

A Study of Intermediate Geomaterials and Highly Erodible Rock

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Final Report

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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Abstract

Although substantial research on soil erodibility has recently been conducted at the federal (e.g., NCHRP 915) and state (e.g., K-TRAN: KSU-15-4; K-TRAN: KSU-18-5) levels, information regarding erosion characteristics of rock or intermediate geomaterials, such as shale, is extremely limited. Shale exposure on cut slopes or natural slopes leads to potential erosion. The objective of this research was to measure the erodibility of Kansas shales, specifically loose, weathered material collected from the surface of cut slopes and the denser, intact specimens below. Because erosion characteristics differ significantly, this study also developed a simple method to predict the time over which shale transitions from not erodible to highly erodible. Samples were collected from five sites that had exposed shale on a cut slope, and the loose material at the top of a Shelby tube was reconstituted for erosion testing and constant head testing to determine hydraulic conductivity. The dense, intact material was tested in the Shelby tube without extrusion for erosion testing and hydraulic conductivity via the falling head permeability test. Falling head tests were performed before and after exposure to controlled freeze-thaw conditions to evaluate changes in permeability and subsequent porosity under Kansas-like environmental conditions—key indicators of erosion potential in shale. An empirical model was also developed to predict the number of freeze-thaw cycles needed for non-erodible intact shales to transform into highly erodible weathered material. The Kansas Department of Transportation could use this thorough analysis to improve decision-making and effective erosion mitigation strategies in similar geological settings. Results of this study also enhance understanding of shale erosion processes, with practical implications for infrastructure safety and environmental protection.

Acknowledgments

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Chapter 1: Introduction

Shale is a sedimentary rock typically comprised of clay minerals, quartz, feldspar, calcium carbonate, and organic materials. However, exposed shale on cut slopes or natural slopes is susceptible to erosion, which can lead to environmental concerns, specifically when unanticipated sediment is transported off-site or across site boundaries. Even minor instances of shale erosion can result in the accumulation of loose debris on roads, posing a persistent safety hazard that can impede transportation. Rapid water flow causes erosion and shale fragmentation by increasing bottom shear stress. Therefore, understanding and effectively managing shale erosion is essential to protect the environment and critical infrastructures; thereby, ensuring the continued safety of the traveling public.

The primary objective of this research was to measure the erosion potential of Kansas shales at the surface and near the surface at a relatively shallow depth (2–3 ft). Considering the relationship between shale porosity and erodibility, this research also investigated the role of freeze-thaw cycles on shale porosity to predict a timeline of increasing shale erodibility by observing the influence of ambient air freeze-thaw cycles on porosity and pore structure change in shale. Understanding the factors that influence shale erosion is essential for effective asset management and implementation of best practices to prevent or minimize shale erosion. Additional research could result in more comprehensive knowledge of how freeze-thaw cycles and changes in pore structure interact and contribute to shale erosion, leading to more effective preventive measures. A brief literature review of shale erosion and relevant measurements to this research follows this introduction. A detailed methods section covers all standard and newly developed approaches to meet the objectives of this study, and the results and discussion sections offer insights into the findings. The report ends with conclusions and recommendations for implementation.

Chapter 2: Literature Review

Previous shale literature has focused on the relationship between porosity and erodibility. For example, Fletcher et al. (2006) suggested that porewater chemistry and oxidation-driven fracturing are important factors for shale weathering. Similarly, Gu et al. (2020) investigated the relationship between shale erosion, porosity, and pore network size, and found that micro fracturing causes physical erosion and chemical weathering in shales. The slaking process, in which water weakens or disintegrates shale, and aggregate stability also influences the erosion resistance of shale (Perry & Andrews, 1982).

Researchers have varying opinions regarding shale classification. Ingram (1953) defined shale as a part of the argillaceous rock group, which includes claystone, siltstone, mudstone, and marl. In general, shale is the highly compacted and fissile equivalent of claystone and siltstone (Underwood, 1967). Shale can also be defined as a rock composed of claystone and siltstone that exhibits breakage along the bedding plane. Other researchers have described shale as a fine-grained rock containing 50%–100% clay-sized particles and at least 25% clay minerals by volume (Attewell & Farmer, 1976). Shales are often categorized as clayey, silty, or sandy, depending on grain-size determination consolidated over time under overlying sediments (Attewell & Farmer, 1976).

2.1 Shale Properties Related to Erosion

Soil erodibility, particularly fine-grained soil erodibility, cannot be directly correlated with geotechnical properties. Common properties researchers have associated with fine-grained soil erodibility include strength, particle size, moisture content, and density (Shan et al., 2015; Kulesza & Karim, 2021; Briaud et al., 2019). As a fine-grained rock, the compressive strength of shale can vary from 1.8 tsf to 1,080 tsf (Walkinshaw & Santi, 1996).

Koncagül and Santi (1999) studied the significance of shale particle size on strength based on mineralogical and intrinsic characteristics of shale rocks. They established a correlation between the uniaxial compressive strength (UCS), slake durability test (SDT), and Shore hardness index (SHI). The correlation coefficient of the UCS-SHI model was 0.57. The UCS values tended

to be high when the SHI values were high, indicating that harder shales (higher SHI) demonstrated more compressive stress resistance (higher UCS).

In another study, Gao et al. (2017) showed that the anisotropic nature of shale is a crucial factor in structural analysis. Anisotropy refers to the mechanical properties and behavior exhibited by shale in response to applied loads or stresses along different directions (Terzaghi et al., 1996). This anisotropy is essential for accurately predicting and comprehending mechanical behavior, such as shale UCS. The moisture content of shale varies between samples or within a given shale formation. Crisci et al. (2019) examined the hydro-mechanical behavior of Opalinus Clay shale at various shallow depths, revealing measured moisture contents of 4.7%–10%, where the moisture content was higher at shallow levels, specifically from the surface to 33 ft.

2.2 Shale Porosity

Because it is an essential factor when evaluating shale reserves, porosity has been extensively studied as a fundamental feature of shale. For example, Huang et al. (2020) evaluated shale porosity from the Longmaxi Formation using seven methods: helium pycnometry, water immersion porosimetry (WIP), nuclear magnetic resonance (NMR), mercury intrusion porosimetry (MIP), gas adsorption (CO₂ and N₂), scanning electron microscopy (SEM), and X-ray computed tomography (CT). Porosity measurements varied from 1.32% to 9.8%, underscoring the effects of diverse testing protocols and sample saturation. Similarly, Dong et al. (2015) assessed the pore systems of the Horn River shale in the Western Canada Sedimentary Basin by analyzing core samples from the Middle and Upper Devonian sequences. Results showed that porosity varied across different shale lithofacies, ranging from 0.62% to 12.04%. The highest porosities were observed in massive and pyritic mudstones with high total organic carbon (TOC), while the lowest porosities were in bioturbated mudstones and carbonates, which had lower TOC levels. The research indicated that porosity is dominant in areas rich in organic matter and that high organic content generally correlates with the development of small pores.

Urumović and Urumović (2016) studied the applicability of the Kozeny–Carman (KC) model, which relates porosity to intrinsic permeability, to determine the hydraulic conductivity and specific surface area of various sediments, including clay soils, based on their composition.

For clayey-silty materials, the study calibrated effective porosity within a grain size less than 0.24 in., showing a good correlation ($R^2 = 0.70$) between the predicted and observed hydraulic conductivity values. This calibration validated the model's effectiveness in clay soils across a wide hydraulic conductivity spectrum, from 10^{-15} in./s to 10^{-5} in./s, as evidenced by a high correlation ($R^2 = 0.97$) for 175 different soil samples. Their research highlighted model effectiveness for clayey materials, enhancing its utility in groundwater flow modeling and contaminant transport by providing reliable estimates of porosity, permeability, and specific surface area.

2.2.1 Shale Porosity Changes and Erosion

Weathering is a mechanical, chemical, or biological process that alters rock and soil, potentially modifying soil or rock characteristics such as hardness, hydraulic conductivity, and compressibility. Through physical, chemical, and biological mechanisms, these weathering processes contribute to the degradation of materials, suggesting that these processes lead to erosion, sedimentation, and the formation of a soil profile (Birchmire, 2005). Rock porosity allows water, oxygen, and other agents to permeate; thereby, facilitating chemical reactions and physical processes that contribute to the weathering and erosion of the rock structure (Brantley et al., 2017). Jin et al. (2011) found that shale disaggregates into chips during the weathering process, creating intergranular pores and fractures that lead to increased porosity. Gu et al. (2020) similarly established a correlation between the physical erosion of shales and their porosity and microstructure by employing three different geological formations with previously studied erosion rates. Porosity was found to influence fluid flow rates and provide the mineral-water interface area for weathering reactions in shale. The correlation between changes in the pore network and shale weathering was also examined by Li et al. (2022). Their results showed that, as shale density decreased, the porosity and specific surface area increased with decreasing depth during weathering.

2.2.2 Freeze-Thaw Effects on Porosity and Compressive Strength

Natural or man-made freeze-thaw cycles involve the repetitive freezing and thawing of water or other liquids. These cycles significantly impact shale pore size, permeability, and damage characteristics (Wang et al., 2022). Wang et al. (2022) conducted varying numbers of freeze-thaw

cycles on shale specimens and found that an increased number of cycles resulted in changes in the shale pore structure. As the size and number of pores increased, the average porosity also increased proportionally. Similarly, Park et al. (2015) studied freeze-thaw cycles and the porosity of various rock specimens, proving that porosity increased in the rock specimens due to the volumetric expansion of water inside the rocks during freeze-thaw cycles. Saturated specimens with high porosity showed rapid deterioration, while specimens with low porosity showed relatively slight changes compared to shale of higher porosity.

Zhao et al. (2019) conducted laboratory experiments on shale samples obtained from various locations to examine the impact of water-induced deterioration on rocks that were exposed to freeze-thaw weathering. The inquiry was initiated by conducting petrographic and geochemical assessments of the shale specimens. These initial tests were then followed by a series of freeze-thaw cycle evaluations, which encompassed a range of 10–40 times and intervals of 15 times. The samples were subjected to freezing at a temperature-controlled cabinet of -4 °F, followed by thawing in distilled water at a temperature of 70 °F. SEM and X-ray diffraction (XRD) analyses were performed on five samples, and sample deterioration was exhibited via weight loss that decreased at the highest rate by 25 freeze-thaw cycles and decreased UCS. The research findings suggest that the microstructure of the specimens, specifically the emergence of fissures, impacted the degree of degradation observed in the oil shale during exposure to approximately 40 freeze-thaw cycles. However, the compressive strength of the shale samples varied, with the highest value being nearly 2.5 times higher than the lowest strength, suggesting that the UCS of shales was affected by the increased number of freeze-thaw cycles. The ultimate compressive strength of the rock samples declined by 51.6% after 40 cycles. Oil shale, which is sedimentary rock known to contain organic material with high compressive strength and high elastic energy, failed catastrophically when tested, while lower-strength samples frequently ruptured at weak surfaces. Therefore, Zhao et al. (2019) emphasized the impact of freeze-thaw cycles on the mechanical characteristics and mineralogical alterations of shale. Minerals in shales have been shown to increase the rock porosity or water absorption; thereby, increasing susceptibility to freeze-thaw weathering and reducing the rock's compressive strength, which causes some minerals to shatter

more readily. These findings align with similar results reported by Li et al. (2022), demonstrating the significant impact of freeze-thaw cycles on shale mechanical properties.

2.3 Other Shale Erosion Factors

When water flows swiftly over shale, the pressure imposed on the bottom layer increases, a phenomenon known as bottom shear stress. This increase in shear stress can cause the shale bed to continuously erode and large shale particles to fragment into smaller bits (Schieber et al., 2010). Schieber et al. (2010) used flume experiments with water velocities ranging from 52 ft/s to 85 ft/s to identify lenticular shale fabric, which is characterized by lenses of varying composition stacked in wavy layers, likely due to erosion and current-driven surficial mud transport. When flow velocities increased, the shale's bottom shear stress also increased, resulting in prolonged bed erosion, or the physical wear and tear of the shale bed caused by the powerful currents and shale fragmentation. Clast disaggregation is the process by which physical or chemical weathering causes these separated shale fragments, or clasts, to break down further and is heightened by increased amounts of shear stress.

Similar to other sedimentary formations, shales are comprised of numerous minerals and aggregates, but the presence of water can influence the stability of these aggregates, particularly in shale, leading to slaking, which results in the weakening or disintegration of the rock. This weakening can affect the structural integrity of a rock formation or a man-made structure. For example, culcrete rock, which is a sedimentary rock with clay minerals, was subjected to a slake durability test to evaluate the rock's resistance to deterioration and disintegration in response to three cycles of drying and wetting, simulating typical environmental conditions for the rock (Franklin & Chandra, 1972). The total mass of the samples decreased by approximately 7.8% after the first run and then were constant in the second and third cycles, according to a quadratic trend. This reduction reinforced the significance of studying slaking when assessing aggregate stability and overall durability of sedimentary rocks such as shale.

Ahukaemere et al. (2020) used the clay dispersion index (CDI), clay flocculation index (CFI), and clay dispersion ratio (CDR) to study the aggregate stability of Imo clay shale, Bende-Ameki shale, and Nkporo clay shale. High CDI and CDR values were connected to decreased

aggregate stability, while high CFI values suggested high stability. The Imo clay shale, thus, showed the highest stability, followed by the Bende-Ameki shale, and then the Nkporo clay shale. This sequence correlated with each shale's clay and organic matter content, with high levels of clay and organic matter enhancing the stability of Imo clay shale, and low organic carbon content reducing the stability of Nkporo clay shale. Overall, the literature review identified factors that influence the porosity and characteristics of shale, to support the idea that Kansas near-surface freeze-thaw cycles are resulting in shale porosity change and, thus, shale erodibility.

Chapter 3: Methodology

3.1 Sample Collection

For this study, the Kansas Department of Transportation (KDOT) selected five shale cut slopes for sampling. All samples were collected in Shelby tubes with 3.5 in. diameters and lengths of at least 2 feet. Two samples were collected at each site. The objective of sampling was to collect specimens through the exposed, weathered portion at the surface through intact shale. Figure 3.1 shows the Kansas sample locations and surface geology at Lawrence, Salina, Neal, Topeka, and Toronto locations. However, the Topeka sample adhered to the Shelby tube, preventing extraction during erosion testing without damaging the sample. Therefore, the Topeka sample was excluded from the erosion analysis.

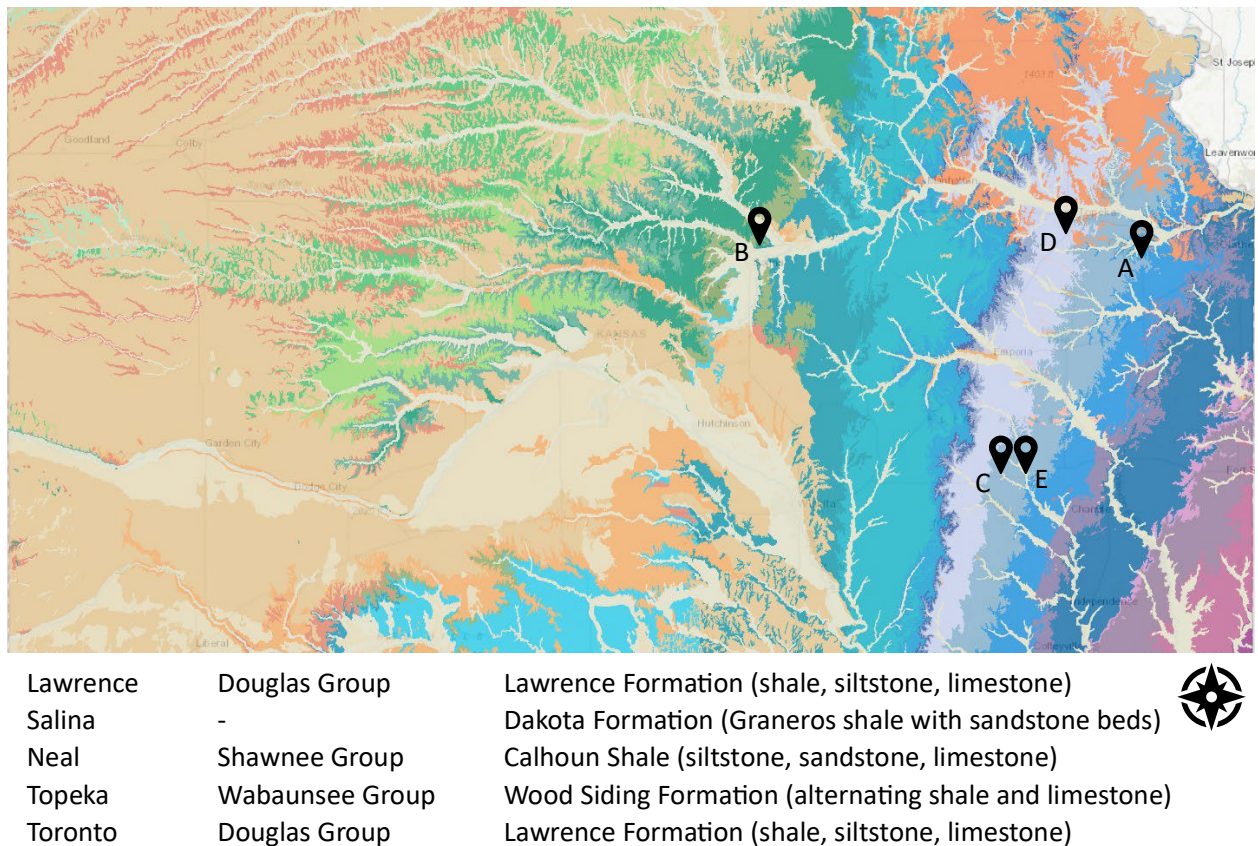


Figure 3.1: Locations of Five Shale Samples and Surficial Geology

3.2 Sample Characterization

The lower half of each Shelby tube contained compacted shales (intact specimens), while the upper half contained loose, weathered rock particles. Both sections were analyzed to determine the gradation and mean particle diameter. Although the top section appeared rocky, it degraded during mechanical sieving and was ultimately characterized as fine-grained. Additional standard geotechnical analyses were conducted to classify the specimens according to the Unified Soil Classification System (USCS) (ASTM D2487, 2017). Because shale is also commonly characterized by a durability index, intact segments of shale were extruded from the Shelby tubes and run through two durability cycles to determine the slake durability index. Figure 3.2 shows photos of the slake durability test on the Lawrence shale. Table 3.1 lists the ASTM standards used in this research.

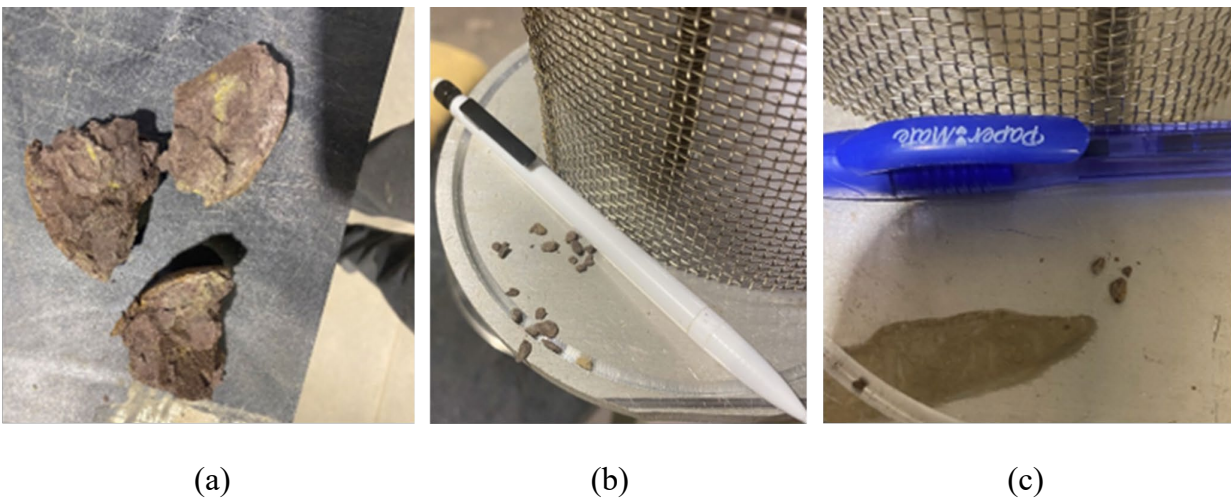


Figure 3.2: Slake Durability Test: (a) Initial Specimen; (b) Cycle 1 Retained Specimen (Type III, Exclusively Small Fragments); (c) Cycle 2 Retained Specimen (Type III)

Table 3.1: Required Soil Properties and Relevant Specifications

Test Name	Specification	Necessary Soil Properties
Moisture Content	ASTM D2216 (2019)	Percent moisture
Sieve Analysis	ASTM C136 / C136M (2019)	Distribution of particle sizes
Hydrometer Test	ASTM D7928 (2021)	Median grain size
Atterberg Limit Test	ASTM D4318 (2017)	Liquid limit, plastic limit, plasticity index
Percent Passing #200	ASTM C117 (2017)	Clay and silt sized particle percentage
Slake durability	ASTM D4644 (2010)	Durability index for shale rating

3.3 Methods

3.3.1 Erosion Testing for Critical Shear Stress

This study performed erosion testing on one of the two samples from each site, except Topeka which could not be extruded. Each Shelby tube was cut so that the intact portion of the shale filled at least 6 in. of the tube. The weathered portion was reconstituted to two loose, dry densities in separate Shelby tubes and at the natural water content. Sufficient weathered material was available from each site to perform reconstituted tests at 75 pcf and 87 pcf. All erosion tests were performed using an erosion function apparatus (EFA) that quantified the rate of soil erosion, z (in./hr), at various hydraulic shear stresses, τ (lb/ft²) (Briaud et al., 2001).

The Shelby tube containing the sample was placed on a raised platform (Figure 3.3a) so that the tube and the exposed sample were flush with the bottom of the flume (Figure 3.3b). A minimum target water velocity was selected to prevent soil erosion, after which the velocity increased until measurable erosion occurred. The sample was pushed vertically during the test so that it remained flush with the bottom of the flume as the soil eroded. The push distance was tracked over a set period to determine the soil erosion rate at that velocity. This process continued to higher velocities until at least five velocities were run, or there was insufficient sample to continue to test.

Briaud et al. (2017) developed erosion characterization charts that plot erosion rates versus hydraulic stresses for each specimen. The initial point where no erosion occurs and an erosion measurement are critical because these points are used to determine the critical shear stress and critical velocity. Critical shear stress is the stress at which erosion first occurs, defined as 0.004 in./hr by Briaud et al. (2017), and critical velocity is the water velocity at that shear stress. Additional details regarding EFA testing, including determination of hydraulic shear stress, are discussed in the report K-TRAN: KSU-15-4 (Tucker-Kulesza & Karim, 2017).



(a)



(b)

Figure 3.3: EFA Machine: (a) Raised Platform; (b) Exposed Sample Flush With the Bottom of the Flume

3.3.2 Hydraulic Conductivity Testing

Hydraulic conductivity of the intact shale was determined by conducting falling head experiments according to ASTM D5084 (2024). A custom experimental configuration was built to evaluate the hydraulic conductivity of shales without extracting the specimens from the Shelby tubes, as shown in Figure 3.4. The permeameter was designed to fit a Shelby tube cut to a height of 2 inches. The setup consisted of a vertical, transparent plastic pipe with a diameter of 3.5 in. and a length of 9.5 inches. This pipe was connected to the Shelby tube with a rubber coupler to ensure that no water would leak (Figure 3.4b). The pipe had a ruler attached to measure the initial water level, and filter paper was placed on each exposed shale surface to reduce material loss. A

second rubber coupler connected the Shelby tube to the outflow reservoir, which included a valve to close during saturation (Figure 3.4c).

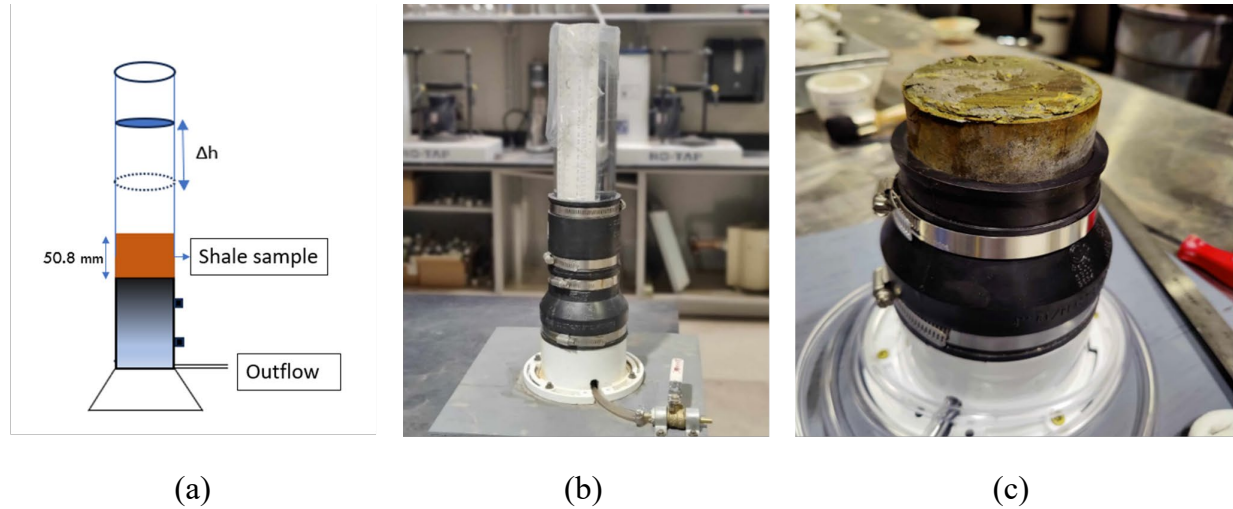


Figure 3.4: Falling Head Permeameter: (a) Schematic; (b) Experimental Setup; (c) Specimen Connected to Lower Reservoir

Samples were placed in the device and saturated for 48 hours by filling the inlet chamber and closing the outlet valve. After saturation, the inlet chamber was refilled to an initial height and allowed to drop over a set time with the open valve to obtain the falling head measurement. Measurements were collected until at least six consecutive measurements yielded consistent results to support the assumption that the sample was fully saturated. This system advantageously allowed efficient measurements of the hydraulic conductivity, followed immediately by freeze-thaw experiments and additional hydraulic conductivity measurements without extracting the sample from the Shelby tube.

Hydraulic conductivity of the degraded shale was determined using a constant head permeability test in accordance with ASTM D2434 (2022). Samples were reconstituted to the relatively loose density of 75 pcf since the initial density could not reliably be obtained. The constant head permeameter was 6 inches in diameter and 4.5 inches tall. Samples were placed in the permeameter and saturated for 1 hour. The time to saturation was reduced because some of the

weathered materials would disperse when inundated for 48 hours. Four constant head measurements were collected for each specimen.

3.3.3 Freeze-Thaw Testing

The Z-Plus Temperature/Humidity Chamber was used to simulate eastern Kansas freeze-thaw conditions. Following the initial falling head permeability test of the shale sample, the samples were subjected to cycles of extreme temperatures. Minimum and maximum temperatures were determined for each site using the Kansas Mesonet. A review of data from 2018–2023 revealed that the minimum temperature was approximately -14 °F, while the maximum temperature was 104 °F. Both air and soil temperature data were available for all sites on the Kansas Mesonet. Although this research is based on soil temperature, the shales were exposed on cut slopes. Air temperature data were used in this study because Kansas Mesonet soil data are reported at sites with sensors buried 2 in. into sod, meaning bare soil temperatures, such as the cut slopes in this study, trend towards air temperature. Each temperature was maintained for 1 hr at -14 °F, followed by 1 hr at 104 °F; thereby, completing a single cycle. The sample weight was measured following each cycle, and the mass of the shale specimen was shown to steadily decrease with each cycle. The process continued until two consecutive weight measurements were obtained.

Surface fissures were also recorded after each cycle. To effectively track the growth and expansion of cracks caused by freeze-thaw cycles, photos of the exact same orientation were obtained after each cycle. Prior to and following each freeze-thaw cycle, the sample was placed on filter paper where a mark on the Shelby tube was aligned with a mark on the filter paper. To ensure consistent image capture, the camera was raised 6.5 in. using a support, meaning all parameters were constant, and the change in crack propagation was qualitatively monitored.

3.3.4 Subsequent Hydraulic Conductivity and Freeze-Thaw Testing

Another hydraulic conductivity test was performed on the sample after the first freeze-thaw series (i.e., until the mass was constant). The sample was placed back in the permeameter and saturated before collecting falling head data. The freeze-thaw experiment and subsequent permeability test were repeated until either the sample was damaged or removed from the Shelby tube, which occurred during the third cycle of freeze-thaw experiments for all specimens. The

samples were designated using the following format: k_Freeze-Thaw Cycle Number_SiteName. k_0 represents the in-situ hydraulic conductivity before any freeze-thaw experimental cycles; k_1 denotes hydraulic conductivity after the first experimental freeze-thaw cycle, which included 10–12 cycles until the weights of the shale samples stabilized; and k_2 represents hydraulic conductivity following the second freeze-thaw experimental cycle, consisting of 10–12 cycles unless the sample was dislodged from the Shelby tube or damaged so that the mass was no longer constant.

3.3.5 Freeze-Thaw Cycles to Time

The number of freeze-thaw cycles at each site was measured using a criterion of two consecutive freezing temperatures (below 32 °F), and then two consecutive thawing temperatures (above 32 °F) from the Kansas Mesonet. Thus, when at least two freezing temperatures were consecutively followed by at least two thawing temperatures, one freeze-thaw cycle was counted. Three consecutive freezing temperatures followed by three or more consecutive thawing temperatures were also considered, which yielded approximately the same number of cycles. Therefore, a minimum of two consecutive freeze-thaw sequences was selected for each cycle. Table 3.2 shows the approximate number of freeze-thaw cycles averaged over five years for each of the five locations. These data were used to report the change in shale porosity over time using the average, such that nine simulated cycles were equivalent to one year for all sites.

Table 3.2: Annual Number of Freeze-Thaw Cycles

Sample Location	Freeze-Thaw Cycle/Year
Salina	8
Lawrence	9
Toronto	10
Neal	9
Topeka	9

3.3.6 Shale Porosity

Gupta and Civan (1994) found that the Kozeny-Carman equation (Carman, 1939; Kozeny, 1927) can characterize the porosity-permeability relationship of rocks. A modified Kozeny-Carman equation was used to adjust for fines as the original Kozeny-Carman was developed for clean sands. The modified Kozeny-Carman relates the intrinsic permeability (K , ft²) to porosity as:

$$K = \frac{d_{eff}^2}{72\tau^2} \frac{n^3}{(1-n)^2}$$

Equation 3.1

Where:

d_{eff} = effective grain size (ft), adjusted for fines,

τ = tortuosity (unitless), and

n = porosity (%).

The effective grain size is:

$$d_{eff} = d_{50}(1 - c_f)$$

Equation 3.2

Where:

d_{50} = median grain size (ft),

c_f = sample clay fraction by mass (% finer 2 μm).

Tortuosity is related to the mean pore channel length (L_p , in.) and the sample length (L , in.) as:

$$\tau = \left(\frac{L_p}{L}\right)^2$$

Equation 3.3

Where all variables are defined.

Equation 3.1 relates intrinsic permeability (ft²) to porosity, where the intrinsic permeability of a porous medium, such as shale, reflects the capacity of the rock to allow fluid flow independent of the fluid properties (Surbeck & Kuo, 2021). In contrast, hydraulic conductivity measures how well a medium can transmit flow and depends on both the material and fluid properties. Hydraulic conductivity is related to intrinsic permeability (K , ft²) as:

$$K = \frac{k\mu}{\rho g}$$

Equation 3.4

Where:

k = hydraulic conductivity (ft/s),

μ = dynamic viscosity of water at the test temperature (lbs-s/ft²),

ρ = density of water at the test temperature (slug/ft³), and

g = gravitational constant (ft/s²).

Tortuosity from Equation 3.3 was assumed to be $\sqrt{2}$ and then reduced successively with each cycle in Equation 3.1 until the weathered specimen results, which were assumed to be 1. A tortuosity of 1 (i.e., pore channel length equal to the sample length) represents the shortest flow path, which was likely when the specimens were fully weathered.

Urumović and Urumović (2016) relate the intrinsic permeability (K , ft²) to effective porosity (n_e , %) using the geometric particle size diameter as:

$$K = \frac{d_g^2 C}{72\tau^2} \frac{n_e^3}{(1-n_e)^2}$$

Equation 3.5

Where:

d_g = geometric mean particle size (ft),

C = 11.25, constant accounting for the density of water, viscosity of water, and gravitational constant, and

n_e = effective porosity.

Effective porosity was used to account for the clay-bound water surfaces due to the relatively high percentage of clay minerals in clay shales. The effective porosity was calculated for each sample at the initial, undamaged intrinsic permeability. The final Kansas shale porosity, defined as:

$$\phi = n_i \frac{n_e}{n_0}$$

Equation 3.6

Where:

n_i = porosity from i^{th} cycle (i.e., via Equation 3.1),

n_e = effective porosity (i.e., cycle 0 intrinsic permeability via Equation 3.5), and

n_0 = porosity of the initial measurement (i.e., cycle 0 intrinsic permeability via Equation 3.1),

was calculated for each site for all cycles. A linear regression was conducted based on data from the Kansas shale porosity as a function of the number of cycles. The prediction line was calculated and a bounded curve, ± 1 standard deviation, was generated to highlight the model's accuracy. The goal of the prediction line was to use the Kansas shale porosity and known number of cycles to predict the number of cycles to achieve porosity of the weathered specimens. This method will allow KDOT to estimate the expected time for exposed cut slopes to transition from intact to fully weathered specimens, or non-erodible to highly erodible materials.

Chapter 4: Results

According to the Unified Soil Classification System (ASTM D2487, 2017), all the specimens in this study were classified as clay. Based on the slake durability and plasticity index shown in Table 4.1, all specimens have a shale rating of 2 or less (Franklin, 1981). Figure 4.1 shows the particle size distribution of the samples.

Table 4.1: Shale Characterization

Location	Color	LL	PI	USCS	Moisture Content (%)	P200 (%)	Slake Durability Index (%)*
Salina	Grey	56	33	CH	9.1	82.8	3.6
Lawrence	Red	50	29	CH	20	98.0	0.3
Toronto	Grey	45	22	CL	8.2	97.2	8.9
Neal	Brown	44	19	CL	8.8	82.3	0.7
Topeka	Grey	37	20	CL	8.7	96.4	2.0

*after second cycle

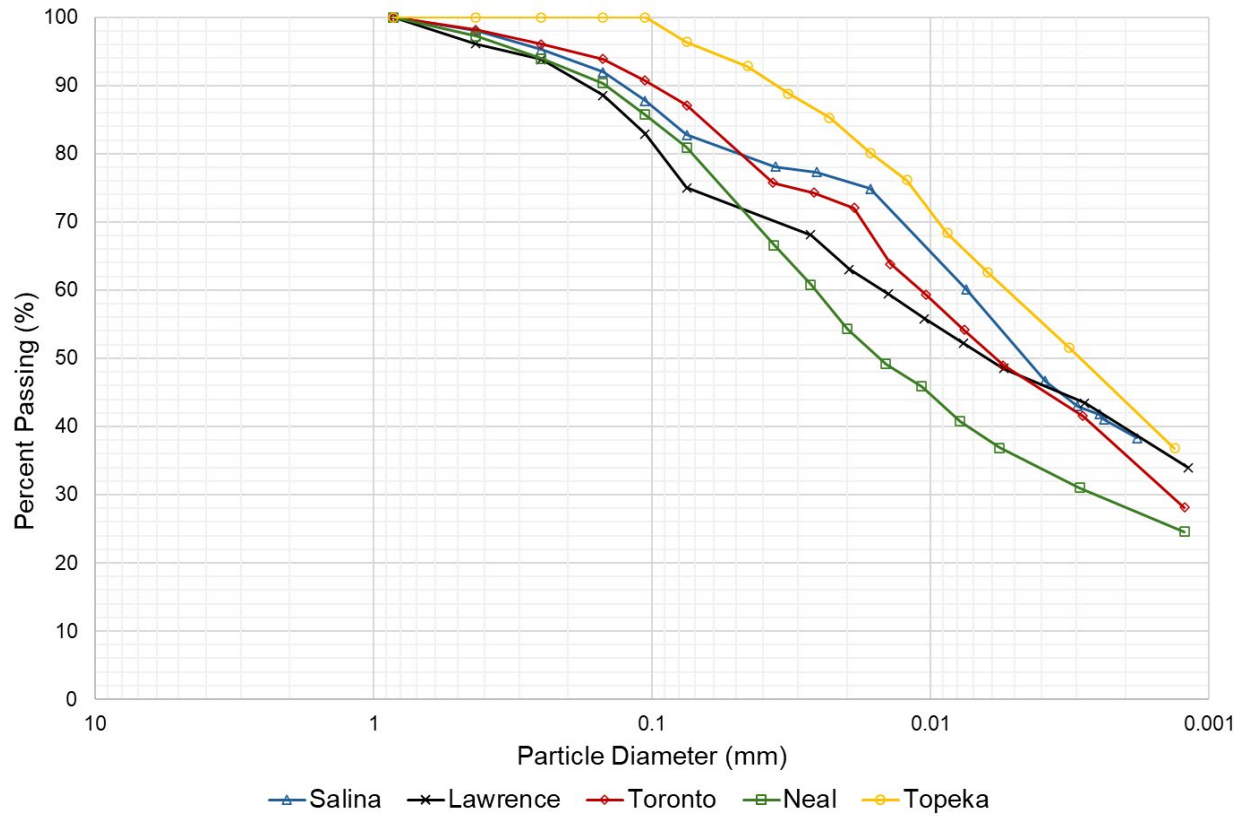


Figure 4.1: Particle Size Distribution of Shale Specimens

Table 4.2 includes the particle size information extracted from the particle size distribution data that were used in the porosity calculations. Although all specimens were fine-grained, Neal was the coarsest sample and Topeka the finest.

Table 4.2: Shale Characteristics Based on Particle Size Distribution

Location	Median Grain Size, D50 (mm)	Geometric Mean Grain Size, Dg (mm)	Percent Finer 0.002 mm (%)
Salina	0.005	0.006	36.9
Lawrence	0.006	0.009	38.7
Toronto	0.006	0.005	34.6
Neal	0.015	0.010	27.5
Topeka	0.003	0.001	43.7

4.1 Erosion Test Results

The erosion results plotted in Figure 4.2 show that the Lawrence, Toronto, and Salina samples compacted at a dry density of 75 pcf, earning a classification of “very high erodibility,” while the 75 pcf Neal sample was classified as “high erodibility.” The Salina and Toronto samples compacted to a dry density of 87.4 pcf and were classified as “very high to high erodibility,” and the Lawrence and Neal samples classified as “high erodibility.” In all cases, the relatively looser sample (75 pcf) was more erodible than the relatively denser sample (87 pcf).

Figure 4.3 shows the critical shear stresses and critical velocities for these specimens, which increased with dry density, meaning soil erodibility decreased as the dry density increased, as expected. The Neal sample was the least erosive of all the loose samples, with a notably higher critical shear stress than the other sites in Figure 4.3b. However, the critical shear stress of the loosest Neal (75 pcf) was higher than the relatively denser Salina, Lawrence, and Toronto specimens (87 pcf).

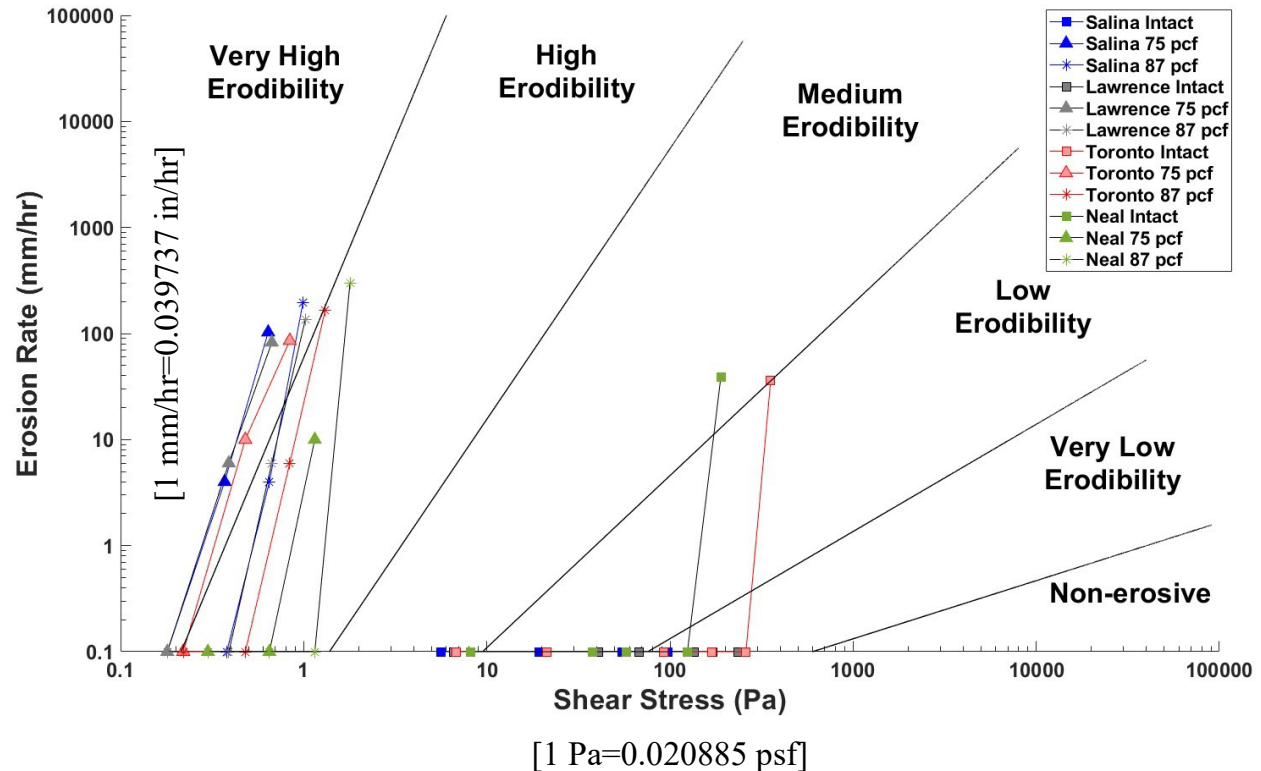


Figure 4.2: EFA Results for Intact Samples and Weathered Specimens

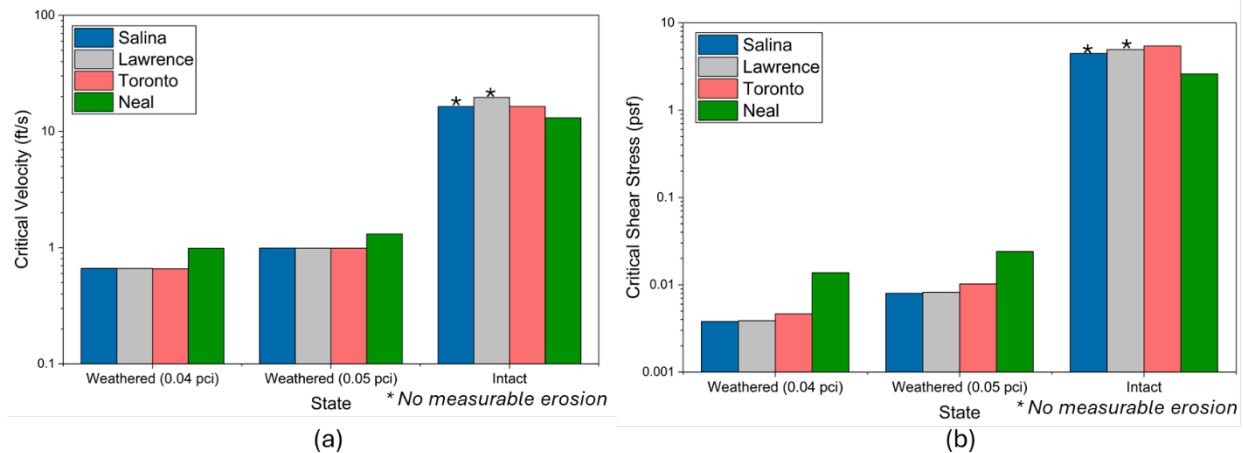


Figure 4.3: Erosion Results for All Sites: (a) Critical Velocity; (b) Critical Shear

All loose, weathered specimens were more erodible than the intact specimens. In fact, only the Toronto and Neal intact samples eroded. Measurable erosion occurred at the highest water velocity for Toronto and Neal. Note that the intact Salina and Lawrence specimens are the final shear stresses and velocities, not the critical shear stresses and velocities because they did not erode. Although all critical shear stress values (i.e., shear stress at erosion or final shear stress when no erosion occurred) in Figure 4.2 plot in the “very low erodibility” zone, the two samples that did erode transitioned to “medium erodibility.” Figure 4.3b shows that all intact specimens had very high final shear stresses. The Toronto sample eroded at 16.4 ft/s and the critical shear stress was the highest at 5.4 psf. The Neal sample eroded at 13.1 ft/s and the critical shear stress was the lowest at 2.6 psf. Because the Lawrence and Salina samples did not erode at the highest water velocity in the EFA, the shear stresses in Figure 4.3b are the minimum expected critical shear stress. The true critical shear stresses for the Lawrence and Salina samples were likely higher than the Toronto specimen.

4.2 Freeze-Thaw Experiment Results

4.2.1 Water Content and Surface Cracks

After each freeze-thaw cycle, the water content was measured, resulting in a consistent pattern where the water content decreased with each cycle. As shown in Figure 4.4, the water content in the Neal shale decreased by 1%–2% with each freeze-thaw cycle, and the cycles

continued until a constant mass was achieved. For example, Neal F-T 1 had a final water content of 0.29% after 12 cycles, but the process continued for two more cycles to ensure stability. Neal F-T 2 had zero moisture content after 11 cycles, but the process continued for one more cycle. Final water contents with freeze-thaw cycles could not be determined until the final dry mass was measured at the end of testing. For this measurement, the process was stopped after two consecutive mass measurements.

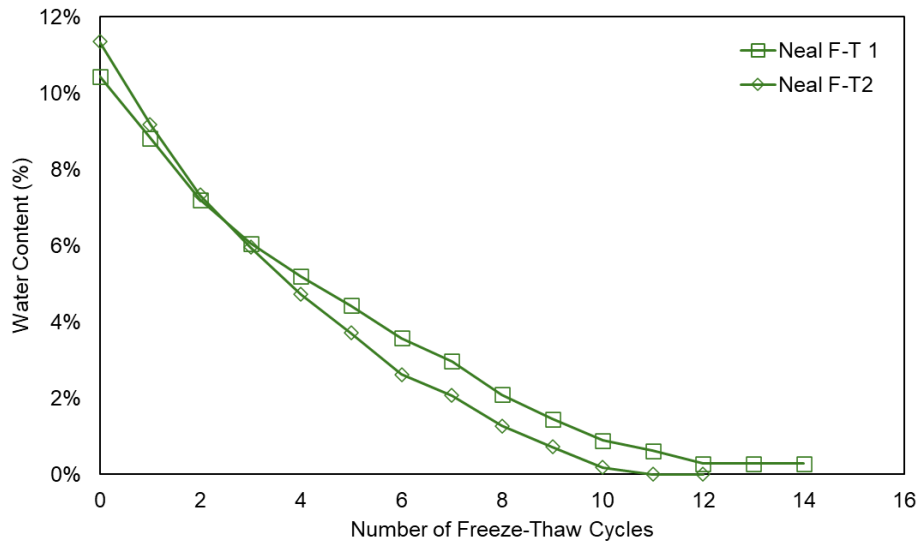


Figure 4.4: Water Content Changes During Freeze-Thaw Cycles for Neal Intact Samples

As water content decreased, the shale experienced increased brittleness and susceptibility to cracking, potentially enhancing permeability and reducing structural integrity. Figure 4.5 shows crack progression in the Neal sample, from the initial measurement to the final for the two rounds of tests. At the end of F-T 1, cycle 11, cracks appeared across the sample, but after resaturating, as shown in Neal F-T 2 (following hydraulic conductivity testing and before F-T testing), the cracks appeared to reseal. However, prevalent cracking was noted at the end, F-T 2, cycle 22. These cracks were also observed in F-T 1, cycle 11, but they were larger and more connected across the sample after the second round, as correlated with the increased hydraulic conductivity following the second round of freeze-thaw testing reported in the following section.

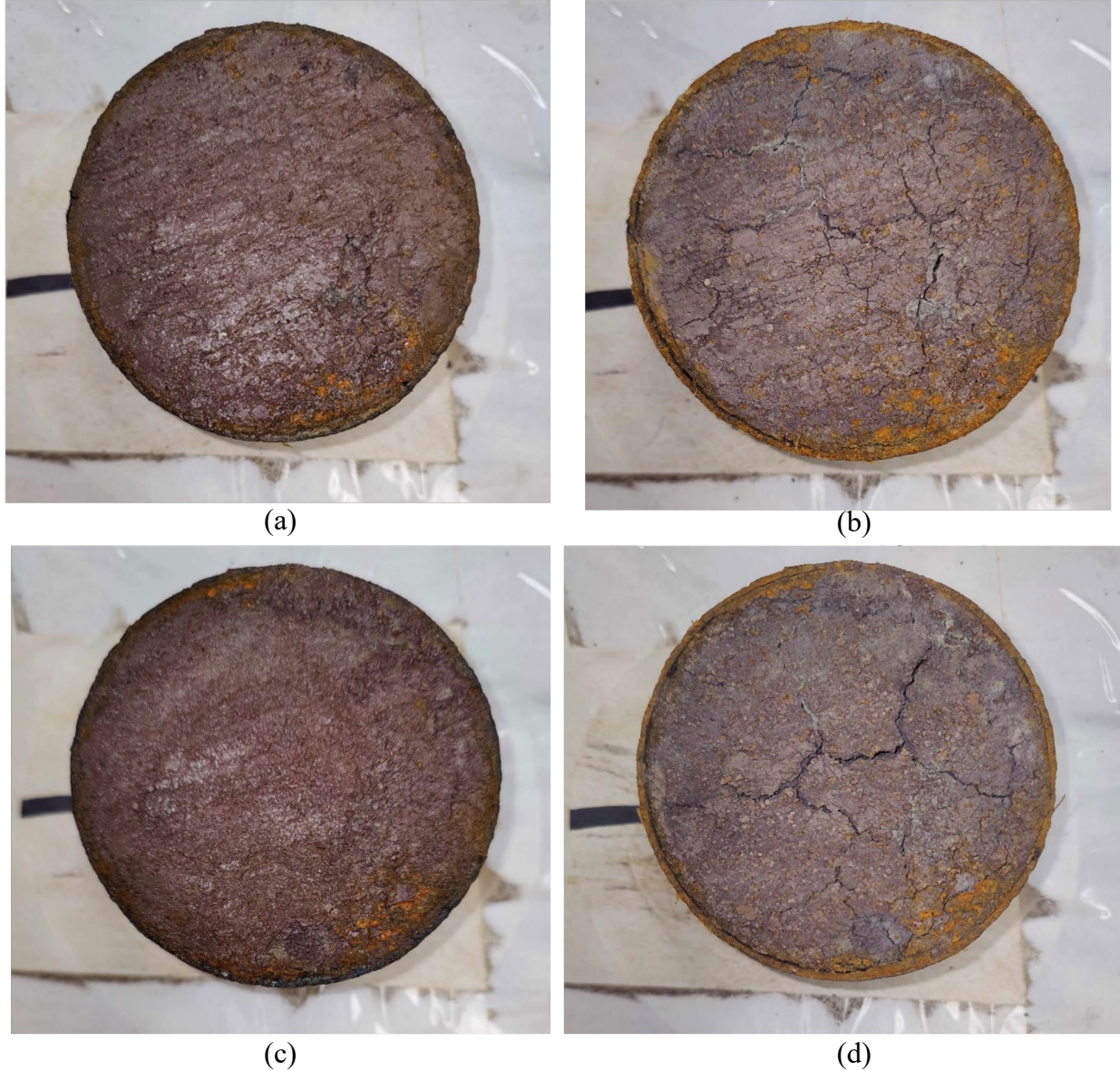


Figure 4.5: Water Content Changes During Freeze-Thaw Cycles for Neal Intact Samples:
 (a) Neal F-T 1, Initial (Cycle 0); (b) Neal F-T 1, End (Cycle 11); (c) Neal F-T 2, Initial; (d)
 Neal F-T 2, End (Cycle 22)

4.2.2 Hydraulic Conductivity

The results of the falling head permeability test conducted on the five shale samples are shown in Figure 4.6. From left to right, the first boxplot, k_0 , shows the hydraulic conductivity for each shale in its intact condition. Followed by k_1 and k_2 , which correspond to the first and second sets of freeze-thaw cycles, respectively. The dashed line in the Neal samples shows where a second test was run, thus an additional k_0 and k_1 . This was done because the first Neal k_1 reduced relative

to k_0 . The additional data supported the k_0 value. The hydraulic conductivities of the Salina, Toronto, and Topeka shale samples were initially lowest, in the order of $10E^{-06}$ in./second. The Neal and Lawrence samples initially had hydraulic conductivities in the order of $10E^{-04}$ in./second. The Salina, Lawrence, Toronto, and one Neal specimen increased in hydraulic conductivity as freeze-thaw cycles occurred. An additional series of measurements on a Toronto specimen and Neal specimen were collected and used for model validation. The validation data are included in the Appendix.

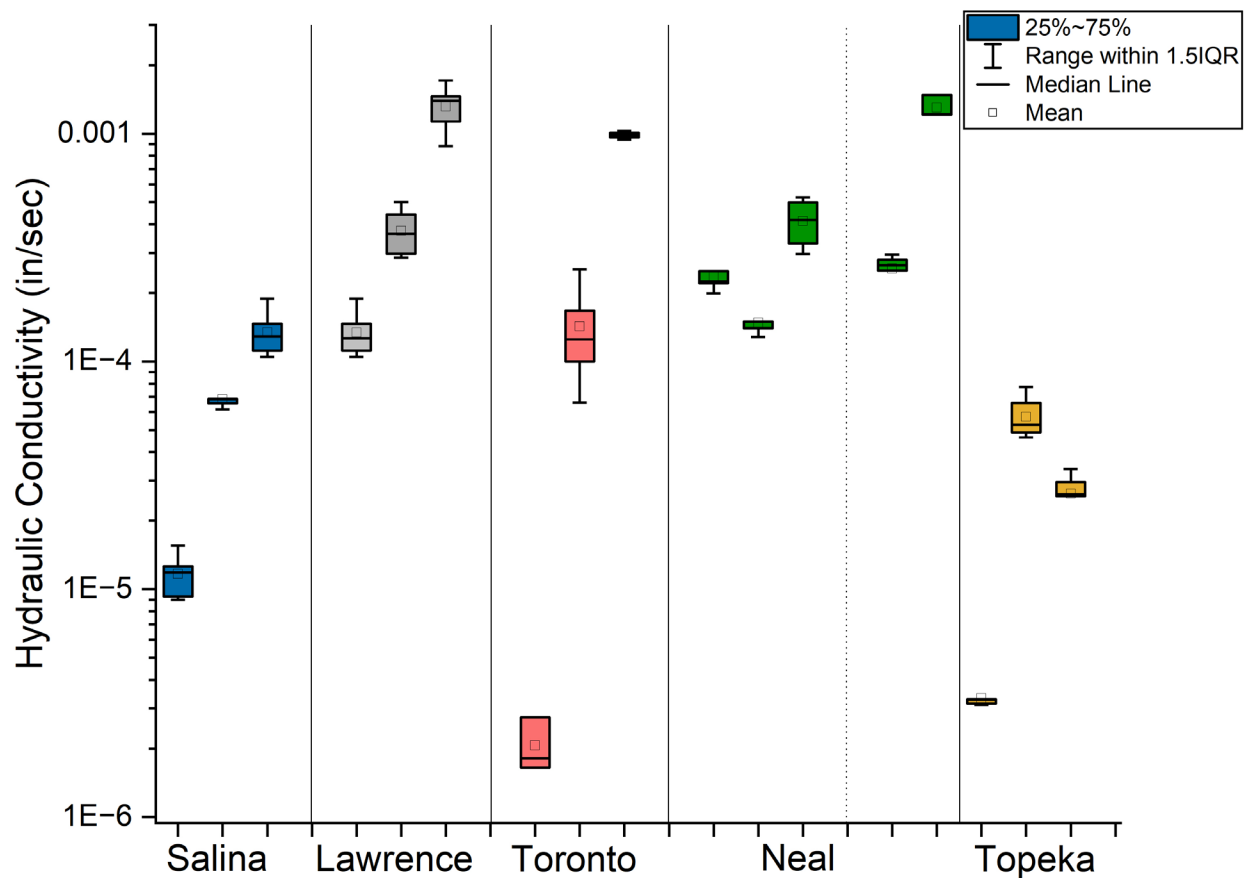


Figure 4.6: Impact of Freeze-Thaw Cycles on Hydraulic Conductivity

The results of the constant head permeability tests for four weathered samples are shown in Figure 4.7. The Topeka sample was not tested. All weathered hydraulic conductivity data are larger (i.e., faster flow) than the falling head data from the same sites. Among the weathered data, the Toronto results are an order of magnitude lower than Salina, Lawrence, and Neal.

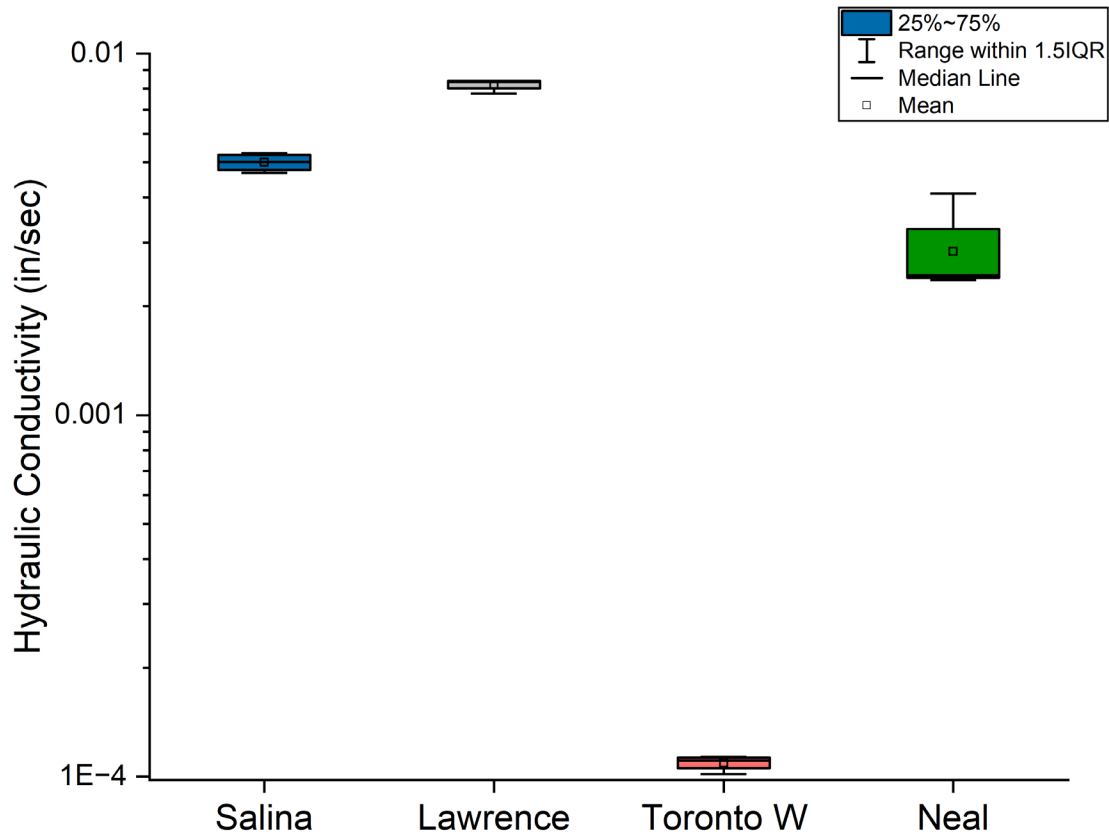


Figure 4.7: Hydraulic Conductivity of Weathered Shale

4.2.3 Kansas Shale Porosity

Understanding how in-situ porosity changes under the impact of freeze-thaw cycles is essential to understanding the erosion characteristics of shales. Therefore, this study utilized hydraulic conductivity data to determine the ratio of porosity after accounting for fines and effective porosity to further account for bound water in the clay. Kansas shale porosity changes were monitored after various freeze-thaw cycles, revealing the natural transition from intact to weathered conditions without damaging the shale.

Table 4.3 shows the intrinsic permeability (K , ft^2), tortuosity (τ), effective porosity (n_e), and the Kansas shale porosity (ϕ) for each sample as a function of the number of freeze-thaw cycles. Tortuosity of the Lawrence sample was taken as 1 for all samples due to its high hydraulic conductivity, potentially due to sample disturbance. The second Topeka specimen, which was the highest measurement for that site, was removed from the analysis.

Table 4.3: Freeze-Thaw Cycles Required for Shale Degradation

Location	Freeze-Thaw Cycle Number	K_{Average} (ft ²)	τ (unitless)	n_e (%)	$\phi = n_i * \frac{n_e}{n_0}$ (%)
Salina	0	3.25E-13	1.41	19.7	19.7
	8	1.90E-12	1.37	-	26.5
	16	3.75E-12	1.33	-	28.7
Lawrence	0	3.73E-12	1.00	25.1	25.1
	11	1.04E-11	1.00	-	28.9
	21	4.83E-11	1.00	-	32.6
Toronto	0	5.75E-14	1.41	14.0	14.0
	10	3.96E-12	1.37	-	32.3
	22	2.74E-11	1.31	-	40.0
Neal	0	6.55E-12	1.41	33.4	33.4
	22	9.58E-12	1.29	-	35.5
	40	3.62E-11	1.21	-	41.4
Topeka	0	8.77E-14	1.41	28.8	28.8
	21	8.04E-13	1.31	-	39.8

The porosity ratio is the Kansas porosity at the measured cycle over the effective porosity, which is also the Kansas porosity at cycle zero. For example, from Table 4.3, the average porosity of the Salina sample at eight cycles was 26.5% and the effective porosity was 19.7%, meaning the porosity ratio at eight cycles for Toronto was 1.35. A regression line was fit to these data to represent a general trend of porosity ratio versus the number of cycles for Kansas shales to estimate the unknown number of freeze-thaw cycles required to reach porosity of the weathered specimens for each site using the following equation:

$$n_w = (0.016T + 1.17) * n_e$$

Equation 4.1

Where:

n_w = weathered specimen porosity (Equation 3.1),

T = number of temperature cycles, and

n_e = effective porosity (Equation 3.5).

The number of cycles for the weathered shale was determined for each site using measured porosity in the degraded state relative to each effective porosity. Figure 4.8 shows the effective porosity versus freeze-thaw cycles and the model (Equation 4.1). An additional Toronto specimen and Neal specimen not included in the model are shown with hatched markers. These serve as

model validation—both are within two standard deviations. The number of temperature cycles for the weathered samples were predicted using Equation 4.1 and shown with filled markers. The predicted Toronto and Neal data are based on the respective validation sample initial effective porosities. Unfortunately, there were not sufficient samples for Salina and Lawrence validation; therefore, those weathered data predictions are based on the effective porosities in Table 4.3.

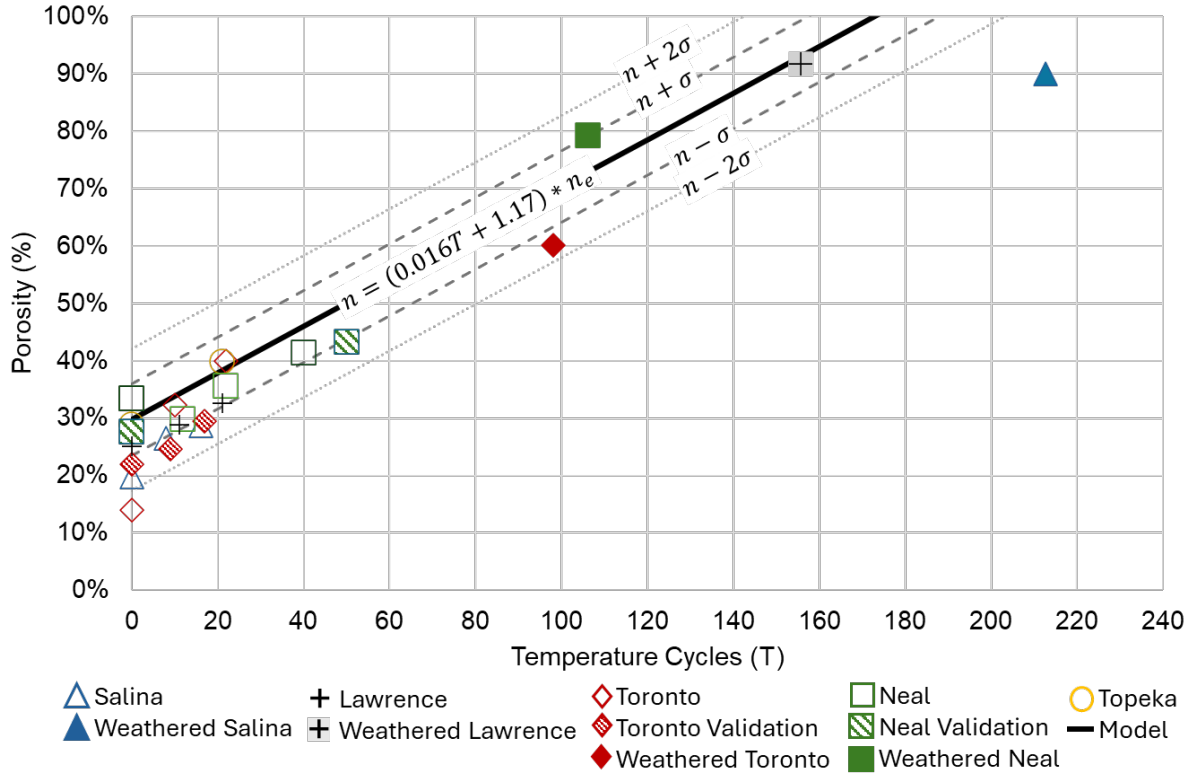


Figure 4.8: Porosity Versus Freeze-Thaw Cycles

The Salina sample experienced the greatest increase in porosity, starting at 19.7% (before freeze-thaw) and ending at 90.0%. The large increase resulted in a poor model fit and prediction of 213 temperature cycles. By contrast, the Toronto validation sample started at 21.9% effective porosity and ended at 60.1%, which was predicted to occur after 98 cycles. All measurements, except the initial Toronto and weathered Salina, were within two standard deviations of the model with 56% of the data falling within one standard deviation. The mean absolute error (MAE) of the model including all validation and weathered data is 6.24%. If Salina validation is excluded, the MAE is 5.42%.

Table 4.4 shows the number of freeze-thaw cycles and number of years required to reach degraded porosity of the four shale samples. Based on the temperature data in Table 3.2, nine freeze-thaw cycles per year were used for all sites. As shown, Salina required the highest number of freeze-thaw cycles to reach degraded porosity, while Toronto needed the least number of freeze-thaw cycles. The prediction indicated that the Toronto sample would degrade within 11 years, while degradation for the Salina sample was predicted to exceed 23 years.

Table 4.4: Number of Freeze-Thaw Cycles for Weathered Porosity

Shale Location	Number of Cycles to Reach Degraded Porosity	Number of Years to Reach Degraded Porosity
Salina	213	23.7
Lawrence	156	17.4
Toronto	98.5	10.9
Neal	107	11.9

Chapter 5: Discussion

This study directly measured the erodibility of four shale samples in intact and weathered states. Research objectives included determining the erodibility of the samples and estimating how long the degradation process may take to transition from intact material to the loose material on exposed cut slopes in Kansas. Establishing this timeline may allow KDOT to incorporate these predictions in an asset management plan.

However, erosion testing of the intact shale was difficult because all the samples showed very limited erodibility. Previous research on shale erosion used methods such as cavitation jet tests, which force erosion by increasing upstream pressure and measuring mass loss (Chi et al., 2022), thereby correlating erosion rate with upstream pressure rather than assessing the natural erodibility of intact shale on slopes. Therefore, this study utilized EFA testing, which can apply relatively high sheet flow-like conditions, similar to the flow regime over a cut slope. Although the Neal and Toronto samples eventually eroded, they did so at very high water velocities, while the intact Salina and Lawrence samples did not erode. In weathered states, all specimens were very erodible, with Neal shale demonstrating the most erosion resistance. Overall, the erosion characteristics of the intact shale and weathered shale were similar in identical conditions. Results of slake durability testing, the common measurement used to characterize shale (Erguler & Shakoor, 2009), also yielded similar durability results among the specimens. Shale ratings based on the slake durability indices and plasticity indices were between 1 and 2. Although Franklin (1981) recommended limiting cut-slope angles to 3H:1V for a stable cut slope in shales with this rating, results of the erosion testing showed that limiting the slope does not limit the shale erodibility. Initially the material was very erosion resistant, but it became highly erodible as it weathered. Limiting the slope angle was not expected to minimize overall erosion.

Because the erosion, slake durability, and general geotechnical properties of the specimens did not vary significantly, this study sought to determine if the time to transition to a highly erodible sediment could be developed. Field experience from these sites indicated that the time to degrade is variable once a slope is cut and the shale is exposed. Shale erodibility is commonly associated with porosity, where higher porosity indicates higher potential to erode, so the

prediction method in this study was based on porosity. Advanced methods such as mercury intrusive porosimeter can directly measure porosity (Huang et al., 2020), but sample preparation destroys the specimen. This study utilized hydraulic conductivity as an analogous measurement to estimate porosity from a modified version of the Kozeny-Carman equation. Hydraulic conductivity testing also allowed changes in porosity to be monitored via a series of freeze-thaw tests that were used to degrade the samples. Walkinshaw and Santi (1996) identified a shale hydraulic conductivity range of 3.9^{-11} in./sec to 3.9^{-6} in./sec for cut slope and embankment design. The results of this study showed hydraulic conductivity for intact shales ranging from 3.9^{-7} in./sec to 3.9^{-4} in./seconds.

As expected, hydraulic conductivity in this study increased with increasing numbers of freeze-thaw cycles. Using nuclear magnetic resonance, Wang et al. (2022) found that hydraulic conductivity increases with freeze-thaw cycles, while Bowders and McClelland (1994) analyzed freeze-thaw impact on shale hydraulic conductivity and suggested that freeze-thaw cycles cause the expansion and contraction of water within the shale matrix, leading to larger pores and fissures. The enlarged pathways ease fluid flow through the shale, consequently enhancing hydraulic conductivity. The enlarged pathways were tracked via qualitative analysis of the surface of the specimens. As shown in Figure 5.1, the fractures enlarged over time but maintained a consistent pattern between successive hydraulic conductivity tests, suggesting that a limited number of new branching cracks also appeared on the surface. The crack pattern in the oven-dried condition appeared as a cross-sectional crack on the shale surface, as similarly observed by Rayhani et al. (2008). Tracking the crack evolution revealed whether new cracks formed or existing ones expanded, and in which direction they grew with each cycle.



Figure 5.1: Crack Development on Toronto Shale Surface: (a) Surface Crack After 8th Freeze-Thaw Cycle; (b) Surface Crack After 18th Freeze-Thaw Cycle

The porosity prediction model, based on the hydraulic conductivity data, was used to determine the number of cycles required to achieve the weathered state. For example, the Salina shale required 213 cycles to reach the porosity of degraded shale, and the Lawrence shale required 156 cycles to reach the degraded shale porosity. The model was validated with an extra Neal sample not used in the dataset and run to 50 cycles. The prediction suggested that the Neal shale would require approximately 106 cycles to reach the porosity of degraded shale, translating to approximately 12 years. A second Toronto validation specimen was run to 17 cycles, from which the model predicted 98 cycles to degrade, or approximately 11 years. The two samples with fewer cycles predicted to degrade were also the two that eroded in the EFA, the Neal and Toronto samples.

Chapter 6: Conclusions and Recommendations

Although weathered shales are commonly observed on natural or cut slopes in Kansas, this is not their original condition. Shales degrade gradually from an intact state to weathered sediments, resulting in sediment transport that must be managed. Therefore, accurate prediction of the onset of erosion for intact shales is essential. The simple, effective approach developed in this study used the falling head permeability test on a specimen within the Shelby tube to measure hydraulic conductivity of the samples. The Shelby tube with sample was then exposed to successive freeze-thaw cycles representative of temperatures in eastern Kansas, followed by another series of falling head tests. The results were used to calculate the Kansas shale porosity because an increase in porosity is associated with an increase in erodibility. This method showed how porosity changed under freeze-thaw cycles and established that each site was unique. For example, the porosity of the Toronto sample increased slowly, while the Salina sample increased more rapidly. The novelty of the falling head setup for shale samples in the Shelby tube was its ability to keep the shale samples intact, allowing for accurate measurement of initial porosity and tracking changes due to freeze-thaw cycles. The prediction results showed that the Toronto site would degrade the fastest and Salina the slowest. Two validation tests showed that the model trend is consistent with specimens outside the dataset. Additionally, three of the four degraded specimens, which were not used in model development, fall to the right of the model line, which is conservative.

Researchers and engineers can use the methods established in this study on in-situ shales to predict degradation timelines without highly specialized erosion testing. Collecting in-situ shales and conducting the falling head permeability test ensures that the shale properties remain unaffected. Although a similar hydraulic conductivity apparatus could be made with couplers on either side of a Shelby tube to connect a top and bottom reservoir, the samples should be back-saturated (i.e., flow driven from the bottom of the sample upwards by a differential head reservoir) to ensure the samples are fully saturated. Furthermore, the bottom reservoir should include a stiff mesh on which the Shelby tube rests to support the specimen.

Samples in this study were contained via filter paper, and minimal material was lost due to strong adhesion with the Shelby tube. However, future results would be more systematic by modifying the hydraulic conductivity apparatus to back-saturate the specimens and with a mesh over the bottom reservoir. This study was also limited by time since back saturating without applied pressure to force the water upwards requires significantly more time than gravity-driven flow (i.e., weeks versus days). The systematic study of freeze-thaw cycles followed by hydraulic conductivity tests until the samples became unsuitable for further testing provides a new, simple method for KDOT to gain insights into when shales may start to degrade. The regression model, herein, is not recommended to predict future samples since the samples and number of tests in this study were limited. Instead, future testing and analysis should be built on this model to allow for timely precautionary measures, such as the use of geotextiles, to maintain slope stability and prevent erosion.

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Appendix

Table A.1: Validation Data Not Included in Linear Regression Model

Location	Freeze- Thaw Cycle Number	k _{Average} (in/sec)	K _{Average} (ft ²)	τ (unitless)	n _e (%)	$\phi = n_i * \frac{n_e}{n_0}$ (%)
Toronto	0	1.25E-5	3.44E-13	1.41	22.0	22.0
	9	1.87E-5	5.21E-13	1.37	-	24.6
	17	5.29E-5	1.47E-13	1.33	-	29.5
Neal	0	1.27E-4	3.54E-12	1.41	27.6	27.6
	50	2.52E-3	7.00E-11	1.16	-	43.2

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