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THE USE OF LIME TO STABILIZE CLAY SOIL AGAINST
INTERNAL EROSION

by

Rawan Ibrahim Aqel

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Dedication

This work is dedicated to my family and to my life partner whom this work was not possible without their love and support...

Abstract

Internal erosion failure of soils in hydraulic structures is one of the most catastrophic failures in civil engineering projects. Therefore, it is vital to stabilize the soil against this phenomenon. Different materials and methods have been used to stabilize the soil in general such as cement, lime, fly ash, oil shale ash, burnt sludge and other solid wastes. The main objective of this study is to investigate the potential use of lime as a new stabilizing agent against internal erosion of cohesive soil. To achieve the goal of this research, two types of soils CH (Clay of High Plasticity) and ML (Low plastic silt) were selected and used. The selection of the cohesive soils was based on the physical properties of the soils such as gradation, clay content, silt content and Atterberg's limits. The two types of soils were mixed with lime at different percentages; by the dry weight of the soils. Specimens were remolded at 95% of maximum dry density and optimum moisture content. Two identical specimens from each soil were prepared at 95% of maximum dry density and optimum water content with 0.0% lime as control specimens. The Hole Erosion Test was employed to test the remolded specimens at three different curing times namely; 1 day, 2 days, and 7 days from the time of preparation. The different erosion parameters of the soil such as the friction factor, critical shear stress, and the coefficient of soil erosion, were evaluated and used to calculate the Erosion Rate Index. It was found that lime is more effective when used with CH type soil than with ML type of soil. The addition of 2.0% of lime by the dry weight of the soil will stabilize the CH type of soil, while more than double this percentage is needed to stabilize the ML type of soil. The Erosion Rate Index increased up to 5.7 (very slow erosion rate) at 2.0% and 5.0% lime for CH and ML type of soil, respectively. Additionally, it was found that the increase in the percentages of lime increased the Critical Shear Stress significantly and an increase in curing time increased the Erosion Rate Index and improved the stabilization of both soils against internal erosion.

Keywords: *Soil erosion; soil stabilization; internal erosion; piping erosion; hole erosion test; hole erosion index; lime stabilization.*

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Chapter 1. Introduction

In this chapter, a short introduction about internal erosion and piping is provided. The seriousness of the problem associated with internal erosion and piping in earthfill dams is discussed. Afterwards, the objectives as well as the main contribution of this study will be presented. Finally, this chapter ends with the thesis organization.

1.1 Overview

Erosion is one of the main attention areas to civil engineers especially when it falls under internal erosion of soil. Internal Erosion takes place when the flow forces are greater than resistance forces resulting from seepage in the reservoir of hydraulic earth structures. This erodes soil particles within the structure and transports them downstream [1]. (Wan and Fell, 2004, Lachouette, et al. 2008, Bezzazi, et al., 2010, Benaissa, et al. 2010) stated that internal erosion is the main cause of instability in earth fill dams and embankments [2][3][4][5]. Whereas Foster, et al. , (2000) proved that the piping and internal erosion are the main two factors causing failure of embankment dams [6].

Piping is one of the major and most dangerous types of internal erosion. It involves formation of a continuous tunnel where water flows between the upstream and downstream of the earth structure. This pipe will facilitate the eroding of the surrounded soil driven by the hydraulic gradient.

Piping erosion is extremely dangerous because the structure may fail completely within short time after the breach becomes obvious [7]. It is obviously hard to know the signs for failure; therefore, the best way to avoid such catastrophic failures of embankment structures is to take precaution measures by stabilizing the used soil against internal erosion formerly. This can be achieved by adding stabilizing materials that will interact with the soil particles to create a stronger structure. Moreover, it will prevent or at least reduce the piping effect and hence postpone the occurrence of failure of the structure.

In this research characteristics of stable soil will be discussed as well as methods to stabilize the soil. The main outcome of this research will be the possibility of using

lime as a cheap and available material for stabilizing the clayey soil against internal erosion. The optimum percentage of lime to achieve the above will be determined.

1.2 Thesis Objectives

The main objective of this study is to investigate the potential use of Quick lime to stabilize cohesive clayey soil against internal erosion. Two types of cohesive soils are mixed with different percentages of quick lime. Samples are prepared from the mixture and are tested to later calculate the rate of internal erosion at different lime contents and curing times. The Hole Erosion Test (HET) is conducted on the remolded specimens prepared at 95% of maximum dry density and at optimum moisture content to simulate field compaction conditions. The parameters obtained from the erosion test are used to determine the Erosion Rate Index (I_{HET}). Results are analysed to optimize the lime content and curing time to stabilize the cohesive soils against internal erosion.

1.3 Research Contribution

This work will help Geotechnical Engineers to utilize cohesive soil at its highest performance in engineering projects such as earth fill dams, embankments, and other earthfill structures. The investigation may lead to recommend lime; as a cheap and available stabilizing agent against internal erosion of cohesive soil. The result may show that the addition of a reasonable amount of lime to the soil will stabilize and prevent a catastrophic failure of a multi-million value projects and save lives and assets.

Moreover, this work will create a potential for future studies on the use of other materials such as fly ash, oil shale ash and some other solid wastes to stabilize soils against internal erosion. Lime stabilization of soil against internal erosion may be extended to stabilize the soil on highways and pavements which is also an ongoing area of study.

1.4 Thesis Organization

The rest of the thesis is organized as follow: Chapter 2 provides a background and explains the need of the further investigation of the topic by having a thorough literature review. In this chapter internal erosion of soil, its needs, factors affecting it and tests carried to find it out will be studied. Moreover, soil stabilization and lime stabilization will be discussed. Chapter 3 states the methodology that will be used in this thesis study. Chapter 4 explains in detail the experimental setup, procedure for the

experiment and the analysis procedure with all equations to be used. All the results obtained in the test and its analysis will be presented in Chapter 5. Moreover, a full sample calculation will be there. Chapter 6 contains the main conclusions as well as the recommendations and future work suggestions.

Chapter 2. Background and Literature Review

Stabilizing Soil against internal erosion is a well-known research area in which various studies have been made to fulfil this requirement. This literature review intends to know how far the studies have gone in studying soil stabilization against internal erosion.

This literature review is divided into three main sections. The first section discusses the internal erosion of soil in general and it has three subsections. Section 2.1.1 discusses internal erosion in earthfill dams and embankments. It also discusses the stages of internal erosion. Section 2.1.2 discusses the factors affecting the internal erosion of soil. And Section 2.1.3 lists the tests used to evaluate the internal erosion of soil. Hole Erosion Test (HET) is discussed in deep along with its updating developments, drawbacks, and effectiveness. The second Section of the Literature Review is discussing soil stabilization against internal erosion and the need of soil stabilization. Moreover, soil stabilization using different additives such as cement, fly ash, fibers, polymers, etc... is reviewed. Last section reviews lime as stabilizer of soil against internal erosion.

2.1 Internal Erosion of Soil

Internal erosion is a common phenomenon in hydraulic structures that takes place when the water seepage forces become more than the erosion resistance forces developed by the soil in a way that soil particles start to move and gets carried away by the water flow. This seepage forces induce erosion in both natural soil deposits and engineering embankment fill structures. Moreover, erosion through a structure does not happen uniformly and it increases where there is a concentration of seepage and water velocity [8]. Several changes take place in soil during erosion process. It causes changes in void ratio, hydraulic conductivity, and shear strength of the soil.

2.1.1 Internal erosion of soil in earthfill dams and embankments. Different types of internal erosion are recognized in hydraulic structures such as classical piping, progressive erosion, blowout (heave, uplift), scour and internal instability. Piping is one of the major and most dangerous types of internal erosion. It involves formation of a

continuous tunnel where water will flow between the upstream and downstream of the earth structure. This pipe will facilitate the eroding of the surrounded soil driven by the hydraulic gradient. Piping erosion is extremely dangerous because the structure may fail completely within short time after the breach becomes obvious [7]. Suffusion is another type of erosion that can be distinguished as a major type of internal erosion. It takes place when the small particles transported and pass through the pores of cohesion-less granular soils. Many factors affecting the suffusion such as density, grading and seepage flow. When the soil is susceptible to suffusion, the small particles washed away result in changing the microstructure of the soil which may induce mutation conditions in the soil. Figure 2-1 shows the piping formation in earthfill dams.

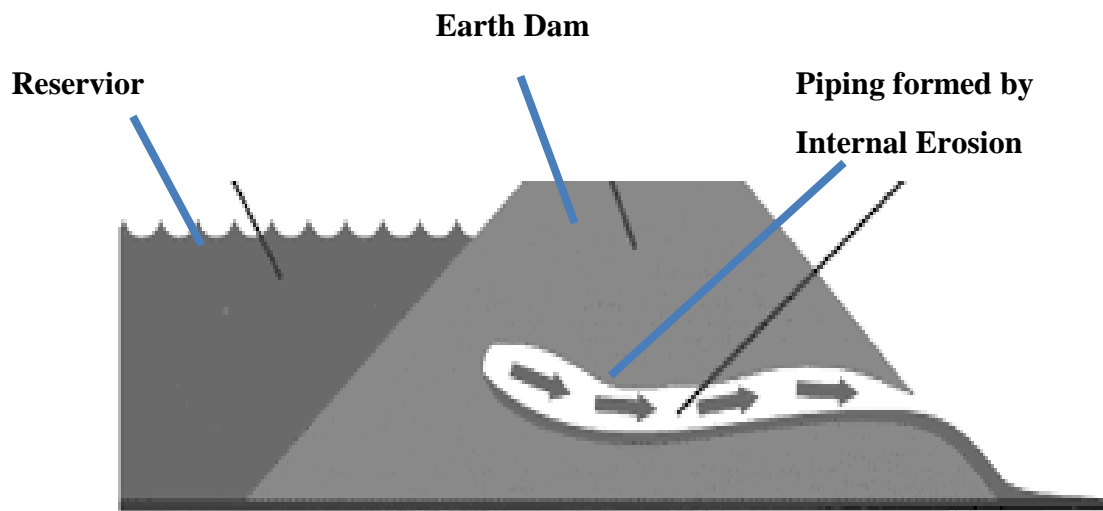


Figure 2-1: Piping Formation in Earth Fill Dam Due to Internal Erosion [9]

A recent study by Chang, D.S., et al., (2012) indicated that internal erosion can be initiated in embankment dams by four major components; leak erosion, backward erosion, soil contact erosion, and suffusion [9]. These mainly take place through embankment, foundation, or in between. Furthermore, Fell, et al. (2003) showed that erosion consists of four phases, where it starts by initiation, followed by continuation of erosion, then it will be forming piping, and finally forming a breach. Forming a breach, depends mainly on the ability of the soil to sustain an open pipe along with other factors such as hydraulic gradient, upstream and downstream conditions, and the rate of enlargement of the water path diameter.

Breach may occur by one of the following [10]:

- 1- Gross enlargement of the pipe.
- 2- Slope instability of the downstream face.
- 3- Unravelling of the downstream face.
- 4- Overtopping (may be due to settlement of the crest from the suffusion and/or the formation of sinkhole from a pipe in the embankment)

Figure 2-2 shows the piping effect in embankment:

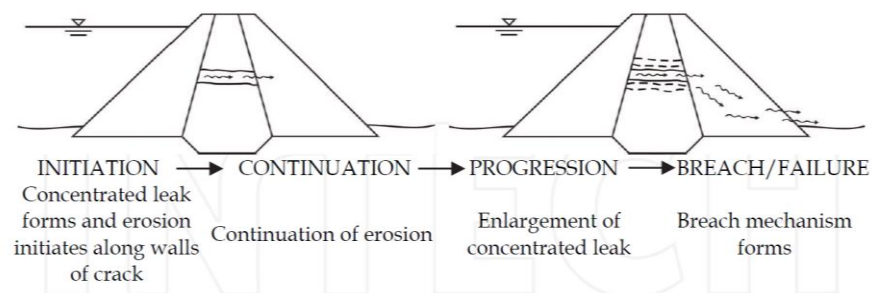


Figure 2-2 Piping in Embankment [10]

A study on un-fissured soil showed that this soil experienced backward erosion and then suffusion. The backward erosion is defined as the detaching of soil particles from each other by seepage forces and hence causing them to move from downstream to upstream. Whereas, suffusion erosion is due to the internal adjustment of unstable soils. Figure 2-3 and Figure 2-4 illustrate this behaviour of erosion in earth structures caused by backward erosion [10].

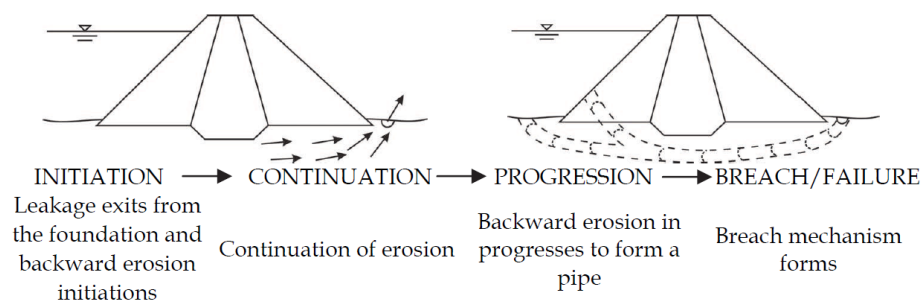


Figure 2-3 Piping in Embankment Initiated by Backward Erosion [10]

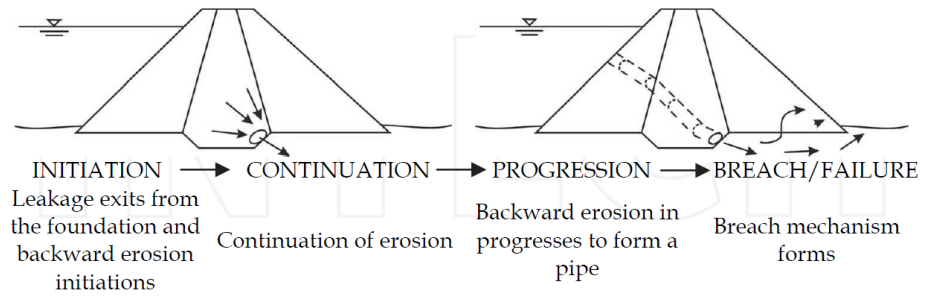


Figure 2-4: Piping from Embankment to Foundation Initiated by Backward Erosion [10]

Another type of erosion called concentrated leak erosion may happen in a crack that exists in the embankment or its foundation. This crack may be caused by differential settlement, desiccation, freezing and thawing, and by hydraulic fracture. Or it may also happen when there is a continuous permeable zone containing coarse material or poorly compacted materials which form an interconnecting voids system. The concentration of flow causes erosion of the walls of the crack or interconnected voids. Figure 2-5 shows this type of erosion.

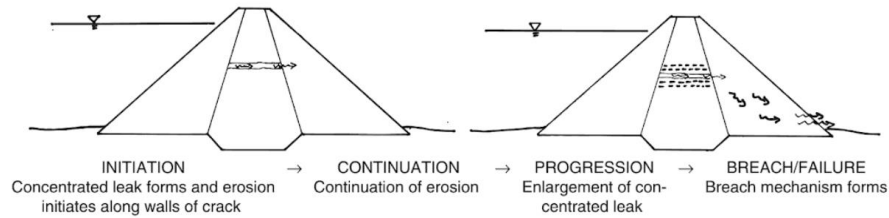


Figure 2-5 : Internal Erosion in the embankment in a concentrated leak [10].

In general soils contain some minerals that dissolve by water seepage especially if the soil contain gypsum, anhydrite, and halite . The dissolution of such soil minerals in embankment structures weaken the dam and furthermore such erosion resulted in sinkhole and huge settlement in the dam structure resulting in major failure.

2.1.2 Factors affecting internal erosion of soil. Erodibility of soil, water velocity inside the soil mass, and the geometry of the earth structure through its size and shape can be considered the main factors effecting the erosion phenomenon. Erodibility can be defined as the relationship between water velocity and the corresponding erosion rate experienced by the soil. However, this definition presents a problem as per Briaud (2008), as water velocity is a vector quantity which varies everywhere in the flow and is theoretically zero at the soil-water intercede. Therefore, erodibility of soil can be best defined as the relationship between the erosion rate ($\dot{\epsilon}$) and the shear stress (τ) [11].

On the above definition of erodibility, Briaud (2008) proved that there is a direct relationship between the erosion rate and shear stress and the type of the soil. Figure 2-6 shows the erosion categories as proposed by Briaud (2008). From Figure 2-6 it can be noted that grain size controls coarse grained soil erosion whereas plasticity controls fine soil erosion.

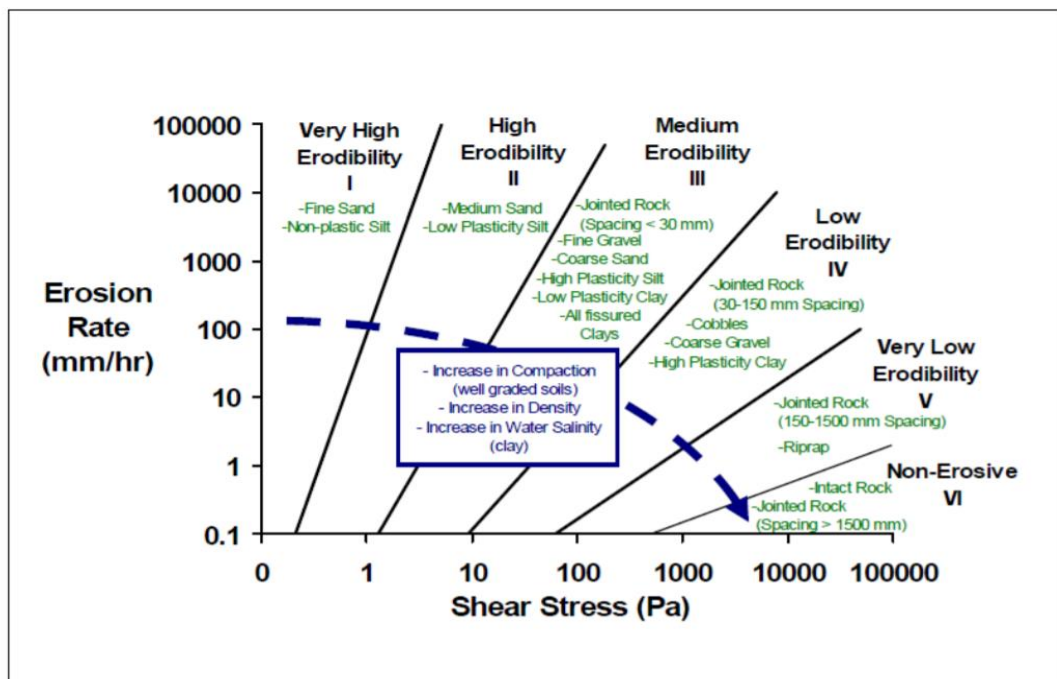


Figure 2-6: Proposed erosion categories for soils and rocks based on shear stress [11]

Briaud (2008) has also shown that other factors control the erodibility of the soil such as soil water content, unit weight, plasticity index, void ratio, soil swell, percent

passing sieve # 200, soil pH, and clay minerals. In general, these factors resemble the physical and mineral composition of the soil [11].

Moreover, Ke and Takahashi (2012), showed that non-cohesive gap graded soil erodes more because of the reduction in the strength and effectiveness of shearing resistant forces that results from the absence of some grain sizes [12].

On the same topic, other factors such as soil laying at site, the degree of compaction, and the homogeneity of the soil affect the soil erodibility [13]. Moreover, new factors affecting erosion of the soil were introduced by Skempton and Brogan (1994) and Tomlison and Vaid (2000) such as water flow velocity, flow direction, hydraulic gradient, and possible chemical reactions in the soil [14] [15].

Furthermore, Sherard, et al. (1967) stated that soils with greatest piping resistance are the well compacted high plasticity clays. In second place of resistance comes the well graded coarse sand and sand gravel mixture, where the uniform fine cohesion-less sands are the least resistant to piping effect. [16]

Wan and Fell (2004) indicated that the rate of erosion is significantly influenced by the degree of compaction, water content, and dependent on the soil fines and clayey size content. It was found that the soil at the dry side of the optimum water content on the compaction curve erodes more than the soil at the wet side with higher dry density. Whereas, for coarse grained and non-plastic soil, the erosion was more at higher dry density and the dry side of the optimum moisture content [2].

Casagrande (1968) stated that analysing erosion of soil started in the beginning of 20th century by Blight (1910) and lane (1935). Their studies showed that the erosion depends mainly on the type of soil. It was found that fine sand and silt are more susceptible to erosion than coarse sand or gravel. They introduced a new factor called percolation factor “*C*” as a function of three parameters defined in water head between upper stream and downstream, two directions (horizontal and vertical) water flow path, and the soil type. They concluded that in order to avoid erosion in the soil; “*C*” value should be greater than a minimum value based on the type of soil as shown in Table 2-1 [17].

Table 2-1: The Minimum Values of Percolation factors (C) to Avoid Piping Erosion, per Blight and Lane Criteria [11]

Material	$C_B = \frac{\sum b + \sum t}{h}$ (Blight criteria)	$C_L = \frac{\sum t + \frac{1}{3}\sum b}{h}$ (Lane criteria)
Fine sand and silt	18	8.5
Coarse sand	12	6.0
Gravel and sand	9	3.0
Boulders, gravel and sand	4	2.5

2.1.3 Tests for internal erosion evaluation. Various tests are addressed in the literature to evaluate soil internal erosion. These are, but not limited to, Pinhole Test [16], Jet Erosion Test [18] [19], Hole Erosion test, and Slot Erosion test [2].

In Pinhole Test, a flow of water passing through 1 mm hole in a specimen under hydraulic head is started to measure dispersibility and erodibility of fine-grains soil. Dispersibility of soil is assessed by visual inspection of the hole size after completing the test. Moreover, the effluent colour and flow through the hole gives an indication of erosion [16].

Whereas, Jet Erosion Test can be performed at site or on a sample. Where a hydraulic jet is produced by a 6.35 mm diameter nozzle that is 38-190 mm away from the surface of the soil sample. The water head is selected and usually held constant through the test duration. A scour on the soil surface beneath the jet will form and this scour is measured using a point gage that passes through the nozzle [20].

Hole Erosion Test (HET) simulate water flow under piping erosion condition like that takes place in earth fill dams in nature. Four steps to carry the HET First prepare a sample of soil compacted in a standard mold. Second, create a hole of 6 mm diameter throughout the longitudinal dimension of the sample to create a pipe for the water flow. Insert the sample in the test apparatus and finally run the water through the hole under a constant hydraulic head between the two ends of the sample [2].

The efficiency of HET as a screening tool for assessing risk of internal erosion of embankment dam was assured by Reclamations' Dam Safety Office who has commissioned a research team headed by Farrar [21]. Moreover, the simplicity as well as the straightforward use of the HET were highlighted as main advantages along with

the low cost of the test [2]. Throughout the literature search, it was noticed that many researches have approached the HET in their research projects and studies.

On the other side, Cao, et al. (2002) highlighted some limitations of the HET such as that the critical shear stress obtained from the best fit line between the erosion rate and the shear stress of the soil sample should be less than the initial shear stress in order to meet the model condition of collecting data during progressive erosion [22].

Moreover, assuming a one-dimensional model in that the diameter increases uniformly along the water flow path length may be another limitation, as some locations may erode more than others [22]. On the same type of test, Haghghi, et al. (2013) suggested an improvement of Hole Erosion Test by adding a turbidimeter and changing the analysis procedure to include the turbidity signal [23].

Slot Erosion Test (SET) is similar to Hole Erosion Test (HET) except that it deals with a much larger soil specimen compacted inside a 15 cm wide, 10 cm deep and 100 cm long rigid sample box. A slot is formed along one face of the sample. Afterwards, an eroding fluid is passed through the slot of the soil sample and it will initiate erosion. The width of the slot is measured at chosen time intervals and calculations will be done afterwards to estimate the coefficient of soil erosion (C_e) [2].

Moreover, Wan and Fell (2004) introduced a new erosion rate index (I_{HET}) value that gives indication about the soil susceptibility to erosion. The value of I_{HET} varies between 0 to above 6. The erosion decreases as the erosion rate index (I_{HET}) value increases as shown in Table 2-2 [2].

Table 2-2 : Qualitative Terms for Representative Erosion Rate Index [2]

Group Number	Erosion Rate Index	Description
1	< 2	Extremely Rapid
2	2-3	Very Rapid
3	3-4	Moderately Rapid
4	4-5	Moderately Slow
5	5-6	Very Slow
6	>6	Extremely Slow

Using Hole Erosion test (HET) and the Slot Erosion Test (SET), Wan and Fell (2004) used rates of internal erosion per unit area and hydraulic shear stress as indicators of soil erosion in cracks formed in embankment dams. Two main conclusions were drawn; first conclusion is that the type of soil plays major role in changing all values of erosion indicators and parameters. This was done by comparing course-grained, non-cohesive soils with fine grained soils; where the first type of soil eroded more rapidly and has lower critical shear stresses. Second conclusion is summarized in that soil properties, water properties, and cementing materials mainly affect erosion of soil [2].

2.2 Soil Stabilization

Soil stabilization is defined as the alternation or conservation of the soil physical and/or chemical properties for the purpose of improving its engineering characteristics and performance.

As per ASTM,1992, the soil is stabilized for three main purposes. These are: increased strength for the soil by enhancing the load-bearing capacity, permeability improvement, and traffic usage among others [24]. A main challenge to civil engineers is where clayey sub-grade exists; as clayey soil with high clay content have the tendency to swell when moisture content increases therefore the need for soil stabilization rises [25].

Soil stabilization can be achieved by either mechanically mixing the natural soil with non-soluble materials and stabilizing the material together to achieve homogeneity and desired engineering properties. Or by adding stabilizing material; where this material will react chemically with the soil and improve its engineering properties [26].

Generally, there are two common techniques for soil stabilization. These are mechanical stabilization and chemical stabilization. Mechanical Stabilization results in increasing the dry density and decreasing the void ratio of the soil. Moreover, mechanical stabilization is also defined as the process of enhancing the soil properties by changing its gradation. Mechanical stabilization is mainly achieved by densification of the soil by applying dynamic energy using various sorts of rollers, rammers, vibration techniques and in some cases blasting. It may also be achieved by mixing two types of

soil to attain an enhanced material that is superior to its components or by adding material that is insoluble in soil and works as reinforcement system [27] [28] [29].

Chemical stabilization, which is the second known technique for soil stabilization, depends mainly on the chemical reaction that happens between the soil particles and the additives. Chemical stabilization is considered to produce a soil with higher strength and durability than mechanical or physical stabilization [24].

In chemical stabilization different materials such as cement, fly-ash, lime, polymers, etc... are added to the soil. These materials chemically interact with the soil to improve its engineering properties.

The stabilization level and technique mainly depends on the type of soil. As per Sherwood (1993) fine grained materials are the easiest to stabilize because of their large surface area in relation to their particle diameter. On the other hand, silty material may prove difficult during the soils stabilization process as it is sensitive to a small increase in moisture content. Whereas, organic and peat soil are rich in water, have high porosity and high organic content. This type of soil has a high exchange capacity where it can hinder the hydration process. Therefore, a successful stabilization of this soil can only be achieved by proper stabilizer selection as well as the proper amount [30]

Multiple factors may affect stabilized soil strength. These are, but not limited to, organic matter, Sulphates, Sulphides, compaction, moisture content, temperature, and freeze-thaw and dry-wet effects [28]. Moreover, both physical and chemical stabilizations can be used together to achieve soil stabilization; for example, by adding lime as well as geo-fiber and geotextile together [28] [29] [31].

2.2.1 Need for soil stabilization. The need for stabilizing the soil against internal erosion is vital to reduce and eliminate the risk associated with this phenomenon. Fooster, et al. (2000) proved that the piping and internal erosion are the main two factors that caused failure of embankment dams [6].

The soil used to build up the earth-fill dams shall be categorized as strong stable soil against all the natural and artificial forces around it. Weak soil is defined as the soil that exhibit significant changes in its physical or mechanical properties due loading, changes in water content, or any environmental changes in the ambience. This

definition is frequently related to cohesive soil (mainly clay soil). On the other hand, clayey soils are generally characterized to have high expansion, high compressibility and settlement, low bearing capacity, and excessive erosion. These characteristics of a soil are the most important for a Civil Engineer to consider when designing /constructing any project to avoid project failure.

Recalling the above characteristics of strong stable soil, highly erodible soils are considered unreliable when designing hydraulic structures and embankment works, unless their physical and chemical characteristics are changed, which, rises the need for soil stabilization.

2.2.2 Soil stabilization studies. Several research studies have focused on searching for optimal stabilizers that decrease the effects of internal erosion in soils and ensure high stabilization. Researchers stabilized different soils against swelling, compressibility, settlement, collapsibility, and other undesirable physical properties using various additives [32]. Fibers, cement, lime, and solid wastes are example on materials added to the soil to stabilize it.

A recent study by Attom, et al. (2018) addressed the use of cement-polymer fiber admixture to stabilize the soil by reducing its collapsibility. In this study, it was found that adding 5% of this admixture with a ratio of 6:1 cement to fiber by dry weight of the soil changed the soil from very high collapsibility to almost no collapsibility range [33].

Furthermore, Attom, el. al (2017) further studied the effect of burned sludge age on the shear strength of clay soil. Where the sludge ash was burned at 550 °C and mixed with two soils at different percentages. The study showed the addition of about 7.5% of burned sludge to the clay soil increased both the cohesion and angle of internal friction of the soil [34].

On non-traditional stabilizers, H.M. Jafar (2013), studied the effect of adding Salt (NaCl) on commercial clay, River Air Soil, sand, and gravel. He found that treating the soil with 8% NaCl would result to an increase of 700 kN/m² in the unconfined compressive strength of the soil. Moreover, the maximum dry density of the same soil sample increased from 1.85 g/cm³ to 1.92 g/cm³ [35].

Further on non-traditional stabilizers, Tamadher (2007) added various amounts of Chloride compounds (CaCl_2 , MgCl_2 , and NaCl) to the soil with different percentages (2%, 4%, and 6%). He aimed to study the effect of these additives on consistency limits, compaction characteristics, and compressive strength. It was found that the increase in the percentage of each Chloride compound will increase the maximum dry density and will decrease the optimum moisture content. Moreover, the Atterberg limits decrease with the increase in the compounds content [36].

Lignosulfonate which is a non-toxic admixture that can stabilize soil effectively without causing any adverse environmental impact on the ground was used by Indraratna, et al. (2010). The test results have shown improvement in the erosional parameters such as critical shear stress and coefficient of soil erosion with the increase in the amount of Lignosulfonate added [37]

Lime treatment of soil was studied by Harrier, et al. in multiple studies. Where the effect of lime treatment was highlighted in a series of results belonging to series of studies. It was found that the shrinkage limit of lime treated soils were shifted towards higher moisture content and well above the optimum moisture content. The material has become non-dispersive in the standard crumb-test. And the critical shear stress was reduced by one or two orders of magnitude in the Hole Erosion Test and Jet Erosion Test [38].

Tang, et al. (2008) studied the use of synthetic fibers to improve the strength properties of expansive soil. In his study, it was found that adding synthetic fibers will strengthen the expansive soil, as well as transform the stress strain curve from a softening type to a hardening type [39].

On nylon and palmary fibers as additives, Al-Akhras, et al. (2008) used these fibers to improve the swelling properties of clayey soil. It was found that there is an inversely linear relation between the percentage of nylon or palmary fibers in the soil and the swelling pressure and hence the swell potential of soil. Moreover, it was found that palmary fibers were more effective on reducing the swelling pressure of the clayey soil [40].

Kumar et al. tested specimens of expansive soil mixed with fly-ash alone, lime alone, and fly ash and lime together at different percentages and different curing times. It was proven that expansive soil can be stabilized successfully by the combined action of lime and fly-ash [41].

2.3 Lime Stabilization

Lime treatment of soil is a process that improves the workability of clayey materials and imparts them strong mechanical properties after compaction [42]. Whereas, lime stabilization is well known technique that is used to stabilize clayey cohesive soils.

2.3.1 Lime as a material, its applications, its advantages, and disadvantages. Lime is a form of quick lime (calcium oxide CaO), hydrated lime (calcium hydroxide ($\text{Ca}[\text{OH}]_2$), or slurry. Hydrated lime is produced when quick lime chemically reacts with water. As per McDowell (1959), soil-lime mixture was used in road constructions thousand years ago by ancient Egyptian, Greeks, and Romans civilizations [43]. (McCaustland, 1925 also showed that hydrant lime was used to strengthen the short stretches in highways since 1924 as a first stabilizing agent [44]. Moreover, it was extensively used in constructing highways in the Second World War. Anon (1985, 1990), addressed the use of lime to improve engineering properties of sub-base and subgrade materials in rail roads, airports, embankments, slopes, and to improve the soil under foundation slabs [45], [46].

Lime can be used to treat soil in various ways. It can be used for short term objectives such as drying up of soil and improving soil workability and short-term strength. It also can be used for permanent structural stabilization of soils [47].

Advantages of using lime as stabilizer includes attaining stabilized soil in few hours because of the fast curing time of lime, and retaining high quality raw materials for quality application by small additions of lime. Moreover, savings on replacing soil layers, adding aggregate and disposal charges of material are major advantages especially in roads construction because of the large amount of area involved in such projects [48].

As stated by Jawadm et al. (2014) the below enhancements/advantages happen to the soil when lime is added to it [29]:

- 1- Enhancement in soil workability
- 2- Increase in soil strength.
- 3- Increase in durability.
- 4- Increase in compressibility.
- 5- Decrease in maximum dry density.
- 6- Increase in optimum moisture content.
- 7- Decreased Plasticity index resulted from a decrease in liquid limit and an increase in plastic limit.
- 8- Increase in soil fatigue strength.
- 9- Decreased swell potential and volume change.

On the other side, Jawad, et al. highlighted the below disadvantages of using lime in stabilizing soil [29]:

- 1- Carbonation which is the reaction happening between free lime and atmospheric carbon dioxide where it produces CaCO_3 . CaCO_3 is a Cementing material, however its production should be controlled for three main reasons; first it has weak bonding. Second, it is a soluble salt that may pulverize if exposed to air for long times. And finally it consumes the calcium ions which shall be used in the pozzolanic reaction to strengthen the soil.
- 2- Sulphate attack: when soil is treated with material that contained soluble Sulphate soil, a loss in strength may happen because of the soil distress, heaving and disintegration may happen from the reaction between Sulphate and water.
- 3- Environmental impact because of the production of calcium-based material where huge amount of carbon dioxide is emitted.

Glendenning, et al. (1997), provided a summary for the stabilization mechanism for improving clay soil in situ using lime piles. He stated that lime have been widely used in road construction to improve the soil workability, shear strength and bearing capacity by mixing the clay subgrades with Lime. Whereas the use of lime as a deep stabilizer was less common, three distinct methods existed. First is in China Japan, Singapore, and Scandinavia where lime columns have been used to prepare soft ground

for foundations. Secondly in USAR where lime slurry pressure injection was used. The third method is about lime piles which consist of holes in the ground filled with lime [49]

2.3.2 Lime as stabilizer. When lime is added to the clay particles in the presence of water, several complex reactions take place. At the initial stage three reactions happen, these are defined as drying, modification, and stabilization.

In drying, when quick lime is added, it reacts chemically on immediate basis with water and releases heat, soil gets dried as water previously present at soil is used to achieve this reaction. As shown in Figure 2-7 below, Water Content (W_n) is reduced to (W'_n) after treatment with lime, which means water content have become less [48].

In modification stage, a quick cation exchange between the calcium ion of the lime and metallic ions on the surface of the clay particles will make an immediate effect on the properties of the clay. This cation exchange reaction will convert the repulsion of clay particles to attraction between the particles and will lead to a flocculated state due to changing of the density of the electrical charges around the clay particles. In this stage, the plasticity index (PI) decrease significantly, as well as the soil tendency to swell and shrink (refer Figure 2-7). This process is also called flocculation and agglomeration and occurs in a matter of hours [48]

In stabilization stage, the PH of the soil increase to more than 10.5, where it enables the clay particles to break down. When clay is broken down, silica and alumina are released to react with the calcium free ions coming from the lime to form Calcium-Silicate-Hydrates (CSH) and Calcium-Aluminate-Hydrate (CAH). This is pozzalonic reaction. These hydrates form the matrix that increases the strength of the soil. As this matrix is formed, soil silica and alumina will react to form cementitious materials which in turn increases the soil durability and strength. The soil is hence transferred from weak granular material to hard nearly impermeable material. Moreover, the following soil properties are achieved: lower dispersion, less swelling and lower settlement, and increases particle size, increases strength and increases permeability [48] [50].

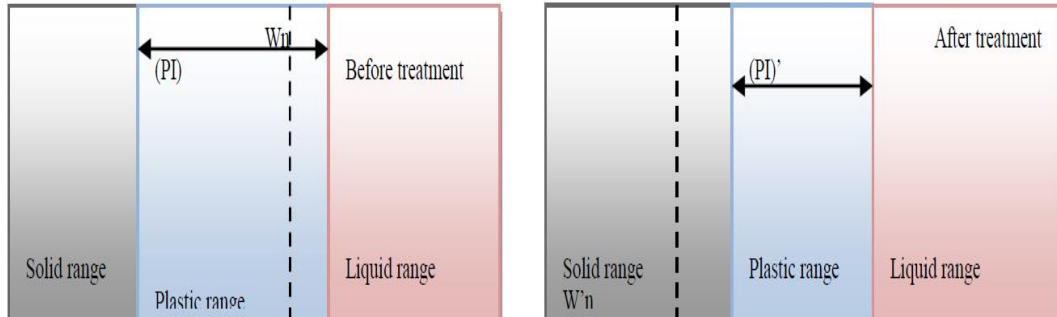


Figure 2-7 : Effect of Liming in Consistency of Soil [48]

It should be indicated that lime fixation should be satisfied in the soil. Lime fixation means that further addition of lime will not do any changes in plastic limit of the soil. Fixation limits is usually between 1% and 5% by dry weight of the soil. The amount of lime above this percent will not strengthen the soil [52]. James, et al. mentioned that when a soil is tested in a lab and found unsuitable it is no more rejected. The same soil is tested for the percentage of lime needed to stabilize this soil and bring it into specifications. James, et al. have studied the lime requirements for lime stabilization by a quick test. It was proven that PH tests on soil samples can determine the optimum lime requirement for the soil [53].

Other factors affecting the properties of the mixture include soil type, lime type and curing conditions. Clayey soil is mainly made from three types of minerals; kaolinite, montmorillonite, and quartz. The addition of lime has more effect on clay soil with high montmorillonite content, where the largest increase in plastic limits of clayey soils is noticed. Whilst the plastic limits of kaolinitic clays have increased but for a lesser extent [54]. Moreover, montmorillonite clay responded faster to lime, where it has achieved the strength earlier than kaolinitic clays. However, the strength achieved by Kaolinitic clays after some time was more than that achieved by montmorillonite clay at the same time [55].

In general, quick lime will enhance soil strength more than hydrated lime due to the presence of Ca^{2+} in greater amount. However, hydrated lime is more safe and easier to handle. Moreover, the increasing amount of lime will increase the strength but only for a particular curing period. In addition to that, the type and amount of clay materials used will influence the optimum lime content [50]. Temperature has a

significance influence on strength achieved. A more than 30°C temperature of curing time will increase the strength of lime treated soil dramatically [55].

Furthermore, in lime stabilization, the liquid limit of the soil decreases and plastic limit increases, hence the plasticity index decreases. The optimum moisture content increases and the maximum dry density decreases [56].

The methodology of stabilizing soil includes the below steps [48]:

1- Scarification and initial pulverization:



Figure 2-8: Scarification and initial pulverization of Soil [48]

2- Lime spreading:



Figure 2-9: Lime Spreading [48]

3- Preliminary Mixing and Watering:



Figure 2-10: Preliminary Mixing and Watering [48]

4- Final mixing and pulverization:



Figure 2-11: Final Mixing and Pulverization [48]

5- Compaction:



Figure 2-12: Compaction [48]

6- Final curing:



Figure 2-13: Final Curing [48]

Chapter 3. Methodology

In this chapter, the problem statement is presented as well as the method used to answer the problem question will be addressed. A brief explanation about the test used will be presented.

Overcoming the problem of internal piping of earth dams theoretically is hard to achieve for the complexity of the conditions as well as the multiple variables involved. The optimum way to study the effect of internal piping is by experimental tests rather than investigating the internal erosion characteristics of soil [57]. For this purpose, the Hole Erosion Test (HET) was introduced. As per Wan and Fell (2002, 2004) HET is considered a fast, reliable, and cheap index test to evaluate the rate of internal erosion of the soil. This test procedure simulates the field internal erosion in earth fill dams and embankment fill [2] [58].

The Hole Erosion Test (HET) is commonly used to quantify the critical stress and the rate of piping erosion progression. In this test a characteristic internal erosion time is defined and expressed as a function of the initial hydraulic gradient and the coefficient of surface erosion [57]. Moreover, the rate of enlargement of the soil tunnel (erosion rate) is calculated from these two parameters. Borelli, et al. (2006) and Lachouette, et al. (2008) have presented an analytical model of this test, where the inner tube radius evolution is developed as a function of time in an approximated formula [3] [57].

In this research HET procedure will be used to study the effect of adding lime on two types of clayey soil to stabilize it against internal erosion (piping). The two soils originate from Jordan. Both soils initial properties will be determined such as specific gravity, gradation, compaction parameters and Atterberg limits. Maximum dry density and optimum moisture content were calculated and used in preparing the testing samples.

In this experiment, adequate number of specimens from the two soils will be prepared at different quick lime content. Where, six identical samples will be prepared for each lime content of each soil and tested at three different curing times (24 hours,

48 hours, and 7 days). For each curing time two samples to be tested and the average value of the results to be taken. Moreover, one more sample with no lime content will be prepared for comparison. See Figure 3-1 and Figure 3-2 for details about the samples.



Figure 3-1 : Samples Prepared from Soil #1.

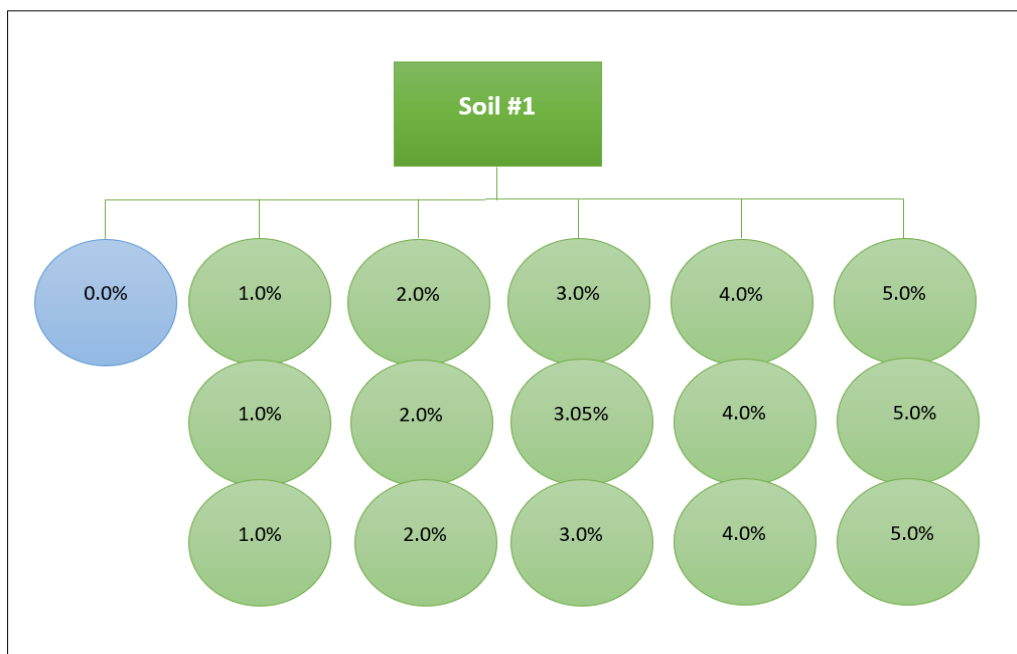


Figure 3-2 : Samples Prepared from Soil #2.

All specimens will be prepared in the standard proctor density mold under standard ASTM procedure at 95% of maximum dry density and optimum water content condition. Afterwards, a 6 mm diameter hole will be drilled throughout the longitudinal direction of the samples to simulate a concentrated leak pipe of 10.16 cm length.

The Hole Erosion Test will be employed to evaluate the rate of erosion of the compacted samples at each percentage for the two types of soils. In this test, the tested sample will be placed between two different heads of water inlet (upper-stream) and outlet (downstream). The water will be allowed to flow throughout the hole with a difference in head between inlet and outlet of a value in the range of 500 mm to 1200 mm. Head value will be chosen within this range to initiate erosion. The chosen head between inlet and outlet remains constant throughout the test but might be changed after a minimum of 45 minutes of a running test time with no failure in sample. The hydraulic gradient, flow rate at any time, and the diameter of the hole at the end of the test should be measured. Through calculations, the diameter of hole at any time throughout the test can be determined using the recorded data. Additionally, the erosion rate per unit surface area and wall shear stress along the hole will be calculated at any time of the test. From the above measured and calculated parameters, the Erosion Rate Index (I_{HET}) will be determined along with the Critical Shear Stress (τ_c) values. Figure 3-3 shows the HET schematic Diagram.

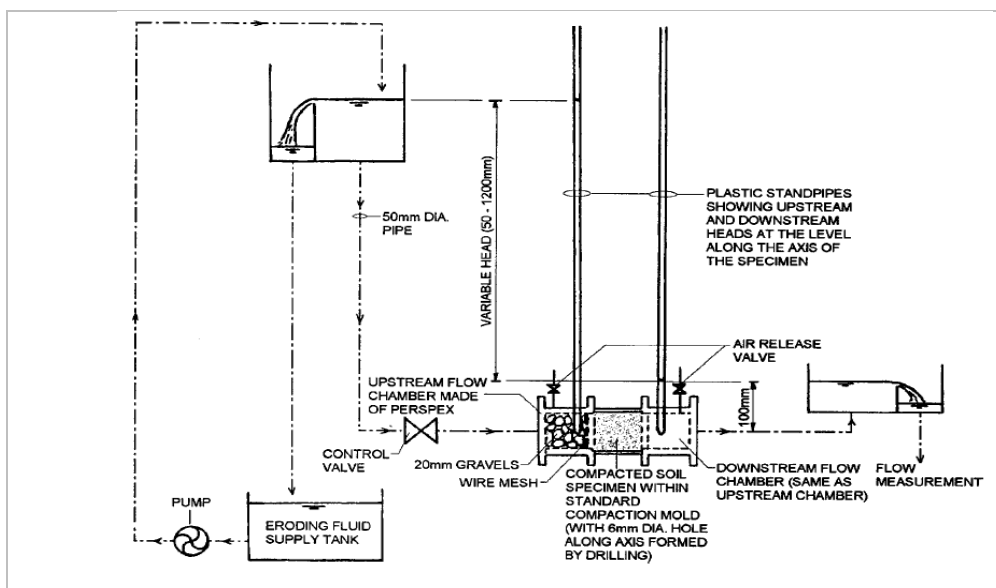


Figure 3-3: Schematic Diagrams of Hole Erosion Test Assembly [2].

Chapter 4. Experimental Setup and Test Procedure

In this chapter, the Hole Erosion Test is proposed to test the soil specimens against internal erosion. The implantation of this test will be presented as well as sample preparation procedure and sample testing procedure. Moreover, the test analysis procedure will be discussed in detail in the last part of this chapter.

As discussed earlier in the methodology in Chapter 3, two types of clayey cohesive soils will be selected for testing using HET Procedure. Atterberg's limits, gradation, specific gravity, maximum dry density, and optimum water content of the selected soils will be determined in accordance of ASTM standard procedures (procedure numbers are listed in Section 4.1).

4.1 Samples Preparation Procedure

The procedure of the Sample preparation will be as follow:

- 1- Select the Soil.
- 2- Oven Dry a 3 Kg of the Soil.
- 3- Sieve the soil using Sieve #4.
- 4- Determine the initial characteristics of the soils including Atterberg limits using ASTM D-4318, compaction parameters (maximum dry density and optimum moisture content) using ASTM D-698, and soil gradation using ASTM D-421 and ASTM D-422 [59].
- 5- Calculate the amount of water and lime to be added to each soil sample using different percentages of lime to fill a standard proctor mold. Use ((0.5%, 1%, 1.5%, and 2%) for Soil #1 and (1%, 2%, 3%, 4%, and 5%) for Soil #2.
- 6- Mix water, oven dried soil, and lime together.
- 7- Compact the soil mixture in the proctor mold. Prepare six samples from each lime percentage.
- 8- Drill the sample using 6 mm diameter rod at the centre of the sample and through the longitudinal direction.

- 9- Preserve the samples inside their molds in a Plastic bag where they will be tested later at different curing times (24 hours, 48 hours, and 7 days). Figure 4-1 shows one sample after 24 hours curing and before testing.



Figure 4-1: Sample after 24 hours Curing.

4.2 Sample Testing Procedure

Test procedure can be summarized in following steps:

- 1- Fill the upstream chamber with 20 mm gravel to create a filter for the sample and to regularize the water flow.
- 2- Fix the sample in its place between the upper and lower streams with the rubber band and the bolts as shown in the apparatus in Figure 4-2 below.
- 3- Adjust the water head to be constant of 60 cm to the level of the soil specimen
- 4- Open the valve to allow water to flow in through the sample and the drilled hole.
- 5- Measure the flow rate through the outgoing pipe at the downstream side of the sample at different time intervals while the test is run.
- 6- Keep the test running for at least 45 minutes or until the sample fails.
- 7- Remove the sample from the test apparatus and measure the diameter of the hole at the downstream side of the sample at end of the test. Figure 4-3 shows one sample diameter after testing.

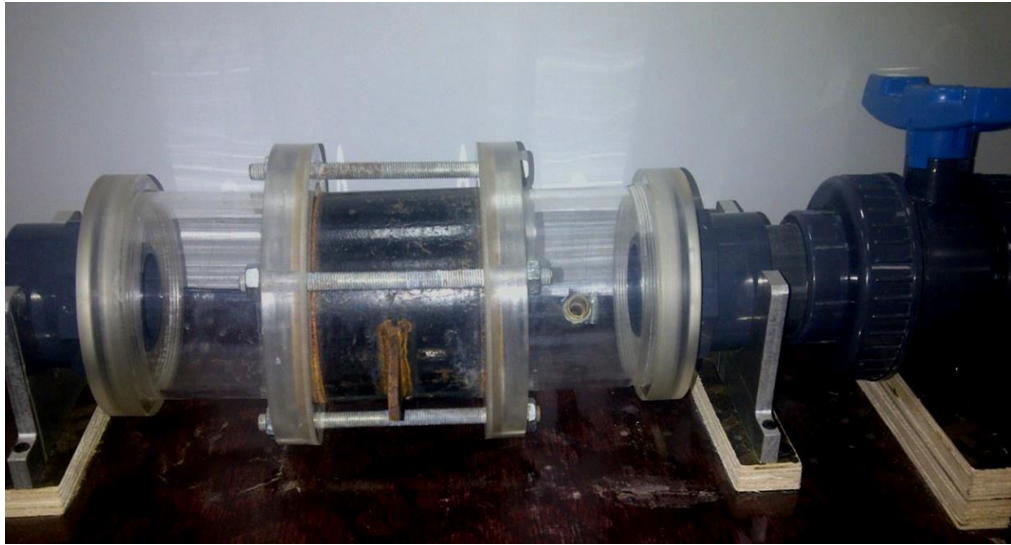


Figure 4-2: Sample Fixation in Apparatus used for HET procedure



Figure 4-3: Sample of 0% lime after testing for 2 hours.

4.3 Test Analysis

As mentioned above, the HET Test is mainly carried to determine the characteristics of erosion of soil which can be reflected by the value of the erosion rate index. During the test, the following are measured:

- 1- Hydraulic gradient across the sample.
- 2- Flow rate of water through the sample at different timings at known intervals.
- 3- The diameter of the hole at the start of the test (Φ_0).
- 4- The diameter of the hole at end of the test (Φ_f); if the shape is irregular measure the diameter at different angles and take the average.
- 5- Initial properties of the soil.

The following can be calculated using the above recorded data:

- 1- The Friction Factor at any time (F_{Lt}, F_{Tt})
- 2- The diameter of hole at any time throughout the test (Φ_t)
- 3- The hydraulic shear stress along the hole (τ_t)
- 4- The erosion per unit surface area ($\dot{\epsilon}_t$)
- 5- The Coefficient of Soil Erosion (C_e)
- 6- The Critical Shear Stress (τ_c)
- 7- The Erosion Rate Index (I_{HET})

From the above seven parameters the following two are the most significant:

- 1- The Critical Shear Stress (τ_c)
- 2- The Erosion Rate Index (I_{HET})

These two can mainly be obtained from the best fit line relation the rate of erosion per unit area and shear stress; such that: $\dot{\epsilon}_t = C_e(\tau_t - \tau_c)$; where,

$\dot{\epsilon}_t$ is the rate of erosion per unit surface area of the hole at time t (kg/s/m²);

C_e is the coefficient of soil erosion (s/m);

τ_t is hydraulic shear stress along the hole at time t (N/m²)

τ_c is the critical shear stress (N/m²)

4.3.1 Procedure to calculate erosion rate index (I_{HET}).

- 1- Determine the initial and final flow conditions; whether Laminar or Turbulent flow by calculating Reynolds Number as below:

$$V_t = \frac{4 \cdot Q}{\pi \cdot \Phi_t^2} \quad (1)$$

$$R_e = \frac{V_t \cdot \Phi_t}{\nu} \quad (2)$$

where; V_t = estimated mean flow velocity in the hole in m/sec.

Q_t = Flow rate at time t in m³/sec.

Φ_t = Diameter of performed hole at time t in m

ν = Kinematic viscosity in m²/sec = 1.004 * 10⁻⁶ m²/sec

note: if Reynold Number is more than 2000 then the flow is identified as Turbulent. Consider Transitional flow a turbulent flow.

- 2- Determine the initial and final friction factors based on the initial diameter (Φ_0 = 6mm) and the measured diameter at the end of the test (Φ_f) by using one of the following equations based if the flow is Laminar or Turbulent:

Laminar Flow:

$$f_L = \frac{\pi \cdot \rho_w \cdot g \cdot s \cdot \Phi_t^3}{16Q} \quad (3)$$

Turbulent Flow:

$$f_T = \frac{\pi^2 \cdot \rho_w \cdot g \cdot s \cdot \Phi_t^5}{64Q^2} \quad (4)$$

where; ρ_w = Density of eroding fluid in kg/m³.

g = Acceleration of gravity m/sec²

s = Hydraulic gradient across the soil specimen= ($\Delta h/L$) where L is the Sample length)

Q_t = Flow rate in m³/sec

- 3- Draw the relation between the initial and final friction factors versus time. This relation is assumed to be varying linearly with time.

- 4- Find the friction factors throughout the time of the test where the water flow was measured.
- 5- Calculate the diameter throughout the test using (5) or (6):

Laminar Flow:

$$\Phi_t = \left(\frac{16 \cdot Q \cdot f_L}{\pi \cdot \rho_w \cdot g \cdot S} \right)^{1/3} \quad (5)$$

Turbulent Flow:

$$\Phi_t = \left(\frac{64 \cdot Q^2 \cdot f_T}{\pi^2 \cdot \rho_w \cdot g \cdot S} \right)^{1/5} \quad (6)$$

- 6- Find the rate of slope change between each two points as per below equation:

$$\frac{d\Phi}{dt} = \frac{\Phi_{t+1} - \Phi_t}{(t+1) - t} \quad (7)$$

- 7- Calculate the wall shear stress (τ) using the following equation

$$\tau_{\text{HET}} = \rho_w \cdot g \cdot \frac{\Phi_t}{4} \cdot S \quad (8)$$

where; L = length of Sample, m

- 8- Calculate the rate of erosion (ϵ_t) at different test times using the below equation:

$$\dot{\epsilon}_{\text{HET}} = \frac{\rho_w}{2} \cdot \frac{d\Phi_t}{dt} \quad (9)$$

where;

ρ_d = Dry Density of soil in Kg/m^3

$d\Phi/dt$ = rate of diameter change calculated at step 6 above.

- 9- Plot the erosion rate (ϵ_t) versus wall shear stress (τ_t) of the tested sample.
- 10- Draw best fit line of the above plot in $\epsilon_t = C_e \cdot \tau_t + b$.
- 11- Determine C_e which is equal to the slope of the best fit straight line of the plot.

12- Calculate I_{HET} using (10):

$$I_{HET} = -\log C_e \quad (10)$$

13- Calculate the Critical Shear Stress (τ_c) by extrapolation the best fit line between (ϵ_t) and (τ_t) to zero. The Value of Critical Shear Stress (τ_c) is equal to the x-intercept value and can be calculated from (11), where “ b ” is the b intercept of the best fit line:

$$\tau_c = \frac{-b}{c_e} \quad (11)$$

14- Use Table 4-1 to categorize the erosion. To be noted that the higher the erosion index, I_{HET} , the higher the resistance of soil to erosion.

Table 4-1: Erosion Rate index [2]

Group number	Erosion Rate Index	Description
1	<2	Extremely rapid
2	2-3	Very rapid
3	3-4	Moderately rapid
4	4-5	Moderately slow
5	5-6	Very slow
6	>6	Extremely slow

Soils are classified in 6 groups per their I_{HET} values. Where I_{HET} values fall between 0 to 6 and above. The increase I_{HET} value is an indication of more resistance to erosion. Table 4-1 shows the erosion rate index as categorize by Wan and Fell (2004) [2]. Full procedure of calculating the erosion rate index, I_{HET} , is shown in the flow chart shown in Figure 4-4.

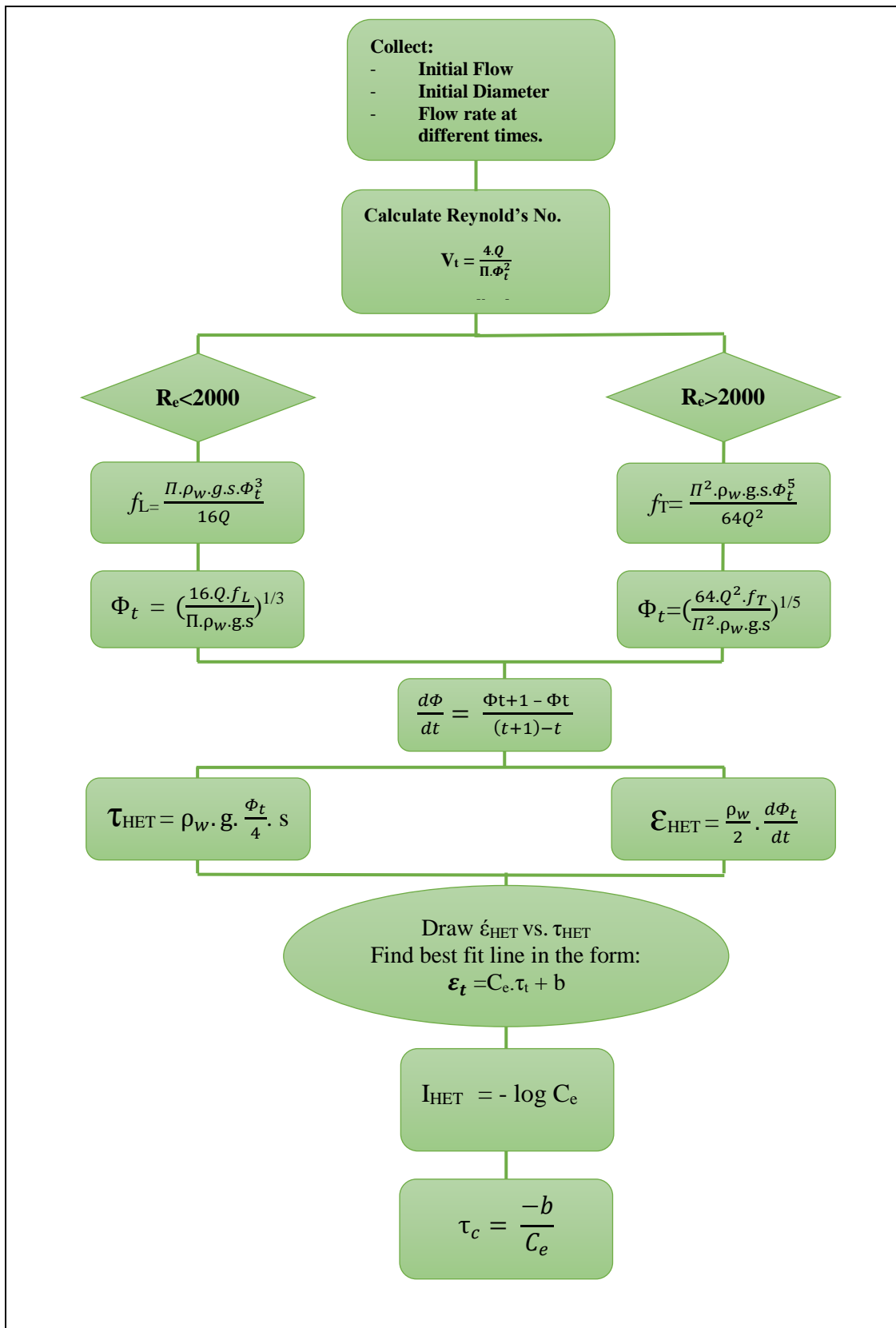


Figure 4-4: Procedure of Calculating I_{HET}

Chapter 5. Results and Analysis

In this chapter, the results of the experimental work carried on the two types of clayey soil will be presented and analysed. As mentioned previously in Chapter 1, the main objective of this study is to stabilize clayey soils against the dangerous phenomena of internal erosion. Quick lime was used as a chemical stabilizer to stabilize both soils against internal erosion. Soil samples were mixed with different percentages of lime between 0.5% and 5 % by dry weight of soil. One sample of each type of soil was prepared and tested in which it had 0% lime (original state of soil).

For Soil #1 a 5% of lime sample was prepared and tested in which it was found extra stable when tested after 24 hours of curing time and hence the lime percentages were decreased to be in the range between 0.5% and 2% with 0.5 % increment for Soil #1. Whereas for Soil #2 percentages ranged from 1% to 5% with 1% increment.

All Samples were prepared at 95% of maximum dry density at the optimum moisture content. These parameters were determined in the lab by proctor test under ASTM D-698 standards [59]. Samples were tested at three different curing times; after 24 hours, 48 hours, and 7 days of preparation time. The Hole Erosion Test (HET) was conducted on all specimens, the results of the HET test were used further to calculate the erosion parameters of both soils at different lime percentages and different curing times.

This chapter is mainly divided into four main sections. Section 5.1 states the initial physical properties for both tested soils. Section 5.2 defines the experimental parameters used to calculate the soil erosion parameters, and displays a full sample calculation on one soil sample. Section 5.3 and Section 5.4 analyse the effect caused by adding lime with various percentages and curing times on the various soil erosion parameters such as diameter of the water path (Φ), critical shear stress (τ_c), and erosion rate index (I_{HET}).

5.1 Initial Physical Properties of the Tested Soils

The initial properties of both soils were determined using ASTM standard testing procedures. Grain Size Distribution was done using under ASTM D-421 and

ASTM D-422 procedure and the results are shown in Table 5-1. Similarity Atterberg's limits where obtained using ASTM D-4318 procedure and results are displayed in

Table 5-2. Proctor Test was also done on both soils and the results of maximum dry density and optimum moisture content are shown in

Table 5-3. ASTM D-698 was used for the Proctor Test. Specific Gravity of both soils is also presented in the same table. The values of Specific Gravity were obtained using ASTM D-854 procedure [59]. Moreover, the Compaction Curve of Soil #1 and Soil #2 are shown in Figure 5-1 and Figure 5-2 respectively.

Both Soils are classified using the Unified Soil Classification System. Soil #1 was classified to be CH; Clayey soil with high plasticity. Whereas Soil #2 was classified to be ML Soil; Silty Soil with Low plasticity. The effect of soil type and gradation on the percentage of lime needed to stabilize the soil will be discussed in Section 5.5.

Table 5-1: Grain Size Distribution

Grain Size Distribution		
Type	Soil #1	Soil #2
Clay (%)	65	17
Silt (%)	21	44
Sand (%)	14	39

Table 5-2: Atterberg's Limits

Atterberg's Limits		
Parameter	Soil #1	Soil #2
LL (%)	67	32
PL (%)	29	25
PI	38	7

Table 5-3: Compaction Parameters and Soil Classification

Compaction Parameters		
Parameter	Soil #1	Soil #2
γ_{dmax} (kg/m ³)	1330	1905
w _{op} (%)	35	13
Specific Gravity (G _s)	2.67	2.65

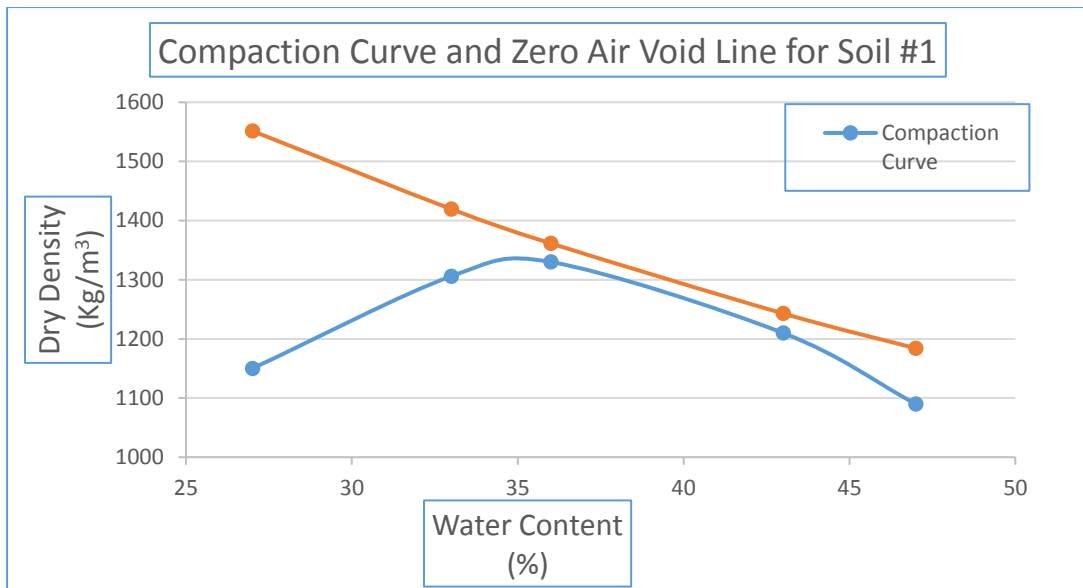


Figure 5-1 :Compaction Curve and Zero Air Void Line for Soil #1.

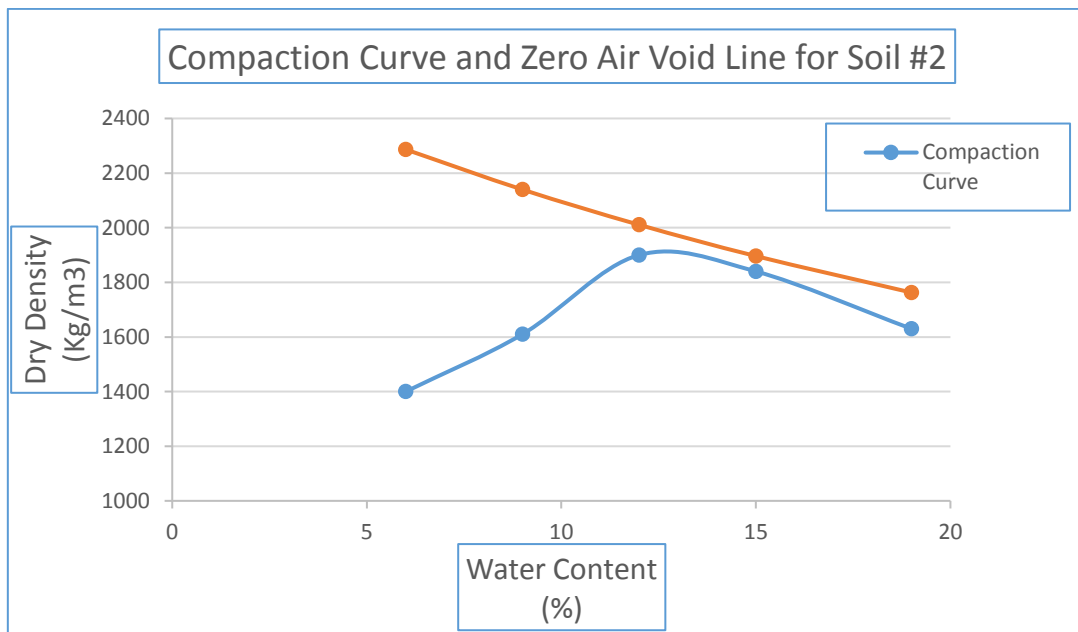


Figure 5-2 :Compaction Curve and Zero Air Void Line for Soil #2.

The above mentioned parameters were used for the below:

- 1- Preparing the soil samples at 95% of maximum dry density from maximum dry density and at optimum moisture content.
- 2- Analysing the data from the Hole Erosion Test to get the soil erosion parameters.

Moreover, Table 5-4 shows the mineral composition of each soil:

Table 5-4: Mineral Composition of Soil #1 and Soil #2

Mineral	Soil #1 (%)	Soil #2 (%)
Kaolinite	55	25
Illite	13	35
Montmorillonite	8.1	7.1
Chlorine	19	11
Vermiculite	-	-

5.2 Experimental Parameters and Sample Calculation

In this section a sample calculation for a Soil #1 sample of 0.5 % added quick lime by weight that was tested after 24 hours of curing will be presented. The main output of these calculation is Erosion Rate Index (I_{HET}) which is derived from the coefficient of soil erosion (C_e). This coefficient is obtained by drawing the relationship between the rate of erosion per unit area ($\dot{\epsilon}$) and the shear stress (τ_c) at different timings of the test. To calculate the two aforementioned variables, friction factors to be calculated from the initial and final state of the soil sample using initial and final diameters of the water path hole as well as initial and final water flow in the same hole. Further, the diameter at any time of the test can be calculated, as well as the rate of the change in the diameter per unit time. From all the above the rate of erosion per unit area ($\dot{\epsilon}$) and the shear stress (τ_t) at different timings of the test can be calculated and plotted in which the coefficient of soil erosion (C_e) and consequently the Erosion Rate Index (I_{HET}) can be determined from this plot. One more important parameter to be obtained as a result of this analysis is the Critical Shear Stress of each soil Sample (τ_c) which will also be calculated from the best fit relationship between the rate of erosion per unit area ($\dot{\epsilon}$) and the shear stress (τ_c) at different timings of the test.

In order to use the Hole Erosion Test and its analysis procedure, a set of parameters shall be identified as constants in the analysis equations. These are either standard values or parameters calculated by the lab experiments mentioned in Section 5.1. These parameters are shown in Table 5-5 for Soil #1 and for Soil #2 in Table 5-6.

Table 5-5 :Experimental Parameters for HET procedure for Soil #1

Parameter	Unit	Value
Water Density (ρ_w)	Kg/m ³	1000
Gravity (g)	m/sec ²	9.81
Hydraulic Gradient (s_t)		5.91
Soil Dry Density (ρ_d)	Kg/m ³	1264.45

Table 5-6 : Experimental Parameters for HET procedure for Soil #2

Parameter	Unit	Value
Water Density (ρ_w)	Kg/m ³	1000
Gravity (g)	m/sec ²	9.81
Hydraulic Gradient (s_t)		5.91
Soil Dry Density (ρ_d)	Kg/m ³	1810

Notes:

- Water Density and Gravity values are standard fixed values for all soils.
- Hydraulic gradient (s_t) depends on the difference in head across the soil sample ends and the length of the soil sample of each sample at time t.
Such that $s_t = \Delta h/L$; where L is the length of the soil sample.
- Soil Dry Density (ρ_d) is determined for each soil using Proctor compaction test and is identified as 95% of the maximum dry density.

A sample calculation for Soil #1 with 0.5% added lime by dry weight of soil and tested after 24 hours of preparations is shown below.

During the Test, the below data is collected. Table 5-7 shows the data collected for 0.5% quick lime at 24 hours curing time of Soil #1 sample:

- 1- Initial and final Diameter (Φ_0 and Φ_f)
- 2- Water flow at different timings of the Test (Q_0, Q_1, \dots, Q_f)
- 3- Difference in Head across the water Sample (Δh)
- 4- Length of water path through the sample (L)

Table 5-7 : Data collected for Soil #1 sample containing 0.5% lime at 24 hours curing time

Test Time (min)	Volume (cm ³)	Time (sec)	Φ_t (mm)
0	130	1.8	6
15	127	1.4	
30	171	1.6	
45	405	1.7	20

Below, the analysis procedure will be identified in detail as steps.

▪ **Step #1: Determining flow conditions (Turbulent or Laminar):**

From the above data, the flow conditions, either Turbulent or Laminar shall be determined using (1), (2), the initial water flow, and the hole diameter at time Zero. The Calculated Reynold's number was calculated to be equal to 15,259. Referring to the calculated Reynold's number the flow condition is defined to be Turbulent as the value of Reynold number more than 2000.

▪ **Step #2: Calculating friction factors (f_{Tt}) at different test timings:**

From the data in Table 5-7 and based on the flow conditions defined as Turbulent in step #1 the initial and final friction factors are calculated using (4) and Shown in Table 5-8.

Table 5-8: Initial and Final Friction Factors for soil #1 sample containing 0.5% lime at 24 hours curing time

Test Time (min)	Test Time (sec)	(A) Volume (m ³)	(B) Time (sec)	(A/B) Q_t (m ³ /sec)	Measured Φ_t (m)	f_{Tt} (Kg/m ² /sec)
0	0	0.00013	1.84	0.0001	0.0060	13.3294
45	2700	0.000405	1.71	0.0002	0.0200	504.1197

As friction Factors varies linearly with time, a graph is drawn between the above two points (Test Time and f_{Tt}). The friction factors throughout the test timing were determined from the linear equation shown on Figure 5-3 and listed in Table 5-9.

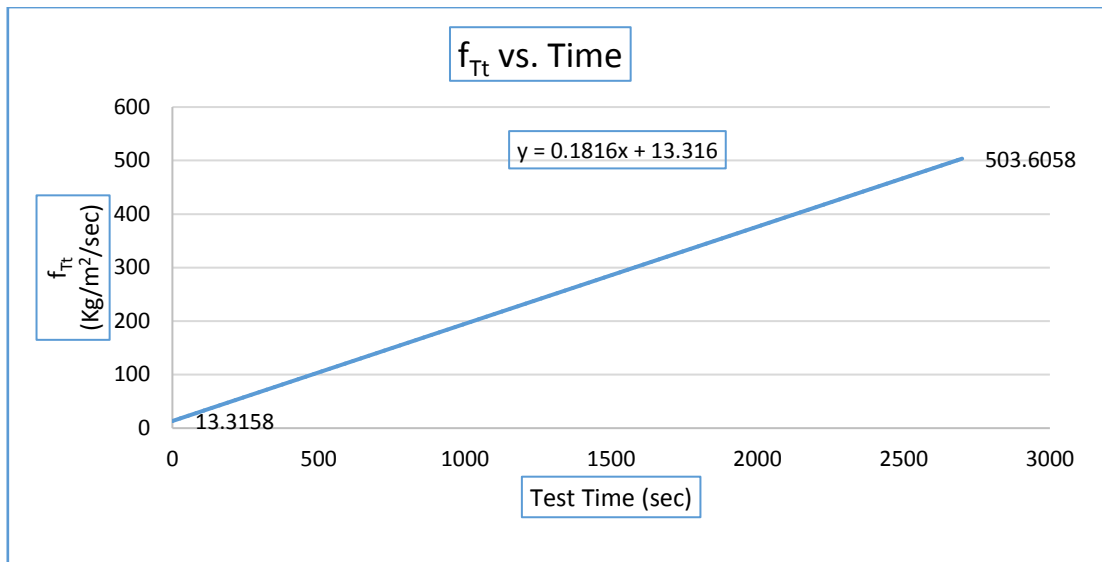


Figure 5-3 : Friction Factors versus Test Time (Soil #1 Sample with 0.5% lime tested at 24 hours curing time)

Table 5-9 :Friction factors at different test timings (Soil #1 Sample with 0.5% lime tested at 24 hours curing time)

Test Time (sec)	f _{Tt} (Kg/m ² /sec)
0	13.3294
900	176.9261
1800	340.5229
2700	504.1197

- **Step #3: Calculating the hole diameter (Φ_t) at different test timings and rate of change in diameter ($\frac{d\Phi_t}{dt}$) :**

From the water flow values collected throughout the test timing and the friction factors calculated in step #2 above, the diameter of the hole where water is passing can be calculated at any time using (6) as the flow was defined as Turbulent. Furthermore, the rate of change of diameter per unit time can be calculated using (7).

The results of diameter and rate of change of diameter per unit time are shown in Table 5-10.

Table 5-10 :Hole Diameter (Φ_t) at different test timings and rate of change in diameter ($\frac{d\Phi_t}{dt}$) (Soil #1 Sample with 0.5% lime tested at 24 hours curing time)

Test Time (min)	Test Time (sec)	Q_t (m ³ /sec)	f_{Tt} (Kg/m ² /sec)	Φ_t (m)	$\frac{d\Phi_t}{dt}$
0	0	7.22E-05	13.3294	0.0060	0.00E+00
15	900	9.07E-05	176.9261	0.0110	5.58E-06
30	1800	0.000107	340.5229	0.0134	2.66E-06
45	2700	0.000238	504.1197	0.0200	7.31E-06

- **Step #5: Calculating rate of erosion per unit area ($\dot{\epsilon}$) and shear stress (τ_t) at different test timings:**

Using the results obtained above, (8), and (9) the rate of erosion per unit area ($\dot{\epsilon}$) and shear stress (τ_t) at different test timings are calculated and shown in Table 5-11.

Table 5-11 :Rate of Erosion per unit area ($\dot{\epsilon}$) and shear stress (τ_t) at Different Test Timings (Soil #1 Sample with 0.5% lime tested at 24 hours curing time)

Test Time (min)	Test Time (sec)	Q_t (m ³ /sec)	Φ_t (m)	$\frac{d\Phi_t}{dt}$	τ_t (N/m ²)	$\dot{\epsilon}_t$ (Kg/sec/m ²)
0	0	7.22E-05	0.0060	0.00E+00	86.8996	0.0000
15	900	9.07E-05	0.0110	5.58E-06	159.6673	0.0035
30	1800	0.000107	0.0134	2.66E-06	194.3422	0.0017
45	2700	0.000238	0.0200	7.31E-06	289.6654	0.0046

- **Step #6: Calculating erosion rate index (I_{HET}) and critical shear stress (τ_c)**

To obtain the Erosion Rate Index (I_{HET}) and Critical Shear Stress (τ_c), the best fit line between the points relating the rate of erosion per unit area ($\dot{\epsilon}$) and the shear stress (τ_t) at different test timings was drawn. The equation of the best fit line was also found. Results are shown in Figure 5-4.

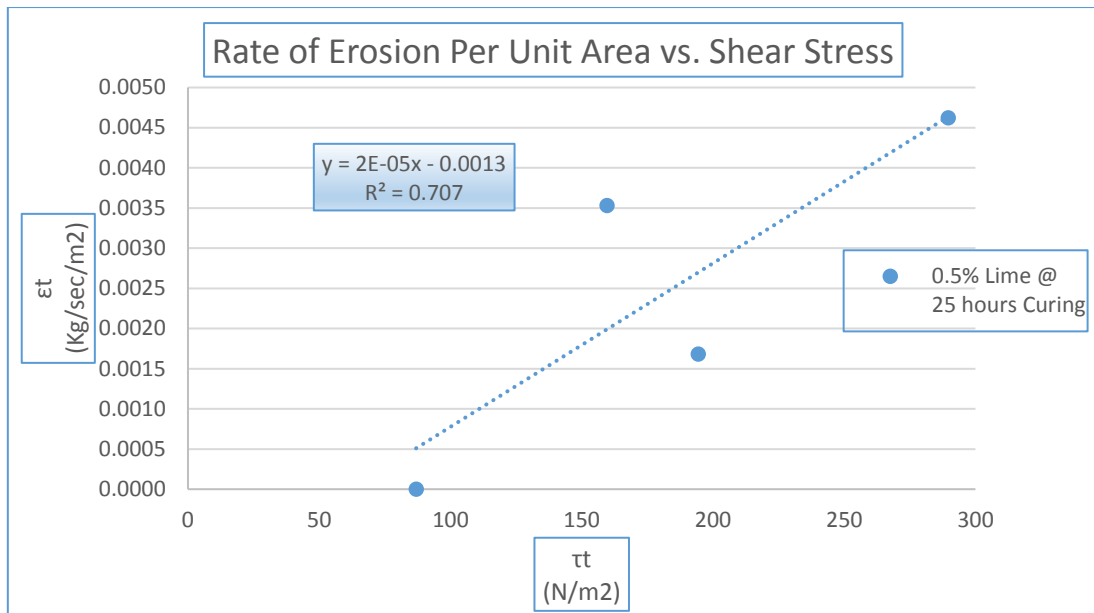


Figure 5-4: Rate of Erosion per unit area (ϵ_t) versus the Shear Stress (τ_t) at Different Test Timings (Soil #1 Sample with 0.5% lime tested at 24 hours curing time)

From the best fit line equation above, (10) and (11), the Results for Soil #1 Sample with 0.5% lime tested at 24 hours curing time is shown in Table 5-12.

Table 5-12 : Erosion Parameters of Soil #1 Sample with 0.5% lime tested at 24 hours curing time

Erosion Parameters			Value
Name	Symbol	Unit	
Coefficient of Erosion	C_e	None	2.00E-05
Critical Shear Stress	τ_c	N/m ²	65.00
Erosion Rate Index	I_{HET}	None	4.70

5.3 Effect of Adding Lime on Soil Erosion Parameters

Two types of soils, Soil #1 and Soil #2, were tested against internal erosion. One sample of each soil was tested with no addition of lime (0% Lime). While, for the purpose of studying the effect of adding lime; Soil #1 samples containing 0.5%, 1%, 1.5%, and 2% of quick lime were tested. And Soil #2 containing 1%, 2%, 3%, 4%, and 5% of quick lime were also tests.

For Soil #1, a sample containing 5% lime was tested and no erosion happened after two hours of continuous water flow. Flow rate through the water path was almost constant throughout the test time and the final diameter exhibited no change from initial diameter, hence it was excluded from calculations and the percentages for soil #1 were reduced to be in the range between 0.5% and 2% with 0.5% increment. Moreover, both the 1.5% sample and 2% sample were stable when tested after 24 hours curing time and therefore no further testing on 48 hours and 7 days was done.

Table 5-14 and Table 5-15 show the final results for all samples of Soil #1 and Soil #2 respectively. The tables mainly present the Erosion parameters including: Critical Shear Stress (τ_c), Erosion Rate Index (I_{HET}) and Final Diameter (Φ_f), noting that the Initial Diameter (Φ_0) was 6 mm.

Table 5-13 : Erosion Parameters of Soil #1

Percent Lime	Erosion Parameter	Curing Time		
		24 Hours	48 Hours	7 Days
0.0%	I_{HET}	4.5		
	τ_c	50		
	Φ_f (mm)	22		
0.5%	I_{HET}	4.7	5.0	5.1
	τ_c	65	70	75
	Φ_f (mm)	20	10	7
1.0%	I_{HET}	5.0	5.1	5.2
	τ_c	70	75	83
	Φ_f (mm)	10	8	7
1.5%	I_{HET}	5.4		
	τ_c	87		
	Φ_f (mm)	7		
2.0%	I_{HET}	5.7		
	τ_c	100		
	Φ_f (mm)	6.5		

Table 5-14 : Erosion Parameters of Soil #2

Percent Lime	Erosion Parameter	Curing Time		
		24 Hours	48 Hours	7 Days
0.0%	I _{HET}	2.9		
	τ_c	33		
	Φ_f (mm)	45		
1.0%	I _{HET}	3.7	4.0	4.1
	τ_c	43	50	57
	Φ_f (mm)	42	40	33
2.0%	I _{HET}	4.1	4.2	4.4
	τ_c	51	56	58
	Φ_f (mm)	36	28	22
3.0%	I _{HET}	4.3	4.4	4.5
	τ_c	54	57	60
	Φ_f (mm)	31	27	19
4.0%	I _{HET}	4.7	5.0	5.2
	τ_c	65	80	86
	Φ_f (mm)	15	10	7
5.0%	I _{HET}	5.2	5.7	5.7
	τ_c	67	100	100
	Φ_f (mm)	9	7	7

In the following sub-sections, the effect of lime percentage added to the different types of clayey soils on the Erosion parameters such as diameter of the water path, critical shear stress, and erosion rate index will be studied and analysed.

5.3.1 Effect of adding lime on diameter of hole. To visualize the effect of adding lime on the final diameter of the water path the relation between the final diameter of the water path versus the lime percentage added on both soil types is plotted and shown in Figure 5-5.

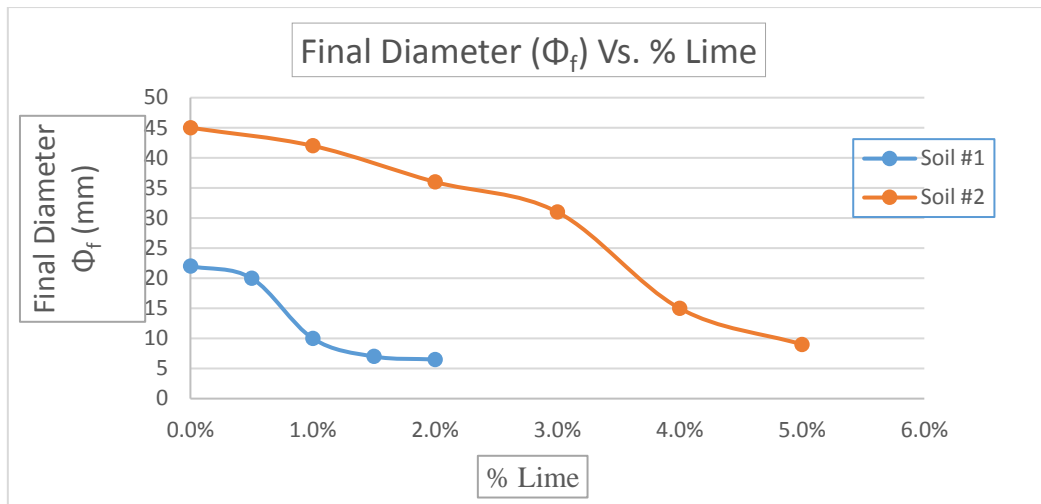


Figure 5-5: Relation between Final Diameter of Water Path and Percent Lime at 24 hours curing time for Soil #1 and Soil #2.

It can be clearly seen that the relation between the percentage lime added and the final diameter of the water path is inversely related. That is an increase in the lime percentage added to the soil would achieve a reduction in the final diameter of the water path and the closer to the initial diameter it will be. Moreover, 2% by dry weight of Soil #1 reduced the change in diameter by 97% in comparison with 0% lime. Where for Soil #1 the enlargement of diameter at 0% lime was 16 mm and was only 0.5 mm at 2%. Similarly, the same was achieved by 5% lime added to Soil #2, where, the enlargement of diameter was equal to 39 mm at 0% lime while at 5% the enlargement was only 2 mm.

5.3.2 Effect of adding lime on critical shear stress. Critical Shear Stress (τ_c) was plotted against percentage of lime added to both soils in Figure 5-6 for Soil #1 and Soil #2. It is noticed that an increase in lime percentage would lead to an increase in the critical shear stress of the soil. For Soil #1 at 2% lime the critical shear stress reached 100 N/m² at 24 hours curing time. This is a 50% increase in critical shear stress of Soil #1 at the stabilizing lime percentage of 2%, in comparison to 50 N/m² critical shear stress at 0% lime.

Similarly, but with a greater percentage, a 203% increase in critical shear stress was achieved for Soil #2 with the addition of 5% lime by dry weight of soil to the sample. Where the critical shear stress increased from 33 N/m² at 0% lime to 100 N/m² at 5% lime addition and 48 hours curing time.

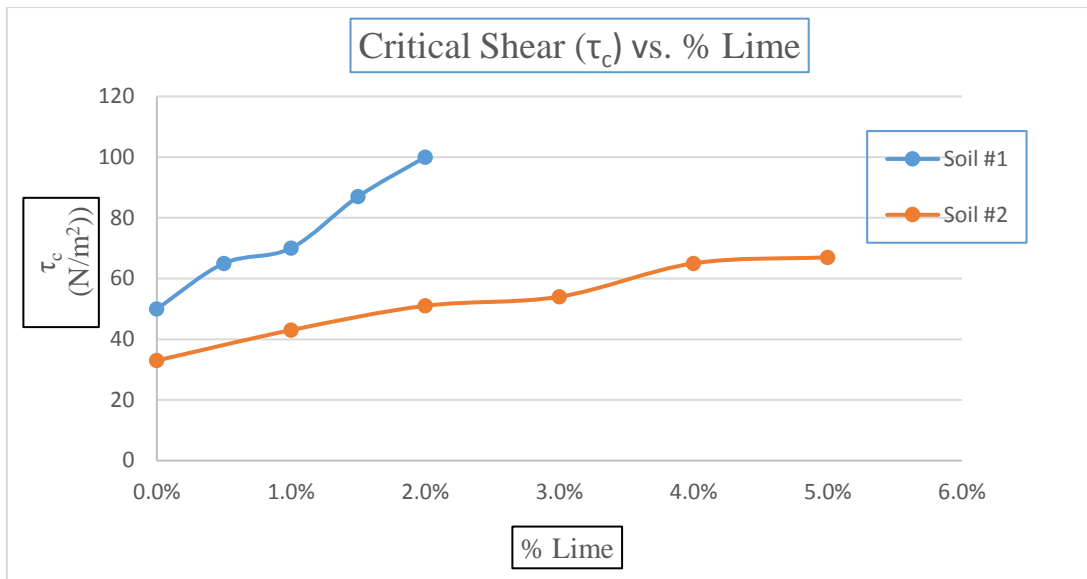


Figure 5-6 : Relation between Critical Shear (τ_c) and Percent Lime at 24 hours curing time for Soil #1 and Soil #2.

5.3.3 Effect of adding lime on erosion rate index (I_{HET}). As mentioned earlier, the main objective of this research is to study the effect of addition of lime on internal erosion behaviour of the soil. In this research the Hole Erosion Test and its analysis procedure were adopted to analyse this effect. The main output of the Hole Erosion Test analysis is the Erosion Rate Index (I_{HET}). I_{HET} is used to classify the soil based on its resistance to erosion. Fan and Well (2004) have classified soil based on the value of the Erosion Rate Index (I_{HET}) as per Table 2-2 [2]. I_{HET} value ranges from less than 2 to more than 6, for the first category to be classified to have extremely rapid erodibility while the last category to have extremely slow erodibility. Figure 5-7 shows the relationship between lime percentage added and I_{HET} value at 24 hours curing time. It is obvious, for both soils, an increase in lime percentage will lead to an increase in I_{HET} value and hence an increase in the stability of the soil.

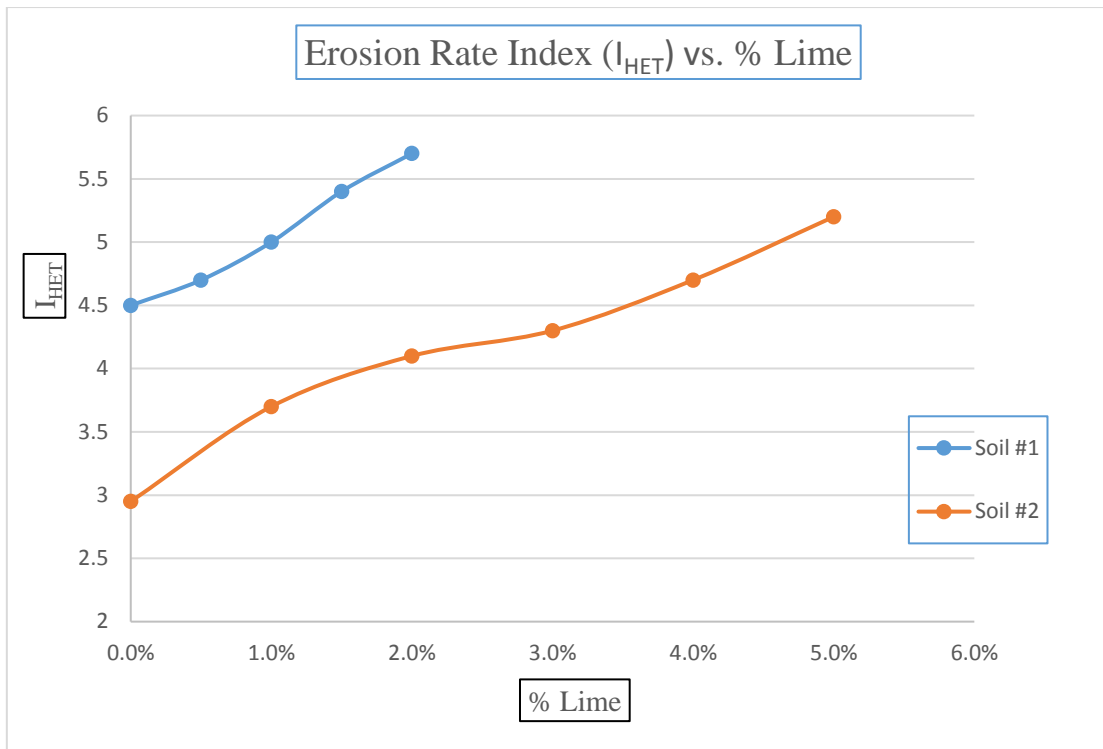


Figure 5-7 : Relation between Erosion Rate Index (I_{HET}) and Percent Lime at 24 hours curing time for Soil #1 and Soil #2.

Figure 5-8 shows the overall I_{HET} value increase for Soil #1. Where the erosion rate index initially for the soil with no added lime was 4.5 which is classified per Fan and Well (2004) and as Table 2-2 to be moderately slow erodible soil [2]. Where by an addition of 2% lime by weight of soil the I_{HET} value increased to 5.7 at 24 hours curing time. The new value of erosion rate index of 5.7 makes Soil #1 classified as a very slow erodible soil.

Similarly, Figure 5-9 shows the overall I_{HET} value increase for Soil #2. Where the initial Erosion Rate Index Soil #2 with no added lime was 2.9 which is classified per Table 2-2 to be very rapidly erodible soil. Where by an addition of 5% lime by weight of soil the I_{HET} value increased to 5.7 at 7 days curing time. The new value of erosion rate index of 5.7 makes Soil #2 classified as a very slow erodible soil.

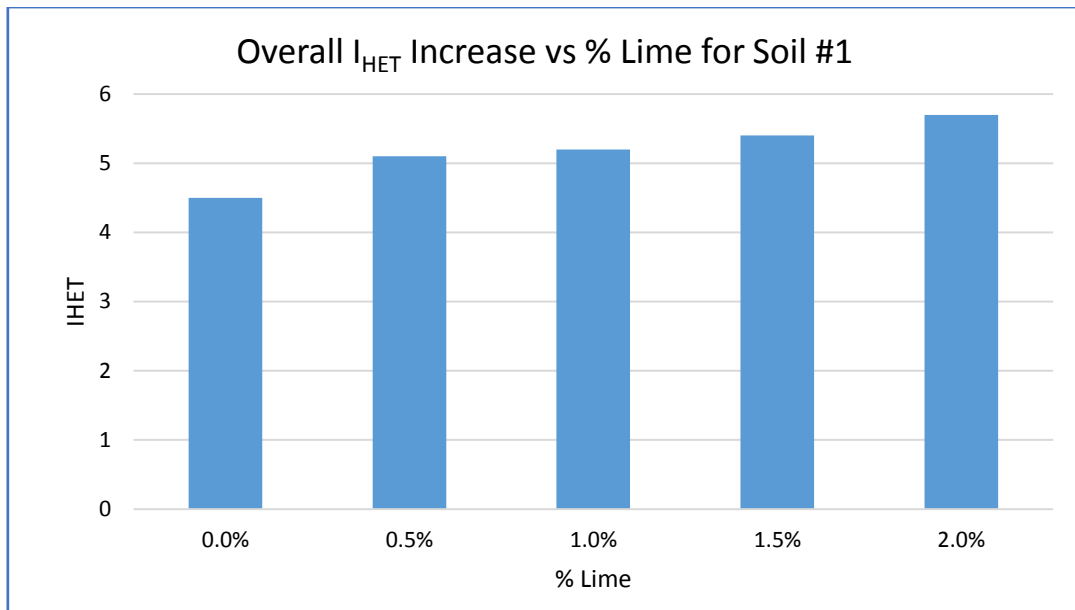


Figure 5-8 :Overall Increase in I_{HET} Values versus Lime Percentage for Soil #1.

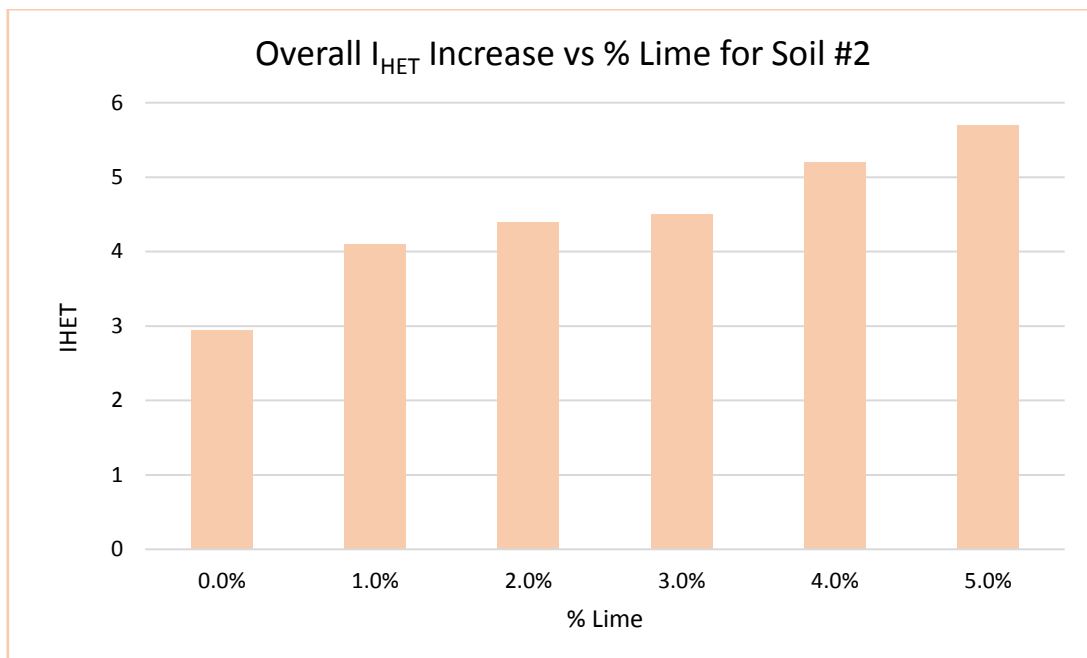


Figure 5-9 :Overall Increase in I_{HET} values versus Lime Percentage for Soil #2.

Moreover, a relation between the Erosion Rate Index and the Final Diameter of the water path in the soil sample was plotted in Figure 5-10. It is clear from this figure that the larger the Erosion Rate Index (I_{HET}) the lower is the final diameter of the water path in the soil sample and the less erodible is the soil.

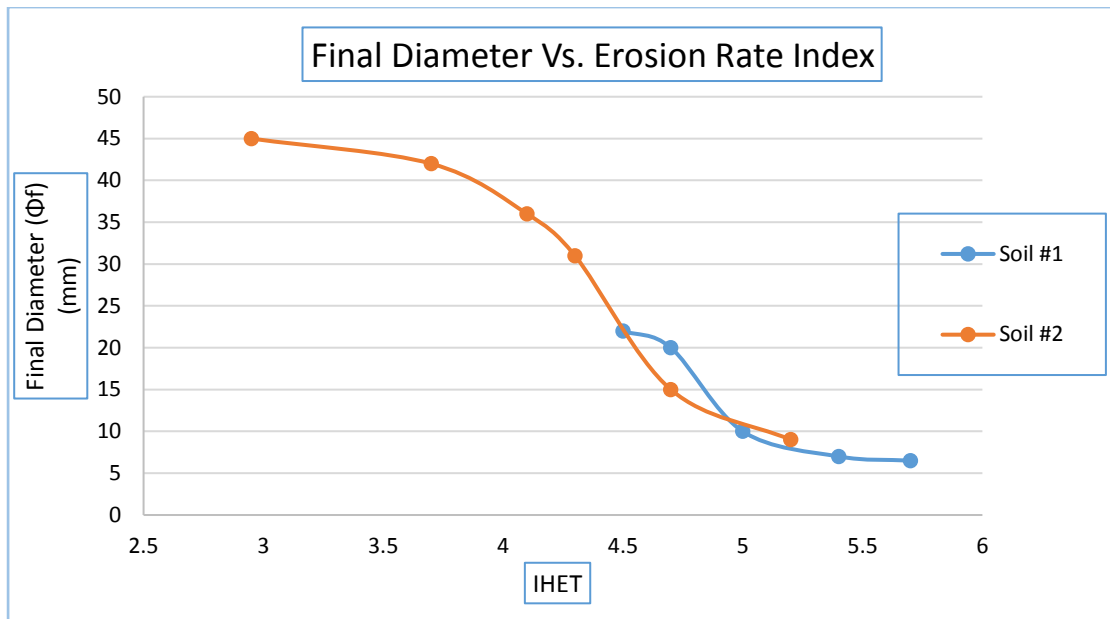


Figure 5-10 : Relation between Final Diameter of water path and the Erosion Rate Index (I_{HET}) at 24 hours curing time for Soil #1 and Soil #2.

Table 5-15 and Table 5-16 summarize, for Soil #1 and Soil #2 respectively, the change in erosion parameters such as final diameter of water path (Φ_f), Critical Shear Stress (τ_c), and finally the Erosion Rate Index (I_{HET}). Moreover, a description of the erodibility of soil is given based on the Erosion Rate Index (I_{HET}) value in the last column of the same tables.

Table 5-15 :Erosion Rate Parameters for Soil #1

% Lime	Φ_f (mm)	τ_c (N/m ²)	I_{HET}	Description of Erosion
0.0 %	22	50	4.5	Moderately Slow
0.5 %	7	75	4.7	Moderately Slow
1.0 %	7	83	5.0	Moderately Slow
1.5 %	7	87	5.4	Very Slow
2.0 %	6.5	100	5.7	Very Slow

Table 5-16 : Erosion Rate Parameters for Soil #2:

% Lime	Φ_f (mm)	τ_c (N/m ²)	I_{HET}	Description of Erosion
0.0 %	45	33	2.9	Very Rapid
1.0 %	33	57	4.1	Moderately Slow
2.0 %	22	58	4.4	Moderately Slow
3.0 %	19	60	4.5	Moderately Slow
4.0 %	7	86	5.2	Very Slow
5.0 %	7	100	5.7	Very Slow

From Table 5-15 and Table 5-16 it can be concluded that for Soil #1, 2% of added lime by dry weight of soil were sufficient to stabilize the soil against internal erosion. Where the achieved Erosion Rate index of 5.7 value, classifies the soil to be a very slow erodible soil. Moreover, the Hole Erosion Test ran on the soil sample containing 2% lime for two continuous hours (120 minutes) with no significant change in diameter nor a significant change in flow, where the flow stayed almost constant throughout the test running time.

Similarly, for Soil #2, 5% of added lime by dry weight of soil were sufficient to stabilize the soil against internal erosion. Where its achieved Erosion Rate index of 5.7 value, classifies the soil to be a very slow erodible soil. Moreover, the Hole Erosion Test ran on the soil sample containing 5% lime for four continuous hours (240 minutes) with no significant change in diameter nor a significant change in flow, where the flow stayed almost constant throughout the test running time.

5.4 Effect of Lime Percentage and Curing Time on Soil Erosion Parameters

When dealing with materials in engineering projects, especially when those materials are mixed with other materials to chemically interact, curing time shall be given a significant attention and consideration. Usually this curing time is used to increase the strength and stability of the material used. In this research quick lime was used as a stabilizing agent for two types of clayey soils. Quick lime is known to be cured almost fully in the first 48 hours. The testing of the samples at various lime percentages happened at three curing times; 24 hours, 48 hours, and 7 days. In the following sections, the effect of curing time on erosion parameters will be analysed.

Furthermore, the combined effect of increase in lime percentage and in curing time will be analysed. The erosion parameters studied versus the above mentioned are: the diameter of the water path (Φ_f), Critical Shear Stress (τ_c), and Erosion Rate Index (I_{HET}).

5.4.1 Effect of lime percentage and curing time on diameter of water path.

Figure 5-11 and Figure 5-12 show the relationship between the final diameter of the water path versus the percentage of lime added at three different curing times (24 hours, 48 hours, and 7 days) for both soils; Soil #1 and Soil #2. It is obvious from these figures that the diameter curve for both soils at 7 days is the lowest among the three curing

curves. This indicates that the change in final diameter becomes lower as curing time is increased.

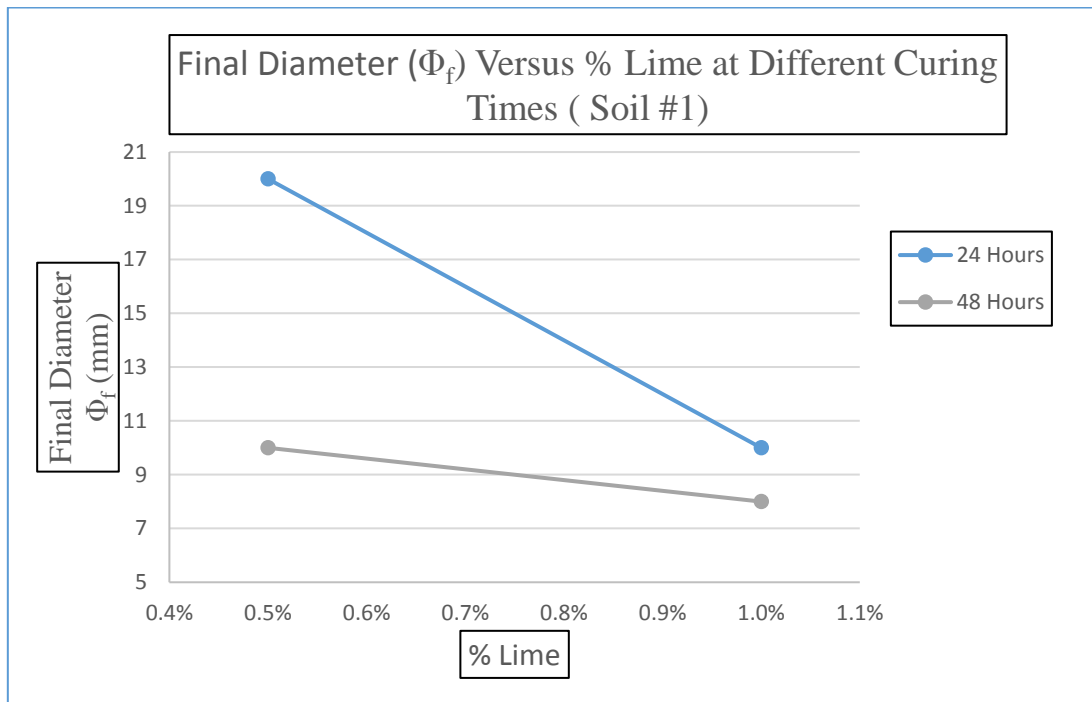


Figure 5-11 : Effect on increase in lime percentage and curing Time on Final Diameter of Water Path (Φ_f) for Soil #1.

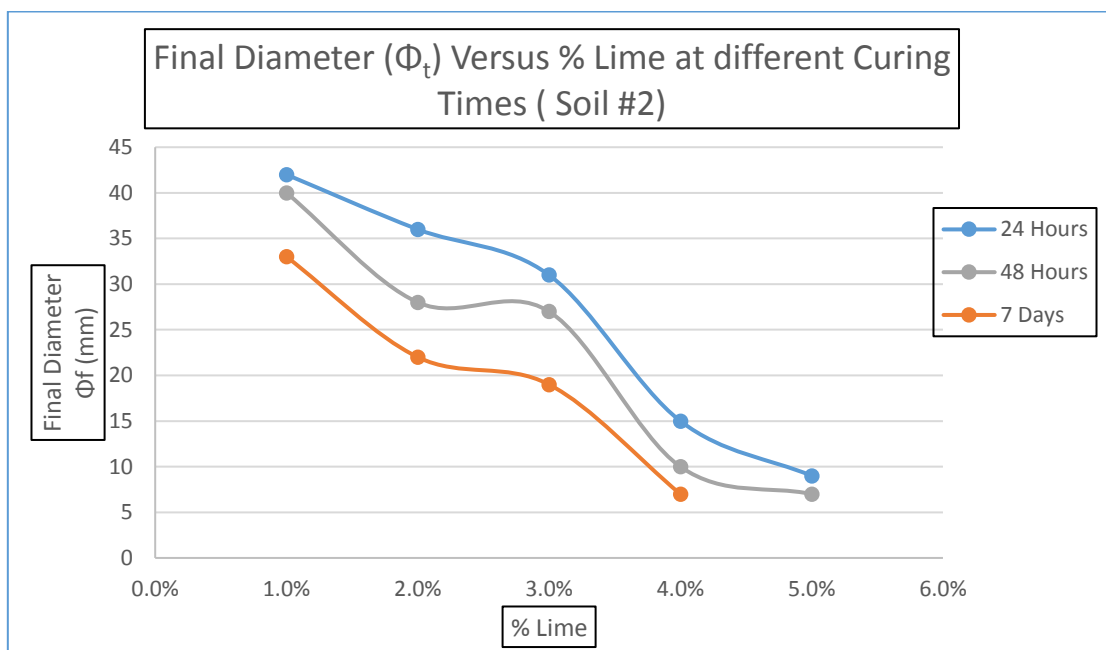


Figure 5-12 : Effect on increase in lime percentage and curing Time on Final Diameter of Water Path (Φ_f) for Soil #2.

5.4.2 Effect of lime percentage and curing time on critical shear stress.

Figure 5-13 and Figure 5-14 present the relationship between the critical shear stress and the percentage of lime added at three different curing times (24 hours, 48 hours, and 7 days) for both soils, Soil #1 and Soil #2 respectively. It is obvious from these bar charts that the critical shear for both soils at 7 days is the highest among the three curing bars at each lime percentage. This indicates that the critical shear stress of the soil is increased as the curing time is increased.

Furthermore, an increase in lime percentage will continue increasing the critical shear stress. Where if lime is added further than the lime fixation point, the soil will be stabilized, while the extra lime will work on increasing the soil strength. That is why at higher lime percentages the critical shear value exhibit a larger jump between different curing times as shown in Figure 5-13 and Figure 5-14.

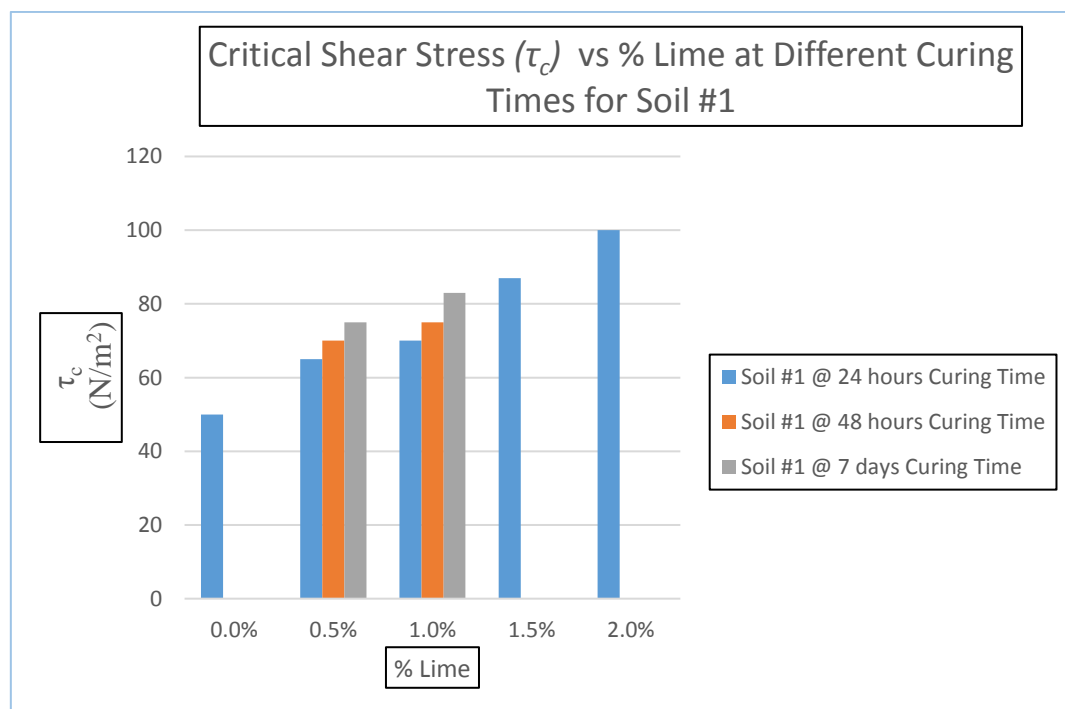


Figure 5-13 : Effect on increase in lime percentage and curing Time on Critical Shear Stress (τ_c) for Soil #1.

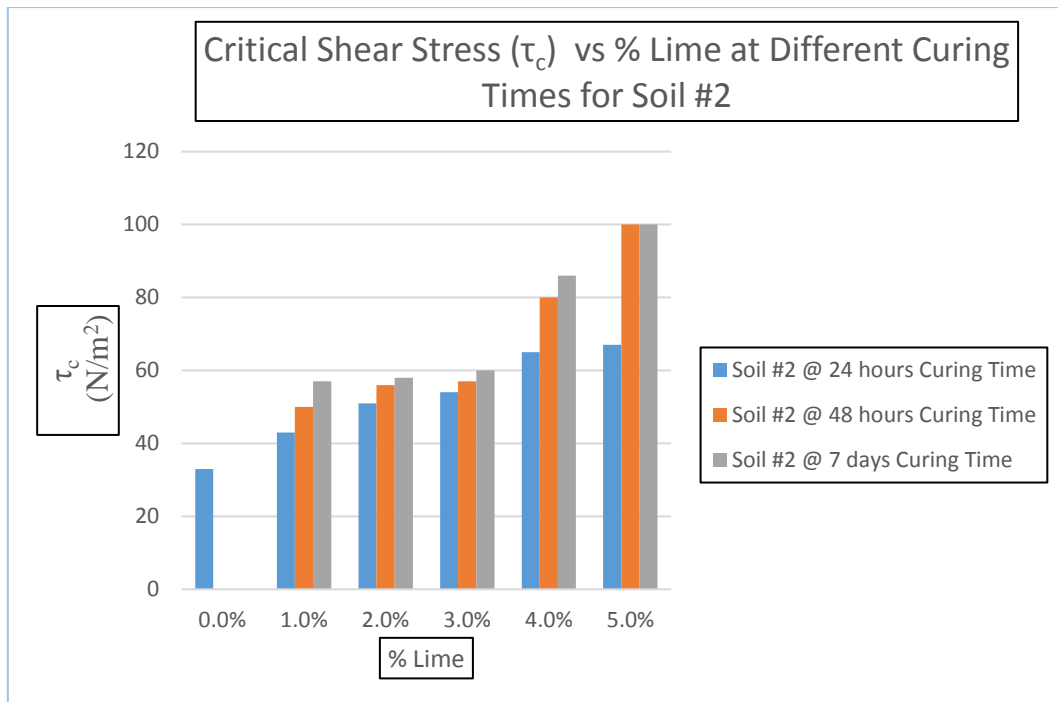


Figure 5-14 : Effect on increase in lime percentage and curing Time on Critical Shear Stress (τ_c) for Soil #2.

5.4.3 Effect of lime percentage and curing time on erosion rate index (I_{HET}).

Figure 5-15 and Figure 5-16 presents the relationship between the Erosion Rate Index and the percentage of lime added at three different curing times (24 hours, 48 hours, and 7 days) for both soils, Soil #1 and Soil #2 respectively. It is obvious from these charts that the Erosion Rate Index for both soils at 7 days is the highest amongst the three curing bars at each lime percentage. This indicates that the Erosion Rate Index (I_{HET}) of the soil is increases as the curing time is increased.

Furthermore, at higher lime percentage the increase in the Erosion Rate Index (I_{HET}) becomes less; this is back to two reasons, first is that lime fixation has been achieved and a further increase in lime percentage will not increase the stability of soil against internal erosion, rather it will continue to increase the strength of the soil. Second reason is that usually quick lime is cured after 48 hours and an increase of curing time further will not have a significant impact.

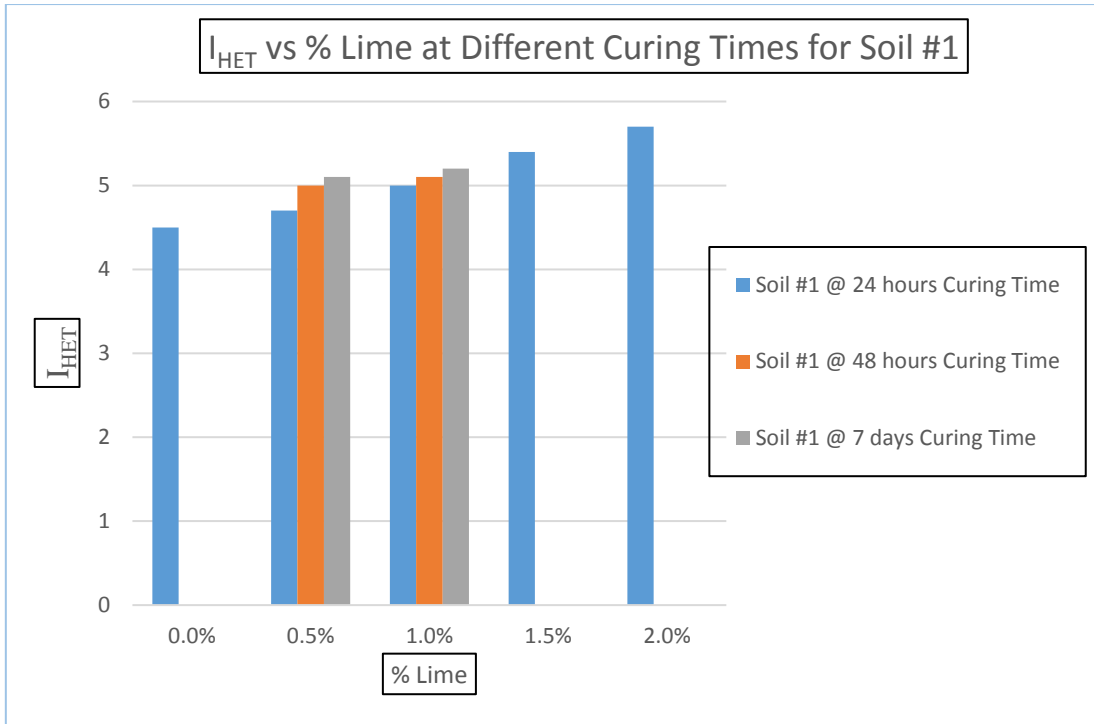


Figure 5-15 : Effect on increase in lime percentage and curing Time on Erosion Rate Index (I_{HET}) for Soil #1.

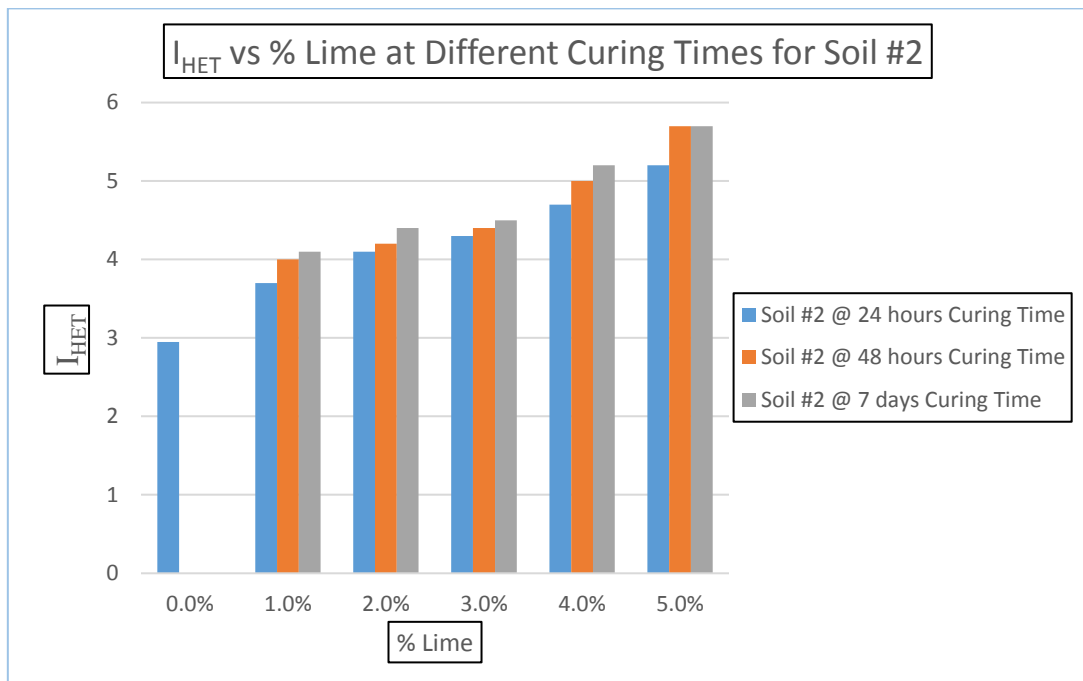


Figure 5-16 : Effect on increase in lime percentage and curing Time on Erosion Rate Index (I_{HET}) for Soil #2.

5.5 Effect of Soil Type and Gradation of the Soil on the Percentage of Lime Needed to Stabilize the Soil Against Internal Erosion

As mentioned in Section 5.1 earlier, Soil #1 is classified as CH soil and Soil #2 is classified as ML Soil as per Unified Soil Classification System. CH soil is a clayey Soil with low plasticity with high percentage of clay. This is also obvious from the grain size distribution shown in Table 5-1 that states that Soil #1 has 65% clay. While Soil #2, which is a ML soil, described as Silty Soil with low plasticity, has only 17% clayey material. This explains why soil #1 needed only 2% to stabilize it, while soil #2 required 5% of lime to stabilize it. It is because lime mainly reacts with clayey material in the soil. This explains the difference in percentages needed. Therefore, the type of soil and the percentage of clayey material in the soil plays a major role in determining the percentage of the lime needed to stabilize the soil against internal erosion.

Chapter 6. Conclusion and Future Work

In this thesis, the stabilization of clayey soil against internal erosion was studied through a comprehensive experimental testing procedure. Quick Lime was used as the stabilizing agent. Hole Erosion Test was implemented to simulate the flow of water through embankment dams and hence simulated the piping erosion that can happen throughout the body of the embankment dam.

The main objective of this study was to investigate the potential use of lime to stabilize cohesive soil against internal erosion. The objective was achieved by conducting Hole Erosion Tests on several samples of two types of clayey soils. One CH soil and one ML soil. Various lime percentages were added to each soil and the effect of this on the erosion parameters such as final diameter of water path (Φ_f), Critical Shear Stress (τ_c) and the Erosion Rate Index (I_{HET}) was studied. The results were analysed to optimize the lime content and curing time to stabilize each type of cohesive soils against internal erosion.

The main findings of this study are stated below:

1. An increase in lime percentage will exhibit a significant reduction on the final diameter of the water path of the samples for both clayey soil types.
2. An increase in lime percentage will exhibit a significant increase in the Critical Shear Stress for both clayey soils.
3. An increase in lime percentage will exhibit an increase in the Erosion Rate Index (I_{HET}). This increase has improved Soil #1 classification from-moderately slow erodible soil to very slow erodible soil. Whereas, it has improved Soil #2 classification from being very rapid erodible soil to very slow erodible soil; three categories up.
4. The test results showed that by adding 2.0% lime by dry weight of Soil #1 and curing the sample for 48 hours, the soil was stabilized against internal erosion with an Erosion Rate Index (I_{HET}) of “5.7”. Whereas a 5.0% lime by dry weight of Soil #2 and 48 hours curing time, the soil was stabilized against internal erosion with an Erosion Rate Index (I_{HET}) of “5.7”.

5. It was noticed that lime is more effective with CH soil than with ML soil with sand. Only 2.0% of lime with curing time 48 hours will stabilize CH soil, While ML soil with sand needed 5.0% of lime at 48 hours to get stabilized against internal erosion. This is because the lime mainly reacts with clayey particles to produce a stabilized soil, therefore, the higher the percentage of clay in the soil the more reaction will happen with the lime components and the more stable soil will be achieved.

As future works on the same area of study of this theses the following can be studied further:

1. Study the effect of the soil initial physical properties such as cohesion, optimum moisture content, maximum dry density, Atterberg's limits, angle of friction, and gradation on internal erosion, erosion rate index and critical shear stress
2. Further study the use of other stabilizing agents on internal erosions such as fly ash, oil shale ash, and other soiled waste materials
3. Investigate the effect of the test used, Hole Erosion Test, on the Erosion Rate Index values. And use the improvements on Hole Erosion Test available in literature.
4. Use another types of tests to obtain the same erosion parameter and compare between the various tests efficiencies.

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Appendix A: Calculations for Soil #1

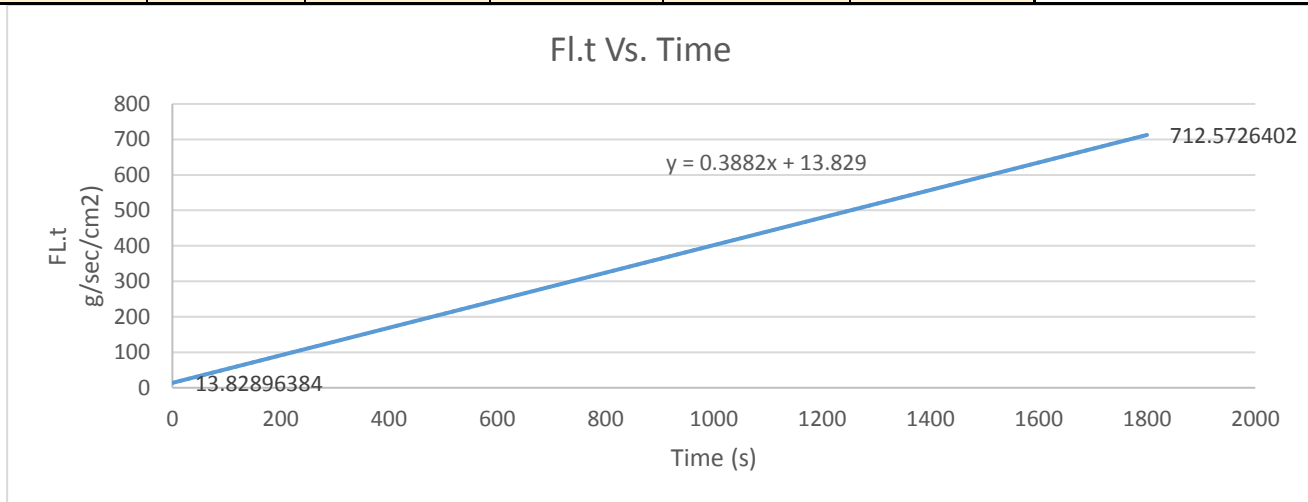
A1- Calculation of Base Soil#1:

Base Soil	% lime	Testing Time	Soil
	0%	24 Hours	Soil #1

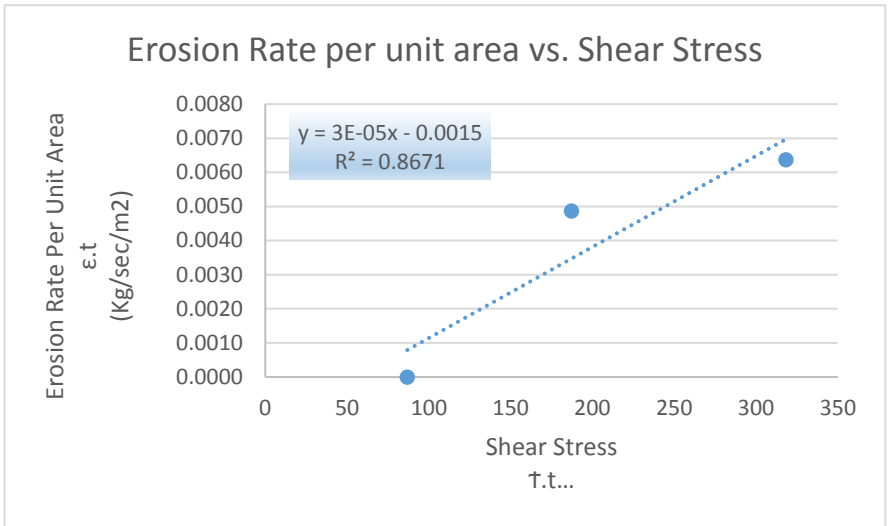
Data Collected						
Parameter	Unit	Value		Water Head Data		
Water Density (ρ_w)	kg/m ³	1000		Upstream	0	
Gravity (g)	m/sec ²	9.80		Down Stream	60	
Hydraulic Gradient (st)		5.91		Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1263.5				
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)			
0	163	2.3	6			
15	198	2.1				
30	305	1.2	22			

Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ_t (mm)	V_t	R_e	Flow Type
0	163	2.3	6	3	14973	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q_t (m ³ /sec)	F_{Tt} (Kg/m ² /sec)	Φ_t (m)	Slope	B-Intercept
0	0	0.000163	2.3	7.08696E-05	13.82896384	0.006	0.388190931	13.82896
30	1800	0.000305	1.2	0.000254167	712.5726402	0.022		
Flt	=	slope	t	+	F10			
Flt	=	0.388190931	t	+	13.82896384			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{τt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.000163	2.3	0.0001	13.8290	0.0060	0.0000000000	86.8110	0.0000
15	900	0.000198	2.1	0.0001	363.2008	0.0129	0.0000077006	187.0858	0.0049
30	1800	0.000305	1.2	0.0003	712.5726	0.0220	0.0000100772	318.3071	0.0064



Slope	y-intercept
0.00003	-0.0015

Variable	Unit	Value
Tc	N/m2	50.00
Ce	None	3.000E-05
I	None	4.52

A2- Calculation of 0.5% lime at 24 hours curing time -Soil#1:

0.5%	% lime	Testing Time	Soil
	0.5%	24 Hours	Soil #1

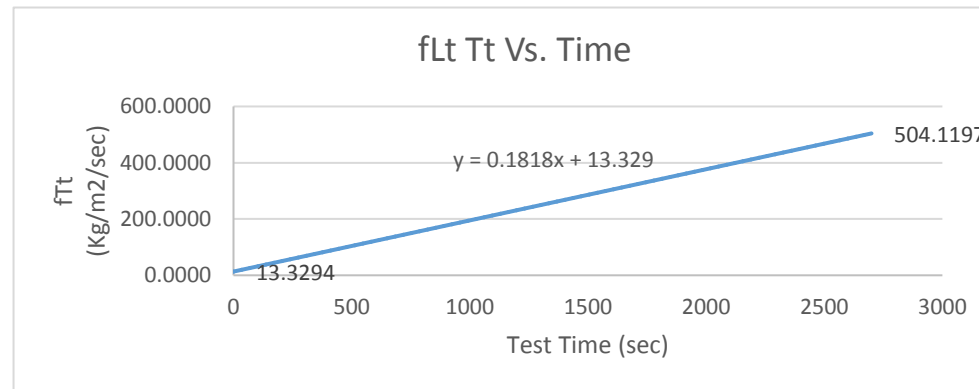
Data Collected					
Parameter		Unit	Value	Water Head Data	
Water Density (ρ_w)		kg/m ³	1000	Upstream	0
Gravity (g)		m/sec ²	9.80	Down Stream	60
Hydraulic Gradient (s_t)			5.91	Specimen Length	10.16
Soil Density (ρ_d)		kg/m ³	1263		

Test Time (min)	Volume (cm ³)	Time (sec)	Φ_t (mm)
0	130	1.8	6
15	127	1.4	
30	171	1.6	
45	405	1.7	20

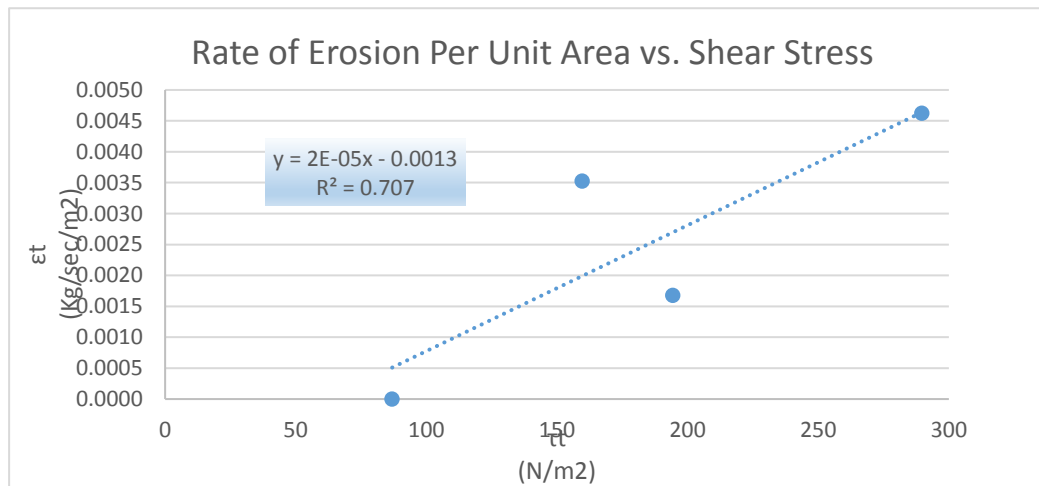
Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ_t (mm)	V_t	Re	Flow Type
0	130	1.8	6	2.553310887	15258.83	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q_t (m ³ /sec)	F_{Tt} (Kg/m ² /sec)	Φ_t (m)	Slope	B-Intercept
0	0	0.00013	1.8	0.0001	13.3294	0.0060	0.1818	13.3294
45	2700	0.000405	1.7	0.0002	504.1197	0.0200		

F_{Tt}	=	slope	t	+	F_{I0}
F_{Tt}	=	0.18177417	t	+	13.3293943



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{Tt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.00013	1.8	7.22222E-05	13.3294	0.0060	0.00E+00	86.8996	0.0000
15	900	0.000127	1.4	9.07143E-05	176.9261	0.0110	5.58E-06	159.6673	0.0035
30	1800	0.000171	1.6	0.000106875	340.5229	0.0134	2.66E-06	194.3422	0.0017
45	2700	0.000405	1.7	0.000238235	504.1197	0.0200	7.31E-06	289.6654	0.0046



Slope	y-intercept
0.00002	-0.0013

Variable	Unit	Value
Tc	N/m2	65.00
Ce	None	2.00E-05
I	None	4.70

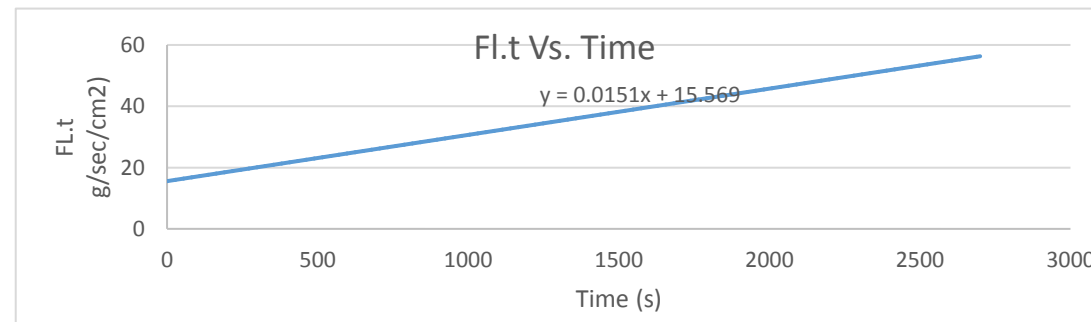
A3- Calculation of 0.5% lime at 48 hours curing time -Soil#1:

0.5%	% lime	Testing Time	Soil
	0.5%	48 Hours	Soil #1

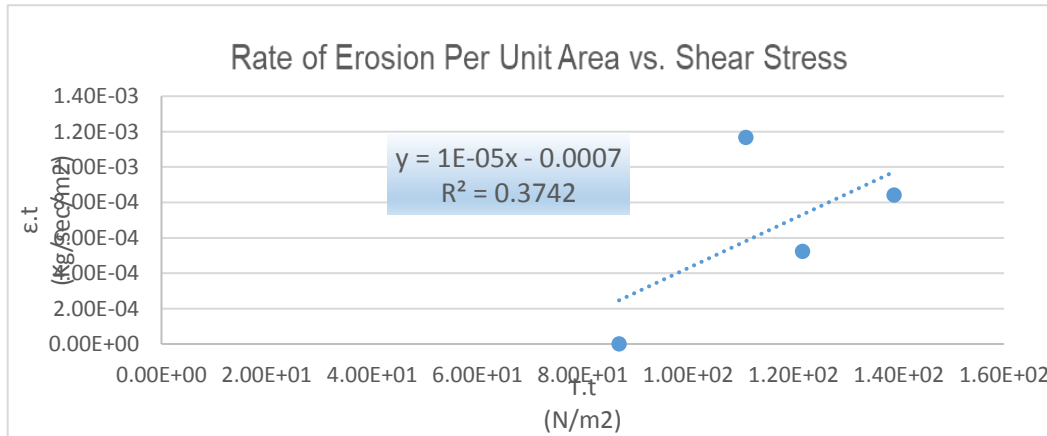
Data Collected				
Parameter	Unit	Value	Water Head Data	
Water Density (ρ_w)	kg/m ³	1000	Upstream	0
Gravity (g)	m/sec ²	9.80	Down Stream	60
Hydraulic Gradient (s_t)		5.91	Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1263		
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)	
0	147	2.2	6	
15	252	2.8		
30	225	2.4		
45	228	2	10	

Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ_t (mm)	V_t	R_e	Flow Type
0	147	2.2	6	2.3622589 53	14117.08538	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q_t (m ³ /sec)	F_{Tt} (Kg/m ² /sec)	Φ_t (m)	Slope	B-Intercept
0	0	0.000147	2.2	6.68182E-05	15.56860888	0.006	0.01508730 3	15.568608 88
45	2700	0.000252	2	0.000126	56.30432729	0.01		
FTt	=	slope	t	+	F _{l0}			
FTt	=	0.0150873	t	+	15.56860888			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{τt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.000147	2.2	6.68182E-05	15.56860888	0.0060	0	8.69E+01	0.00E+00
15	900	0.000252	2.8	0.00009	29.14718168	0.0077	1.84701E-06	1.11E+02	1.17E-03
30	1800	0.000225	2.4	0.00009375	42.72575448	0.0084	8.28053E-07	1.22E+02	5.23E-04
45	2700	0.000228	2	0.000114	56.30432729	0.0096	1.33335E-06	1.39E+02	8.42E-04



Slope	y-intercept
0.00001	-0.0007

Variable	Unit	Value
Tc	N/m ²	70.00
Ce	None	1.00E-05
I	None	5.0

A4- Calculation of 0.5% lime at 7 days curing time -Soil#1:

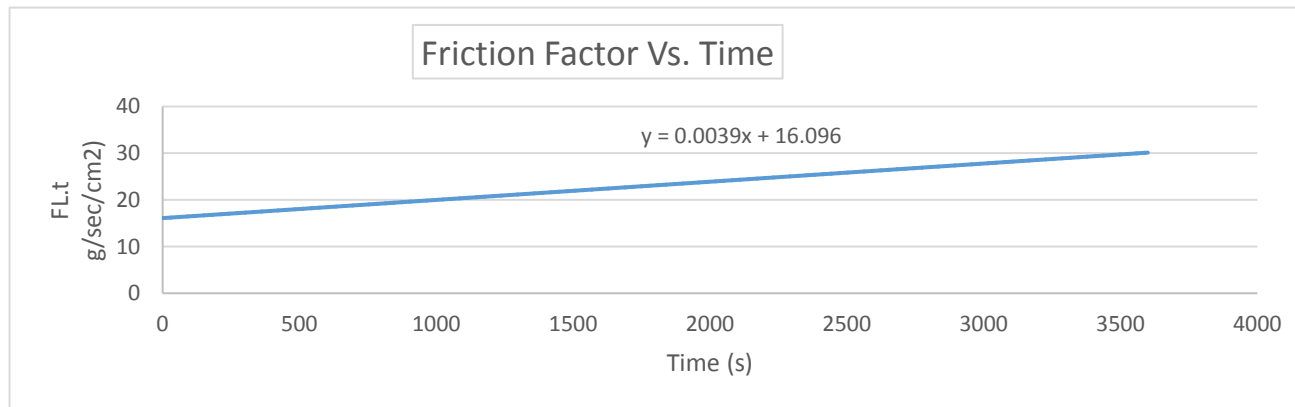
0.5%	% lime	Testing Time	Soil
	0.5%	7 days	Soil #1

Data Collected				
Parameter	Unit	Value	Water Head Data	
Water Density (ρ_w)	kg/m ³	1000	Upstream	0
Gravity (g)	m/sec ²	9.80	Down Stream	60
Hydraulic Gradient (s_t)		5.91	Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1263		
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)	
0	138	2.1	6	
15	160	2.3		
30	177	2.6		
45	125	1.8		
60	113	1.6	7	

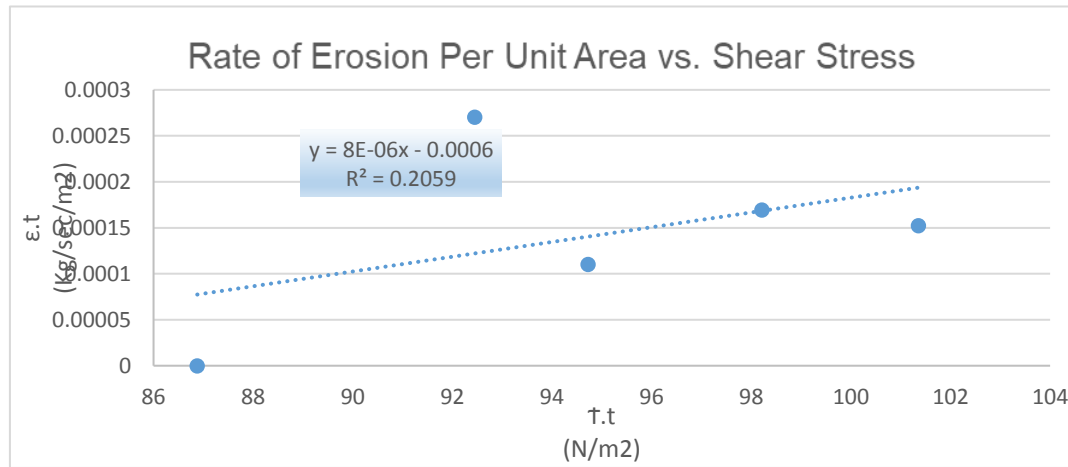
Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ_t (mm)	V_t	Re	Flow Type
0	138	2.1	6	2.323232323	13883.85851	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q.t (m ³ /sec)	FTt (Kg/m ² /sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.000138	2.1	6.57143E-05	16.09605817	0.006	0.003895562	16.09605817
60	3600	0.000113	1.6	0.000070625	30.1200815	0.007		

FTt	=	slope	t	+	FIO
FTt	=	0.00389556	t	+	16.09605817



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{τt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.000138	2.1	6.57143E-05	16.09605817	0.0060	0	86.877	0
15	900	0.00016	2.3	6.95652E-05	19.602064	0.0064	4.27774E-07	92.45155317	0.000270246
30	1800	0.000177	2.6	6.80769E-05	23.10806983	0.0065	1.74207E-07	94.72174584	0.000110056
45	2700	0.000125	1.8	6.94444E-05	26.61407566	0.0068	2.68E-07	98.21419764	0.000169309
60	3600	0.000113	1.6	0.000070625	30.1200815	0.0070	2.4113E-07	101.3565	0.000152334



Slope	y-intercept
0.000008	-0.0006

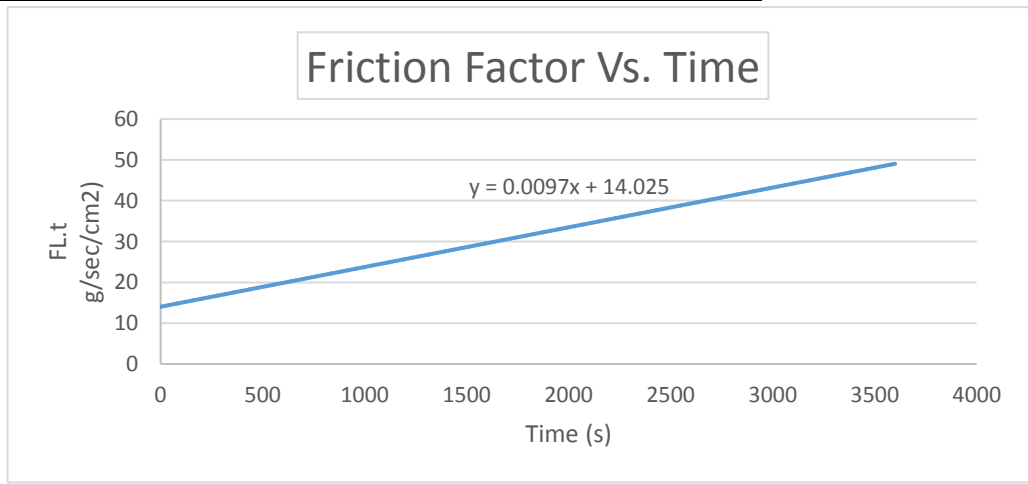
Variable	Unit	Value
Tc	N/m2	75.00
Ce	None	8.00E-06
I	None	5.10

A5- Calculation of 1% lime at 24 hours curing time -Soil#1:

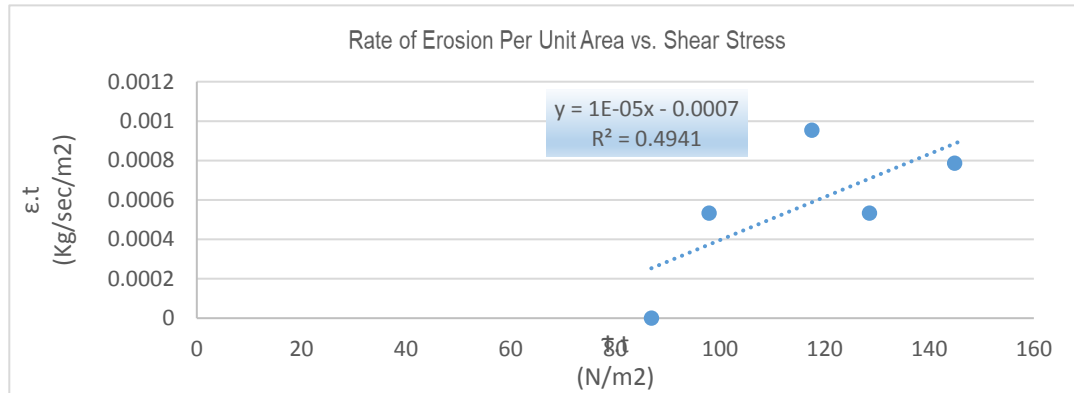
1.0%	% lime	Testing Time	Soil
	1.0%	24 hours	Soil #1

Data Collected				
Parameter	Unit	Value	Water Head Data	
Water Density (ρ_w)	kg/m ³	1000	Upstream	0
Gravity (g)	m/sec ²	9.80	Down Stream	60
Hydraulic Gradient (s_t)		5.91	Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1263		
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)	
0	176	2.5	6	
15	201	2.7		
30	220	2.2		
45	166	1.5		
60	270	2	10	

Flow Type calculations								
Test Time (min)	Volume (cm ³)	Time (sec)	Φ.t (mm)	V _t	Re	Flow Type		
0	176	2.5	6	2.488888889	14873.83798	Turbulent		
Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	Slope	B-Intercept
0	0	0.000176	2.5	0.0000704	14.02470703	0.006		
60	3600	0.00027	2	0.000135	49.0473251	0.01	0.009728505	14.02470703
FTt	=	slope	t	+	F10			
FTt	=	0.00972851	t	+	14.02470703			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{τt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.000176	2.5	0.0000704	14.02470703	0.0060	0	86.877	0
15	900	0.000201	2.7	7.44444E-05	22.78036155	0.0068	8.45167E-07	97.89083482	0.000533934
30	1800	0.00022	2.2	0.0001	31.53601607	0.0081	1.50932E-06	117.5596699	0.000953516
45	2700	0.000166	1.5	0.000110667	40.29167058	0.0089	8.4506E-07	128.5721123	0.000533867
60	3600	0.00027	2	0.000135	49.0473251	0.0100	1.24489E-06	144.795	0.000786461



Slope	y-intercept
0.00001	-0.0007

Variable	Unit	Value
Tc	N/m ²	70.00
Ce	None	1.00E-05
I	None	5.00

A6- Calculation of 1% lime at 48 hours curing time -Soil#1:

1.0%	% lime	Testing Time	Soil
	1.0%	48 hours	Soil #1

Data Collected					
Parameter	Unit	Value		Water Head Data	
Water Density (ρ_w)	kg/m ³	1000		Upstream	0
Gravity (g)	m/sec ²	9.80		Down Stream	60
Hydraulic Gradient (s_t)		5.91		Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1263			
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)		
0	200	2.8	6		
15	148	2			
30	130	1.6			
45	138	1.7			
60	130	1.5	8		

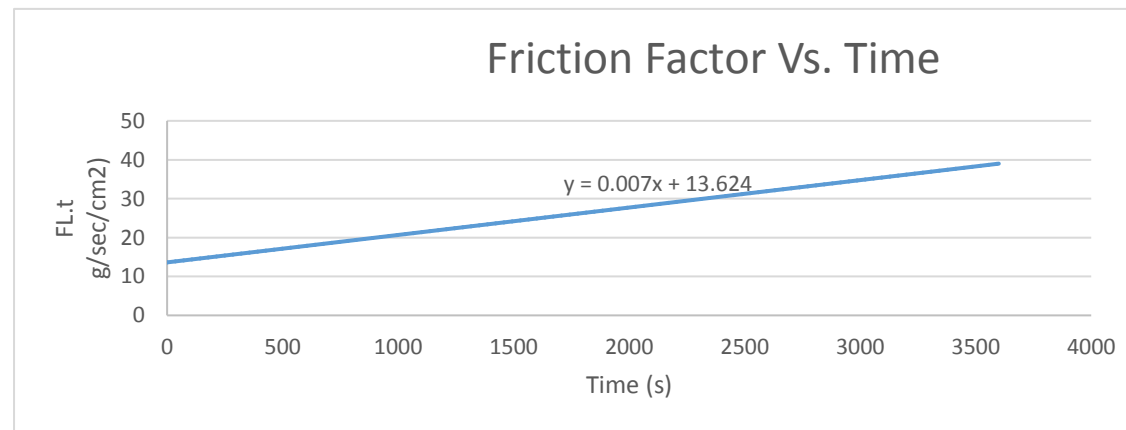
Flow Type calculations

Test Time (min)	Volume (cm ³)	Time (sec)	Φ.t (mm)	V _t	R _e	Flow Type
0	200	2.8	6	2.525252525	15091.15055	Turbulent

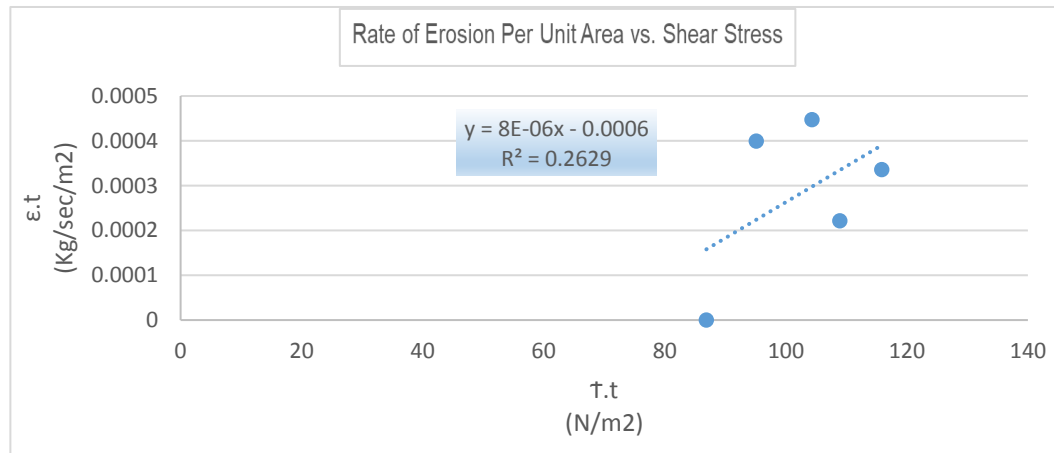
Friction Factors Calculations

Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	Slope	B-Intercept
0	0	0.0002	2.8	7.14286E-05	13.62370363	0.006		
60	3600	0.00013	1.5	8.66667E-05	38.99676781	0.008	0.007048073	13.62370363

FTt	=	slope	t	+	FIO
FTt	=	0.00704807	t	+	13.62370363



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{τt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.0002	2.8	7.14286E-05	13.62370363	0.0060	0	86.877	0
15	900	0.000148	2	0.000074	19.96696968	0.0066	6.3221E-07	95.11567888	0.000399399
30	1800	0.00013	1.6	0.00008125	26.31023572	0.0072	7.07854E-07	104.3401095	0.000447187
45	2700	0.000138	1.7	8.11765E-05	32.65350177	0.0075	3.50434E-07	108.9068034	0.000221386
60	3600	0.00013	1.5	8.66667E-05	38.99676781	0.0080	5.31725E-07	115.836	0.000335917



Slope	y-intercept
0.000008	-0.0006

Variable	Unit	Value
Tc	N/m2	75.00
Ce	None	0.000008
I	None	5.10

A7- Calculation of 1% lime at 7 days curing time -Soil#1:

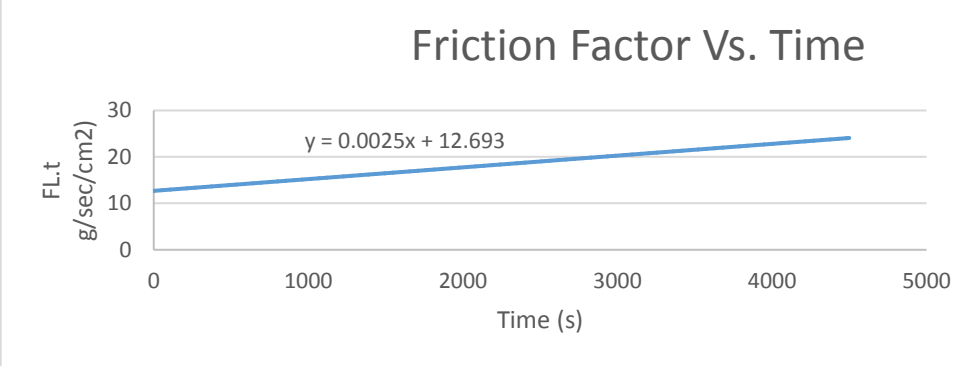
1.0%	% lime	Testing Time	Soil
	1.0%	7 days	Soil #1

Data Collected				
Parameter	Unit	Value	Water Head Data	
Water Density (ρ_w)	kg/m ³	1000	Upstream	0
Gravity (g)	m/sec ²	9.80	Down Stream	60
Hydraulic Gradient (s_t)		5.91	Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1263		
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)	
0	148	2	6	
15	150	2		
30	152	2		
45	154	2		
75	158	2	7	

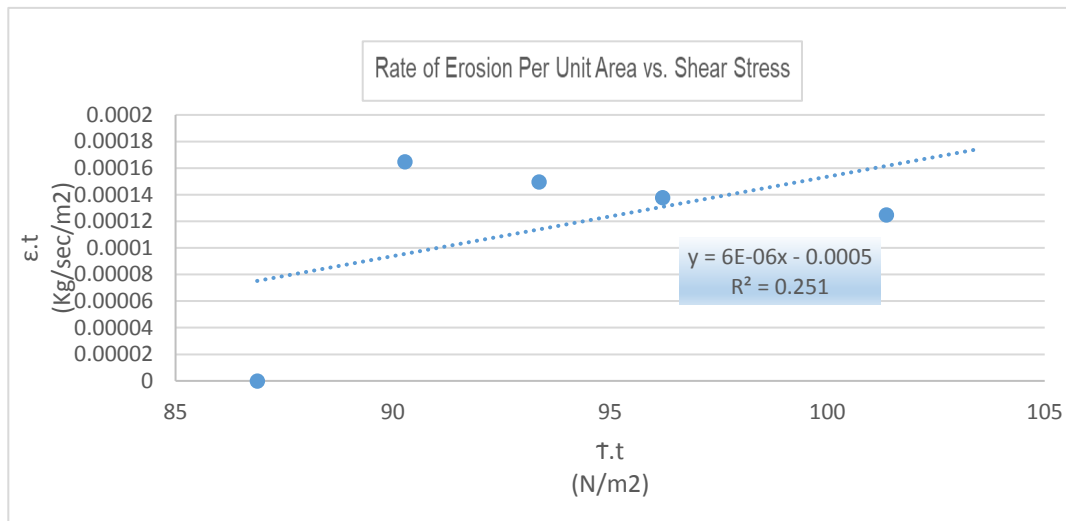
Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ.t (mm)	V _t	R _e	Flow Type
0	148	2	6	2.616161616	15634.43197	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	Slope	B-Intercept
0	0	0.000148	2	0.000074	12.69333309	0.006	0.002528675	12.69333309
75	4500	0.000158	2	0.000079	24.07237176	0.007		

FTt	=	slope	t	+	FIO
FTt	=	0.00252868	t	+	12.69333309



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{τt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.000148	2	0.000074	12.69333309	0.0060	0	86.877	0
15	900	0.00015	2	0.000075	14.96914082	0.0062	2.60646E-07	90.273623	0.000164663
30	1800	0.000152	2	0.000076	17.24494856	0.0064	2.36739E-07	93.35870308	0.00014956
45	2700	0.000154	2	0.000077	19.52075629	0.0066	2.1833E-07	96.20388497	0.00013793
75	4500	0.000158	2	0.000079	24.07237176	0.0070	1.97698E-07	101.3565	0.000124896



Slope	y-intercept
0.000006	-0.0005

Variable	Unit	Value
Tc	N/m ²	83.33
Ce	None	0.000006
I	None	5.22

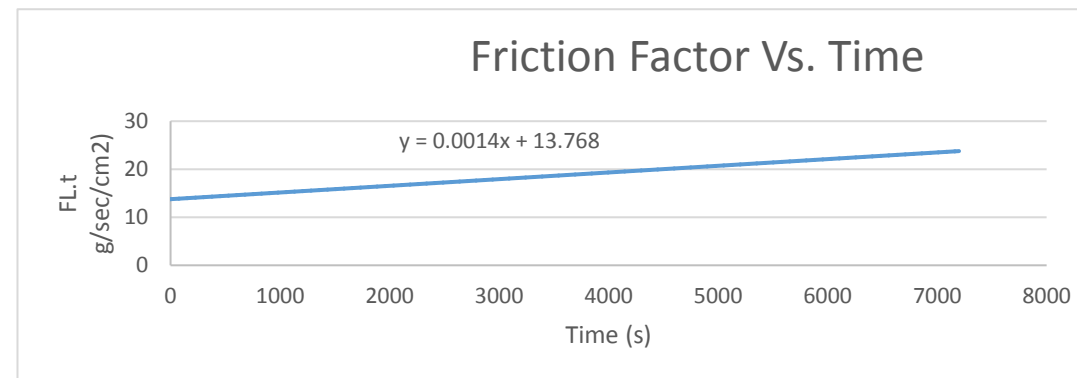
A8- Calculation of 1.5% lime at 24 hours curing time -Soil#1:

1.5%	% lime	Testing Time	Soil
	1.5%	24 hours	Soil #1

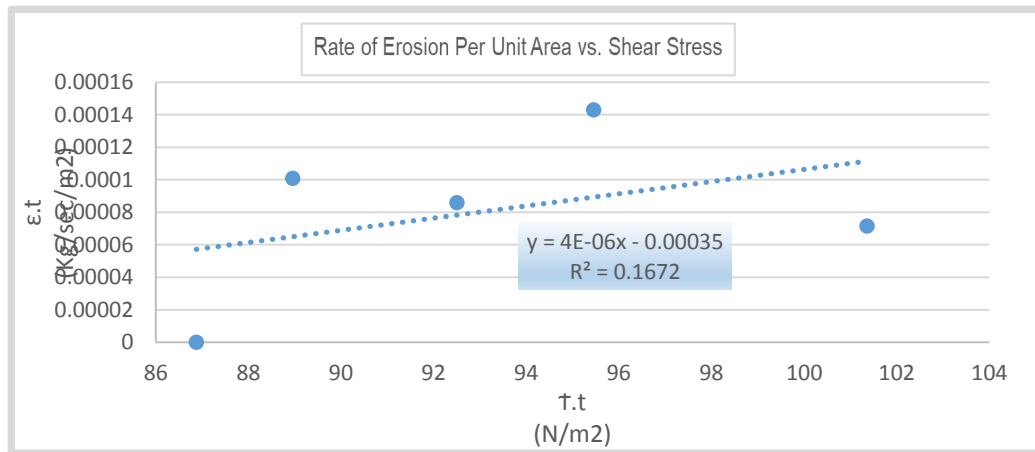
Data Collected					
Parameter	Unit	Value	Water Head Data		
Water Density (ρ_w)	kg/m ³	1000	Upstream	0	
Gravity (g)	m/sec ²	9.80	Down Stream	60	
Hydraulic Gradient (s_t)		5.91	Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1263			
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)		
0	135	1.9	6		
15	166	2.3			
45	140	1.9			
60	154	2			
120	159	2	7		

Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ.t (mm)	V _t	Re	Flow Type
0	135	1.9	6	2.511961722	15011.72344	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	Slope	B-Intercept
0	0	0.000135	1.9	7.10526E-05	13.7682512	0.006	0.001389205	13.7682512
120	7200	0.000159	2	0.0000795	23.77052682	0.007		
FTt	=	slope	t	+	FIO			
FTt	=	0.0013892	t	+	13.7682512			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{Tt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.000135	1.9	7.10526E-05	13.7682512	0.0060	0	86.877	0
15	900	0.000166	2.3	7.21739E-05	15.01853565	0.0061	1.59526E-07	88.95586994	0.00010078
45	2700	0.00014	1.9	7.36842E-05	17.51910456	0.0064	1.36043E-07	92.50157922	8.59453E-05
60	3600	0.000154	2	0.000077	18.76938901	0.0066	2.26377E-07	95.45162131	0.000143014
120	7200	0.000159	2	0.0000795	23.77052682	0.0070	1.1328E-07	101.3565	7.15649E-05



Slope	y-intercept	
0.000004	-0.00035	
Variable	Unit	Value
Tc	N/m ²	87.5
Ce	None	0.000004
I	None	5.39

A9- Calculation of 2% lime at 24 hours curing time -Soil#1:

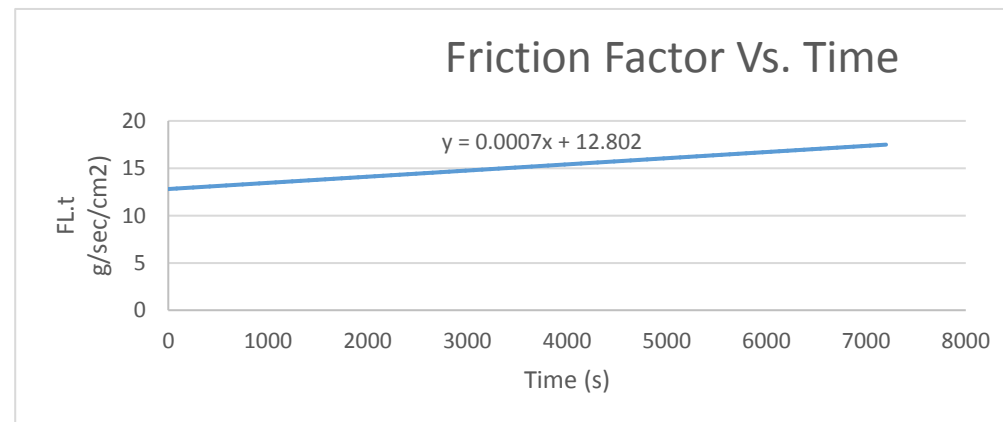
2.0%	% lime	Testing Time	Soil
	2.0%	24 hours	Soil #1

Data Collected					
Parameter	Unit	Value	Water Head Data		
Water Density (ρ_w)	kg/m ³	1000	Upstream	0	
Gravity (g)	m/sec ²	9.80	Down Stream	60	
Hydraulic Gradient (s_t)		5.91	Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1263			
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)		
0	140	1.9	6		
15	170	2.3			
30	127	1.7			
45	160	2.1			
90	153	2			
120	154	2	6.5		

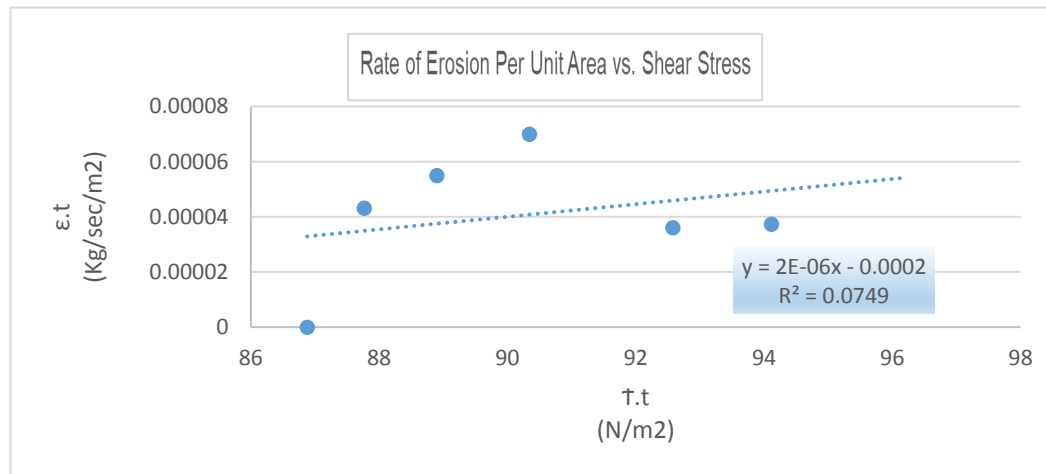
Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ_t (mm)	V_t	Re	Flow Type
0	140	1.9	6	2.604997342	15567.7132	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q.t (m ³ /sec)	FTt (Kg/m ² /sec)	Φ_t (m)	Slope	B-Intercept
0	0	0.00014	1.9	7.36842E-05	12.80236623	0.006		
120	7200	0.000154	2	0.000077	17.49315713	0.0065	0.000651499	12.80236623

FTt	=	slope	t	+	F ₁₀
FTt	=	0.0006515	t	+	12.80236623



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q _t (m ³ /sec)	f _{Tt} (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ _t (N/m ²)	ε _t (Kg/sec/m ²)
0	0	0.00014	1.9	7.36842E-05	12.80236623	0.0060	0	86.877	0
15	900	0.00017	2.3	7.3913E-05	13.38871509	0.0061	6.83261E-08	87.76739463	4.3165E-05
30	1800	0.000127	1.7	7.47059E-05	13.97506395	0.0061	8.70368E-08	88.90161961	5.49855E-05
45	2700	0.00016	2.1	7.61905E-05	14.56141282	0.0062	1.10662E-07	90.34372027	6.99109E-05
90	5400	0.000153	2	0.0000765	16.3204594	0.0064	5.71519E-08	92.57805288	3.61057E-05
120	7200	0.000154	2	0.000077	17.49315713	0.0065	5.90374E-08	94.11675	3.72969E-05



Slope	y-intercept
0.000002	-0.0002

Variable	Unit	Value
Tc	N/m2	100
Ce	None	0.000002
I	None	5.70

Appendix B: Calculations for Soil #2

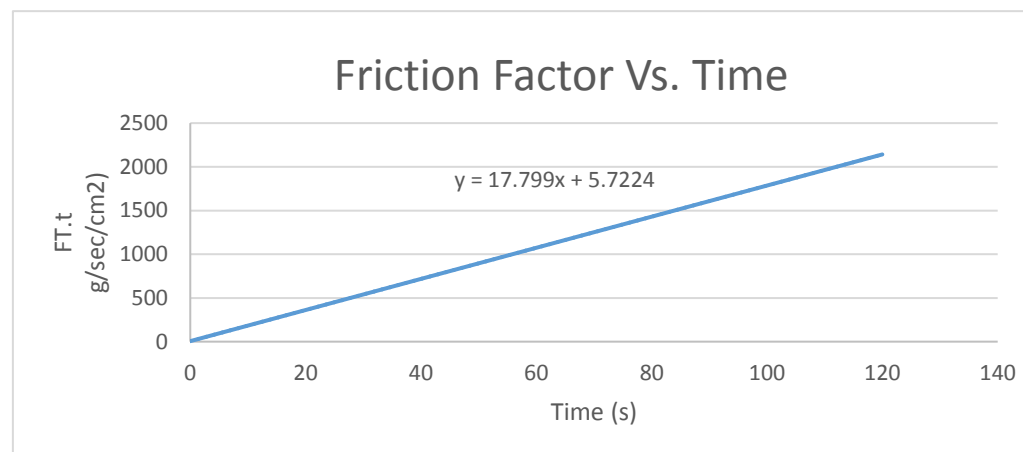
B1-Calculation of Base Soil -Soil#2:

Base Soil	% lime	Testing Time	Soil
	0.0%	24 hours	Soil #2

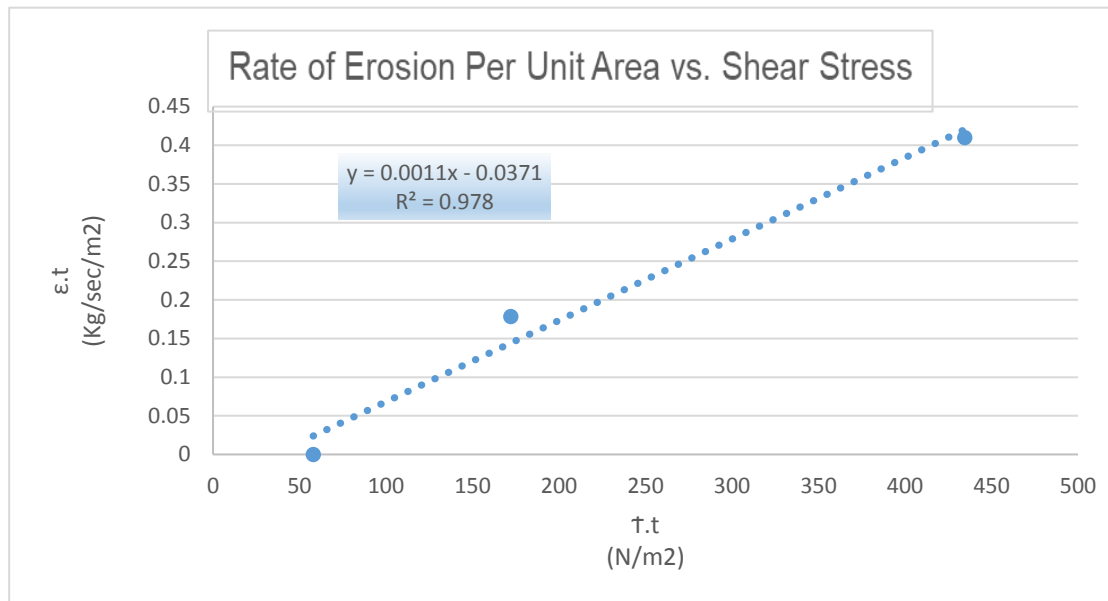
Data Collected					
Parameter	Unit	Value		Water Head Data	
Water Density (ρ_w)	kg/m ³	1000		Upstream	0
Gravity (g)	m/sec ²	9.80		Down Stream	60
Hydraulic Gradient (s_t)		5.91		Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1810			
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)		
0	180	2	6		
1	200	2			
2	860	1.2	45		

Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ.t (mm)	V _t	R _e	Flow Type
0	180	2	6	3.18	19014.84969	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	Slope	B-Intercept
0	0	0.00018	2	0.00009	5.722368632	0.006	17.79875009	5.722368632
2	120	0.00086	1.2	0.000716667	2141.572379	0.045		
FTt	=	slope	t	+	Ft0			
FTt	=	17.7987501	t	+	5.722368632			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q.t (m ³ /sec)	FTt (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ.t (N/m ²)	ε.t (Kg/sec/m ²)
0	0	0.00018	2	0.00009	5.722368632	0.0060	0	57.93307087	0
1	60	0.0002	2	0.0001	1073.647374	0.0178	0.000197139	172.1419479	0.178411108
2	120	0.00086	1.2	0.000716667	2141.572379	0.0450	0.000452861	434.4980315	0.409838892



Slope	y-intercept
0.0011	-0.0371

Variable	Unit	Value
Tc	N/m ²	33.72727273
Ce	None	0.0011
I	None	2.958607315

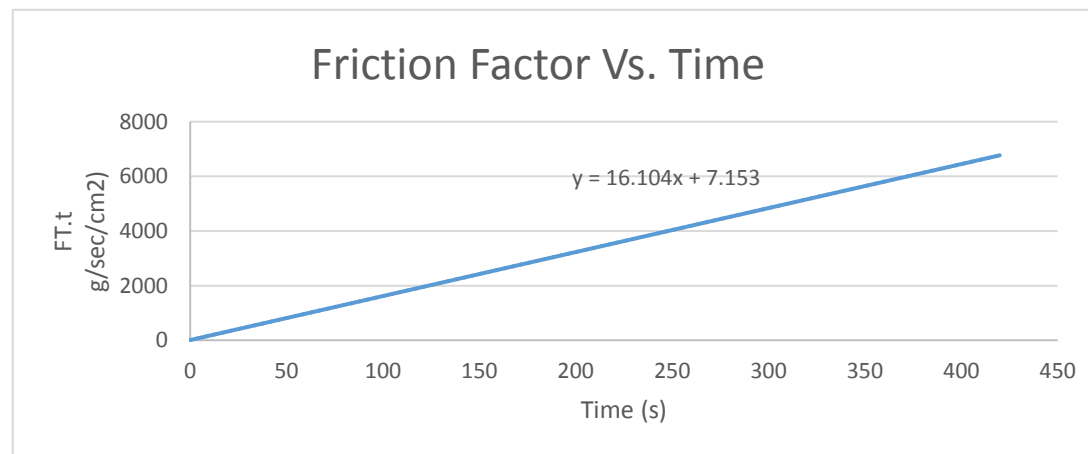
B2- Calculation of 1% lime at 24 hours curing time -Soil#2:

1.0%	% lime	Testing Time	Soil
	1.0%	24 hours	Soil #2

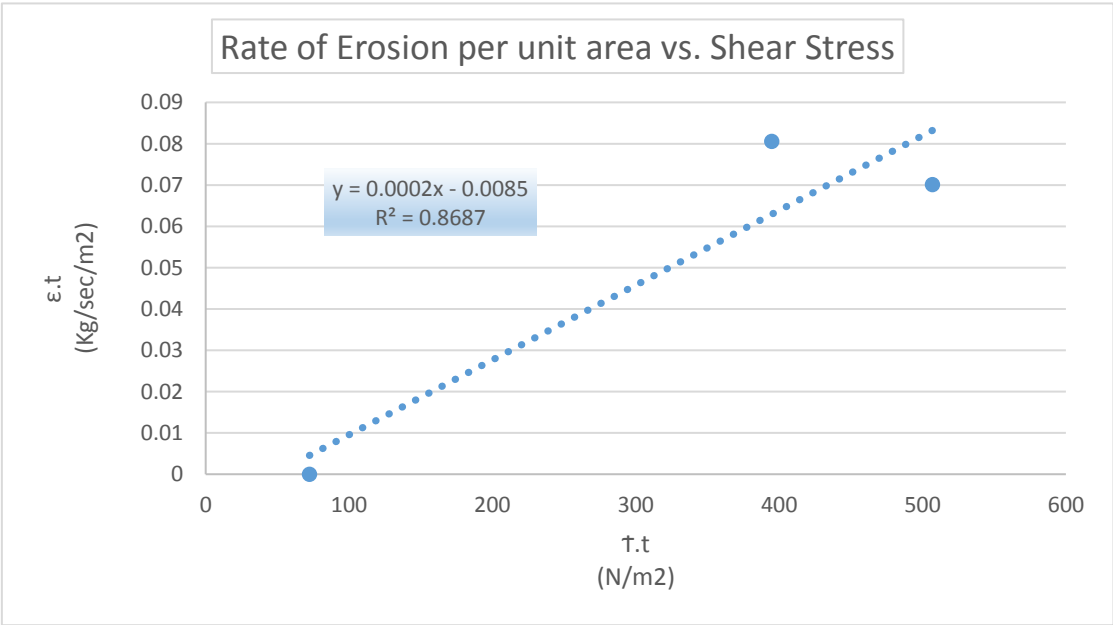
Data Collected					
Parameter	Unit	Value	Water Head Data		
Water Density (ρ_w)	kg/m ³	1000	Upstream	0	
Gravity (g)	m/sec ²	9.81	Down Stream	50	
Hydraulic Gradient (st)		4.92	Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1810			
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)		
0	180	2	6		
5	480	2			
7	493	1.3	42		

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	180	2	6	3.181818182	19014.84969	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.00018	2	0.00009	7.152960791	0.006		
7	420	0.000493	1.3	0.000379231	6771.017394	0.042	16.10443913	7.152960791
FTt	=	slope	t	+	FIO			
FTt	=	16.1044391	t	+	7.152960791			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	dΦt/dt	τ.t (N/m2)	ε.t (Kg/sec/m2)
0	0	0.00018	2	0.00009	7.152960791	0.0060	0	72.41633858	0
5	300	0.00048	2	0.00024	4838.484699	0.0327	8.9009E-05	394.7014858	0.080553108
7	420	0.000493	1.3	0.000379231	6771.017394	0.0420	7.74776E-05	506.9143701	0.070117229



Slope	y-intercept
0.0002	-0.0085

Variable	Unit	Value
Tc	N/m ²	42.5
Ce	None	0.0002
I	None	3.698970004

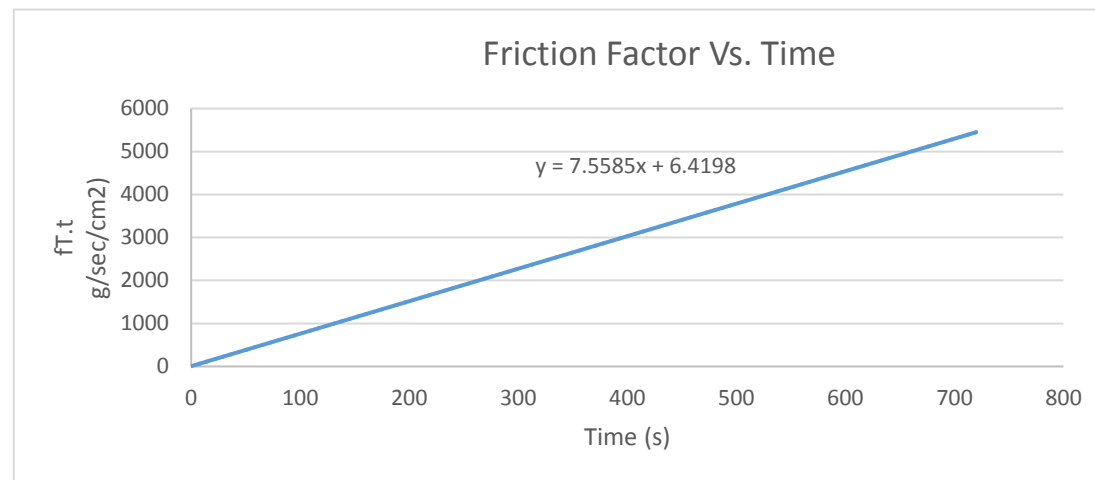
B3-Calculation of 1% lime at 48 hours curing time -Soil#2:

1.0%	% lime	Testing Time	Soil
	1.0%	48 hours	Soil #2

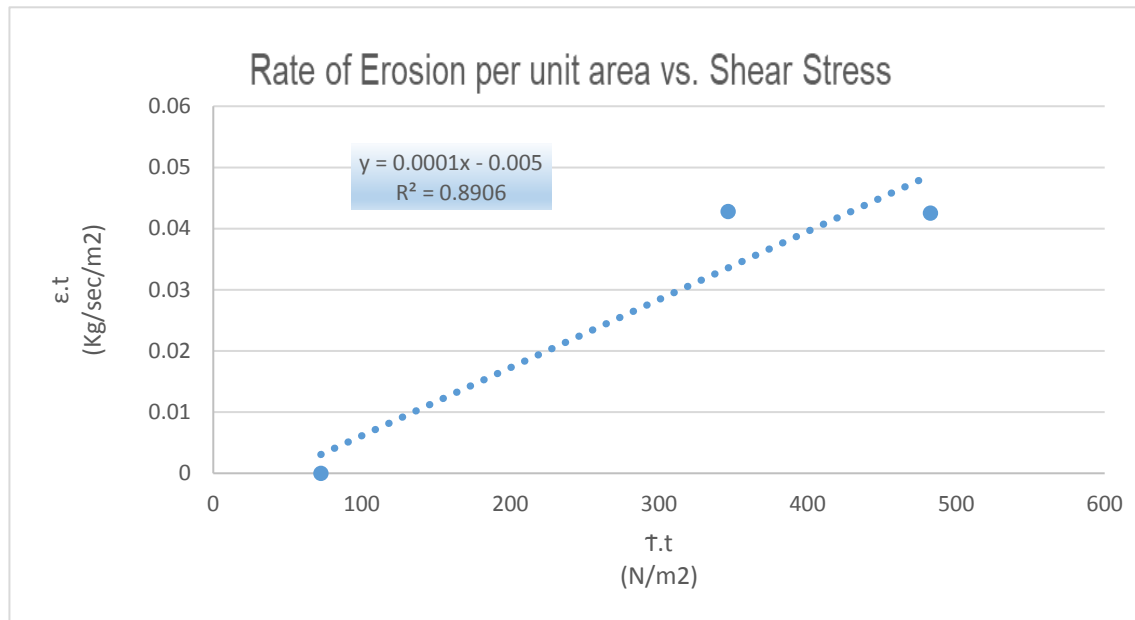
Data Collected				
Parameter	Unit	Value	Water Head Data	
Water Density (ρ_w)	kg/m ³	1000	Upstream	0
Gravity (g)	m/sec ²	9.81	Down Stream	50
Hydraulic Gradient (st)		4.92	Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1810		
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)	
0	190	2	6	
8	400	2		
12	711	1.9	40	

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	190	2	6	3.358585859	20071.23023	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.00019	2	0.000095	6.419831845	0.006		
12	720	0.000711	1.9	0.000374211	5448.570422	0.04	7.558542487	6.419831845
FTt	=	slope	t	+		F10		
FTt	=	7.55854249	t	+		6.419831845		



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	dΦt/dt	τ.t (N/m2)	ε.t (Kg/sec/m2)
0	0	0.00019	2	0.000095	6.419831845	0.0060	0	72.41633858	0
8	480	0.0004	2	0.0002	3634.520225	0.0287	4.7316E-05	346.5323681	0.042820966
12	720	0.000711	1.9	0.000374211	5448.570422	0.0400	4.70347E-05	482.7755906	0.042566401



Slope	y-intercept
0.0001	-0.005

Variable	Unit	Value
Tc	N/m ²	50
Ce	None	0.0001
I	None	4

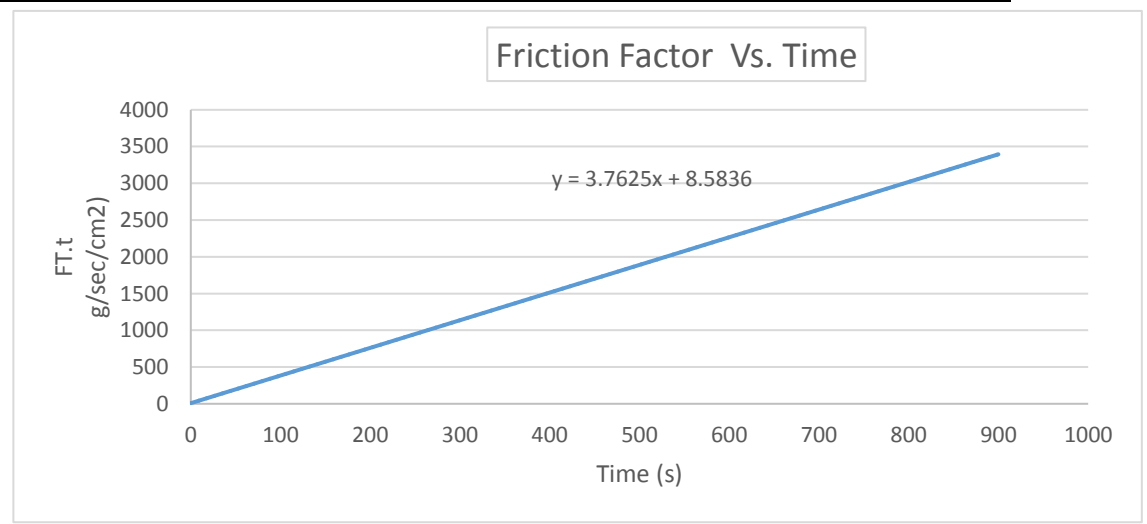
B4-Calculation of 1% lime at 7 days curing time -Soil#2:

1.0%	% lime	Testing Time	Soil
	1.0%	7 days	Soil #2

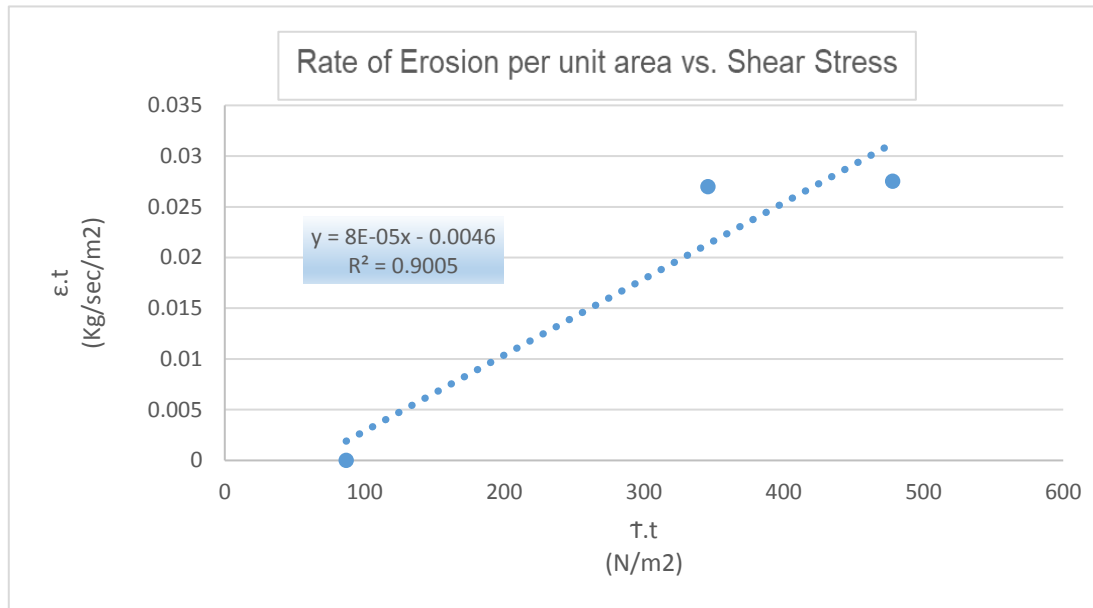
Data Collected					
Parameter	Unit	Value	Water Head Data		
Water Density (ρ_w)	kg/m ³	1000	Upstream	0	
Gravity (g)	m/sec ²	9.81	Down Stream	60	
Hydraulic Gradient (st)		5.91	Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1810			
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)		
0	180	2	6		
10	350	2			
15	610	1.9	33		

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	180	2	6	3.181818182	19014.84969	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.00018	2	0.00009	8.583552949	0.006		
15	900	0.00061	1.9	0.000321053	3394.791364	0.033	3.762453124	8.583552949
FTt	=	slope	t	+		Ft0		
FTt	=	3.76245312	t	+		8.583552949		



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	dΦt/dt	τ.t (N/m2)	ε.t (Kg/sec/m2)
0	0	0.00018	2	0.00009	8.583552949	0.0060	0	86.8996063	0
10	600	0.00035	2	0.000175	2266.055427	0.0239	2.9796E-05	345.82526	0.026965337
15	900	0.00061	1.9	0.000321053	3394.791364	0.0330	3.04081E-05	477.9478346	0.027519326



Slope	y-intercept
0.0001	-0.005

Variable	Unit	Value
Tc	N/m ²	50
Ce	None	0.0001
I	None	4

B5-Calculation of 2% lime at 24 hours curing time -Soil#2:

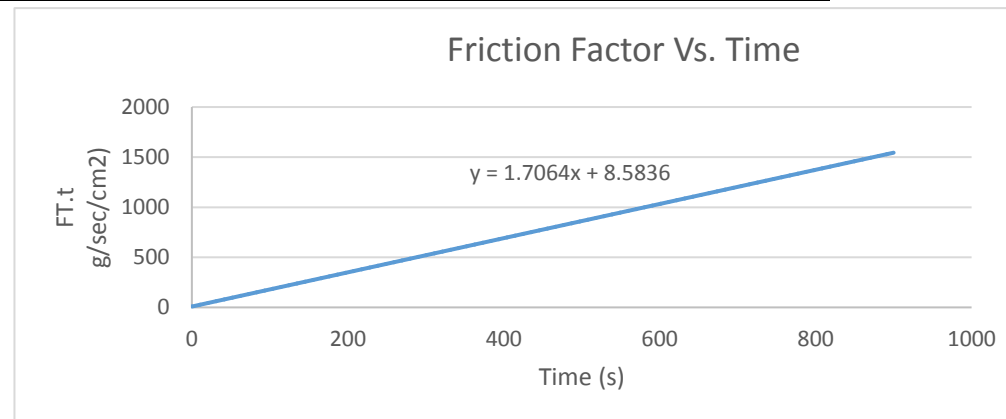
2.0%	% lime	Testing Time	Soil
	2.0%	24 hours	Soil #2

Data Collected					
Parameter	Unit	Value		Water Head Data	
Water Density (ρ_w)	kg/m ³	1000		Upstream	0
Gravity (g)	m/sec ²	9.81		Down Stream	60
Hydraulic Gradient (st)		5.91		Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1810			
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)		
0	180	2	6		
8	320	2			
15	710	1.2	36		

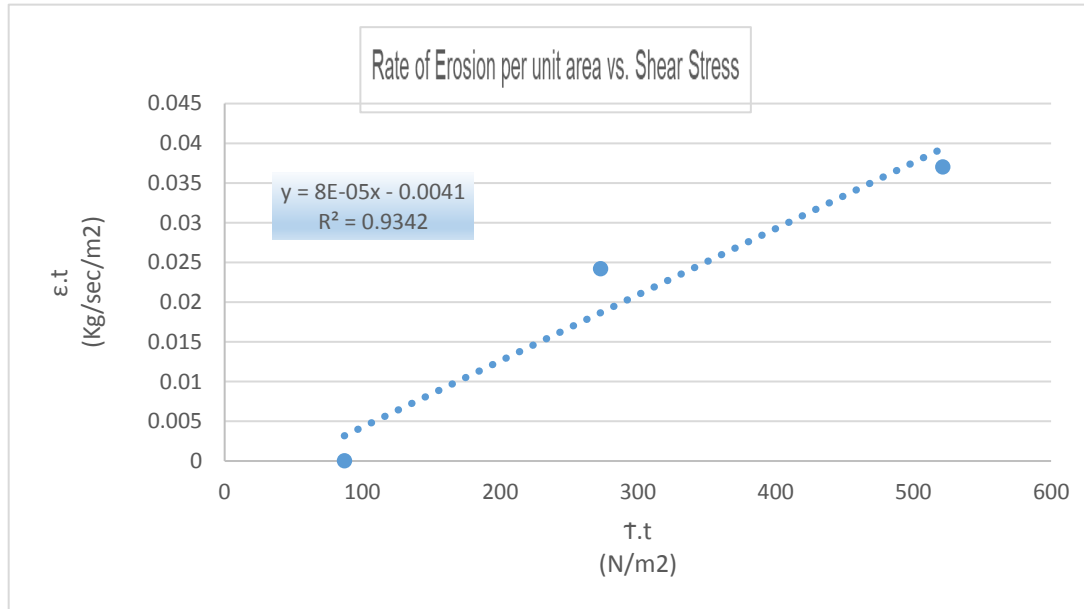
Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	180	2	6	3.181818182	19014.84969	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.00018	2	0.00009	8.583552949	0.006		
15	900	0.00071	1.2	0.000591667	1544.379954	0.036	1.706440446	8.583552949

FTt	=	slope	t	+		F10
FTt	=	1.70644045	t	+		8.583552949



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	d Φ t/dt	$\tau.t$ (N/m2)	$\epsilon.t$ (Kg/sec/m2)
0	0	0.00018	2	0.00009	8.583552949	0.0060	0	86.8996063	0
8	480	0.00032	2	0.00016	827.674967	0.0188	2.67373E-05	272.7767459	0.024197292
15	900	0.00071	1.2	0.000591667	1544.379954	0.0360	4.08716E-05	521.3976378	0.036988809



Slope	y-intercept
0.00008	-0.0041

Variable	Unit	Value
Tc	N/m2	51.25
Ce	None	0.00008
I	None	4.096910013

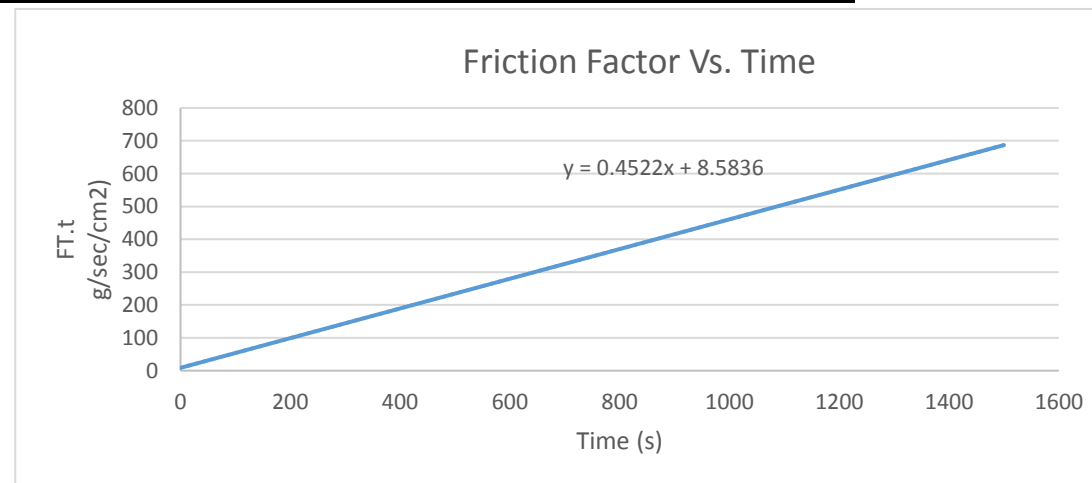
B6-Calculation of 2% lime at 48 hours curing time -Soil#2:

2.0%	% lime	Testing Time	Soil
	2.0%	48 hours	Soil #2

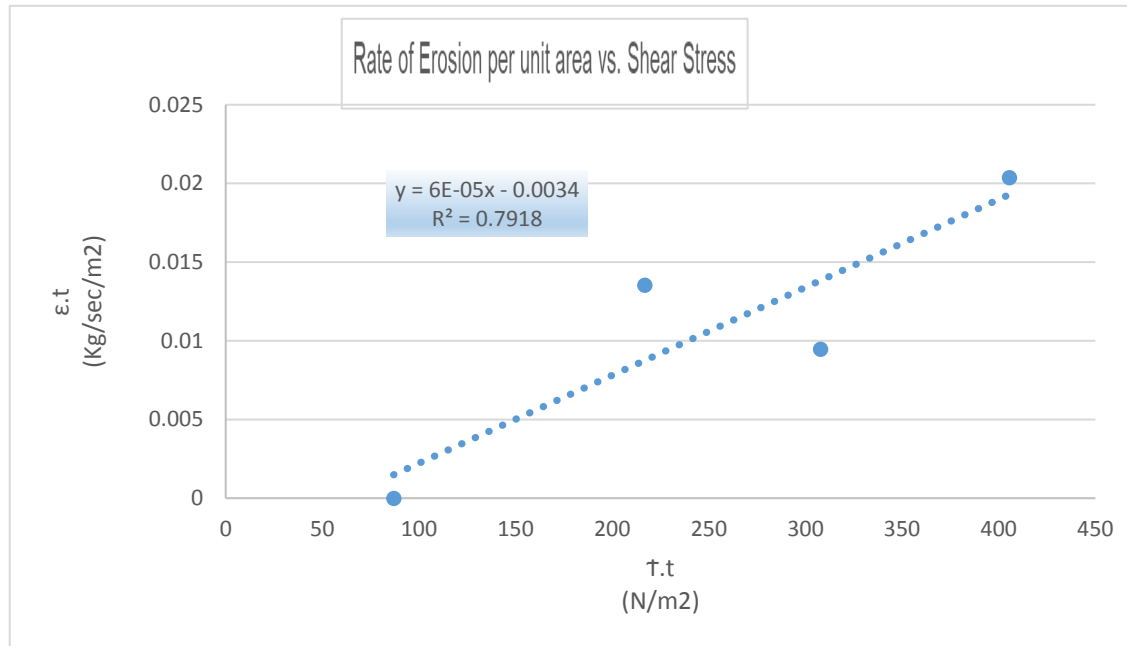
Data Collected											
Parameter	Unit	Value									
Water Density (ρ_w)	kg/m ³	1000	<table border="1" style="margin-left: auto; margin-right: auto;"> <thead> <tr> <th colspan="2">Water Head Data</th> </tr> </thead> <tbody> <tr> <td>Upstream</td> <td style="text-align: center;">0</td> </tr> <tr> <td>Down Stream</td> <td style="text-align: center;">60</td> </tr> <tr> <td>Specimen Length</td> <td style="text-align: center;">10.16</td> </tr> </tbody> </table>	Water Head Data		Upstream	0	Down Stream	60	Specimen Length	10.16
Water Head Data											
Upstream	0										
Down Stream	60										
Specimen Length	10.16										
Gravity (g)	m/sec ²	9.81									
Hydraulic Gradient (st)		5.91									
Soil Density (ρ_d)	kg/m ³	1810									
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)								
0	180	2	6								
10	310	2									
20	530	2									
25	710	1.5	28								

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	180	2	6	3.181818182	19014.84969	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.00018	2	0.00009	8.58355294	0.006	0.45216701	8.58355294
25	1500	0.00071	1.5	0.000473333	686.834077	0.028		
FTt	=	slope	t	+	FIO			
FTt	=	0.4521670	t	+	8.58355294			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FLt (Kg/m2/sec)	Φ.t (m)	dΦt/dt	τ.t (N/m2)	ε.t (Kg/sec/m2)
0	0	0.00018	2	0.00009	8.583552949	0.0060	0	86.8996063	0
10	600	0.00031	2	0.000155	279.8837629	0.0150	1.49516E-05	216.8281214	0.013531167
20	1200	0.00053	2	0.000265	551.1839728	0.0212	1.04585E-05	307.7124391	0.00946498
25	1500	0.00071	1.5	0.000473333	686.8340777	0.0280	2.25131E-05	405.5314961	0.020374372



Slope	y-intercept
0.00006	-0.0034

Variable	Unit	Value
Tc	N/m2	56.66666667
Ce	None	0.00006
I	None	4.22184875

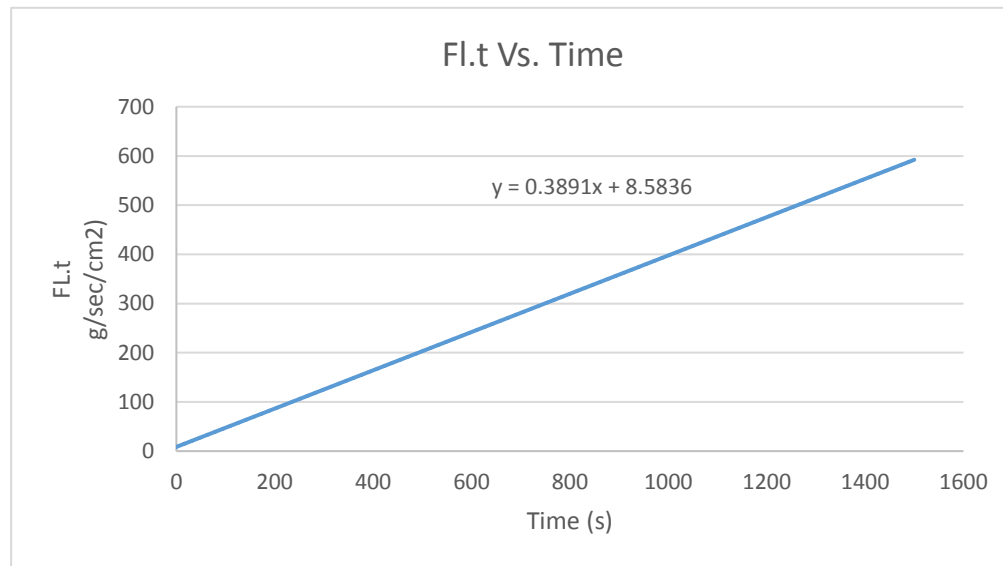
B7-Calculation of 2% lime at 7 days curing time -Soil#2:

2.0%	% lime	Testing Time	Soil
	2.0%	7 days	Soil #2

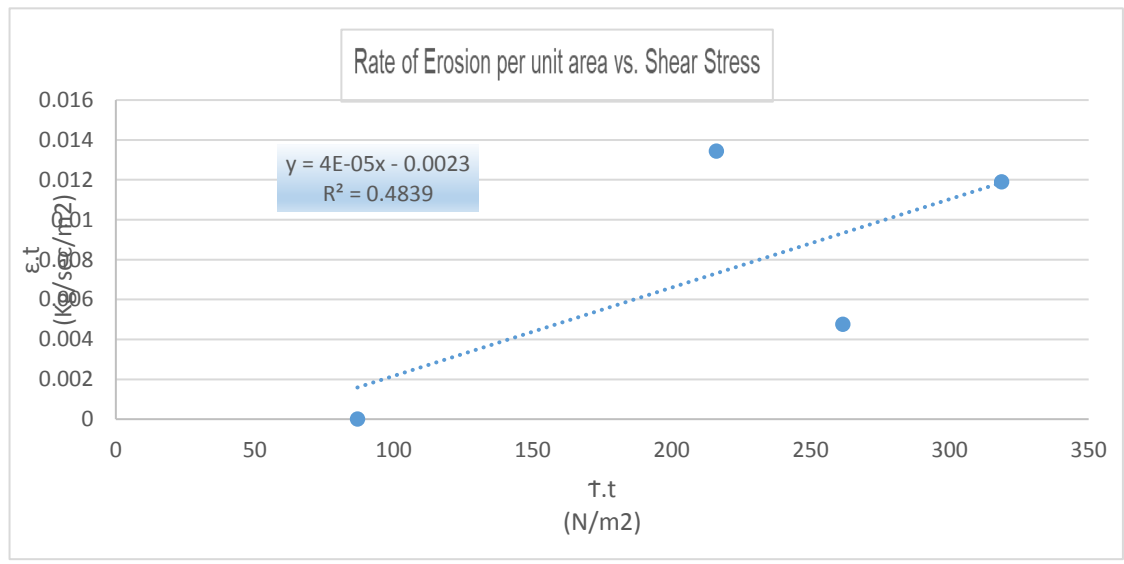
Data Collected						
Parametr	Unit	Value	Water Head Data			
Water Density (ρ_w)	kg/m ³	1000	Upstream		0	
Gravity (g)	m/sec ²	9.81	Down Stream		60	
Hydraulic Gradient (st)		5.91	Specimen Length		10.16	
Soil Density (ρ_d)	kg/m ³	1810				
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)			
0	180	2	6			
10	330	2				
20	380	2				
25	530	1.9	22			
Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)	V_t	Re	Flow Type
0	180	2	6	3.181818182	19014.84969	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	Slope	B-Intercept
0	0	0.00018	2	0.00009	8.583552949	0.006		
25	1500	0.00053	1.9	0.000278947	592.1949837	0.022	0.389074287	8.583552949

FTt	=	slope	t	+	F10
FTt	=	0.38907429	t	+	8.583552949



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	d Φ t/dt	$\tau.t$ (N/m2)	$\epsilon.t$ (Kg/sec/m2)
0	0	0.00018	2	0.00009	8.583552949	0.0060	0	86.8996063	0
10	600	0.00033	2	0.000165	242.0281252	0.0149	1.48506E-05	215.9504593	0.013439764
20	1200	0.00038	2	0.00019	475.4726975	0.0181	5.24456E-06	261.5254417	0.004746323
25	1500	0.00053	1.9	0.000278947	592.1949837	0.0220	1.31431E-05	318.6318898	0.011894492



Slope	y-intercept
0.00004	-0.0023

Variable	Unit	Value
Tc	N/m2	57.5
Ce	None	0.00004
I	None	4.397940009

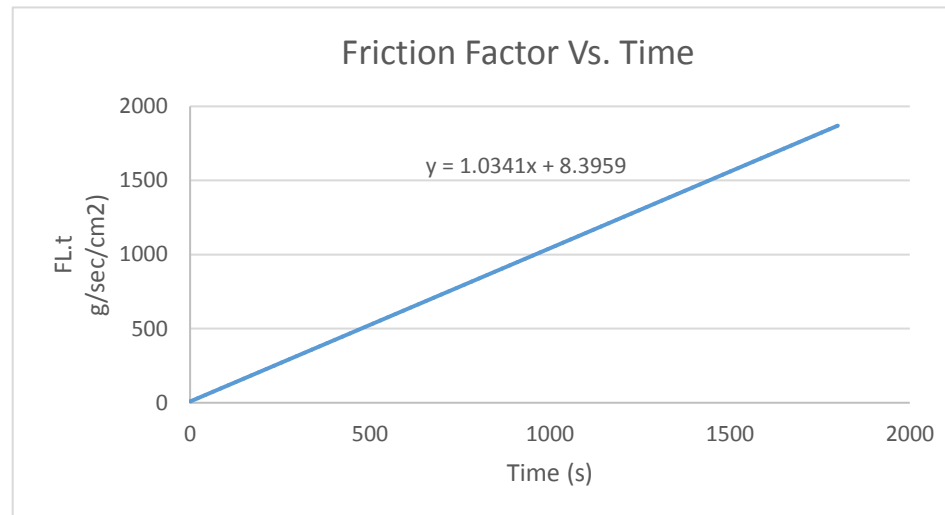
B8-Calculation of 3% lime at 24 hours curing time -Soil#2:

	% lime	Testing Time	Soil
3.0%	3.0%	24 hours	Soil #2

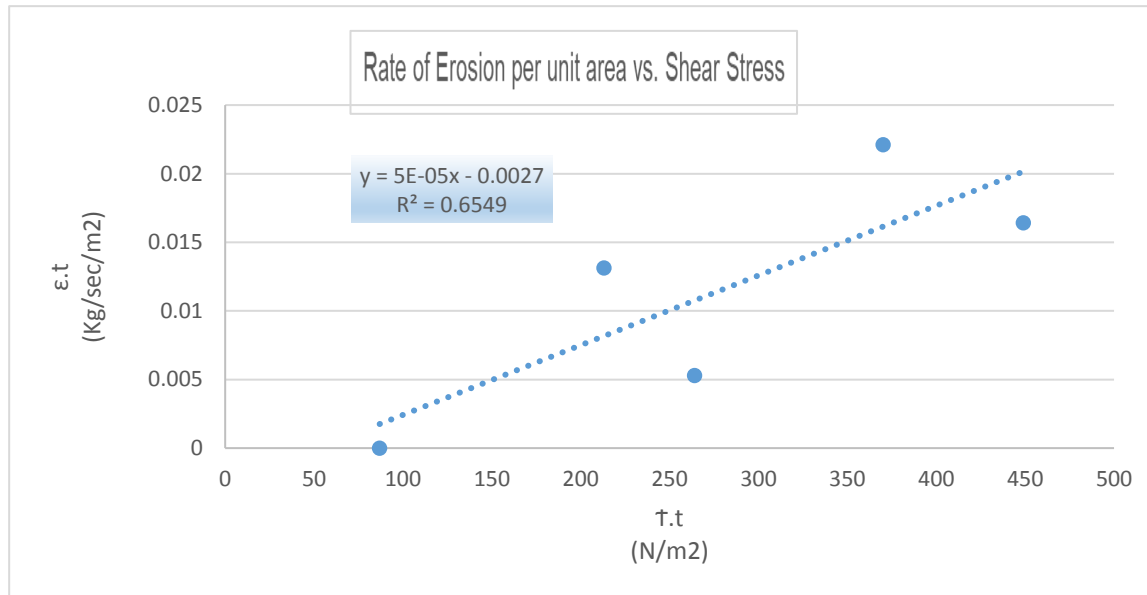
Data Collected					
Parameter	Unit	Value	Water Head Data		
Water Density (ρ_w)	kg/m ³	1000	Upstream	0	
Gravity (g)	m/sec ²	9.81	Down Stream	60	
Hydraulic Gradient (st)		5.91	Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1810			
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)		
0	182	2	6		
10	198	2			
20	240	2			
25	500	2			
30	740	2	31		

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	180	2	6	3.181818182	19014.84969	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.000182	2	0.000091	8.395939969	0.006		
30	1800	0.00074	2	0.00037	1869.82464	0.031	1.034127056	8.395939969
FTt	=	slope	t	+	Ft0			
FTt	=	1.03412706	t	+	8.395939969			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	d Φ /dt	$\tau.t$ (N/m2)	$\epsilon.t$ (Kg/sec/m2)
0	0	0.000182	2	0.000091	8.395939969	0.0060	0	86.8996063	0
10	600	0.000198	2	0.000099	628.8721733	0.0147	1.45209E-05	213.0855209	0.0131414
20	1200	0.00024	2	0.00012	1249.348407	0.0182	5.85849E-06	263.9955455	0.005301931
25	1500	0.0005	2	0.00025	1559.586523	0.0256	2.44291E-05	370.1393732	0.022108308
30	1800	0.00074	2	0.00037	1869.82464	0.0310	1.81455E-05	448.9812992	0.016421695



Slope	y-intercept
0.00005	-0.0027

Variable	Unit	Value
Tc	N/m ²	54
Ce	None	0.00005
I	None	4.301029996

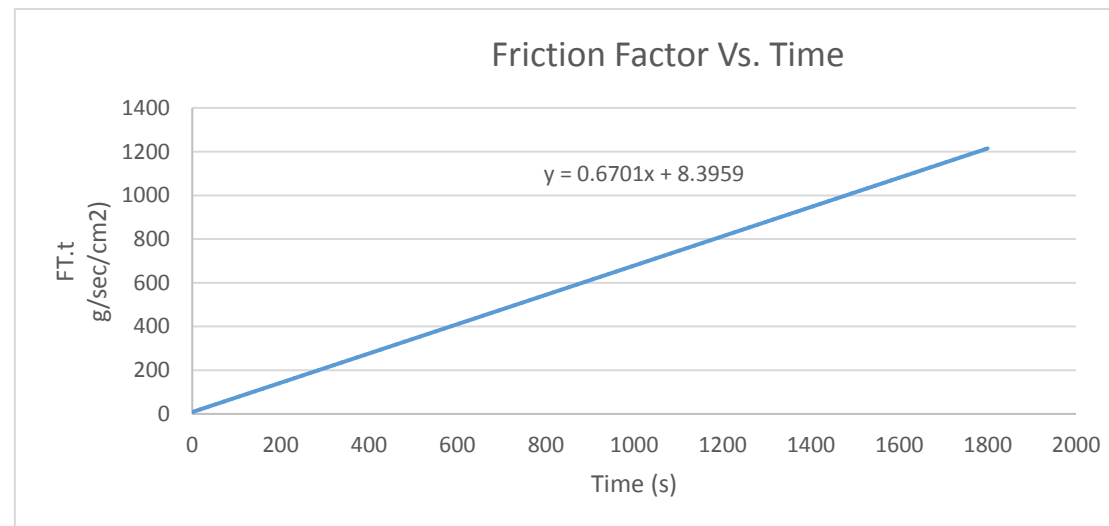
B9-Calculation of 3% lime at 48 hours curing time -Soil#2:

3.0%	% lime	Testing Time	Soil
	3.0%	48 hours	Soil #2

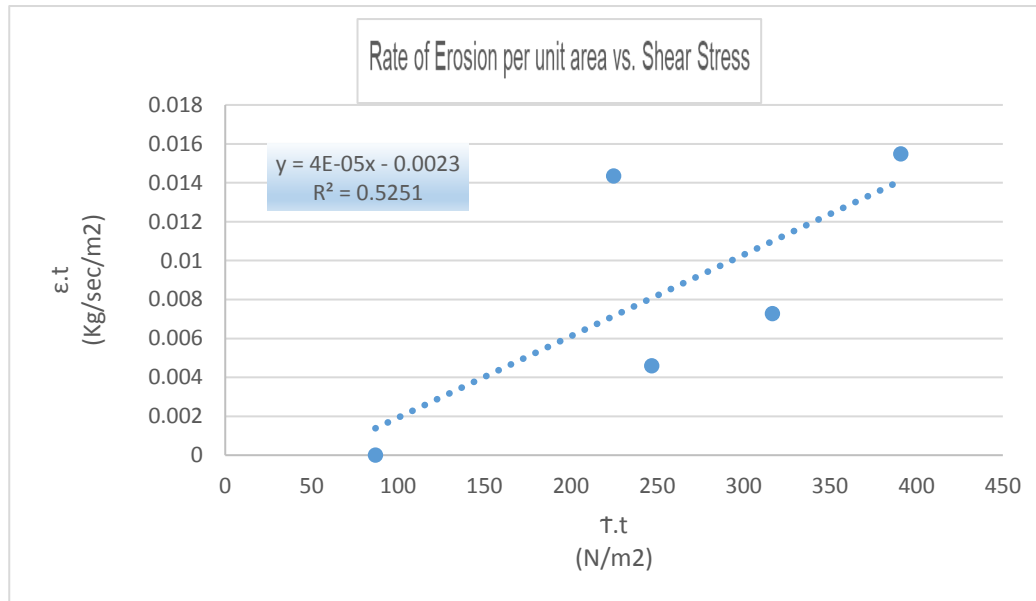
Data Collected				
Parameter	Unit	Value	Water Head Data	
Water Density (ρ_w)	kg/m ³	1000	Upstream	0
Gravity (g)	m/sec ²	9.81	Down Stream	60
Hydraulic Gradient (st)		5.91	Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1810		
Test Time (min)	520	Time (sec)	$\Phi.t$ (mm)	
0	182	2	6	
10	280	2		
15	290	2		
25	420	2		
30	650	2	27	

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	182	2	6	3.217171717	19226.1258	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.000182	2	0.000091	8.395939969	0.006	0.670136175	8.395939969
30	1800	0.00065	2	0.000325	1214.641055	0.027		
FTt	=	slope	t	+	Ft0			
FTt	=	0.67013618	t	+	8.395939969			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ .t (m)	d Φ t/dt	τ .t (N/m2)	ϵ .t (Kg/sec/m2)
0	0	0.000182	2	0.000091	8.395939969	0.0060	0	86.8996063	0
10	600	0.00028	2	0.00014	410.477645	0.0155	1.5863E-05	224.7483455	0.014356004
15	900	0.00029	2	0.000145	611.5184976	0.0170	5.08454E-06	246.8405512	0.004601504
25	1500	0.00042	2	0.00021	1013.600203	0.0219	8.03913E-06	316.7002766	0.007275413
30	1800	0.00065	2	0.000325	1214.641055	0.0270	1.71112E-05	391.0482283	0.015485662



Slope	y-intercept
0.00004	-0.0023

Variable	Unit	Value
Tc	N/m2	57.5
Ce	None	0.00004
l	None	4.397940009

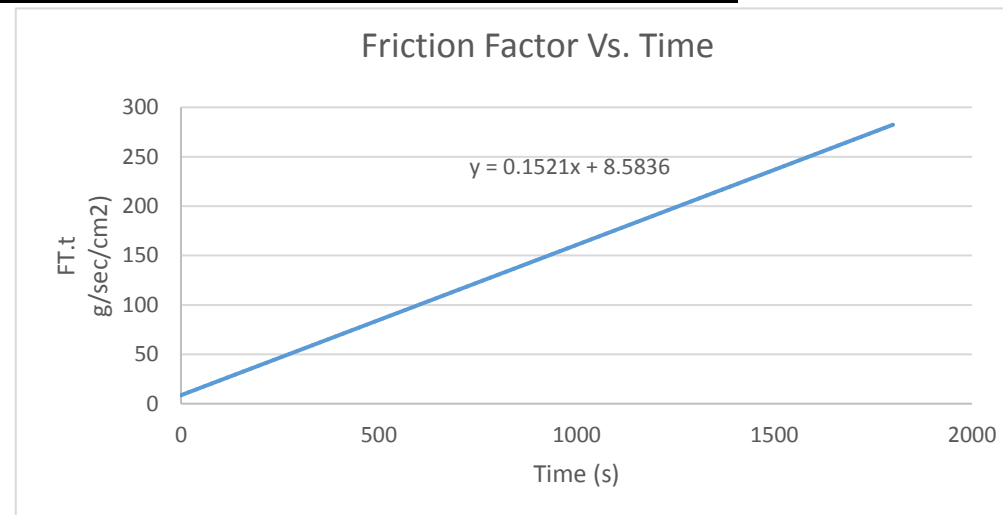
B10- Calculation of 3% lime at 7 days curing time -Soil#2:

3.0%	% lime	Testing Time	Soil
	3.0%	7 days	Soil #2

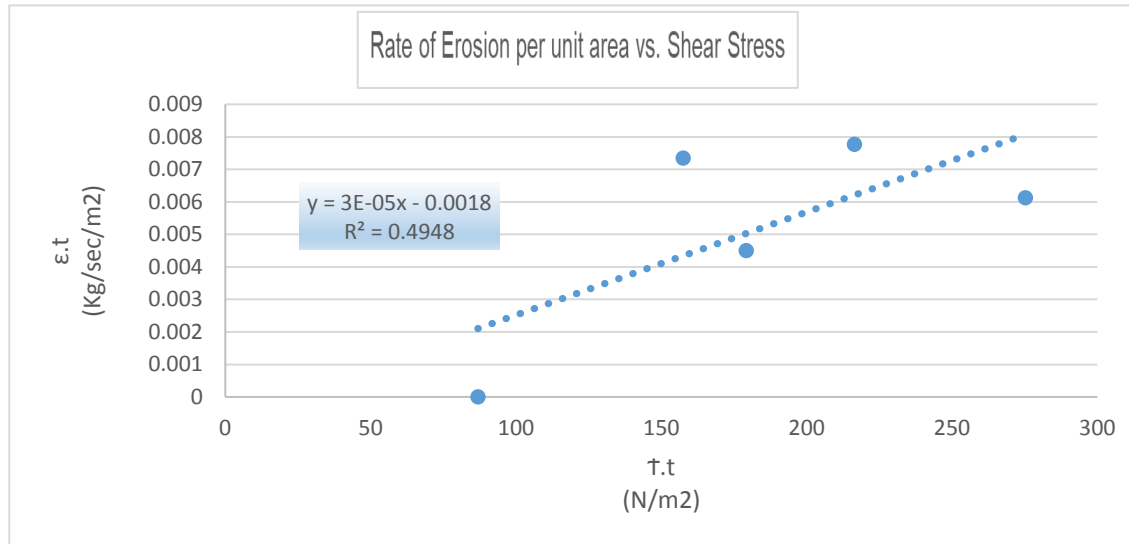
Data Collected					
Parametr	Unit	Value	Water Head Data		
Water Density (ρ_w)	kg/m ³	1000	Upstream	0	
Gravity (g)	m/sec ²	9.81	Down Stream	60	
Hydraulic Gradient (st)		5.91	Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1810			
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)		
0	180	2	6		
10	350	3			
15	400	3			
20	560	3			
30	560	2	19		

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	180	2	6	3.181818182	19014.84969	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.00018	2	0.00009	8.583552949	0.006	0.152114146	8.583552949
30	1800	0.00056	2	0.00028	282.3890156	0.019		
FTt	=	slope	t	+	Ft0			
FTt	=	0.15211415	t	+	8.583552949			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	dΦt/dt	τ.t (N/m2)	ε.t (Kg/sec/m2)
0	0	0.00018	2	0.00009	8.583552949	0.0060	0	86.8996063	0
10	600	0.00035	3	0.000116667	99.85204051	0.0109	8.12257E-06	157.4843824	0.007350922
15	900	0.0004	3	0.000133333	145.4862843	0.0124	4.97786E-06	179.1130759	0.004504961
20	1200	0.00056	3	0.000186667	191.1205281	0.0149	8.58371E-06	216.4091221	0.007768257
30	1800	0.00056	2	0.00028	282.3890156	0.0190	6.76332E-06	275.1820866	0.006120803

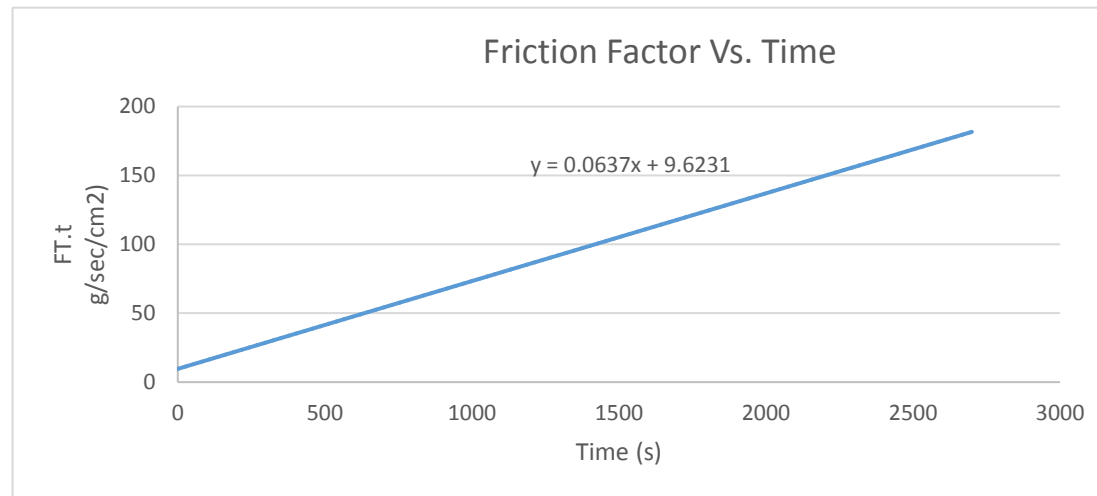


Slope	y-intercept
0.00003	-0.0018

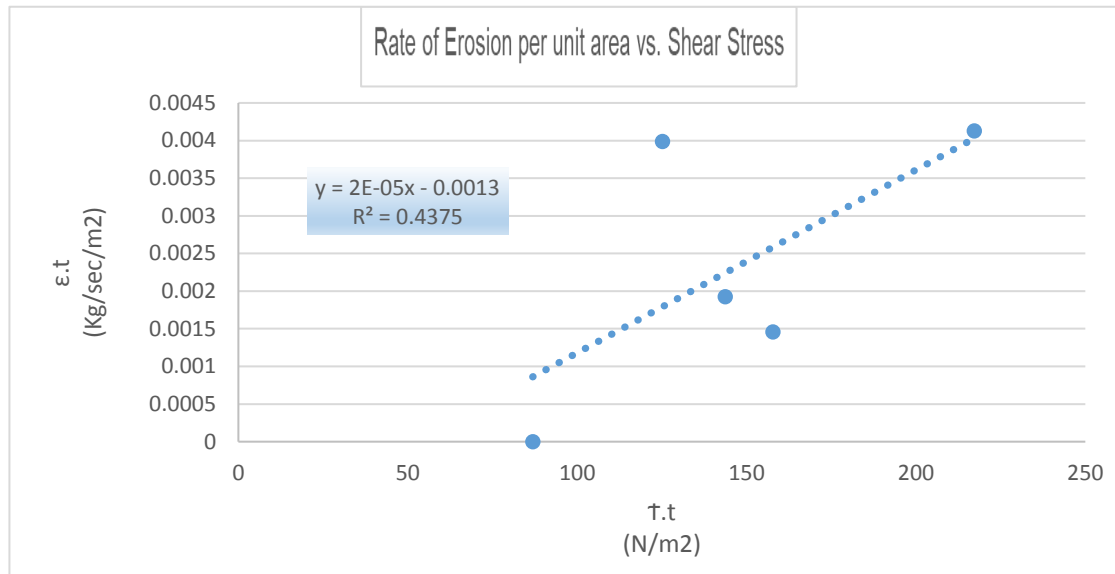
Variable	Unit	Value
Tc	N/m2	60
Ce	None	0.00003
I	None	4.522878745

Flow Type calculations						
Test Time (min)	Volume (cm ³)	Time (sec)	Φ.t (mm)	Vt	Re	Flow Type
0	170	2	6	3.005050505	17958.46915	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m ³)	Time (sec)	Q.t (m ³ /sec)	FTt (Kg/m ² /sec)	Φ.t (m)	Slope	B-Intercept
0	0	0.00017	2	0.000085	9.623083583	0.006	0.06371418	9.623083583
45	2700	0.00029	1.5	0.000193333	181.6513689	0.015		
FTt	=	slope	t	+	Ft0			
FTt	=	0.06371418t		+	9.623083583			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q.t (m ³ /sec)	FTt (Kg/m ² /sec)	Φ.t (m)	dΦt/dt	τ.t (N/m ²)	ε.t (Kg/sec/m ²)
0	0	0.00017	2	0.000085	9.623083583	0.0060	0	86.8996063	0
10	600	0.00019	2	0.000095	47.85159144	0.0086	4.40915E-06	125.2149275	0.003990279
20	1200	0.0002	2	0.0001	86.08009929	0.0099	2.13141E-06	143.736789	0.001928925
30	1800	0.00021	2	0.000105	124.3086071	0.0109	1.61232E-06	157.7478129	0.001459152
45	2700	0.00029	1.5	0.000193333	181.6513689	0.0150	4.56475E-06	217.2490157	0.004131096



Slope	y-intercept
0.00002	-0.0013

Variable	Unit	Value
Tc	N/m ²	65
Ce	None	0.00002
I	None	4.698970004

B12- Calculation of 4% lime at 48 hours curing time -Soil#2:

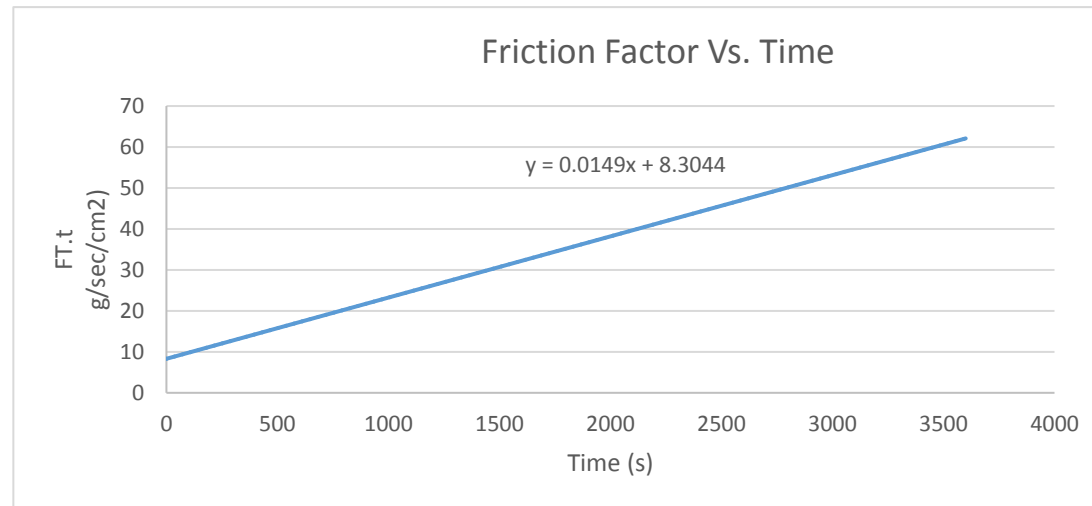
4.0%	% lime	Testing Time	Soil
	4.0%	48 hours	Soil #2

Data Collected				
Parameter	Unit	Value	Water Head Data	
Water Density (ρ_w)	kg/m ³	1000	Upstream	0
Gravity (g)	m/sec ²	9.81	Down Stream	60
Hydraulic Gradient (st)		5.91	Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1810		

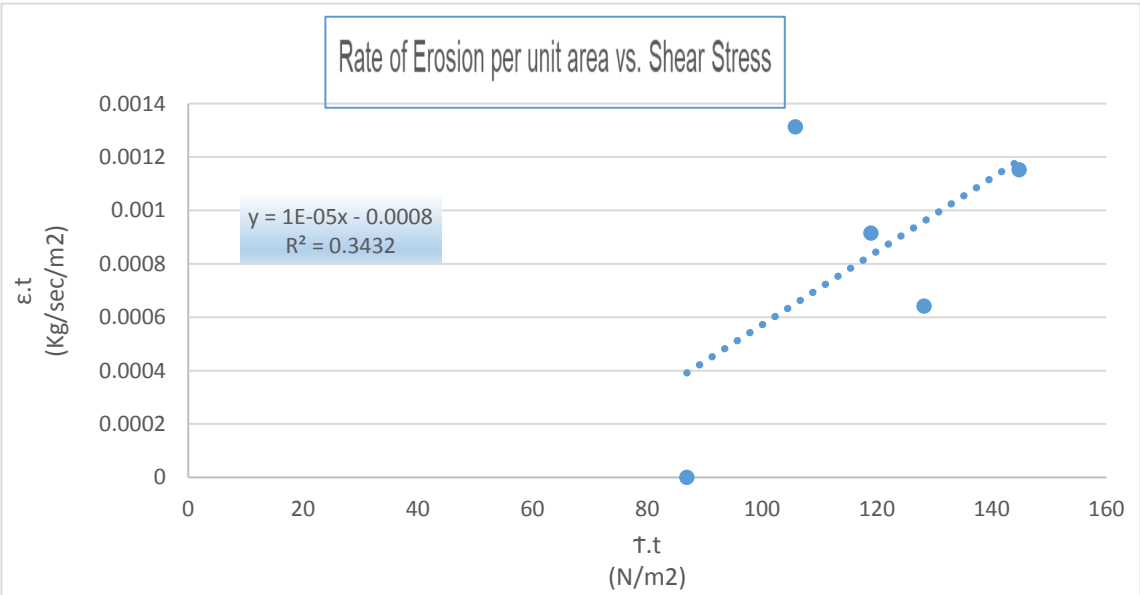
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)
0	183	2	6
15	185	2	
30	195	2	
45	200	2	
60	240	2	10

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	V_t	Re	Flow Type
0	183	2	6	3.234848485	19331.76385	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.000183	2	0.0000915	8.30443177	0.006		
60	3600	0.00024	2	0.00012	62.09167353	0.01	0.0149409	8.30443177
FTt	=	slope	t	+	F10			
FTt	=	0.0149409t		+	8.30443177			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ.t (m)	dΦt/dt	τ.t (N/m2)	ε.t (Kg/sec/m2)
0	0	0.000183	2	0.0000915	8.30443177	0.0060	0	86.8996063	0
15	900	0.000185	2	0.0000925	21.75124221	0.0073	1.45101E-06	105.8134545	0.001313165
30	1800	0.000195	2	0.0000975	35.19805265	0.0082	1.0105E-06	118.9852043	0.000914498
45	2700	0.0002	2	0.0001	48.64486309	0.0089	7.09348E-07	128.2315182	0.00064196
60	3600	0.00024	2	0.00012	62.09167353	0.0100	1.27359E-06	144.8326772	0.001152598



Slope	y-intercept
0.00001	-0.0008

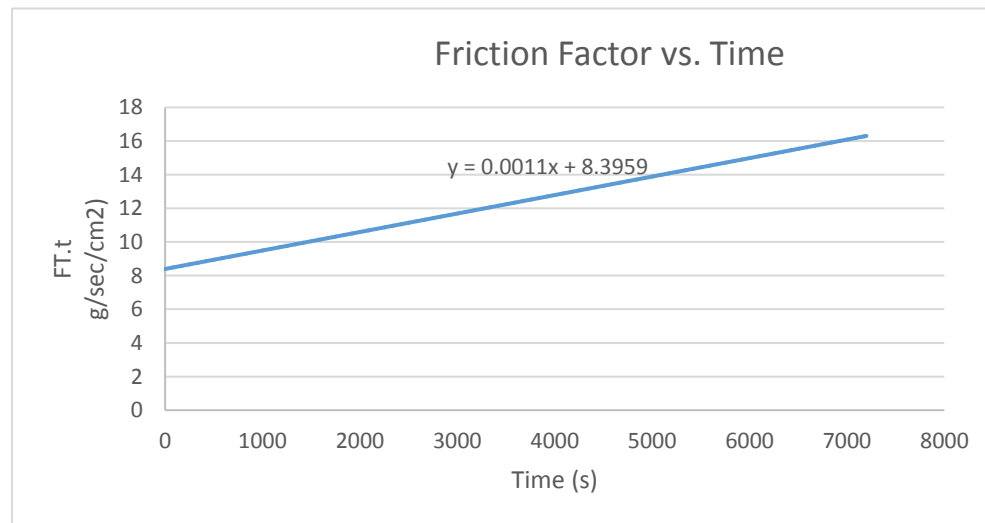
Variable	Unit	Value
Tc	N/m2	80
Ce	None	0.00001
I	None	5

B13- Calculation of 4% lime at 7 days curing time -Soil#2:

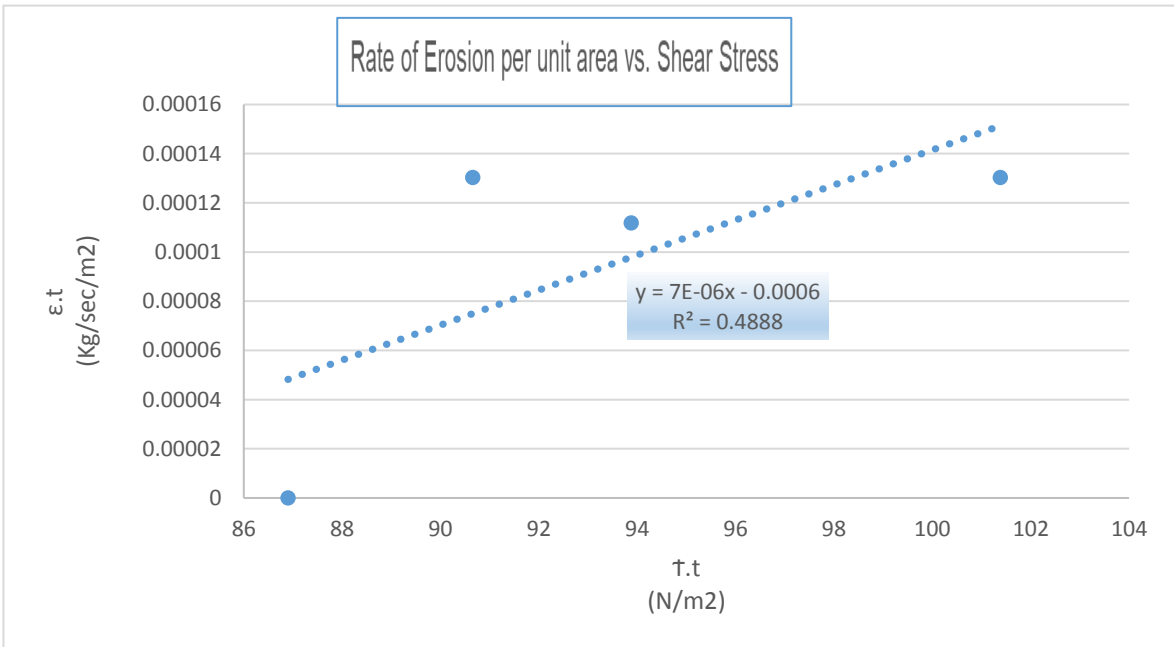
4.0%	% lime	Testing Time	Soil
	4.0%	7 days	Soil #2

Data Collected				
Parameter	Unit	Value	Water Head Data	
Water Density (ρ_w)	kg/m ³	1000	Upstream	0
Gravity (g)	m/sec ²	9.81	Down Stream	60
Hydraulic Gradient (st)		5.91	Specimen Length	10.16
Soil Density (ρ_d)	kg/m ³	1810		
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)	
0	182	2	6	
30	182	2		
60	182	2		
120	192	2	7	

Flow Type calculations								
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type		
0	182	2	6	3.217171717	19226.1258	Turbulent		
Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.000182	2	0.000091	8.395939969	0.006	0.001098599	8.395939969
120	7200	0.000192	2	0.000096	16.30585558	0.007		
FTt	=	slope	t	+	F10			
FTt	=	0.0010986	t	+	8.395939969			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	Φ .t (m)	d Φ t/dt	$\dot{\tau}$.t (N/m2)	ϵ .t (Kg/sec/m2)
0	0	0.000182	2	0.000091	8.395939969	0.0060	0	86.8996063	0
30	1800	0.000182	2	0.000091	10.37341887	0.0063	1.44024E-07	90.6542829	0.000130341
60	3600	0.000182	2	0.000091	12.35089777	0.0065	1.23489E-07	93.87363809	0.000111758
120	7200	0.000192	2	0.000096	16.30585558	0.0070	1.44021E-07	101.382874	0.000130339



Slope	y-intercept
0.000007	-0.0006

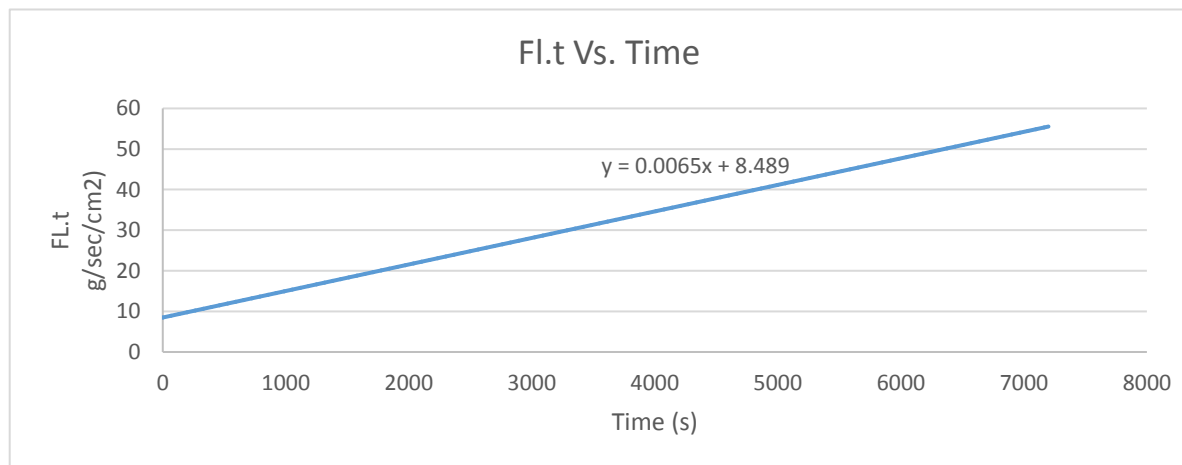
Variable	Unit	Value
Tc	N/m ²	85.71428571
Ce	None	0.000007
I	None	5.15490196

B14- Calculation of 5% lime at 24 hours curing time -Soil#2:

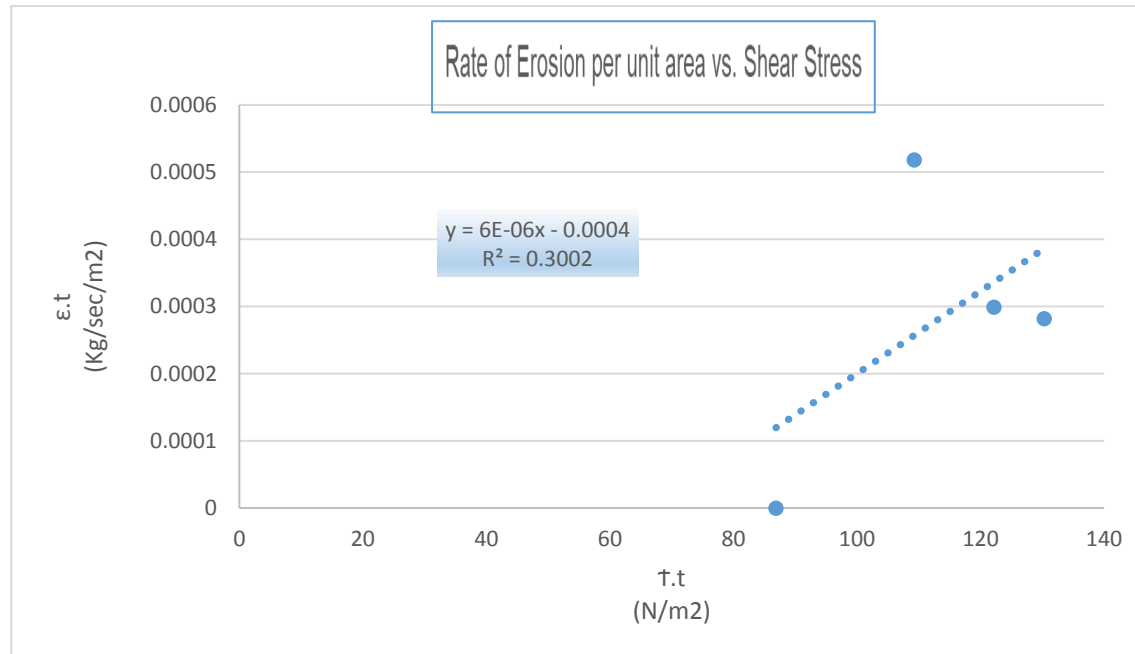
5.0%	% lime	Testing Time	Soil
	5.0%	24 hours	Soil #2

Data Collected					
Parameter	Unit	Value	Water Head Data		
Water Density (ρ_w)	kg/m ³	1000	Upstream	0	
Gravity (g)	m/sec ²	9.81	Down Stream	60	
Hydraulic Gradient (st)		5.91	Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1810			
Test Time (min)	Volume (cm ³)	Time (sec)	$\Phi.t$ (mm)		
0	181	2	6		
45	183	2			
90	187	2			
120	195	2	9		

Flow Type calculations								
Test Time (min)	Volume (cm ³)	Time (sec)	Φ.t (mm)	Vt	Re	Flow Type		
0	181	2	6	3.199494949	19120.48775	Turbulent		
Friction Factors Calculations								
Test Time (min)	Test Time (sec)	Volume (m ³)	Time (sec)	Q.t (m ³ /sec)	FTt (Kg/m ² /sec)	Φ.t (m)	Slope	B-Intercept
0	0	0.000181	2	0.0000905	8.488969065	0.006	0.006534746	8.488969065
120	7200	0.000195	2	0.0000975	55.5391429	0.009		
FTt	=	slope	t	+	Ft0			
FTt	=	0.00653475	t	+	8.488969065			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time (sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FLt (Kg/m2/sec)	$\Phi.t$ (m)	d Φ t/dt	$\tau.t$ (N/m2)	$\epsilon.t$ (Kg/sec/m2)
0	0	0.000181	2	0.0000905	8.488969065	0.0060	0	86.8996063	0
45	2700	0.000183	2	0.0000915	26.13278425	0.0075	5.72654E-07	109.2931545	0.000518252
90	5400	0.000187	2	0.0000935	43.77659944	0.0084	3.307E-07	122.2251097	0.000299283
120	7200	0.000195	2	0.0000975	55.5391429	0.0090	3.11635E-07	130.3494094	0.00028203



Slope	y-intercept
0.000006	-0.0004

Variable	Unit	Value
Tc	N/m2	66.66666667
Ce	None	0.000006
I	None	5.22184875

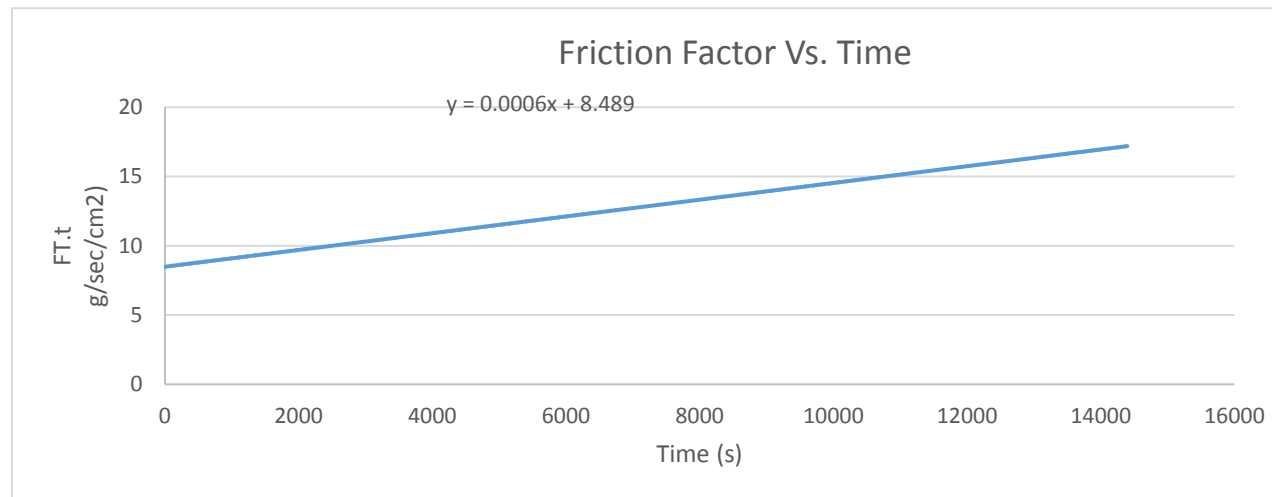
B15- Calculation of 5% lime at 48 hours curing time -Soil#2:

5.0%	% lime	Testing Time	Soil
	5.0%	48 hours	Soil #2

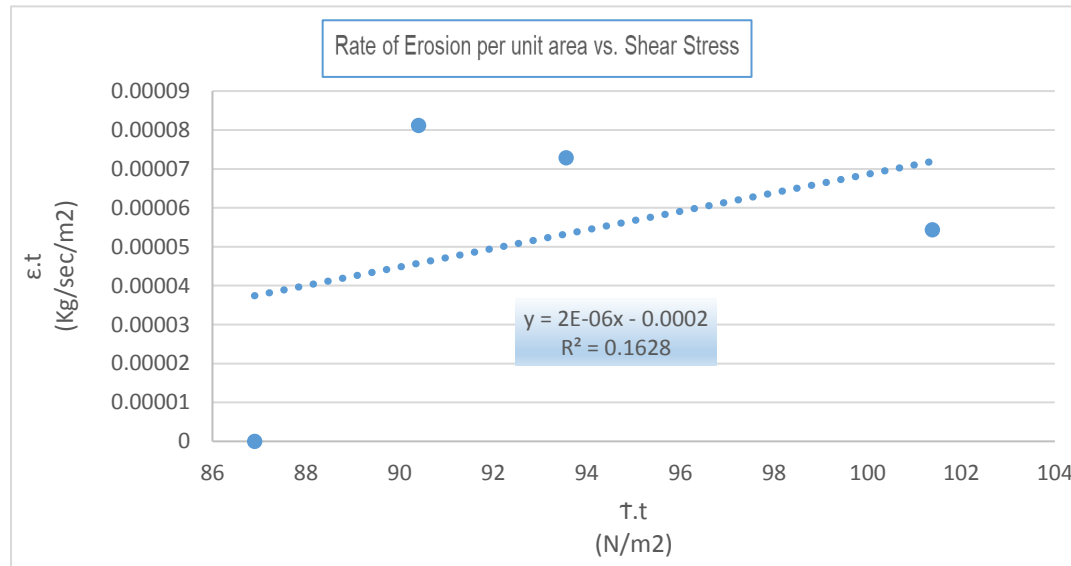
Data Collected					
Parameter	Unit	Value	Water Head Data		
Water Density (ρ_w)	kg/m ³	1000	Upstream	0	
Gravity (g)	m/sec ²	9.81	Down Stream	60	
Hydraulic Gradient (st)		5.91	Specimen Length	10.16	
Soil Density (ρ_d)	kg/m ³	1810			
Test Time (min)	Volume (cm ³)	Time (sec)	Φ.t (mm)		
0	181	2	6		
45	183	2			
90	185	2			
240	187	2	7		

Flow Type calculations						
Test Time (min)	Volume (cm3)	Time (sec)	$\Phi.t$ (mm)	Vt	Re	Flow Type
0	181	2	6	3.199494949	19120.48775	Turbulent

Friction Factors Calculations								
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	Slope	B-Intercept
0	0	0.000181	2	0.0000905	8.488969065	0.006	0.000604202	8.488969065
240	14400	0.000187	2	0.0000935	17.18948383	0.007		
FTt	=	slope	t	+	Ft0			
FTt	=	0.0006042	t	+	8.488969065			



Shear Stress and Erosion Rate Calculations									
Test Time (min)	Test Time(sec)	Volume (m3)	Time (sec)	Q.t (m3/sec)	FTt (Kg/m2/sec)	$\Phi.t$ (m)	d Φ t/dt	$\tau.t$ (N/m2)	$\epsilon.t$ (Kg/sec/m2)
0	0	0.000181	2	0.0000905	8.488969065	0.0060	0	86.8996063	0
45	2700	0.000183	2	0.0000915	10.12031558	0.0062	8.96526E-08	90.40545488	8.11356E-05
90	5400	0.000185	2	0.0000925	11.7516621	0.0065	8.05242E-08	93.55433998	7.28744E-05
240	14400	0.000187	2	0.0000935	17.18948383	0.0070	6.00581E-08	101.382874	5.43526E-05



Slope	y-intercept
0.000002	-0.0002

Variable	Unit	Value
Tc	N/m2	100
Ce	None	0.000002
I	None	5.698970004

Vita

Rawan Ibrahim Aqel was born in 1990, in Jerusalem, Palestine. She received her primary and secondary education in Palestine and accomplished an International Bilingual Diploma (IB) as a High school degree in 2008. She received her B.Sc. degree in Civil Engineering with a minor in Business Administration from Birzeit University, Palestine, in 2013. From 2013 she worked in multiple companies such as USAID, Palestine, as a Civil Engineer and in Petrofac International Limited, UAE, as a Project Engineer

In 2016, she joined the Civil Engineering master's program in the American University of Sharjah. Simultaneously with her masters she have worked as a graduate teaching assistant.