EFFECT OF MOISTURE CONTENT, DRY DENSITY AND CURING TIME ON THE EROSION RESISTANCE OF TWO RIVER NILE DEPOSITS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT FOR THE REQUIREMENTS OF THE DEGREE OF MASTER OF SCIENCE IN BUILDING TECHNOLOGY

BY

HASSAN AMIN MOHAMMED AHMED
B.Sc. (HONOUR), CIVIL ENGINEERING

BUILDING AND ROAD RESEARCH INSTITUTE
UNIVERSITY OF KHARTOUM

JULY 2008
DEDICATED

TO

MY

COUNTRY
ABSTRACT

Geotechnical engineers recognized dispersive soils in the last century while investigating failures of many earth dams around the world. When these soils are blindly used in the construction of embankments or encountered in dam foundations, they greatly increase the risk of piping and lead in many instances to failures. Nevertheless, dispersive soils have been successfully used in construction of earth fills provided that suitable defensive design details, especially fine filters and high care for construction quality control, are adopted.

In this study, erodibility and dispersivity of two River Nile alluvial soils, proposed for use as core material for Merowe Dam, were investigated to study the effects of compaction water content, dry density and curing time on their erosion resistance. One of the samples was rendered slightly dispersive (Sample A), while the other one was highly dispersive (Sample B).

The study was performed by preparing compacted specimens with different moisture contents and dry densities using a split mould especially manufactured to have internal dimensions similar to the cylindrical pinhole test specimen. The pinhole test for dispersivity was used to assess the erosion resistance of the compacted specimens after being allowed to cure for different periods of time.

The results of the study indicate that the higher the dry density and moisture content and the longer the curing period, the better is the erosion resistance for the slightly dispersive Sample (A) material, and that the improvement with time is more for the lower moisture contents and
densities. The erosion resistance of the highly dispersive Sample (B) material improved very slightly after more than one year of curing for the specimen with the highest bulk density and relatively low air voids.
تمكّن المهندسون الجيولوجيون من التعرف على التربة القابلة للتفكك (dispersive soil) خلال بحثهم عن أسباب إنهيار عدد من السدود الترابية حول العالم في القرن الماضي. إن استخدام التربة القابلة للتفكك في تشييد الردميات أو وجوها في أساسات السدود يزيد كثيراً من القابلية للنح الخافي مما يؤدي في كثير من الأحيان إلى التلقيح الكامل. على الرغم من ذلك فإنه تم استخدام التربة القابلة للتفكك، كما ويمكن استخدامها، في إنشاء الردميات الترابية بعد عمل الإجراءات الوقائية المناسبة خاصة استخدام المضمي ومراعاة ضبط الجودة.

في هذه الدراسة تم بحث تأثير المحتوى الرطبي عند الدمك، الكثافة الجافة والمعالجة الزمنية على القابلية للنح وتفكك عينتين من تربة النيل الرسوبية المفترحن لكونها مواد دينية لسد مروي. وجدت إحدى العينتين (عينة أ) قليلة القابلية للتفكك بينما وجدت العينة الأخرى (عينة ب) عالية القابلية للتفكك.

أجريت الدراسة بدء عينات اختبار بمحتويات رطبية وكثافة جافة مختلفة. تم تجهيز العينات بواسطة قالب صناعي خاصاً ويكون من نصفي إسطوانة لها مقاسات داخلية مطابقة للمستخدمة لعينة اختبار التقلب (Pinhole Test). تم استخدام اختبار التقلب في هذه الدراسة لمحاربة ومقارنة القابلية والمقاومة للنح لعينات الاختبار المدمّكة بعد السماح بمعالجتها زمنياً لفترات زمنية متغيرة.

نتائج الدراسة تشير إلى أن المقاومة للنح للعينة (أ) تنخفض بزيادة المحتوى الرطب أثناء وطول مدة المعالجة الزمنية، وأن ذلك التحسن كان أكبر للعينات ذات المحتويات الرطوبة والكثافات القاحلة القليلة، بينما مقاومة النح للعينة (ب) تحسنت قليلاً جداً بعد أكثر من عام من المعالجة، وذلك للعينة ذات الكثافة الكلية الأعلى والفراغات الهوائية الأقل نسبةً.
ACKNOWLEDGEMENT

I wish to express my great appreciation and thanks to Dr. Ahmed Mohammed Elsharief for his kind supervision and endless support during the course of the study.

Many thanks are extended to the staff of the Building and Road Research Institute (BRRI) of the University of Khartoum (U of K) for their kind assistance. Special thanks to the laboratory staff for their continuous support and help in the laboratory testing.

The unlimited support of my family, colleagues and friends is also highly appreciated.
NOTATIONS

CEC   Cation Exchange Capacity
CL    Low plastic clay
D1    Highly dispersive
D2    Dispersive
DD    Dry Density
ESP   Exchangeable Sodium Percentage
ICOLD International Commission of Large Dams
MC    Moisture Content
MDD   Maximum Dry Density
ML    Low plastic silt
ND1   Non dispersive
ND2   Very slightly dispersive
ND3   Slightly dispersive
ND4   Moderately dispersive
OMC   Optimum Moisture Content
SAR   Sodium Adsorption Ratio
SCS   Soil Conversation Service
TDS   Total Dissolved Salts
USBR  United States Bureau of Reclamation
# Table of Content

ABSTRACT ........................................................................................................ II

ملخص البحث .................................................................................................. V

NOTATIONS ............................................................................................. VII

TABLE OF CONTENT ........................................................................... VIII

CHAPTER ONE ......................................................................................... 1

INTRODUCTION ..................................................................................... 1
  1.1 General ......................................................................................... 1
  1.2 Objectives of the Research ......................................................... 3
  1.3 Material and Methodology ......................................................... 3
  1.4 Thesis Layout ............................................................................. 3

CHAPTER TWO ........................................................................................ 5

DISPERSIVITY AND DISPERSIVE SOIL .......................................... 5
  2.1 Introduction .................................................................................. 5
  2.2 Recognition and Significance ...................................................... 5
  2.3 Nature and Occurrence .............................................................. 7
  2.4 Distinction and Identification ...................................................... 7
    2.4.1 General Identification .......................................................... 7
    2.4.2 Physical Laboratory Tests ...................................................... 9
    2.4.3 Chemical Laboratory Testing ............................................. 11
    2.4.4 Evaluation of Physical and Chemical Dispersivity Tests Result .................................................. 17
  2.5 Problems Associated with Dispersive Soil ................................. 19
2.6 Filters for Dispersive Soils..............................................................20
2.7 Use of Dispersive Soils in Earth Dams..............................................23

CHAPTER THREE ..................................................................................26
THE LABORATORY STUDY ......................................................................26
3.1 Introduction......................................................................................26
3.2 Material Collection and Storage ......................................................26
3.3 Classification of Samples and Preliminary Testing..........................27
3.4 Dispersivity Testing..........................................................................30
3.5 Pinhole Test.....................................................................................32
3.6 The Plan for the Main Testing and the Preparatory Works.............33
3.7 The Study Program..........................................................................42
   3.7.1 Main Testing Program.................................................................42
   3.7.2 Additional Testing Program.......................................................43

CHAPTER FOUR.....................................................................................57
ANALYSIS, DISCUSSION AND INTERPRETATION OF TEST RESULTS ..................................................................................57
4.1 Introduction......................................................................................57
4.2 Identification and Classification of Samples.................................58
4.3 Effect of Moisture Content and Dry Density on Erodibility of the Samples ...........................................................................60
   4.3.1 Effect on Erodibility of the Slightly Dispersive Sample (A) Material.................................................................60
   4.3.2 Effect on Erodibility of the Highly Dispersive Sample (B) Material.................................................................61
4.4 Effect of Curing on Erodibility of the Samples.........................62
4.4.1 Effect on Erodibility of the Slightly Dispersive Sample (A) Material........................................................................................................................................62

4.4.2 Effect on Erodibility of the Highly Dispersive Sample (B) Material........................................................................................................................................64

4.5 General Discussion: ......................................................................................................................64

CHAPTER FIVE ...............................................................................................................................68

CONCLUSIONS AND RECOMMENDATIONS........................................................................68

5.1 Introduction..................................................................................................................................68

5.2 Conclusions.................................................................................................................................69

5.3 Recommendations for Further Research...............................................................................70
CHAPTER ONE

INTRODUCTION
CHAPTER ONE

INTRODUCTION

1.1 General

Soil erosion is one of the main factors affecting the safety and the serviceability of earth structures. Piping failures are historically the most common and the most severe failures that occurred for embankment dams. The reason is that erosion rapidly increases with time upon widening of cracks or leakage paths. Most of the reported piping failures were caused by either the usage of unsuitable material in different zones, or the inadequate compaction, or both.

Erodibility of earth fills is dependent on many different factors such as the origin and the nature of the material used, the integrity of the soil mass and permeability of the compacted soil, in addition to other external factors including water, climate, loading conditions and settlements.

The natural tendency of clayey soils to disperse (deflocculate) is known as dispersivity. All dispersive soils are erodible to some degree, usually high, but erodibility depends also on factors other than clay fraction.

The recognition of dispersivity is, of course, an important task when selecting core material for an earth core dam. Sometimes, and for reasons regarding the availability, suitability and cost of the existing material that can be used for construction, it may be necessary to use dispersive fine-grained soils in building the dam core. Hence, researches and dam construction practice (ICOLD, 1990) concluded that it is possible to use
dispersive clay as a core material, taking into account the following measures:

- A critical fine filter must be well designed and constructed.
- The most exposed and critical zones in the core can be treated by either lime or gypsum.
- A considerable care shall be taken of the compaction and site compaction control.

It has been proved (Sherard et al (1977, 1984); Vaughan & Soares (1982)) that an adequate filter can retain dispersive soils even with small continuous leaks and high water pressures. Small amounts of either lime or gypsum have proved to be sufficient for treating dispersive soil to be non dispersive (Stone (1977); Harmse (1980); Forbes et al (1980); Wagener (1980); Wagener et al (1981)). But, there is no clear information on the effects of the compaction parameters and the time factor on the erodibility of dispersive and non dispersive soils.

In this concern, it may be useful to study the effects of the compaction moisture content and the density obtained, in addition to the curing of the material in the compacted state, on the erosion behavior of the proposed material for dam core construction.

Regarding the curing in the compacted state, it was noticed that some non dispersive soils when air dried and pinhole tested gave dispersive results, but, when cured for sufficient period in the compacted state and then tested, become non dispersive (Sherard et al (1976); Schafer (1978)).

Now, a question is raised on whether curing of compacted dispersive soils, for specified moisture contents and densities, could affect the
erodibility and the erosion behavior of dispersive soils, considering that remoulded clayey soils may exhibit property changes with ageing including thixotropic hardening.

1.2 Objectives of the Research
The main objective of this research was to study the effect of moisture content, dry density and curing time on the erosion resistance of two potentially erosive fine-grained soils.

1.3 Material and Methodology
For the purposes of this study, two samples from the River Nile alluvial deposits were chosen, one is a relatively young Nile silt and the other is a highly desiccated silty clay from the upper terraces of the Nile. The two samples were obtained from the Northern State, about 40 km upstream of the Merowe town. Materials from the same sources were investigated as a core material for a proposed dam in Merowe.

This study was performed by preparing compacted specimens with different moisture contents and dry densities and testing them after different curing times to observe their erodibility. The pinhole test was used to indicate the erosion resistance of the compacted specimens.

1.4 Thesis Layout
The Thesis has the following layout:

Chapter One is an introductory chapter defining the aim of the study, highlighting the material used and the methodology adopted and outlining the profile of the Thesis.
Chapter Two gives general information on soil dispersivity and its significance, and describes the different types of tests and methods usually employed to identify dispersive soils in addition to how dispersive soils can be used in construction of earth dams.

Chapter Three describes, in detail, the laboratory study including material collection and storage, basic classification tests, preparation of specimens, the main testing program and the additional tests conducted based on the results of the originally planned tests. The Chapter also presents the results of all the tests performed in this study.

Chapter Four includes analysis and interpretation of the results obtained during the course of the study. It discusses the effects of the moisture content, dry density and curing time on the erodibility and the erosion resistance of the tested samples. Summary of the main results is presented.

Chapter Five states the main conclusions drawn from the analysis of results of the study. It also gives some recommendations for future studies.
CHAPTER TWO

DISPERSIVITY AND DISPERSIVE SOIL
CHAPTER TWO

DISPERSIVITY AND DISPERSIVE SOIL

2.1 Introduction

In the second half of the last century, the recognition of the fact that certain clayey soils are highly erodible in comparison with other ones with the same appearance and index properties was an important contribution to the art of design and construction of earth dams. Such soils have harmful effects on the behavior of earth embankments, leading sometimes to their failure.

Dispersive soils are soils that disperse (defloculate) easily and rapidly without significant mechanical assistance in water of low-salt content. Such soils usually have a high proportion of their adsorptive capacity saturated with sodium cation. Dispersive soils also generally have a high shrink-swell potential and offer low permeability in the intact state.

Dispersion occurs in cohesive soils when the repulsive forces between clay particles exceed the attractive forces, in this manner bringing about deflocculation, so that in the presence of relatively pure water the particles repel each other to form colloidal suspension.

2.2 Recognition and Significance

Although the soil dispersivity was known for agricultural soil scientists before 1940, it was only recognized by the geotechnical engineers in the 1960's in Australia and 1970's in USA. This knowledge was learned from the failure of a considerable number of embankments and homogeneous
dams in both countries (Ingles & Wood (1964); Aitchison & Wood (1965); Rallings (1966); Sherard et al (1972, 1976)).

The difference in the erosion behavior of dispersive and non dispersive soils, as postulated by Sherard et al (1974), results from the fact that for non dispersive soils there is a definite threshold velocity below which flowing water causes no erosion. The individual clay particles cling to each other and are only removed by water flowing with a certain erosive energy. For dispersive soils, there is no threshold velocity to start erosion. The colloidal clay particles go into suspension even in quiet water and being therefore highly susceptible to erosion and piping.

On the other hand, general experience has shown that natural soil deposits and dams consisting of low sodium (ordinary erosion resistant) soils are not eroded in the same spectacular fashion in tunnels and deep gullies.

The mechanism by which a dispersive soil is eroded involves the structure of the soil in one hand and the character of the interaction between the pore water and eroding fluids on the other hand (Elges, 1985). The presence of exchangeable sodium is an important factor contributing towards dispersive behavior in soils. This is expressed in terms of the exchangeable sodium percentage (ESP). One of the main properties which also claimed to govern the susceptibility of clay to dispersion is the total content of dissolved salt in the pore water (Sherard et al, 1976). The lower the content of dissolved salts in the pore water, the greater is the susceptibility of sodium saturated clays to dispersion. From the eroding fluid point of view, the susceptibility of clay mass to dispersion piping is also influenced by the total content of dissolved salts.
in the reservoir water in the same order of the dissolved salts in the pore water; salty water causes less erosion to dispersive soils than pure water.

2.3 Nature and Occurrence
Because clays have stronger affinity for divalent calcium and magnesium cations than for monovalent sodium, dispersive sodium clays are less common in nature than ordinary clays (which have primarily divalent cations). By contrast, it is more common in some areas and geological settings than others. Sherard (1976) pointed out that, most dispersive soils are alluvial clays or residual soils from claystone or shales. They could have different colors such as red, grey, brown, yellow, whitish and transitions among these. No black-colored soils, with obviously high organic content, have tested dispersive, however, according to Fell et al (1992) this needs to be treated with caution, since some “black cotton” soils are dispersive. Furthermore, fine-grained soils that are known to be derived from in situ weathering of igneous and metamorphic rocks have been non dispersive as well as soils derived from limestone.

From the very earlier studies, it was believed that the problems of dispersive clay erosion were confined largely to soils formed in arid and semi-arid climates; but, later, the same soils and erosion problems have been found to exist in humid climates in various locations in many countries (Elges, 1985).

2.4 Distinction and Identification
2.4.1 General Identification
Several visual features commonly identify dispersive clays, notably gully erosion and field tunneling (piping and jugging) together with excessive turbidity in any storage water. A lack of these features does not
necessarily imply that the soils are non-dispersive. Usually in areas where there are no man-made excavations or embankments in the area, there is a little or no evidence from surface appearance that the soil is highly erodible. Mostly, because the ground surface is covered with a thin layer of protective silty sand from which the dispersive clay particles have been removed, or has a protective layer of topsoil or vegetation. A clay soil, which softens rapidly with a greasy feel, on contact with water, is indicative of dispersive clay.

It seems likely that most of the dispersive soils have substantial quantities of montmorillonite (in general appreciable content of smectite, the active clay group including montmorillonite). Most kaolinite clays are non-dispersive, while some illites tend to be dispersive (Sherard et al, 1976). However, there is no clear difference in the clay mineralogy between dispersive and non-dispersive soils.

No relationship was found between the Atterberg limits or activity and soil dispersivity (Sherard (1976); Donaldson (1975); Bell & Maud (1994); Bell & Walker (2000)). On the other hand, if the soil has less than 10% clay particles there may not be enough colloids to support dispersive behavior.

Since a dispersive soil does not lend itself to be identified by the range of conventional tests usually employed by the soil mechanics laboratories, some specialized tests have been developed in order to assess the dispersivity of the soil. These can be divided into physical and chemical tests.
2.4.2 Physical Laboratory Tests

The physical tests show the effect of dispersivity of the soil, that is, the natural susceptibility of the soil to deflocculate in the presence of pure water. The most common physical tests used for this purpose are:

1. Crumb test
2. Double hydrometer test
3. Pinhole test

The crumb test and double hydrometer tests indicate the tendency of the soil to disperse, and the pinhole test gives an indication of the erodibility of the soil.

The crumb test is the simplest of the physical tests and indicates the tendency of the soil to deflocculate in the presence of distilled water. It consists of placing crumbs of soil into a beaker of distilled water, or 0.05 M NaOH solution, and noting the reaction as the soil begins to hydrate. The crumb test gives a good indication of the dispersivity of the soil, but it is not always highly reproducible. Furthermore, some dispersive soils may give a non-dispersive reaction in the crumb test. However, it can be considered as a good rapid indicative test for soil dispersivity.

The double hydrometer test is one of the first methods developed for soil dispersivity assessment. This test was developed from the original method proposed by Volk (1937). It is a measure of the water stable aggregates in soil. In this test, the particle size distribution is first measured using the standard hydrometer test, in which the sample is dispersed in the hydrometer bath with strong mechanical agitation and a chemical dispersant, represented by Curve A, Figure (2.1). A second hydrometer test is made without strong mechanical agitation and without
a chemical dispersant, represented by Curve B, Figure (2.1). Curve B shows less colloidal particles than Curve A and is a measure of the clay to disperse naturally. By definition, percent dispersion is the ratio of clay size particles (d<0.005 mm) in the two tests.

The double hydrometer test is generally a reliable test with high reproducibility.

![Typical double hydrometer test result](image)

Figure (2.1): Typical double hydrometer test result

The pinhole test has been developed by Sherard et al (1976) for direct measurement of the dispersivity and erodibility of compacted fine-grained soils. In this test, distilled water is caused to flow through a 1 mm diameter hole formed in a specimen of compacted clayey soil. Dispersivity is assessed by observing effluent color and changes of flow rates through the hole, in addition to the visual inspection of the diameter of the hole after completion of the test. The water emerging from dispersive clay carries a suspension of colloidal particles, while the water
from erosion-resistant clay is crystal clear. The details of the test apparatus and procedure are included in ASTM D4647–93 and BS 1377: Part5:1990.

The pinhole test is widely considered to be one of the most reliable physical tests to reflect soil dispersivity and erodibility, because it simulates the action of water draining through a pipe in soil. It is not developed to be a quantitative tool for measuring rates of erosion as a function of the velocity of flowing water.

The test can be carried out on undisturbed samples as well as on recompacted soil specimens. The test results are highly reproducible and can easily be categorized into one of the six categories: the dispersive categories, D1 and D2, and the non-dispersive categories, ND1, ND2, ND3 and ND4 as described in BS 1377: Part5:1990 and Method A of ASTM D4647–93 (Reapproved 1998).

2.4.3 Chemical Laboratory Testing
The chemical testing has the purpose of indicating the amounts of the cations in the soil structure, namely, sodium (Na), calcium (Ca), magnesium (Mg) and potassium (K), with special emphasis to the sodium and its relative present. Both exchangeable cations and saturation extract cations are usually determined in this instance. Exchangeable cations are those on the surfaces of clay minerals whereas saturation extract cations are those present in the pore water.

The exchangeable cations are measured in terms of milliequivalent per 100 gm of dry soil and are expressed as (CEC). Then the exchangeable sodium percentage (ESP) is calculated as follows:
ESP = \frac{Na_{exch}}{CEC} \times 100 \quad (%) \\
\text{Where } Na_{exch} \text{ is the amount of sodium on the exchange complex, in terms of milliequivalents per 100 gm of dry soil, and}

CEC = Na_{exch} + Ca_{exch} + Mg_{exch} + K_{exch} \\
\text{Where: } Ca_{exch}, Mg_{exch} \text{ and } K_{exch} \text{ are the same as described above for } Na_{exch}.

The cation exchange capacity (CEC) of the soil is due to the type and nature of clay minerals present. Clay minerals that tend to be associated with dispersivity are 2:1 phyllosilicates including the smectite group. The CEC of these clays is typically in the range of 40 to 150 milliequivalents per 100 gm of clay. Thus, the CEC of dispersive soils is likely to fall into this range. However, the CEC alone cannot be used to identify dispersive soils, as other factors, such as high organic content, may contribute to the high CEC values (Bolt & Bruggenwest (1986)).

Elges (1985) suggested a threshold ESP value of 10%, above which soils that have their free salts leached by seepage of relatively pure water are prone to dispersion. According to Gerber & Harmse (1987), soils with ESP values above 15% are highly dispersive. They also produced a chart for the determination of dispersive potential using ESP (%) vs. CEC (meq/100 gm clay), Gerber & Harmse (1987). The ESP vs. CEC chart appears to be one of the most reliable of the chemical methods of dispersivity determination. This presumably is because it is a combination
of two parameters fundamental to dispersivity. However, dispersive soil identification using this chart does not always correspond well with those recognized by the pinhole test. That mostly because the pinhole test is a measure of soil erodibility rather than dispersivity.

In the pore water salts testing; number of tests is conducted on the pore water. For these tests, a sample of the clay at the natural water content is mixed with distilled water until the consistency is approximately that of the Atterberg liquid limit, at which point the soil scientists refer to as "saturated soil paste". This is allowed for a number of hours until equilibrium takes place between the salts in the pore water and on the cation exchange complex. Subsequently, a small quantity of the pore water is extracted from the saturated soil paste (10 to 25 milliliters), usually using a vacuum and a filter. This extracted pore water is called the saturation extract. This saturation extract is then tested by conventional water testing procedures employed by the chemist to determine the amounts of the main metallic cations in solution (calcium, magnesium, sodium and potassium), in terms of milliequivalent per liter. The total dissolved salts (TDS) equals to the sum of these four cations:

\[ \text{TDS} = \text{Ca}^{++} + \text{Mg}^{++} + \text{Na}^{+} + \text{K}^{+} \]

Where \( \text{Ca}^{+}, \text{Mg}^{++}, \text{Na}^{++} \) and \( \text{K}^{+} \) are dissolved salts in milliequivalents per liter of saturation extract.

The sodium adsorption ratio (SAR) can then be calculated by the formula:
The SAR is used to quantify the role of sodium when free salts are present in the pore water (soils with TDS greater than 40 milliequivalents per liter). If no free salts are present the use of SAR to help define dispersive soils is not applicable. However, even soils with high TDS, which are initially in a flocculated state, can become dispersive if the salts are leached out.

Ingles & Metcalf (1972) suggested that to assess dispersivity potential, the exchangeable sodium percentage (ESP) and total ionic concentration of the pore water (TDS) should be determined. Then, for montmorillonite and illite clays, Figure (2.3) is used to determine whether the soil is in a flocculated or dispersed (deflocculated) state, and whether a change in pore water chemistry during filling of the reservoir can lead to dispersion.

In this diagram, filling of the reservoir of (Dam A) maintains a stable flocculated state, but for (Dam B), dispersion would occur. This can be readily related to the dilution of the pore water salts.

McDonald et al (1981) produced a revision of Figure (2.3) to include some work by Moriwaki & Mitchell (1977). Figure (2.4) presents their revision and indicates that the Ingles & Metcalf (1972) boundaries were reasonable except that dispersion could occur in montmorillonites at higher ESP than indicated by the earlier work. They also pointed out that ESP can vary a lot on any dam, and they suggested the use of pinhole test
for situations where water would be flowing (e.g. a crack in a dam) and crumb test for quiet conditions (e.g. reservoir). It was also pointed out that, where soils which are rich in bicarbonates, are allowed to dry out, precipitation of relatively insoluble CaCO$_3$ may occur, results in a lower Ca$^{++}$ ion concentration and hence an increase potential for dispersion.

Another approach for identification of dispersive soils by the pore water (saturation extract testing) is the one proposed by Sherard et al (1975). They used the total dissolved salts (TDS) for the purpose of assessing dispersivity as the total of the ions: calcium, magnesium, sodium and potassium. They also expressed the sodium content as a percentage of the TDS. They claimed that, the higher the percentage sodium (%Na) and the lower the total dissolved salts (TDS), the higher is the susceptibility of sodium clays to dispersion and went on to develop a dispersivity chart based on these two parameters, Figure (2.5). The percentage sodium plotted against total dissolved salts has frequently shown a poor overall agreement with the results of physical tests and Craft & Acciardi (1984) maintained that pore water cations data does not provide adequate identification of dispersive soil. Anon (1990) suggested that, the cations present in the pore water may be independent of the mineralogy of the soil, resulting from environmental conditions influencing the soil.
Figure (2.3): Dispersivity potential in relation to the exchangeable sodium percentage and total ionic concentration of the pore water, after Ingles & Metcalf (1972)

Figure (2.4): Dispersivity potential in relation to the exchangeable sodium percentage and total ionic concentration of the pore water, after McDonald et al (1981)
Subsequently, Bell & Maud (1994) suggested that the saturation extract may not contain all the ions which are responsible for dispersion. However, the pore water analysis is still used for identifying dispersive soils, but, of course, it is not recommended to use it alone, or even to use only one test, for identification of dispersive soils whether it is physical or chemical one. No single test proved to be suitable and sufficient for identifying the dispersivity of all soils (Sherard et al (1976); Bell & Walker (2000)).

2.4.4 Evaluation of Physical and Chemical Dispersivity Tests

Results
There are some limitations for each of the physical and chemical testing and reliable results are not always obtained. As mentioned before, no one test has proved totally successful in identifying dispersive soils. The physical tests may fail to identify dispersive soils when free salts are

Figure (2.5): Relation between dispersion and soil pore water chemistry, after Sherard et al (1976)
present in solution in the pore water, which often occurs with sodium saturated soils. If no free salts are present in the pore water the use of the chemical testing for the pore water to help define dispersive soils is not applicable. However, even soils with high total dissolved salts, which are initially in a flocculated state, can become dispersive if the salts are leached out.

Bell & Walker (2000) tried to undertake an evaluation of the reliability of the results of physical and chemical dispersivity testing by means of discriminant analysis. They concluded that the results of the crumb test, the pinhole test, the SAR value and the assessments provided by the CEC vs. ESP and TDS vs. % Na charts represented the best parameters to be used in a rating system. Their rating system developed using the discriminant analysis showed the sequence of reliability sorted with the pinhole test as the most reliable test then the CEC vs. ESP chart then the crumb test then the SAR approach and lastly the TDS vs. % Na.

The United States Bureau of Reclamation (USBR) generally conducts the crumb test with the pinhole test and the double hydrometer test on investigations of soil dispersivity. In cases where the results of the pinhole, crumb and double hydrometer tests disagree the general order of reliability adopted by USBR is pinhole followed by crumb and double hydrometer.

In Australia and South Africa the most common and apparently most reliable test being used is the ESP test method which is purely chemical method.
2.5 Problems Associated with Dispersive Soil

Problems associated with dispersive soils include gully erosion and failure of soil to perform adequately as a construction material. Gully erosion results in soil loss, silting of reservoirs and dissection of land, reducing the land available for agricultural purposes. Where a surface layer of dispersive clay is underlain by pervious sand or gravel, rain water flows downward through initial leakage channels, formed as the result of drying cracks, animal holes or holes left by decaying roots, the walls of the leakage channels are rapidly eroded forming vertical tunnels and sinkholes.

Piping of material initiated by dispersion of clay particles along cracks and fissures and propagated by seepage water, often causing total failure of slopes of natural deposits and more seriously of earth dams and embankments.

Failures of earth dams constructed with dispersive soils are associated with a rapid filling to the reservoir either immediately or after a lengthy period of drought or change of water quality. Most failures are by piping through the embankments with subsequent total failure in a relatively short period of time.

According to (Sherard et al (1984); Sherard (1984); Sherard & Dunnigan (1985)), from the stand point of view of resistance of clay to erosion of concentrated leaks, it is believed that this is not so important. All clays will erode under severe conditions and it is not considered reasonable or conservative to rely on the relatively feeble erosion resistance of clayey soil to provide defense against piping of a concentrated leak. The
principal job of the core is to be impervious. Prevention of piping is the role of the filters.

2.6 Filters for Dispersive Soils

The main line of defense against dispersive clay erosion is the suitable filters located downstream of the clay. These filters shall prevent the excessive loss of material through small concentrated leakage channels developed due to differential settlements, shrinkage cracks, layering, hydraulic fracturing, slumping caused by earthquakes or any other deflection cracks. Cracks and small concentrated leaks (sometimes not readily observed) may develop through impervious sections of embankment dams even those designed and constructed according to good modern practice. They can not be totally avoided and must be taken into account in the design, construction and monitoring of dams (Sherard et al, 1985).

Terzaghi’s conventional filter criteria for granular soils is dealing only with slowly seeping water through pores of the base soil and according to Sherard et al (1984) filters meet these criteria would not be effective in controlling erosion in the more severe condition where a concentrated leak develops through the dam core from the reservoir and discharge into the filter. If the downstream face of the base soil is protected by a filter which is fine enough to prevent loss of material from the base soil, then the leak is sealed by one or both of two mechanisms:

- The rate of flow is reduced by the filter to the extent that the leak can be sealed by swelling of the base soil and closure of the leakage path.
- The material carried out of the crack is caught up in the pore spaces of the filter, resulting in clogging of the filter and sealing off the leak at the filter interface.

Intensive research works were performed in 1980’s for designing filters to retain clayey soils (both dispersive and non dispersive) with concentrated leaks. Melvill & Mackellar (1980) have developed a large diameter high pressure filter test with an artificial crack (5 mm diameter pinhole) in the base soil. They used the results of their testing to design filters for the dispersive clay core of the 75 m high Elandsjagt dam.

Vaughan & Soares (1982), while reviewing the partial piping failure of Balderhead dam in England, they claimed that in some base soils self filtering could not be relied upon, and that it was necessary to design filters to prevent the passing of the clay flocs into the filter. Consequently, they proposed the concept of a ‘perfect filter’ by preparing a sample from the floc sizes by sedimentation and introduce them to the filter experiment in a dilute suspension, which might be considered as a very conservative criterion.

Sherard et al (1984) and Sherard & Dunnigan (1985) have carried out a very comprehensive laboratory testing on an extensive range of clayey soils including some dispersive clays, to check filter criteria. They used both slurry tests and large diameter pinhole tests. These tests have generally shown that ‘critical filters’ meeting accepted conservative criteria would prevent significant erosion and safely control the concentrated leak in a stable equilibrium condition, or seal it. It has been confirmed that sands and gravelly sands with average \( D_{15} \) size of 0.5 mm or smaller are conservative filters for most clayey soils in nature, even
highly dispersive soils, with $d_{85}$ size of 0.03 mm or larger. More detailed criteria have also been introduced for various impervious soils depending on their content of fines (passing No 200 sieve) ignoring the gravel content. These criteria already incorporate an adequate factor of safety, and are therefore conservative. They are presented in Table (2.1) below:

<table>
<thead>
<tr>
<th>Soil Group</th>
<th>% Fines (&lt;0.075mm) excluding gravels (of material &lt;4.75 mm)</th>
<th>Recommended Design Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>85% to 100%</td>
<td>$D_{15}/d_{85} \leq 9$</td>
</tr>
<tr>
<td>2</td>
<td>40% to 85%</td>
<td>$D_{15} \leq 0.7$ mm</td>
</tr>
<tr>
<td>3</td>
<td>0% to 15%</td>
<td>$D_{15}/d_{85} \leq 4$</td>
</tr>
<tr>
<td>4</td>
<td>15% to 40%</td>
<td>Between group 2 &amp; 3</td>
</tr>
</tbody>
</table>

It is worth mentioning that these filter criteria have been found to apply regardless of the potential dispersiveness of the base soil.

De Mello (1989) discussed the Sherard and Dunnigan tests, and suggested that they can be plotted to show that the recommended criteria still have a significant probability of failure, if one allows for statistically reasonable segregation of the filter as placed. There would seem to be some validity in the argument but against this, is the good practical experience when such a criteria are used.

It is also so important for the filter material to be non cohesive by limiting the content of fines, otherwise it will have less permeability and could sustain open cracks when saturated and allows for erosion of the base soil.
2.7 Use of Dispersive Soils in Earth Dams

As postulated by many researchers, such as Sherard (1984) and Fell et al (1992), the considerable number of dispersive soil failures investigated have almost all been through homogeneous dams with no filters or poor coarse filters and minimal engineering attention in construction (most of them were small or medium size structures).

Because of the widespread existence of dispersive clays in nature, it is inevitable that, among the thousands of dams with wholly satisfactory experience many have impervious cores of dispersive clay. Also, several major dams, e.g. Mnjoli dam in Swaziland, Elandsjagt dam, Los Esteros dam and Goederrouw dam have been built with impervious sections, which were identified as being dispersive clay. The fact that these, and other dams, are behaving satisfactorily shows that dams can be constructed with dispersive clays provided that certain necessary precautions are taken during design and construction.

Where the only economical source of impervious soil available is dispersive, and where the selected earth dam is more economical than alternate dams, it is considered reasonable and appropriate practice to use such dispersive fine-grained soils in construction of the dam core, paying more attention to the defensive design details.

The main precautions that should be adopted when dispersive soil is to be used in construction of core dams:

1- Properly designed and constructed filters:
Sherard et al (1984) have proven conclusively that erosion of dispersive soils can be controlled by properly designed filters provided:

- Within the embankment downstream of the clay core to control erosion of the fine-grained core material.
- On the foundation, if it is dispersive soil, either as a horizontal drain or as a filter layer between the foundation and rock fill.
- Around outlet pipes.

2- Proper compaction of the soil:

Dispersive soils, particularly if being placed around outlet pipes, or at the contact between the earth fill and the concrete structures, must be properly compacted to minimize the probability of piping failure. ICOLD (1990) recommend compaction at water content above optimum water content so as to avoid a deflocculated soil structure, to avoid brittleness which will promote formation of cracks, and to ensure obtaining low permeability. Permeability lower than $10^{-5}$ cm/sec is always required. Fell et al (1992) recommended the water content to be between optimum and optimum+2% and not below optimum-1%, and a density ratio of greater than 98% of the Standard Proctor. Thin layers are preferred and care must be taken to avoid drying of the surface of layers of earth fill, which could result in cracking.

3- Careful detailing of pipes through the embankment:

If possible, pipes through embankments should be avoided since it is very difficult to ensure good compaction around the pipe, and differential settlement can also lead to cracking of the soil. If pipes must be placed through an embankment constructed by dispersive soil then it is desirable to support the pipes on concrete footings.
and either use filter to surround the downstream end of the pipe, or modify the dispersive soil round the pipe with lime or gypsum to render it less dispersive, or both.

4- Lime or gypsum modification of the soil, if necessary:
Most dispersive soils can be altered to non dispersive by adding little amount of lime or gypsum. The process incorporated is a cation exchange one, exchanging sodium ions (Na⁺) with calcium ions (Ca++) coming from the lime or the gypsum. The required amount of either lime or gypsum could be 2% to 4% well mixed with the soil, better with pulverizer to breaks up the soil and facilitates the mixing.

5- Sealing of cracks in the abutment and cut-off trench:
If the soil used for construction is dispersive, particular care must be taken to seal cracks in the cut-off foundation, and the sides of the cut-off trench so the soil will not erode in the cracks. For rock foundations grouting to enough depth is useful, and slush concrete or shotcrete may be used on the outside surfaces. If the cut-off trench is in soil, it may be necessary to provide a filter on the downstream side.
CHAPTER THREE

THE LABORATORY STUDY
CHAPTER THREE
THE LABORATORY STUDY

3.1 Introduction
This Chapter presents, in details, the laboratory study which was performed on two soil samples, known to be potentially dispersive, to study and observe their erodibility and erosion resistance behavior in relation to different densities, compaction moisture contents and curing time or aging.

The main objective of this laboratory study is to observe the effects of moisture content and dry density of some remoulded specimens of potentially erosive soils on their erosion resistance at different curing periods after remoulding. It was assumed that the remoulded specimens are representative of compacted material in earth embankments or cores of fill dams. The time factor is reflected by the time before exposure to flowing water, i.e. first water filling of reservoir.

3.2 Material Collection and Storage
For the purposes of this study, two samples were collected from the River Nile sedimentary deposits, one from the homogeneous clayey Nile silt (Sample (A)) from the flood plains of the Nile, and the other from a sandy clay material found in the upper terrace of the Nile (Sample (B)). These two samples were obtained from the Northern State, about 40 km upstream of Merowe town. Materials from the same sources were tested during investigations for the core material of Merowe Dam Project (BRRI (2001)) and were known to have moderate to high dispersion characteristics.
After being collected, the two samples were immediately stored in well closed and sealed drums to prevent drying out. Drying out is usually not desirable for a material intended to be tested for dispersivity, as mentioned before in Chapter 2. The samples were then transported to the laboratories of Building and Road Research Institute (BRRI) of the University of Khartoum.

**3.3 Classification of Samples and Preliminary Testing**

The two samples were first tested for their main index properties and some other tests that are considered useful to assess the nature of the material as related to erodibility.

To classify and identify the two sample types, the following tests were carried out:

- Natural moisture content
- Atterberg limits (liquid, plastic and shrinkage limits)
- Grain size distribution (sieve analysis and hydrometer)
- Specific gravity
- Standard Proctor test
- Modified Proctor test
- Free swell

The results are displayed in Table (3.1). Accordingly the two samples (A and B) could be classified as low plastic silt and low plastic clay respectively. The grain size distribution curves are presented in Fig (3.1), while the compaction test results (Standard and Modified Proctor) for sample (A) and sample (B) are shown in Figure (3.2) and Figure (3.3) respectively.
Table (3.1): Classification of samples, A and B

<table>
<thead>
<tr>
<th>Sample</th>
<th>N.M.C (%)</th>
<th>L.L (%)</th>
<th>P.L (%)</th>
<th>P.I (%)</th>
<th>Fines (%)</th>
<th>S.G</th>
<th>S.L (%)</th>
<th>F.S (%)</th>
<th>Classification (USCS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>21.3</td>
<td>37</td>
<td>25</td>
<td>12</td>
<td>81.4</td>
<td>2.76</td>
<td>15.9</td>
<td>78</td>
<td>ML</td>
</tr>
<tr>
<td>B</td>
<td>9.8</td>
<td>43</td>
<td>25</td>
<td>18</td>
<td>61.4</td>
<td>2.71</td>
<td>17.4</td>
<td>56</td>
<td>CL</td>
</tr>
</tbody>
</table>

Figure (3.1): Grain size distribution curves for samples A and B
Standard Proctor
MDD = 16.20 KN/m³, OMC = 20.6%
Modified Test:
MDD = 17.90 KN/m³, OMC = 17.0%

Figure (3.2): Standard and Modified compaction tests results for samples A

Standard Test
MDD = 16.13 KN/m³, OMC = 21.3%
Modified Test:
MDD = 17.80 KN/m³, OMC = 16.5%

Figure (3.3): Standard and Modified compaction tests results for sample (B)
3.4 Dispersivity Testing

The two samples were tested for dispersivity by the following tests:
- Pinhole test
- Double hydrometer test
- Crumb test
- Exchangeable cations (CEC and ESP)
- Pore water cations (SAR)

The results of the pinhole test and the crumb test are shown in Table (3.2). The results of the chemical dispersivity testing are presented in Table (3.3). Fig (3.4) and Fig (3.5) show the results of the double hydrometer tests for sample (A) and sample (B) respectively. Sample (A) is non dispersive from the results of the pinhole test and the crumb test while it is slightly to moderately dispersive from the results of the double hydrometer and the chemical testing. The results of all dispersivity tests for sample (B) showed that it is highly dispersive.

Table (3.2): Results of Pinhole Test and Crumb Test for Samples A and B

<table>
<thead>
<tr>
<th>Sample</th>
<th>Pinhole Test Result</th>
<th>Crumb Test Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MC (%)</td>
<td>DD (kN/m³)</td>
</tr>
<tr>
<td>A</td>
<td>23.34</td>
<td>15.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>25.17</td>
<td>15.30</td>
</tr>
</tbody>
</table>
Table (3.3): Results of the Chemical Dispersivity Testing

<table>
<thead>
<tr>
<th>Sample</th>
<th>CEC (m. equivalents per 100 gm)</th>
<th>ESP (%)</th>
<th>SAR ((milliequivalent/Liter)^0.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>34.5</td>
<td>13.0</td>
<td>13.8</td>
</tr>
<tr>
<td>B</td>
<td>41.3</td>
<td>42.7</td>
<td>43.0</td>
</tr>
</tbody>
</table>

Figure (3.4): Double hydrometer test result for sample (A)
3.5 Pinhole Test

The pinhole test was selected as the main method for testing and observing erodibility of the tested specimens at varying dry density, moisture content and curing time. The pinhole test was considered suitable for this laboratory study for the following reasons:

- It is a direct measure of the erodibility of compacted soils.
- It simulates the flow of water in cracked earth fill.
- The various grades of its results are useful in checking and comparing the results.
- Its results are reproducible.
- Remoulded specimens with varying moisture contents and densities can be tested.
Several test specimens were prepared from the two soil samples to cover a wide range of moisture content and density.

It was found more practical and controllable to prepare the specimens with the same dimensions as the pinhole test specimen to reduce disturbance and/or density changes experienced when samples are extracted from compaction moulds.

Each specimen had to be pinhole tested after certain curing period of time at specified moisture content and dry density.

3.6 The Plan for the Main Testing and the Preparatory Works

Thirty six test specimens were prepared for each sample to cover a wide range of moisture content and density. The specimens were divided into six groups, each group with six identical specimens, according to their moisture content and dry density condition (A1 to A6 and B1 to B6; see Table (3.4)).

Three moisture contents were selected for preparation of specimens, covering the range of (OMC-2.1) % to (OMC+2.9) % for sample (A) and (OMC-4.3) % to (OMC+3.7) % for sample (B). The dry densities used were either 88% or 95% or 105% of the Standard Proctor MDD for each sample. These ranges may fairly be considered to include the normal and probable ranges for implementation of most earth fill works.

Table (3.4), Figure (3.6) and Figure (3.7) show the selected values of moisture content and dry density for the six groups of specimens to be prepared from each sample, compared with the Optimum Moisture Content and Maximum Dry Density of the Standard Proctor test.
Table (3.4): The selected moisture contents and dry densities for the preparation of specimens from samples A and B

<table>
<thead>
<tr>
<th>Sample (A)</th>
<th>Sample (B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OMC= 20.6%, MDD= 16.20 KN/m³</td>
<td>OMC= 21.3%, MDD=16.13 KN/m³</td>
</tr>
<tr>
<td>sample</td>
<td>MC (%)</td>
</tr>
<tr>
<td>A1</td>
<td>18.5</td>
</tr>
<tr>
<td>A2</td>
<td>18.5</td>
</tr>
<tr>
<td>A3</td>
<td>20.5</td>
</tr>
<tr>
<td>A4</td>
<td>20.5</td>
</tr>
<tr>
<td>A5</td>
<td>20.5</td>
</tr>
<tr>
<td>A6</td>
<td>23.5</td>
</tr>
</tbody>
</table>

Figure (3.6): The selected moisture contents and dry densities for the preparation of specimens from sample (A)
The six “identical” specimens from each group were to be pinhole tested after:

- No curing (to be tested immediately after preparation)
- 6 hours
- 1 day
- 3 days
- 7 days
- 1 month

For this plan to be achieved, the first step was to establish an accurate procedure for obtaining samples with the required moisture contents within error of about +/-0.5%. The next step was to compact each set of specimens to the desired dry density within acceptable error.
Sample Preparation:

Since all the specimens had to be pinhole tested, specimens with the typical dimensions as the pinhole test specimen were to be prepared. A small mould was manufactured with internal dimensions equal to the dimensions of the specimen used in the pinhole test. The mould had also to allow easy removal of remoulded specimen without disturbance. According to these requirements, the mould was manufactured by dividing a steel cylinder, with the required length and with slightly smaller diameter, longitudinally into two halves. The two halves were to be tied together properly by means of a hose clip. The internal diameter was finally adjusted to the required diameter after the two halves were properly tied. The hose clip was always used to tie the two halves of the mould before filling it, and were taken out to allow easy removal of the two halves surrounding the specimen after being compacted.

The mould was tested by randomly preparing some specimens from the study samples, A and B, trying to cover the range of moisture contents and dry densities required for the study. It was found that a specimen could be remoulded inside the tied mould in 5 layers and could be removed out from the mould, with some care, obtaining a specimen in good condition.

The sample preparation included screening of the material through a 2 mm size sieve. The material was carefully screened through the sieve inside plastic bags trying to prevent drying out of the material. It was, sometimes, a difficult operation and took long time especially for sample (A) material, which has the highest moisture content. Close attention was always paid during this operation not to allow the material to dry out.
After the material was screened through the 2 mm size sieve, its moisture content was measured and it was then stored in a desiccator.

The moisture content of the specimens was adjusted as follows. The actual moisture content was measured for the screened material and was recorded as the initial moisture content (MCi). The amount of water (W) gm needed to be added to weight of (wt) gm of the material to bring its moisture content to a specified value, MCf, was calculated by the formula:

$$W = \frac{(MCf-MCi) \times wt}{(1+MCi)}$$

The calculated amount of water was weighed and added to the material. The material was then properly mixed inside a plastic bag. Samples to check the target moisture content were taken. The plastic bag was then properly tied and placed inside the dessicator.

To prepare any set of specimens with target moisture content and dry density, the bulk weight needed to fill the volume of the mould was calculated by multiplying the bulk density times the volume of the mould. The bulk density was basically computed using the required dry density and moisture content. The calculated bulk weight was used to fill the mould in five equal layers. The number of layers is the same number as the standard number of layers for the preparation of the pinhole test specimen.

Every layer was filled and compacted using a small tamping rod until the thickness of the layer became 7.6 mm (one fifth of the depth of the
mould). After compaction, the hose clip was taken out and the two halves were removed carefully by hammering very lightly on the edges of the mould.

Following the procedure mentioned above, the 72 specimens, 36 for each sample, were prepared in accordance with the desired moisture contents and dry densities showed in Table (3.4). It was found that these required moisture contents and dry densities could be obtained reasonably with very small errors.

Some specimens were broken or disturbed during the preparation work, i.e. during compaction, removal from the mould or during insertion of the specimen inside the pinhole test cylinder. For these conditions, other specimens were prepared to replace the failed ones.

The prepared specimens were placed in the dessicator for the assigned curing time.

The operation of compaction of specimens in the mould is shown below in Figure (3.8). Figure (3.9) presents the removal of the specimen from the mould, while Figure (3.10) displays the operation of weighting the specimen before placing it in a plastic bag and storing it in the dessicator.
Figure (3.8): Compaction of specimens in the mould
Figure (3.9): Removal of the specimen from the mould
Figure (3.10): Weighting the specimen before placing it in a plastic bag and storing it in the desiccator
3.7 The Study Program

3.7.1 Main Testing Program

All the 72 samples were pinhole tested after the planned curing times were attained. At the specified time of testing a specimen, it was taken out from the dessicator. The seal was removed and the specimen was weighed. The weight was recorded and compared with the initial weight before sealing and storing. The specimen was then gently entered into the mould of the pinhole test to the required position which is 50 mm from one end and 12 mm from the other end. After that the test nipple was placed in the center of the specimen from the 12 mm space edge. The pinhole test needle with 1 mm diameter was used to form the pin-hole in the specimen through the nipple while putting some support at the other end to avoid disturbance of the specimen.

After the hole was correctly formed, a wire mesh was placed at the 12 mm edge, the space was filled by clean and dry pea gravel and the side cover was then used as required. The same was done to the other side using 2 meshes.

After the pinhole mould became ready for testing, it was placed in the pinhole test apparatus and the original testing procedure mentioned in Chapter 2 was followed by causing distilled water to flow through the hole under 50, 180, 380 and 1020 mm heads for 5 minutes for each head except for the head 50 mm which was allowed for additional 5 minutes. The color and turbidity of the out-flow were observed. The discharge of the out flowing water was determined for every head by recording the time needed to fill a 50 ml measuring cylinder. The test was stopped by closing the in-flow water valve whenever the out-flow water was not substantially clear, otherwise it was stopped after 5 min of applying the
1020 mm head. In some cases, when there was no out flow after the 50 mm head was applied, or when the flow was stopped by clogging of the hole after moments of the 50 mm head application, the mould was removed from the apparatus, opened and the hole was reformed before restarting the test again. Usually, this was sufficient to allow continuation of the test. In case of no out-flow the specimen was removed from the mould and a new specimen was prepared to replace the failed one.

The information for every specimen in the pinhole test was recorded, including:

- the test moisture content
- the dry density, calculated from the measured bulk density and the measured moisture content
- the curing time
- the heads applied when the specimens were pinhole tested and their subsequent flow rates
- the observed diameter of the hole after test
- any special remarks or observations during the testing

All the specimens were identified after the test to one of the grades of the pinhole test: D1 (highly dispersive), D2 (dispersive), ND4 (moderately dispersive), ND3 (slightly dispersive), ND2 (very slightly dispersive) and ND1 (non dispersive). Table (3.5) includes the recorded information for specimens made from both samples and their pinhole test records.

3.7.2 Additional Testing Program
In addition to the specimens prepared to replace the damaged ones, some more specimens were prepared and tested when the result of the pinhole test was not very clear and/or marginal. Also, as a consequence of the
analysis of the results of the originally planned work, it was deemed useful to add some additional specimens with other moisture content and density or to test for more curing times. Furthermore, some of sample (A) material was dried and tested to investigate the effect of drying out on the pinhole test results. A description of the retesting and the additional work planned and executed is given below.

All damaged specimens in the different stages of the preparation and the testing works were replaced by newly prepared specimens. Some specimens were replaced more than one time especially specimens prepared with lower densities or lower moisture contents.

Seven specimens were added to test another set of moisture content and dry density for Sample (B). More specimens were prepared from both samples and tested after more than one year of curing. The additional specimens were as follows:

- Sample (A): two specimens for the two sets of moisture content and dry density which were found to be dispersive and improved with time to less dispersive. These two specimens were (OMC-2.1%, 95% of MDD) and (OMC, 88% of MDD) and were cured and tested after more than one and half year to check the effect of longer curing time.

- Sample (B): a complete set was added, to the original six sets, to test the highest moisture content (OMC+3.7%) with a higher dry density (101% of MDD). Also, additional specimen was added for each of the seven sets so as to be cured for more than one year.

Sample (A) material was found to be slightly dispersive to non dispersive, although material from the same source was rendered dispersive in the
previous investigation. Since improper storage could allow the material to dry out and could affect the pinhole test results, as mentioned in Chapter two, some of Sample (A) material was allowed to dry out for about two weeks in a shaded area. Six dried specimens were then pinhole tested immediately after remoulding. The specimens were prepared with the same moisture contents and dry densities used to test sample (A).

The pinhole test results for all the additionally tested specimens as replacement or for extended curing time are included in Table (3.5). The pinhole test results for the specimens made of the dried Sample (A) specimens are shown in Table (3.6).
### Table (3.5): Pinhole Test Results for Sample (A) and Sample (B); original testing and all additional tests

<table>
<thead>
<tr>
<th>Sample</th>
<th>Specimen</th>
<th>Curing Time</th>
<th>Measured Moisture Content (%)</th>
<th>Measured Dry Density (kN/m³)</th>
<th>Applied Water Head (mm)</th>
<th>Water Flow Rate (ml/min)</th>
<th>Observed Water Color</th>
<th>Hole Dia after test (mm)</th>
<th>Pinhole Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>A1-1</td>
<td>None</td>
<td>18.40</td>
<td>17.04</td>
<td>50 180 380</td>
<td>0.60 1.35 2.38</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Problem with apparatus. Test not completed. New specimen prepared.</td>
</tr>
<tr>
<td></td>
<td>A1-1a</td>
<td>None</td>
<td>18.50</td>
<td>17.02</td>
<td>50 180 380 1020</td>
<td>0.21 0.56 1.06 2.27</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>A1-2</td>
<td>6 hrs</td>
<td>18.38</td>
<td>17.02</td>
<td>50 180 380 1020</td>
<td>0.32 0.70 1.09 2.27</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>A1-3</td>
<td>1 day</td>
<td>18.45</td>
<td>17.03</td>
<td>50 180 380 1020</td>
<td>0.29 0.70 1.04 2.00</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>A1-4</td>
<td>3 days</td>
<td>18.47</td>
<td>17.03</td>
<td>50 180 380 1020</td>
<td>0.24 0.56 1.02 2.00</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>A1-5</td>
<td>7 days</td>
<td>18.30</td>
<td>17.04</td>
<td>50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Specimen was destroyed</td>
</tr>
<tr>
<td></td>
<td>A1-5a</td>
<td>7 days</td>
<td>18.54</td>
<td>17.00</td>
<td>50 180 380 1020</td>
<td>0.20 0.50 0.86 1.92</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>Sample</td>
<td>Specimen</td>
<td>Curing Time</td>
<td>Measured Moisture Content (%)</td>
<td>Measured Dry Density (kN/m³)</td>
<td>Applied Water Head (mm)</td>
<td>Water Flow Rate (ml/min)</td>
<td>Observed Water Color</td>
<td>Hole Dia after test (mm)</td>
<td>Pinhole Test Result</td>
<td>Remarks</td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>-------------</td>
<td>-------------------------------</td>
<td>-------------------------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td>----------------------</td>
<td>------------------------</td>
<td>----------------------</td>
<td>---------</td>
</tr>
<tr>
<td>A2-1</td>
<td>None</td>
<td>18.78</td>
<td>15.36</td>
<td>50</td>
<td>0.42</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td>Low flow rate</td>
<td></td>
</tr>
<tr>
<td>A2-2</td>
<td>6 hrs</td>
<td>18.57</td>
<td>15.38</td>
<td>50</td>
<td>0.42</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td>Low flow rate</td>
<td></td>
</tr>
<tr>
<td>A2-3</td>
<td>1 day</td>
<td>18.73</td>
<td>15.37</td>
<td>50</td>
<td>0.36</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td>Low flow rate</td>
<td></td>
</tr>
<tr>
<td>A2-4</td>
<td>3 days</td>
<td>18.50</td>
<td>15.40</td>
<td>50 180</td>
<td>0.36 1.04</td>
<td>Not clear</td>
<td>&gt;1.5</td>
<td>D1/D2</td>
<td>Low flow rate though the coming water not clear. New sample was used</td>
<td></td>
</tr>
<tr>
<td>A2-4a</td>
<td>3 days</td>
<td>18.40</td>
<td>15.38</td>
<td>50 180 380 1020</td>
<td>0.34 0.68 1.14 2.50</td>
<td>Clear</td>
<td>&gt;1.0</td>
<td>ND1/ND2</td>
<td>The coming water not very clear but clear. New sample was used</td>
<td></td>
</tr>
<tr>
<td>A2-4b</td>
<td>3 days</td>
<td>18.38</td>
<td>15.38</td>
<td>50</td>
<td>-</td>
<td>Dark</td>
<td>-</td>
<td>D1</td>
<td>Hole blocked.</td>
<td></td>
</tr>
<tr>
<td>A2-5</td>
<td>7 days</td>
<td>18.29</td>
<td>15.40</td>
<td>50 180 380 1020</td>
<td>0.31 0.72 1.25 2.63</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2-6</td>
<td>1 month</td>
<td>18.42</td>
<td>15.38</td>
<td>50 180 380 1020</td>
<td>0.24 0.63 1.02 2.17</td>
<td>clear then slightly dark then clear</td>
<td>About 2.0</td>
<td>ND1/ND2</td>
<td>Water is not very clear at 50 mm head but continues to be more clear till becomes very clear for 380 and 1020 mm heads.</td>
<td></td>
</tr>
<tr>
<td>A2-7</td>
<td>&gt;1.5 year</td>
<td>18.61</td>
<td>15.36</td>
<td>50 180 380 1020</td>
<td>0.43 0.81 1.32 2.38</td>
<td>clear</td>
<td>About 1.0</td>
<td>ND1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**A2**
Target MC 18.5 %
Target DD 15.39 KN/m³
<table>
<thead>
<tr>
<th>Sample</th>
<th>Specimen</th>
<th>Curing Time</th>
<th>Measured Moisture Content (%)</th>
<th>Measured Dry Density (kN/m³)</th>
<th>Applied Water Head (mm)</th>
<th>Water Flow Rate (ml/min)</th>
<th>Observed Water Color</th>
<th>Hole Dia after test (mm)</th>
<th>Pinhole Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A3-1</td>
<td>None</td>
<td>20.74</td>
<td>17.01</td>
<td>50</td>
<td>180</td>
<td>0.42</td>
<td>0.89</td>
<td>1.52</td>
<td>2.78</td>
<td>ND1</td>
</tr>
<tr>
<td>A3-2</td>
<td>6 hrs</td>
<td>20.64</td>
<td>17.00</td>
<td>50</td>
<td>180</td>
<td>0.25</td>
<td>0.60</td>
<td>0.98</td>
<td>1.92</td>
<td>ND1</td>
</tr>
<tr>
<td>A3-3</td>
<td>1 day</td>
<td>20.87</td>
<td>16.99</td>
<td>50</td>
<td>180</td>
<td>0.31</td>
<td>0.79</td>
<td>1.25</td>
<td>2.50</td>
<td>ND1</td>
</tr>
<tr>
<td>A3-4</td>
<td>3 days</td>
<td>20.84</td>
<td>16.99</td>
<td>50</td>
<td>180</td>
<td>0.34</td>
<td>0.79</td>
<td>1.32</td>
<td>2.78</td>
<td>ND1</td>
</tr>
<tr>
<td>A3-5</td>
<td>7 days</td>
<td>20.79</td>
<td>16.99</td>
<td>50</td>
<td>180</td>
<td>0.42</td>
<td>0.98</td>
<td>1.61</td>
<td>3.33</td>
<td>ND1</td>
</tr>
</tbody>
</table>

A3
Target MC 20.5 %
Target DD 17.05 KN/m³

Hole blocked and reformed successfully.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Specimen</th>
<th>Curing Time</th>
<th>Measured Moisture Content (%)</th>
<th>Measured Dry Density (kN/m³)</th>
<th>Applied Water Head (mm)</th>
<th>Water Flow Rate (ml/min)</th>
<th>Observed Water Color</th>
<th>Hole Dia after test (mm)</th>
<th>Pinhole Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A4-1</td>
<td>None</td>
<td>20.29</td>
<td>15.40</td>
<td>50</td>
<td>0.36</td>
<td>0.77</td>
<td>1.22</td>
<td>2.27</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>380</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4-2</td>
<td>6 hrs</td>
<td>20.46</td>
<td>15.37</td>
<td>50</td>
<td>0.36</td>
<td>0.83</td>
<td>1.32</td>
<td>2.50</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>380</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4-3</td>
<td>1 day</td>
<td>20.38</td>
<td>15.40</td>
<td>50</td>
<td>0.36</td>
<td>0.79</td>
<td>1.19</td>
<td>2.17</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>380</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4-4</td>
<td>3 days</td>
<td>20.33</td>
<td>15.40</td>
<td>50</td>
<td>0.31</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>ND1</td>
<td>Hole blocked.</td>
</tr>
<tr>
<td>A4-4a</td>
<td>3 days</td>
<td>20.45</td>
<td>15.38</td>
<td>50</td>
<td>0.32</td>
<td>0.67</td>
<td>1.04</td>
<td>1.85</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>380</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4-5</td>
<td>7 days</td>
<td>20.09</td>
<td>15.43</td>
<td>50</td>
<td>0.34</td>
<td>0.68</td>
<td>1.06</td>
<td>2.08</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>380</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1020</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A4
Target MC 20.5 %
Target DD 15.39 KN/m³
### Table (3.5)...cont.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Specimen</th>
<th>Curing Time</th>
<th>Measured Moisture Content (%)</th>
<th>Measured Dry Density (kN/m^3)</th>
<th>Applied Water Head (mm)</th>
<th>Water Flow Rate (ml/min)</th>
<th>Observed Water Color</th>
<th>Hole Dia after test (mm)</th>
<th>Pinhole Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A5-1</td>
<td>None</td>
<td>20.14</td>
<td>14.30</td>
<td>50</td>
<td>180</td>
<td>0.42</td>
<td>slightly dark to Clear</td>
<td>2.0</td>
<td>D2/ND4</td>
<td>Flow rate relatively small. Water color clear then slightly dark then clear then barely visible color with some falling small particles.</td>
</tr>
<tr>
<td>A5-1a</td>
<td>None</td>
<td>20.28</td>
<td>14.27</td>
<td>50</td>
<td></td>
<td>0.34</td>
<td>Dark</td>
<td>2.0</td>
<td>D1</td>
<td>Water clear at beginning</td>
</tr>
<tr>
<td>A5-1b</td>
<td>None</td>
<td>20.63</td>
<td>14.24</td>
<td>50</td>
<td>180</td>
<td>0.43</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A5-1c</td>
<td>None</td>
<td>20.80</td>
<td>14.23</td>
<td>50</td>
<td></td>
<td>-</td>
<td>Dark</td>
<td>-</td>
<td>D1</td>
<td>Hole clogged</td>
</tr>
<tr>
<td>A5-2</td>
<td>6 hrs</td>
<td>20.35</td>
<td>14.28</td>
<td>50</td>
<td></td>
<td>-</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td>Hole blocked and reformed.</td>
</tr>
<tr>
<td>A5-3</td>
<td>1 day</td>
<td>20.32</td>
<td>14.28</td>
<td>50</td>
<td></td>
<td>-</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td>Hole blocked and reformed.</td>
</tr>
<tr>
<td>A5-4</td>
<td>3 days</td>
<td>20.24</td>
<td>14.29</td>
<td>50</td>
<td></td>
<td>-</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td>Water becoming very turbid</td>
</tr>
<tr>
<td>A5-5</td>
<td>7 days</td>
<td>20.21</td>
<td>14.29</td>
<td>50</td>
<td>180</td>
<td>0.33</td>
<td>Moderately dark</td>
<td>&gt;2.0</td>
<td>D1/ND4</td>
<td>Clear water till after 7 minutes.</td>
</tr>
<tr>
<td>A5-5a</td>
<td>7 days</td>
<td>20.67</td>
<td>14.22</td>
<td>50</td>
<td>180</td>
<td>0.39</td>
<td>Dark</td>
<td>&gt;2.0</td>
<td>D1/ND2</td>
<td>Water clear at first then changed gradually to dark.</td>
</tr>
<tr>
<td>A5-6</td>
<td>1 month</td>
<td>20.74</td>
<td>14.22</td>
<td>50</td>
<td>180</td>
<td>0.52</td>
<td>clear then slightly dark then clear</td>
<td>About 2.0</td>
<td>ND1/ND2</td>
<td>Water is not very clear at 50 mm head but continues to be clearer till becomes very clear for 380 and 1020 mm heads.</td>
</tr>
<tr>
<td>A5-7</td>
<td>&gt;1.5 year</td>
<td>20.75</td>
<td>14.22</td>
<td>50</td>
<td>180</td>
<td>0.36</td>
<td>clear but not very clear</td>
<td>About 2.0</td>
<td>ND1/ND2</td>
<td></td>
</tr>
<tr>
<td>Sample</td>
<td>Specimen</td>
<td>Curing Time</td>
<td>Measured Moisture Content (%)</td>
<td>Measured Dry Density (kN/m³)</td>
<td>Applied Water Head (mm)</td>
<td>Water Flow Rate (ml/min)</td>
<td>Observed Water Color</td>
<td>Hole Dia after test (mm)</td>
<td>Pinhole Test Result</td>
<td>Remarks</td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>-------------</td>
<td>-------------------------------</td>
<td>----------------------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td>-----------------------</td>
<td>-------------------------</td>
<td>----------------------</td>
<td>---------</td>
</tr>
<tr>
<td>A6-1</td>
<td>None</td>
<td>23.34</td>
<td>15.40</td>
<td>50</td>
<td>180 380 1020</td>
<td>0.35 0.76 1.25 2.17</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A6-2</td>
<td>6 hrs</td>
<td>23.56</td>
<td>15.38</td>
<td>50</td>
<td>180 380 1020</td>
<td>0.36 0.79 1.25 2.27</td>
<td>Clear</td>
<td>1.0</td>
<td>ND1</td>
<td>The coming water not very clear but clear</td>
</tr>
<tr>
<td>A6-2a</td>
<td>6 hrs</td>
<td>23.47</td>
<td>15.39</td>
<td>50</td>
<td>180 380 1020</td>
<td>0.43 0.91 1.43 2.78</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A6-3</td>
<td>1 day</td>
<td>23.34</td>
<td>15.40</td>
<td>50</td>
<td>180 380 1020</td>
<td>0.32 0.70 1.16 2.17</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A6-4</td>
<td>3 days</td>
<td>23.42</td>
<td>15.38</td>
<td>50</td>
<td>180 380 1020</td>
<td>0.54 1.16 1.79 3.13</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A6-5</td>
<td>7 days</td>
<td>23.33</td>
<td>15.41</td>
<td>50</td>
<td>180 380 1020</td>
<td>0.39 0.83 1.32 2.50</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
</tbody>
</table>

A6
Target MC 23.5 %
Target DD 15.39 kN/m³
<table>
<thead>
<tr>
<th>Sample</th>
<th>Specimen</th>
<th>Curing Time</th>
<th>Measured Moisture Content (%)</th>
<th>Measured Dry Density (KN/m³)</th>
<th>Applied Water Head (mm)</th>
<th>Water Flow Rate (ml/min)</th>
<th>Observed Water Color</th>
<th>Hole Dia after test (mm)</th>
<th>Pinhole Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>B1-1</td>
<td>None</td>
<td>17.21</td>
<td>16.87</td>
<td>50</td>
<td>1.11</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-2</td>
<td>6 hrs</td>
<td>17.28</td>
<td>16.86</td>
<td>50</td>
<td>1.09</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-3</td>
<td>1 day</td>
<td>17.10</td>
<td>16.87</td>
<td>50</td>
<td>1.25</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-4</td>
<td>3 days</td>
<td>17.08</td>
<td>16.88</td>
<td>50</td>
<td>1.11</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-5</td>
<td>7 days</td>
<td>17.33</td>
<td>16.85</td>
<td>50</td>
<td>1.16</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-6</td>
<td>1 month</td>
<td>17.45</td>
<td>16.82</td>
<td>50</td>
<td>1.09</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B1-7</td>
<td>&gt; 1 yr</td>
<td>17.53</td>
<td>16.83</td>
<td>50</td>
<td>1.06</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>B2-1</td>
<td>None</td>
<td>17.06</td>
<td>15.30</td>
<td>50</td>
<td>1.28</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B2-2</td>
<td>6 hrs</td>
<td>17.34</td>
<td>15.28</td>
<td>50</td>
<td>1.14</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B2-3</td>
<td>1 day</td>
<td>17.32</td>
<td>15.26</td>
<td>50</td>
<td>1.04</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B2-4</td>
<td>3 days</td>
<td>17.34</td>
<td>15.27</td>
<td>50</td>
<td>1.00</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B2-5</td>
<td>7 days</td>
<td>17.30</td>
<td>15.28</td>
<td>50</td>
<td>1.02</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B2-6</td>
<td>1 month</td>
<td>17.49</td>
<td>15.25</td>
<td>50</td>
<td>1.09</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B2-7</td>
<td>&gt; 1 yr</td>
<td>17.55</td>
<td>15.23</td>
<td>50</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Specimen was destroyed</td>
</tr>
<tr>
<td>B3</td>
<td>B3-1</td>
<td>None</td>
<td>21.27</td>
<td>16.87</td>
<td>50</td>
<td>1.16</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3-2</td>
<td>6 hrs</td>
<td>21.03</td>
<td>16.91</td>
<td>50</td>
<td>1.06</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3-3</td>
<td>1 day</td>
<td>21.37</td>
<td>16.87</td>
<td>50</td>
<td>1.16</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3-4</td>
<td>3 days</td>
<td>21.09</td>
<td>16.89</td>
<td>50</td>
<td>1.09</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3-5</td>
<td>7 days</td>
<td>21.02</td>
<td>16.89</td>
<td>50</td>
<td>1.02</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3-6</td>
<td>1 month</td>
<td>21.08</td>
<td>16.89</td>
<td>50</td>
<td>1.22</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3-7</td>
<td>&gt; 1 yr</td>
<td>21.03</td>
<td>16.91</td>
<td>50</td>
<td>0.91</td>
<td>Slightly dark</td>
<td>&gt;1.5</td>
<td>D2</td>
<td>50 mm: very slightly dark color. 180 mm: slightly to moderately dark color</td>
</tr>
</tbody>
</table>
Table (3.5)...cont.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Specimen</th>
<th>Curing Time</th>
<th>Measured Moisture Content (%)</th>
<th>Measured Dry Density (KN/m³)</th>
<th>Applied Water Head (mm)</th>
<th>Water Flow Rate (ml/min)</th>
<th>Observed Water Color</th>
<th>Hole Dia after test (mm)</th>
<th>Pinhole Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B4</td>
<td>B4-1</td>
<td>None</td>
<td>21.24</td>
<td>15.29</td>
<td>50</td>
<td>1.00</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4-2</td>
<td>6 hrs</td>
<td>21.29</td>
<td>15.29</td>
<td>50</td>
<td>1.22</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4-3</td>
<td>1 day</td>
<td>21.29</td>
<td>15.28</td>
<td>50</td>
<td>1.19</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4-4</td>
<td>3 days</td>
<td>21.13</td>
<td>15.30</td>
<td>50</td>
<td>1.06</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4-5</td>
<td>7 days</td>
<td>20.88</td>
<td>15.34</td>
<td>50</td>
<td>1.22</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4-6</td>
<td>1 month</td>
<td>20.71</td>
<td>15.36</td>
<td>50</td>
<td>1.02</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B4-7</td>
<td>&gt; 1 yr</td>
<td>20.88</td>
<td>15.33</td>
<td>50</td>
<td>1.39</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td>B5</td>
<td>B5-1</td>
<td>None</td>
<td>21.16</td>
<td>14.16</td>
<td>50</td>
<td>1.02</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5-2</td>
<td>6 hrs</td>
<td>20.91</td>
<td>14.20</td>
<td>50</td>
<td>1.14</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5-3</td>
<td>1 day</td>
<td>21.33</td>
<td>14.14</td>
<td>50</td>
<td>1.00</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5-4</td>
<td>3 days</td>
<td>20.90</td>
<td>14.21</td>
<td>50</td>
<td>1.16</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5-5</td>
<td>7 days</td>
<td>20.77</td>
<td>14.22</td>
<td>50</td>
<td>1.39</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5-6</td>
<td>1 month</td>
<td>20.96</td>
<td>14.20</td>
<td>50</td>
<td>1.11</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B5-7</td>
<td>&gt; 1 yr</td>
<td>21.14</td>
<td>14.17</td>
<td>50</td>
<td>1.32</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Specimen was destroyed</td>
</tr>
<tr>
<td>B6</td>
<td>B6-1</td>
<td>None</td>
<td>25.17</td>
<td>15.30</td>
<td>50</td>
<td>1.14</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6-2</td>
<td>6 hrs</td>
<td>25.04</td>
<td>15.32</td>
<td>50</td>
<td>1.00</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6-3</td>
<td>1 day</td>
<td>25.18</td>
<td>15.31</td>
<td>50</td>
<td>1.16</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6-4</td>
<td>3 days</td>
<td>25.18</td>
<td>15.30</td>
<td>50</td>
<td>1.04</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6-5</td>
<td>7 days</td>
<td>25.21</td>
<td>15.29</td>
<td>50</td>
<td>1.22</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6-6</td>
<td>1 month</td>
<td>25.00</td>
<td>15.31</td>
<td>50</td>
<td>1.00</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
</tbody>
</table>

Specimen was destroyed
<table>
<thead>
<tr>
<th>Sample</th>
<th>Specimen</th>
<th>Curing Time</th>
<th>Measured Moisture Content (%)</th>
<th>Measured Dry Density (KN/m³)</th>
<th>Applied Water Head (mm)</th>
<th>Water Flow Rate (ml/min)</th>
<th>Observed Water Color</th>
<th>Hole Dia after test (mm)</th>
<th>Pinhole Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>B7</td>
<td>B7-1</td>
<td>None</td>
<td>24.72</td>
<td>16.31</td>
<td>50</td>
<td>1.22</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7-2</td>
<td>6 hrs</td>
<td>24.77</td>
<td>16.33</td>
<td>50</td>
<td>1.11</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7-3</td>
<td>1 day</td>
<td>24.68</td>
<td>16.31</td>
<td>50</td>
<td>1.16</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7-4</td>
<td>3 days</td>
<td>24.71</td>
<td>16.34</td>
<td>50</td>
<td>1.02</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7-5</td>
<td>7 days</td>
<td>24.43</td>
<td>16.35</td>
<td>50</td>
<td>1.25</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7-6</td>
<td>1 month</td>
<td>24.72</td>
<td>16.33</td>
<td>50</td>
<td>1.14</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B7-7</td>
<td>&gt; 1 yr</td>
<td>24.62</td>
<td>16.34</td>
<td>50</td>
<td>1.32</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td></td>
</tr>
</tbody>
</table>

**Table (3.5)...cont.**
<table>
<thead>
<tr>
<th>Sample</th>
<th>Specimen</th>
<th>Curing Time</th>
<th>Measured Moisture Content (%)</th>
<th>Measured Dry Density (KN/m³)</th>
<th>Applied Water Head (mm)</th>
<th>Water Flow Rate (ml/min)</th>
<th>Observed Water Color</th>
<th>Hole Dia after test (mm)</th>
<th>Pinhole Test Result</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>A1-D</td>
<td>None</td>
<td>18.75</td>
<td>16.96</td>
<td>50 180 380 1020</td>
<td>0.28 0.74 1.16 2.00</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>A2-D</td>
<td>None</td>
<td>18.85</td>
<td>15.35</td>
<td>50</td>
<td>0.50</td>
<td>Dark</td>
<td>&gt;1.5</td>
<td>D1</td>
<td>At the very beginning the water was clear, but rapidly it became dark and dark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>A3-D</td>
<td>None</td>
<td>23.70</td>
<td>16.60</td>
<td>50 180 380 1020</td>
<td>0.33 0.78 1.25 2.17</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>A3-d</td>
<td>None</td>
<td>20.23</td>
<td>17.09</td>
<td>50 180 380 1020</td>
<td>0.31 0.61 1.04 2.00</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>Sample</td>
<td>Specimen</td>
<td>Curing Time</td>
<td>Measured Moisture Content (%)</td>
<td>Measured Dry Density (KN/m³)</td>
<td>Applied Water Head (mm)</td>
<td>Water Flow Rate (ml/min)</td>
<td>Observed Water Color</td>
<td>Hole Dia after test (mm)</td>
<td>Pinhole Test Result</td>
<td>Remarks</td>
</tr>
<tr>
<td>--------</td>
<td>----------</td>
<td>-------------</td>
<td>-------------------------------</td>
<td>-----------------------------</td>
<td>------------------------</td>
<td>-------------------------</td>
<td>----------------------</td>
<td>-----------------------</td>
<td>----------------------</td>
<td>---------</td>
</tr>
<tr>
<td>A4</td>
<td>A4-D</td>
<td>None</td>
<td>21.83</td>
<td>15.22</td>
<td>50  180  380  1020</td>
<td>0.36  0.75  1.19  2.17</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>A4-d</td>
<td>None</td>
<td>20.27</td>
<td>15.42</td>
<td>50  180  380  1020</td>
<td>0.31  0.69  1.09  2.00</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>A5-D</td>
<td>None</td>
<td>21.89</td>
<td>14.11</td>
<td>50  180</td>
<td>0.45  0.91</td>
<td>Slightly to Moderately dark</td>
<td>&gt;1.5</td>
<td>D2/ND4</td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>A5-d</td>
<td>None</td>
<td>20.37</td>
<td>14.29</td>
<td>50  180</td>
<td>0.35 -</td>
<td>Moderately dark to dark</td>
<td>&gt;1.5</td>
<td>D2/ND4</td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>A6-D</td>
<td>None</td>
<td>24.54</td>
<td>15.27</td>
<td>50  180  380  1020</td>
<td>0.42  0.91  1.47  2.50</td>
<td>Very Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
<tr>
<td>A6</td>
<td>A6-d</td>
<td>None</td>
<td>23.16</td>
<td>15.45</td>
<td>50  180  380  1020</td>
<td>0.33  0.76  1.19  2.27</td>
<td>Clear</td>
<td>1.0</td>
<td>ND1</td>
<td></td>
</tr>
</tbody>
</table>
CHAPTER FOUR

ANALYSIS, DISCUSSION AND INTERPRETATION OF THE RESULTS
CHAPTER FOUR

ANALYSIS, DISCUSSION AND INTERPRETATION OF TEST RESULTS

4.1 Introduction

This chapter summarizes the results of the laboratory study and analyzes them to examine whether there are effects of moisture content, dry density and curing time on the erosion resistance of compacted specimens prepared from the material of the two studied samples.

According to the original plan for both samples, six different sets of specimens, each with specific moisture content and dry density, were prepared and pinhole tested after curing in the compacted state for various periods starting from no curing to more than one year of curing. Additional specimens were prepared and tested either for replacing destroyed specimens during sampling and testing, when the results were doubtful or marginal, whenever it was useful to test another set of moisture content and density or testing for more curing time. In addition, some specimens were prepared after drying of sample (A) in order to visualize if drying will cause changes in the pinhole test results or not. All the results of the preliminary testing and the main planned pinhole dispersivity tests as well as the results of all the additional testing were presented in Chapter Three. The results of the pinhole tests performed for the specimens prepared and cured at the subsequent stages of the study were shown in Table (3.5) and summarized in Table (4.1).
4.2 Identification and Classification of Samples

According to the visual inspection and the classification tests, the two samples can be described as follows. Sample (A) is brownish clayey silt with relatively high natural moisture content of 21.3 %. The fines content is more than 80 % while both the liquid limit and the plasticity index were relatively low to medium (37 % and 12 % respectively), indicating that the content of silt is high in the material. According to the Unified Soil Classification System (USCS) Sample (A) material can be classified as ML.

Sample (B) is light brown sandy clay with some calcareous material. It is drier than Sample (A) with comparably low moisture content (10 %). In accordance with the USCS Sample (B) can be classified as CL since the fines content is 61.4 % and the liquid limit and the plasticity index are 43% and 18 % respectively. From the grading curves for both samples, shown in Figure (3.1), Sample (B) contains more coarse sizes of sand and gravel than Sample (A) does. The compaction parameters for both samples are more or less the same, i.e. 21 % for the OMC and 16.1 KN/m³ to 16.2 KN/m³ for the MDD.

The appreciable amount of CaCO₃ found in Sample (B) material as calcareous concretions may indicate high dispersivity of the material. According to McDonald et al (1981), soils which are rich in bicarbonates when allowed to dry out, precipitation of relatively insoluble CaCO₃ may occur, resulting in a lower concentration of Ca⁺⁺ and hence an increased potential for dispersion.

The two samples were thought to be moderately to highly dispersive according to earlier investigation carried out on materials from the same
sources. However, Sample (A) was found to be slightly dispersive to non dispersive. This conclusion has been drawn from the various dispersivity tests results, shown in the last Chapter. For the Author, this might be due to differences in sample preparation. In the previous investigation the sampling, transportation and storage of samples caused drying out of the samples. Drying out of some non-dispersive clay could alter the pinhole test results to erratic dispersive results (Sherard et al (1976); Schafer (1978)).

In order to study the effect of drying of sample (A) material on its dispersivity as tested in the pinhole test, some of the material was allowed to dry out for about two weeks in a shaded area, after which six specimens were prepared and immediately pinhole tested. The specimens were prepared with the same moisture contents and dry densities used for the laboratory study of sample (A). The results of the pinhole tests for this dried material, as shown in Table (3.6) of the previous chapter, were almost typical to the results of the material without drying and curing. The specimens were all found to be non dispersive except the two with the lowest dry density and lowest moisture content. This may support that Sample (A) material may be different from the one previously tested and rendered dispersive, although it was sampled from the same area. Otherwise, the material previously investigated could have been exposed to more drying conditions and for longer period compared to the dried Sample (A) material which was dried for only two weeks in a shaded area with relatively high humidity and no direct sun light. Also, in the previous testing the material was dried out intentionally to sieve it through the 2 mm sieve, after which the moisture content was adjusted to the desired moisture content for testing. This seems to be the main reason
for having the dispersive results at that time. In the current study, the material was sieved wet and not allowed to dry.

However, having such slightly dispersive to non dispersive sample (A) material was considered an advantage for trying to compare between dispersive and non dispersive soils in view of this erodibility study.

4.3 Effect of Moisture Content and Dry Density on Erodibility of the Samples

4.3.1 Effect on Erodibility of the Slightly Dispersive Sample (A) Material

As shown in Table (3.4), three levels of moisture content were examined for Sample (A), which are 18.5% (OMC-2.1%), 20.5% (approximately = OMC) and 23.5% (OMC+2.9%). Total of three dry densities were examined, 17.05, 15.39 and 14.26 KN/m$^3$; comparing with the MDD they are 105%, 95% and 88% respectively. The three moisture contents tested and the corresponding densities are as follows:

- MC=18.5% (OMC-2.1%): the two higher densities were used for testing this relatively low moisture content. The results for the higher density were found to be always non dispersive regardless of the curing time. The specimens with the other dry density of 15.39 KN/m$^3$ (95% of MDD), when tested, were found to be dispersive and continued to be dispersive with curing times and only changed to very slightly dispersive to non dispersive after 7 days, 1 month and more than 1.5 year curing times.

- MC=20.5% (approximately = OMC): all the three densities were tested for this moisture content. For the two higher densities the results were always non dispersive for all curing
times tested up to 7 days. The third dry density used (only 88% of MDD) is the lowest density and may reflect the case of insufficient compaction of material at its OMC, which corresponds to application of less compaction effort. The specimens were rendered dispersive until after 3 days of curing. Only little change occurred after 7 days of curing. After 1 month and more than 1.5 years of curing, the results were found to be very slightly dispersive.

- MC=23.5% (about OMC+3%): only the dry density of 15.39 KN/m³ (95% of MDD) was tested for this relatively high moisture content, which may be similar to some preferred criteria for earth works when very low permeability is desirable. However, in many instances more density is usually asked for but generally not less than the 95% of MDD. The results for this combination of moisture content and density were always non dispersive whatever the curing time is.

4.3.2 Effect on Erodibility of the Highly Dispersive Sample (B) Material

Three moisture contents were tested, 17.0% (OMC-4.3%), 21.0% (approximately = OMC) and 25.0% (OMC +3.7%), using four levels of dry density of 16.91, 16.28, 15.32 and 14.19 KN/m³ (105%, 101%, 95% and 88% of MDD, respectively), see Table (3.4). The specimen with dry density of 16.28 KN/m³ was not in the original plan and was added to test the higher moisture content of 25.0% for as higher density as possible.

For this dispersive Sample (B) material and for such a wide range of moisture content (about 4% above and below OMC), the results were found to be dispersive. Only a negligible very slight change has been
exercised after more than one year of curing for the sample with moisture content of about OMC and the highest tested dry density of 105% of MDD. The material became dispersive instead of highly dispersive, which is not a significant change in the erosion resistance.

4.4 Effect of Curing on Erodibility of the Samples

4.4.1 Effect on Erodibility of the Slightly Dispersive Sample (A) Material

The curing times originally planned for testing all sets of specimens made from sample (A) material with different moisture contents and dry densities, were the no curing, 6 hours, 1 day, 3 days, 7 days and 1 month curing periods of time. From the six sets of specimens, the four ones with the relatively higher moisture contents and dry densities were found to be always non dispersive in the pinhole test. Consequently, they were not tested for the last planned 1 month curing time.

The other 2 sets are the one with the lowest planned moisture content (OMC-2.1) % with 95% of MDD, and the other with the lowest planned dry density, 88% of MDD, compacted with OMC%. For these two sets the results of the pinhole test were more or less dispersive for all the planned curing times except for the last two, 7 days and 1 month. For the specimens with the lowest moisture content and the higher dry density the results were slightly dispersive to non dispersive after 7 days and 1 month of curing and clearly non dispersive for the additional specimen which cured for more than 1.5 year. For the other set of specimens with the lowest dry density and the higher moisture content the results were moderately dispersive after 7 days and slightly dispersive after 1 month as well as after more than 1.5 year curing time for the added specimen. The
results of the pinhole test for Sample (A) specimens are presented schematically in Figure (4.1).

Figure (4.1): Pinhole Test Results for Sample (A), Moisture Contents: (a) <OMC, (b) ≈OMC and (c) >OMC
The specimens that were cured and tested after more than one and half year of curing, were added to have more idea on the improvement of the erosion resistance of Sample (A) material with time.

It can be concluded that there was an improvement in the erosion resistance of sample (A) material with time, and that this improvement was more noticeable for the samples with low bulk density (low moisture content and/or low dry density) since their erodibility was higher before curing in the compacted state.

4.4.2 Effect on Erodibility of the Highly Dispersive Sample (B) Material

All the results of the pinhole testing for Sample (B) specimens were, with no exception, dispersive for all curing times up to 1 month. In order to see whether some improvement in the erosion resistance could happen after longer curing periods, additional specimens were prepared with all the planned moisture contents and dry densities. After more than one year of curing these specimens were pinhole tested and the results were still dispersive as they were before, except that a minor change in the result for the specimen prepared at the highest dry density using the OMC was exhibited. This change was from highly dispersive to dispersive, which could be considered as a negligible change with no real significance in the erosion resistance behavior. However, it may indicate that more improvement can be expected for very longer curing periods especially if cured under loaded condition.

4.5 General Discussion:

From the findings of the above analysis, it can be said that the better erosion resistance of the slightly dispersive to non dispersive Sample (A)
material corresponded to the high moisture contents (above OMC) and the high densities (more than 95% of MDD). The high values of dry density and moisture content are interactive; the higher the moisture content, the lower the dry density that could be obtained with the same compaction effort. The high values of both dry density and moisture content may be expressed by the high bulk density (BD) or the low percentage of air voids (A %). The bulk density is increased with increasing of both the dry density and the moisture content, while the content of the air in the voids is lower for higher dry density and higher moisture contents. Table (4.2) presents the values of the bulk densities and the percentage of the air voids computed from the planned dry densities and moisture contents for the study of sample (A) and Sample (B). It shows that for Sample (A), the specimens that showed lower resistance to erosion were the ones with the lower bulk densities and the higher air voids percentages. For sample (B), the specimen that exhibited very little improvement in the erosion resistance after about one year was the one with the highest bulk density and the second lowest air voids percentage.

Also, from the analysis and the results presented in Figures (4.1) and (4.2), there was some improvement in the erosion resistance with time for the cured specimens compacted from Sample (A) material. This improvement is more noticeable for the specimens with lower moisture contents and dry densities, which showed less erosion resistance.
### Table (4.1): Summary of the Pinhole Test Results for Sample (A) and Sample (B)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Target Moisture Content (%)</th>
<th>Target Dry Density (kN/m³)</th>
<th>Pinhole Test Result After Curing Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>No curing</td>
</tr>
<tr>
<td>A1</td>
<td>18.5</td>
<td>17.05</td>
<td>ND1</td>
</tr>
<tr>
<td>A2</td>
<td>18.5</td>
<td>15.39</td>
<td>D1</td>
</tr>
<tr>
<td>A3</td>
<td>20.5</td>
<td>17.05</td>
<td>ND1</td>
</tr>
<tr>
<td>A4</td>
<td>20.5</td>
<td>15.39</td>
<td>ND1</td>
</tr>
<tr>
<td>A5</td>
<td>20.5</td>
<td>14.26</td>
<td>D1/ND4</td>
</tr>
<tr>
<td>A6</td>
<td>23.5</td>
<td>15.39</td>
<td>ND1</td>
</tr>
<tr>
<td>B1</td>
<td>17.0</td>
<td>16.91</td>
<td>D1</td>
</tr>
<tr>
<td>B2</td>
<td>17.0</td>
<td>15.32</td>
<td>D1</td>
</tr>
<tr>
<td>B3</td>
<td>21.0</td>
<td>16.91</td>
<td>D1</td>
</tr>
<tr>
<td>B4</td>
<td>21.0</td>
<td>15.32</td>
<td>D1</td>
</tr>
<tr>
<td>B5</td>
<td>21.0</td>
<td>14.19</td>
<td>D1</td>
</tr>
<tr>
<td>B6</td>
<td>25.0</td>
<td>15.32</td>
<td>D1</td>
</tr>
<tr>
<td>B7</td>
<td>25.0</td>
<td>16.28</td>
<td>D1</td>
</tr>
</tbody>
</table>

Note: ND1 indicate non dispersive, ND2 indicate very slightly dispersive, ND4 indicate moderately dispersive, D1 indicate highly dispersive, D2 indicate dispersive
Table (4.2): Bulk Densities and Air Voids for Sample (A) and Sample (B)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Target Moisture Content (%)</th>
<th>Target Dry Density (KN/m³)</th>
<th>Bulk Density (KN/m³)</th>
<th>Air Voids (%)</th>
<th>Pinhole Test Result After Different Curing Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>18.5</td>
<td>17.05</td>
<td>20.20</td>
<td>6.5</td>
<td>Always non dispersive</td>
</tr>
<tr>
<td>A2</td>
<td>18.5</td>
<td>15.39</td>
<td>18.24</td>
<td>15.6</td>
<td>Dispersive up to 7 days curing time after which changed to non dispersive</td>
</tr>
<tr>
<td>A3</td>
<td>20.5</td>
<td>17.05</td>
<td>20.55</td>
<td>3.0</td>
<td>Always Non dispersive</td>
</tr>
<tr>
<td>A4</td>
<td>20.5</td>
<td>15.39</td>
<td>18.54</td>
<td>12.5</td>
<td>Always Non dispersive</td>
</tr>
<tr>
<td>A5</td>
<td>20.5</td>
<td>14.26</td>
<td>17.18</td>
<td>18.9</td>
<td>Dispersive up to 7 days curing time after which changed to non dispersive</td>
</tr>
<tr>
<td>A6</td>
<td>23.5</td>
<td>15.39</td>
<td>19.01</td>
<td>7.9</td>
<td>Always Non dispersive</td>
</tr>
<tr>
<td>B1</td>
<td>17.0</td>
<td>16.91</td>
<td>19.78</td>
<td>9.8</td>
<td>Always dispersive even after more than year of curing</td>
</tr>
<tr>
<td>B2</td>
<td>17.0</td>
<td>15.32</td>
<td>17.92</td>
<td>18.2</td>
<td>Always dispersive even after more than year of curing</td>
</tr>
<tr>
<td>B3</td>
<td>21.0</td>
<td>16.91</td>
<td>20.46</td>
<td>3.0</td>
<td>Always dispersive. Negligible decrease in dispersivity occurred after more than a year</td>
</tr>
<tr>
<td>B4</td>
<td>21.0</td>
<td>15.32</td>
<td>18.54</td>
<td>12.1</td>
<td>Always dispersive even after more than year of curing</td>
</tr>
<tr>
<td>B5</td>
<td>21.0</td>
<td>14.19</td>
<td>17.17</td>
<td>18.6</td>
<td>Always dispersive even after more than year of curing</td>
</tr>
<tr>
<td>B6</td>
<td>25.0</td>
<td>15.32</td>
<td>19.15</td>
<td>6.0</td>
<td>Always dispersive even after more than year of curing</td>
</tr>
<tr>
<td>B7</td>
<td>25.0</td>
<td>16.28</td>
<td>20.40</td>
<td>0.1</td>
<td>Always dispersive even after more than year of curing</td>
</tr>
</tbody>
</table>
CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS
CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

Previous researches on dispersivity showed that, dispersive soils (only relatively recently known) when blindly used in construction of embankments or encountered in dam foundations, greatly increased the risk of piping and lead to reported failure of considerable number of embankment dams. Nevertheless, dispersive soils have been and may be used in construction of earth fills provided that suitable defensive design details, especially filters, and high care for construction quality control are adopted.

In this study, erodibility and dispersivity of two soils proposed for use as core material for the Merowe dam project were investigated to study the effects of compaction water content, dry density and curing time on their erodibility. The two samples were obtained from the flood plain and terraces of the River Nile in the vicinity of the dam site. The pinhole test was used as the main tool to observe and compare the erosion resistance of different states of moisture content, dry density and curing time tested for both samples.

For preparation of specimens, a special two half-cylinder mould was manufactured having internal dimensions similar to the cylindrical pinhole test specimen. Using the mould, specimens were prepared from the two samples by compaction of the material at specified moisture contents into the mould to different specified dry densities. The specimens, after being removed from the mould, were sealed in plastic
bags and stored for the required curing time before the pinhole testing. Specimens were tested after no curing and after curing times up to more than one year.

The main conclusions of the study are listed below. Some recommendations for future studies are also presented.

5.2 Conclusions
The following conclusions were drawn from this study:

- There is noticeable effect of density and compaction water content on the erosion resistance of the slightly dispersive Sample (A) material. The specimens with the higher dry densities and moisture contents were erosion resistant while only the ones with low moisture contents and low densities were rendered dispersive. Slightly erosive/dispersive soils could therefore be improved by good compaction with moisture content on the wet side of the Optimum Moisture Content of the Standard Proctor test.

- The highly erosive Sample (B) material was not improved by increased dry density and moisture content.

- The curing of the slightly dispersive Sample (A) specimens resulted in improved erosion resistance with curing time. This was clear for the specimens with the relatively lower dry densities and moisture contents. This improvement towards better erosion resistance was more or less gradual with time starting from 7 days of curing. After 1 month and more than 1.5 year the results were slightly dispersive to non dispersive. Consequently, it may be considered advantageous for compacted earth fills, especially if they are slightly dispersive or non dispersive, to be allowed to stay for sometime before exposure to eroding water.
• Sample (B) which is a highly dispersive material was only very slightly affected by curing and its dispersive behavior did not change with curing time until after more than one year. Only a very slight change was encountered for the specimen with the highest dry density and about the Optimum Moisture Content. The pinhole test showed the material to be dispersive instead of highly dispersive which is not a considerable change in the erosion resistance behavior, but is probably an indication of improved behavior after relatively long time.

• Better erosion resistance was generally measured for the specimens with higher bulk densities and lower air voids, especially for Sample (A).

5.3 Recommendations for Further Research

For future research on soil erodibility, the following topics are recommended for studying:

• The improvement of the erosion resistance with curing time for compacted material under loaded condition, simulating the situation in the field.

• The dispersion-swelling relation in view of clay mineralogy and chemistry.

• How the curing in the compacted state can result in property changes of soil, including the erosion resistance behavior?

• Effects of short term and long term changes in natural water content (especially drying) in erodibility of soils.
REFERENCES


4. ASTM D 4221-99 “Standard test method for Dispersive characteristics of clay soil by double hydrometer”.

5. ASTM D 4647-93 (Reapproved 1998) “Standard test method for Dispersive characteristics of clay soil by the pinhole test”.

6. ASTM D 6572-00 “Standard test method for Dispersive characteristics of clay soil by the crumb test”.


10. BRRI, University of Khartoum & Institute of Soil Mechanics and
71

Rock Mechanics, University of Karlsruhe (2004) “Merowe Dam Project, Additional geotechnical investigation on core material”.

11. BRRI, University of Khartoum (2001) “Merowe Dam Project, Geotechnical investigation report”.


