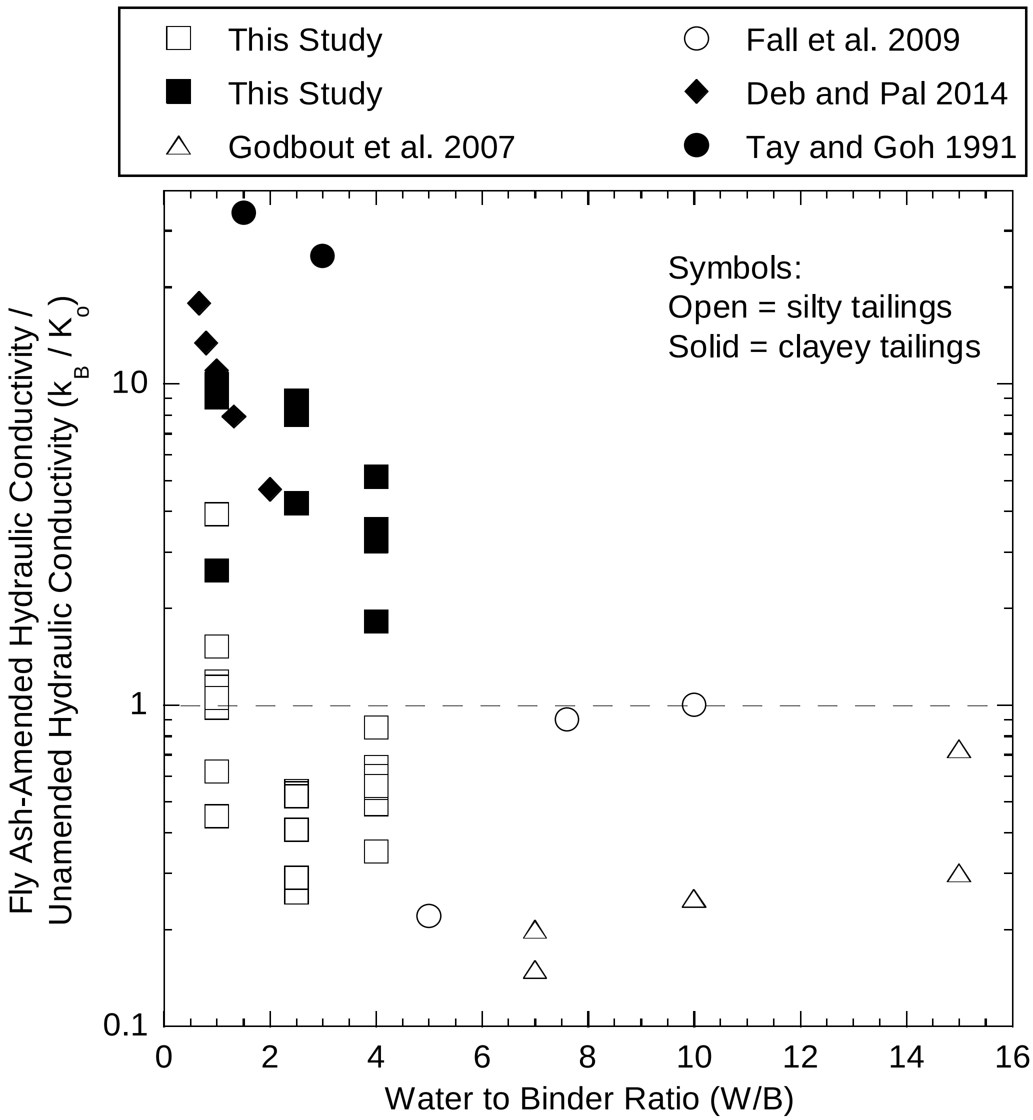


Fig 4.8. Relationship between normalized hydraulic conductivity (k_B/k_0) and water to binder ratio (*W/B*) for all fly ash-amended tailings specimens evaluated in this study compared with data from literature in regards silty and clayey tailings.

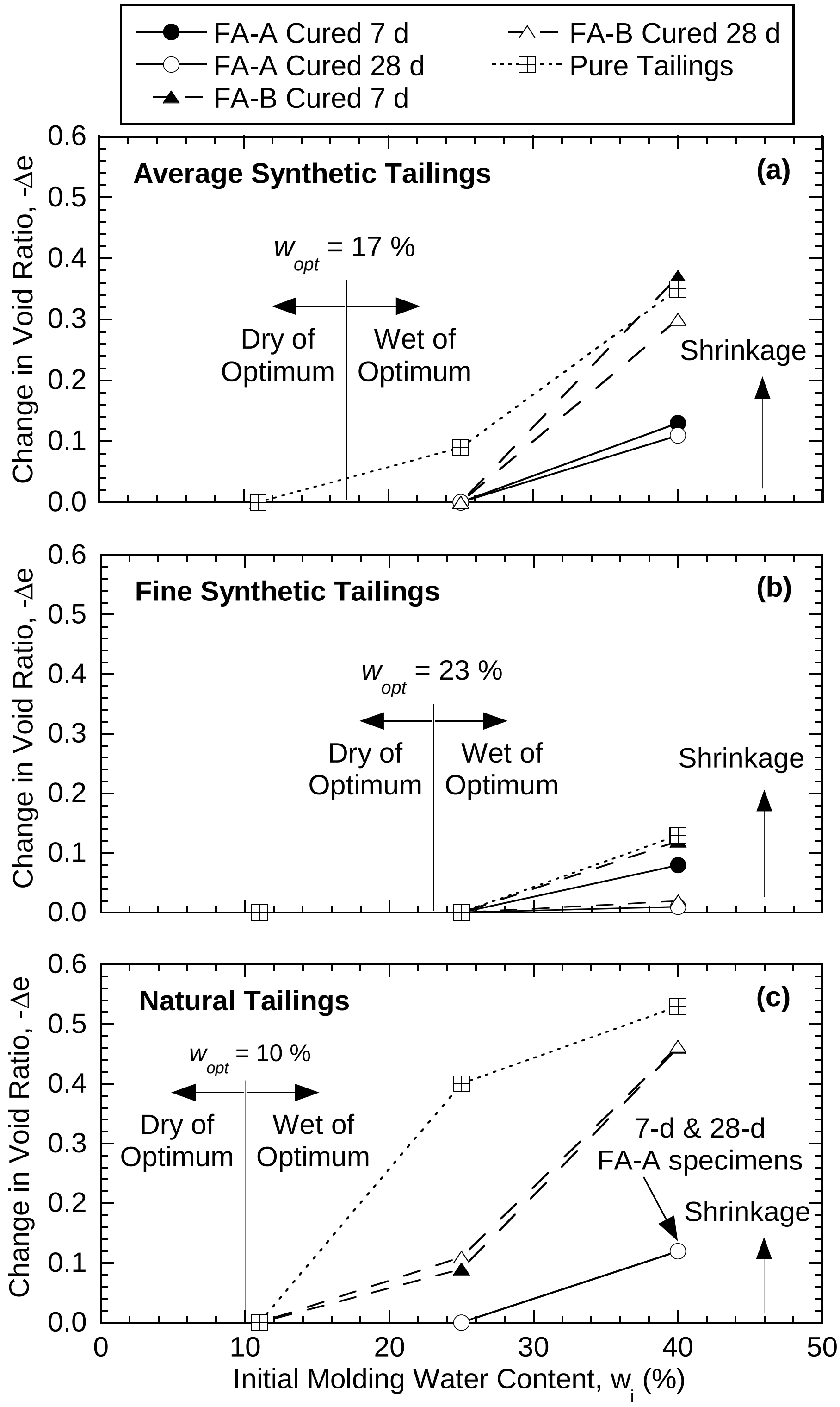
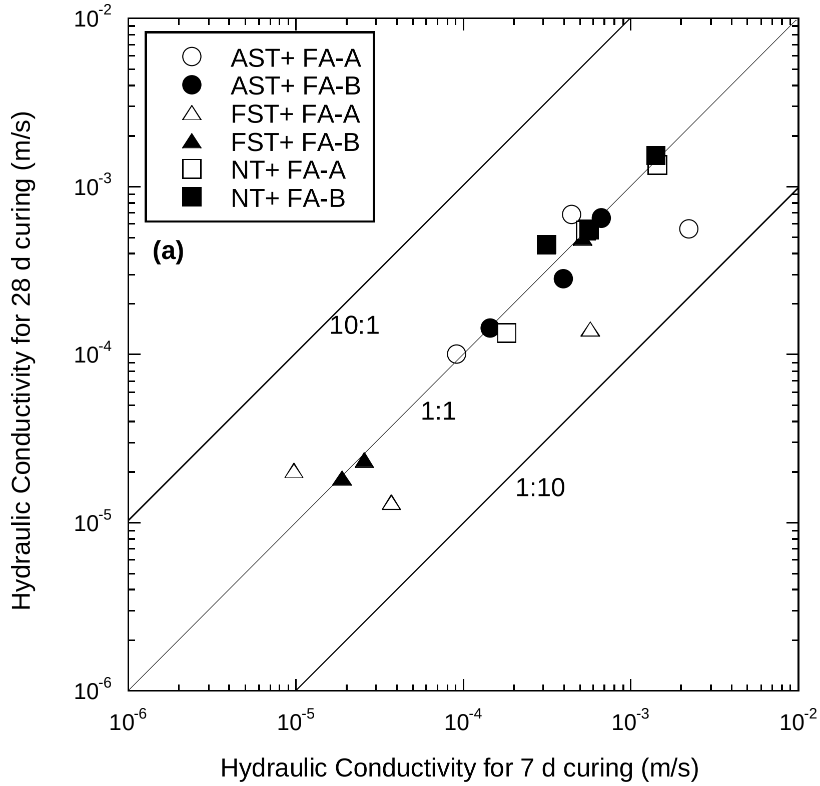


Fig. 4.9. Relationships between the change in void ratio and initial molding water content for (a) average synthetic tailings, (b) fine synthetic tailings, and (c) natural tailings. Change in void ratio computed as the different between final and initial void ratios [$-\Delta e = -(e_f - e_i)$].



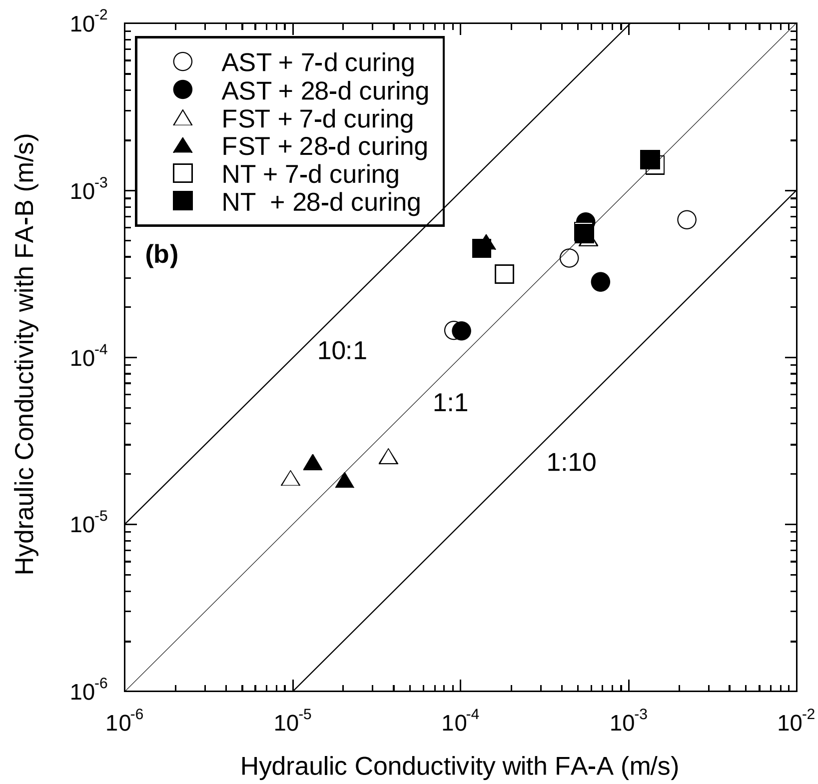


Fig. 4.10. Hydraulic conductivity of amended tailings with effect of (a) 7, and 28 days curing time; and (b) fly ash A and fly ash B.

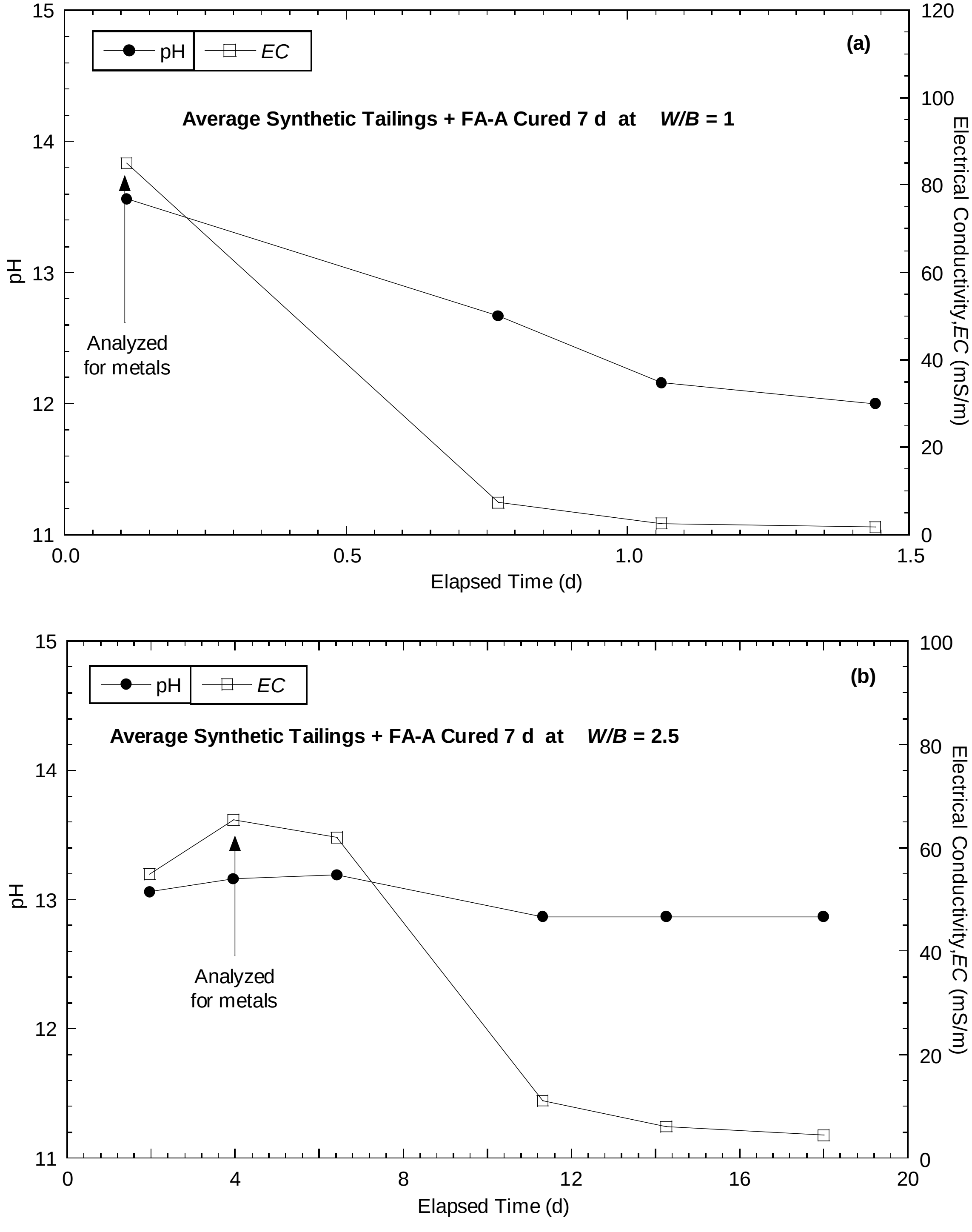


Fig. 4.11. Temporal relationships of effluent leachate pH and electrical conductivity (EC) that exhibit (a) first flush and (b) lagged response leaching patterns.

CHAPTER 5: SUMMARY AND CONCLUSIONS

5.1 Summary and Conclusion

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 and contaminant leaching potential. Hydraulic conductivity tests were conducted on (i) pure tailings and (ii) fly ash-amended tailings in flexible-wall permeameters using a constant head method. Experimental results of fly ash-amended tailings were evaluated with regards to *k* and associated effluent chemistry to identify potential reuse applications in transportation-related earthwork projects and other geotechnical engineering projects.

The following conclusions were drawn from this study.

- Hydraulic conductivity (*k*) of all unamended and fly ash-amended mine tailings exhibited anticipated trends 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 amended average synthetic tailings and natural tailings (i.e., low-plasticity silts) decreased two to five times *k* of 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 formation of cementitious bonds between tailings particles that 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 and 28 d were approximately equal, and agree with past research that indicates there is negligible influence of an increase in hydration time from 7 to 28 d on k of fly ash-amended tailings and soils.
- 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 is 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, or in embankment fill. The *k* of low-plasticity clay tailings-fly ash mixtures at *W/B* = 2.5 and 4 met hydraulic criteria for reuse in a sub-base layer, and for flowable fill at *W/B* = 1.
- Concentrations of Ag and Cd for amended tailings were below the drinking water MCLs and toxicity limits, whereas concentrations of Cr and Cu for amended tailings, and in particular for FA-A, exceeded drinking water MCLs and toxicity limits. These different metal concentrations were linked to the solubility and mobility of the different metals in alkaline solutions, which were observed for all fly ash-amended tailings.
- All tailings amended with FA-B can be used in transportation-related earthwork projects from an environmental aspect, whereas tailings amended with FA-A may lead to elevated Cr and Cu concentrations above the toxicity limits. A case-by-case evaluation likely is needed for fly ash that will be considered for reuse in transportation earthwork applications to assess potential heavy metals that can be leached.

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APPENDIX A: Hydraulic Conductivity Testing

A.1 Introduction

Numerous variations of laboratory hydraulic conductivity cells are available to estimate the hydraulic conductivity, including flexible-wall (triaxial) cells or rigid-wall (e.g., oedometer cells or single and or double-ring compaction molds) cells (Olson and Daniel 1981; Zimmie et al. 1981; Daniel et al. 1985; and Daniel 1994). However, the flexible-wall tests typically are preferred since the cell water press the latex membrane against the test specimen and thereby eliminate the sidewall leakage as well as the ability to control of the effective stress conditions and the degree of saturation with using back-pressure. Several approaches could be used to measure the laboratory hydraulic conductivity included: constant head, falling-head, falling headwater-rising tailwater, and constant-flow method. The constant head tests are associated the simplicity of interpretation of data and also the constant head reduces misperception because of the changed in volume of air bubbles especially when the soil is not saturated (Olson and Daniel 1981). The guidelines and recommendations for the laboratory of hydraulic conductivity with flexible-wall permeameter are provided in ASTM D5084-10. Among these include: permeant liquid, back pressure saturation, preparation of test specimens, recommended maximum hydraulic gradient, calculation and measurement of hydraulic conductivity test, and termination criteria.

The hydraulic conductivity or coefficient of permeability is defined as the ability of a fluid to flow through a porous medium (e.g., soil) in response to a gradient, and is proportional to Henry Darcy's law 1856, as follows:

$$q = kiA$$

where q is the rate of flow, A is the cross-sectional area of the matrix flow, and i is the hydraulic gradient. The i is a difference in the hydraulic head loss associated with flow through the specimen (ΔH) divided by the length of the specimen (L) (i.e., $i = -\Delta H / L$).

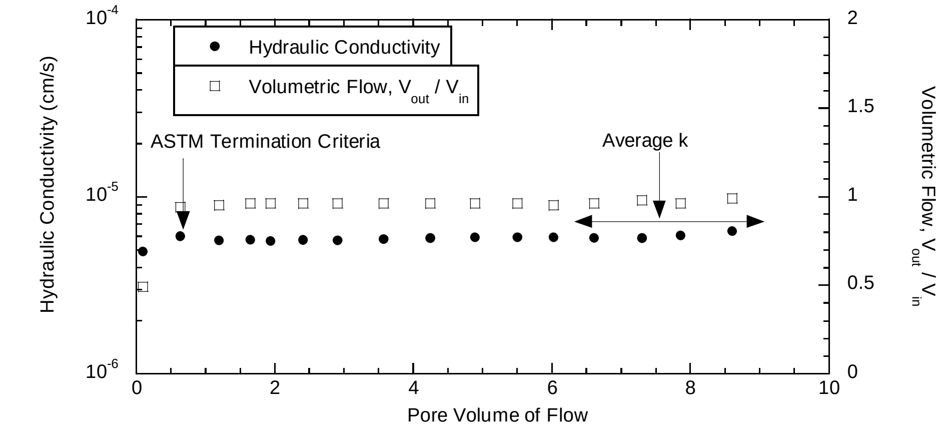
The hydraulic conductivity for a soil is dependent on the properties of both the soil matrix and the permeant liquid, as follows (e.g., Olson and Daniel 1981):

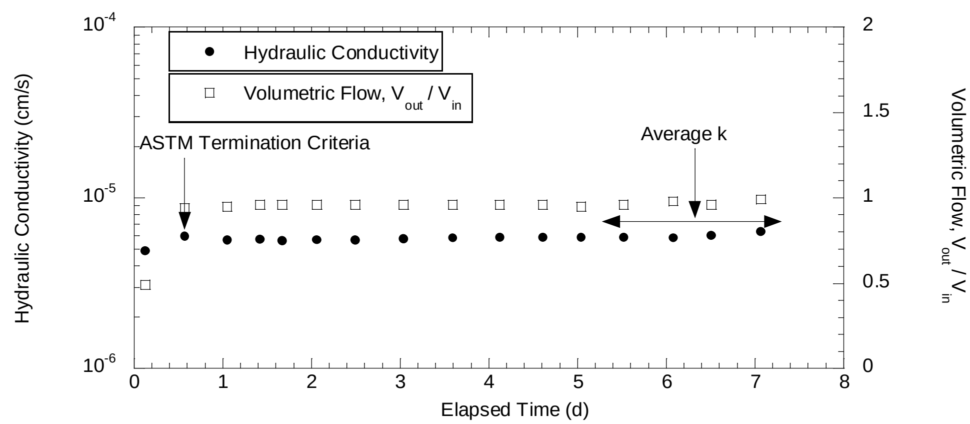
$$q = -K \frac{\gamma}{\mu} iA$$

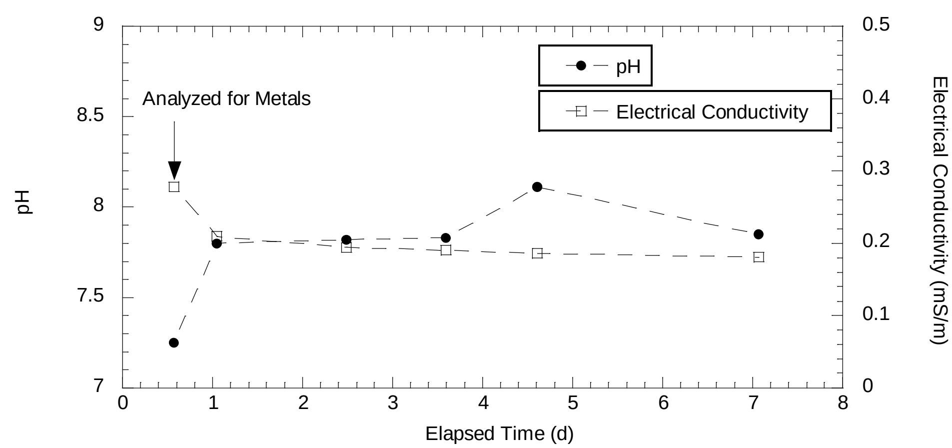
where K is the intrinsic permeability of the soil, γ is the unit weight of the permeant liquid, μ is the viscosity of the permeant liquid. Shackelford 1994 reported the intrinsic permeability denotes the effect of soil structure on the hydraulic conductivity such as, particle and pore size distribution, and soil type. Also, the pH and ionic strength of permeant liquid could affect the hydraulic conductivity.

APPENDIX B: A compilation of experimental data from all hydraulic conductivity tests on all materials in this study.

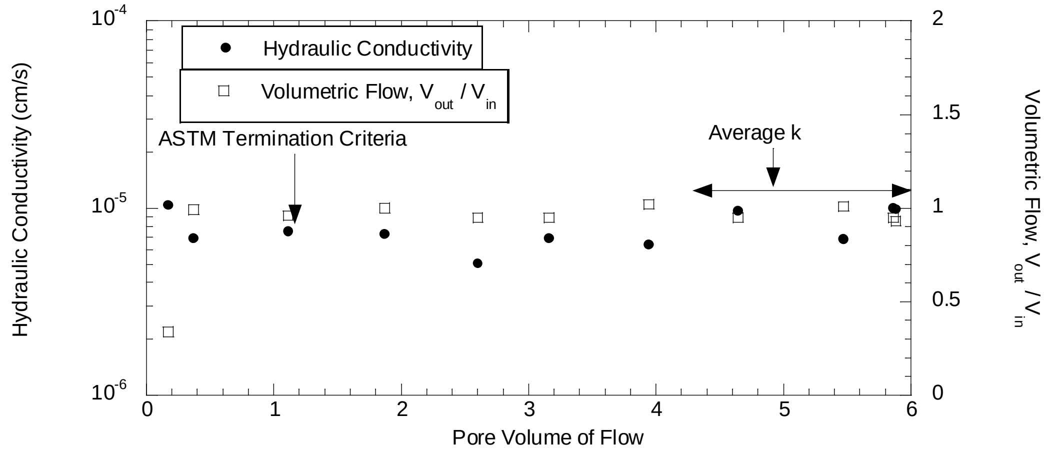
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
1	AST	-	-	-	1.55	0.71	11.2	0.71	26.4	$5.7x10^{-6}$

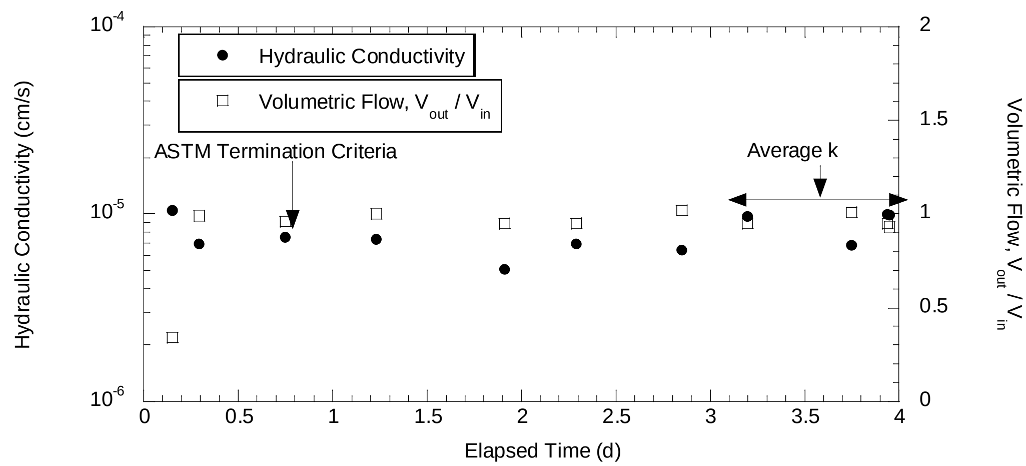


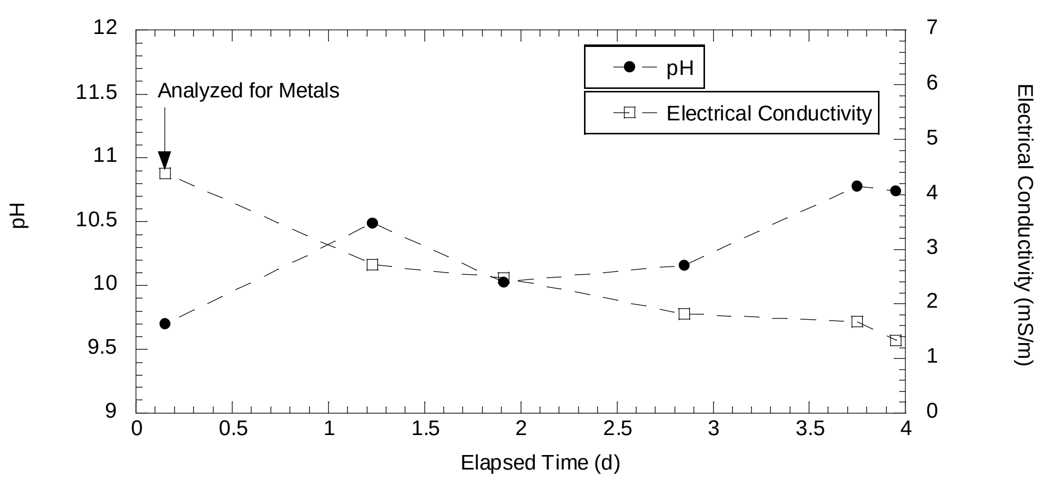




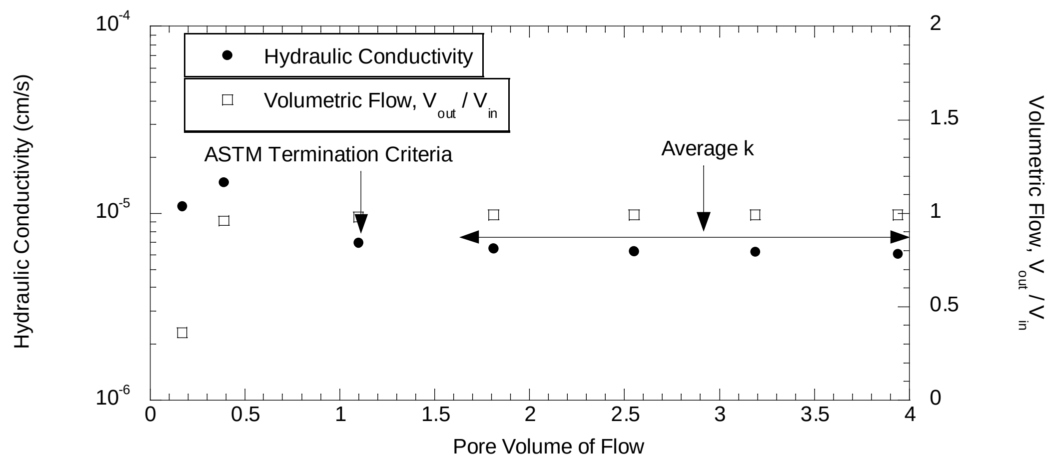
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
2	AST	1	B	7	1.55	0.69	11.8	0.69	26.4	6.7x10^{-6}

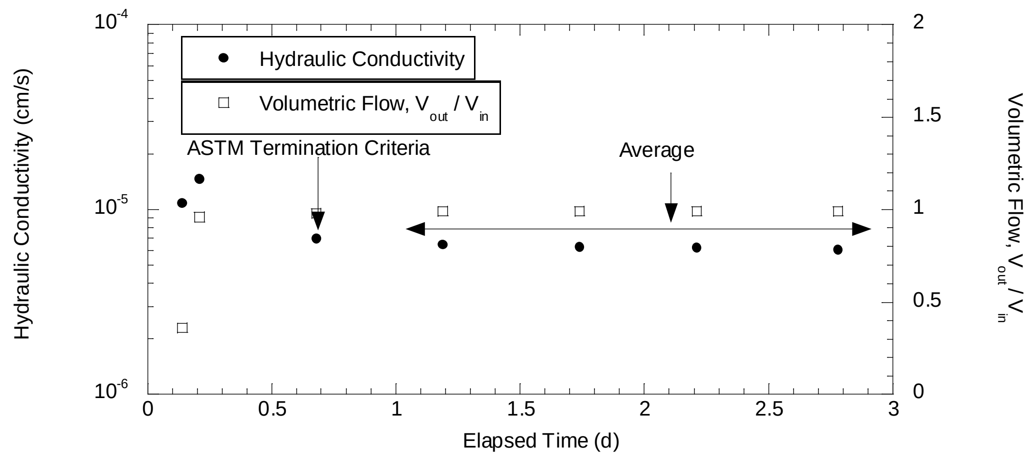


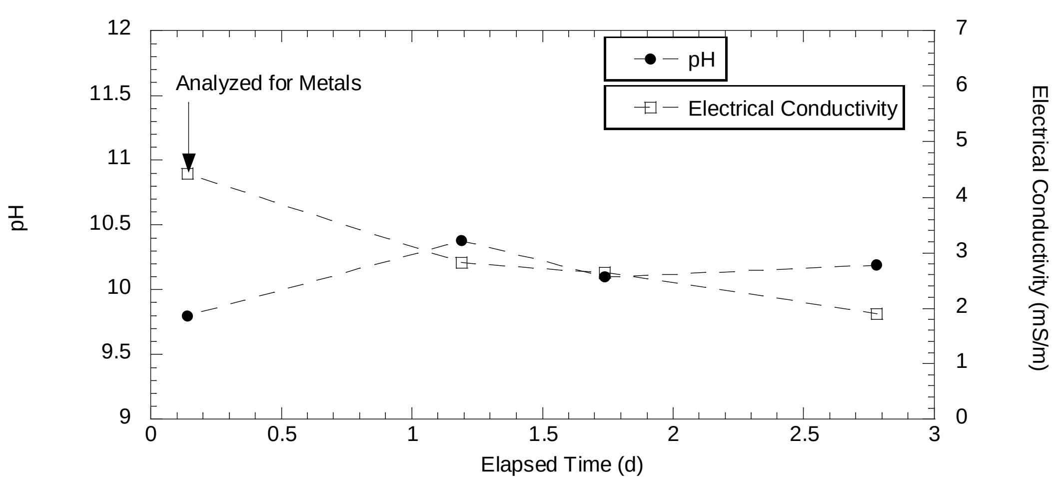




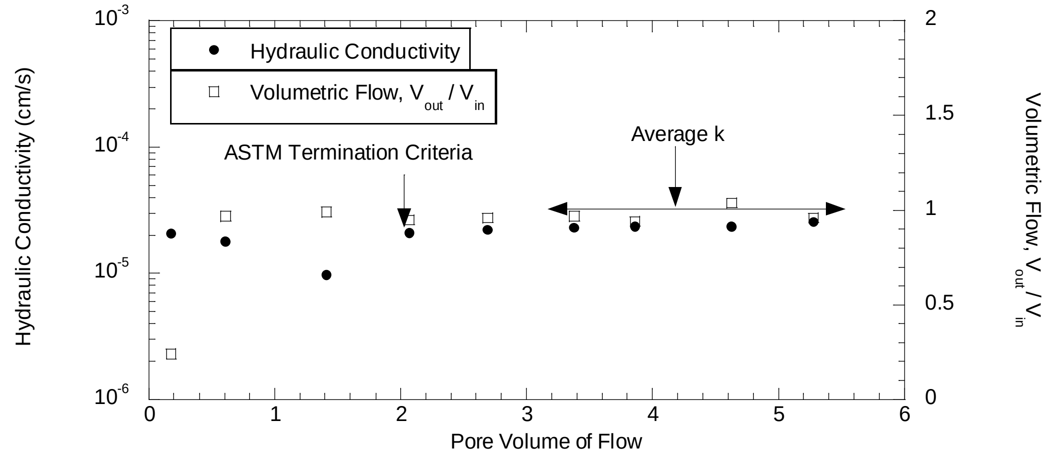
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
3	AST	1	B	28	1.55	0.69	11.2	0.69	25.9	6.5x10^{-6}

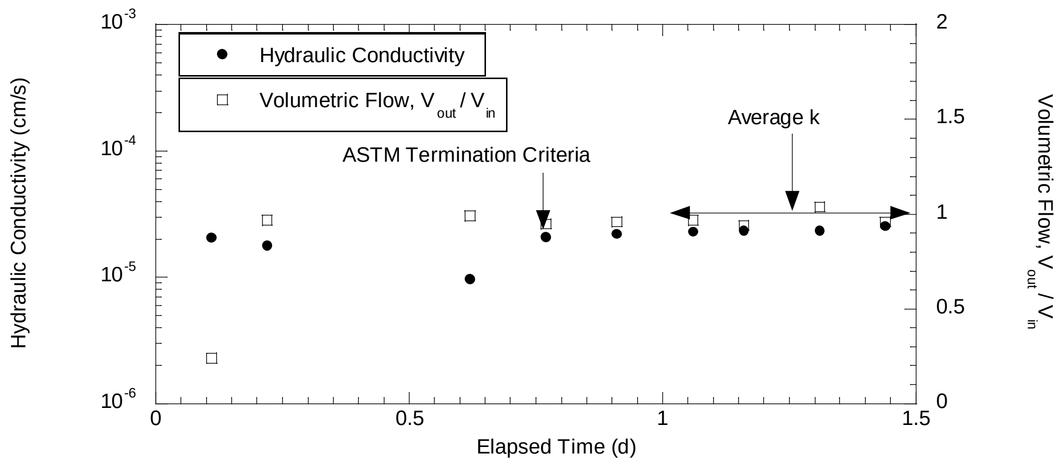


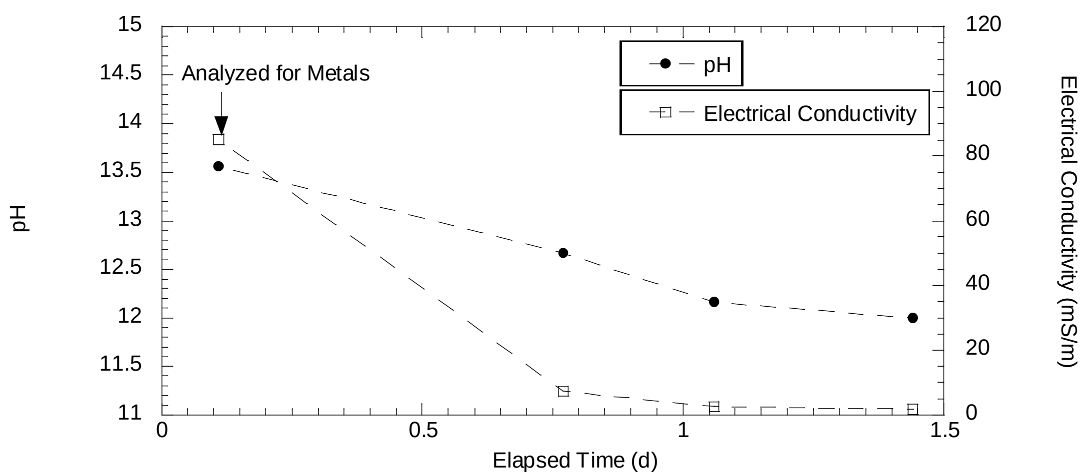




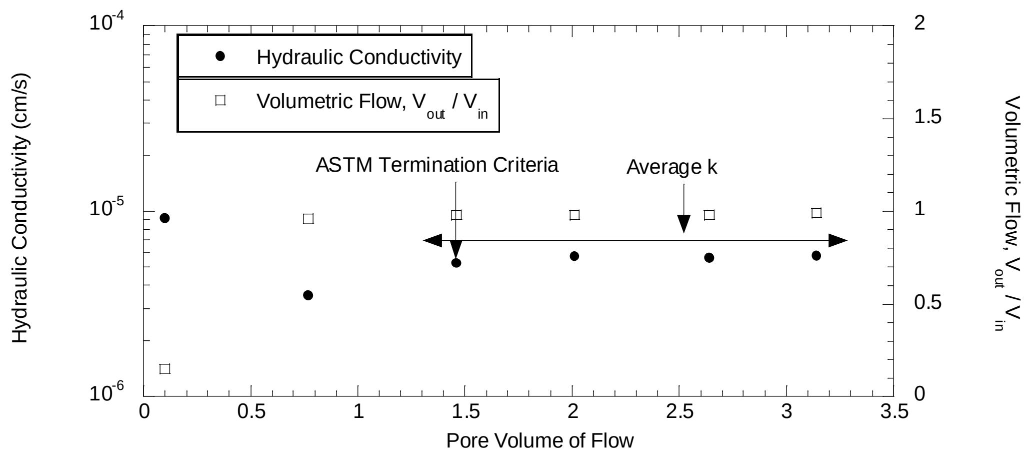
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
4	AST	1	A	7	1.52	0.73	11.3	0.73	29.8	2.2×10^{-5}

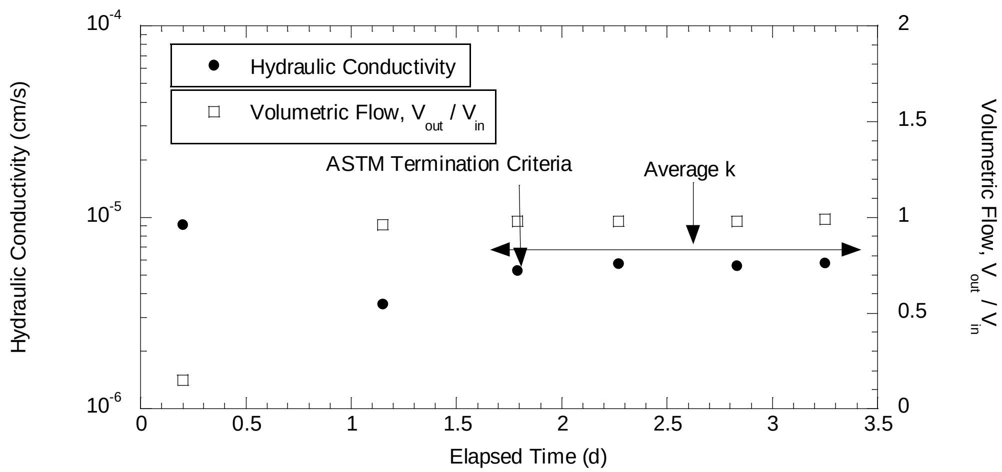


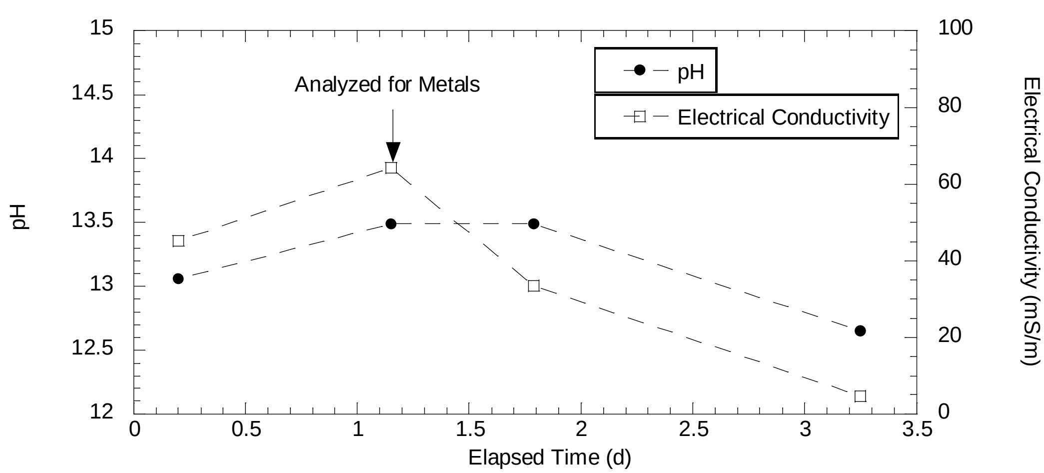




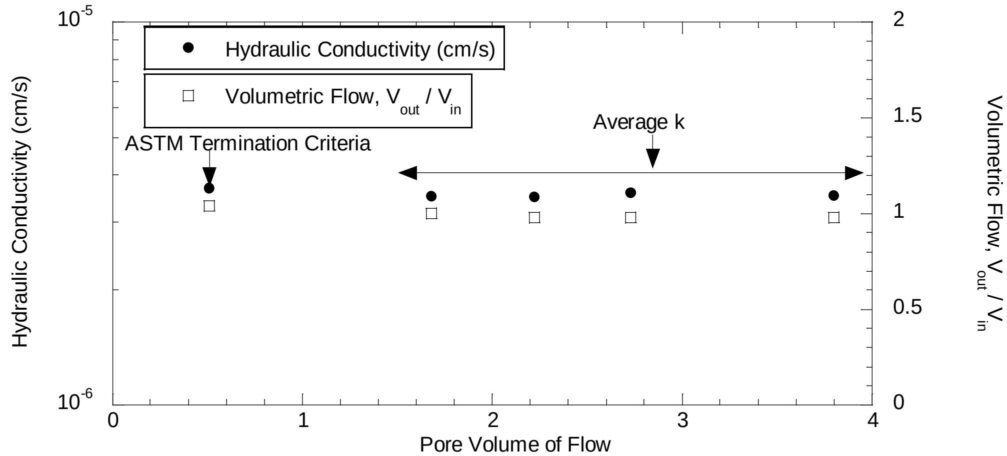
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
5	AST	1	A	28	1.5	0.76	9.5	0.76	28.3	5.6x10^{-6}

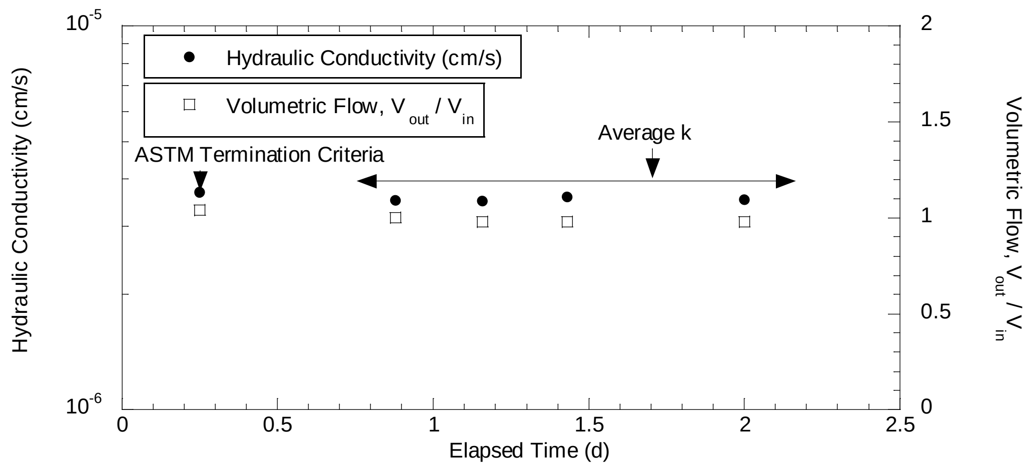


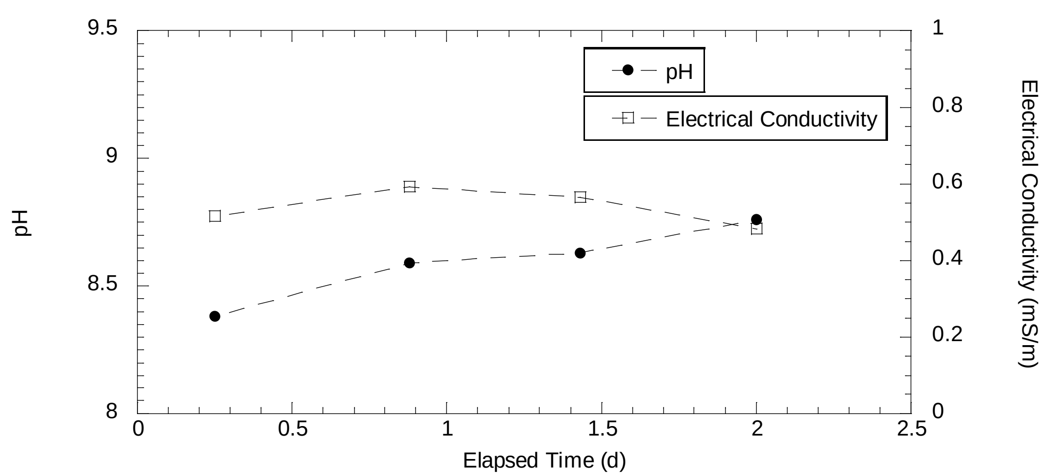




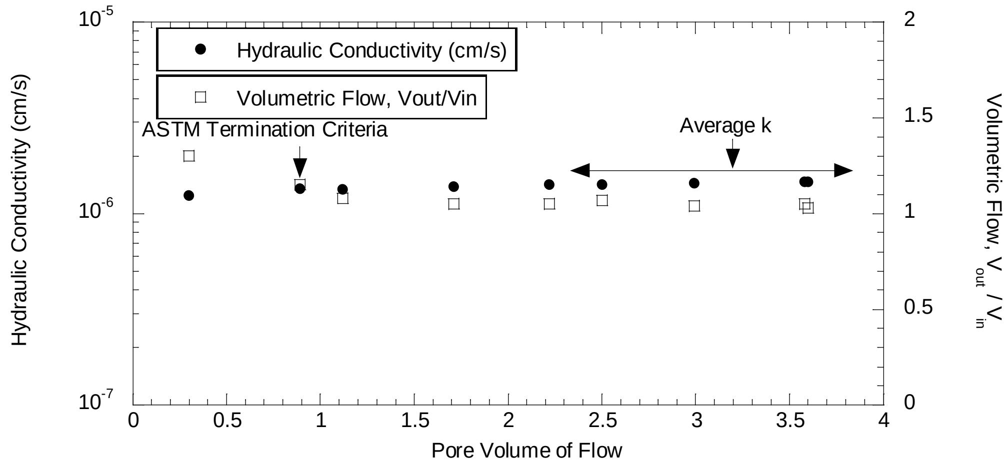
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
6	AST	-	-	-	1.48	0.80	25.4	0.70	24.2	3.5×10^{-6}

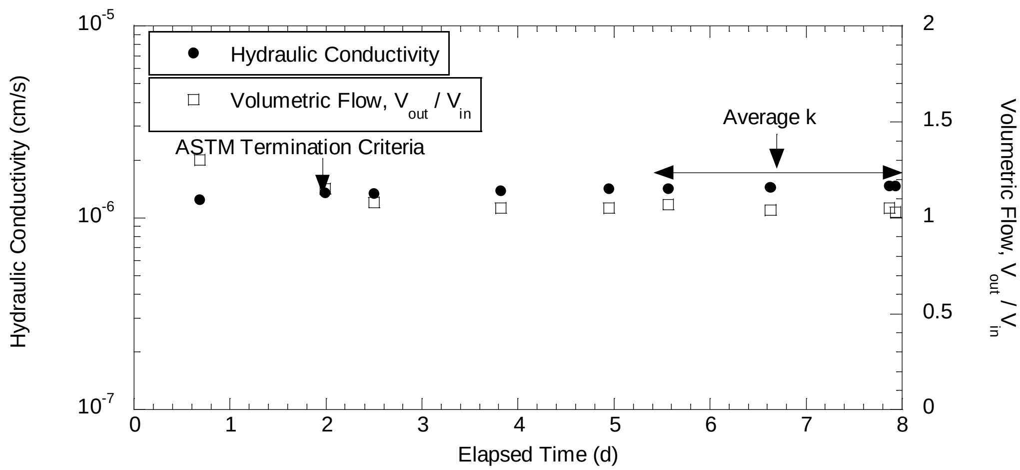


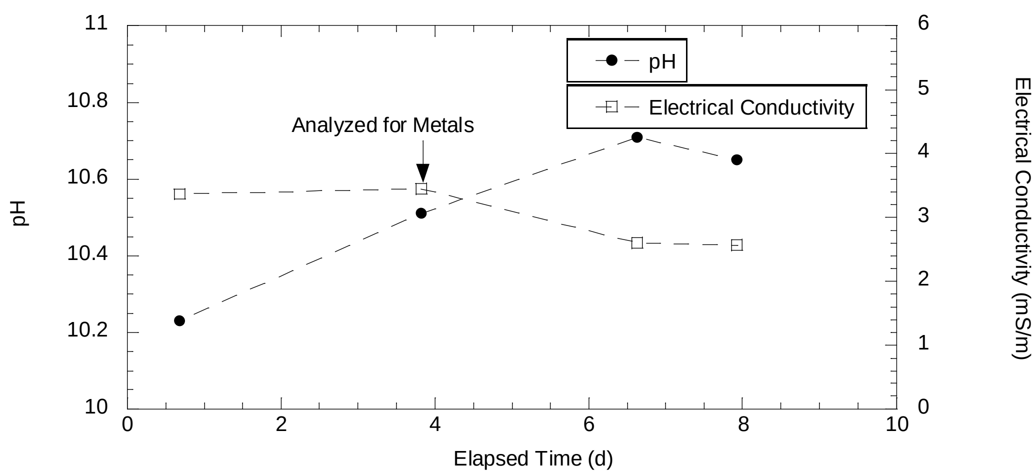




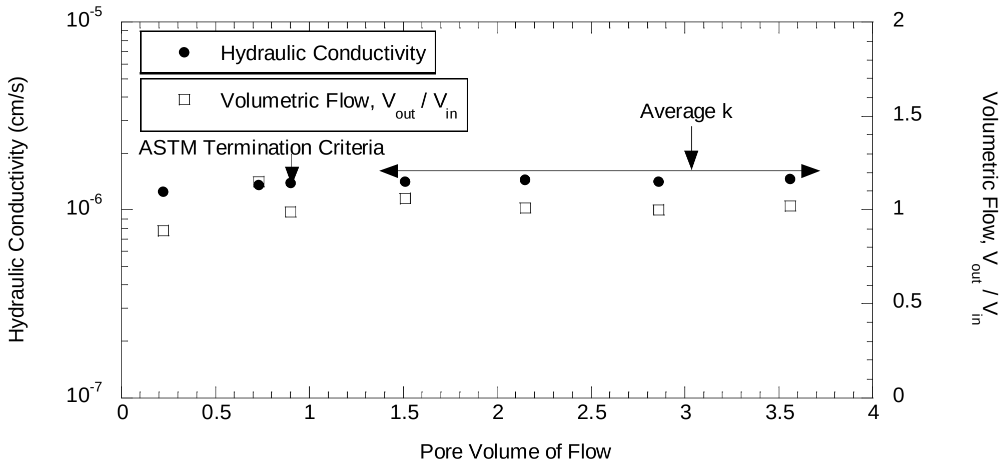
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
7	AST	2.5	B	7	1.58	0.66	25	0.66	22.8	1.5×10^{-6}

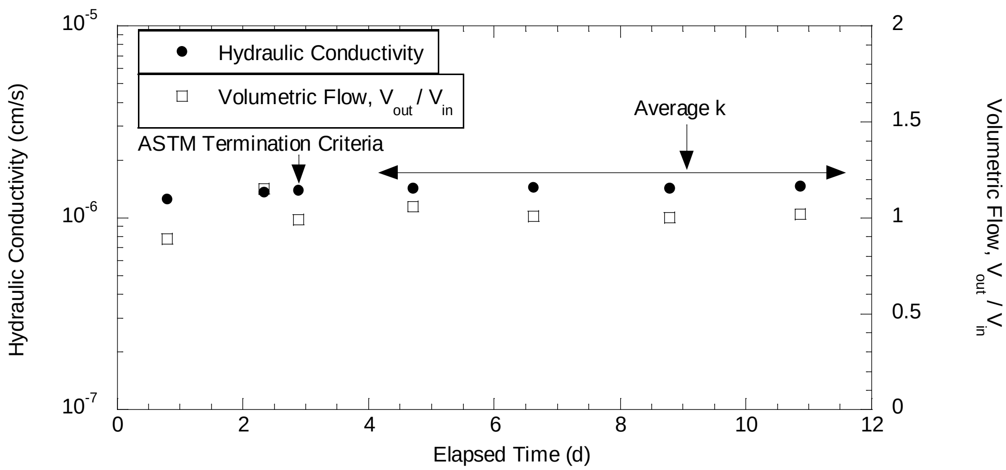


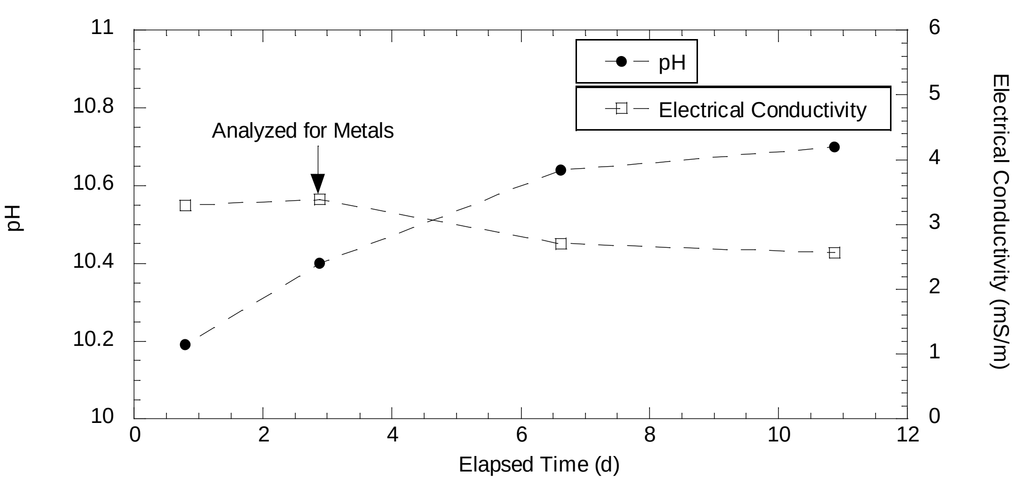




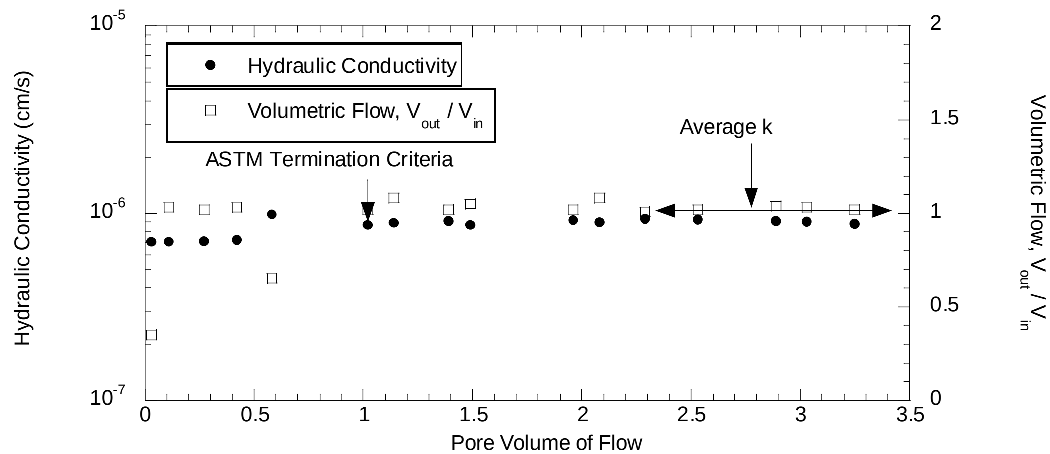
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
8	AST	2.5	B	28	1.6	0.63	23.4	0.63	22.5	1.4x10^{-6}

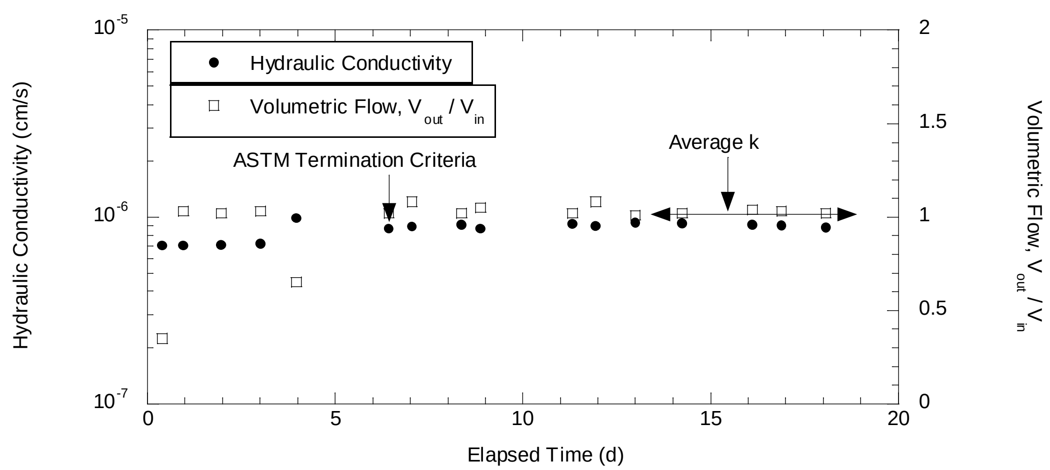


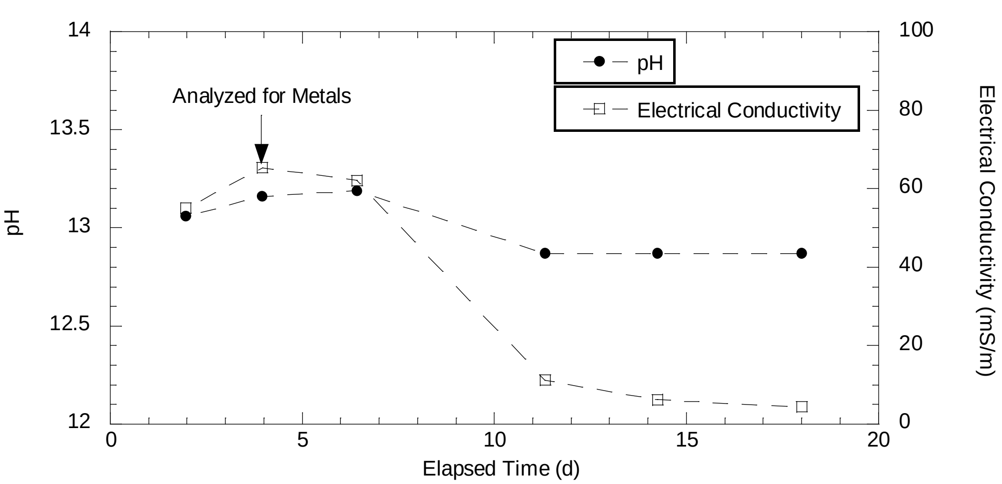




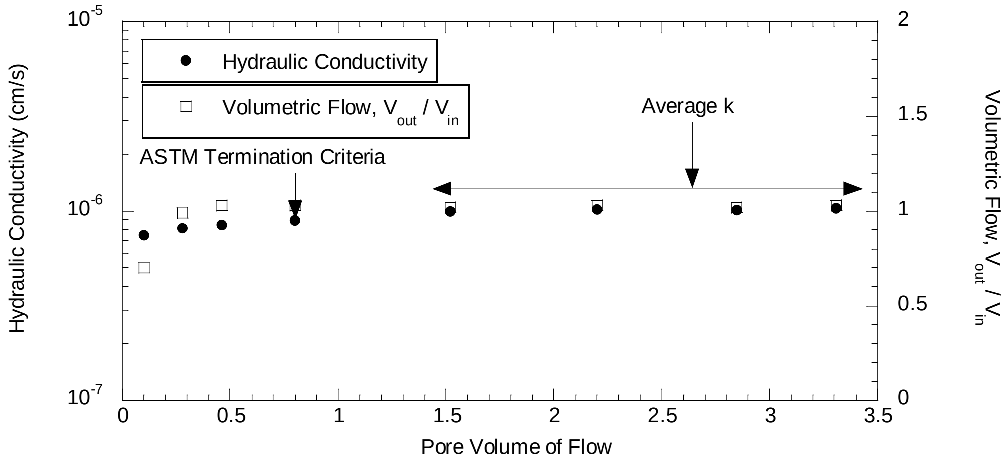
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
9	AST	2.5	A	7	1.53	0.73	24.5	0.73	26.1	9.2×10^{-7}

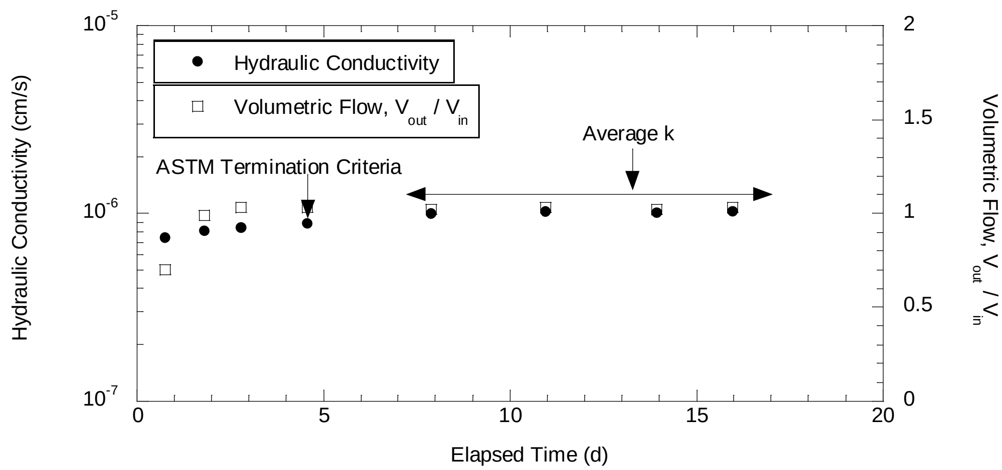


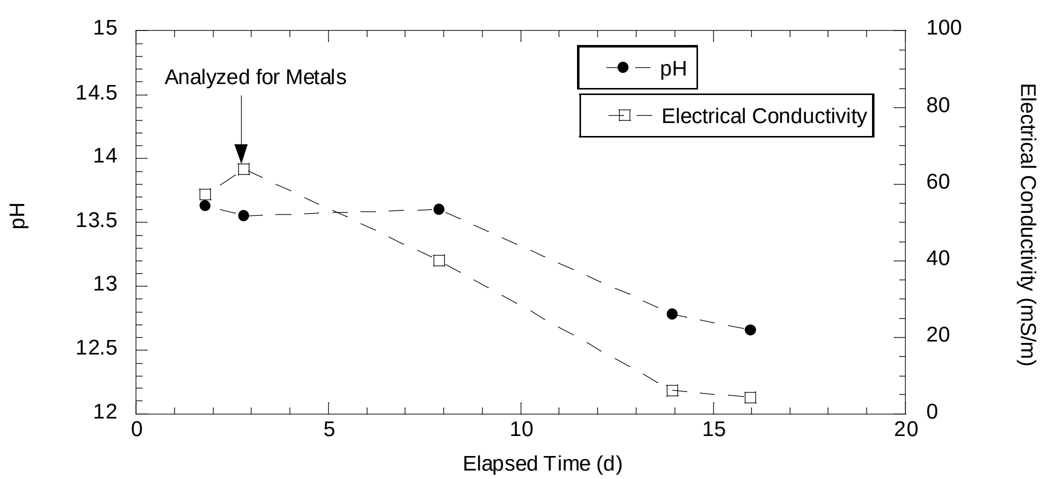




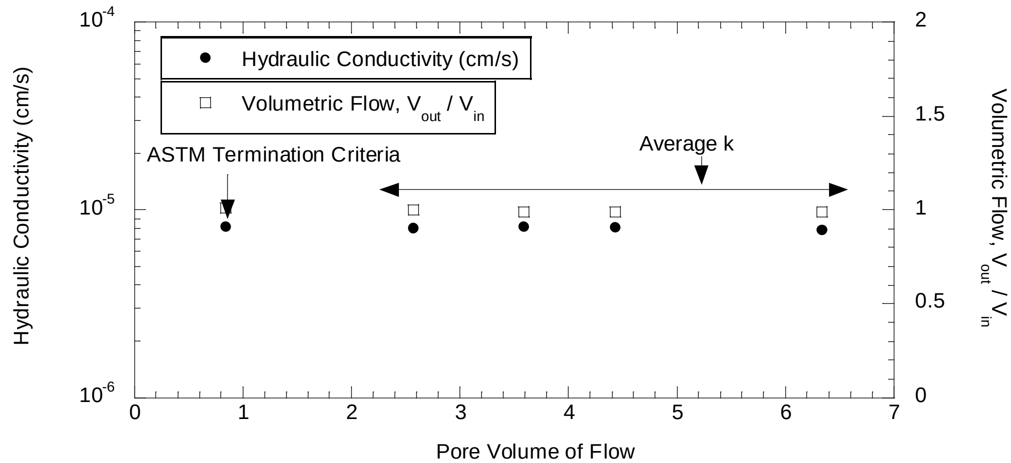
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
10	AST	2.5	A	28	1.55	0.70	23.8	0.70	26.3	1.0×10^{-6}

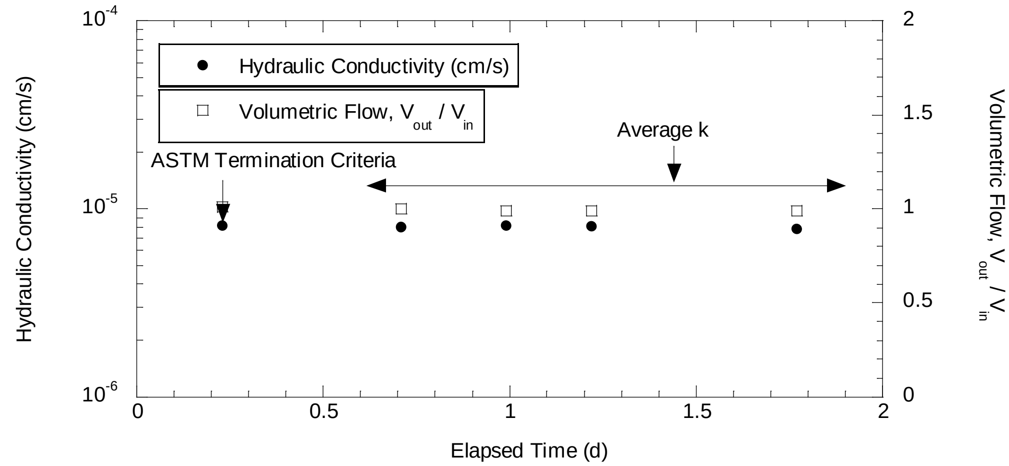


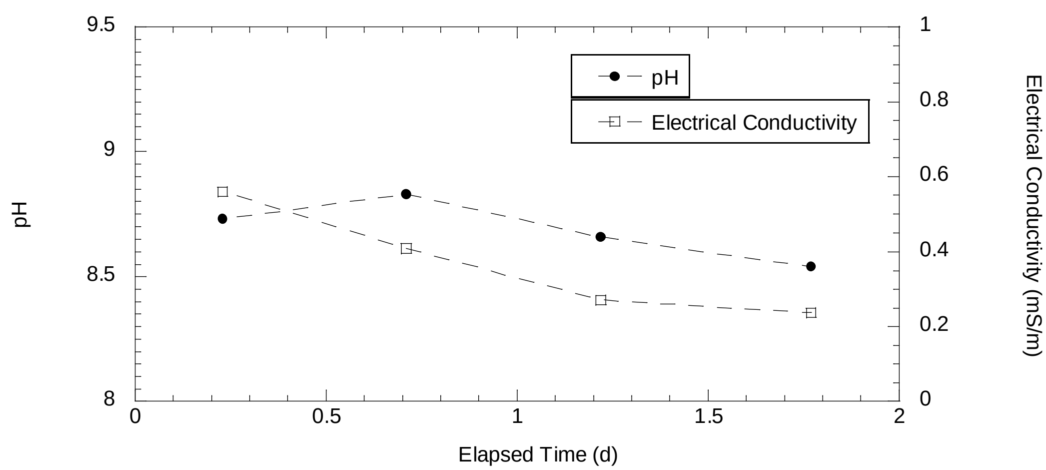




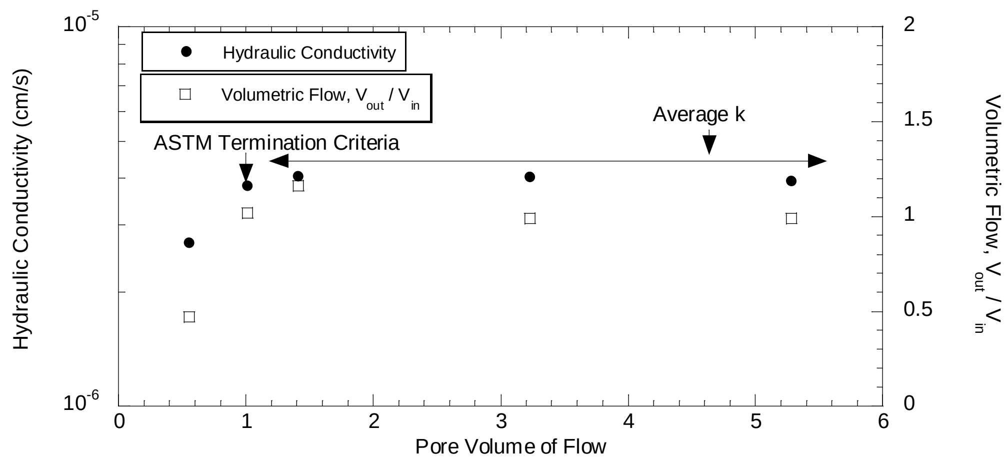
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
11	AST	-	-	-	1.24	1.13	39	0.78	29.7	8.0×10^{-6}

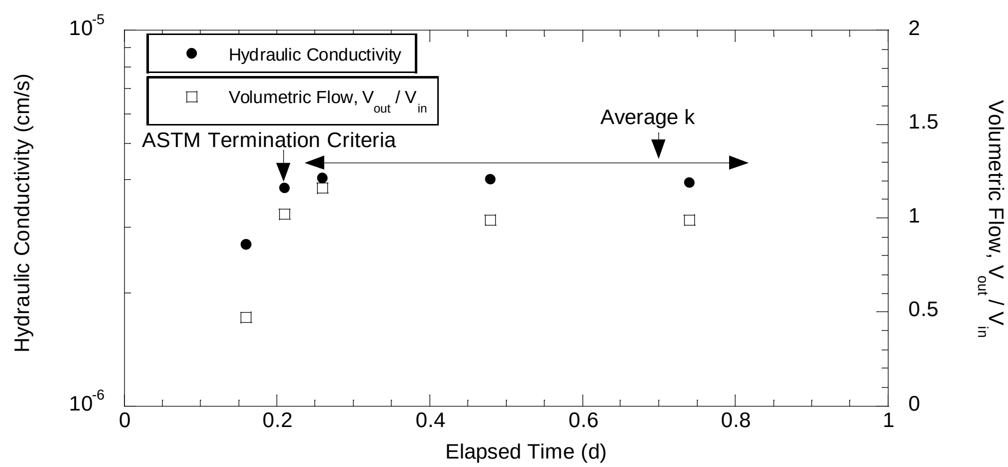


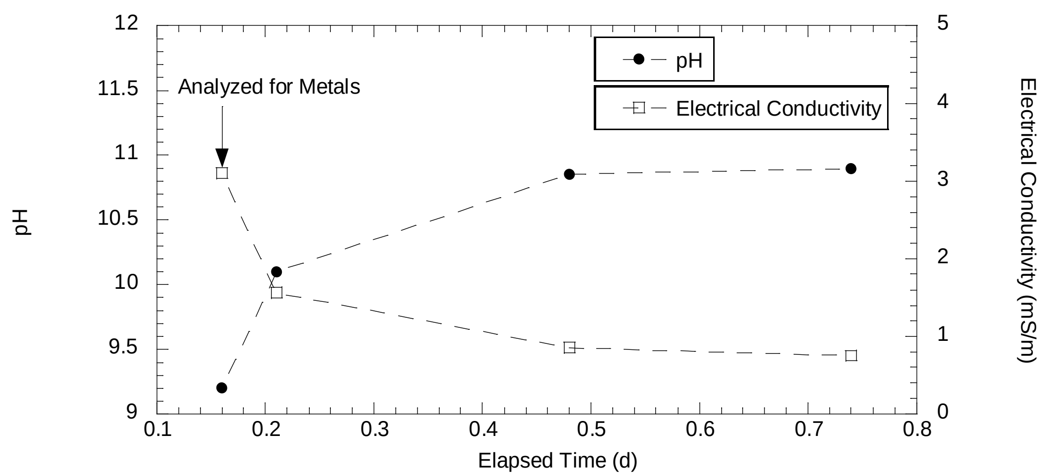




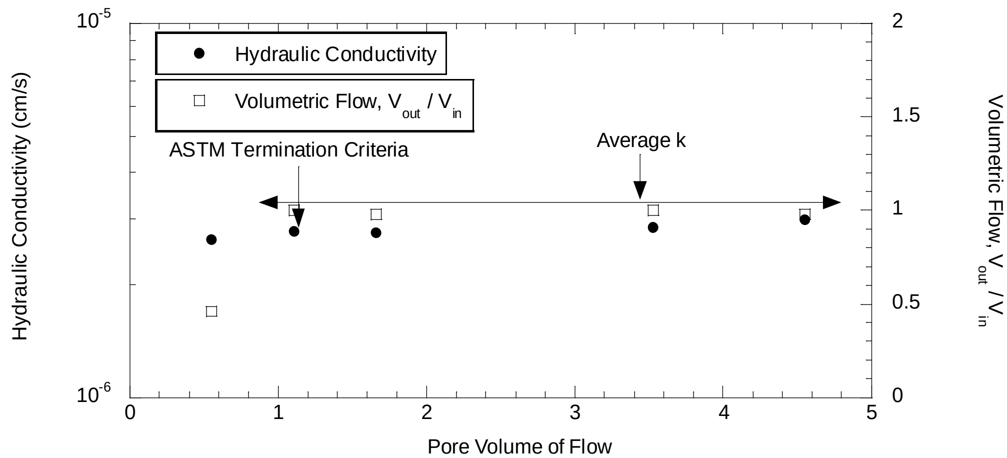
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
12	AST	4	B	7	1.4	0.87	38	0.60	24.4	4.0×10^{-6}

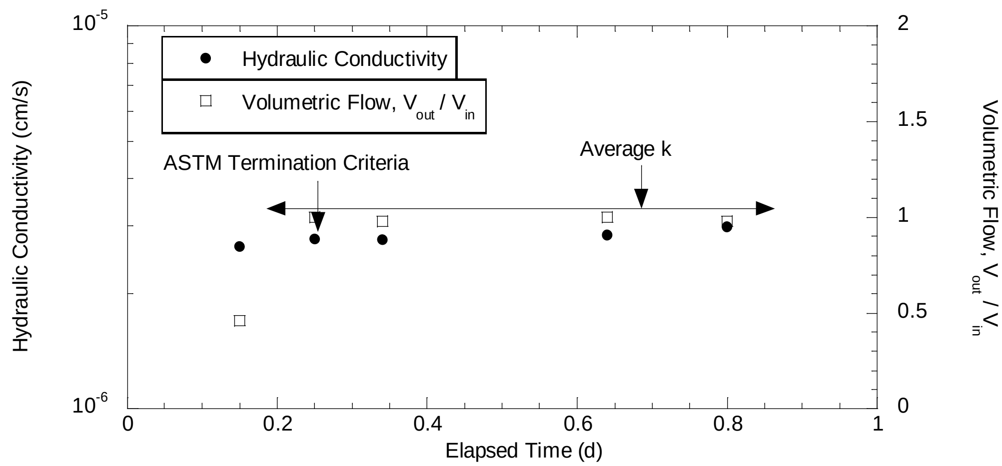


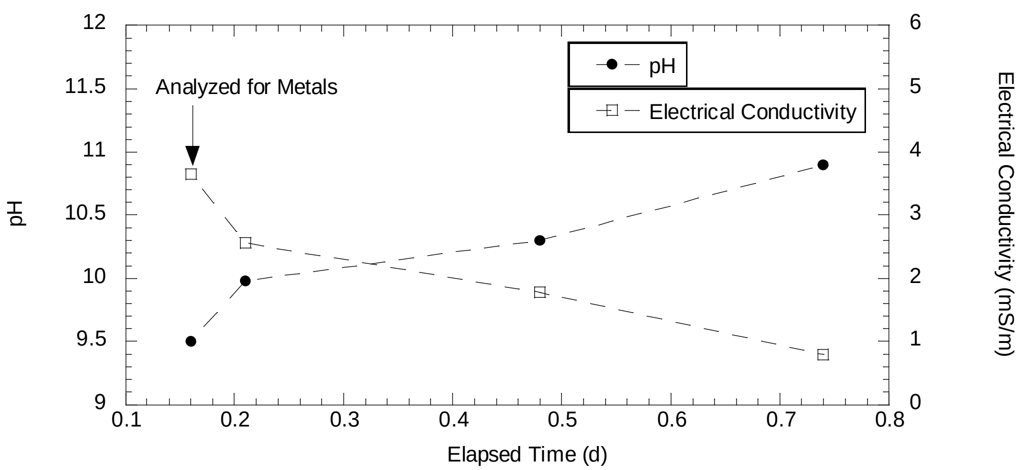




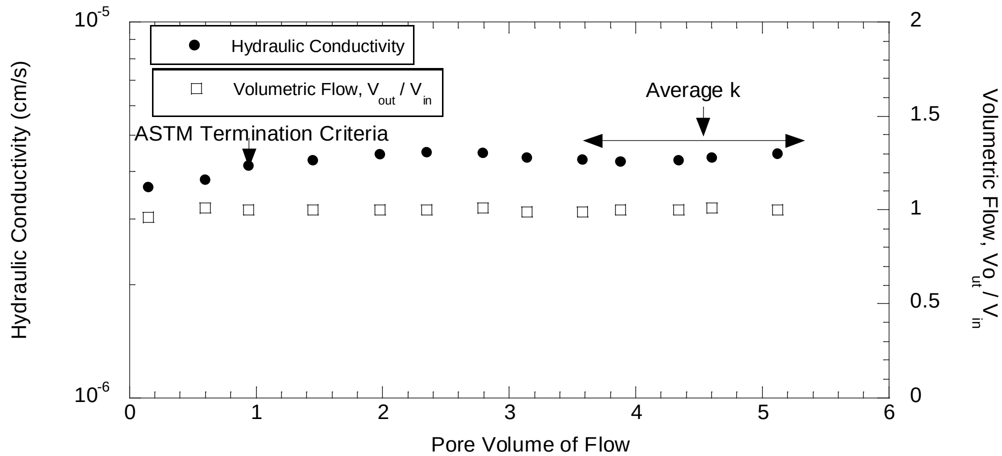
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
13	AST	4	B	28	1.46	0.79	39	0.68	25.1	2.8x10^{-6}

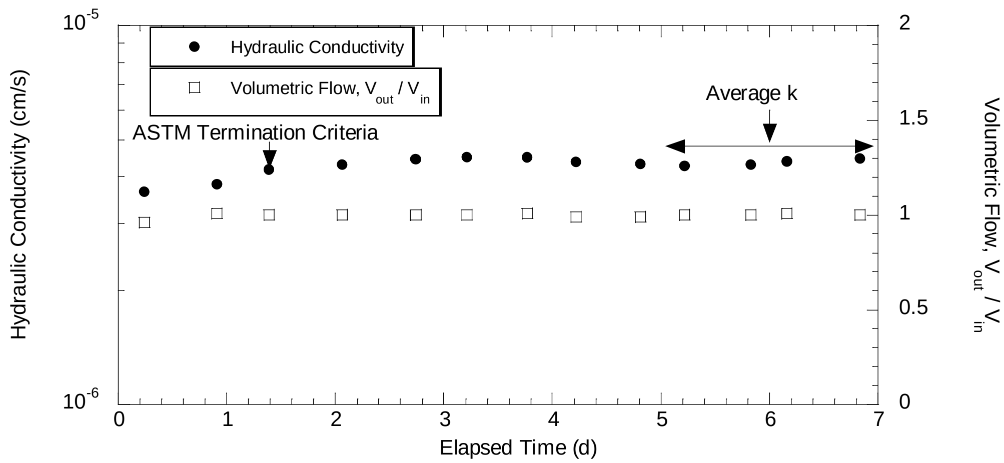


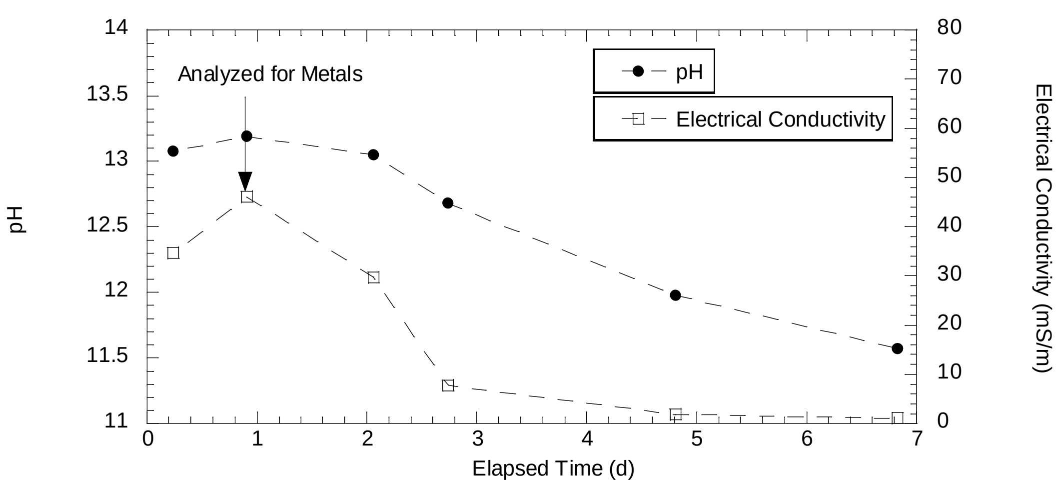




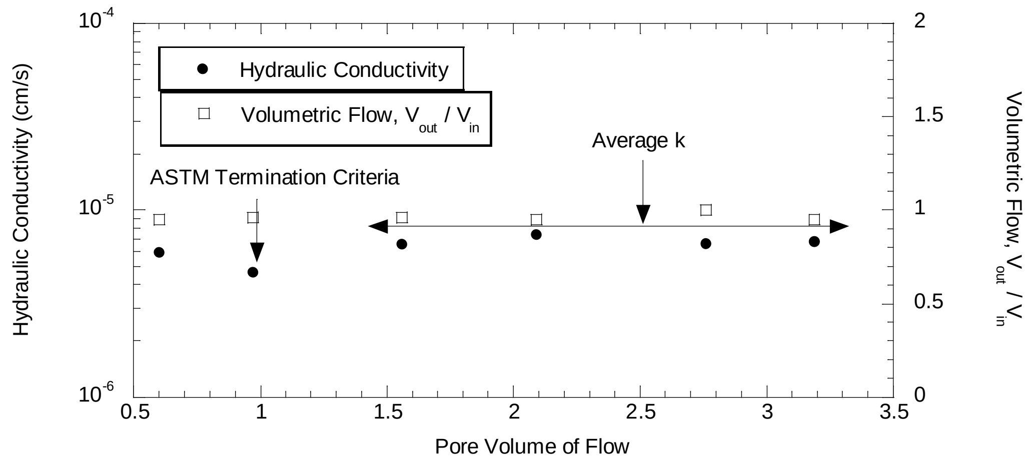
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
14	AST	4	A	7	1.31	1.03	38	0.904	37.08	4.45×10^{-6}

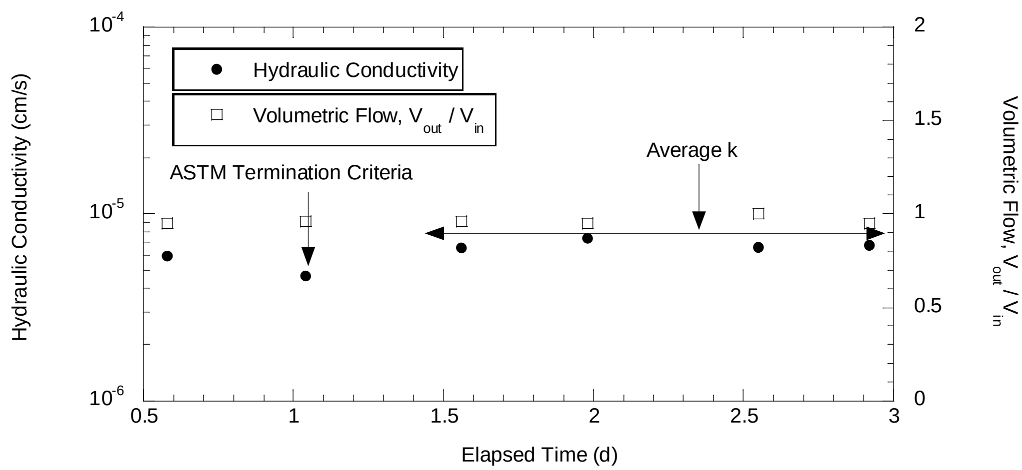


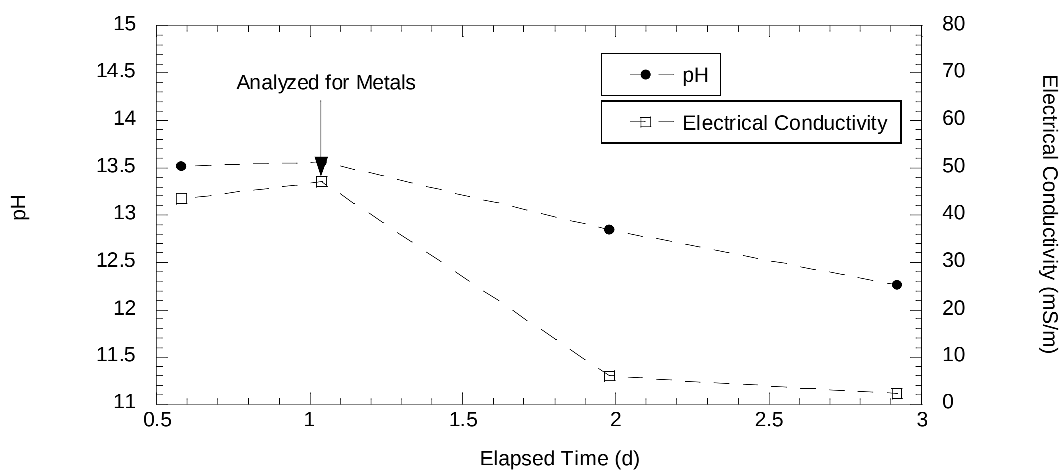




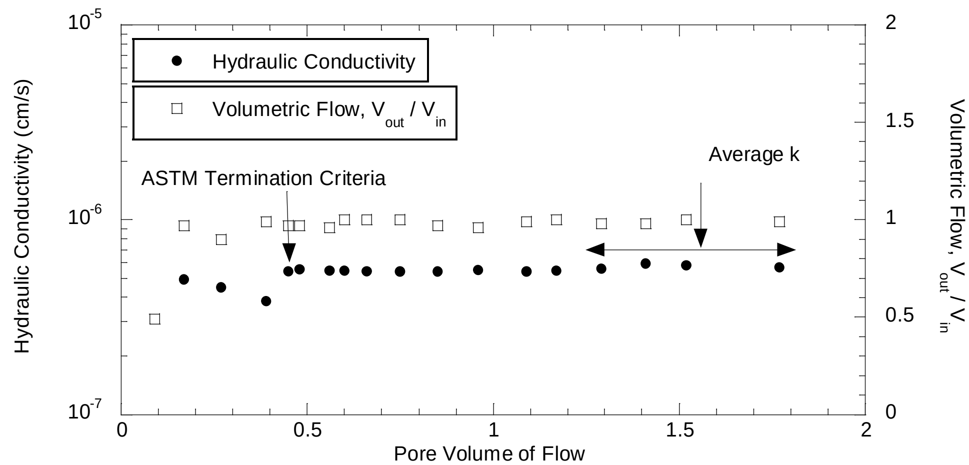
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
15	AST	4	A	28	1.3	1.04	38.7	0.94	37.8	6.8x10^{-6}

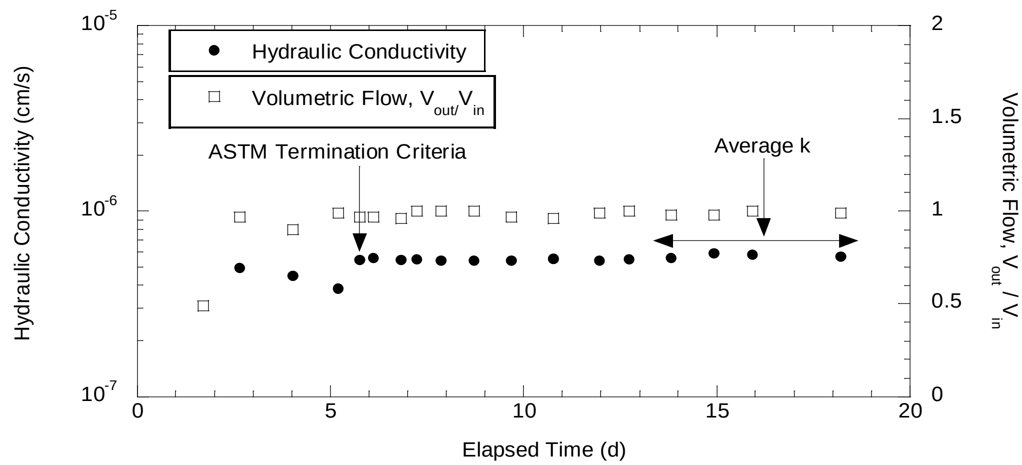


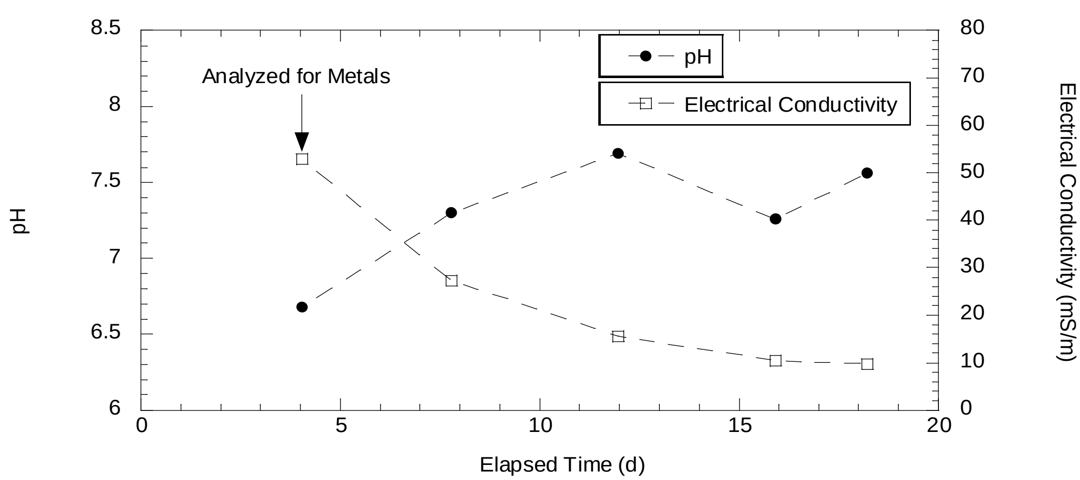




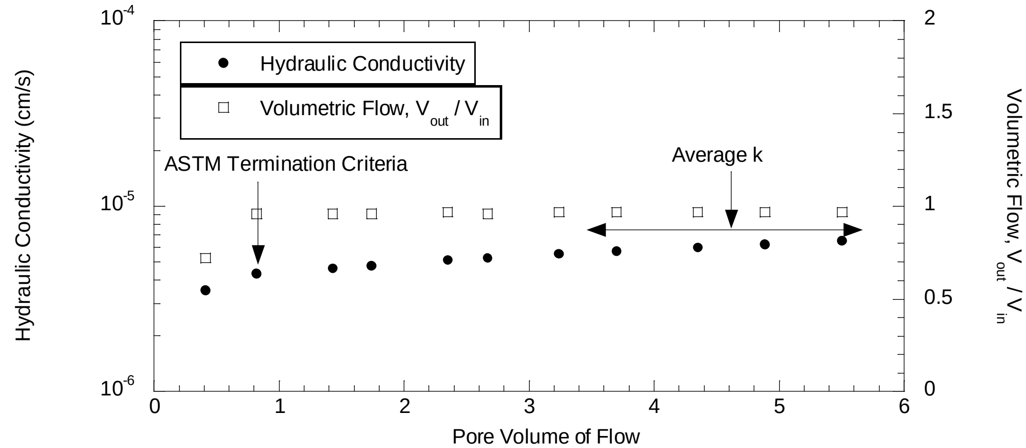
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
1	FST	-	-	-	1.41	0.87	11.4	0.87	33	5.5x10^{-7}

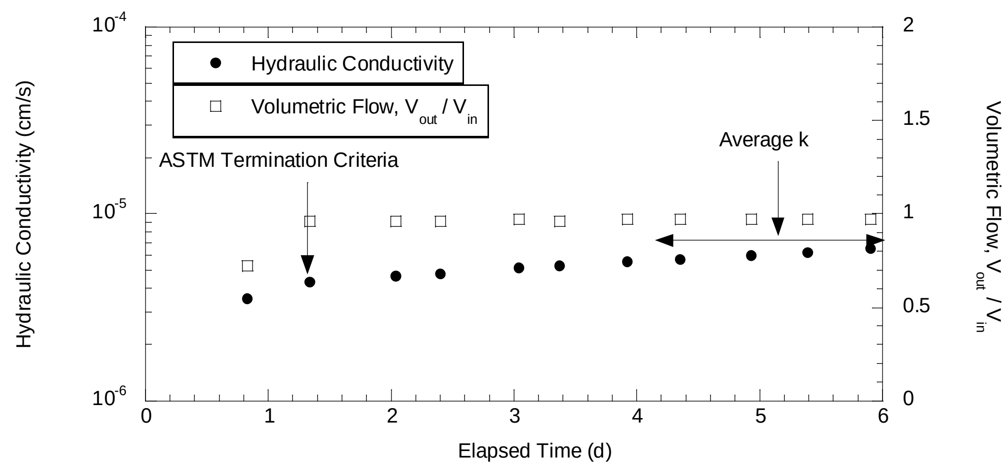


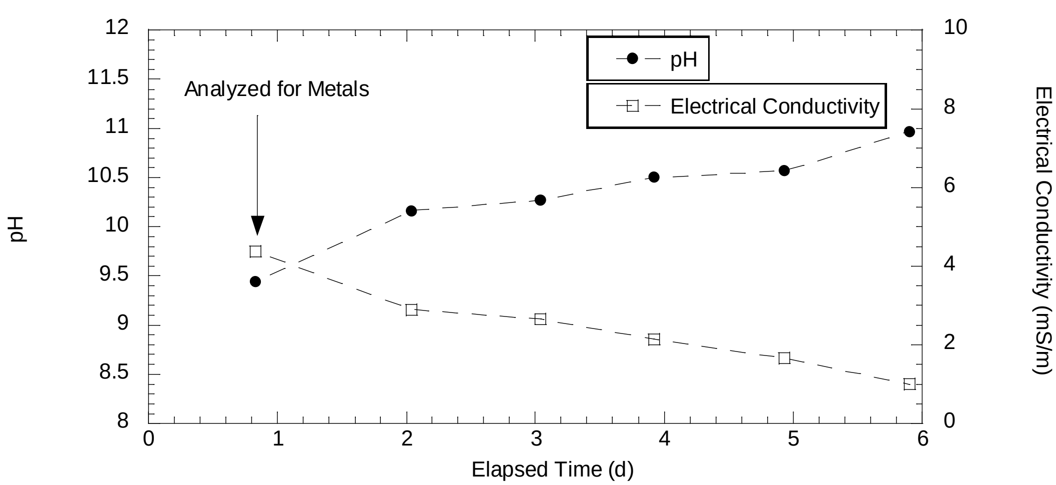




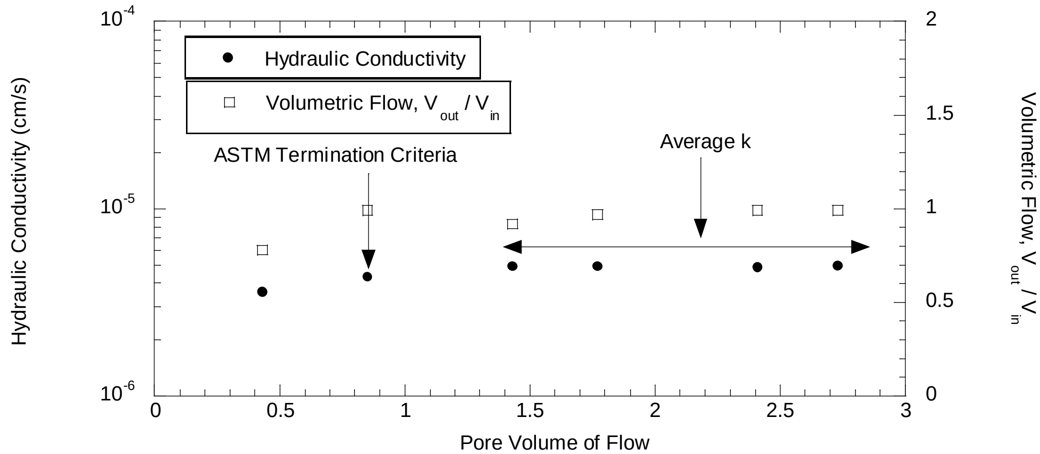
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
2	FST	1	B	7	1.38	0.88	12.6	0.88	34.2	$5.1x10^{-6}$

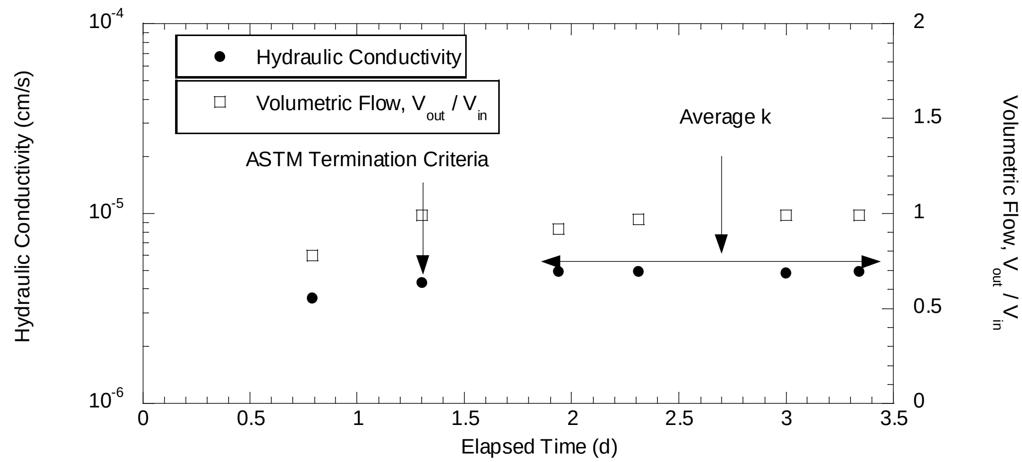


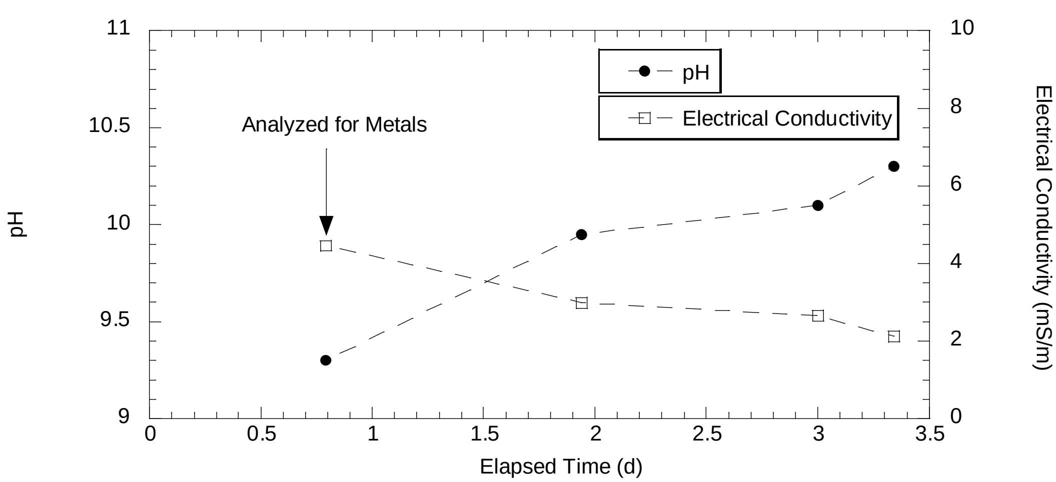




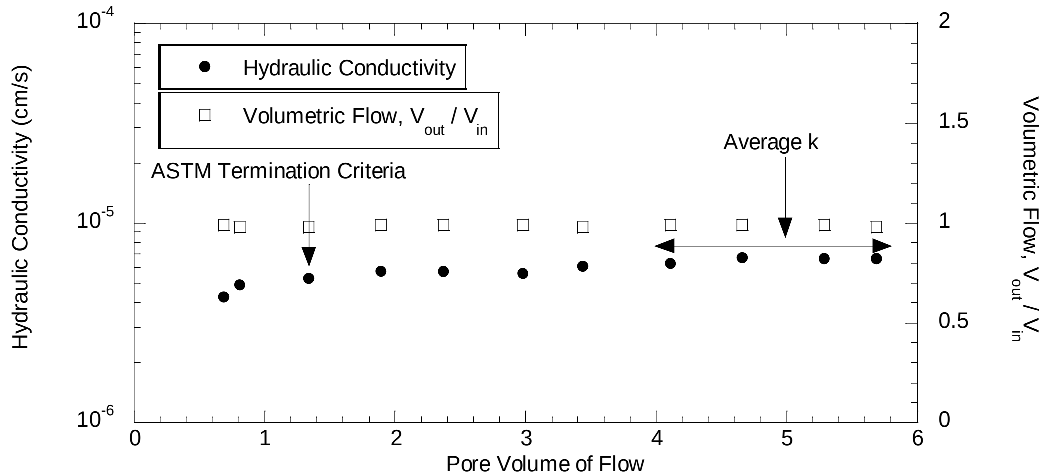
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
3	FST	1	B	28	1.39	0.86	11.6	0.86	32.9	4.9x10^{-6}

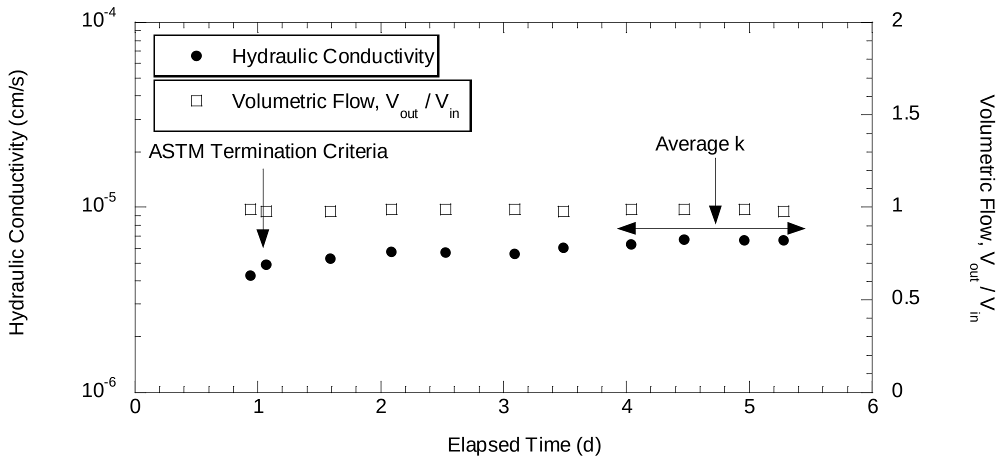


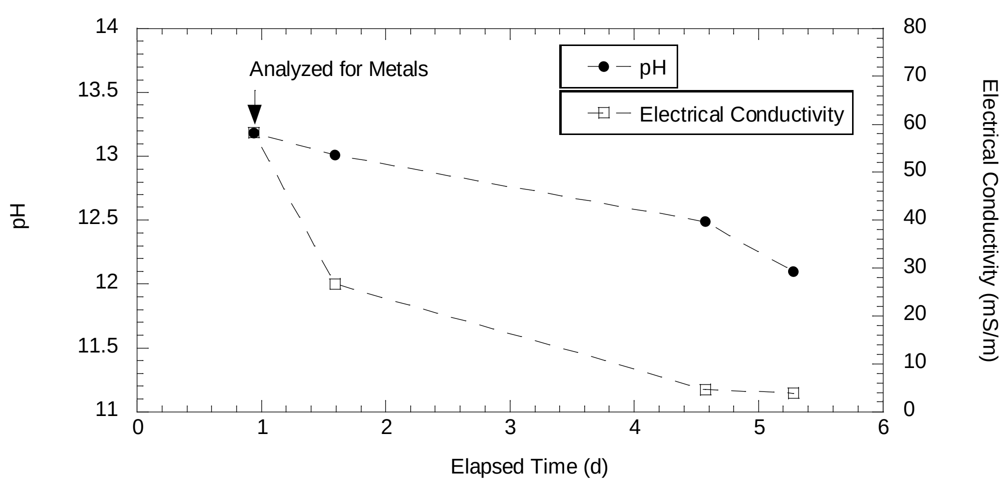




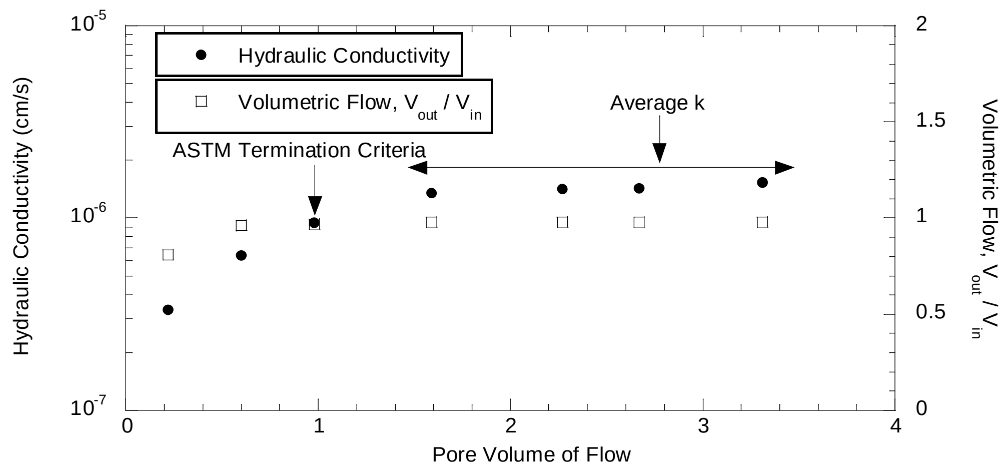
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
4	FST	1	A	7	1.42	0.85	9.7	0.85	34.8	5.8x10^{-6}

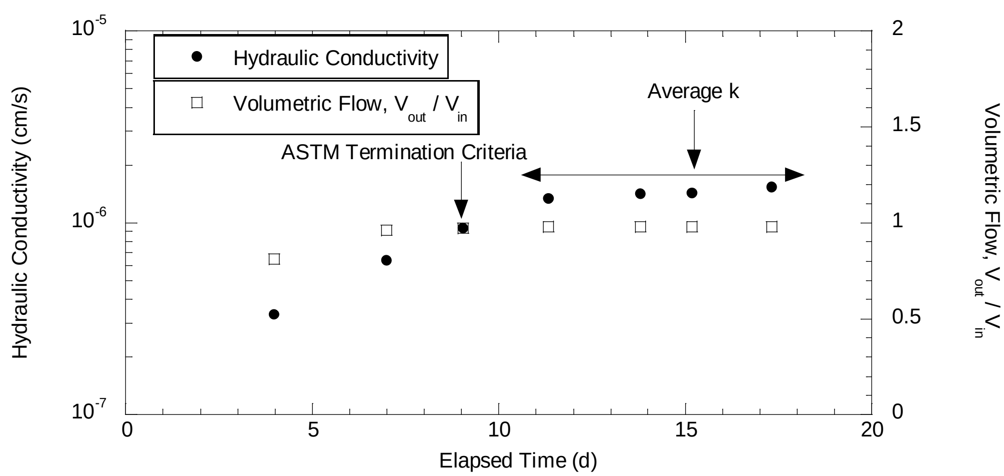


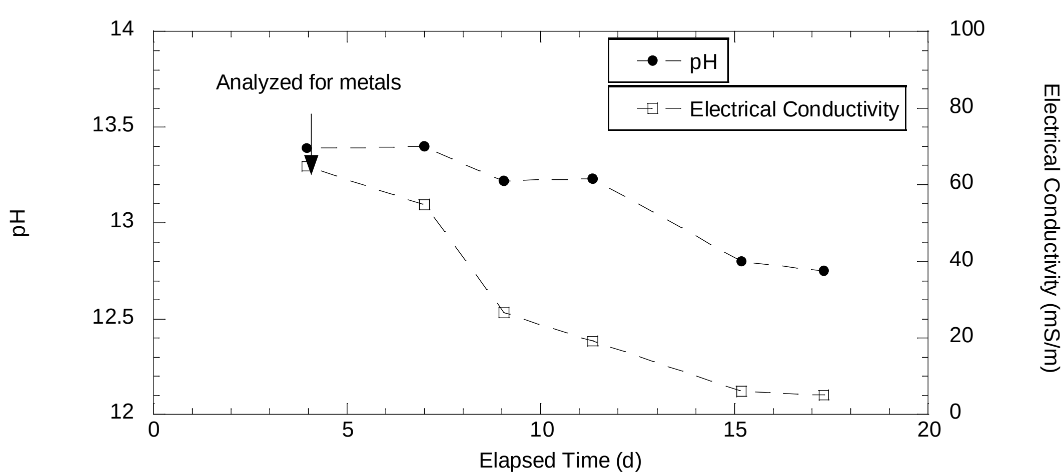




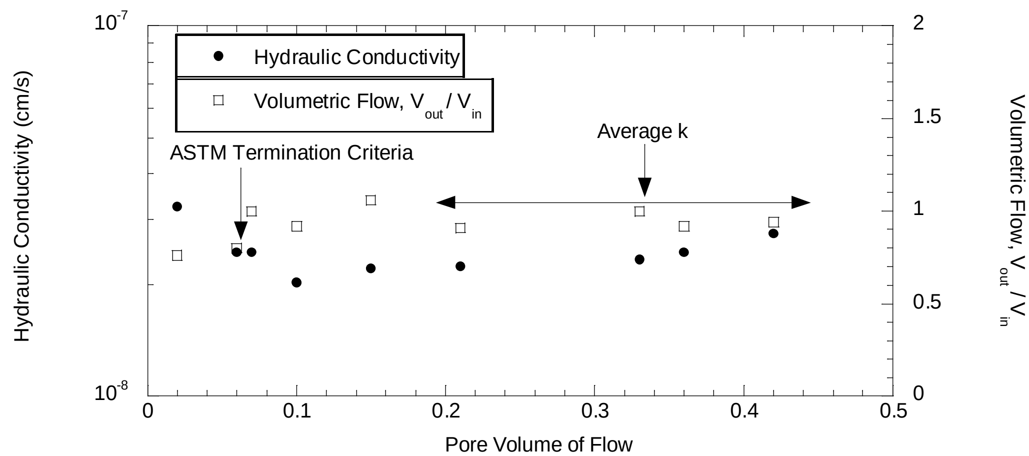
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
5	FST	1	A	28	1.47	0.78	10.3	0.83	35.4	1.4×10^{-6}

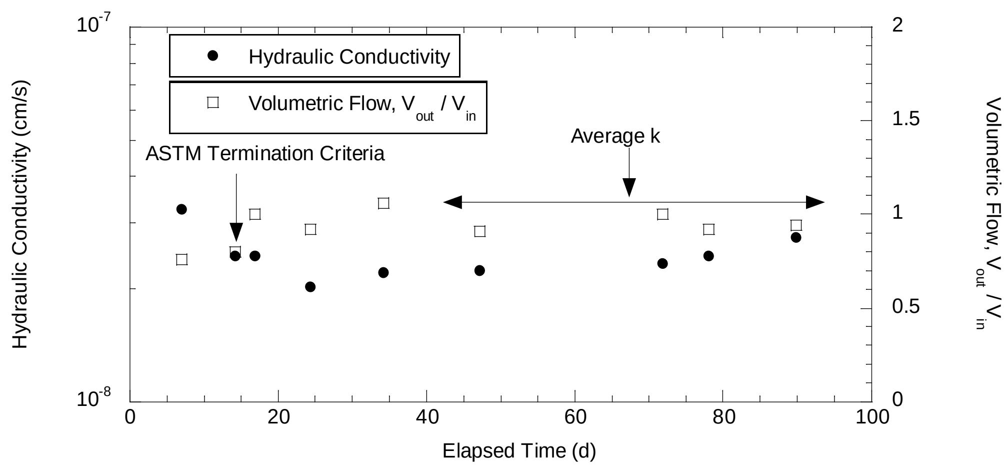


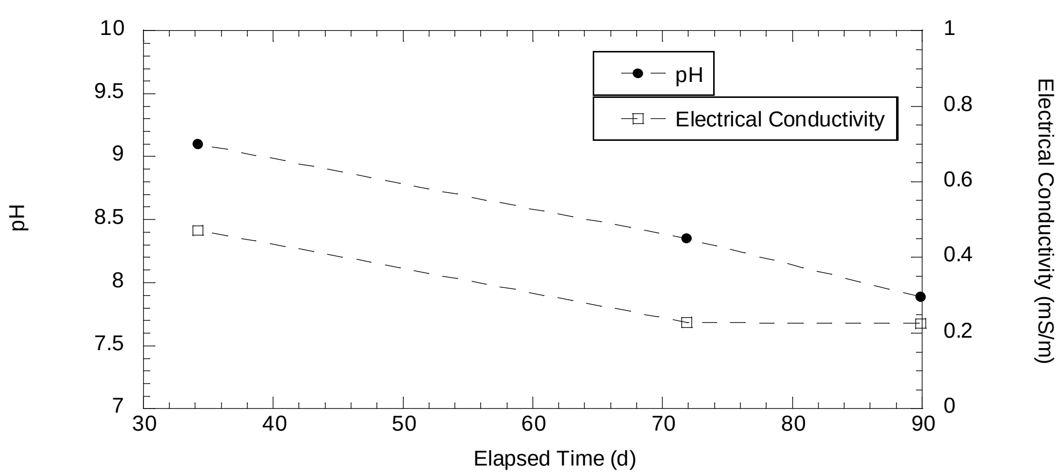




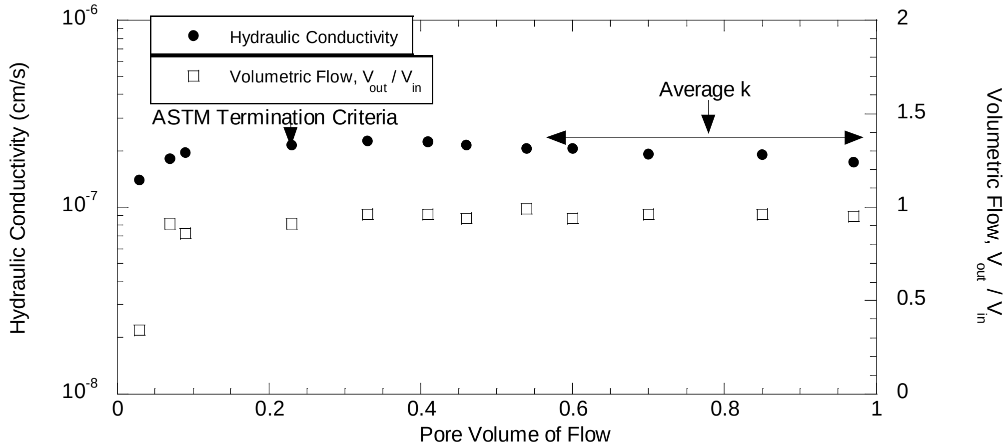
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
6	FST	-	-	-	1.52	0.72	24	0.72	25.8	2.3x10^{-8}

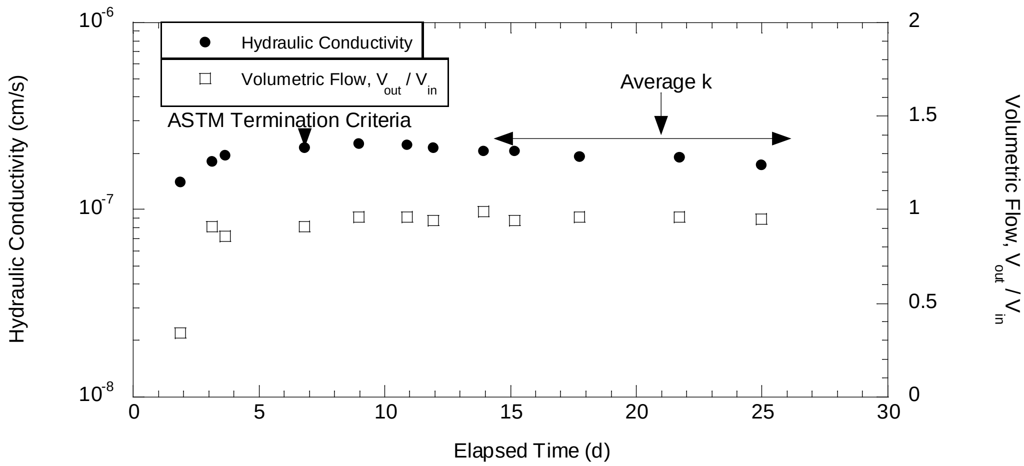


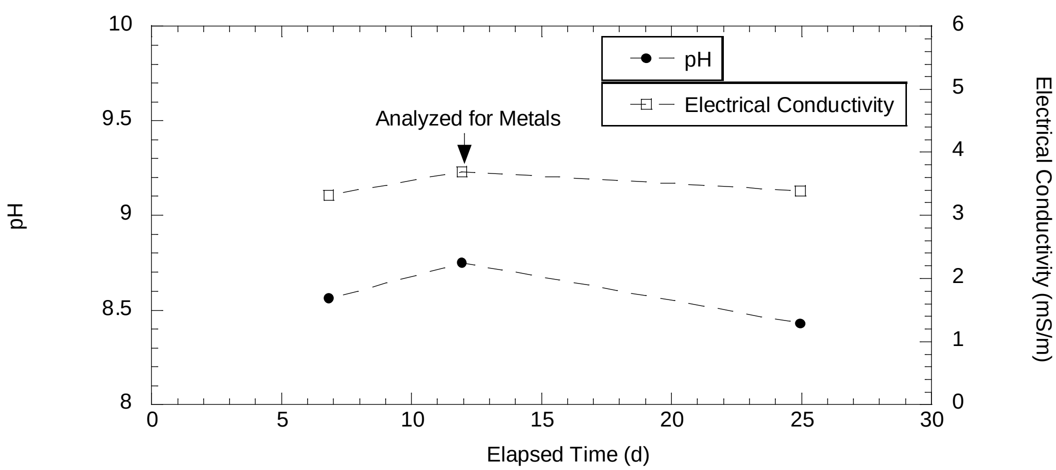




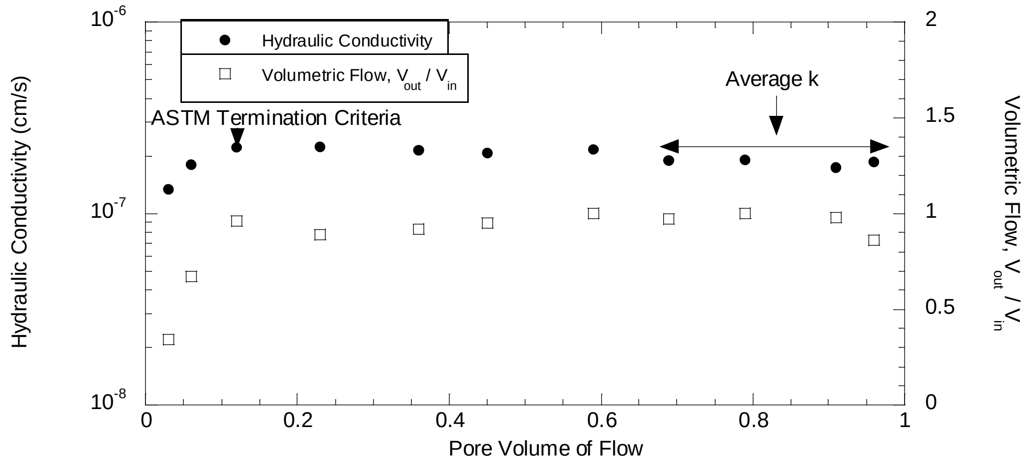
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
7	FST	2.5	B	7	1.49	0.74	25.1	0.74	26.8	1.9x10^{-7}

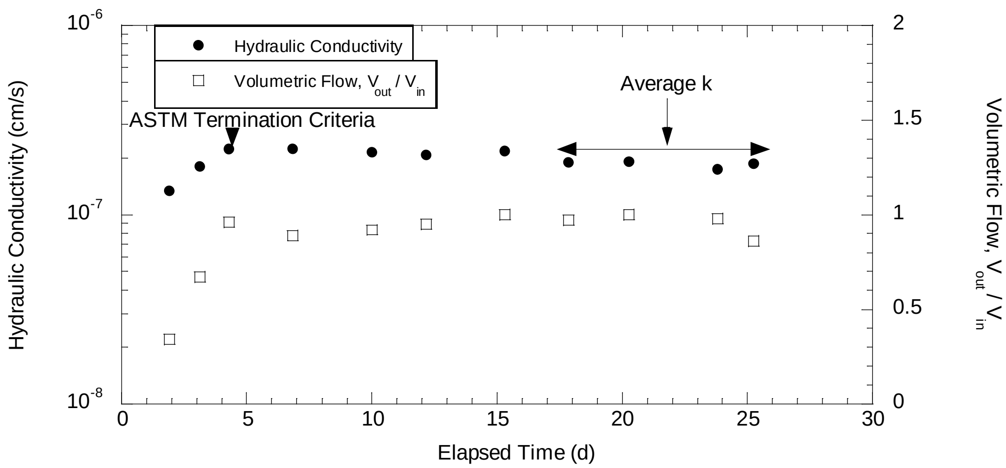


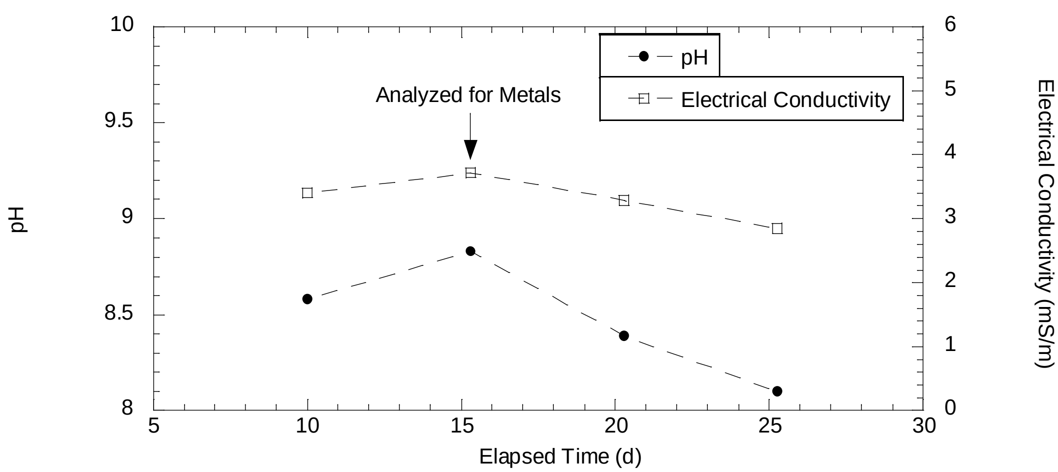




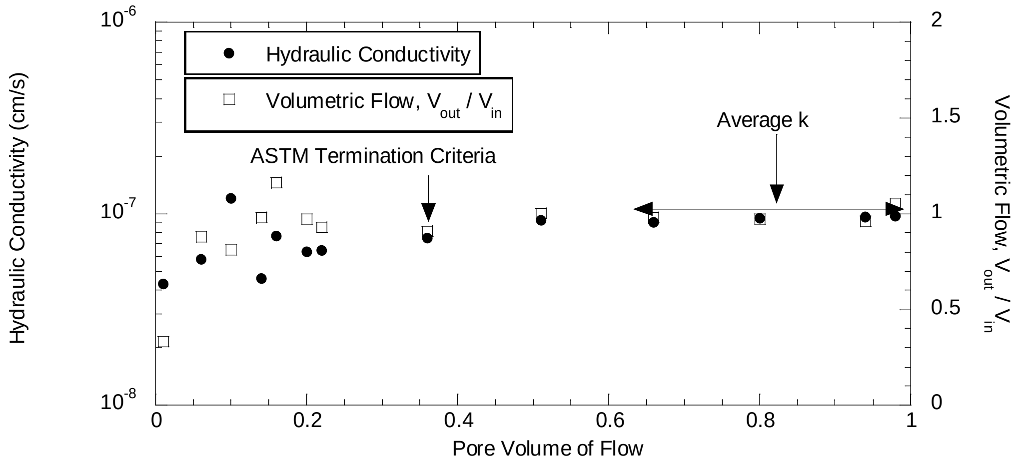
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
8	FST	2.5	B	28	1.48	0.75	25	0.75	26.5	1.8×10^{-7}

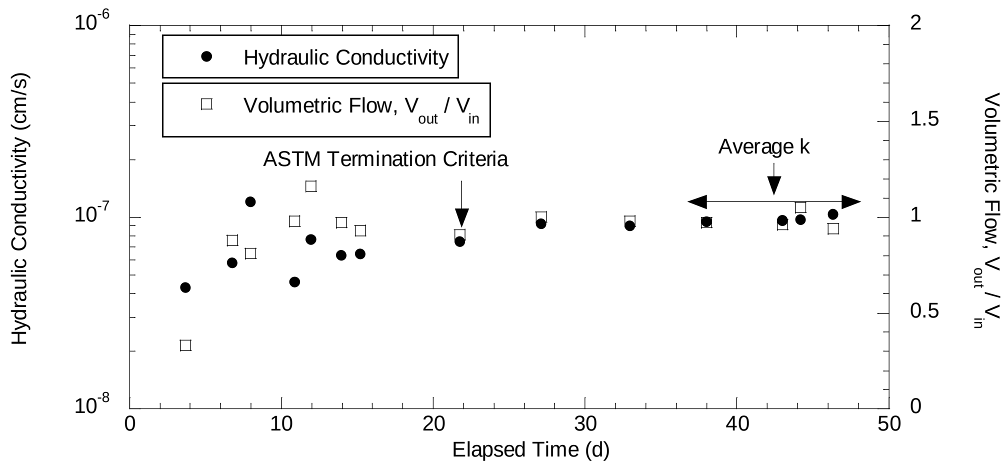


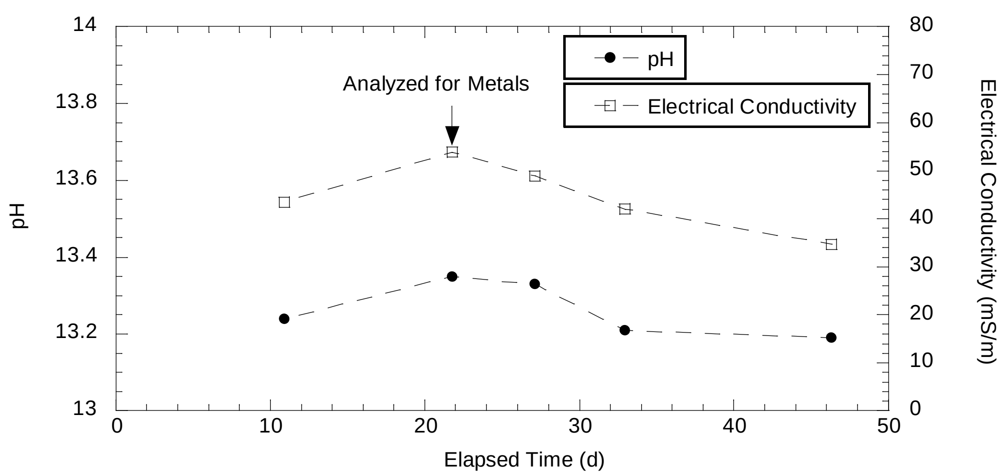




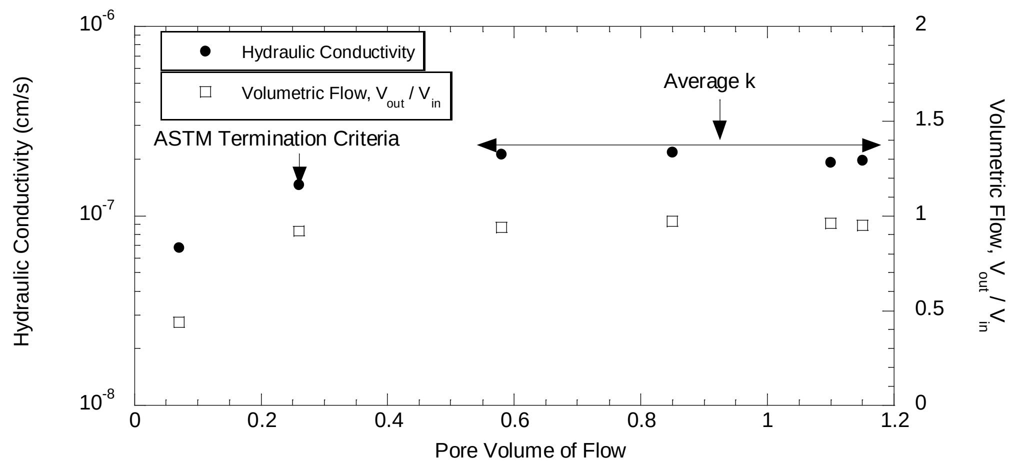
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
9	FST	2.5	A	7	1.52	0.72	24.5	0.72	28.3	9.8×10^{-8}

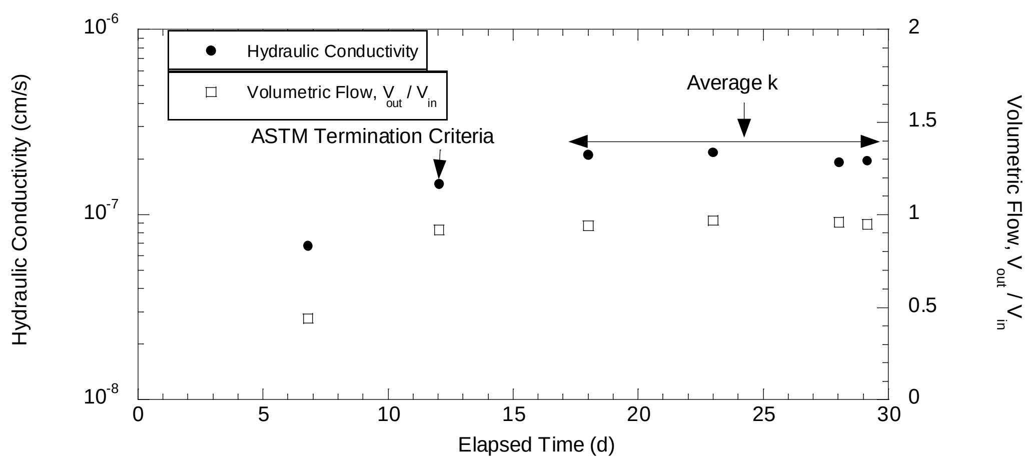


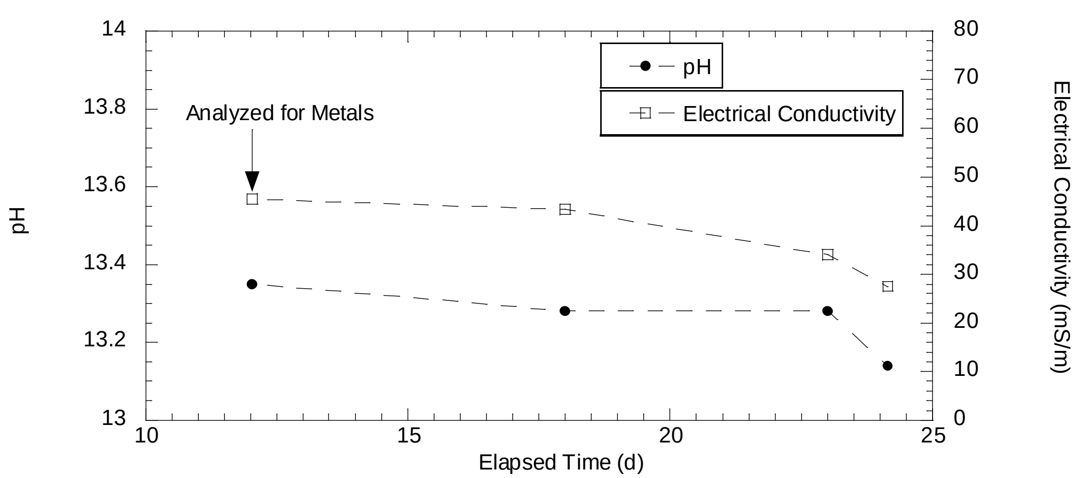




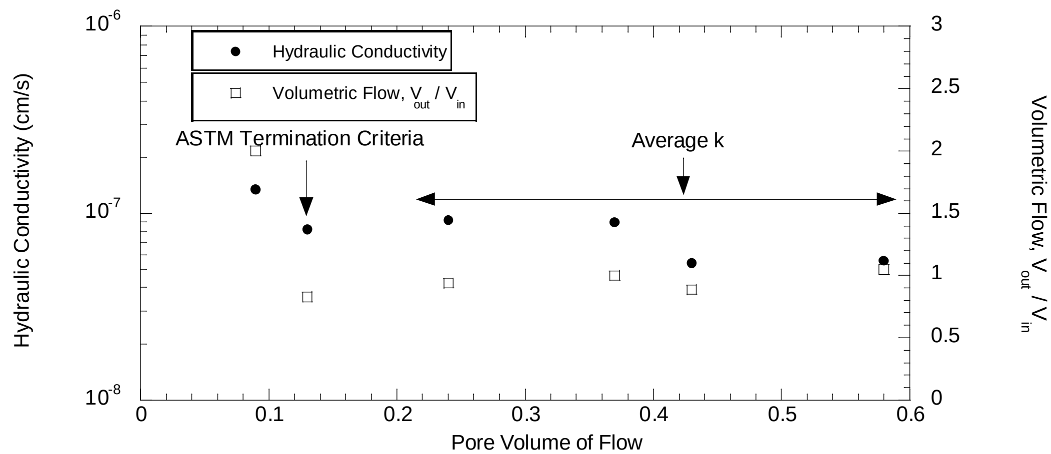
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
10	FST	2.5	A	28	1.52	0.73	24.5	0.73	29.4	2.0x10^{-7}

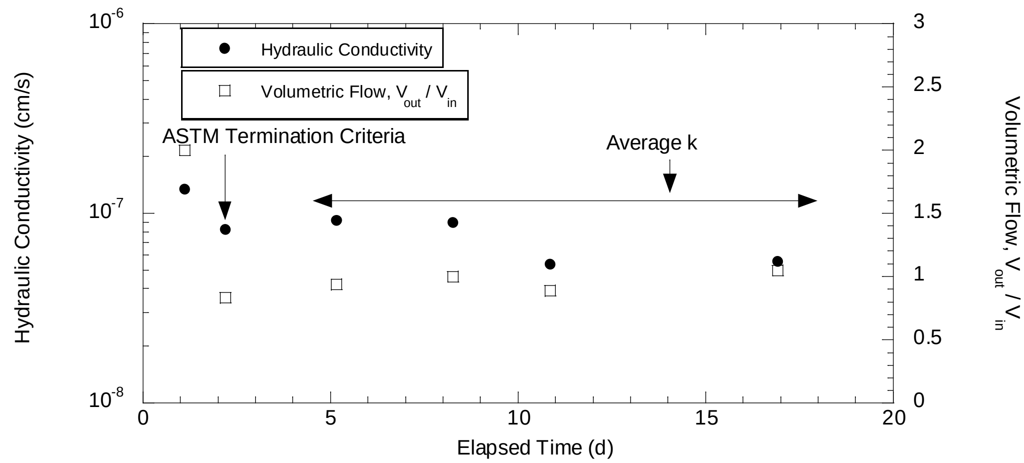


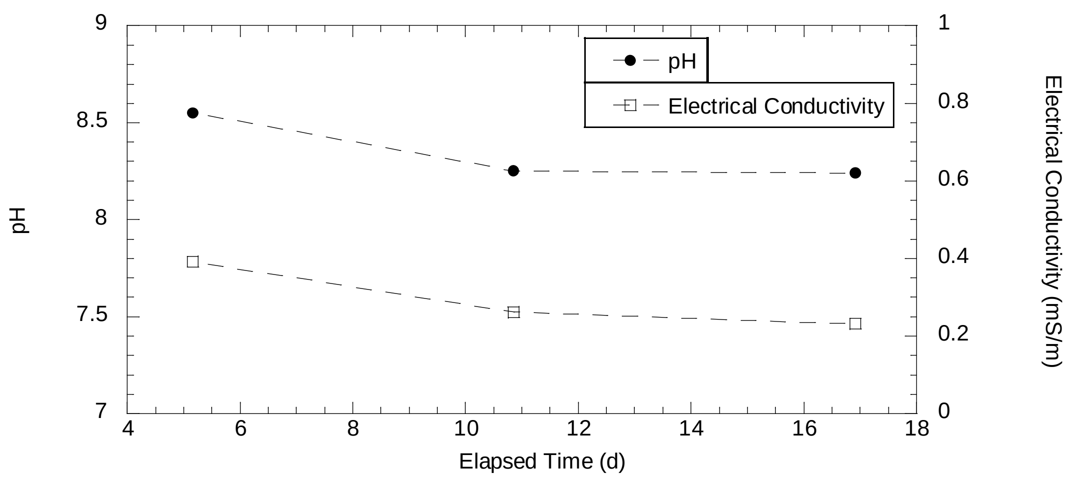




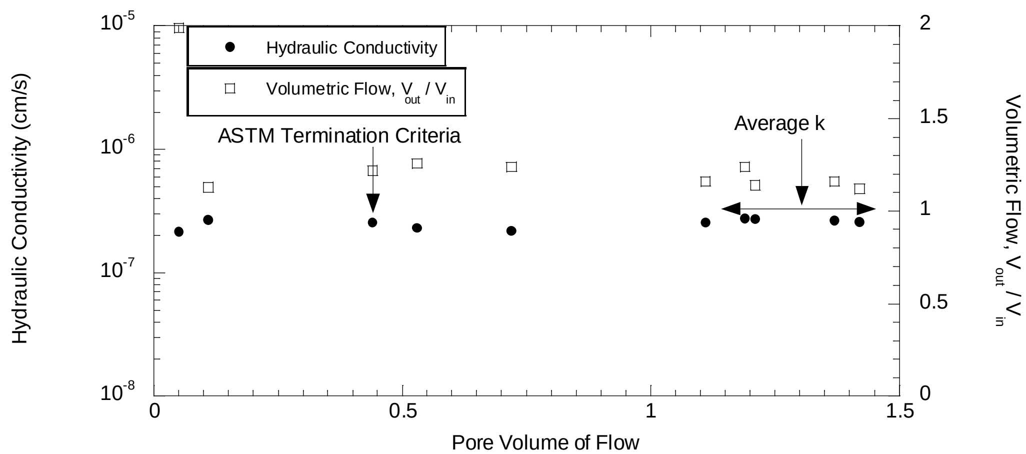
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
11	FST	-	-	-	1.23	1.13	41	1.00	38.7	7.3x10^{-8}

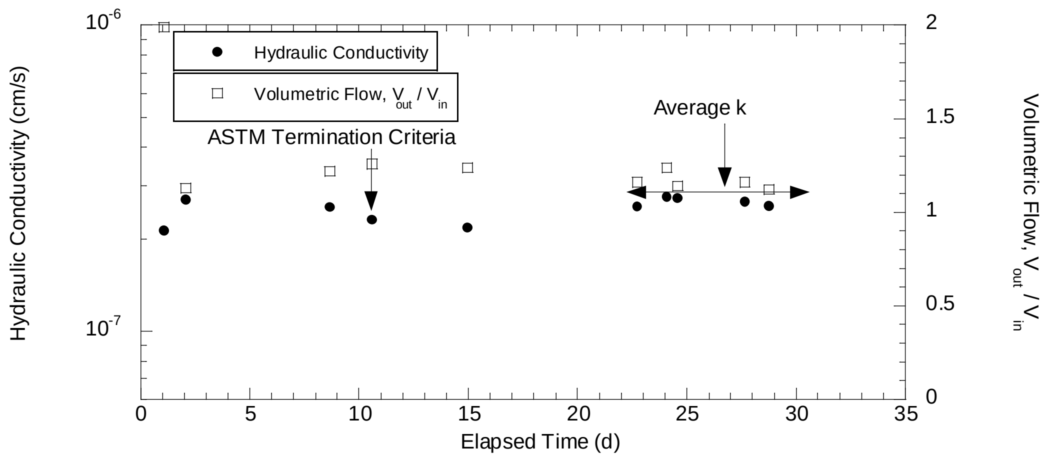


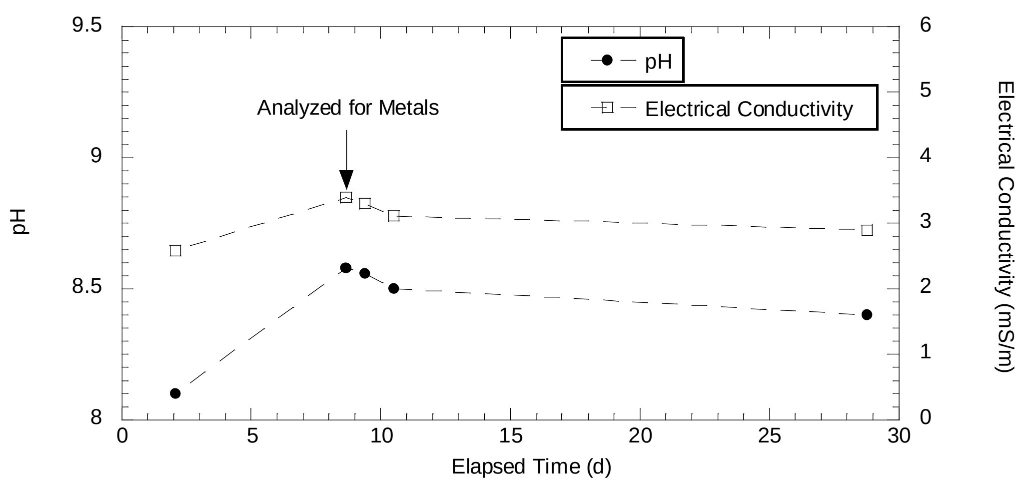




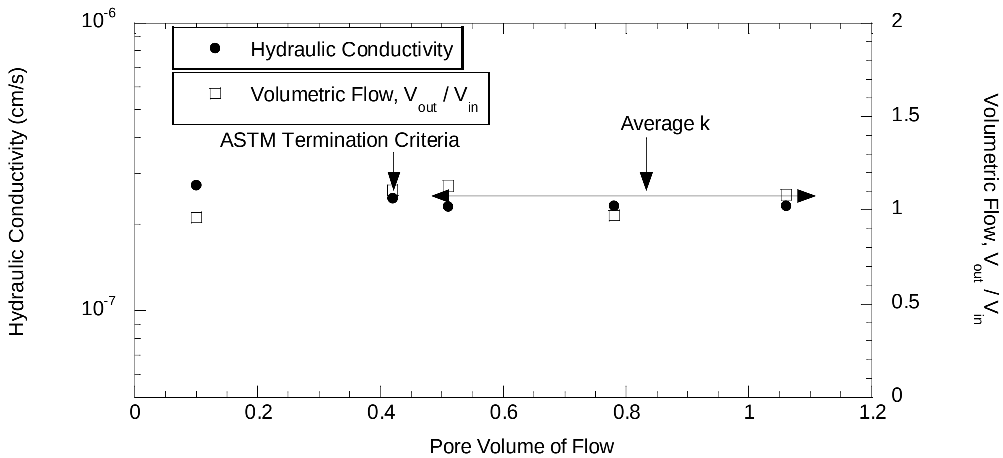
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
12	FST	4	B	7	1.25	1.13	39.4	0.97	36.8	2.6x10^{-7}

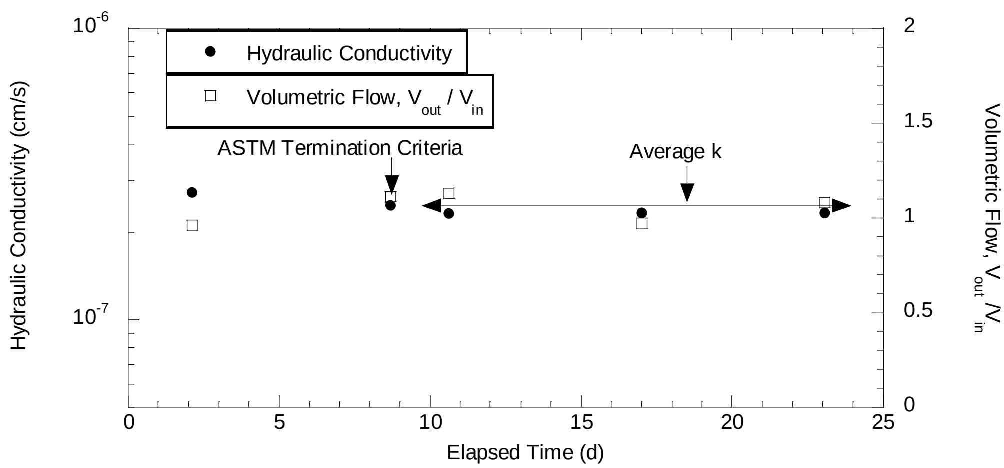


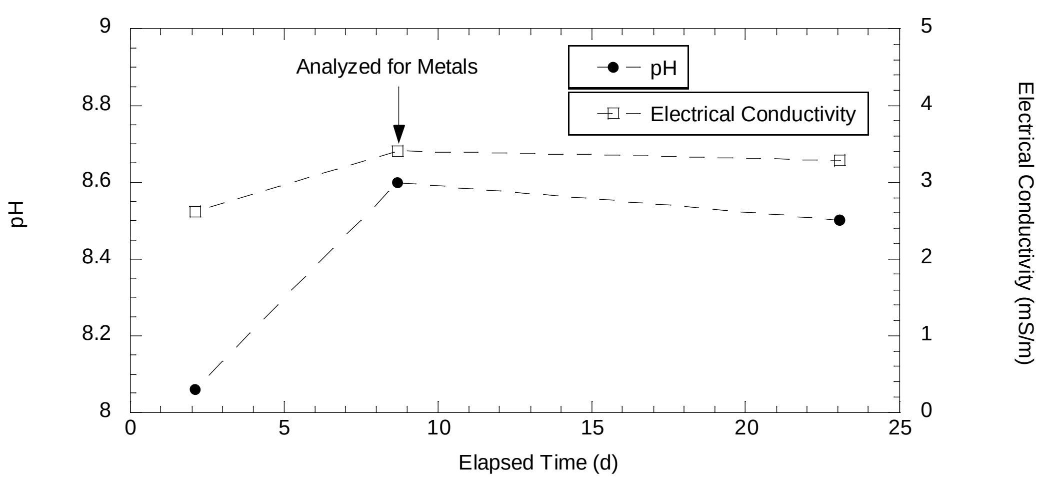




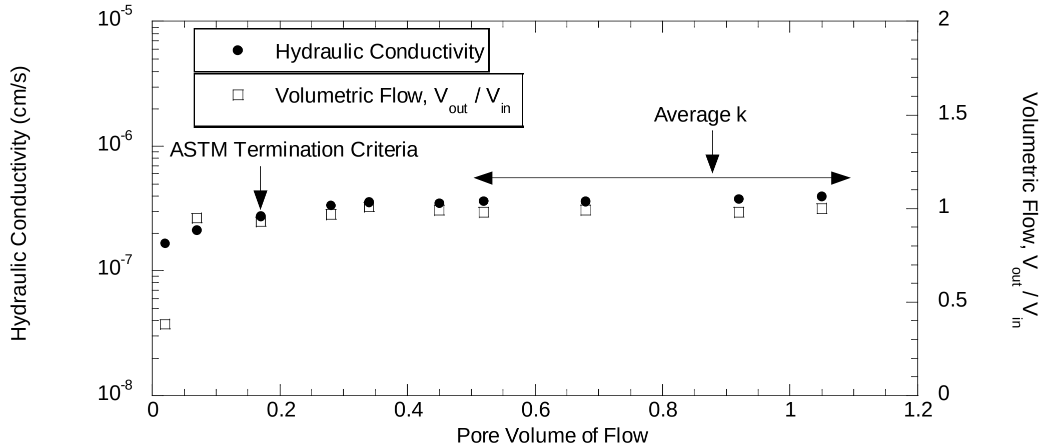
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
13	FST	4	B	28	1.27	1.09	39	1.02	36.4	2.4x10^{-7}

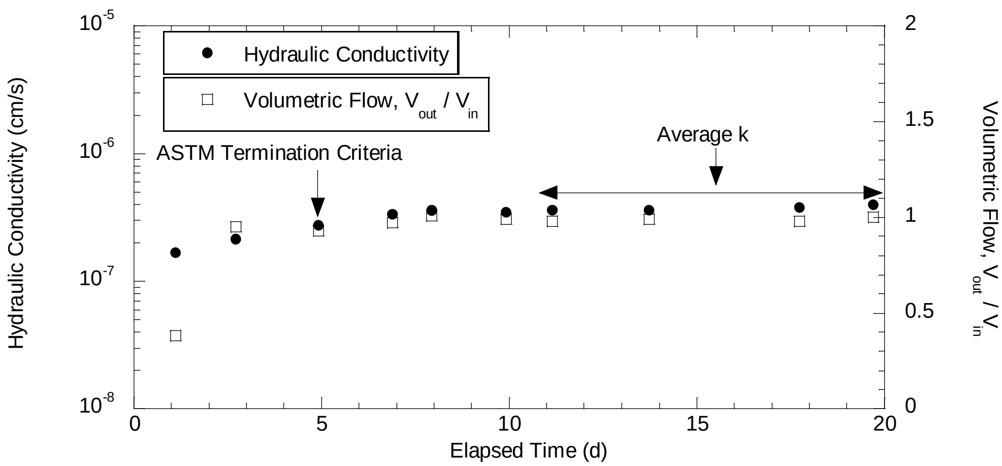


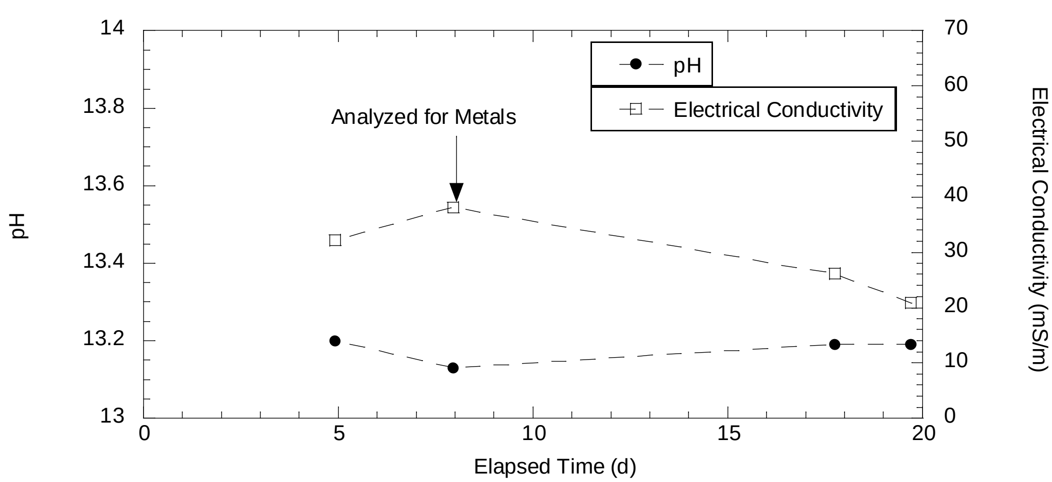




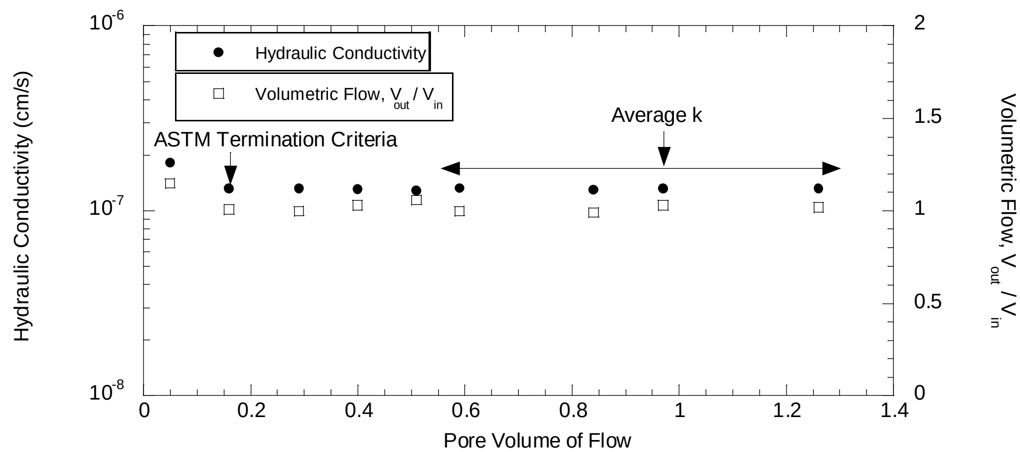
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
14	FST	4	A	7	1.21	1.17	41	1.09	42.3	3.7x10^{-7}

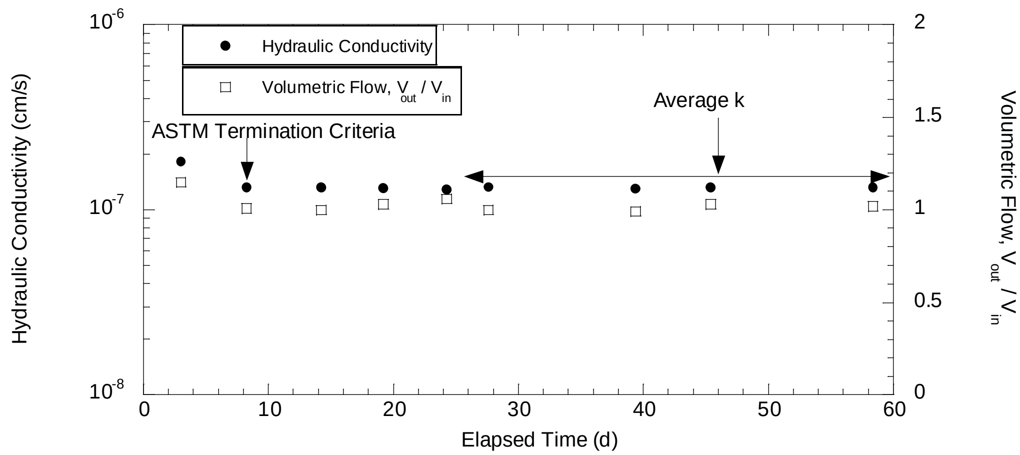


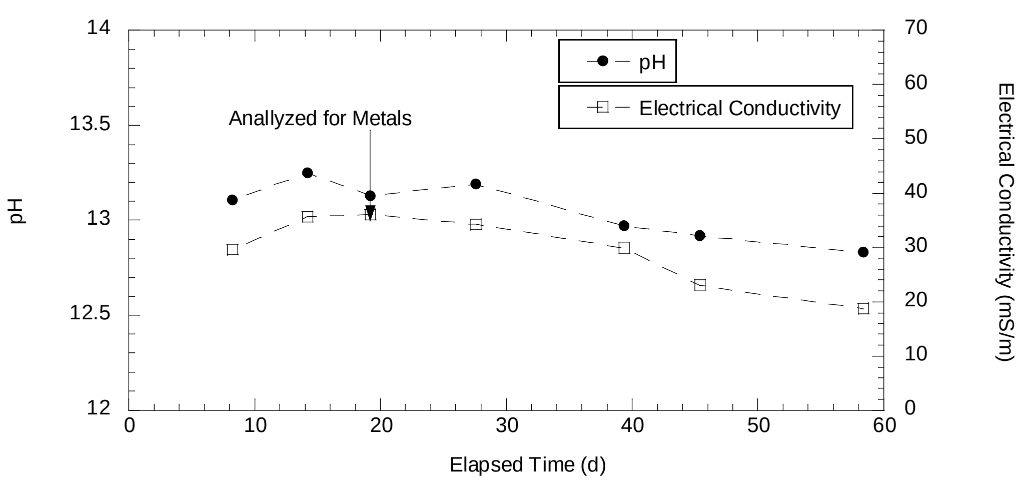




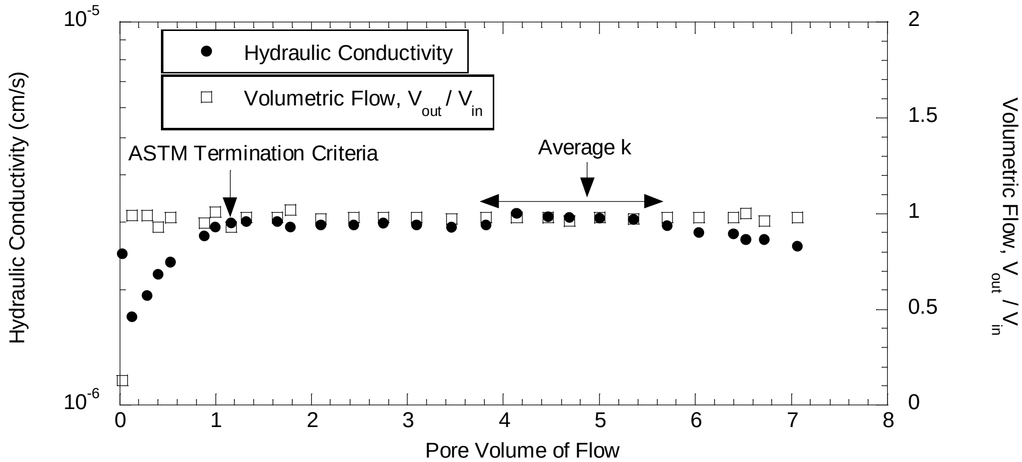
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
15	FST	4	A	28	1.21	1.17	41	1.1	43.0	1.3x10^{-7}

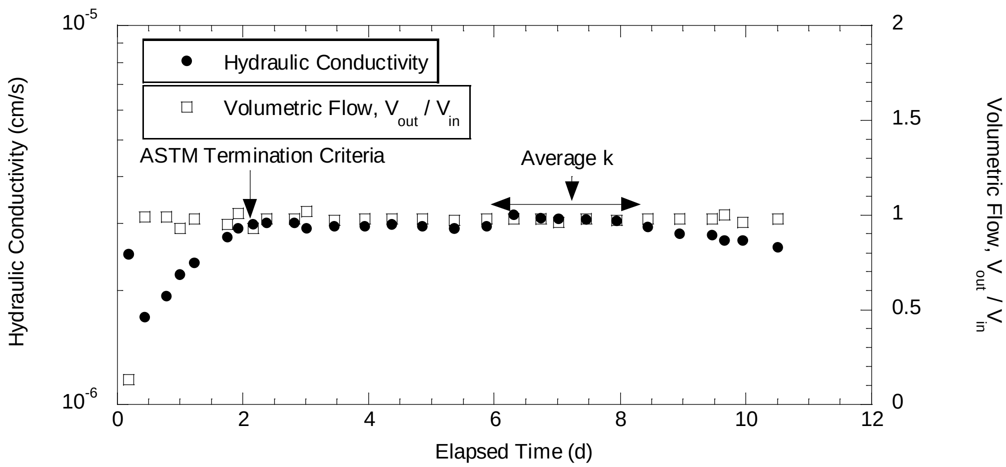


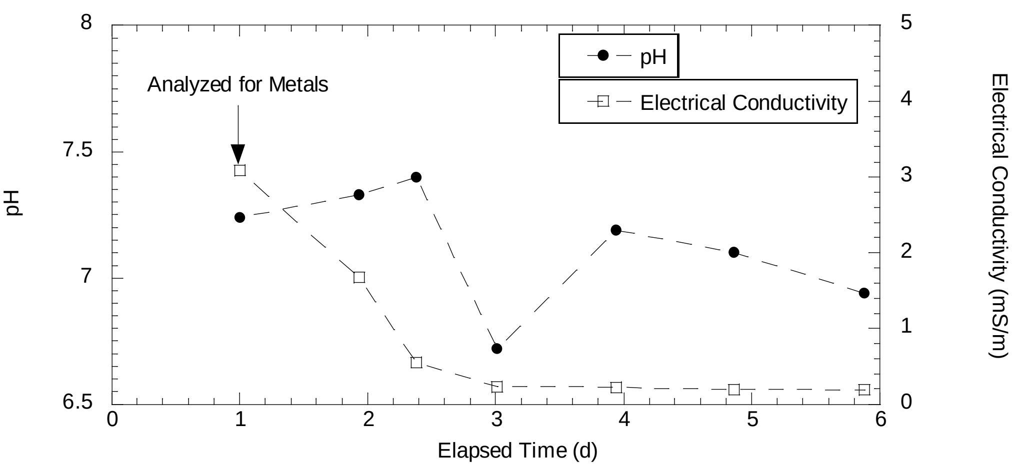




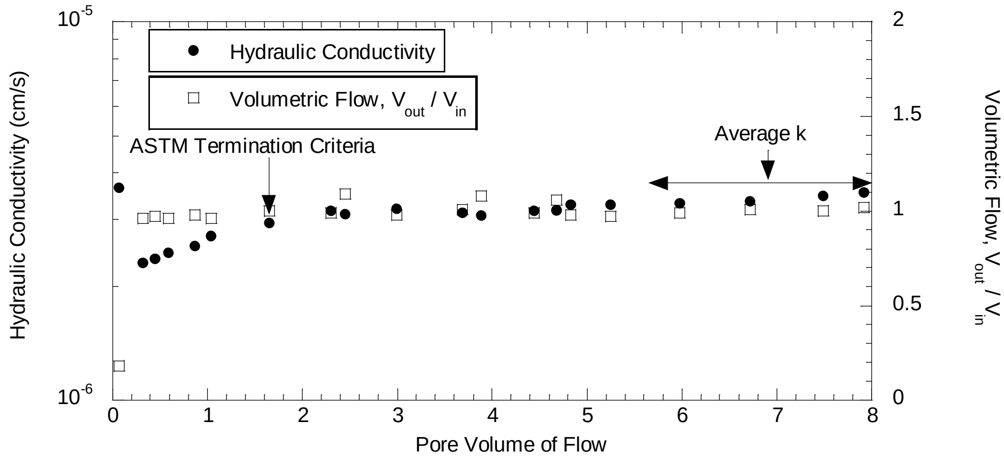
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
1	NT	-	-	-	1.95	0.574	12.2	0.574	16.81	$3.0\text{x}10^{-6}$

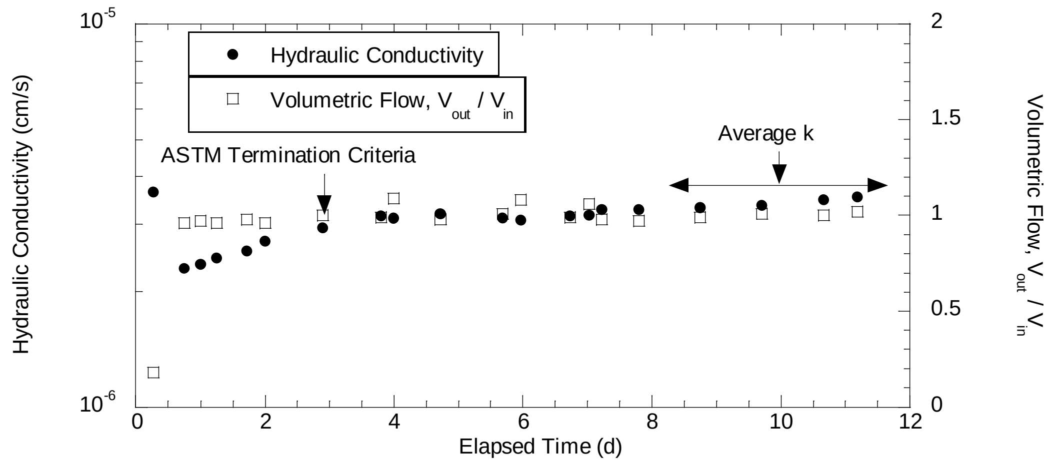


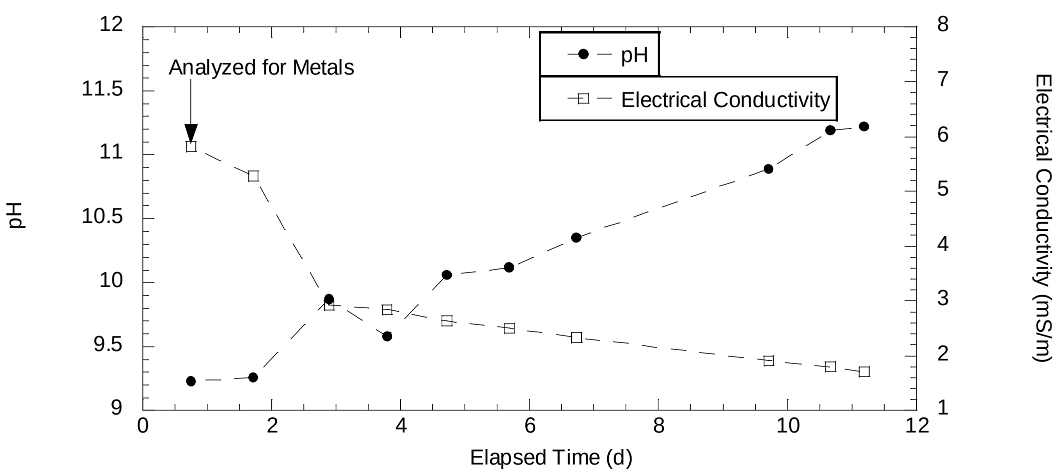




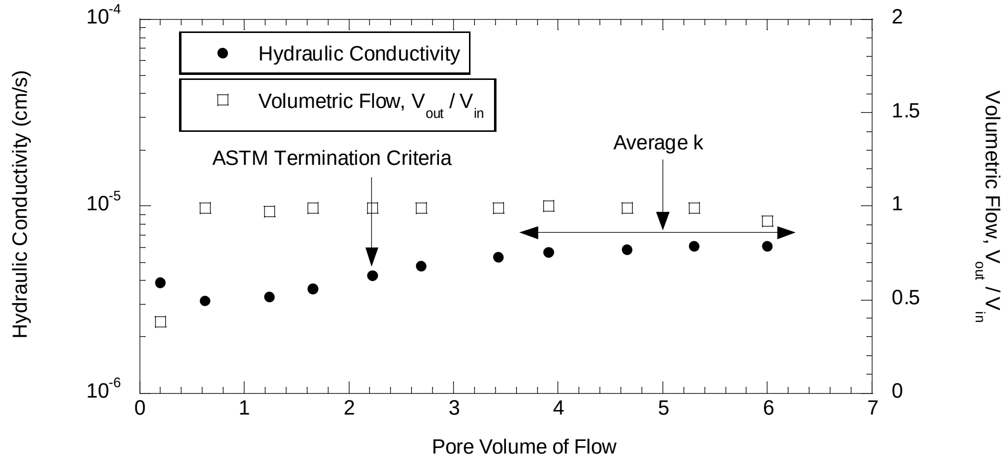
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
2	NT	1	B	7	1.83	0.62	11.9	0.62	18.6	3.1×10^{-6}

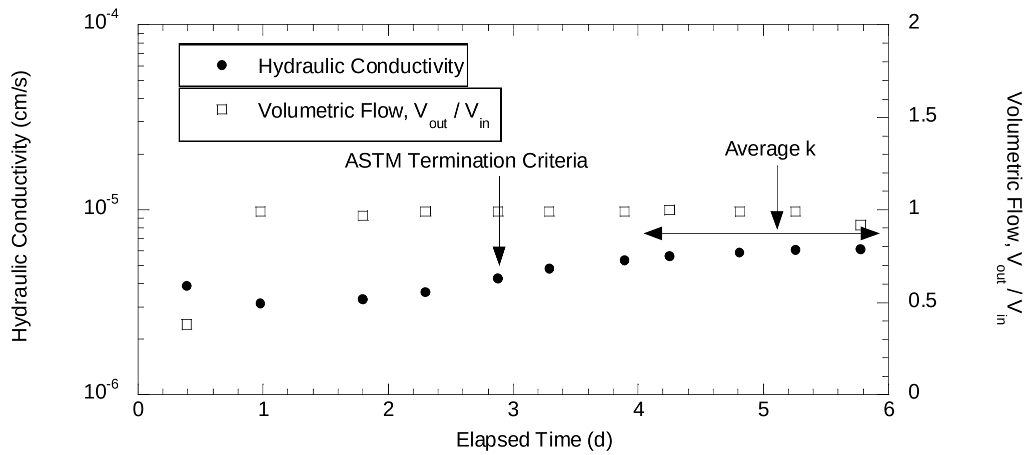


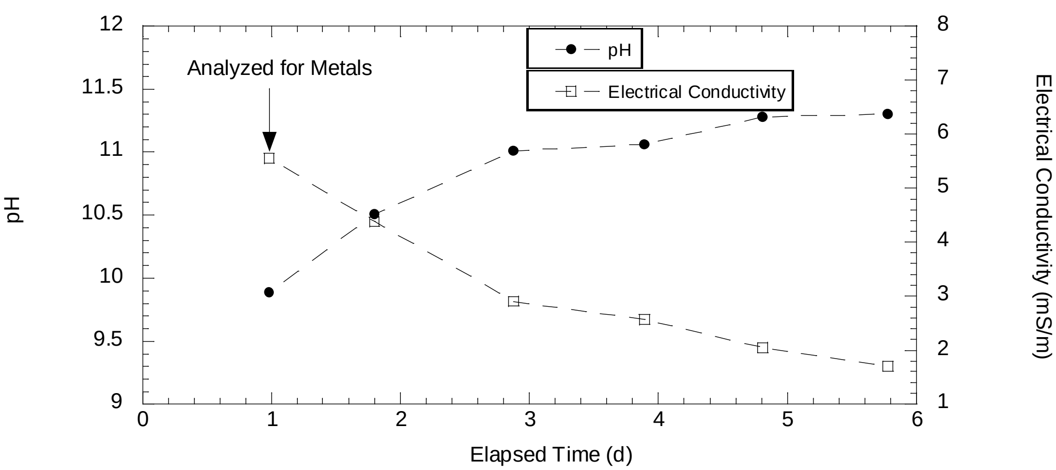




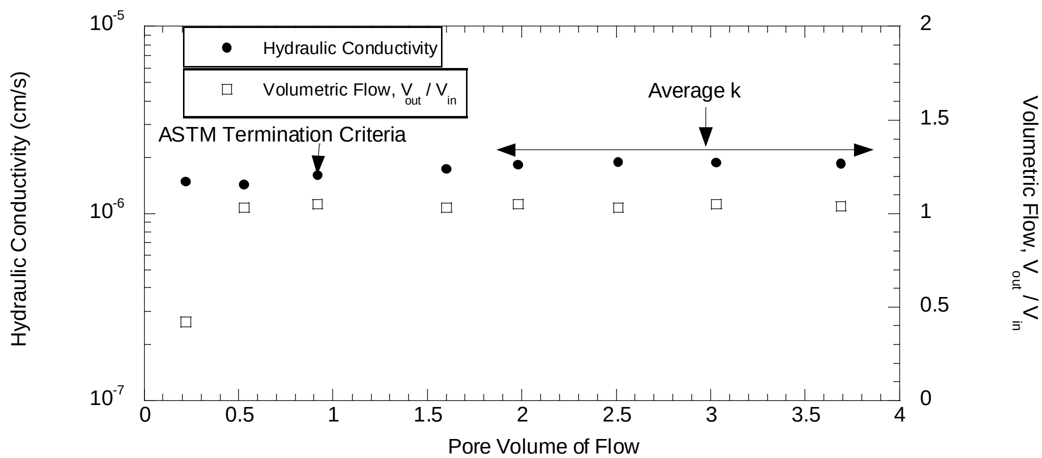
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
3	NT	1	B	28	1.84	0.61	11.9	0.61	18.6	4.5x10^{-6}

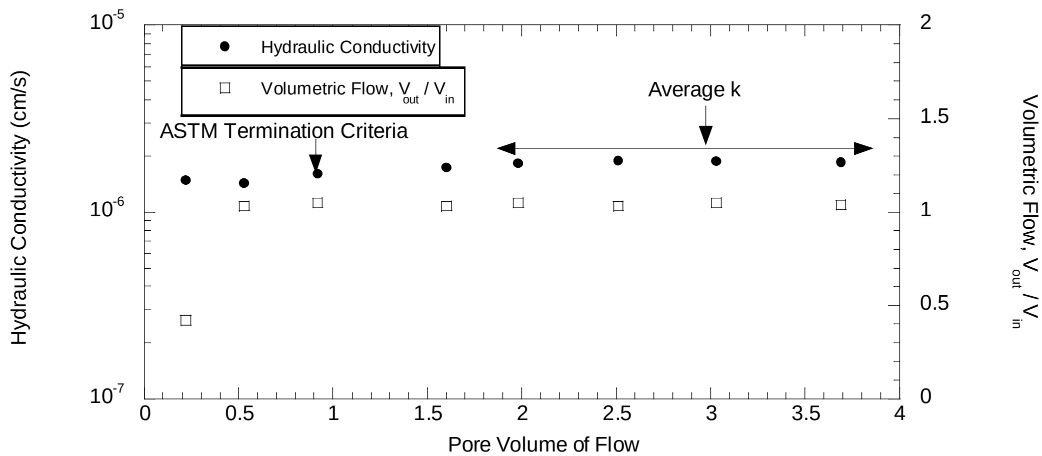


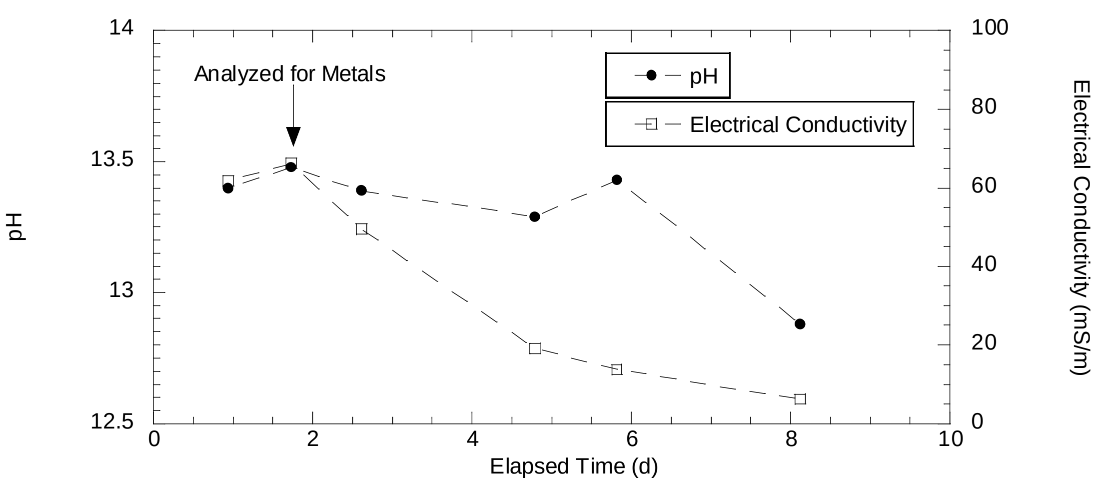




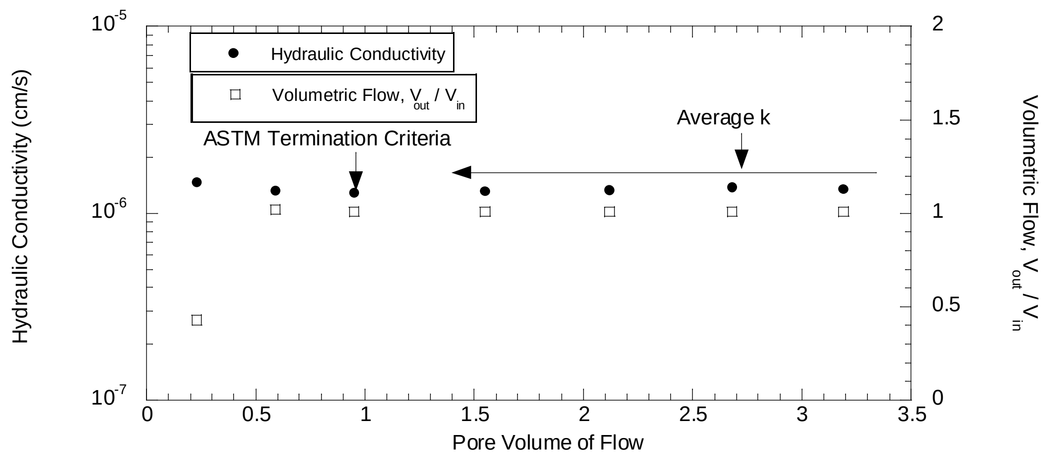
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
4	NT	1	A	7	1.87	0.61	11	0.61	19.9	1.8x10^{-6}

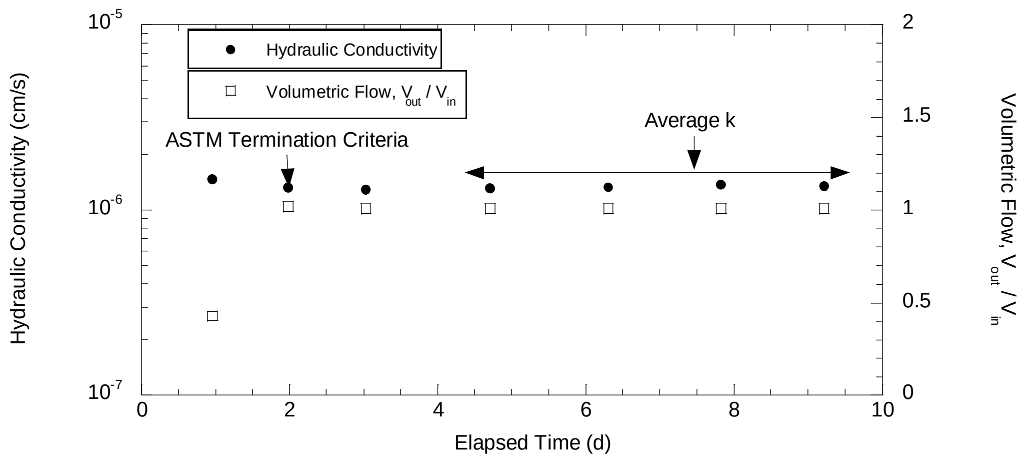


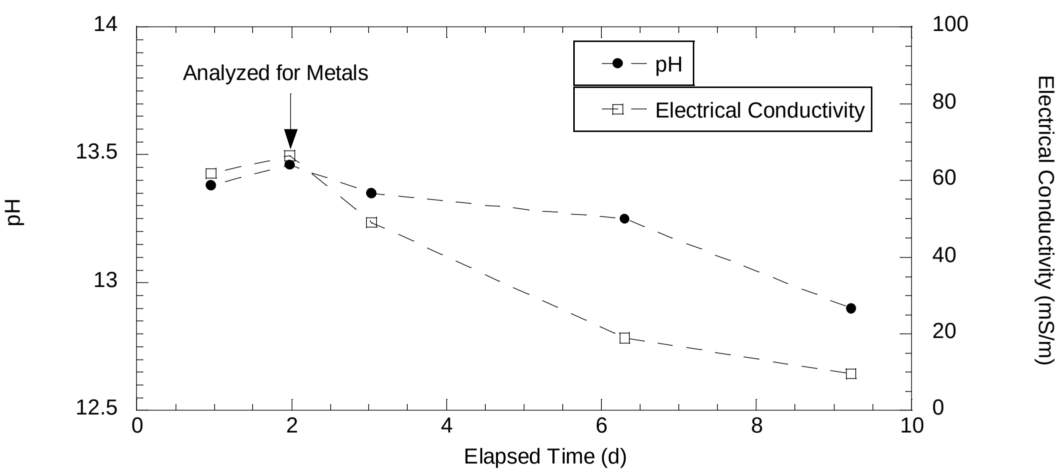




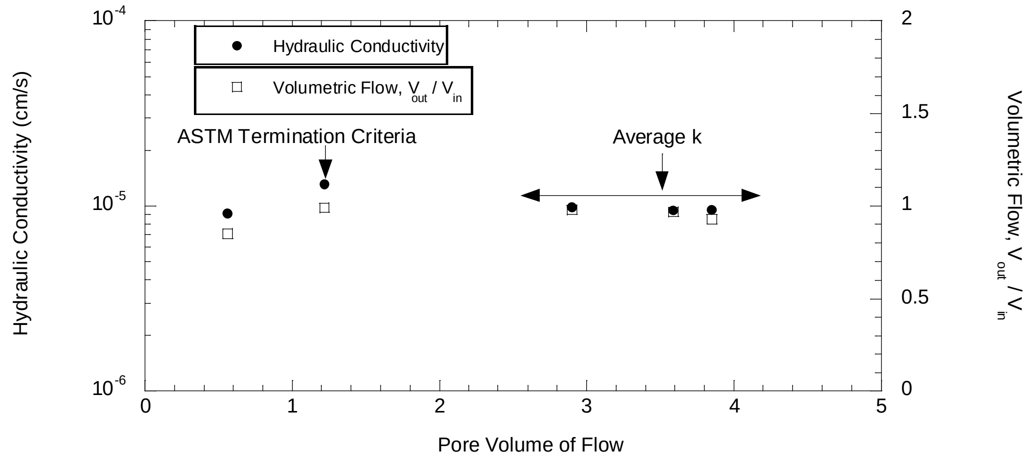
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
5	NT	1	A	28	1.88	0.60	11	0.60	19.7	1.3×10^{-6}

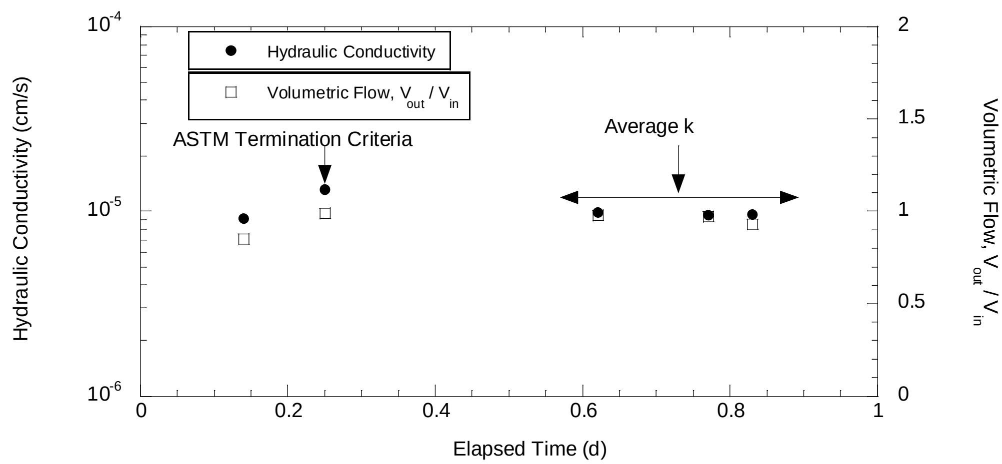


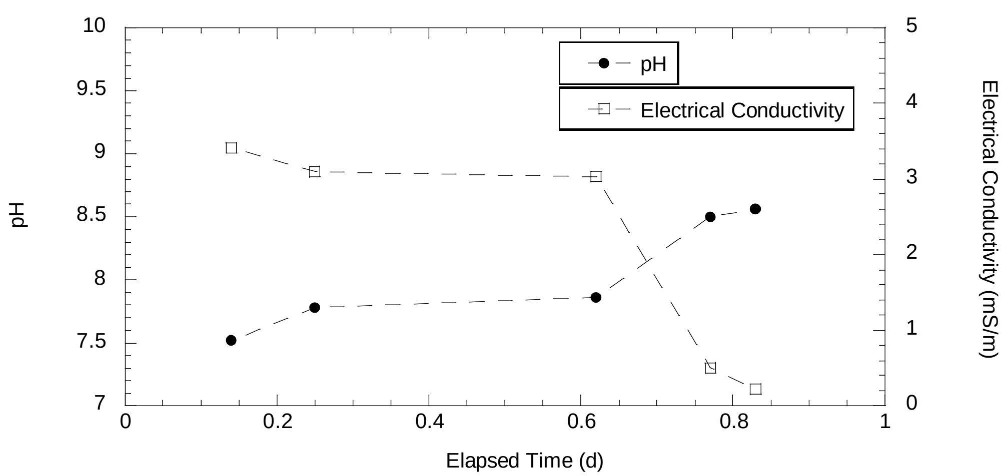




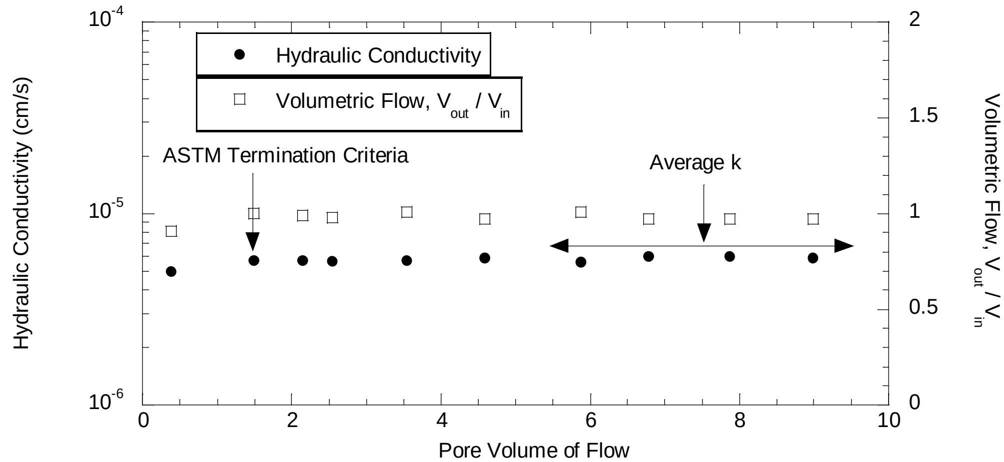
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
6	NT	-	-	-	1.51	1.03	27	0.63	20.5	1.0x10^{-5}

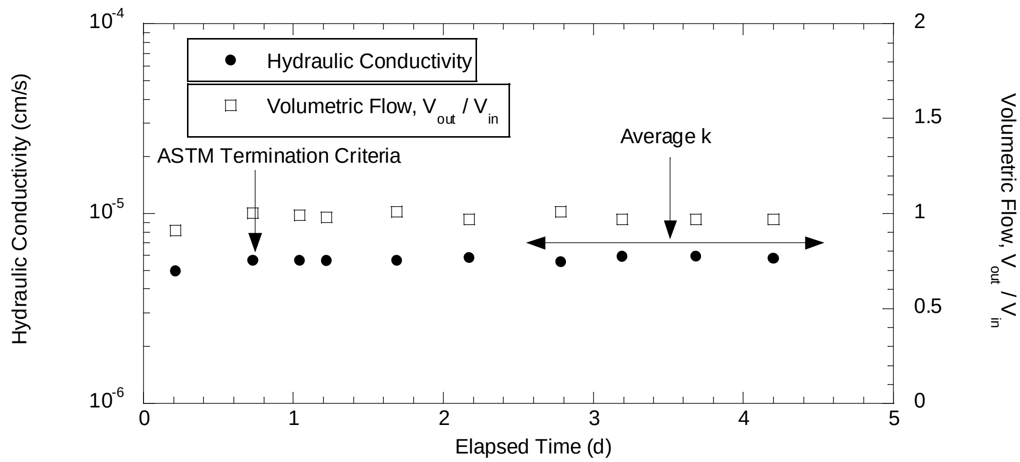


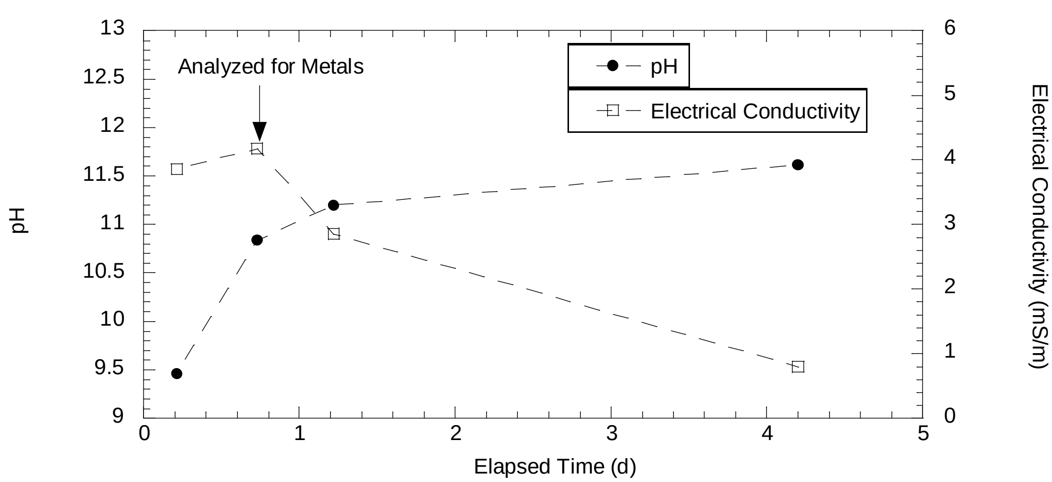




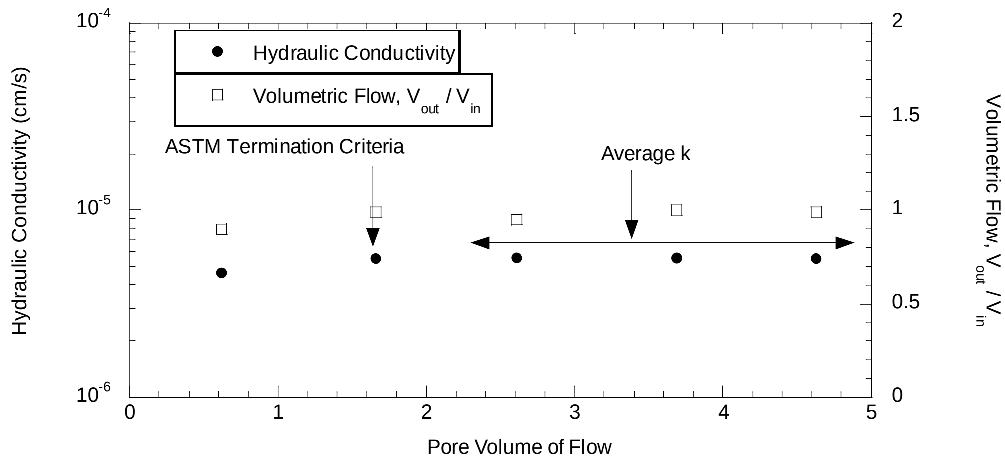
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
7	NT	2.5	B	7	1.8	0.65	21.6	0.55	19.5	5.7x10^{-6}

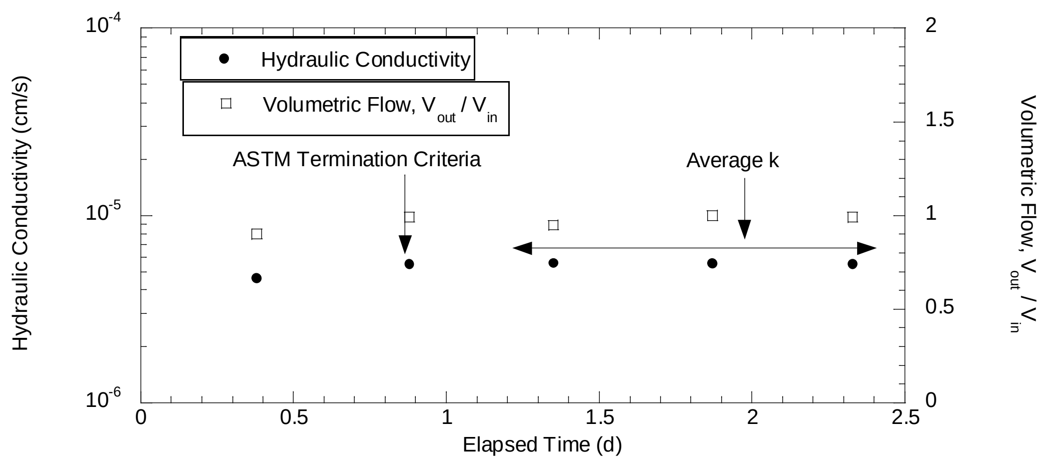


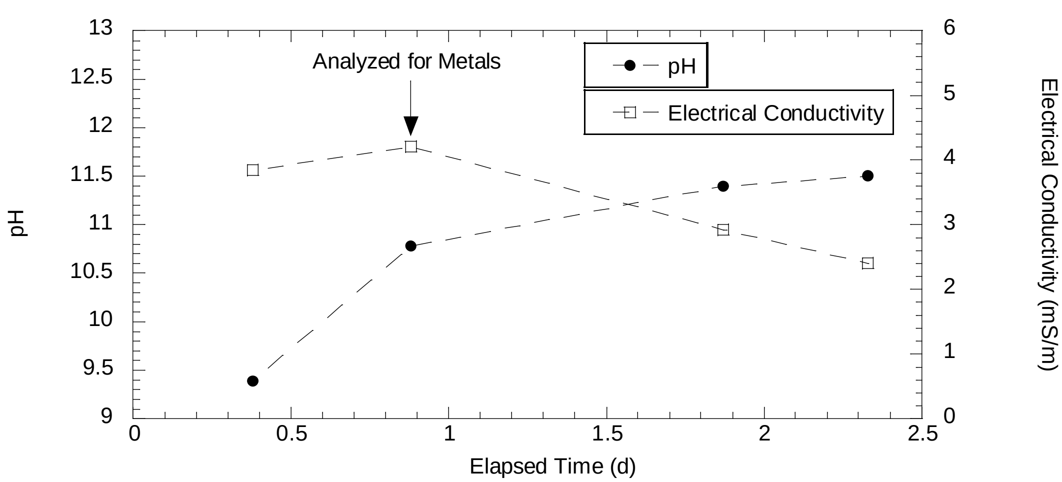




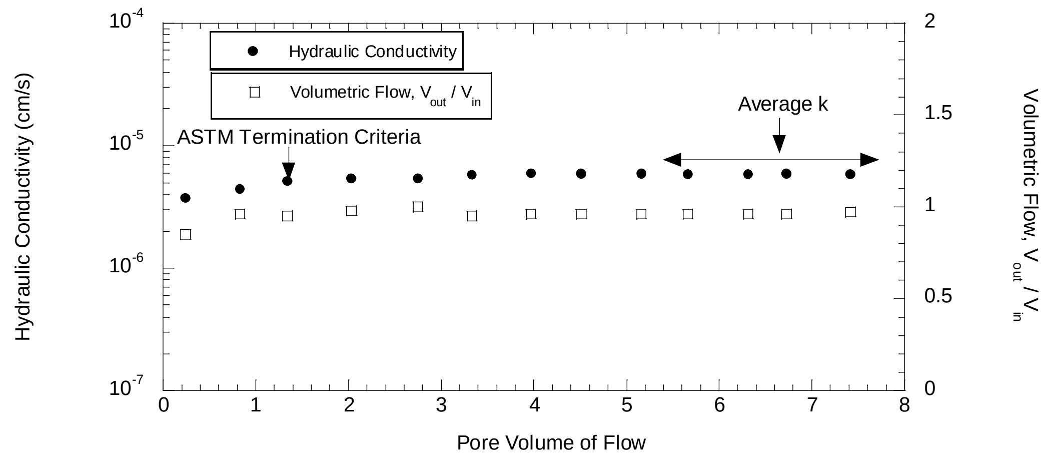
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
8	NT	2.5	B	28	1.79	0.66	21.1	0.55	19.6	5.5×10^{-6}

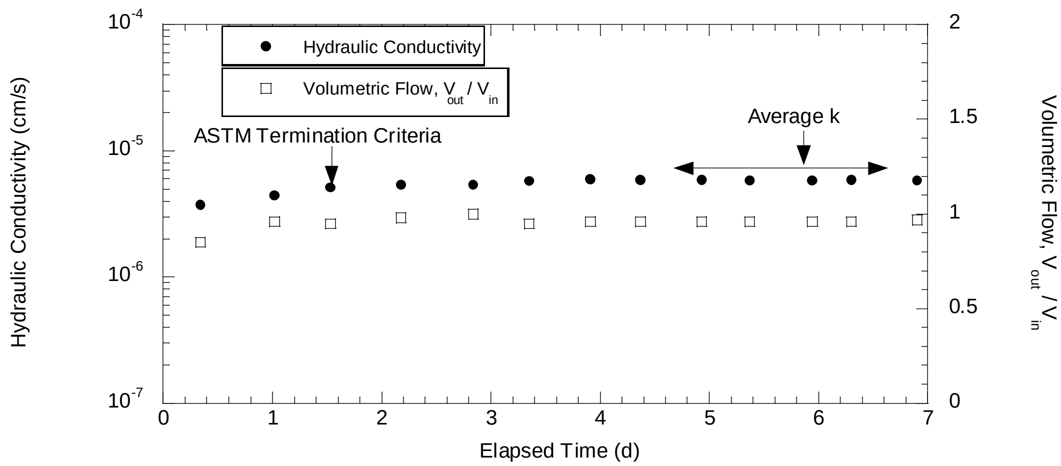


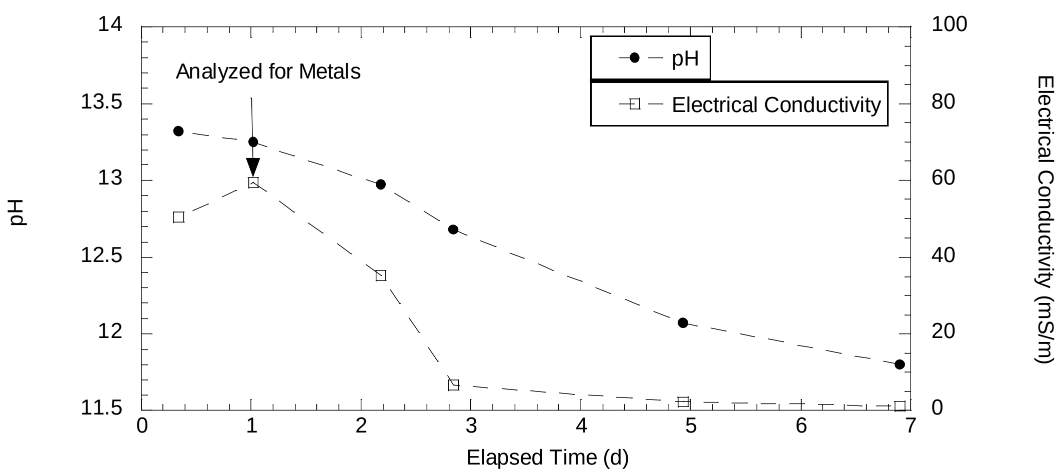




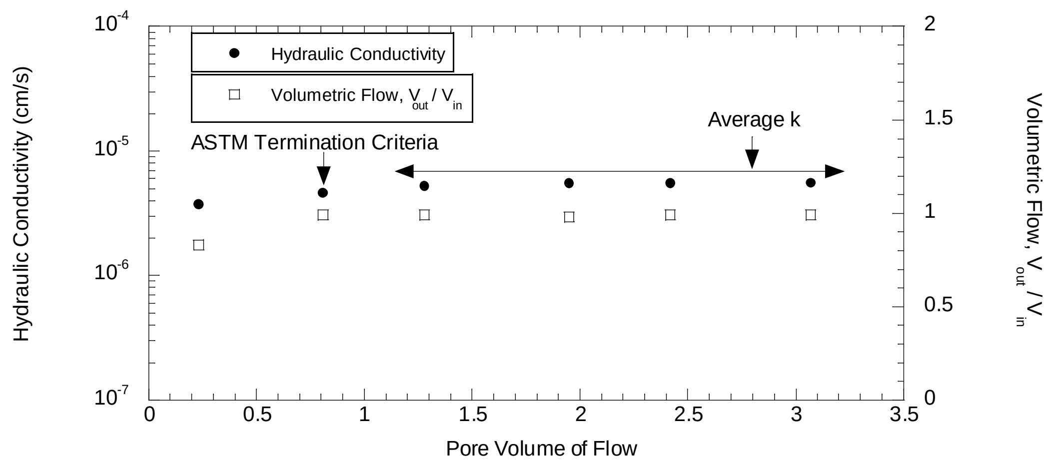
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
9	NT	2.5	A	7	1.68	0.79	23.3	0.79	25.1	5.4x10^{-6}

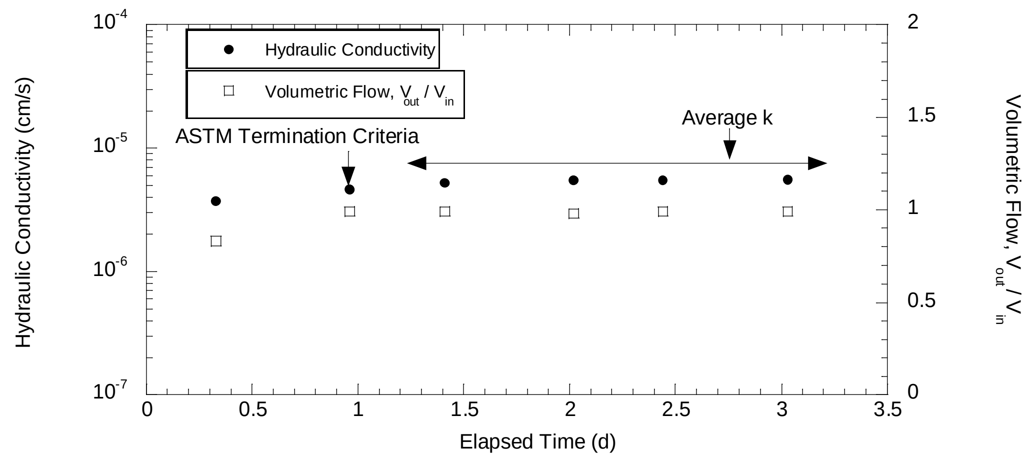


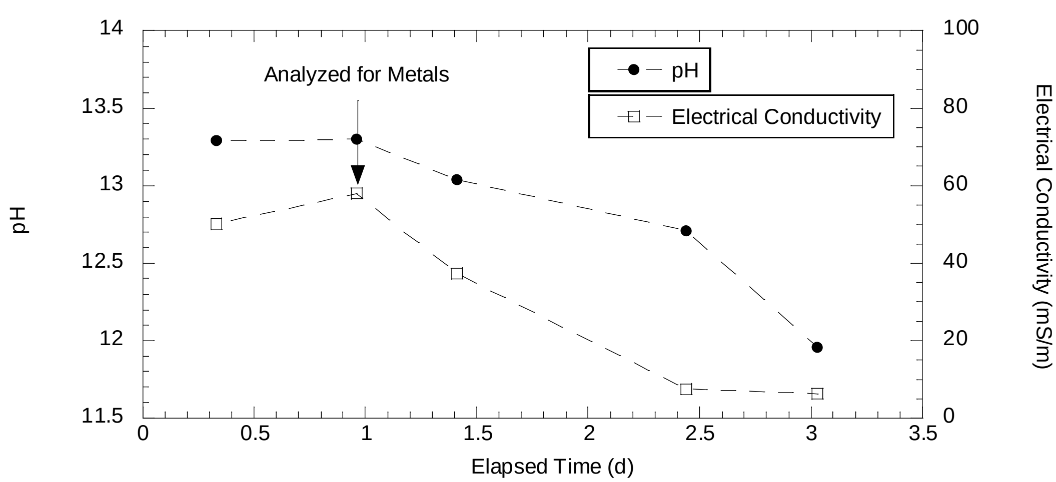




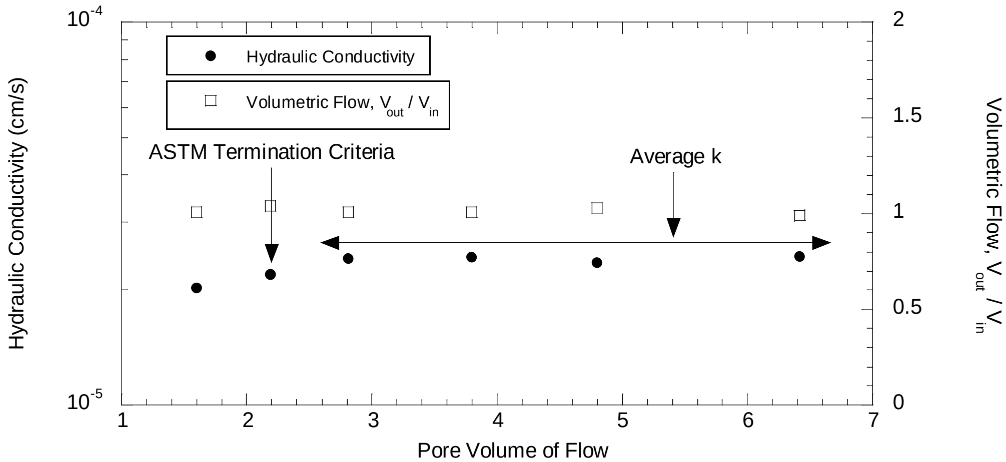
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
10	NT	2.5	A	28	1.69	0.78	23.3	0.78	24.9	5.4x10^{-6}

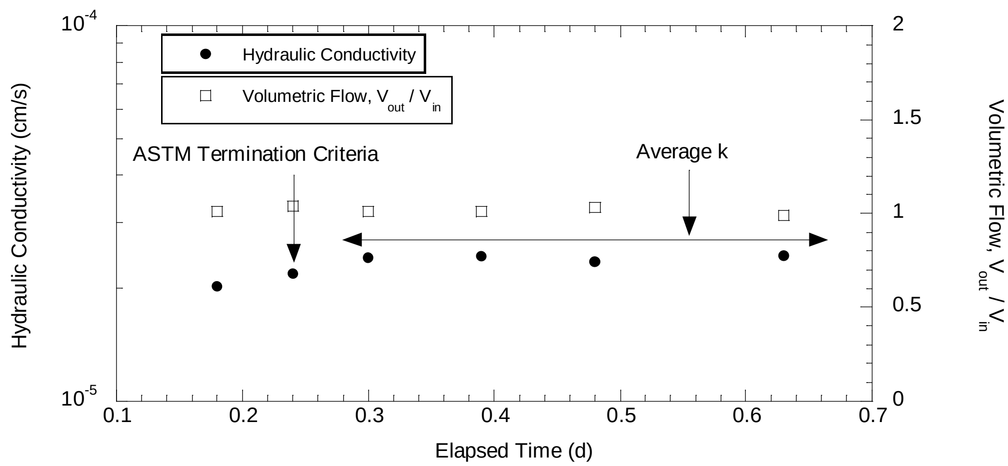


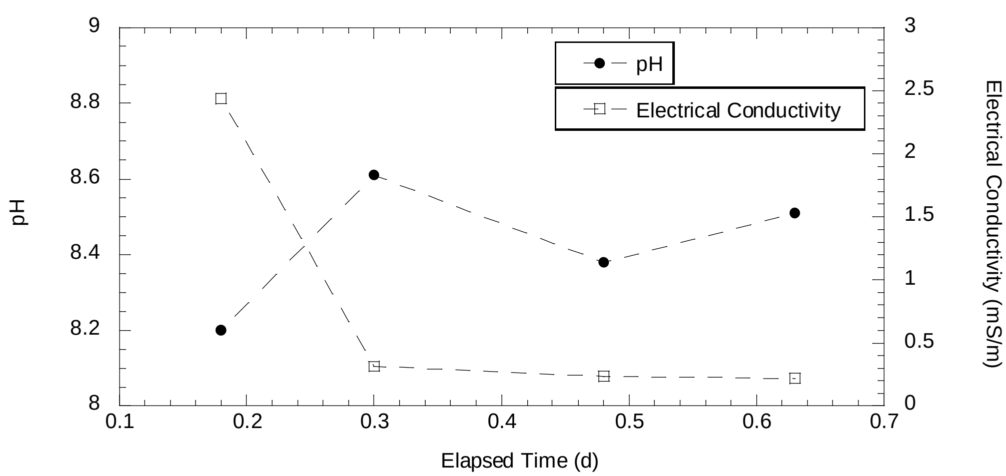




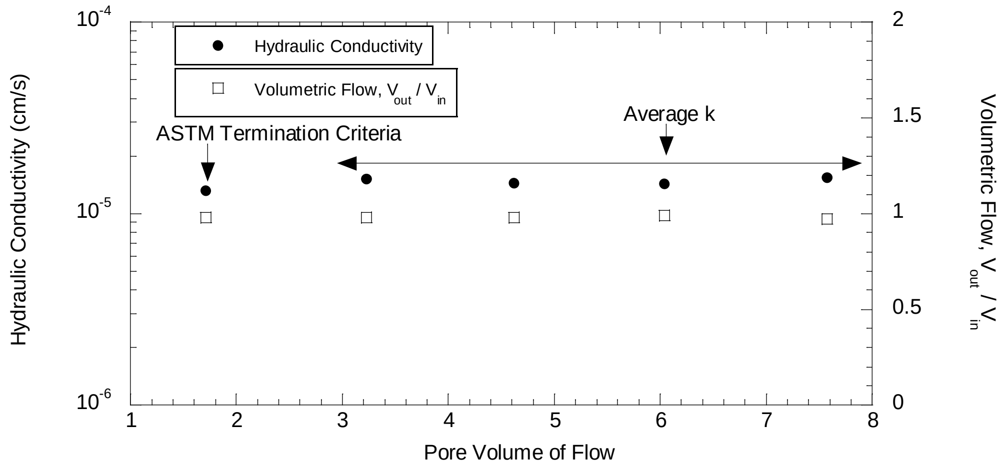
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
11	NT	-	-	-	1.41	1.18	36.4	0.64	22.3	$2.4x10^{-5}$

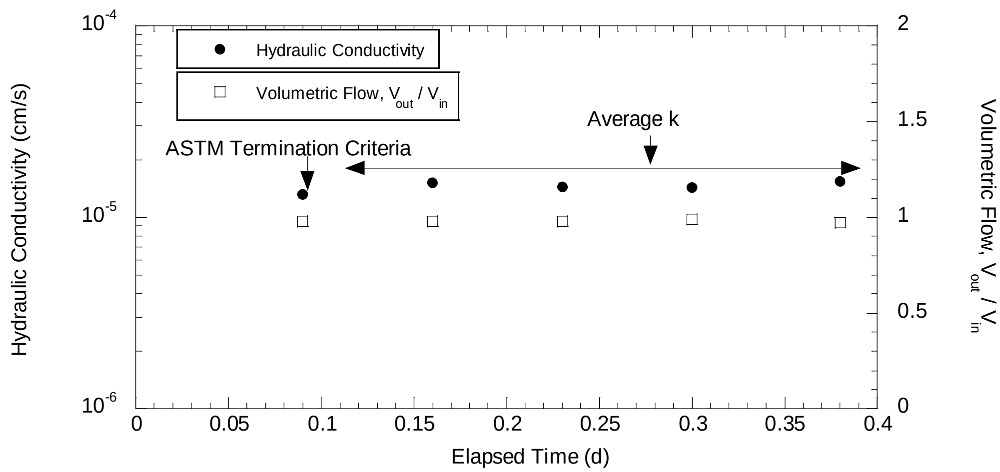


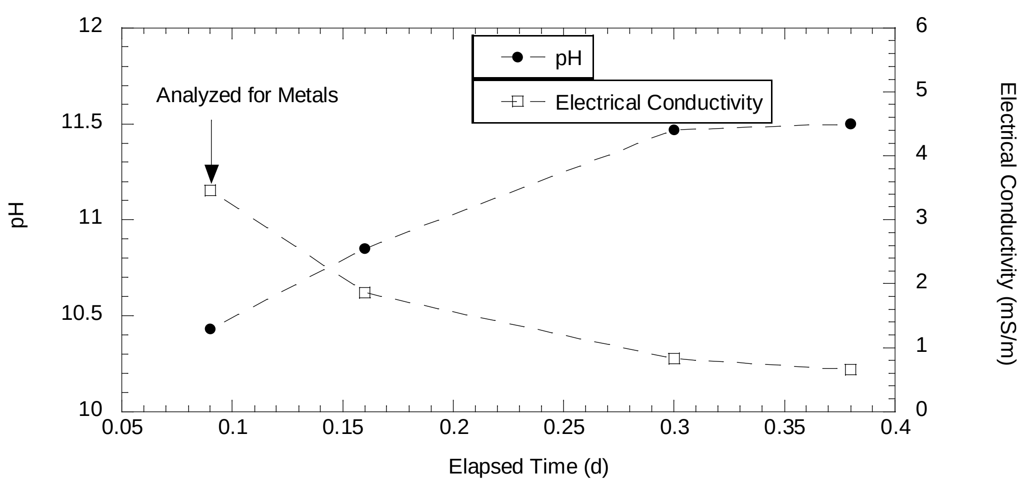




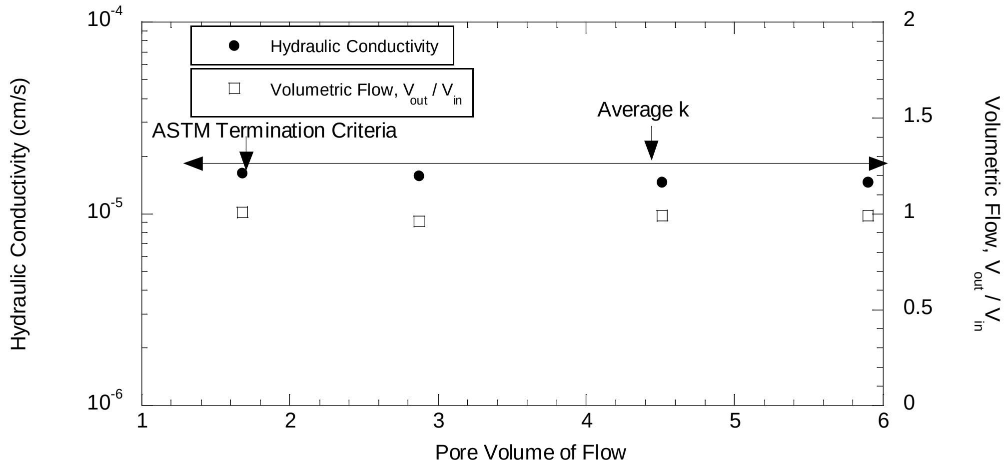
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
12	NT	4	B	7	1.4	1.12	36.1	0.66	23.4	1.4x10^{-5}

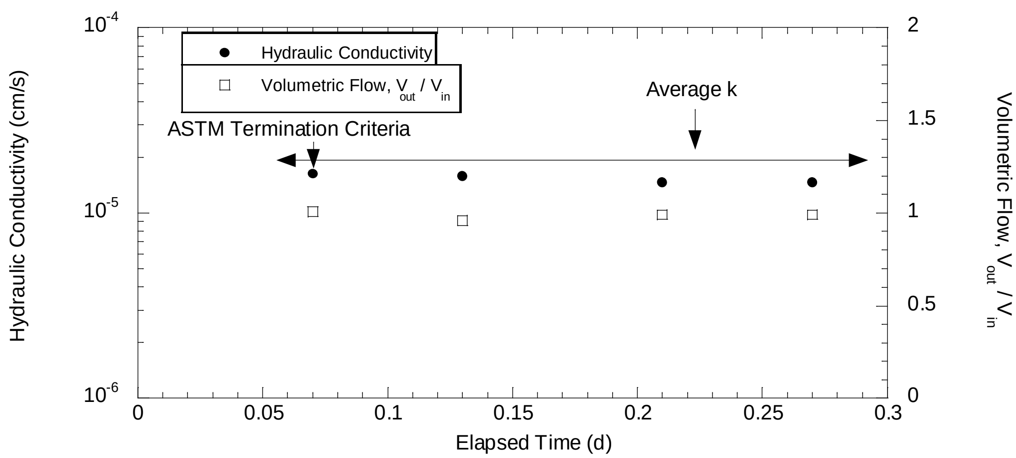


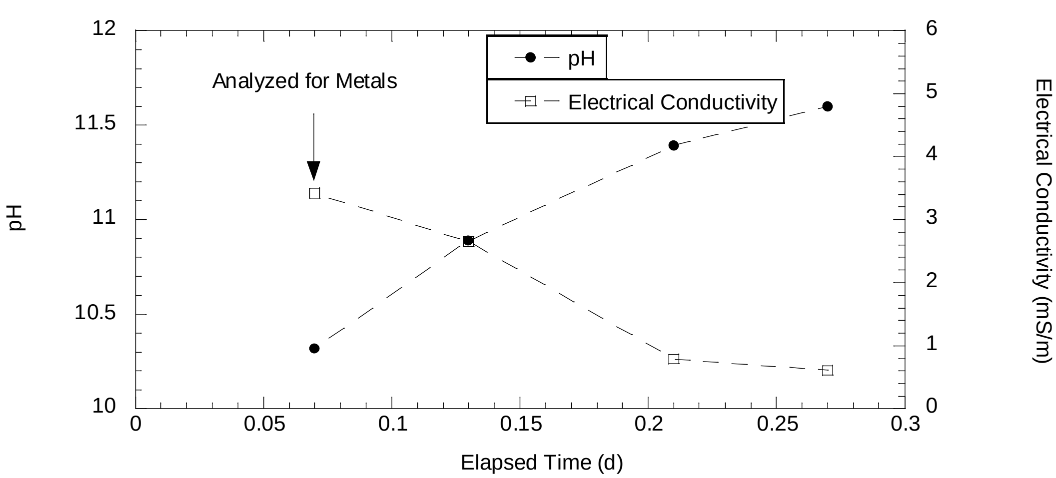




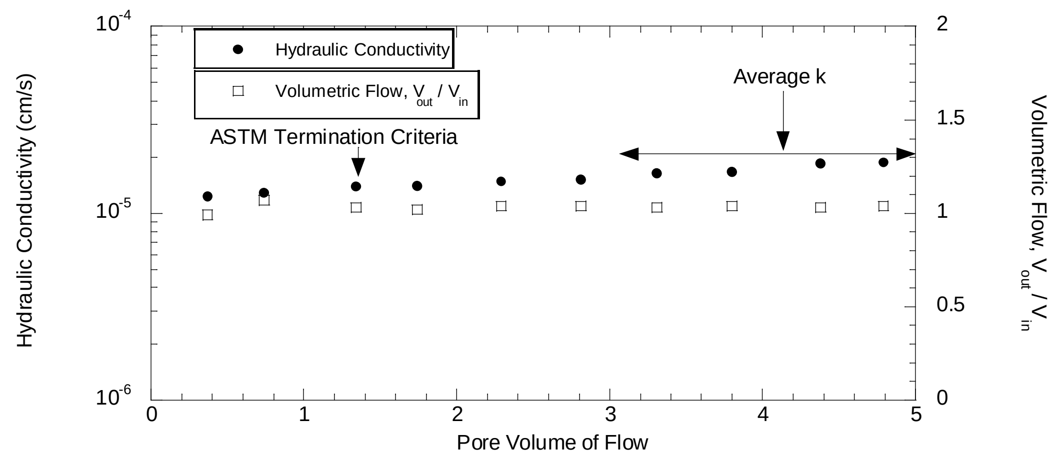
Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
13	NT	4	B	28	1.39	1.14	37.6	0.68	23.7	1.5x10^{-5}

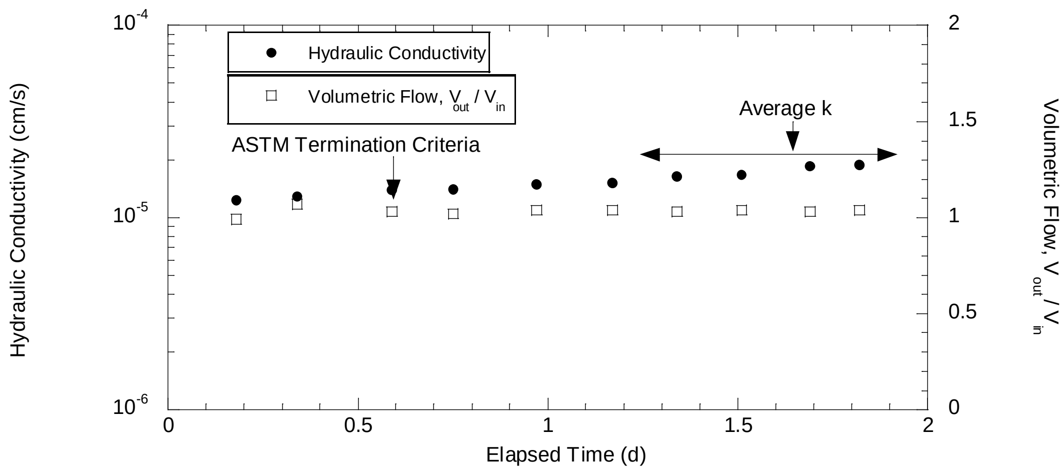


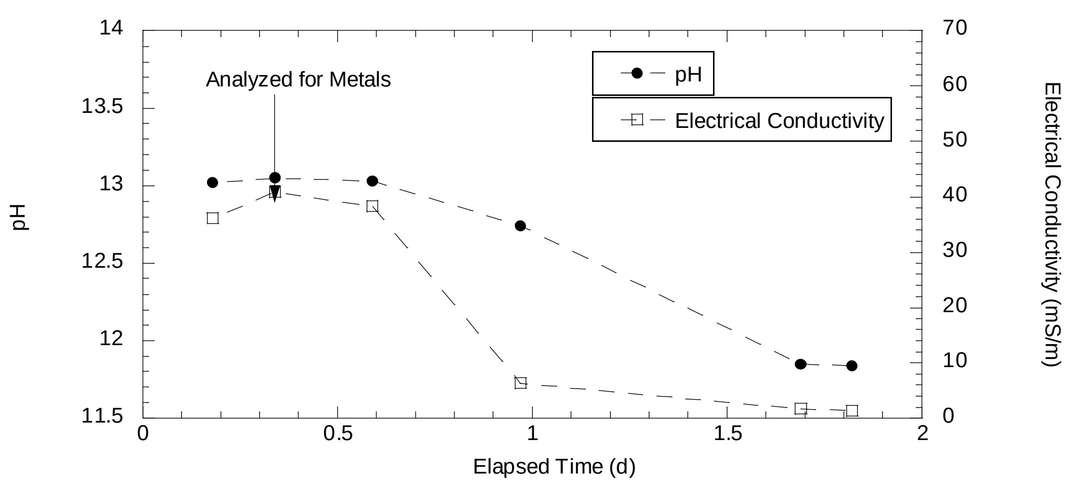




Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	k (cm/s)
14	NT	4	A	7	1.44	1.09	35.7	0.97	31.8	1.5x10^{-5}







Test No.	Material	W/B	Fly ash	Curing time (d)	ρ_d (g/cm^3)	e_i	w_i (%)	e_f	w_f (%)	*k* (cm/s)
15	NT	4	A	28	1.44	1.09	36.3	0.97	32.1	1.3x10^{-5}