SOIL STABILIZATION AGAINST INTERNAL EROSION USING CEMENT AND FIBER-CEMENT MIXTURE

by

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Dedication

This work is dedicated to each equally, my pride and joy, my parents

Abstract

Internal erosion of soil is the main cause of failure in many engineering hydraulic structures especially embankment dams. Understanding the internal erosion behavior and stabilizing the soil against this phenomenon is a major goal of geotechnical engineers. This work includes the results of a comprehensive experimental testing program to study the internal erosion behavior and to stabilize two types of soils (sand and clay) using cement and fiber- cement mixture. The sand and clayey soils were mixed with different percentages of cement and fiber-cement mixture by the dry weight of the soil and tested against internal erosion at different curing time. The Hole Erosion Test (HET) was employed to evaluate the erosion behavior and erosion index of the used soils. The results showed that the treatment of sandy soils with 4% cement by dry weight of sand caused a significant reduction in the internal erosion and substantial increase in the shear stress and erosion rate index. Similarly, the treatment of clayey soil, with up to 1% fiber-cement mixture by the dry weight of the soil, resulted in significant increases in the shear stress and the erosion rate index. Additionally, this study presents the effect of curing time of cement on the erosion index of the soils.

Search terms: Internal Erosion; Piping Erosion; Soil Erosion; Soil Stabilization; Risk Assessment.

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Chapter 1 **Introduction**

1.1 Problem Statement

Earth structures, one of the oldest types of structures, are used in hydraulic engineering projects such as dams, levees, dicks and embankments. These structures are built to retain water within a limited area for the purposes of irrigation, drinking water, water diversion, flood prevention and employed water energy to generate electric energy. Soil in its various types and sizes is the main material in the foundation of hydraulic earth structures. Improvement and stabilization of soils have been the objectives of many engineering researchers, societies and foundations that are interested in designing effective dam projects and assessing the safety of hydraulic structures.

Researchers have been observing for long time that the hydraulic earth structures in general, and embankment dams in particular, are subjected to severe damages even after long periods of successful operation. Such damages lead to catastrophic accidents and dam failure causing high human and material losses. Identification of causes of these accidents has been of major concerns to many researchers. Foster et al. [1], in their attempts to assess the safety of dams that had been subjected to failures and accidents, recognized that piping, slop instability, overtopping, and earthquakes are the main causes of problems affecting the safety of large embankment dams. However, they indicated that the internal erosion and piping are the most significant causes, representing approximately 50% of all failures. Additionally, the Bureau of Reclamation, Hanneman [2], found out in its inventory of more than 220 major embankment dams, which 99 internal erosion accidents occurred after tens of years of successful operations. Failures due to internal erosion are also common on small dams and ponds distributed in the countryside of Europe [3].

Because of its importance in the hydraulic earth structures, the phenomenon of internal erosion still needs to be better understood and deeply studied. Internal erosion is defined as the seepage of water in the body or foundation of the hydraulic structure from the reservoir in the upstream side to the downstream side. This flowing fluid generates forces that erode soil particles causing a hole within the structure, with time the hole becomes bigger and leaks under the infrastructure. Piping is the term used to designate this leakage because of void formation that develops between the upstream and downstream sides [4]. Piping occurs through the soil under the foundations and causes an abrupt collapse of structures [4]. The rate of piping is very fast and only a few moments can separate its initiation from the complete flow break.

Various tests and techniques have been developed to scale the phenomenon of internal erosion and study the erosion characteristics of soil samples in the laboratories. The most recognized tests are the Jet Erosion Test, the Slot Erosion Test, and the Hole Erosion Test. The Jet Erosion Test evaluates the internal erosion through spillways by a jet positioned above the center of a submerged sample. The Slot Erosion Test is used to measure internal erosion in a large amount of soil compacted in an aluminum box and tested with a specific hydraulic gradient.

The Hole Erosion Test (HET), developed by Wan and Fell [5], is a procedural laboratory system for assessing the soil resistance to internal erosion. The HET simulates a flow condition similar to that occurring during piping erosion of embankment dams. The HET also measures the rate of soil erosion. This test is done by compacting the soil specimen in a standard mold. The test is conducted under a hydraulic constant gradient. Among the three tests, the (HET) is considered as the most applicable and economical test. Benaissa [4] evaluates the HET as a simple, fast, and a well-adapted method to simulate the erosion behavior during the piping development for all investigated cases.

The scaling of internal erosion or resistance to erosion, is not the only concern for researchers investigating characteristics of soils used in structure foundations. But there are other concerns such as the search for the chemical and mechanical ways to improve the properties of such soils, including those related to erosion. Such methods lead to eliminating soil problems and stabilizing soils against internal erosion. This in turn reduces the possibility of damage in the hydraulic structure body and the failure of dams due internal erosion. The Addition of the cementing agents, such as lime, to soil or the inclusion of randomly distributed elements, such as fibers, are common techniques to stabilize and reinforce soils and improve their physical and engineering properties [6]. Stabilized and reinforced soils are composite materials that result from combination and optimization of the properties of individual constituent materials.

Not much research has been conducted on soil stabilization against internal erosion using chemical treatments. Indraratna [7], Herrier et al. [8] used some chemical additives to stabilize the soils against erosion. Indraratna [7] evaluated the internal erosion behavior of erodible soil stabilized by lignosulfonate and cement as chemical admixtures. Herrier et al. [8], along with the other researchers, used lime to stabilize the soil against internal erosion and to improve the workability of the clay materials and develop better mechanical properties.

It has been noticed that there are few number of studies on fiber-reinforced soils [9]. However, fiber inclusions have been shown to cause significant modifications and improvements in the physical and engineering behavior of soils. Consoli et al. [6] studied engineering behavior of sand reinforced with polyethylene terephthalate fiber separately and also when it was combined with Portland cement. The study's findings show that the inclusion of polyethylene terephthalate fiber increased the peak and ultimate strength of both cemented and non-cemented soil and reduced the brittleness of the cemented sand. Ôzkul and Baykal [10] show that there were significant contributions of inclusion of rubber fibers in strengthening the low-plasticity kaolin of clay. Kumar et al. [11] show that the percentage of increase in split tensile strength and unconfined compressive strength reached to 100% if it mixed with 1.5% of 6 mm crimped fibers and lime-fly ash-soil specimens, also, the gain in these indices further increased, reaching 135%, when 1% of 12 mm plain fibers were used. Al-Akhras et al. [9] show that both nylon and palmary fibers linearly reduced the swelling pressure and the swelling potential of the clayey soils, the higher the percentage of fiber content in the soil the more impact it had on these swelling properties. Additionally, it was noted that palmary fibers had more impact on reducing the swelling pressure of soils than the nylon fibers.

To the best of author's knowledge no research studies on the effectiveness of fibers inclusion to stabilize soils against internal erosion have been reported in the literature. The previous findings of research on the physical properties of fibers-reinforced soils show that the inclusion of fibers in soils to improve their quality is a promising approach. However, there is a need to study the erosion characteristics of soils treated with fibers separately or combined with cement. In this research, the behavior of soils due to its chemical treatment with fibers was observed and evaluated using the HET. The findings obtained in this study will help the researchers who are interested in soil stabilization to develop better understanding of the role of fibers in stabilizing soils against internal erosion.

1.2 Thesis Objectives

The main objective of this study is to stabilize clay soils and sandy soils against internal erosion. Two materials will be mixed with the soils mainly cement and a cement-fiber mixture. This will be achieved as follows:

1. Two types of soils (sand and clay) will be selected. The selection of sand is based on the gradation. However, the clay soil was selected based on plasticity indices.
2. The sand will be mixed with cement at different percentages and prepared and tested against erosion. All samples were remolded at 95% relative compaction and optimum moisture content.
3. The clay soil was mixed with a cement-fiber mixture at different percentages. All tested samples were prepared at 95% relative compaction and optimum moisture content. The specimens were tested against internal erosion.
4. The Hole Erosion Test was conducted to investigate the stability of the soils against internal erosion.
5. Optimize the percentage of the used stabilizers added to both types of soils.

1.3 Thesis Outline

The structure of this study is organized as follows:

Chapter 1: Introduction to the background of the problem explaining the need for the investigation of soil stabilization against internal erosion and piping using composite materials, and a description of the objectives of this study.

Chapter 2: A review of the literature dealing with the phenomena of internal erosion including the principal mechanism in piping, its scaling with focus on the Hole Erosion Test (HET), and the treatment.

Chapter 3: A description of the study's methodology, including details about the experimental procedures, apparatus, and methods of analysis of the HET test data.

Chapter 4: The results and analysis, and discussion of the findings from the conducted HET tests on soil samples.

Chapter 5: The conclusions and recommendations for further research based on the findings of the laboratory tests presented in Chapter 4.

Chapter 2 **Literature Review**

This chapter presents an overview to the phenomena of soil erosion and its impacts on the safety of embankment dams and other landfills. Also, the review includes recent research on the soil's physical and chemical properties and their effects on the erodibility. The literature review also contains research conducted on the stabilizing foundations under hydraulic structure and its effect to improve soil resistance against erosion. Mainly the literature review is divided into five sections. In the first Section 2.1, two areas are covered in the literature review, mainly findings of statistical investigations on the causes of embankment dam failures and why there is a need to evidences of the failure causes using experiments. Section 2.2 sheds light on how soil erosion and piping are formed in hydraulic structures. Research on soil properties influence on the internal erosion is a focus of Section 2.3. The Hole Erosion Test (HET) as a method to measure the erosion characteristics of soil, the models to simulate the HET, and the updating developments of the HET are presented in Section 2.4. Section 2.5 in this chapter reviews the studies on soil stabilization against internal erosion by adding additives such as cement, lime, and fibers to improve soil quality.

2.1 Internal Erosion Tests on Embankment Dams

Internal erosion and piping have been reported in statistical investigations and extensive surveys on dam failures as significant causes of failure and accidents affecting earth dams. In 1963, Sherard et al. [12], based upon an extensive survey on dam failures, reported a long list of possible failure causes in earth dams. This included overtopping, embankment and foundation piping, differential settlement and cracks, embankment and foundation slides, slides during construction, earthquake damage, reservoir wave action, damage due to borrowing animals, damage caused by water soluble material, flow slides due to spontaneous liquefaction, and damage due to surface drying.

Foster et al. [1] carried out a survey on 128 dam failures and they reported that failure in earth dams could be the result of piping, overtopping, slides, and earthquake. In their study, internal erosion and piping were found to be one of the most frequent causes; it represents 47% of all failures, as shown in Table 2.1. Of these failures and accidents, 66% are in the embankment, 32% in the foundations, and 2% from the embankment of the foundation.

Table 2.1: Failure statistics for large dams [1]

Mode of failure	No. of cases	% failures
Internal erosion (Piping)	59	47
- through embankment	39	31
- through foundation	19	15
- embankment to foundation	1	1
Overtopping	60	47
Slides	7	4
Earthquake	2	2

Rico et al. [13] carried out an extensive analysis on data collected from 147 cases of dam failures in the world, in which 26 of them in Europe. In this analysis, the researchers pointed out that earth dam failure can be grouped into ten categories: foundations slop stability, overtopping, mine subsidence, unusual rains, snow melt, piping/seepage, seismic liquefaction, structural, unknown, and management operation. Seepage/piping failure was found to account for 8% of the events in Europe, against 7% in the rest of the world.

On the basis of its database on historical cases of failures for more than 220 major embankment dams, the Bureau of Reclamation [14] found that 99 internal erosion accidents had occurred after decades of successful operations. Failures due to internal erosion are also common on small dams and ponds distributed in the countryside of Europe [3].

The above studies proposed to compile and analyze comprehensive surveys of embankment dam failures and accidents including piping failures. Each incident is assigned to a single category, which contributes most of the dam failure, according to the case description. As Schmertmann et al. [15] highlighted, only empirical and statistical evaluations regarding piping are being provided.   A quantitative evaluation of internal erosion throughout experimental tests in laboratories and by developing a design methodology is based on an appropriate theory to convert laboratory testing results to field design is highly needed. Similarly, Luo et al. [16] points out that “it is necessary to strengthen quantitative research on dam failure conditions of all kinds of dams with different forms, and dam materials." Since soil material properties, such as erodibility and soil strength, have a great influence on dam failures and accidents, Luo et al. [16] also emphasize that there is a necessity to enhance research on dam material properties and their corresponding effects on dam failures.

Farrar et al. [14] indicate that the US Bureau of Reclamation is responsible for the safe performance of many dams located in the West of the Mississippi. Embankment dams are susceptible to uncontrolled seepage and possible failure by piping and internal erosion. Engineers need tests that will assist in evaluating the risk of piping. In the mid 1990's, there was no commonly accepted test for evaluating piping and internal erosion potential. Recently, Reclamation's Dam Safety Office has funded several research programs to improve erosion tests and their ability to perform safety risk analysis. Among these tests is the Hole Erosion Test (HET). Reclamation's goal is "to quantify the HET for standardization so engineers now will have a readily available test for piping and internal erosion for risk analysis." Engemoen [17].

2.2 The Formation of Soil Erosion

Because of its importance in the hydraulic earth structures, the process of internal erosion and its causes still need to be better understood and studied. According to Engemoen [17], many hydraulic, physical or chemical complex variables play a role in the internal erosion process and this in turn explains why there is no widely accepted means to determine the causes of dam failure due to internal erosion.

Internal erosion is defined as the seepage of water in the body or foundation of the hydraulic structure from the reservoir in the upstream side to the downstream side. This flowing fluid generates forces that erode soil particles causing a hole within the structure. With time the whole progress to be a huge fluid leakage occurring under the infrastructure. Piping is the term used to designate this leakage because of void formation that develops between the upstream and downstream sides. Piping occurs through the soil under the foundations and causes an abrupt collapse of the structures sides. According to Benaissa et al. [4], the rate of piping is very fast and only a few moments can separate its initiation from the complete flow break.

Wan and Fell [18] describes the process of internal erosion and piping in four phases:

1. initiation of erosion,
2. continuation of erosion,
3. progression: to develop an internal channel,
4. formation of a breach.

Figure 2.1 shows the process of internal erosion piping through the embankment initiated by a concentrated leak. Similar processes apply for piping through the foundation, and from the embankment to the foundation.

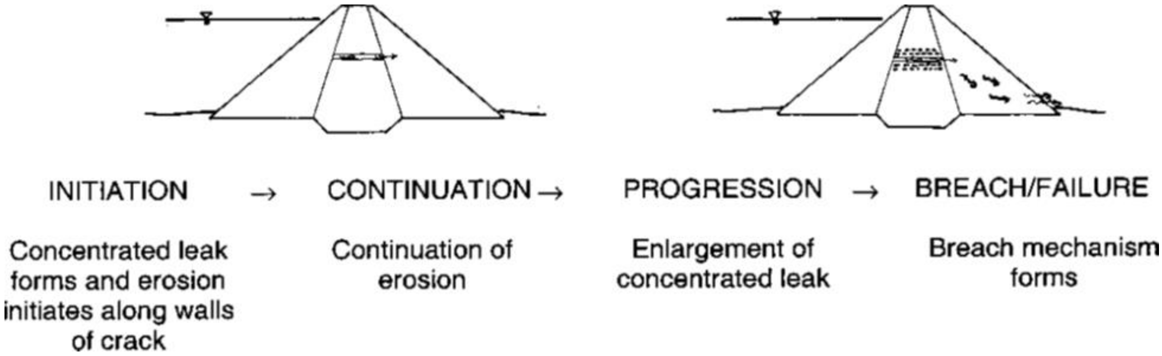

Figure 2.1: Development of internal erosion and piping in embankment [18]

Engemoen [17] presents Reclamation’s approach to determining the threat of internal erosion of dams which describes the process of internal erosion as an “event tree”. The tree presents the four phases described by Wan and Fell [18] and includes a series of the following events that cause failure:

1. The reservoir rises to a critical level.
2. Initiation – Particle erosion begins due to a concentrated leak in the embankment or foundation.
3. Continuation – An unfiltered exit point exists at the location of the concentrated leak.
4. Progression – The material being eroded, or an overlying soil layer, can support a roof (tunnel).
5. Progression – Upstream zones fail to fill a crack or pipe.

6. Progression – Upstream features or constrictions fail to limit or throttle flows.
7. The developing erosion process is not detected and/or human intervention is unsuccessful in stopping the process.
8. The dam breaches.

2.3 Soil Properties Influencing Internal Erosion

According to Hanson et al. [19], characterization of the material properties relevant to the rate of failure is one of the challenges in predicting failure due to internal erosion. The following geotechnical researchers have contributed to the advancement of the knowledge on and understanding of the soil erosion phenomena and its relationship with soil properties and types, Sherard et al. [12] investigated the effect of soil types on piping resistance in earth dam embankments, Briaud [20] investigated the erosion categories for soils and rocks based on shear stress, Cao et al. [21] researched about the effect of water properties on soil, Delgade-Ramos et al. [22] studied the effect of soils' variables on the internal erodibility of clay soil protected by granular filters, and Wan and Fell [5] developed the hole erosion test to measure the erosion properties of soils.

In 1967 Sherard et al. [12] described the relationship between piping resistance in earth dam embankments and soil types. This relationship might be better understood through a continuum of erodibility, the level of erodibility that the soil type has led to placing it in the various erosion points of the continuum. One extreme of the continuum represents the greatest piping resistance whereas the other extreme represents the least piping resistance. Because of its high level of piping resistance the well compacted high plasticity clays are located in the first extreme. At the same time the uniform fine cohesionless sands are located in the other extreme due to their low level of piping resistance. The intermediate level is found in the well graded coarse sand and sand gravel mixtures.

Briaud [20], based on 15 years of erosion testing experience, proposed a classification system of erodibility of soils and rocks in terms of an erosion rate versus shear stress function. Figure 2.2, shows the erosion category chart. Each category has a number to represent the zone in which the erosion function fits. To classify a soil or rock, the function is plotted on the chart and the erodibility category number for the material tested is specified. Note that the chart is populated with soil and rock descriptions and soils span Categories I–IV while rocks span Categories III–VI. Briaud [20] suggested that the proposed chart is a starting point with the idea that further work may lead to better understanding to describe soil and rock within each category.

According to this chart, it seems that grain size and plasticity are two important factors in influencing the erodibility of soils [12]. The variable of grain size controls coarse grained soil erosion and the variable of plasticity have a significant influence on fine grain soil erosion.

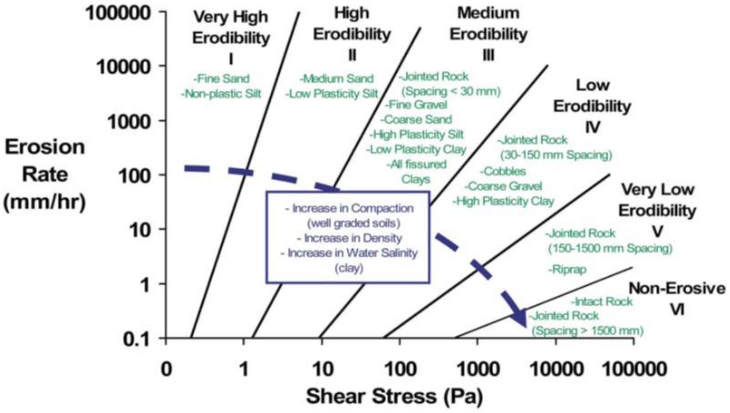

Figure 2.2: Proposed erosion categories for soils and rocks [20]

The soil and water properties influencing erodibility are numerous. Briaud [20] drew a table reflecting expected relationships between some of the most important properties and erodibility of the soils. A list of these properties influencing erodibility is shown in Table 2.2.

Table 2.2: Properties influencing erodibility [20]

Soil water content	**Soil dispersion ratio**
Soil unit weight	**Soil cation exchange cap**
Soil plasticity index	**Soil sodium absorption rat**
Soil undrained shear stress	**Soil pH**
Soil void ratio	**Soil temperature**
Soil swell	**Water temperature**
Soil mean grain size	**Water salinity**
Soil percent passing #200	**Water pH**
Soil clay minerals	

The erodibility of soils varies significantly from one soil to another; therefore the erodability depends on the properties of the water flowing through the soil. Cao et al. [21] found that, for dispersive soils, the higher the salt concentration in the water, the more erosion resistant the clay experienced.

Another study on the erosion characteristics in crack in embankment dams was conducted by Delgade-Ramos et al. [22]. The researchers studied the effect of several base soils' variables on the erodibility of clayey soils protected by granular filters. The variables under investigation were plasticity, mineralogy, water content, additives and hydraulic gradient. The effect of these variables on the function of a base soil were assessed by the No Erosion Filter (NEF) test, where firstly the filter materials compacted inside a Perspex cylinder, then add compacted base soil above it, after that form an inner hole across the diameter of the base soil. The study concluded that negative effects on the internal erodibility of clay soil were caused by the hydraulic gradient and water content, however no effect occurred by the plasticity and mineralogy. Moreover, positive effects occurred due to the dispersivity of clay through adding aluminum sulfates to the base soil.

Wan and Fell [5] used rates of internal erosion and hydraulic shear stress as indications of soil erosion in cracks in embankment dams. Using the Hole Erosion Test (HET), and the Slot Erosion Test (SET), they draw two main conclusions. Firstly, the rate of erosion is affected by factors such as soil properties, water properties, and cementing materials. Secondly, by comparing coarse-grained, non-cohesive soils with fine grained soils. It was found that the type of soil plays a significant role in changing the values of erosion indices. The coarse-grained and non-cohesive soil was found to erode more rapidly and has lower critical shear stresses.

Since the erosion rate index is mainly influenced by the degree of compaction and the water content, Wan and Fell [5] have concluded that among the tested soil samples they prepared, the specimens that were compacted to a higher dry density and to the wet side of optimum water content tend to have higher resistance for erosion than those soil samples compacted to a lower dry density and to the dry side of the optimum water content. However, when coarse-grained and non-plastic soil specimens are compacted to a lower dry density and to the dry side of the optimum moisture content, they tend to cause a high erosion index.

2.4 Hole Erosion Test Studies

2.4.1 The Hole Erosion Test (HET)

The Hole Erosion Test (HET) is a procedural laboratory system for assessing the resistance to internal erosion of cohesive soils. It was developed as a constant-hydraulic head configuration by Wan and Fell, [5]. The HET simulates a flow condition similar to that occurring during piping erosion of embankment dams. The HET uses an internal flow through a 6 mm hole pre-drilled in the specimen and the test head starts from 50mm until progressive erosion of the hole is initiated.

Two main parameters are used to describe the erosion rates namely the critical shear stress and the erosion rate index. The hydraulic shear stress that causes erosion is applied to the soil by the flow that is controlled by the hydraulic head. Moreover, the erosion rate index is an indicator for the resistance of soil against erosion. Its value varies from 0-6, indicating high erosion rate at 1 and slow erosion rate (high resistance to erosion) at 6 as shown in Table 2.3.

Table 2.3 Qualitative terms for representative erosion rate index [5]

Group Number	Erosion Rate	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

To perform the HET in the laboratory, four sequenced steps should be followed. First, select a 117 mm length sample of soil compacted in a Standard Proctor mold. Second, a hole is predrilled along the centerline axis in the soil sample. The hole has a quasi-cylindrical form with radius 6 mm. Third, the sample is installed into a test apparatus and then water flows through the hole under a constant hydraulic head that is applied between the tube extremities. The water is increased incrementally until progressive erosion is produced. Fourth, once erosion is observed, the test is continued at a constant hydraulic head for up to 45 minutes.

Having completed the laboratory stage of the HET, the analysis is performed to compute hydraulic stress and the erosion rate [5]. First, measurements of the increasing flow rate are used. Second, the HET calculates the initial and final friction factors at the begging and the end of the test by measuring the diameter of the hole at the start (time = 0, Diameter = 6 mm) and at the end of the test. By using the calculated friction factor at the start and end of the test, the diameter of the hole can be estimated at any time throughout the test, as the friction factors are assumed to vary linearly during the test time.

The effectiveness and efficiency of HET has been dedicated to evaluation by many researchers in the area of internal erosion [14] [4]. Benaissa et al. [4] evaluated the HET as a simple, fast, and well adapted method to simulate erosion behavior during piping development for all investigated cases. Reclamation’s Dam Safety Office commissioned a research team leading by Farrar [14] to evaluate the HET for assessing dam safety. The researchers concluded that the HET can be used as an effective screening tool for assessing risk of internal erosion of embankment dams. They also mentioned that, because of its simplicity and low cost, the HET can be an efficient tool and attractive to many water resource engineers charged with dam safety evaluations. M. Luthi [23] highlighted the main advantages of the HET explaining that it is simple and straightforward to use, and that tests can be performed in an economical manner without the requirement for large amounts of soil. Thus, HET has been applied in several research projects, and there is a growing data base for erosion characteristics of many different types of soil that will help to understand the relationship between basic engineering properties and the soil erosion characteristics.

2.4.2 Models for Piping Erosion Applicable to the HET

Bonelli et al. [19] and Bonelli et al. [20] proposed a simplified one-dimensional model for the piping erosion, applicable to the HET test. According to the model developers, the change in the hole radius is an exponential function of the time of internal erosion process and the initial and critical shear stress. The model measures the flow discharge during the test and the initial shear stress, while it predicts the valise of the test time. The measured discharge and the predicted time can be optimized to best fit a linear relation that can be used to obtain the coefficient of soil erosion. The Bonelli model [24] was applied with the assumptions of turbulent flow conditions with large Reynolds numbers; test heads exceeding critical shear stress; constant length and uniform diameter of the pre-drilled hole; consistency of the friction factor, and the hydraulic head and gradient; and the collection of the test data only during the period of progressive erosion.

Wahl et al. [25] noticed two significant advantages that the model offers, one is concerned with diameter and the other is minimization of the impact of short-term anomalies in erosion behavior during a test using the curve-fitting procedure. Also, Benaissa et al. [4] evaluated the model as sufficient in explaining the erosion related to piping problems. The research yields a comprehensive description of the erosion initiation and kinetics for a given soil. These rudimentary models also are able to evaluate the influence of the hydraulic conditions on the kinetics and to quantify the gain in time left to rupture by operating, for example partial drainage of the water reserve.

However, the limitation of this model is that the value of the critical shear stress obtained from the fitted relation should be less than the initial shear stress in order to meet the model condition of collecting the test data during the progressive erosion [21]. Also, it was found that the one-dimensional model cannot predict the eroded shape [2]. The model assumes there is uniformity in the wall shear stress generated by the flow so that erosion rate is also uniform along the hole length. However, the experimental observations demonstrated that the bottom of the hole has undergone much more erosion than the top. In addition to variation in clay concentration, it was observed that erosion can be affected by the wall roughness of the hole. Luthi [23] evaluated the model as a promising one but its applicability to all tests is restricted.

2.4.3 Developments for HET

Lim [26], in his thesis, identified three problems through his observations with the HET. The first problem was that using the method of drilling to initiate the hole caused smearing and remolding of the soil. Such a cause, in turn, led to denser surface layer and a higher critical shear stress. Another problem was the appearance of inhomogeneity in soil samples because of the compaction of the soil into the test mold. The last problem was the influences of slaking and its role in reducing a hole's length and make difficulties in defining the final diameter of the hole. To solve these problems, Lim [26] suggested the use of the diameter of the eroded hole in the estimation of friction factors; the use of higher number of compaction layers in sample preparation; and the use of his method for correcting slaking if the hole's length is more than 40mm.

Wahl et al. [25] proposed two methods for HET data analysis. The first is a deterministic method in which the variations of the friction factor during HET was studied, and a model for estimating intermediate values of the friction factor was developed. The second method is the fitting of the observed flow rate record to a non-dimensional numerical model for piping erosion without the need for the determination of the friction factor or the measurement of the final hole's diameter. Both methods of analysis were applied on numerous tests and they yielded similar results. The Bureau of Reclamation [14] has recognized the two methods as new procedures for analyzing test data but they are not applicable for all tests. Thus, the analyst of tests decides whether a method is appropriate and applicable to the test under investigation.

K. Benaissa et al. [4] carried out a two-dimensional modeling of the HET. This modeling describes the biphasic turbulent flow at the origin of erosion taking place inside the soil sample, considering the effect of roughness of the wall and clay concentration in the flowing fluid. Also, the turbulence modeling had shown that the wall shear stress is not uniform along the hole's length and variation in clay concentration and wall roughness considerably influence wall shear stress. Thus, these two factors increase the erosion rate noticeably.

2.5 Soil Stabilization

A highly stable soil substance adds desirable characteristics for construction projects; therefore, improving the strength and stiffness of the soil substances ensure high stabilization. Expansion, contraction, collapsibility and erodibility of soil are unstable terms and considered as a major defect in soil properties.

In hydraulic structures and embankment works, the term soil erosion is an undesirable term and highly avoidable. Highly erodible soils are considered unreliable unless their physical and chemical characteristics are changed. The need for stabilizing the soils against internal erosion is vital to reduce and eliminate risks associated with this phenomenon. Also, effective stabilizing additives should be applicable and available to obtain. Since the internal erosion is a critical phenomenon, several research studies have become concerned with searching for optimal stabilizers that decrease the effects of internal erosion in soils and ensure high stabilization.

2.5.1 Soil Stabilization Using Admixtures

To optimize the physical and engineering characteristics of the soils used in structure foundation in general and to increase their resistance to internal erosion in particular, researchers have proposed various chemical additives such as lime, cement, and fly ash, or combination of these additives as methods to improve and stabilize the behavior of the foundation soils. Research on soil stabilization against internal erosion using chemical treatments has not been investigated much. However, there have been a considerable number of studies on evaluation of the physical and engineering behavior of soils stabilized by cement, lime and other components, or reinforced by fibers inclusions or treated by mixtures of these materials.

2.5.2 Soil Stabilization using Chemical Admixtures

Researchers, such as Bromage et al. [27], have conducted investigations to stabilize the soil against swelling, compressibility, collapsibility and other physical soil properties. In their investigations they used lime, cement, fibers, and solid wastes in addition to other stabilization techniques. Few studies are found in literature related to soil internal erosion stabilization. Researchers, such as Indraratna et al. [7] and Herrier et al. [8], used some chemical additives to stabilize the soils against erosion.

Indraratna et al. [7], measured and evaluated the internal erosion behavior of erodible soil stabilized by lignosulfonate and cement, as chemical admixtures, using a process simulation apparatus for internal crack erosion (PAS ICE). The test results showed that there are improvements in erosion characteristics; shear stress and coefficient of soil erosion when cement and lignosulfonate are added to the erodible soil. Also, the tests demonstrated that lignosulfonate was a more efficient chemical admixture than cement in soil stabilization. The erosion index decreased by approximately twenty six times with the addition of 3.0% cement, whereas the addition of 0.6% lignosulfonate decreased the index by approximately 85 times.

Herrier et al. [8] used lime to stabilize the soil against internal erosion and to improve workability of clayey materials and develop better mechanical properties. These objectives were accomplished through the SOTREDI research project, "SOil TREatment for DIKes". The research was supervised by the Lhoist Group and in collaboration with several research centers and universities. In this project, soil properties such as compressibility, shear resistance, water sensitivity and erosion resistance were measured and described using six different fine soils with different plasticity indexes of silty to clayey soils. Regarding erosion, the results showed that the shrinkage limit of soils was shifted towards higher moisture contents and that the materials became non-dispersive one day after treatment, and thus the critical shear stress for erosion increased, resulting in strongly reducing the risk of piping.

2.5.3 Soil Stabilization using Fibers Admixtures

According Engemon [17], there are a small number of studies on fiber-reinforced soils. However, fiber inclusions have been proved to cause significant modification and improvement in the physical and engineering behavior of soils. Research on fiber-reinforced soils has recently presented laboratory experimental evidences that the addition of fiber content to clayey soils improve their engineering properties. Also, the literature has documented that the swelling properties of soils can be reduced, or may be eliminated by the addition of fibers.

Consoli et al. [6] examined the engineering behavior of sand reinforced with polyethylene terephthalate fiber, obtained from recycling waste plastic bottles. The same behavior was also observed when plastic waste was combined with Portland cement. The study findings showed the inclusion of polyethylene terephthalate fiber increased the peak and ultimate strength of both cemented and un-cemented soil and reduced the brittleness of the cemented sand. Also, fiber content did not affect the initial stiffness.

Ôzkul and Baykal [10] combined rubber fibers (tire buffing) with low-plasticity kaolin clay to evaluate the impact of fiber content on compaction behavior and shear strength of the mixtures. Consolidated-drained and consolidated- undrained triaxial tests were performed at confining stresses ranging from 50 to 300 kPa. The results showed the contribution of inclusion of fiber content in strengthening the clay reached its peak when confining stresses were below 200 and 300 kPa.

Kumar et al. [11] investigated the geotechnical behavior of different soil mixtures (fly ash-soil specimens, lime-soil specimens and lime-fly ash-soil specimens). The addition of polyester fibers to such types of mixed soils was observed to stabilize and improve their strength properties. Test specimens were subjected to compaction tests, unconfined compression tests and split tensile strength tests. The results showed that the percentage of increase in split tensile strength and unconfined compressive strength reached to 100% if just 1.5% of 6 mm crimped fibers were mixed with lime-fly ash-soil specimens (the optimum values were at 8% lime content and 15% fly ash content) in comparison to that of the same mixture without fibers. Also, the gain in these indices further increased, reaching to 135%, when 1% of 12 mm plain fibers were used. The relation between split tensile strength and unconfined compressive strength was examined. The ratio of the two indices increases with increases in the fiber content, which shows that polyester fibers are more efficient when soil is subjected to tension rather than to compression.

Al-Akhras et al. [9] studied the impact of two types of fibers (nylon and palmary fibers) on the swelling properties of clayey soil. Using different types of expansive soils mixed with varying amounts of fibers both swelling pressure, and swell potential were evaluated for each combination. The results of the study showed that both nylon and palmary fibers linearly reduced the swelling pressure and swell potential of the clayey soils. The higher the percentage of fiber content in soil the more impact it had on swelling properties. Also, it was noted that palmary fibers had more impact on reducing the swelling pressure of soils than nylon fibers.

Many researchers have shown a great deal of interest in embankment dams with regards to improving the stabilization of soil in their foundations. The process of internal erosion is controlled by the erodibility of the base soil which depends mainly on the soil, the plasticity, clay mineralogy, soil water content, hydraulic gradient, and additives Delgado-Ramos [22].

Chapter 3 **Experimental Setup and Test Procedure**

Internal erosion is a complex process that is hard to describe by theoretical analysis, and it is influenced by many variables that hard to measure. Therefore, Experimental tests are the best alternative to investigate internal erosion characteristics of soil Boukhemacha et al. [28]. The Hole Erosion Test (HET) was developed as an easy approach to measure the rate of internal erosion [5]. Figure 3.1 shows the schematic diagram of the HET.

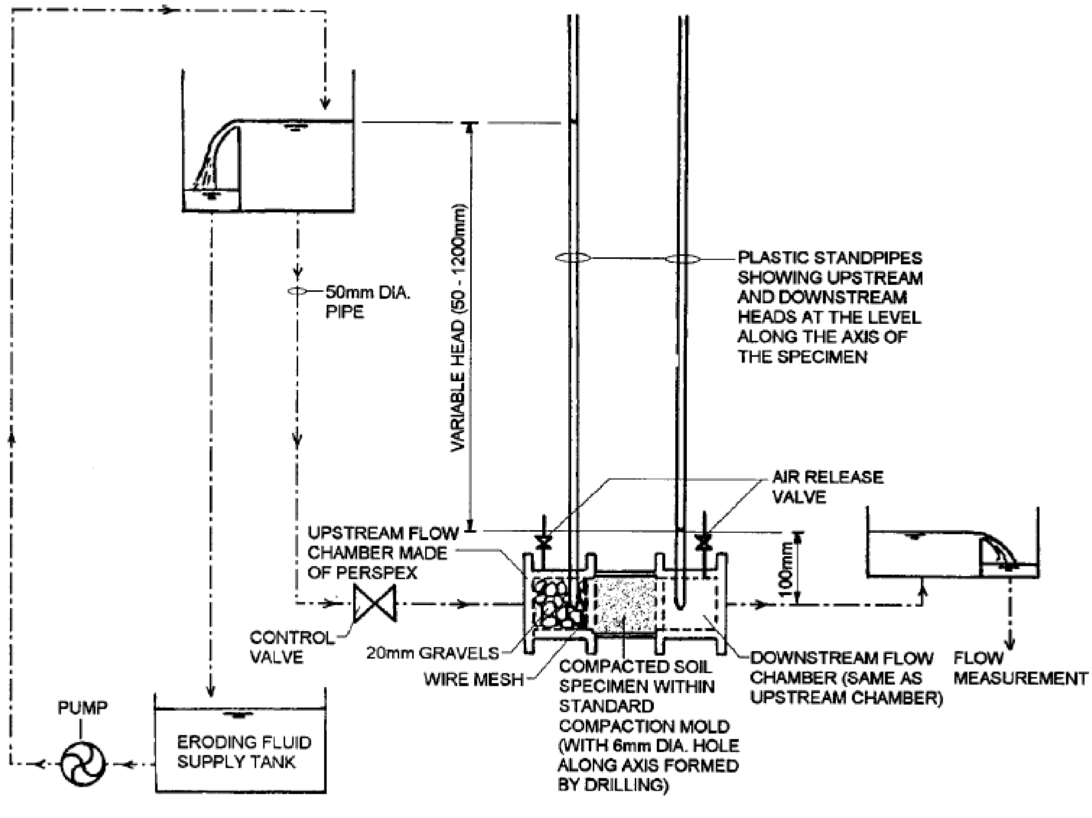

Figure 3.1: HET schematic diagram [5]

The HET is one of the widely accepted laboratory methods, developed to model piping erosion in concentrated leaks in earth filled dams and embankments. Also, when the HET is compared to other erosion tests, it is concluded that it is highly desirable for applications involving piping erosion situations [25]. In the HET, a soil specimen is formed to include a preformed axial hole and a head-controlled flow similar to that occurring during piping erosion [5]. The erosion rate is the measure of enlargement of the soil pipe (erosion rate) which is measured using hydraulic gradient and flow rate. Also, the stress threshold is used to indicate the initiation of erosion. Lachouette et al. [29] presented an analytical model of this test, developed an approximated formula modeling the inner tube radius evolution as function of time.

The current research is a continuation to this line of interest investigating the effects of adding cement-fiber admixture on the internal erosion behavior of soils. Many erosion measurements of various clay and sandy soil samples using HET will be performed in laboratory.

In HET, the soil is compacted in a standard compaction test mold that has a dimension of (4"x8"). In this research, the soil will be compacted in the standard compacted mold in accordance with ASTM (D-698) standard procedures. Then a hole of 6 mm-diameter is drilled along the soil sample as a way to simulate a concentrated leak. After that, the mold is set into the HET apparatus as shown in Figure 3.2. Moreover, the water head at the upstream is set at 25cm then increased at an increment of 20cm until progressive erosion is initiated. After the water head is set, the flow rate at different time intervals is measured and the flow continued for 45 minutes after the initiation of erosion.

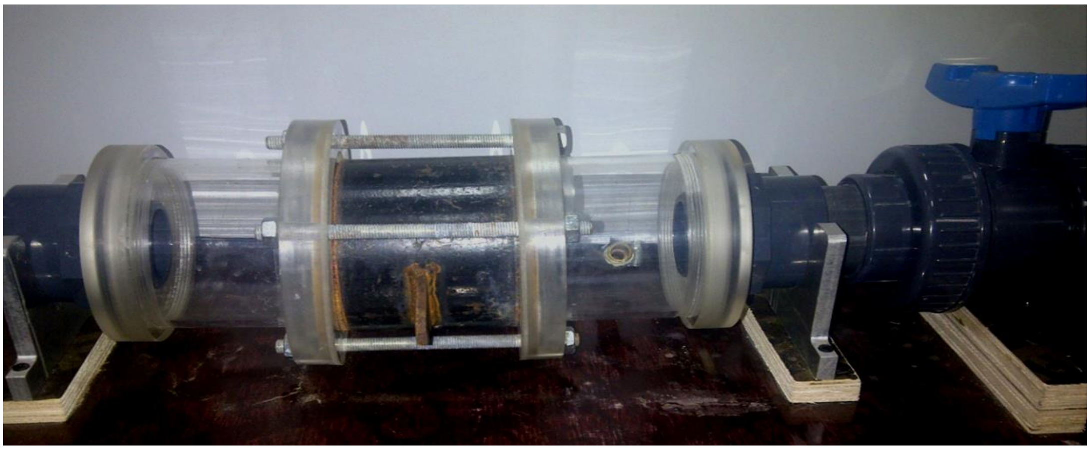

Figure 3.2: HET Apparatus

3.1 Sample preparation

Two types of soil will be selected from different areas in UAE. The first type of soil is a clayey soil and the second type is sandy soil. The initial physical properties of the selected soils such as Atterberg's limits, gradation, maximum dry density and optimum water content will be determined in accordance with ASTM standard procedures.

For HET, the type of soil that has clayey content will be mixed with different percentages of cement-fiber admixture and the sandy type of soil will be mixed with different percentages of cement only. Both soil samples will be compacted in the standard compaction mold, according to ASTM standards. All soil specimens will be prepared at the optimum moisture content and 95% relative compaction. The samples will be sealed with a plastic bag to have uniformity in water distribution inside the samples and to prevent any water loss. The samples will be tested at 2 and 7 days from the time of preparation.

3.2 Test Analysis Procedure

Through the HET test explained earlier, two flow conditions occur when water flows through the concentrated pipe. This flow condition is identified whether it's turbulent or laminar using Equations (1) and (2). If Reynold's number obtained from Equation (2) is less than 4000, the flow is considered to be laminar, while if the velocity is more than 4000, the flow is considered to be turbulent.

The data derived from the HET test procedure proposed previously, the critical shear stress τ_c will be calculated using Equation (3), and the erosion rate index (I) will be calculated using Equation (4).

$$\mathrm{V}_t = \frac{\boldsymbol{4Q}}{\boldsymbol{\pi \emptyset_t^2}} \tag{1}$$

$$R_e = \frac{\boldsymbol{V_t \emptyset_t}}{\boldsymbol{\nu}} \tag{2}$$

V_t: Estimated mean flow velocity in the hole, m/s

ν: Kinematic viscosity, m^2/s ($1.004*10^{-6}$)

Q: Volumetric flow rate, m3/s

$\emptyset_t$: Diameter of the performed hole at time t, m

$$\boldsymbol{\dot{\varepsilon}_t = C_e(\,\tau_t - \tau_c)} \tag{3}$$

$$\boldsymbol{I = -\log C_e} \quad (4)$$

where the C_e is the coefficient of soil erosion

The values of the critical shear stress τ_c in Eq. (3) is obtained from the plot of the rate of erosion per unit surface area ($\dot{\varepsilon_t}$) versus the hydraulic shear stress along the hole at time t (τ_t), which are obtained from Equations (4, 5)

$$\boldsymbol{\tau_t = \rho_w g s_t \frac{\emptyset_t}{4}} \quad (5)$$

where:

ρ_w: Density of the eroding fluid (water), kg/m^3

g: Acceleration due to gravity, N/kg

S_t: Hydraulic gradient across the soil sample

$$\boldsymbol{\dot{\varepsilon_t} = \frac{\rho_d}{2}\frac{d\emptyset_t}{dt}} \quad (6)$$

ρ_d: Dry Density of the soil, kg/m3

For the turbulent or laminar conditions the diameter of the pipe at any time t that is required to calculate the shear stress in Equation (5), is calculated using Equation (7) or (8), respectively as:

$$\emptyset_t = [\frac{64\, Q_t^2\, ft_{L\,t}}{\pi^2 \rho_w g\, s_t}]^{1/5} \quad (7)$$

$$\emptyset_t = [\frac{16\, Q_t\, f_{L\,t}}{\pi \rho_w g\, s_t}]^{1/3} \quad (8)$$

In Equation (7) or (8) the (Q_t) is the flow velocity that is obtained at different time intervals throughout the test, while the $f_{L\,t}$ is the friction factor that is first obtained at time zero of the test at a diameter of the pre-drilled hole of 6 mm as shown in Figure 3.3 and Figure 3.4. Also, it is obtained at the end of the test when the total time of the test is observed and the final diameter of the hole is measured, as shown in Figure (4). After this, a plot of the two measured friction factors ($f_{L\,t}$) with the time intervals is drawn. In this plot, a best fit line is represented on the graph to show the friction factor value at any time of the test. The obtained friction factors at time (t) are used to calculate the diameter of the hole at any time during the test.

After obtaining all the parameters, Equations (1) and (2) are used to measure the rate of erosion in term of erosion rate index I_{HET}. The higher erosion rate index indicates that the soil is more resistance to erosion.

Figure 3.3: Specimen during the test (hole diameter at time zero)

Figure 3.4: Prepared test specimen (hole diameter at the end of the test)

Summarized below are the steps for soil preparation and testing and analysis procedure:

Soil Preparation:

1) Select the soil that will be used for the test
2) Take an amount of around 3 Kg of soil for each sample to be tested
3) Oven dry the selected soil sample
4) Sieve the dried soil sample through sieve No.4
5) Get the optimum Moisture content for the soil to be tested according to the ASTM standard
6) Calculate the portion of additives to be used. For sand soil samples, the portion of cement varied from 1% to 5%. Also, for the clay soil samples, cement to fibers ratio of (5:1) was used for all the samples, while the percentage of the mix varied from 0 % to 3%.
7) Use a tray to mix the soil with the optimum amount of water and the amount of additives to be tested, Cement for sand and Cement-fiber mix for clay.
8) Compact the soil in a standard compaction mold with dimensions of (4"x8") according to ASTM (D-698) standards.
9) Place soil sample in a plastic bag to cure for 2 days, 7 days, and 14 days.

Test Procedure:

1) Drill the prepared soil samples using a 6 mm diameter rod to the axial direction and at the center of the sample.
2) Fill the upstream chamber with 20 mm gravels in order to regulate the speed of water at the upstream side of the sample.
3) Place the soil sample between the upstream and downstream chambers. Also, tighten the sample mold with rubber rings to avoid any leak.
4) Adjust the constant water head to the level appropriate for the prepared soil sample, ranging between 50-120 cm
5) Open the valve to fill the water head with an appropriate amount of water.
6) Open the upstream gate valve to let the water flow through the drilled hole.
7) Increase the water head until progressive erosion is initiated.

8) Measure the flow rate at the downstream side of the apparatus and at different time intervals during the test until 45 min from the initiation of the erosion.
9) Measure the final diameter of the hole after stopping the flow of water.
10) Clean the apparatus from remained soil particles and prepare it to be used for the next test.

Test Analysis Procedure:

1) Check the type of flow throughout the test, whether it was a laminar flow or a turbulent flow, using Equations (1) and (2)
2) Calculate the initial and final values of the friction factor using the corresponding Equation (7 or 8) to the flow condition occurring, also using a diameter value of 6 mm for the initial friction factor and the measured hole's diameter at the end of the test as the final friction factor.
3) Interpolate the values of the friction factor at any time of the test by plotting the linear relationship between the calculated two values of the friction actor and the times ($t=0$ and $t=t_f$).
4) Calculate the values of the flow (Q) using the collected data throughout the test.
5) Calculate the values of the diameter of the hole (∅) any time during the test using Equation (7 or 8)
6) Plot a segment between the diameters and the time when the readings were collected. Derive the slope of every segment (d∅/dt).
7) Estimate the stain value using Equation (6)
8) Using the previously calculated parameters, estimate the shear stress value for every reading during the test using Equation (5)
9) Plot a graph between shear stress and strain and get the slope of the best fit line of the curve.
10) Determine the coefficient of erosion and the erosion rate index using Equations (3 and 4) and using the stress strain graph obtain the value of the critical shear stress $\tau_{c.}$

Chapter 4 **Experimental Results and Analysis**

This chapter presents the results of experimental tests conducted on specimens of two types of soils; sand and clay. This series of experiments was performed in order to test the stabilization of clayey soils and sandy soils against internal erosion. Two stabilizers were mixed with the soils mainly cement and cement-fiber mixture separately. The sand was mixed with cement at different percentages and tested against erosion. The clayey soil was mixed with cement-fiber mixture at different percentages. All tested samples were prepared at 95% relative compaction and optimum moisture content. The specimens were tested against internal erosion. The selection of sand was based on the gradation. However, the clayey soil was selected based on plasticity indices. The HET was conducted to investigate the stability of the two soils against internal erosion using the previously mentioned two mixtures.

Section 4.1 presents an example of the analysis procedures used in determining the initial properties of the soils and the experiment parameters, while the rest of the experimental results and their analysis are presented in the Appendix section. Results and analysis of test data are described in Section 4.2, showing results of testing stabilization of sandy soils against internal erosion using cement. In Section 4.3, results and analysis of test data for stabilization of clayey soils against internal erosion using fiber-cement mix are demonstrated.

4.1 Initial Properties of the Soils and the Experiment Parameters

In this study, each soil sample was subjected to a series of calculations to determine the previously specified parameters. In this section a sample of soil (3% cement, 7 days Curing) was selected as an example to show the procedures used in computing the parameters for the samples used. The main objective of calculations is to obtain the coefficient of soil erosion (C_e), which is required for calculating the erosion rate indices for the soil sample under study. This coefficient is derived from the relationship between critical shear stress and erosion rate per unit area (ε_{HET}). To obtain the two variables, it is required to determine the initial properties of the soils such as derive the friction factors, compute the flow of water in the concentrated leak, and calculate the progress of the diameter of the hole during the test.

The first step in the experimental testing program adopted in this study is to determine the initial properties of the soils, as listed in Table 4.1. These properties are either standard values or obtained from ASTM standard test experiments. In Table 4.1, the first two properties includes ρ_w which is the density of the eroding fluid (water) (which is 1 g/cm^3); and g (the acceleration due to gravity, 980 cm/sec^2) These parameters are fixed for all the soils used in the study. The hydraulic gradient across soil sample is S_t, which is equal to 10.34. This parameter varies according to the condition of each sample. Dry unit weight of the soil γ_d and density of the soil ρ_d are determined based on the type of soil. In this example the soil was sand and γ_d is 16.7 kN/m^3 and ρ_d is 1.70 g/m^3.

Table 4.1: Initial properties of a sample of sand soil (3% cement, 7 days curing)

ρ_w	1 g/cm^3
g	980 cm/sec^2
s_t	10.34
γ_d	16.7 kN/m^3
ρ_d	1.70 g/m^3

Based on the data collected for the flow of water in the pre-drilled hole, the condition of flow is identified. In this example, the velocity of the flow and the Reynold's Number are calculated using Equation (1) and Equation (2) to equal 12,610. By using Moody's diagram, and based on the value of the Reynold's Number the flow condition is turbulent.

The next step is to draw the graph depicting the relation of the friction factor versus time. The diameter of the hole at any time during the test is extracted from the linear relationship between friction factor and time, as shown in Figure 4.1. The first data concerning the friction factor $(f_{L\,t})$ was collected once the erosion was initiated when the hole diameter was 0.6 cm. Then, the friction factor was obtained after 45 min from the initiation of the erosion and the final diameter of the hole was also measured. The initial friction factor F_{L0} and the final friction factor F_{L80} were derived using Equation (7). After that, a plot showing the relation of the two measured friction factors $(f_{L\,t})$ within time was drawn. In this plot, the linear relationship presented in the graph shows the friction factor value at any time during the test. The relation of the friction factor versus time is shown in Figure 4.1, and the linear equation describing this relation is $y = 0.0059x + 0.0568$.

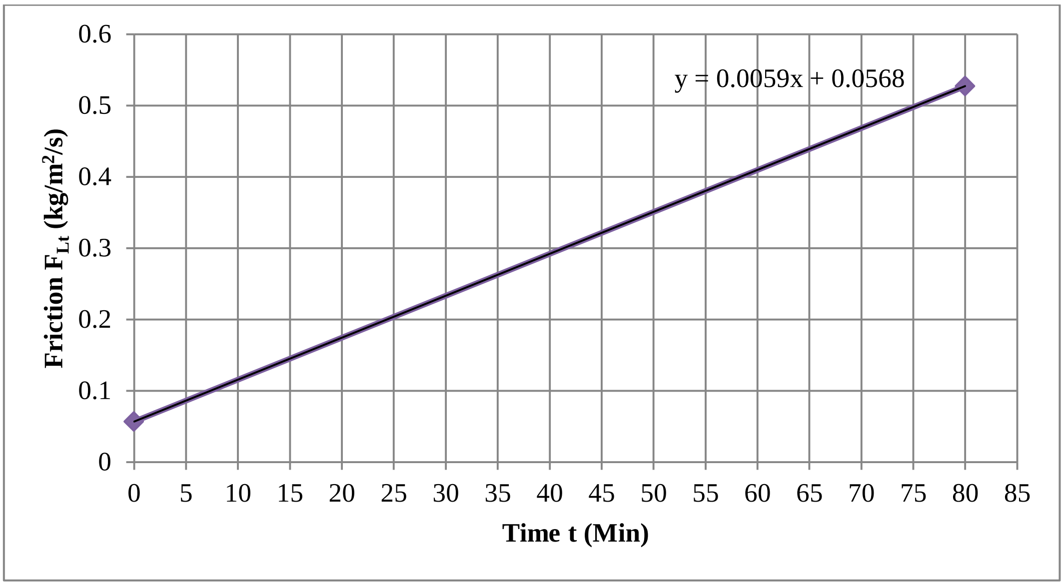

Figure 4.1: Sand soil (sample 3% cement, 7 days curing) - friction factor linear vs. time

From the linear graph four values were selected and four friction factors were extracted, as shown in Table 4.2. At t=0 the fraction factor was 0.0568, and after 80 minutes the factor became 0.5271. In general, the friction factor increased during the test time.

Table 4.2: Friction factors results (sand sample with 3% cement, 7 days curing)

t (min)	**0**	**45**	**65**	**80**
F_{Lt} (g/cm^2/s)	0.0568	0.31	0.43	0.5271

The water flow data that were collected throughout the test are presented in Table 4.3. It is noticed that the flow rate Q_t decreased from 120cm^3/sec to 46.25 cm^3/sec within 80 min. These data were used to calculate the progress of the diameter of the hole during the test. The change in diameter with time is presented in

Table 4.4 and illustrated in Figure 4.2. The slope for each time segment is extracted from Figure 4.2. The slope value is equal to the change of diameter with time (dØ/dt).

Table 4.3: Test results - flow rate

Volume (cm^3)	450	420	271	185
Time (sec)	3.5	3.5	3.65	4
Flow Rate Q_t (cm^3/sec)	120	120	74.25	46.25

Table 4.4: Test results - finale diameter results

Time - t (min)	0	45	65	80
Diameter - $Ø_t$ (cm)	0.6	1.018	1.317	1.5
dØ/dt	0	0.558	0.9	0.732

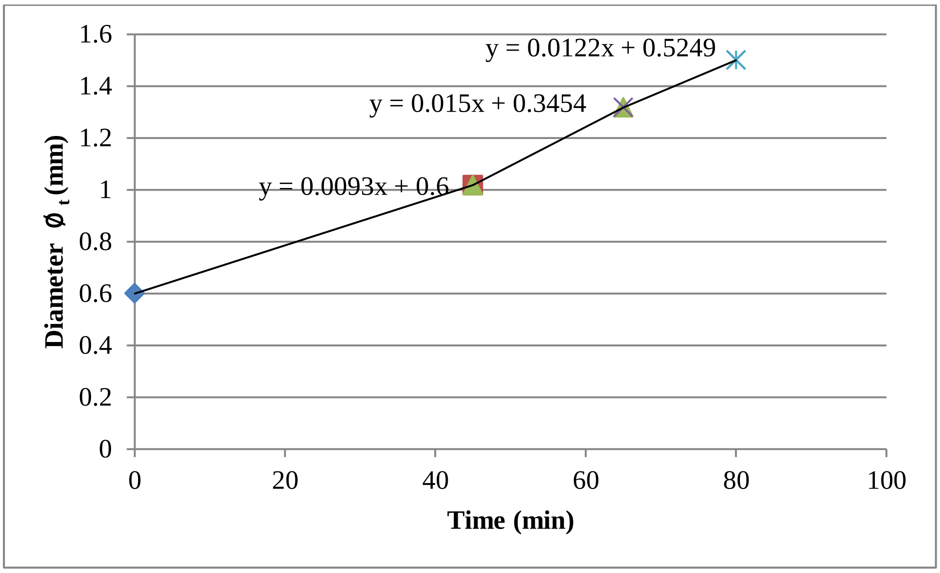

Figure 4.2: Sand soil: (sample: 3% Cement, 7 Days Curing) - Hole diameter results

Table 4.5 presents the shear stress and the erosion rate per unit area data. By plotting the obtained values, as shown in Figure 4.3, the slope of the best fit line presents the Coefficient of soil Erosion (C_e) which is used to calculate the erosion rate index.

Table 4.5: HET results- critical shear stress and erosion rate

Critical Shear Stress – T_{HET} (N/m^2)	152.07	258.05	333.83	380.17
Erosion Rate per Unit Area ε_{HET} ($Kg/s/m^2$)	0	0.0047	0.0077	0.0062

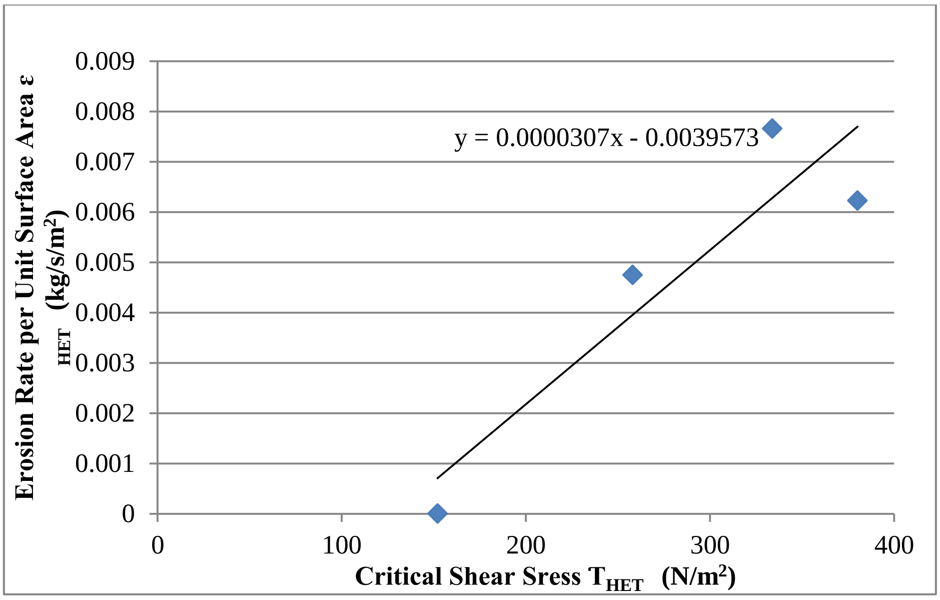

Figure 4.3: Typical results of the Hole Erosion Test (sample: 3% cement, 7 days curing)

4.2 Stabilization of Sandy Soil against Internal Erosion using Cement

The sand soil was prepared as mentioned earlier and tested against internal erosion. Test samples contained different percentages of cement at 1%, 2%, 3%, 4% and 5% by the dry weight of the sand. All prepared samples were sealed for 2 and 7 days to ensure the distribution of water content within the soil and cement mix and to allow enough time for the cement to cure. The following section presents the final data collected during the test for samples with (2%, 3%, and 4%) cement, while the sample that contains (1%) cement was extremely erodible and there was not enough data to be subjected to calculations. Also, for the samples that contained (5%) cement, the flow data were approximately constant throughout the test (2 hours of flow through the hole), and therefore no change in diameter and thus no erosion was observed.

4.2.1 Impact of Cement on Shear Stress and Diameter

In this study, it is investigated whether cement is an influencing factor on soil stabilization. The experiments on sandy soils included the addition of three different percentages of cement to the sandy samples (2%, 3%, and 4%). Shear stresses and hole diameters were computed for different treatments of sandy soils mixed with cements at 2 and 7 days curing. Also, a graph depicting relationship between these two variables under different conditions was drawn**.**

Figure 4.4 and Figure 4.5 show how soil treatments by adding cement influence the values of critical shear stress and final diameter, as stated earlier (Ø = 0.6). In Figure 4.4 it is obvious that the increase of the percentages of cement in sands lead to a significant reduction in the final diameter progressed due to internal erosion. The diameter decreased from 3.4 cm at 2 % cement and 2 days curing to 0.62 cm at 4% cement and 7 days curing. The total reduction in diameter for this specific amount of cement and curing time is equal to 77%. This is considered as a significant reduction in diameter.

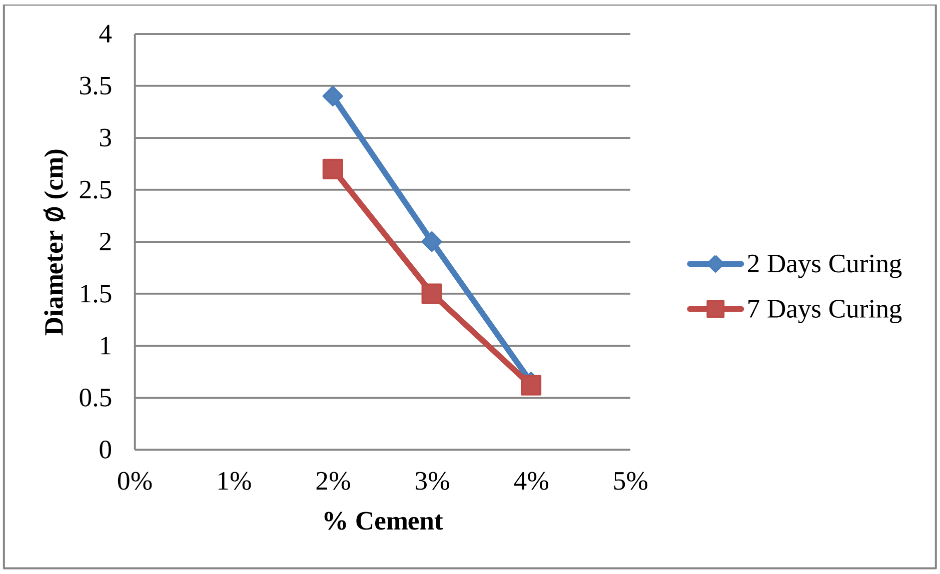

Figure 4.4: HET results (effect of % cement on diameter)

Also, the increase in cement content led to a significant increase in the shear stress of the stabilized sample. Figure 4.5 shows that the critical shear stress increased from 38.08 N/m^2 to 151.39 N/m^2 for the same previously mentioned percentages and curing times. The amount of increase in the shear stress was around 75%.

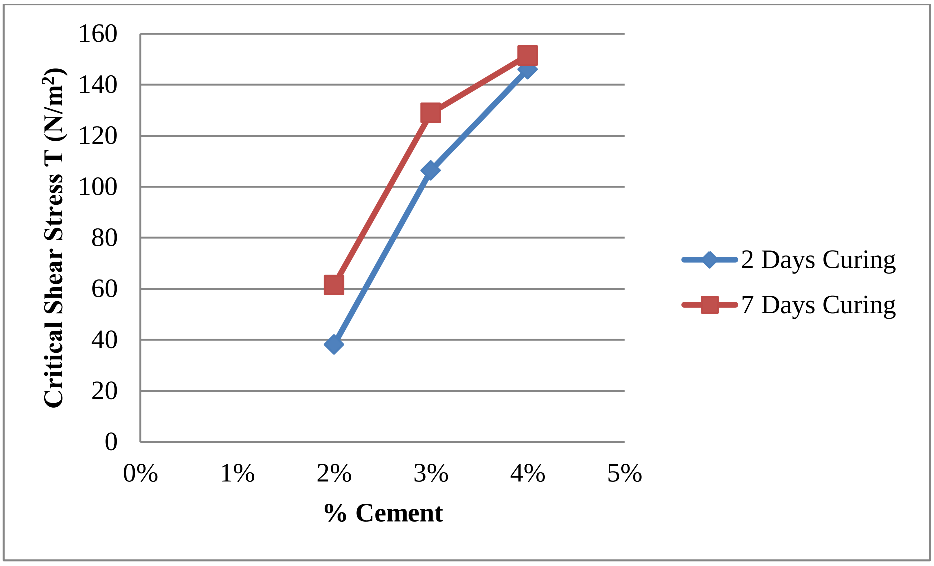

Figure 4.5: HET results (effect of % cement on critical shear stress)

4.2.2 Effect of Curing Time on Shear Stress and Diameter

As mentioned before, the samples used in the experimental testing program were sealed for 2 and 7 days to ensure distribution of the water content in the soil specimens and to provide enough time for cement to cure. The indications of shear stress and diameter were observed under the two times of curing specified in this study. Also, investigation of relationship between the amount of cement added and curing time was performed. Three different figures were obtained to investigate the relationships among cement amount, curing time, shear stress, and diameters.

Figure 4.6 and Figure 4.7 show that at low percentages of cement, the curing time affected the diameter and critical shear stress values while at high percentages of cement the curing time have small or no effect on the shear stress and diameter values.

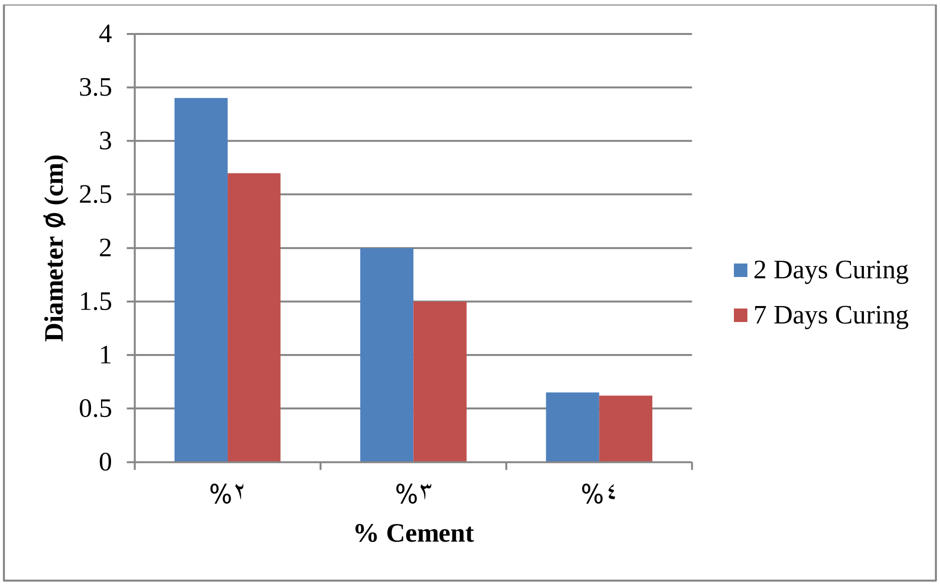

Figure 4.6: HET results (effect of curing time on sample diameter for every % of cement)

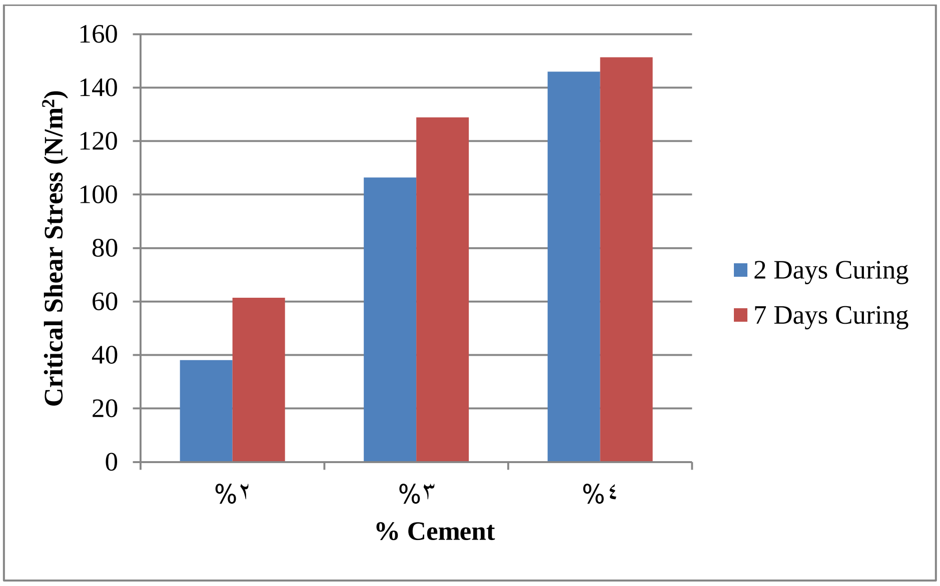

Figure 4.7: HET results (effect of curing time on shear stress)

Figure 4.8 shows the effect of curing time on the percent reduction in diameter due the addition of cement between two curing time intervals. The reduction decreased by 22% and 25% when the curing time increased from 2 days to 7 days at 2% and 3% of cement respectively. While, the reduction in diameter due to curing time at 4% cement was just 5 %.

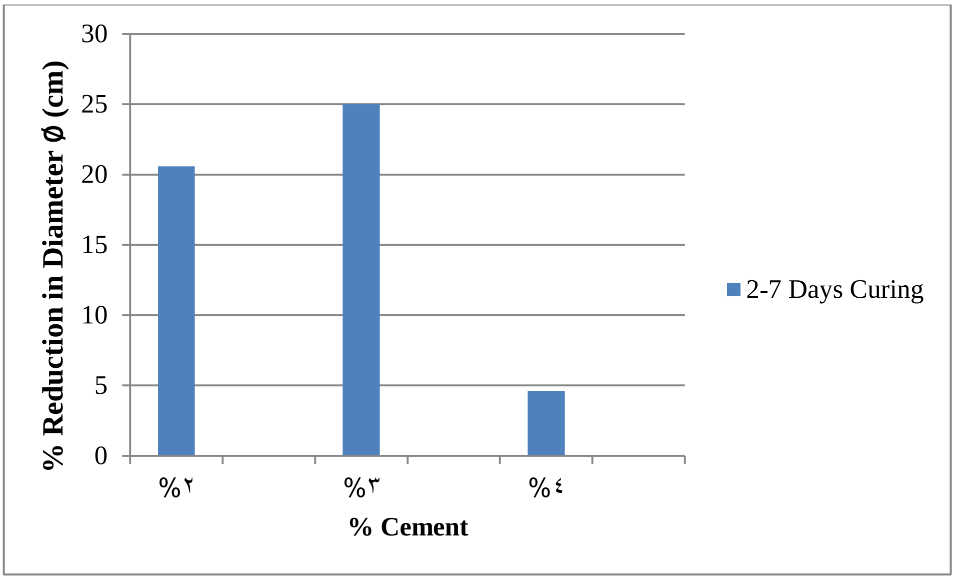

Figure 4.8: Reduction in hole diameter due to curing time

It was noticed that there was no change in diameter of the samples stabilized with 5% cement. This concludes that the curing time has no effect on sand erosion when sand is mixed with 5% cement or higher.

4.2.3 Effect of Cement and Curing Time on Erosion Rate Index

Erosion rate index is an important variable for testing soil stabilization. It is an indicator for the resistance of soil to erosion. In this study, this variable was observed under the impact of cement amounts and curing times. Wan and Fell [17] introduced in Table 2.3, showing the way to interpret the erosion rate index and its value varies from 0-6, indicating high erosion rate at 1 and slow erosion rate (high resistance to erosion) at 6.

Figure 4.9 summarize the effect of the addition of cement on the erosion rate index with respect to the final diameter change of the tested samples. It is clear that the increase in cement percentages gave a higher erosion index and a lower final diameter.

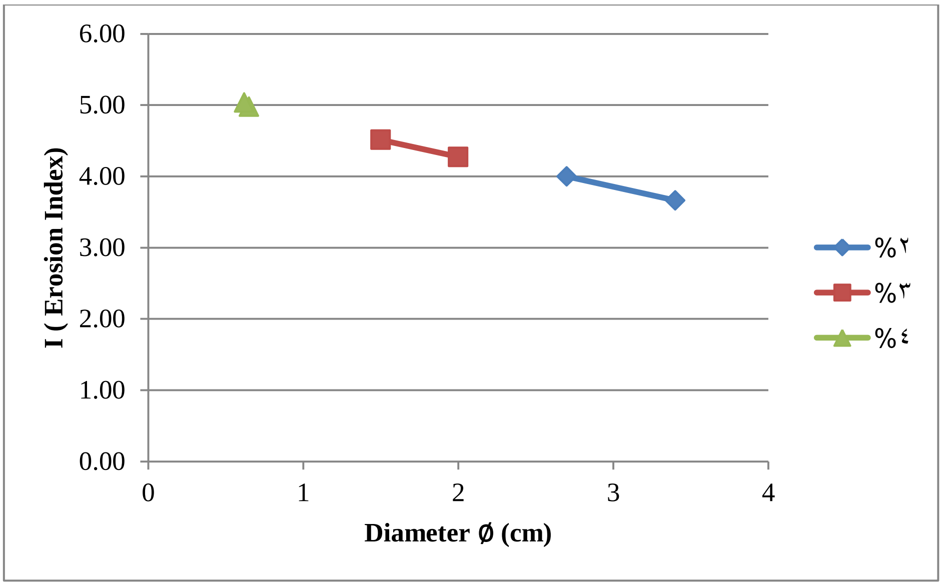

Figure 4.9: Effect of cement addition on the erosion index

Figure 4.10 and Figure 4.11 show how the variable of curing time influences erosion rate index and diameter. A summary of the relations in Figure 4.10 and Figure 4.11 is shown in Figure 4.12. This figure clearly shows that the increase in the percentages of cement content in the sand lead to increase the erosion rate index. The erosion index increased from 3.66 at 2% cement, 2 days curing to 5.04 at 4% cement, 7 days curing. This value of erosion rate index equal to 5.04 at 4% cement and 7 days curing time. This means that the soil is classified as a very slow eroded soil. Therefore, this implies again that 4% of cement at 7 days curing time will stabilize the soil against erosion. However, when an amount of 5% cement was added to the sand and tested against erosion at 2 days and 7 days curing time, it was noticed that the there was no change in diameter over 4 hours testing time, which results in an extremely slow eroded type of soil and as a result stabilize the soil against internal erosion.

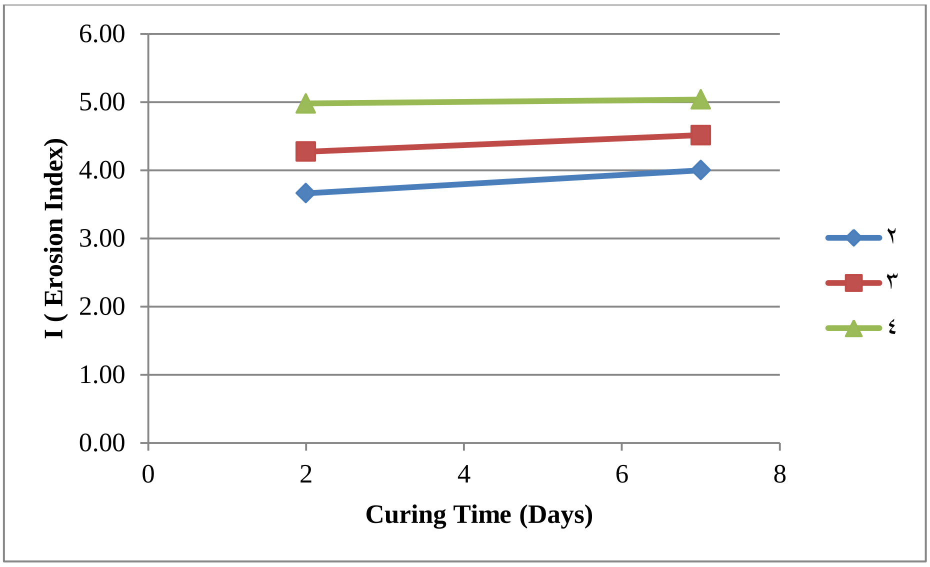

Figure 4.10: Effect of curing time on erosion rate index

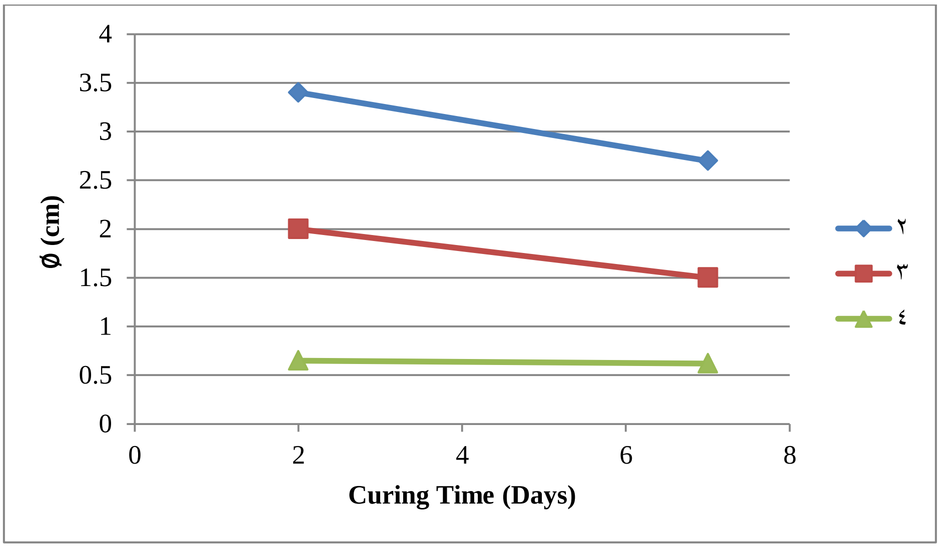

Figure 4.11: Effect of curing time on diameter

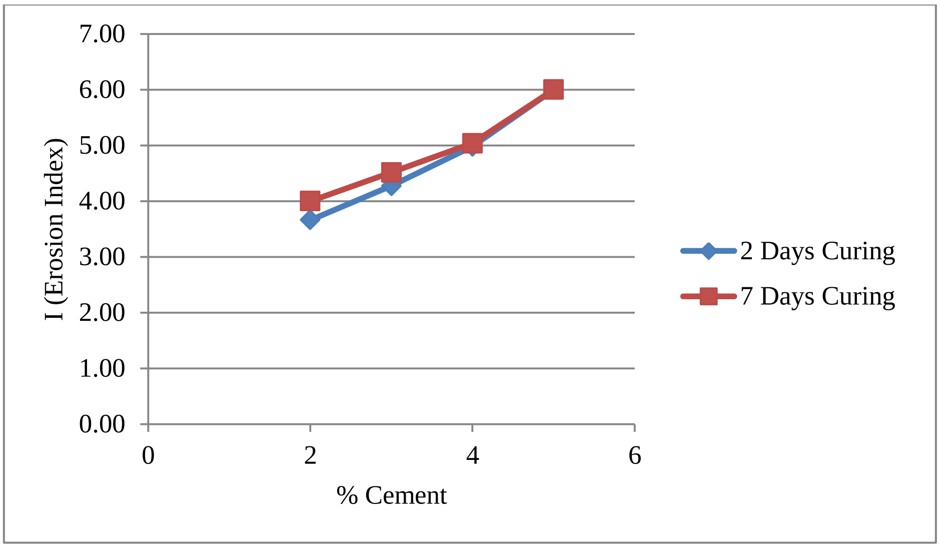

Figure 4.12: Effect of the addition of cement to sand on erosion index

In Table 4.6, the erosion indices are presented along with the descriptions of the internal erosion behavior accordingly. Additionally, the diameters of the predrilled hole after progressing due to the internal erosion, is recorded along with the critical wall shear stress at which erosion is initiated.

Table 4.6: Experimental data on erosion indices for sandy soil samples

%Cement	Curing Days	I (Erosion Rate Index)	Description	Diameter Ø (cm)	Critical Shear Stress T (N/m^2)
2%	2 Days	3.66	Moderately Rapid	3.40	38.07
	7 Days	4.00	Moderately Rapid	2.70	61.40
3%	2 Days	4.27	Moderately Slow	2.00	106.35
	7 Days	4.51	Moderately Slow	1.50	128.90
4%	2 Days	4.98	Moderately Slow	0.65	145.91
	7 Days	5.04	Very Slow	0.62	151.39

4.3 Stabilization of Clayey Soil against Internal Erosion Using Fiber-Cement Mix

In this study, clay is another type of soil under investigation, and fiber-cement is another type of effective additive. It is assumed that fiber-cement is an influencing factor on soil stabilization. The investigation was conducted on clay soil treated at 5:1 cement to fibers ratio and at different percentages (0.25%, 0.5%, 1%, 2% and 3%).

The different HET parameters were measured such as shear stress, diameters, erosion rate index and curing time.

4.3.1 Impact of Fiber-Cement on Shear Stress and Diameter

The experiments on clayey soils included addition of different percentages of fiber-cement to the clayey samples (0.25%, 0.5%, 1%, 2% and 3%). Shear stresses and hole diameters were computed for different specimens of clayey soils mixed with fiber-cements at 2 and 7 days curing. Also, graphs depicting relationship between these two variables under different conditions were drawn.

Figure 4.13 and Figure 4.14 show how the fiber-cement influences the relation between shear stress and final diameter due to erosion. In Figure 4.13, the increase in the percentages of fiber-cement in clayey soils lead to a significant reduction in the final diameter progressed due to internal erosion. The diameter decreased from 3 cm at 0.25 % cement and 2 days curing to 0.62 cm at 3% cement and 7 days curing. The total reduction in diameter for this specific amount of fiber- cement and curing time was equal to 80%. This is considered as a significant reduction in diameter.

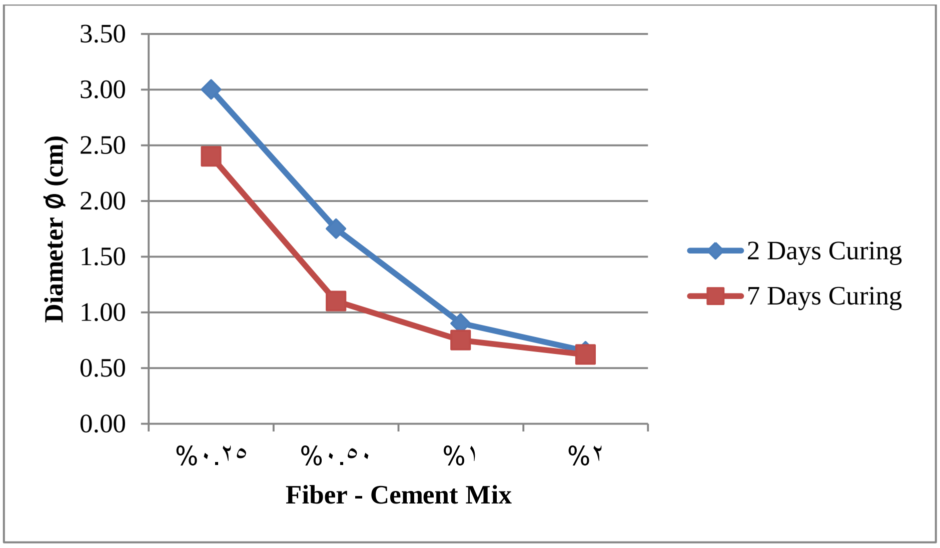

Figure 4.13: HET results (effect of % fiber-cement on diameter)

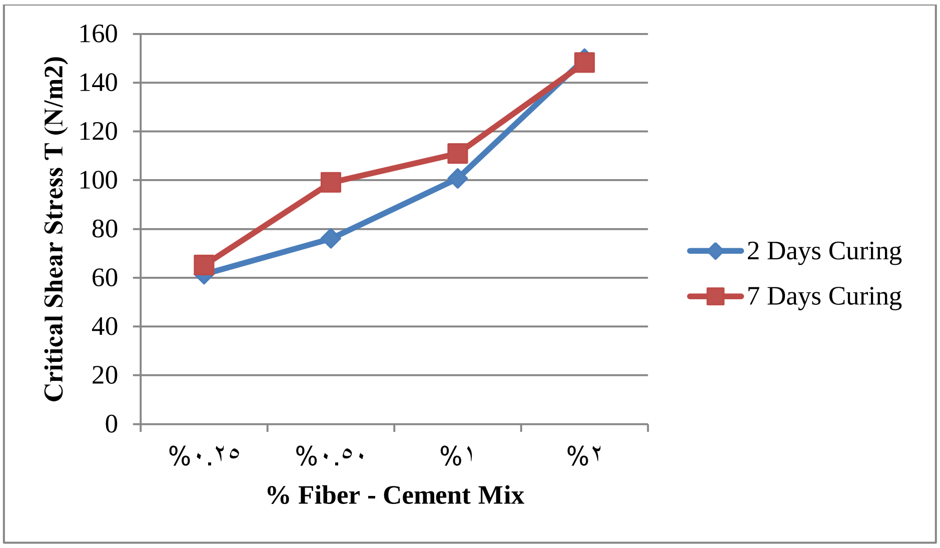

Figure 4.14: HET results (effect of % fiber-cement on critical shear stress)

Also, the addition of fiber-cement to clayey soils lead to a significant increase in the shear stress of the stabilized sample, see Figure 4.14. The critical shear stress increased from 61.40 N/m^2 to 148.15 N/m^2 for the same previously mentioned percentages and curing times with diameters. That caused an increase in the critical shear stress around 58%.

4.3.2 Effect of curing time on shear stress and diameter

Figure 4.15 and Figure 4.16 show that at low percentages of fiber-cement mix.

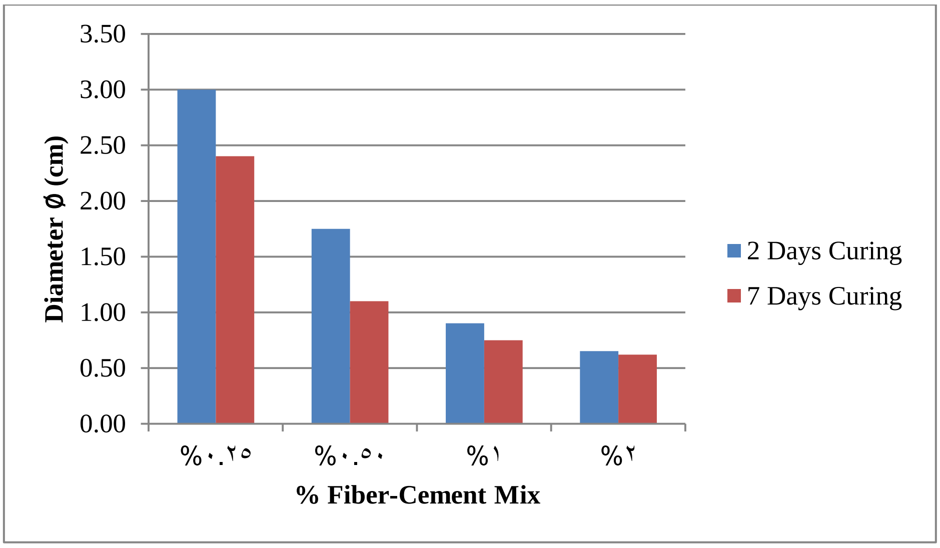

Figure 4.15: HET results (effect of curing time on sample diameter)

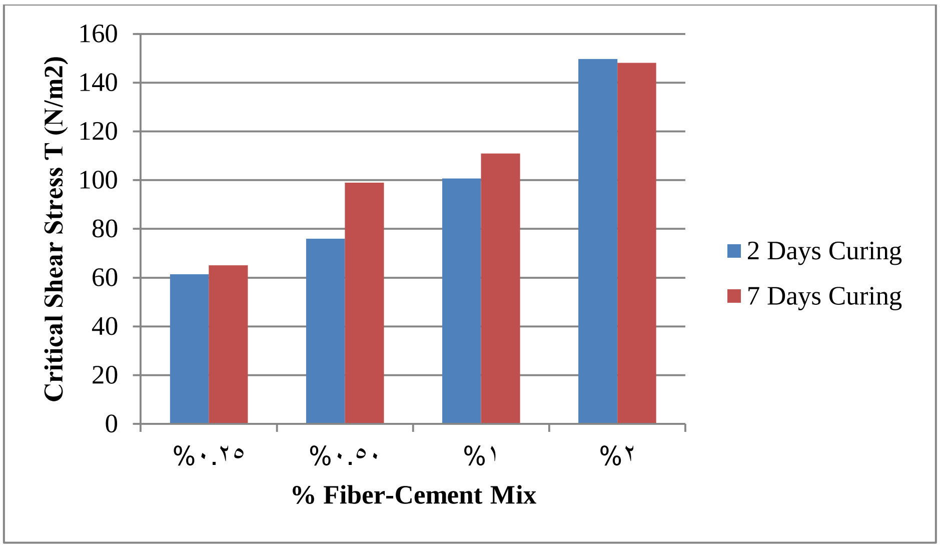

Figure 4.16: HET results (effect of curing time on sample critical shear stress)

As shown above in Figure 4.15 and Figure 4.16 the curing time affected the diameter and shear stress values of soil samples, while at high percentages of fiber-cement the curing time had small or no effect on the shear stress and diameter values.

Figure 4.17 depicts the effect of curing time on the reduction by percent of the diameter due to the addition of the additives. The figure shows the percent reduction between 2 to 7 days curing time. The reduction was decreased by 20%, 37%, and 17% when the curing time increased from 2 days to 7 days at 0.25%, 0.5%, and 1% fiber-cement respectively. While, the reduction in diameter due to curing time at 2% cement was just 5 %.

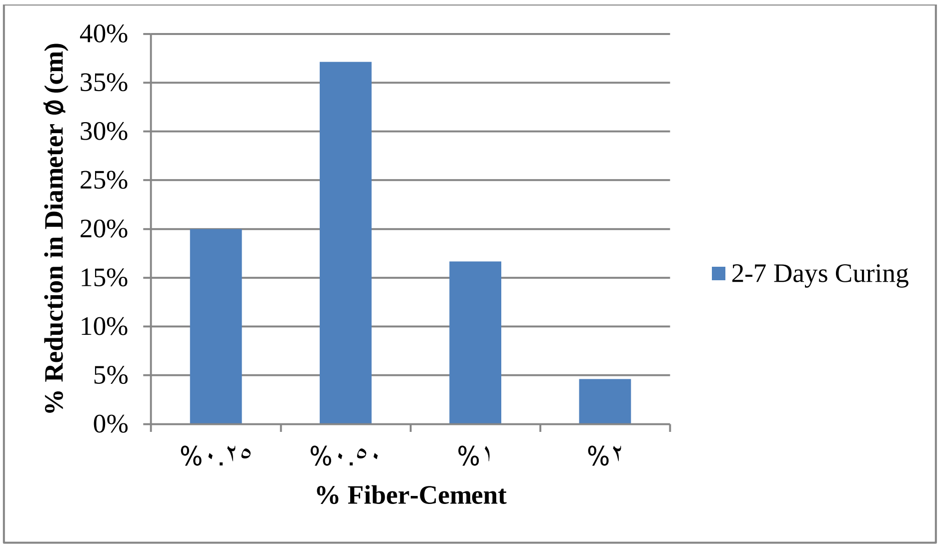

Figure 4.17: Reduction in hole diameter due to curing time

It was also noticed that there was no change in diameter of the samples stabilized with 3% fiber-cement. This demonstrates that the curing time has no effect on clay erosion when sand is mixed with 3% fiber-cement or higher.

4.3.3 Effect of cement and curing time on erosion rate index

Figure 4.18 summarizes the effect of the addition of cement on the erosion index with respect to final diameter change of the tested samples. It is clear that the increase in cement percentages gave a higher erosion rate index and a lower final diameter.

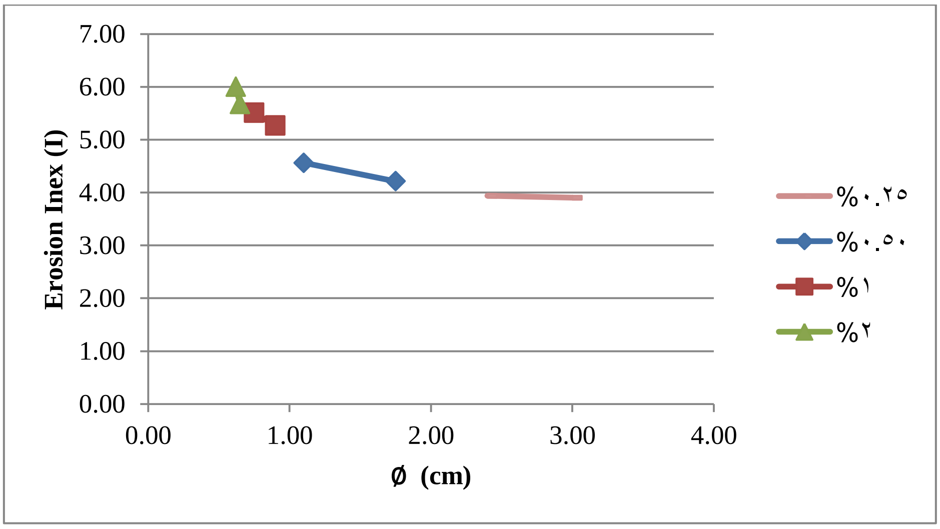

Figure 4.18: HET results - relation between change in erosion index and diameter

Figure 4.19 and Figure 4.20 display the effect of curing time on the erosion rate index and diameter after mixing fiber-cement materials with clay soils. The summary of the two figures is shown in Figure 4.21. This figure clearly shows that the increase in the percentages of fiber-cement content in the clay causes an increase in the erosion rate index. The erosion rate index increased from 3.903 at 0.25% fiber-cement, 2 days curing to 6 at 2% fiber-cement, 7 days curing. This value of erosion index means that the tested soil is classified as a very slow eroded soil.

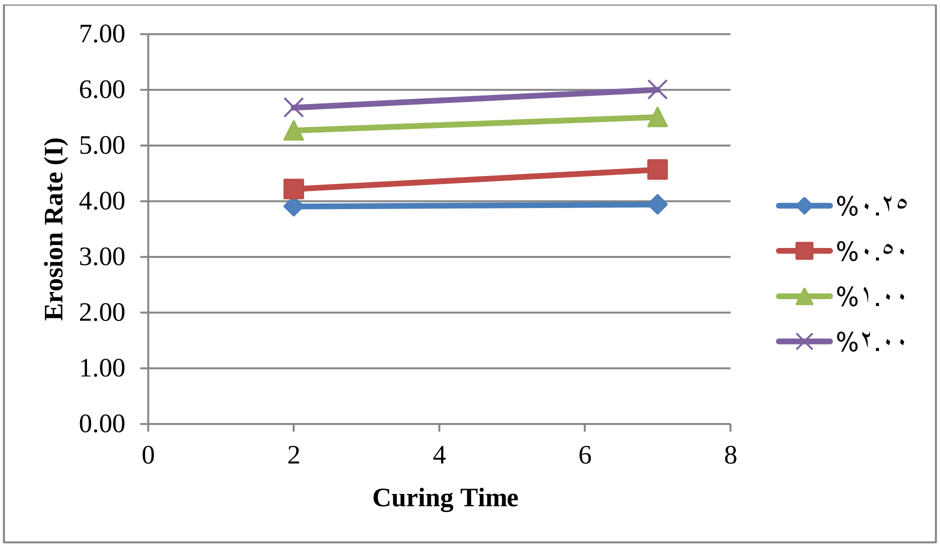

Figure 4.19: Effect of curing time on erosion index (I)

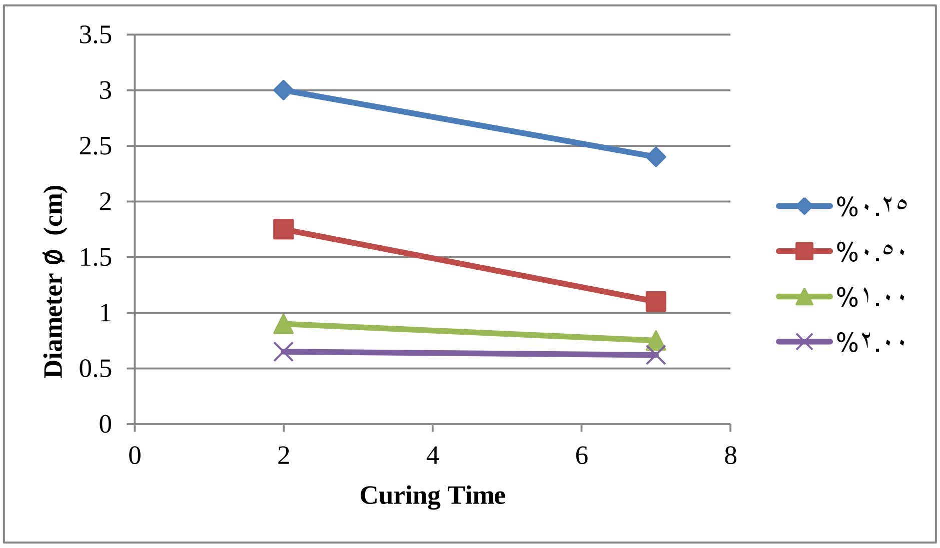

Figure 4.20: Effect of curing time on diameter Ø (cm)

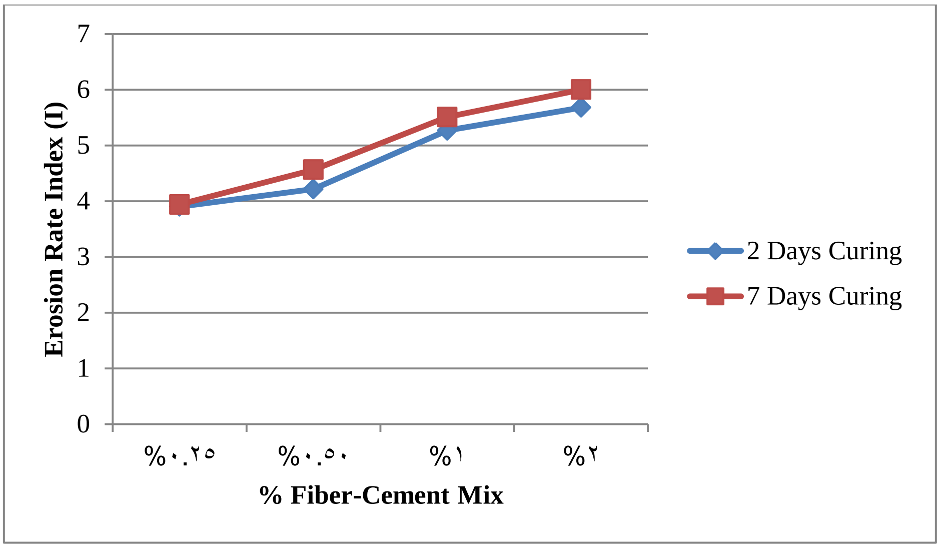

Figure 4.21: Effect of the addition of fiber-cement to clay on erosion rate index

In Table 4.7 the erosion indices are presented along with the descriptions of the internal erosion behavior accordingly. Additionally the diameters of the predrilled hole after progressing due to the internal erosion are recorded along with the critical wall shear stress at which erosion is initiated.

Table 4.7: Experimental data on erosion indices for clayey soil samples

% Cement - Fiber Mix	Curing Days	I (Erosion Rate Index)	Description	Diameter Ø (cm)	Critical Shear Stress T (N/m^2)
0.25%	2 Days	3.90	Moderately Rapid	3.00	61.40
	7 Days	3.94	Moderately Rapid	2.40	65.11
0.50%	2 Days	4.22	Moderately Slow	1.75	76.05
	7 Days	4.56	Moderately Slow	1.10	99.02
1%	2 Days	5.27	Very Slow	0.90	100.67
	7 Days	5.51	Very Slow	0.75	110.90
2%	2 Days	5.68	Very Slow	0.65	149.71
	7 Days	6.00	Extremely Slow	0.62	148.16

Chapter 5 Conclusions and Recommendations

A comprehensive experimental testing program was conducted to study the stabilization of soils against erosion. The Hole Erosion Test (HET) was employed to achieve the object of this research and two types of soils (sand and clay) were used in this investigation.

Additionally, cement and cement-fiber mixtures were used as stabilizing agents for soil against internal erosion.

The main objectives of this study were:

1. To provide a better understanding of erosion behavior and stabilization of sandy soils with cement.
2. To provide a better understanding of erosion behavior and stabilization of clayey materials with fiber- cement mixture.

Erosion behavior of soils were discussed in terms of two different types of stabilization including addition of only cement to sandy soils using different percentages (2%, 3%, and 4%) and addition of different percentages of fiber-cement (0.25%, 0.5%, 1%, 2% and 3%) from the dry weight of the clay. The Hole Erosion Tests (HET) results on sandy soil samples treated with cement yielded the following conclusions:

1. The increase of the percentages of cement in sand leads to a significant reduction in the final diameter due to internal erosion and a significant increase in the shear stress of the stabilized sample.
2. For soils mixed with low percentages of cement, the curing time affects the diameter and shear stress values while for the samples that are mixed with high percentages of cement the curing time has small to no effect on the shear stress and diameter values. The curing time causes no effect on sand erosion when sand is mixed with 5% cement or higher.
3. An increase in the cement content in the sand increases the erosion rate index. Through this research it is found that 4% of cement in sand can significantly stabilize the soil against erosion.

The Hole Erosion Tests (HET) on clayey soil samples treated with cement fiber mixture yielded the following conclusions:

1. Increase in the percentages of fiber-cement in clay leads to a significant reduction in the final diameter due to internal erosion, as well as a significant increase in the shear stress of the stabilized sample.
2. At low percentages of fiber-cement mix, the curing time affect the diameter and shear stress values, while at high percentages of fiber-cement the curing time has little to no effect on the shear stress and diameter values. Curing time has no effect on clay erosion when soil is mixed with 2% fiber-cement or higher.
3. The increase in fiber-cement percentages will give a higher erosion rate index and lower final diameter.
4. By adding 1% of fiber cement mix, and cure the sample for 2 days, the clayey soil is stabilized against erosion and the erosion rate index result is 5.148.

Based on the study results, further research is recommended in the area of soil stabilization. The following is recommendations for future research may be investigated:

1. Study the effect of using available and economical materials to stabilize the soil against erosion, such as, limestone, cutting stone slurry and fly ash and other materials that has been used effectively in soil stabilization.
2. Study the effect of solid waste materials, such as sludge ash, and shredded rubber on stabilizing the soil against erosion.
3. Study the effect of different soil physical parameters such as, the angle of internal Friction (∅), Cohesion (C), the Liquid Limit, and the Plasticity Index on the internal erosion behavior of soil.

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Appendix

The following section contains the records and analysis detailed in section 3.2. For each Hole Erosion Test conducted throughout this research, an evaluation of internal erosion rate for sand and clay soil stabilized using different percentage of admixtures is presented in the following appendix.

Test No: 01	
Type of Soil: Sand	**Curing Time:** 2 Days
Admixture: Cement	**Percent of Admixture:** 2%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.67 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.70 g/cm^3
Hydraulic Water Head (s_t): 6.034	

Test Results - Water Flow					
Test Time (t) (sec)	0	10	20	25	30
Volume (cm^3)	100	135	270	300	450
Time (sec)	1.5	2	2	1.5	1.5
Flow (Q_t) (cm^3/sec)	66.67	67.5	135	200	300

Calculated Friction Factor	
t= 0	**F_{L0} = 0.01594** (g/cm^2/s)
t= 30	**F_{Lt} = 3.725483** (g/cm^2/s)

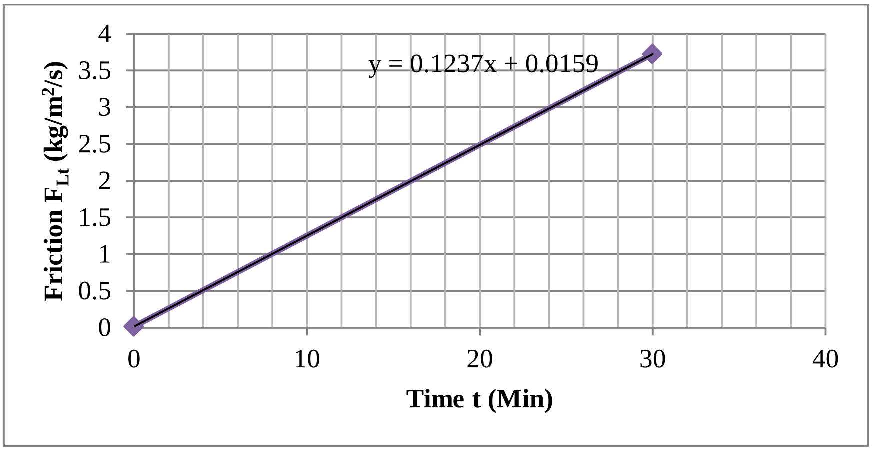

Figure A-1: Test 1 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t					
t (sec)	**0**	**10**	**20**	**25**	**30**
F_{Lt} ($g/cm^2/s$)	0.016	1.250	2.500	3.200	3.7253
$Ø_t$ (cm)	0.6	1.44	2.19	2.69	3.4

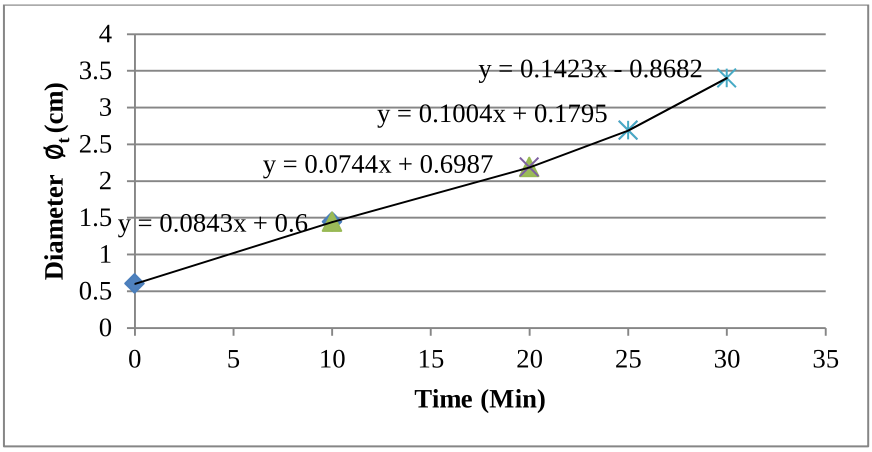

Figure A-2 Test 1 - Hole Diameter Results

Critical Shear Stress and Erosion Rate					
t (sec)	0	10	20	25	30
dØ /dt (cm/sec)	0	5.058	4.464	6.024	8.538
T_t (N/m^2)	88.71	213.30	323.31	397.50	502.67
ε_t ($Kg/s/m^2$)	0	0.0430523	0.037996	0.0512746	0.072673

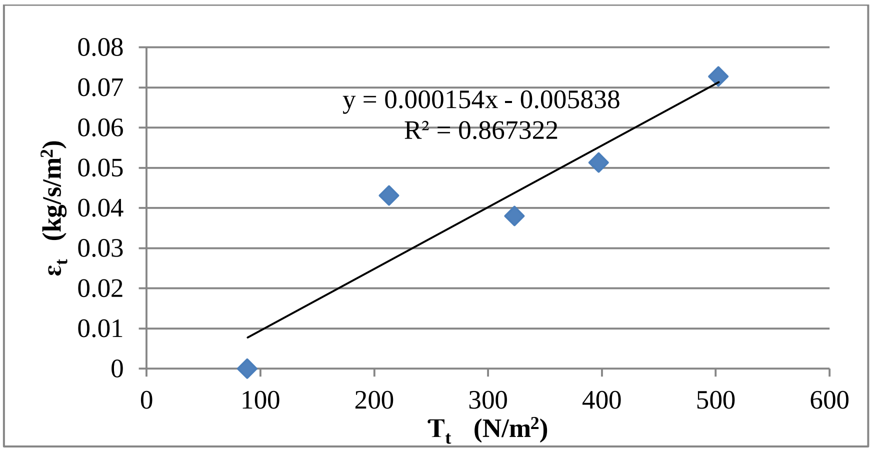

Figure A-3 Test 1 - Typical Results of Hole Erosion Test

T_c (N/m^2)	38.08
Ce	0.000218
I	3.66
Moderately Rapid Erosion	

Test No: 02	
Type of Soil: Sand	**Curing Time:** 7 Days
Admixture: Cement	**Percent of Admixture:** 2%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.67 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.70 g/cm^3
Hydraulic Water Head (s_t): 5.172	

Test Results - Water Flow					
Test Time (t) (sec)	0	10	20	30	40
Volume (cm^3)	222	275	400	370	400
Time (sec)	3.5	4.0	3.5	2.5	2.0
Flow (Q_t) (cm^3/sec)	63.43	68.75	114.28	148.00	200.00

Calculated Friction Factor	
t= 0	**F_{L0} = 0.015093329** (g/cm^2/s)
t= 40	**F_{Lt} = 2.801286243** (g/cm^2/s)

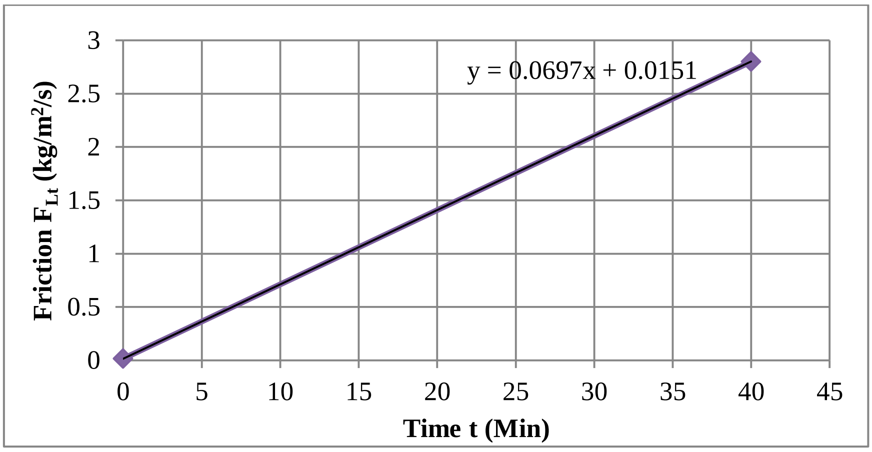

Figure A-4 - Test 2- Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t					
t (sec)	**0**	**10**	**20**	**30**	**40**
F_{Lt} (g/cm^2/s)	0.015	0.650	1.450	2.100	2.801
$\emptyset_t$ (cm)	0.60	1.32	1.89	2.26	2.70

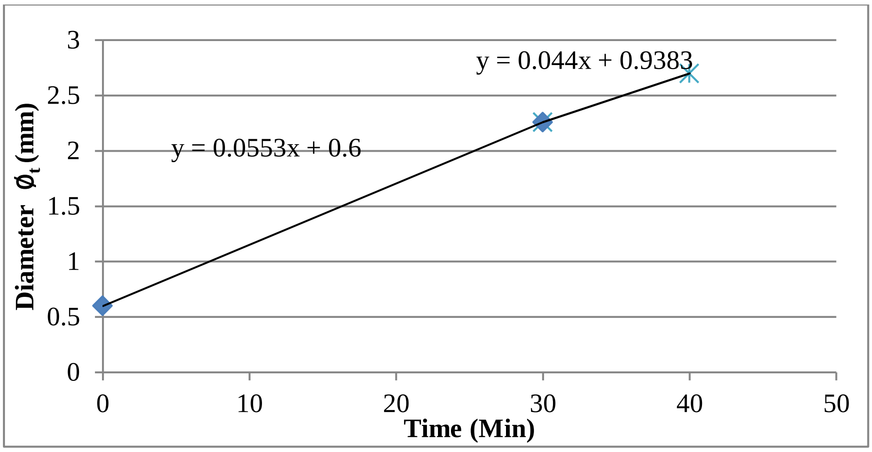

Figure A-5 - Test 2 - Hole Diameter Results

Critical Shear Stress and Erosion Rate					
t (sec)	0	10	20	30	40
dØ /dt (cm/sec)	0	3.32	3.32	3.32	2.64
T_t (N/m^2)	76.03	166.66	239.78	286.34	342.16
ε_t (Kg/s/m^2)	0	0.0282	0.0282	0.02824	0.0225

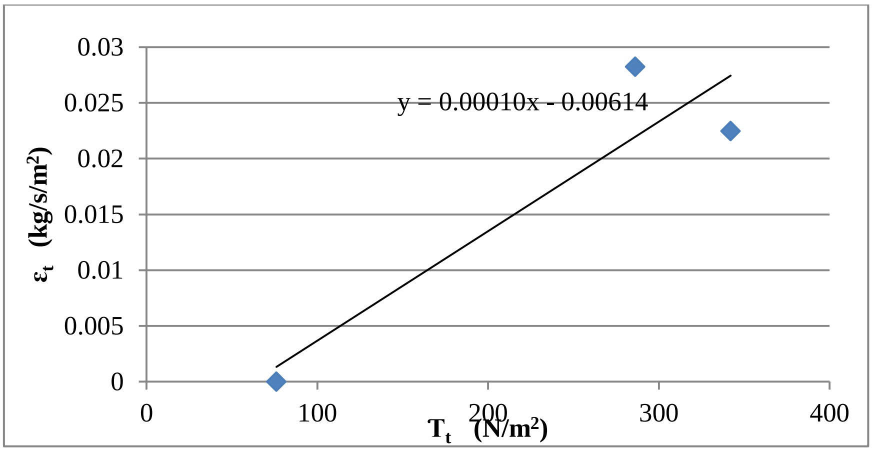

Figure A-6 - Test 2 - Typical Results of Hole Erosion Test

T_c (N/m^2)	61.4
Ce	0.0001
I	4
Moderately Rapid Erosion	

Test No: 03	
Type of Soil: Sand	**Curing Time:** 2 Days
Admixture: Cement	**Percent of Admixture:** 3%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.67 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.70 g/cm^3
Hydraulic Water Head (s_t): 8.621	

Test Results - Water Flow					
Test Time (t) (sec)	0	25	40	55	70
Volume (cm^3)	200	333	380	417	500
Time (sec)	4	3.7	3.3	2.3	1.5
Flow (Q_t) (cm^3/sec)	50	90	115.15	181.30	333.33

Calculated Friction Factor	
t= 0	**F_{L0} = 0.040482** (g/cm^2/s)
t= 70	**F_{Lt} = 0.374835** (g/cm^2/s)

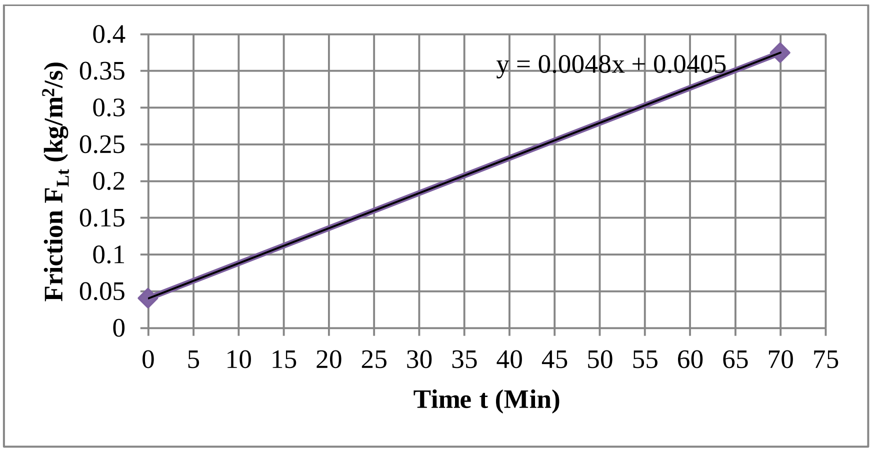

Figure A-7 - Test 3- Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t					
t (sec)	**0**	**25**	**40**	**55**	**70**
F_{Lt} (g/cm^2/s)	0.0405	0.150	0.240	0.300	0.375
$\emptyset_t$ (cm)	0.60	0.99	1.20	1.50	2.00

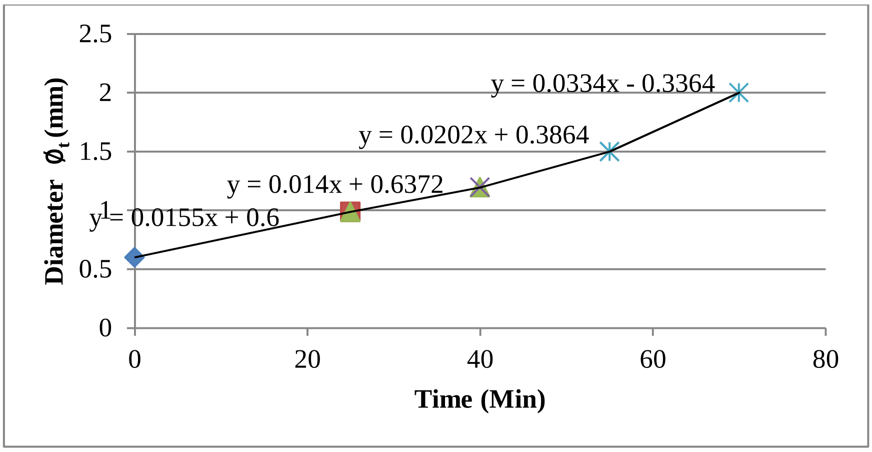

Figure A-8 - Test 3 - Hole Diameter Results

Critical Shear Stress and Erosion Rate					
t (sec)	0	25	40	55	70
dØ /dt (cm/sec)	0	0.93	0.84	1.21	2.00
T_t (N/m^2)	126.72	208.32	252.56	316.67	422.41
ε_t ($Kg/s/m^2$)	0	0.008	0.007	0.010	0.020

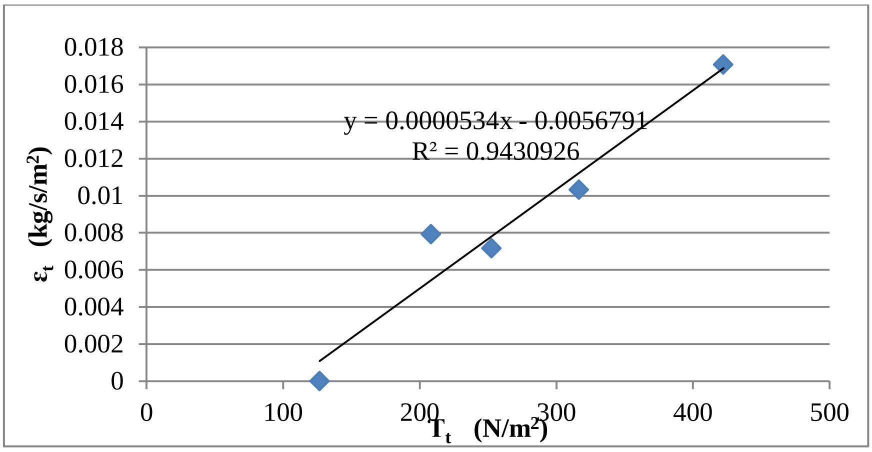

Figure A-9 Test 3 - Typical Results of Hole Erosion Test

T_c (N/m^2)	106.35
Ce	0.000053
I	4.27
Moderately Slow Erosion	

Test No: 04	
Type of Soil: Sand	**Curing Time:** 7 Days
Admixture: Cement	**Percent of Admixture:** 3%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.67 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.70 g/cm^3
Hydraulic Water Head (s_t): 10.34	

Test Results - Water Flow				
Test Time (t) (sec)	0	45	65	80
Volume (cm^3)	185	271	420	450
Time (sec)	4.00	3.65	3.50	3.00
Flow (Q_t) (cm^3/sec)	46.25	74.25	120.00	150.00

Calculated Friction Factor	
t= 0	**F_{L0} = 0.056775561** (g/cm^2/s)
t= 80	**F_{Lt} = 0.527111428** (g/cm^2/s)

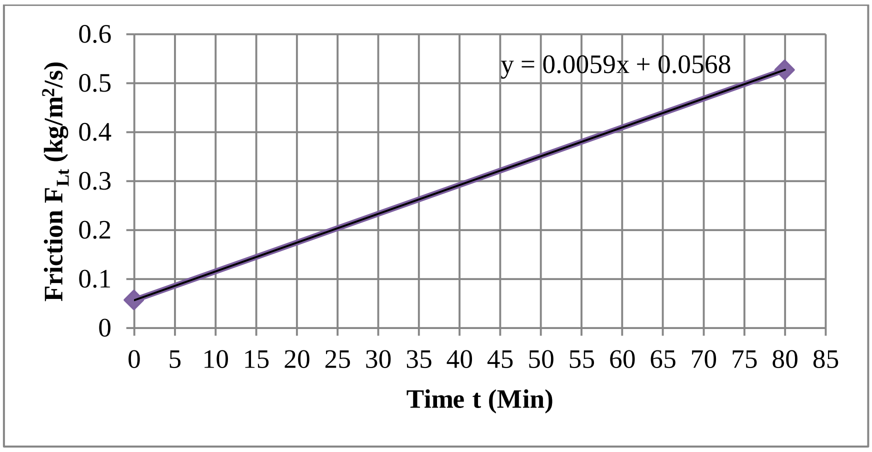

Figure A-10 - Test 4 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t				
t (sec)	**0**	**45**	**65**	**80**
F_{Lt} (g/cm^2/s)	0.056775561	0.31	0.43	0.527111428
$\emptyset_t$ (cm)	0.6	1.02	1.32	1.50

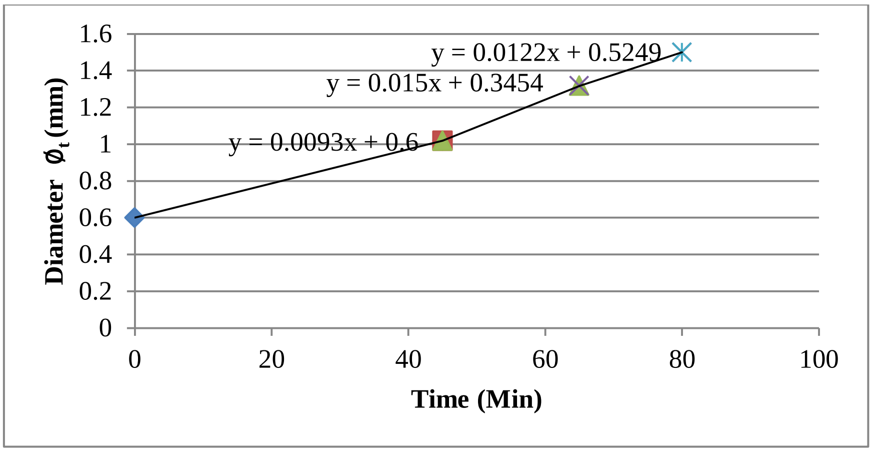

Figure A-11 - Test 4 - Hole Diameter Results

Critical Shear Stress and Erosion Rate				
t (sec)	0	45	65	80
dØ /dt (cm/sec)	0	0.93	0.84	1.21
T_t (N/m^2)	152.07	258.05	333.83	380.17
ε_t (Kg/s/m^2)	0	0.0047	0.0077	0.0062

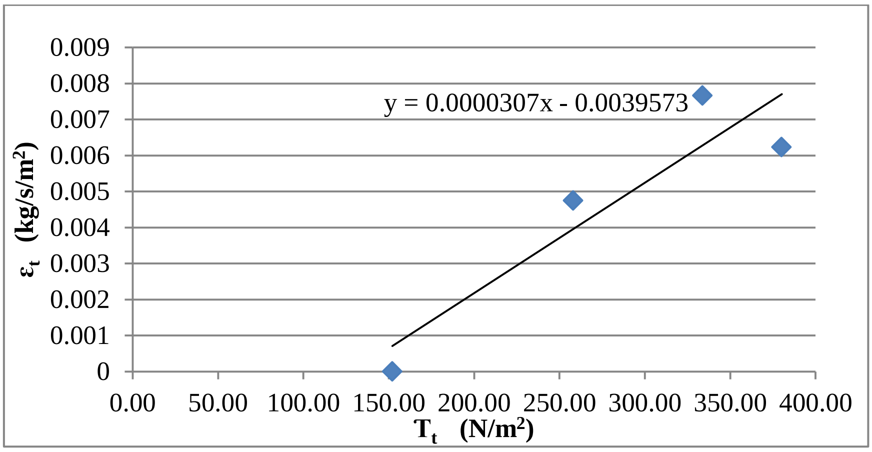

Figure A-12 Test 4 - Typical Results of Hole Erosion Test

T_c (N/m^2)	128.9
Ce	0.0000307
I	4.51
Moderately Slow Erosion	

Test No: 05	
Type of Soil: Sand	**Curing Time:** 2 Days
Admixture: Cement	**Percent of Admixture:** 4%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.67 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.70 g/cm^3
Hydraulic Water Head (s_t): 9.914	

Test Results - Water Flow					
Test Time (t) (sec)	0	160	180	190	200
Volume (cm^3)	185	185	185	185	185
Time (sec)	5	5	5	5	5
Flow (Q_t) (cm^3/sec)	37	37	37	37	37

Calculated Friction Factor	
t= 0	**F_{L0} = 0.0850155** (g/cm^2/s)
t= 200	**F_{Lt} = 0.1268553** (g/cm^2/s)

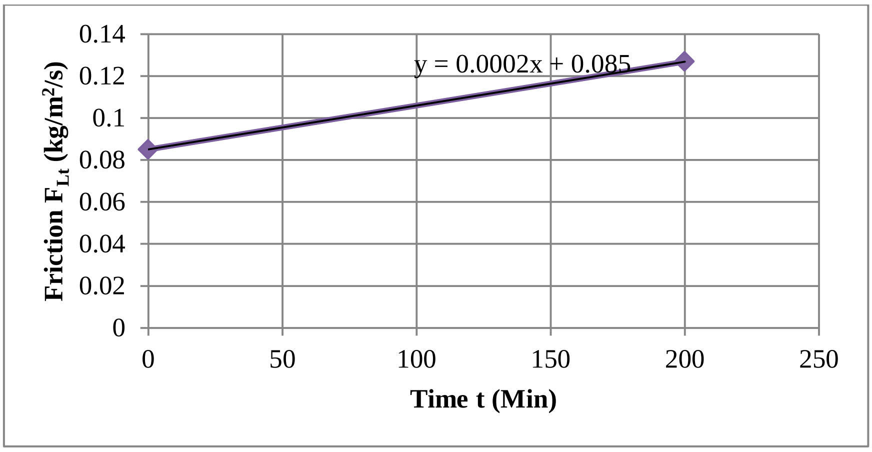

Figure A-13 - Test 5 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t					
t (sec)	**0**	**160**	**180**	**190**	**200**
F_{Lt} (g/cm^2/s)	0.085	0.120	0.122	0.125	0.127
$\emptyset_t$ (cm)	0.6	0.64	0.645	0.648	0.650

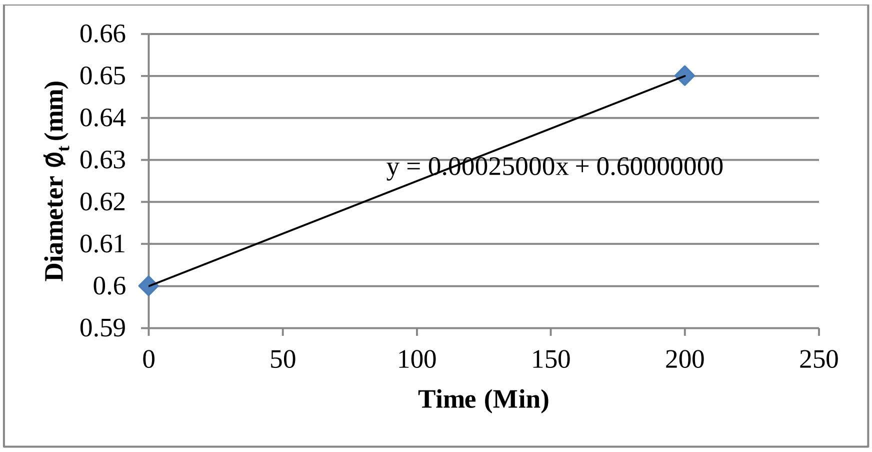

Figure A-14 - Test 5 - Hole Diameter Results

Critical Shear Stress and Erosion Rate					
t (sec)	0	160	180	190	200
dØ /dt (cm/sec)	0	0.015	0.015	0.015	0.015
T_t (N/m^2)	145.73	156.13	156.65	157.41	157.88
ε_t (Kg/s/m^2)	0	0.000128	0.000128	0.0001258	0.000128

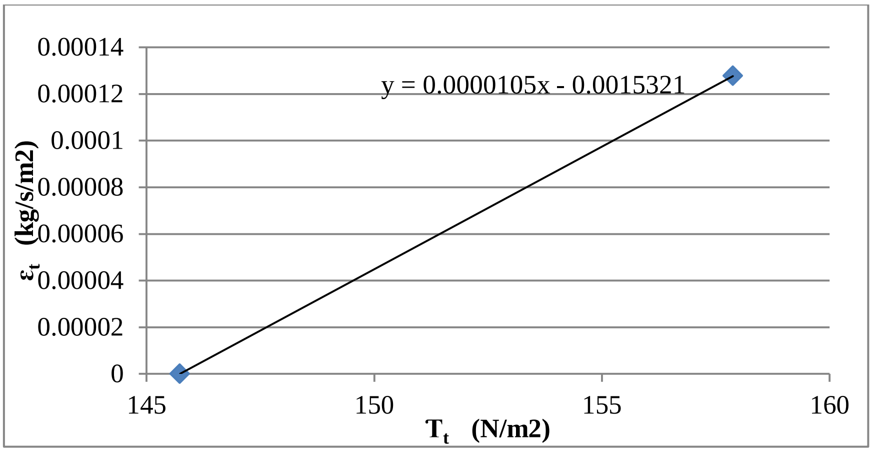

Figure A-15 - Test 5 - Typical Results of Hole Erosion Test

T_c (N/m^2)	145.91
Ce	0.0000105
I	4.98
Moderately Slow Erosion	

Test No: 06	
Type of Soil: Sand	**Curing Time:** 7 Days
Admixture: Cement	**Percent of Admixture:** 4%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.67 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.70 g/cm^3
Hydraulic Water Head (s_t): 10.345	

Test Results - Water Flow					
Test Time (t) (sec)	0	180	190	200	220
Volume (cm^3)	200	200	200	200	200
Time (sec)	5	5	5	5	5
Flow (Q_t) (cm^3/sec)	40	40	40	40	40

Calculated Friction Factor	
t= 0	F_{L0} = **0.075904046** (g/cm^2/s)
t= 220	F_{Lt} = **0.0894267** (g/cm^2/s)

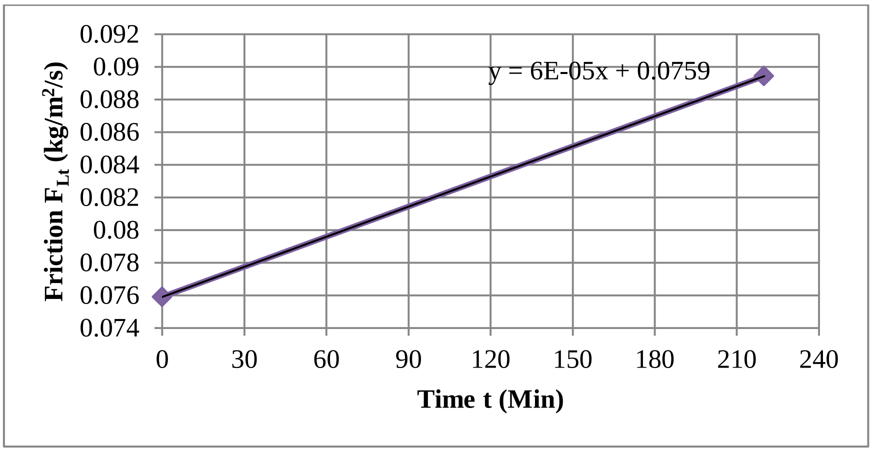

Figure A-16 Test 6 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t					
t (sec)	**0**	**180**	**190**	**200**	**220**
F_{Lt} (g/cm^2/s)	0.075904046	0.087	0.0875	0.088	0.0894267
Ø$_t$ (cm)	0.600	0.617	0.617	0.618	0.650

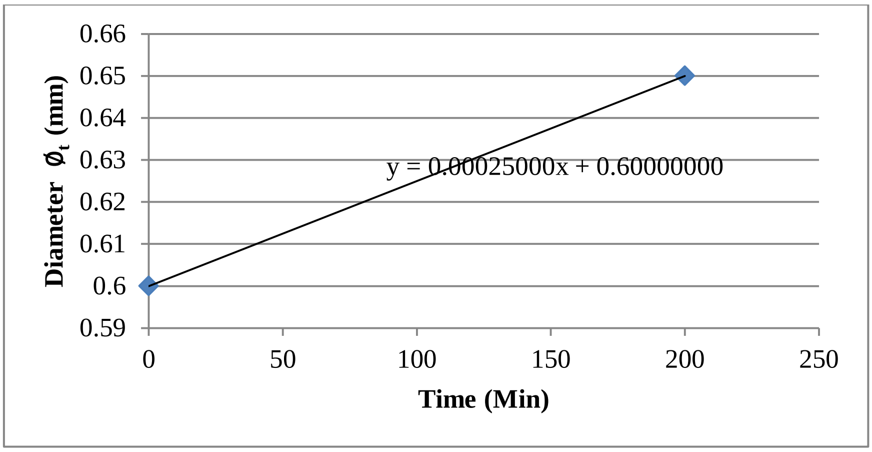

Figure A-17 - Test 6 - Hole Diameter Results

Critical Shear Stress and Erosion Rate					
t (sec)	0	160	180	190	200
dØ /dt (cm/sec)	0	0.0136	0.0136	0.0136	0.0136
T_t (N/m^2)	152.069	156.276	156.455	156.63	164.74
ε_t (Kg/s/m^2)	0	0.000116	0.000116	0.000116	0.000116

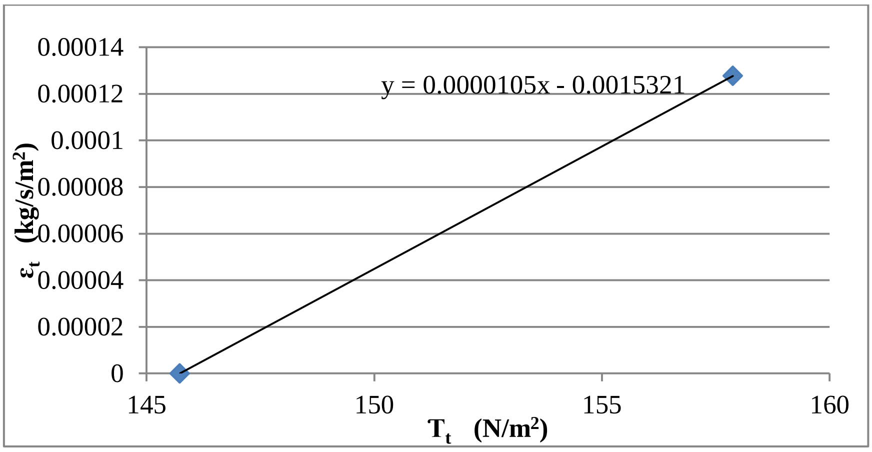

Figure A-18 Test 6 - Typical Results of Hole Erosion Test

T_c (N/m^2)	151.39
Ce	0.0000092
I	5.036
Very Slow Erosion	

Test No: 07	
Type of Soil: Clay	**Curing Time:** 2 Days
Admixture: Fiber-Cement	**Percent of Admixture:** 0.25%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.43 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.46 g/cm^3
Hydraulic Water Head (s_t): 3.448	

Test Results - Water Flow						
Test Time (t) (sec)	0	10	20	30	40	50
Volume (cm^3)	210	210	210	270	270	320
Time (sec)	3	3	3	2.65	2.75	2
Flow (Q_t) (cm^3/sec)	70	70	70	101.88	98.2	160

Calculated Friction Factor	
t= 0	**F_{L0} = 0.008262** (g/cm^2/s)
t= 50	**F_{Lt} =4.94167** (g/cm^2/s)

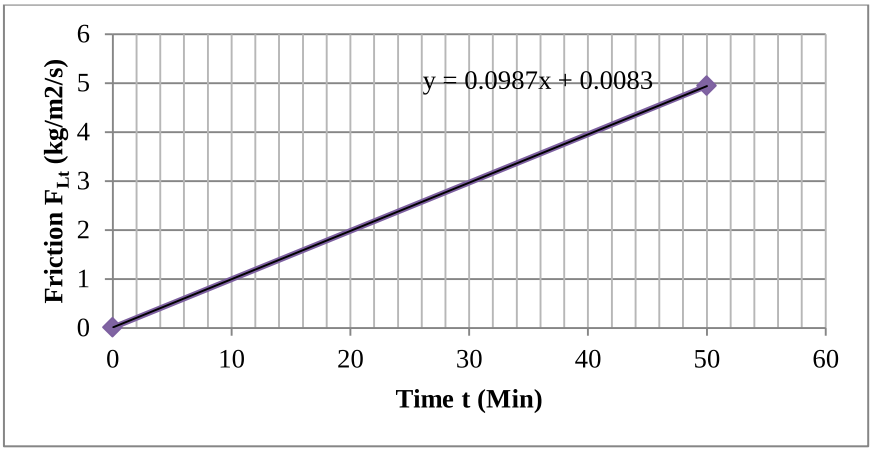

Figure A-19 Test 7 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t						
t (sec)	**0**	**10**	**20**	**30**	**40**	**50**
F_{Lt} (g/cm^2/s)	0.0083	1	2	3	4	4.9417
Ø_t (cm)	0.60	1.57	1.80	2.27	2.37	3.00

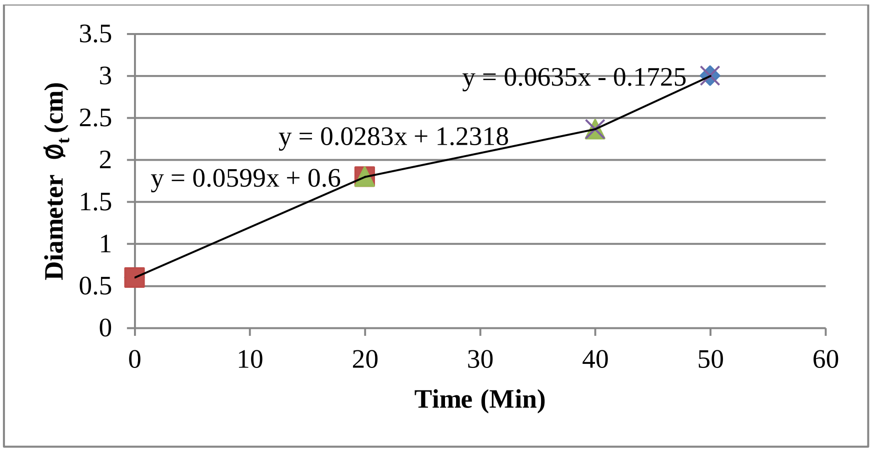

Figure A-20-Test 7 - Hole Diameter Results

Critical Shear Stress and Erosion Rate						
t (sec)	0	10	20	30	40	50
dØ /dt (cm/sec)	0	3.594	3.594	1.698	1.698	3.81
T_t (N/m^2)	50.69	132.28	151.95	191.49	199.84	253.45
ε_t ($Kg/s/m^2$)	0	0.026	0.026	0.0124	0.0124	0.028

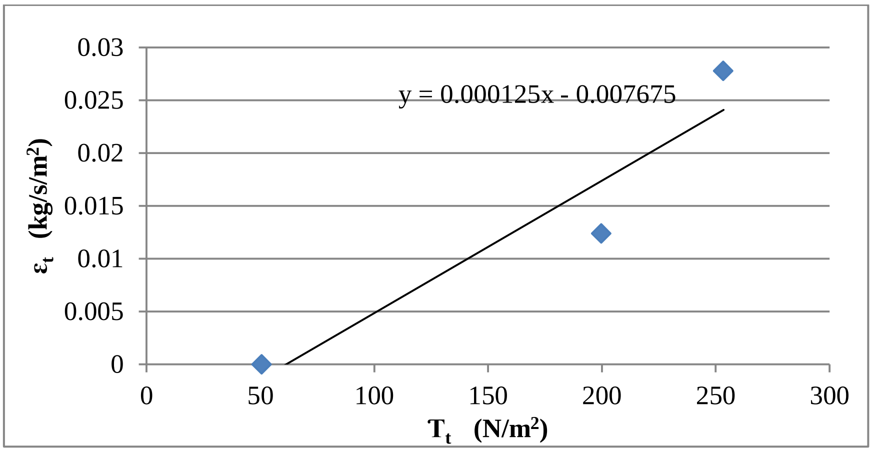

Figure A-21 Test 7 - Typical Results of Hole Erosion Test

T_c (N/m^2)	61.4
Ce	0.000125
I	3.903
Moderately Rapid Erosion	

Test No: 08	
Type of Soil: Clay	**Curing Time:** 7 Days
Admixture: Fiber-Cement	**Percent of Admixture:** 0.25%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.43 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.46 g/cm^3
Hydraulic Water Head (s_t): 3.879	

Test Results - Water Flow						
Test Time (t) (sec)	0	10	20	30	40	50
Volume (cm^3)	200	220	225	280	280	320
Time (sec)	3	3	3	2.65	2.75	2
Flow (Q_t) (cm^3/sec)	66.67	73.33	75.00	105.66	101.82	160.00

Calculated Friction Factor	
t= 0	**F_{L0} = 0.010247** (g/cm^2/s)
t= 50	**F_{Lt} =1.821697** (g/cm^2/s)

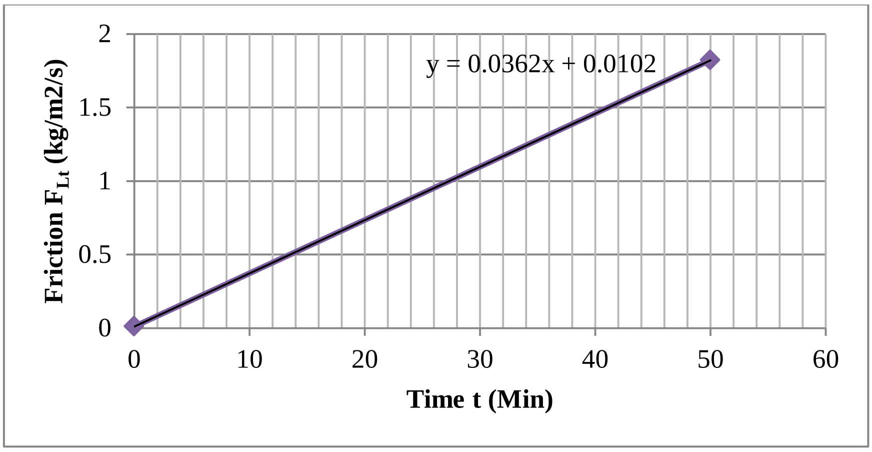

Figure A-22 Test 8 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t						
t (sec)	**0**	**10**	**20**	**30**	**40**	**50**
F_{Lt} (g/cm^2/s)	0.0102	0.4	0.75	1.1	1.45	1.8217
$\emptyset_t$ (cm)	0.600	1.297	1.484	1.838	1.914	2.400

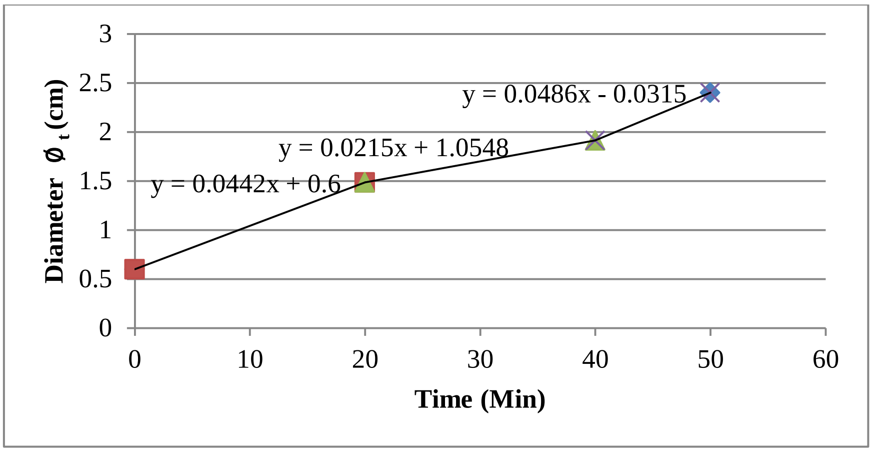

Figure A-23 - Test 8 - Hole Diameter Results

Critical Shear Stress and Erosion Rate						
t (sec)	0	10	20	30	40	50
dØ /dt (cm/sec)	0	2.652	2.652	1.368	1.368	2.916
T_t (N/m^2)	57.03	123.29	141.067	174.68	181.88	228.10
ε_t (Kg/s/m^2)	0	0.026	0.026	0.0124	0.0124	0.0280

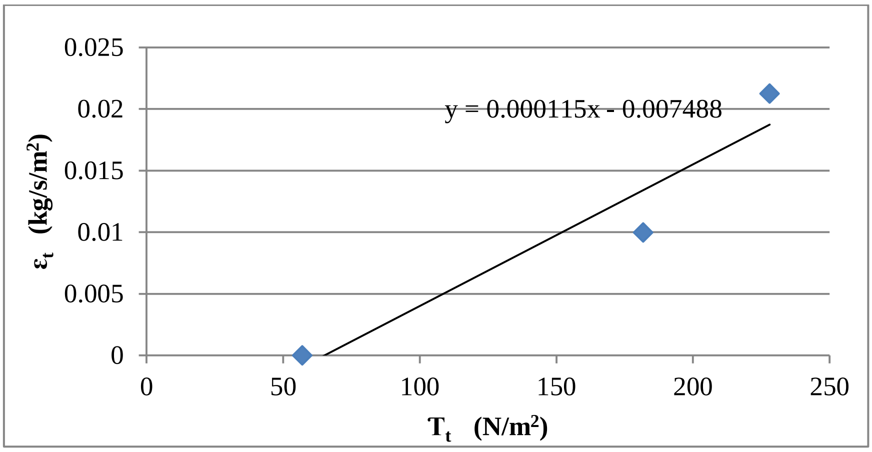

Figure A-24 - Test 8 - Typical Results of Hole Erosion Test

T_c (N/m^2)	65.11
Ce	0.000115
I	3.94
Moderately Rapid Erosion	

Test No: 09	
Type of Soil: Clay	**Curing Time:** 2 Days
Admixture: Fiber-Cement	**Percent of Admixture:** 0.5%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.43 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.46 g/cm^3
Hydraulic Water Head (s_t): 5.172	

Test Results - Water Flow						
Test Time (t) (sec)	0	20	30	40	50	60
Volume (cm^3)	240	240	240	240	240	240
Time (sec)	4.5	4.0	4.0	3.0	2.5	2.0
Flow (Q_t) (cm^3/sec)	53.33	60	60	80	96	120

Calculated Friction Factor	
t= 0	**F_{L0} = 0.021348** (g/cm^2/s)
t= 60	**F_{Lt} =0.890075** (g/cm^2/s)

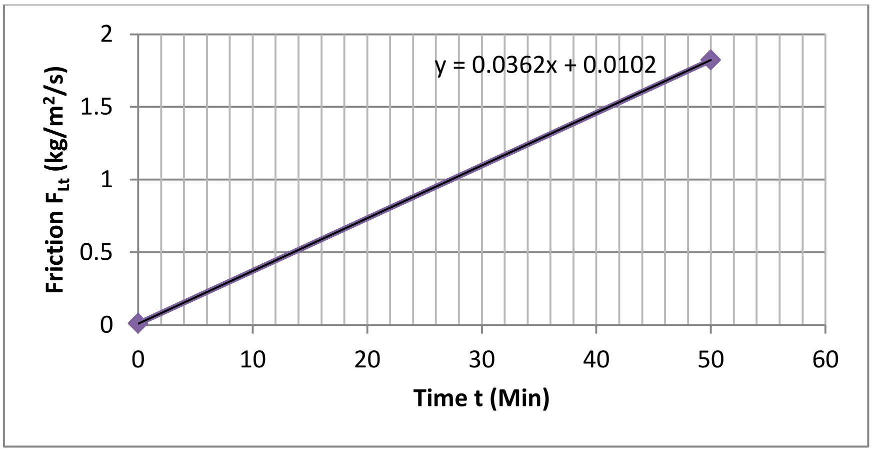

Figure A-25 - Test 9 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t						
t (sec)	**0**	**20**	**30**	**40**	**50**	**60**
F_{Lt} (g/cm^2/s)	0.0213	0.3000	0.4500	0.6000	0.7500	0.8900
$\emptyset_t$ (cm)	0.600	1.067	1.157	1.375	1.547	1.750

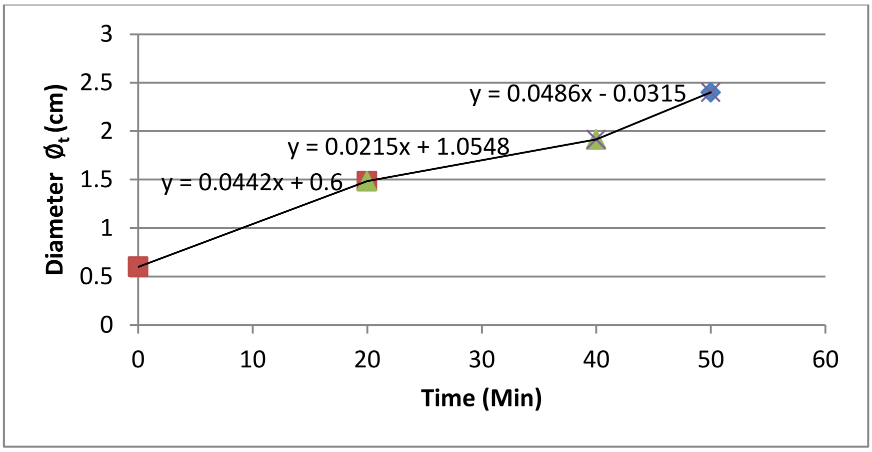

Figure A-26 -Test 9 - Hole Diameter Results

Critical Shear Stress and Erosion Rate						
t (sec)	0	20	30	40	50	60
dØ /dt (cm/sec)	0	1.116	1.116	1.17	1.17	1.218
T_t (N/m^2)	76.034	135.215	146.64	174.26	196.00	221.77
ε_t ($Kg/s/m^2$)	0	0.00814	0.00813	0.00853	0.00853	0.00888

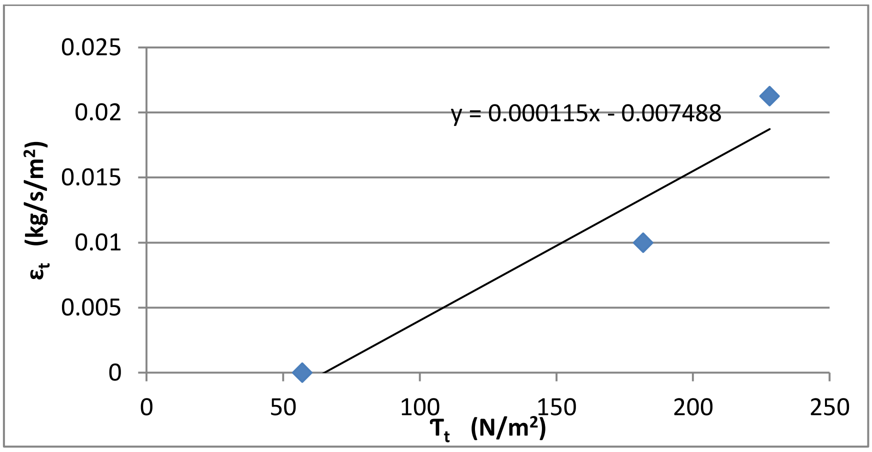

Figure A-27 - Test 9 - Typical Results of Hole Erosion Test

T_c (N/m^2)	76.054
Ce	0.0000609
I	4.215
Moderately Slow Erosion	

Test No: 10	
Type of Soil: Clay	**Curing Time:** 7 Days
Admixture: Fiber-Cement	**Percent of Admixture:** 0.5%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.43 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.46 g/cm^3
Hydraulic Water Head (s_t): 7.759	

Test Results - Water Flow						
Test Time (t) (sec)	0	35	40	50	60	70
Volume (cm^3)	200	200	235	250	265	280
Time (sec)	4	4	4	4	4	4
Flow (Q_t) (cm^3/sec)	50	50	58.75	62.5	66.25	70

Calculated Friction Factor	
t= 0	**F_{L0} = 0.021348** (g/cm^2/s)
t= 70	**F_{Lt} =0.890075** (g/cm^2/s)

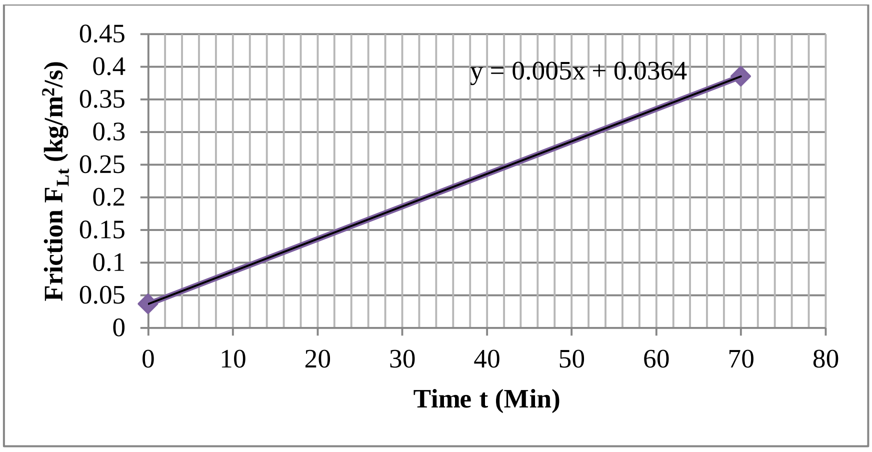

Figure A-28 - Test 10 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t						
t (sec)	**0**	**35**	**40**	**50**	**60**	**70**
F_{Lt} (g/cm^2/s)	0.0364	0.220	0.240	0.275	0.340	0.385
$\emptyset_t$ (cm)	0.60	0.86	0.93	0.98	1.05	1.10

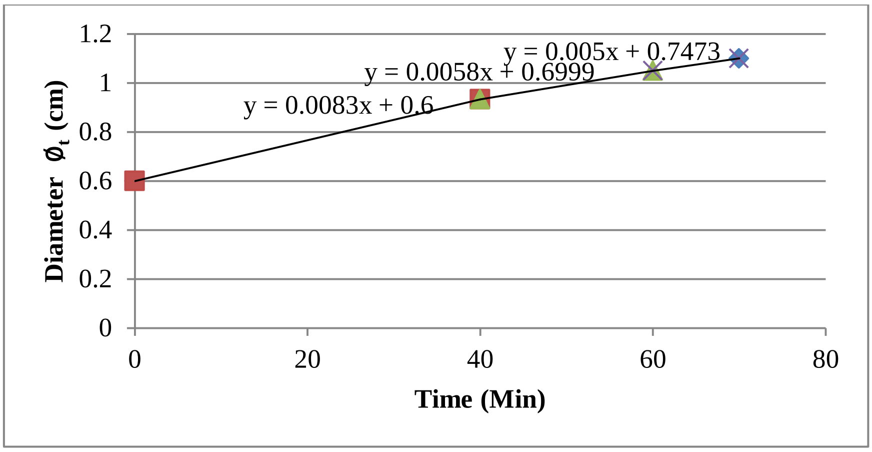

Figure A-29 - Test 10 - Hole Diameter Results

Critical Shear Stress and Erosion Rate						
t (sec)	0	20	30	40	50	60
dØ /dt (cm/sec)	0	0.462	0.462	0.42	0.42	0.3
T_t (N/m^2)	114.05	163.41	177.36	186.82	199.52	209.09
ε_t (Kg/s/m^2)	0	0.00337	0.00337	0.00306	0.00306	0.00219

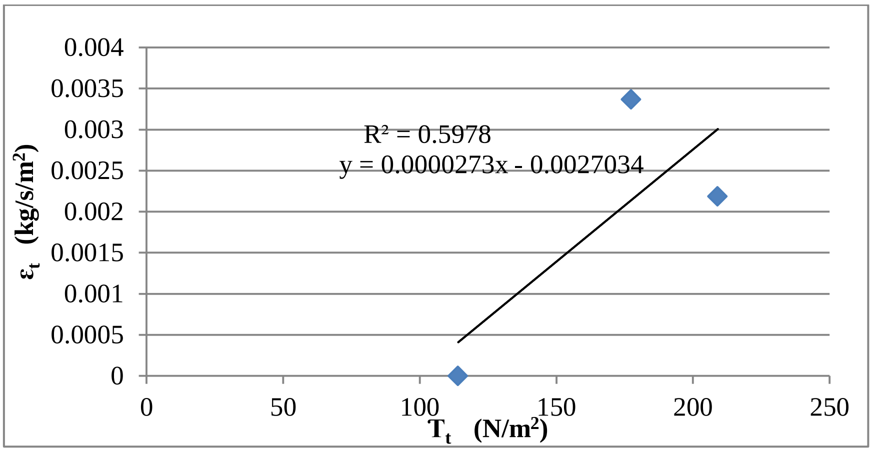

Figure A-30 - Test 10 -Typical Results of Hole Erosion Test

T_c (N/m^2)	99.03
Ce	0.0000273
I	4.564
Moderately Slow Erosion	

Test No: 11	
Type of Soil: Clay	**Curing Time:** 2 Days
Admixture: Fiber-Cement	**Percent of Admixture:** 1%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.43 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.46 g/cm^3
Hydraulic Water Head (s_t): 6.897	

Test Results - Water Flow						
Test Time (t) (sec)	0	30	50	60	70	75
Volume (cm^3)	175	175	178	220	245	270
Time (sec)	4	4	4	4	4	4
Flow (Q_t) (cm^3/sec)	43.75	43.75	44.50	55.00	61.25	67.50

Calculated Friction Factor	
t= 0	**F_{L0} = 0.04230** (g/cm^2/s)
t= 75	**F_{Lt} =0.13494** (g/cm^2/s)

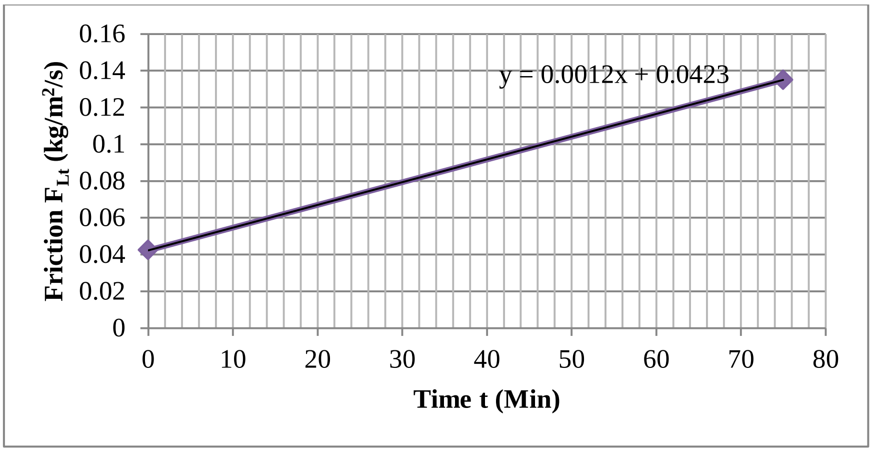

Figure A-31 - Test 11 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t						
t (sec)	**0**	**30**	**50**	**60**	**70**	**75**
F_{Lt} (g/cm^2/s)	0.0423	0.0900	0.1200	0.1300	0.1420	0.1349
$\emptyset_t$ (cm)	0.600	0.698	0.744	0.823	0.875	0.900

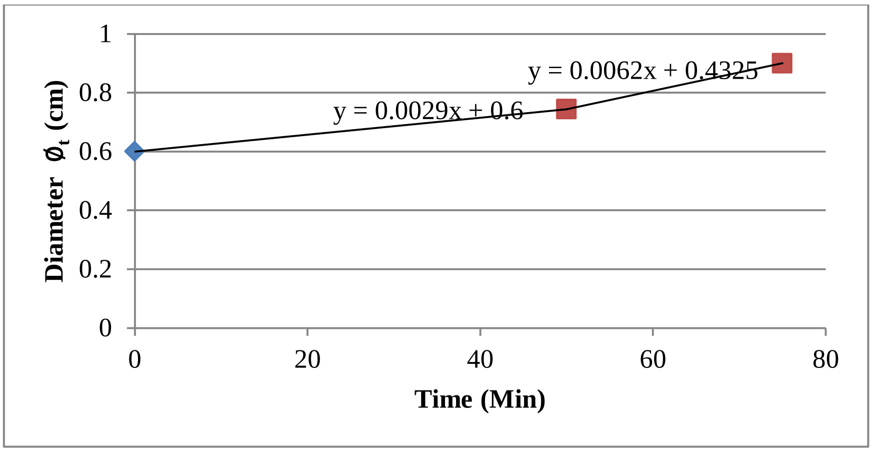

Figure A-32 - Test 11 - Hole Diameter Results

Critical Shear Stress and Erosion Rate						
t (sec)	0	30	50	60	70	75
dØ /dt (cm/sec)	0	0.174	0.174	0.372	0.372	0.372
T_t (N/m^2)	101.38	117.90	125.74	139.07	147.77	152.07
ε_t ($Kg/s/m^2$)	0	0.000127	0.00013	0.00027	0.00027	0.00027

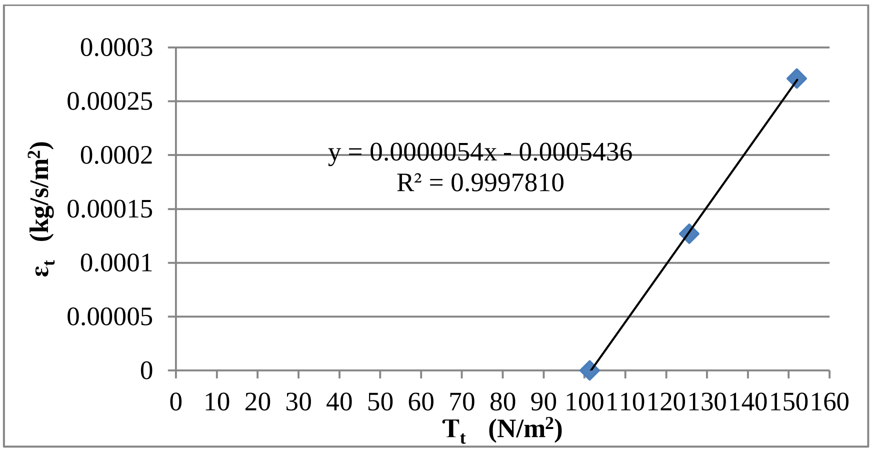

Figure A-33 - Test 11 -Typical Results of Hole Erosion Test

T_c (N/m^2)	100.67
Ce	0.0000054
I	5.267
Very Slow Erosion	

Test No: 12	
Type of Soil: Clay	**Curing Time:** 7 Days
Admixture: Fiber-Cement	**Percent of Admixture:** 2%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.43 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.46 g/cm^3
Hydraulic Water Head (s_t): 7.759	

Test Results - Water Flow						
Test Time (t) (sec)	0	35	40	50	60	80
Volume (cm^3)	200	200	220	240	245	265
Time (sec)	4	4	4	4	4	4
Flow (Q_t) (cm^3/sec)	50.00	50.00	55.00	60.00	61.25	66.25

Calculated Friction Factor	
t= 0	**F_{L0} = 0.036434** (g/cm^2/s)
t= 75	**F_{Lt} =0.063332** (g/cm^2/s)

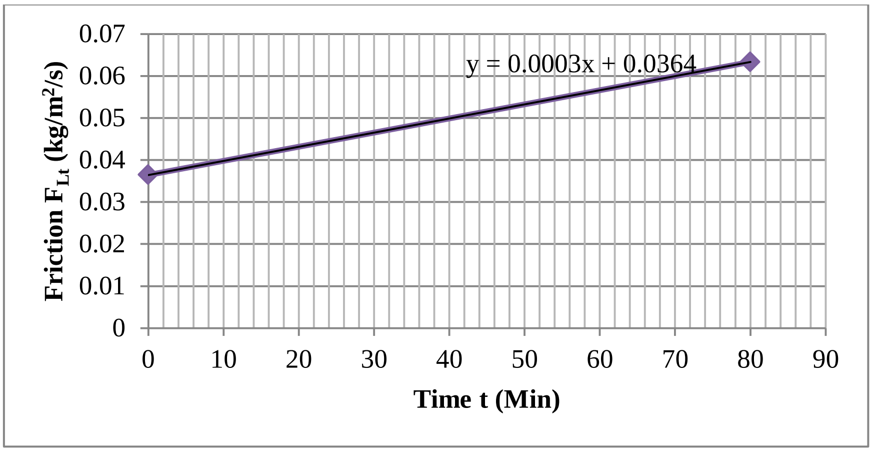

Figure A-34 - Test 12 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t						
t (sec)	**0**	**35**	**40**	**50**	**60**	**80**
F_{Lt} (g/cm^2/s)	0.036	0.049	0.050	0.052	0.057	0.063
ϕ_t (cm)	0.600	0.637	0.664	0.693	0.712	0.750

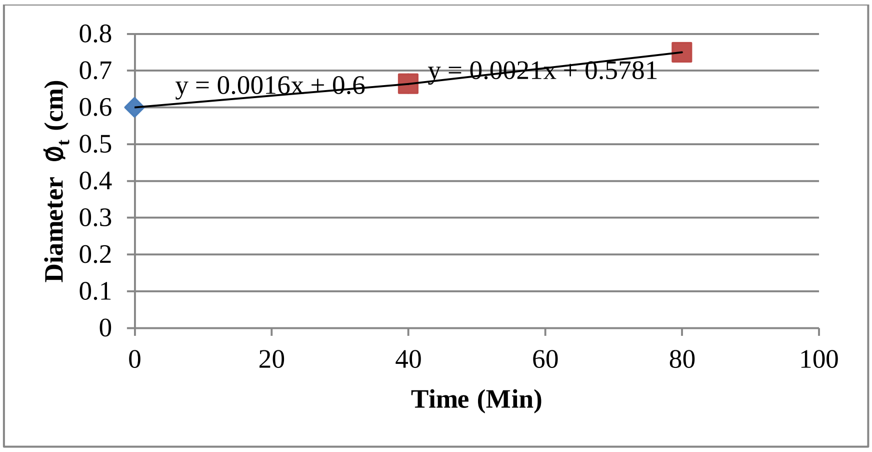

Figure A-35 - Test 12 - Hole Diameter Results

Critical Shear Stress and Erosion Rate						
t (sec)	0	35	40	50	60	80
d$\emptyset$ /dt (cm/sec)	0	0.096	0.096	0.126	0.126	0.126
T_t (N/m^2)	114.05	121.02	126.227	131.73	135.28	142.56
ε_t (Kg/s/m^2)	0	6.99E-05	7E-05	9.18E-05	9.18E-05	9.18E-05

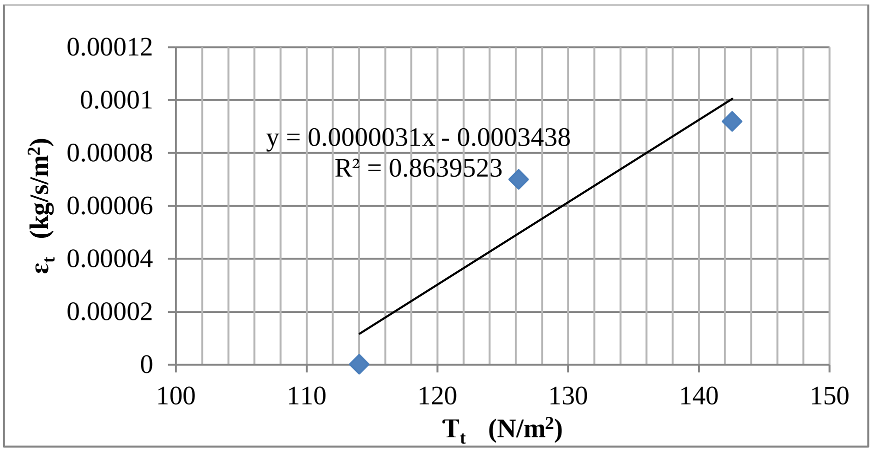

Figure A-36 - Test 12 -Typical Results of Hole Erosion Test

T_c (N/m^2)	110.903
Ce	0.0000031
I	5.509
Very Slow Erosion	

Test No: 13	
Type of Soil: Clay	**Curing Time:**2 Days
Admixture: Fiber-Cement	**Percent of Admixture:** 2%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.43 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.46 g/cm^3
Hydraulic Water Head (s_t): 10.345	

Test Results - Water Flow						
Test Time (t) (sec)	0	45	50	60	70	90
Volume (cm^3)	170	180	185	190	195	200
Time (sec)	4	4	4	4	4	4
Flow (Q_t) (cm^3/sec)	42.50	45.00	46.25	47.50	48.75	50.00

Calculated Friction Factor	
t= 0	**F_{L0} = 0.067237** (g/cm^2/s)
t= 75	**F_{Lt} =0.072486** (g/cm^2/s)

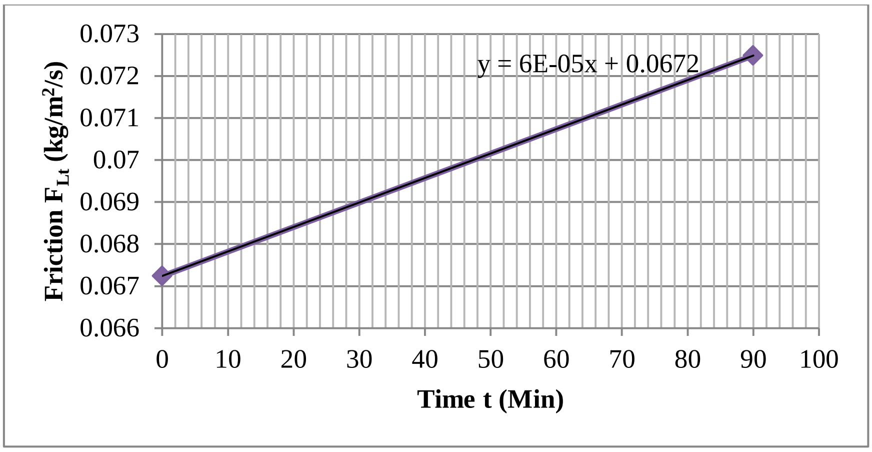

Figure A-37 - Test 13 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t						
t (sec)	**0**	**45**	**50**	**60**	**70**	**90**
F_{Lt} (g/cm^2/s)	0.0672	0.0700	0.0701	0.0708	0.0712	0.0725
$Ø_t$ (cm)	0.600	0.619	0.625	0.633	0.641	0.650

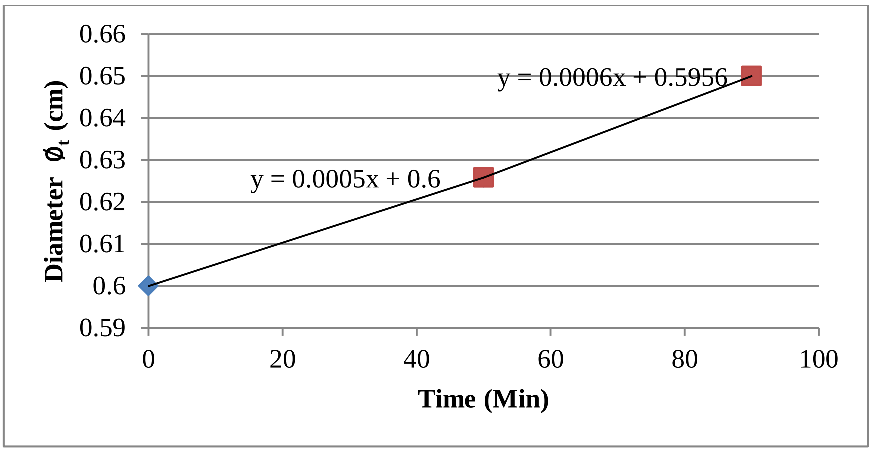

Figure A-38 - Test 13 - Hole Diameter Results

Critical Shear Stress and Erosion Rate						
t (sec)	0	45	50	60	70	90
d∅ /dt (cm/sec)	0	0.096	0.096	0.126	0.126	0.126
T_t (N/m^2)	152.07	156.84	158.62	160.64	162.50	164.74
ε_t (Kg/s/m^2)	0	6.99E-05	7E-05	9.18E-05	9.18E-05	9.18E-05

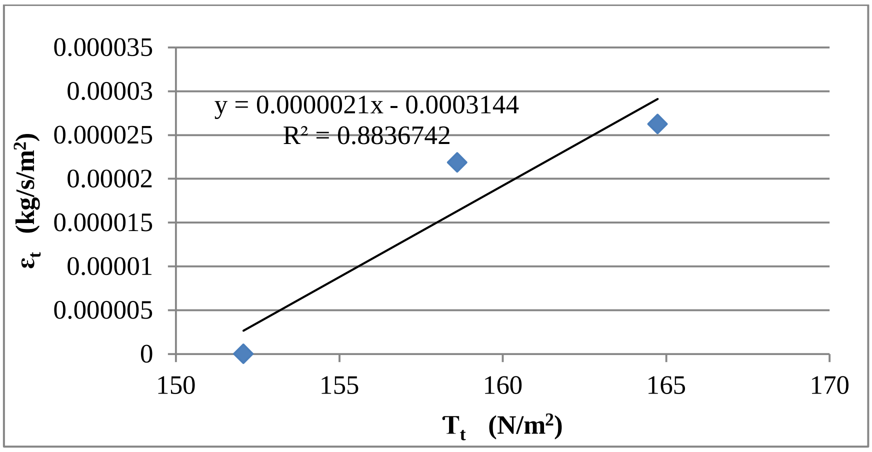

Figure A-39 - Test 13 -Typical Results of Hole Erosion Test

T_c (N/m^2)	149.714
Ce	0.0000021
I	5.678
Very Slow Erosion	

Test No: 14	
Type of Soil: Clay	**Curing Time:** 7 Days
Admixture: Fiber-Cement	**Percent of Admixture:** 2%

Initial Properties of Sample	
Water Density (ρ_w): 1 g/cm^3	**Soil Specific Weight (γ_d):** 1.43 KN/m^3
Specific Gravity (g): 980 cm/sec^2	**Soil Density (ρ_d):** 1.46 g/cm^3
Hydraulic Water Head (s_t): 7.759	

Test Results - Water Flow						
Test Time (t) (sec)	0	65	70	80	90	110
Volume (cm^3)	170	173	177	180	180	180
Time (sec)	4	4	4	4	4	4
Flow (Q_t) (cm^3/sec)	42.5	43.25	44.25	45	45	45

Calculated Friction Factor	
t= 0	**F_{L0} = 0.067237** (g/cm^2/s)
t= 110	**F_{Lt} =0.072486** (g/cm^2/s)

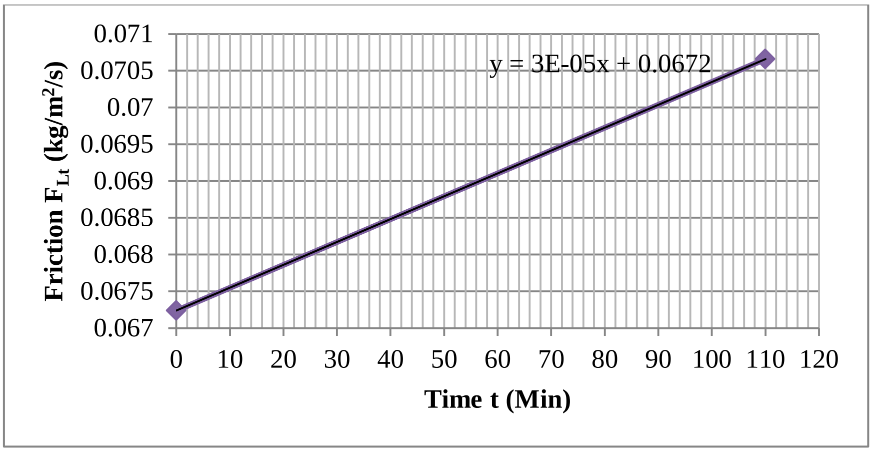

Figure A-40 - Test 14 - Friction Factor linear variation with Time

Friction Factors at time t and Hole Diameter at time t					
t (sec)	**0**	**45**	**50**	**60**	**70**	**90**
F_{Lt} (g/cm^2/s)	0.0672	0.0688	0.0695	0.0697	0.07	0.070658
$Ø_t$ (cm)	0.600	0.607	0.614	0.618	0.619	0.620

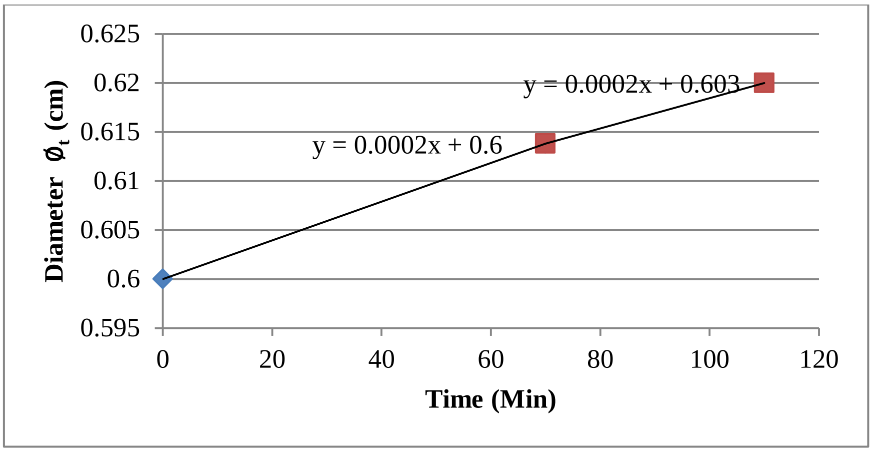

Figure A-41 - Test 14 - Hole Diameter Results

Critical Shear Stress and Erosion Rate						
t (sec)	0	65	70	80	90	110
d∅ /dt (cm/sec)	0	0.012	0.012	0.012	0.012	0.012
T_t (N/m^2)	152.07	153.84	155.57	156.71	156.84	157.14
ε_t (Kg/s/m^2)	0	8.75E-06	8.75E-06	8.75E-06	8.75E-06	8.75E-06

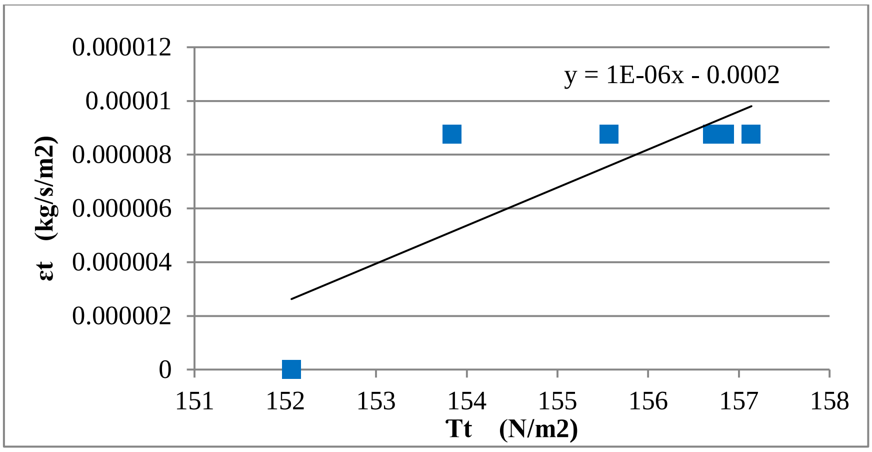

Figure A-42 - Test 14 -Typical Results of Hole Erosion Test

T_c (N/m^2)	148.158
Ce	0.0000001
I	6
Extremely Slow Erosion	

Vita

Lena Basim Al Samarrai was born on the 7th, November 1989, in Baghdad, Iraq. She completed her high school certificate in 2007. In 2011, she graduated with a degree of Bachelor of Science in Civil Engineering from the American University of Sharjah. Soon after graduation, she began her Master of Science in Civil Engineering at the same university. Currently, she is working as a Graduate Geotechnical Engineer at W.S Atkins.