AN INVESTIGATION INTO THE ERODIBILITY OF EARTH WALL UNITS

by

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CERTIFICATE OF AUTHORSHIP / ORIGINALITY

I certify that this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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PREFACE

The perceived lack of durability of earth has been a significant barrier to its acceptance as a modern building material. Major earth buildings that have survived over long periods are mainly located in areas of minimal annual rainfall, are protected by large overhanging eaves, or are covered with protective coatings.

Present standards for testing the durability of earth walls make little or no allowance for climatic conditions. In order for earth construction to be accepted in high rainfall areas in an unprotected state a performance based design criteria is needed that is linked to the climatic conditions relevant to the location of the intended structure.

This investigation examines the influence of climatic factors on field erosion, and relates these to the performance of test specimens in a laboratory spray test. It develops a theoretical framework whereby performance of earth walls in specific climatic locations can be predicted by the performance of specimens tested in the laboratory.

ABSTRACT

This investigation looked at the climatic variables affecting the durability of earth buildings and the relationship between these climatic variables and their laboratory counterparts, with the aim of providing a means whereby performance in the field under known climatic conditions can be predicted by performance in the laboratory

The investigation showed that the major climatic factors influencing the erosion of earth walls due to wind-driven rain are impacting rainfall volume, drop impact velocity (as determined by wind conditions), raindrop size and duration of rainfall. A vertical rain gauge was calibrated with climatic conditions at a test site in Sydney to enable accurate prediction of the volume of water impacting test specimens.

In the laboratory, a standard spray test was modified by introducing a commercially available nozzle, which produces a turbulent spray of individual drops, rather than a stream of water. Erosion rates using this apparatus were found to vary significantly with time, and a correction formula was derived from experimental results to enable comparison to be made between field and laboratory results. Erosion rates per unit volume of water were found to be proportional to impacting velocity raised to the power 2.5 and inversely proportional to the median drop diameter raised to the power 1.2. A material factor was defined as the 60 minute erosion mass loss divided by the 60 minute volume of impacting water spray.

Field tests were carried out over a period of four years and analysed in relation to the associated laboratory test results. Laboratory testing was carried out on one half of split specimens, the other half being subjected to exposure to the weather at Sydney's International Airport, with regular monitoring of wind and rain records.

An empirical model was developed and was used to compare field and laboratory results. This confirmed the importance of impacting volume of water and material factor but in this case the calculated correlation between field and laboratory erosions was not improved by the addition of impact velocity and drop size terms.

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Chapter 1 Introduction

1.1 Types of Earth Buildings

According to Pollock (1999) the use of earth as a building material dates back to at least the Ubaid period in ancient Mesopotamia (5000-4000 B.C.). Easton (1996) has suggested that at least 50 % of the world's population still live in earth houses. Although there are many varieties of earth wall construction nowadays (eg poured earth) the majority of earth wall structures fall into three categories, mud bricks (adobe), rammed earth (pise) or pressed earth bricks

1.1.1 Mud Bricks (Adobe)

Mud bricks or Adobes (Spanish word for mud brick, originating from the Arabic word al-tob) as they are sometimes called, are made by mixing a plastic mixture of clayish material with a binding agent such as straw. The mixed material is formed in wooden moulds and allowed to dry in the sun. Adobe bricks are typically 250mm by 350mm by 100mm in dimension and are laid flat to produce 250mm thick walls.

Mud bricks were around in Biblical times in Egypt ("You are no longer to supply the people with straw for making bricks"- Exodus 5:7) but stone was preferred for its longevity and no complete earth structures remain from these times. One exception is the remains of the walls of the Temple Oval at Khafajah, excavated in the 1930's (Pollock, 1999). This oval was approximately 80m by 60m in plan and is estimated to have required about 5,400 cubic metres of earth to build. It was built about 2500 B.C. in the Early Dynastic 2 period.

Earth was used in many cases as infill material or in the construction of temporary structures. Figure 1.1 shows the remains of a temporary approach ramp built in Karnak in Egypt to enable large pieces of stone to be placed at the upper levels of the Temple of Amman.

With a rainfall rate less than about 200mm per year and little stone mud brick was the natural choice of building material in Mesopotamia and it is still used extensively in the region today.

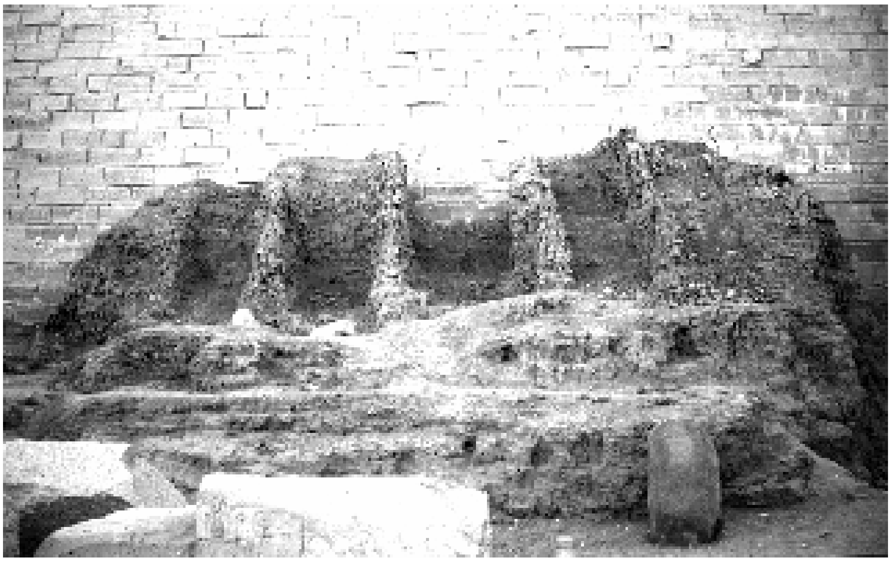


Figure 1.1 Remains of Approach Ramp at Karnak
(Photo taken by Bruce Longfoot)

The Greeks and Romans do not appear to have embraced mud brick building to any great extent. According to Cytryn (1957) mud brick building declined during the Roman period with the development of multi-storey buildings and the need to reduce the width of walls due to space limitations. He does however point out that the Roman historian Pliny " mentions in his writings soil structures in Africa and Spain and praises their advantages and durability" and that he "praises in particular watch towers which were built in Spain by Hannibal during the second Punic war."

There are a few complete mud brick structures that have survived the ravages of time through regular maintenance. Perhaps the oldest existing unprotected earth structure is the Pueblo at Taos, in New Mexico, which is reportedly over 900 years old (Figure 1.2). Here the combination of a dry climate with regular maintenance has led to the survival of this three-storey building.

The Spanish were responsible for introducing mud brick technology to Mexico and South America in the 16^{th} Century and this permeated into the southern states of the

South West of the USA. Although declining in popularity in the USA mud brick construction is still widespread in South America, particularly in Peru

In the east, China has a long history of mud brick construction, and sections of the Great Wall (begun in 214 A.D.) are made of earth. Mud brick construction has a long history in that country and remains prevalent to this day.

Traditional mud brick construction is still widespread in Australia and New Zealand and has recently been revived in South Africa. It is most popular with owner builders but there are also many commercial producers.

In the USA adobe construction, as it is called there, has been popular for centuries. The development of a machine for mass production of adobe blocks by Hans Sumpf in Fresno, California has resulted in the appearance of adobe ”farms” in New Mexico. Blocks in this area are made from the sandy adobe soil of the Rio Grande and are stabilised with bitumen. In 1980, 4.13 million adobe blocks were produced on a commercial basis in New Mexico (Smith and Austin, 1989).
As in Australia, the earth building market in the USA is segregated into a low income self build market and a high-income status seeking market.

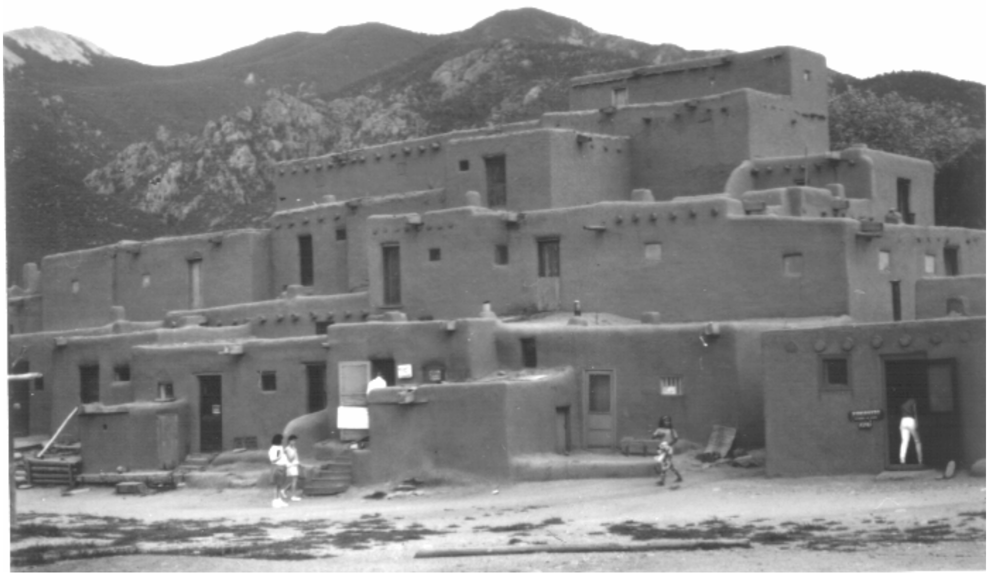


Figure 1.2 - Adobe Pueblo at Taos

In most cases in Australia and New Zealand the external walls of mud brick buildings are to a large extent protected from driving rain by generous eave overhangs, or are built in low rainfall areas. In some cases external coatings such as linseed oil are used to protect the walls from rain attack but on the whole walls are not afforded any protective render coating. In the USA adobe construction is more prevalent in the southwest, and the “adobe” style of building there typically has a painted waterproof render applied over bitumen stabilized adobe bricks to protect the walls from driving rain.

1.1.2 Rammed Earth (Pise)

It seems that the method of construction of rammed earth was introduced by the Romans to France, where the name “Pise” was given to that form of construction. The name pise is a shortening of the French words “pise de terre” (pounded earth). In this method, a dryish mixture of sandy soil is rammed into wall forms. The thickness of rammed earth walls is typically around 600mm but more recently, walls built from earth stabilised with cement are being built with thicknesses around 300mm.

Rammed earth construction was common in France in the 17th and 18th centuries, particular in the area around Lyon. Cytryn (1957) reported the French architect Rondele as stating in 1764 that the walls of a 150-year-old building were very strong and gave the impression of having been built of local sandstone.

In Australia cement stabilized rammed earth construction has become increasingly popular, both for commercial buildings and for domestic houses. In Margaret River in Western Australia it is estimated that stabilized rammed earth houses account for roughly 20% of the houses in the area Figure 1.3 shows a rammed earth wall under construction for a house in Margaret River.

Typically, rammed earth construction is stabilized with around 10% cement in Margaret River and at this level there is very little evidence of extensive erosion due to wind – driven rain. Improvements in ramming technology and formwork have resulted in faster production and smaller wall thicknesses.

Figure 1.3 Rammed Earth House under Construction (Margaret River)

1.1.3 Pressed Earth Brick

Because of its suitability for mechanisation pressed earth bricks were a natural development from the traditional mud brick. In this method, a dryish soil is placed in a steel mould and compacted under high pressure. The moulds are typically 290mm long, 140mm wide and 90mm high yielding bricks weighing about 7kg although in Australia larger bricks weighing around 20kg are common. Soils suitable for making pressed earth bricks are generally sandy loams with clay contents less than 20% and low silt percentage, however a wide variety of soils can be used with clay contents up to 35%.

A combination of the need for low cost building materials which could be mechanically produced, and the advantages obtained from soil stabilisation led to the development of soil brick making machines shortly after the war. The most notable of these machines were the “Winget” machine developed in England in 1948 and the “Landcrete” machine developed in South Africa shortly thereafter. The Winget machine is no longer available but the Landcrete machine (re-developed in Belgium as the Terstaram) is still widely used

The development of a manual brick making press (Cinva Ram) in 1952 saw the expansion of pressed earth brick technology to many un-developed countries such as India. The Cinva Ram press was developed by the Inter-American Housing and Planning Centre (CINVA) at Bogota, Columbia in 1952. Many variations of this press are now available (See Figure 1.4) and their relatively low cost (Around $US300) make them an attractive proposition for owner builders.

Figure 1.4 - Making Pressed Earth Bricks using “Cinva Ram” Type Machine

The extra density obtained by pressing bricks makes them stronger and more resistant to erosion by rain than uncompacted bricks. Typically, densities of around 1750kg/m^3 to 2100kg/m^3 are achieved compared to around 1600 kg/m^3 for traditional Adobe bricks. To improve durability pressed earth bricks are generally stabilised with from 5% to 12% cement, with around 8% being generally suitable for most soils.

The 70’s and 80’s saw a large increase in the availability of fully mechanised block presses, enabling pressed earth brick construction to become financially viable in countries such as Australia where labour is relatively expensive. For example in the United States the “Terrablock” machine introduced in 1985 can produce 5,000 bricks per day. In this machine, suitable soil is screened and then placed in a hopper on top of the machine. A screw auger is then used to mix the soil with cement stabiliser and a set amount of mixed soil is then placed in a steel mould. A petrol motor then provides power to a hydraulic ram, which compacts the specimen. Ejection of the block is also automated. These machines produce bricks with dry densities of around 2000 to 2100 kg/m^3 .

In countries where labour is still relatively inexpensive, hand operated mechanically assisted presses such as the Ceratec press are used to speed up production.

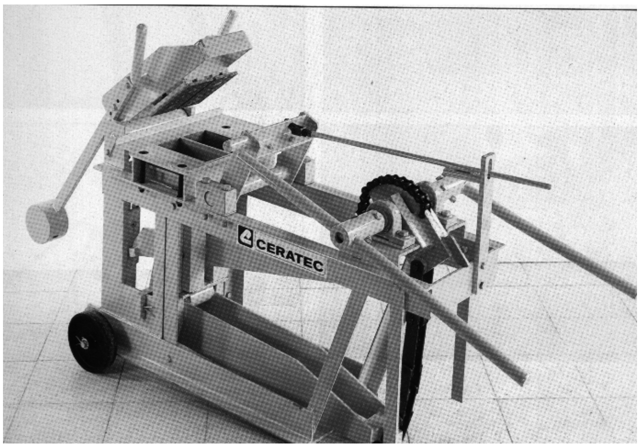


Figure 1.5 - Ceratec Block Making Machine

The Testaram is used today in 10 brickyards in Mayotte producing over 1.5 million pressed earth bricks per year.

Figure 1.6 - Pressed Earth Brick Building under Construction in Mayotte

1.2 Resurgence of Earth Building

Due to their limited durability in an unstabilised state earth buildings have in the past been seen to be inferior to more permanent materials such as stones and fired clay bricks.

"We note also that in the United Kingdom and France that earth walling is limited to the smaller domestic and farm buildings. In the old villages the parish church and the manor house, and any buildings having more considerable architectural pretensions, were invariably built of brick or stone. Thus we may take as a tacit admission that unstabilised earth walling did not possess sufficient permanence to justify the expenditure of a large amount of effort and elaboration in fittings and decorative work." (Fitzmaurice, 1958)

It was only after the development of cement stabilized earth roads in the early 1930's that serious consideration was given to the use of earth as a permanent building material, without any protective coatings. A shortage of materials after the second world war saw a rapid development of pressed earth brick making machines and for a while there was considerable research into the durability of earth construction by people such as Middleton (1952) in Australia and Webb, Cilliers and Stutterheim (1950) in South Africa.

The mid-50's however saw a demand for more "modern" houses in the Western World and earth building was relegated to undeveloped countries, being seen as a low cost housing alternative.

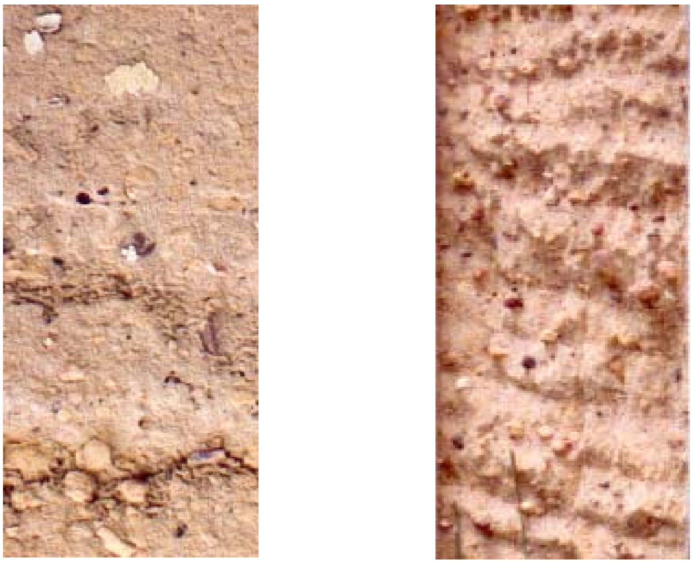
With the advent of the energy crisis in the 70's earth building became popular in quite a few developed countries such as Australia, due to its low embodied energy and perceived thermal effectiveness. Unfortunately, as Fitzmaurice (1958) had found, unstabilised earth buildings require considerable maintenance unless adequately protected from driving rain by wide eaves and often this was contrary to the more modern architectural styles adopted in some western countries, where eaves have been minimized or eliminated.

Professional builders moved into the area and they brought with them a desire for a more consistent permanence, leading to an increase in the use of stabilization, particular in the area of cement stabilised pressed earth bricks and rammed earth. Figure 1.7 shows a new campus for the Charles Sturt University at Albury in New South Wales, Australia, which is constructed entirely of cement stabilized rammed earth.

Figure 1.7 Stabilised Rammed Earth Building at Albury, NSW

1.3 Background to this Investigation

Middleton (1952) constructed many rammed earth test walls at the Commonwealth Experimental Building Station in Sydney in 1949. These experiments demonstrated that after 43 years of exposure, climatic conditions had a dramatic effect on the durability of the test panels. Figure 1.8 shows the north and south faces of one of Middleton's rammed earth panels, clearly indicating the pre-dominance of wind-driven rain from the southerly direction in Sydney.



North Face South Face

Figure 1.8 Rammed Earth Panels at Experimental Building Station

At the same time as professional builders were recognizing the potential of earth as a building material, standard codes of practice were moving towards performance based specifications. Requirements for durability testing present in earth building codes had been developed in specific localities and were not readily transportable to regions where the climatic conditions were significantly different. To satisfy the requirements of performance based codes it became necessary to understand the effect various climatic parameters have on the durability of earth walls and to devise a methodology whereby the performance of specimens in the laboratory could be related to performance in the field. This "Limit State" concept means that, unlike other materials where the erosion resistance is fixed (such as fired clay bricks), the design of earth walls offers the designer the opportunity to uniquely match the erosion resistance of the material with the factored climatic loading.

1.4 Factors Affecting the Durability of Earth Wall Buildings

The durability of building materials can be defined as their resistance to functional deterioration over time. Durability can conveniently be divided into three sub-sections

a) Physical durability – deterioration caused by physical processes such as abrasion or reversal of stress

b) Chemical durability – deterioration caused by chemical reactions such as rusting of steel.

c) Biological durability – deterioration caused by organic breakdown such as dry rot in timber.

The predominant cause of loss of functionality in earth walls is loss of surface area due to erosion (physical attack) by wind-driven rain, and present test methods such as the Australian Bulletin 5 spray test (Middleton, 1952) are a reflection of that form of deterioration. In this investigation therefore the terms "durability" and "erodibility" are sometimes used interchangeably, as they are in the literature, although it is recognized that erodibility is the more narrow definition. In general earth wall units having a high erosion resistance are resistant to other degradation factors such as heat and static water penetration.

There are many factors which contribute to the breakdown of the surfaces of earth wall units. They are

- Influence of material properties –whilst this is most certainly a major factor in mud brick buildings, where increased clay content generally leads to greater erosion resistance, it does not appear to be as big a concern in cement stabilized pressed earth or rammed earth buildings. For these buildings choice of soil is usually related to its ability to be pressed or rammed into a form and the clay contents are usually less than 15%. There is generally little variation in performance between soil types suitable in this case (for the same cement content), although occasionally a particularly reactive clay might be present and cause some problem.
- Influence of stabiliser – without stabilisation most pressed earth or rammed earth wall units would not be very durable. They generally have a low clay content and therefore there is little to hold particles together.
- Influence of compaction – loose material provides very little resistance to the erosive power of rain. In general durability increases exponentially with degree of compaction.
- Influence of freeze thaw and/or chemical attack by airborne salts – it has been shown by Sherwood (1962) that sulphate attack can cause deterioration of clays and it is conceivable that freeze thaw attack could be a problem in some

countries. The effect of these will be to destabilise the surface of units and make them more susceptible to attack by wind-driven rain.

- Effect of micro-climate and position of element in façade – the work presented in this investigation relates to prediction of the field performance of specimens placed in a rack situated one metre above the ground in an open field. Real buildings generate their own micro-climate due to their size and shape, which results in considerable variation in raindrop impact velocities and directions on particular facades. Additionally the local effect of projections such as window sills and splashing at the base of walls will all lead to variations in erosion from that predicted using the simple model developed herein.
- Influence of surface texture - The surface texture of earth wall units can vary significantly depending on the manner in which they have been formed, and this can significantly effect their erosion resistance. Some units have a surface which is akin to a steel trowelled concrete surface whilst other surfaces are deliberately scabbled to achieve aesthetic effects.
- Influence of wetting/drying cycles – cycles of wetting and drying increase surface stresses in the units and will lead to a more rapid breakdown than that due to a constant stream of rain.
- Effect of physical deterioration caused by structural effects such as differential shrinkage - any structural cracking of units will lead to a weakening of their ability to resist attack by wind-driven rain, and will therefore make them less durable.
- Influence of surface coating – many earth walls are coated with protective coatings such as renders which improve their durability.

1.5 Aim of Investigation

This investigation seeks to examine the effect wind-driven rain has on the erodibility of cement stabilized compressed earth units, and to establish a methodology whereby the erodibility of such units can be predicted in particular climatic locations, based on the laboratory performance of sample specimens subjected to accelerated testing.

1.6 Extent of Investigation

This investigation will examine the issue of erodibility as it applies to the performance of sample earth wall units exposed to a water spray in the laboratory and to rainfall in the field. The influence of material parameters on material "resistance" is not directly addressed since the methodology to be developed relates to prediction of the performance of specimens in the field based purely on their performance in the laboratory. The predicted results will be in error to the extent that samples of earth walls provided in real life do not replicate that constructed in the field.

In terms of the practical evaluation of soil sources the methodology to be developed herein is essentially one of "trial and error" whereby proposed soil sources are blended and/or mixed with various proportions of cement and tested to establish whether they meet the specific climatic criteria relevant to their intended location.

This investigation will not examine the issue of the effect of changes in micro-climate nor any other localized effects found in real walls. It seeks to provide a methodological basis which can be extended to the wider problem of tackling such problems. The question of the effect of cement stabilizer will be briefly examined in so far as it provides a guide to how much stabiliser would be required for soils which fail to pass the erosion limits set by the climatic parameters.

1.7 Methodology and Scope of the Investigation

In the field of earth building there has been substantial work relating to developing acceptance tests to satisfy the durability criteria. Such tests are generally unsubstantiated or poorly related to tests in real life situations. **Chapter 2** will look at the various test methods in use for earth wall testing and examine previous research into the durability of earth wall construction.

Besides building engineering, the erosion of materials by liquids is encountered principally in three areas

1. In the area of physical geography rivers and beaches are eroded by the action of moving water.

2. In agricultural engineering soils are eroded by the impact of rainfall falling vertically and
3. In aeronautical engineering materials on aircrafts are eroded by the action of raindrops impacting horizontally at the speed of the aircraft.

All three of these areas have been widely researched. **Chapter 3** will review the extent of this literature and examine how some of the theories developed in these areas can be related to the problem of the erosion of earth walls.

Chapter 4 examines the characteristics of wind driven rain, with particular emphasis on the concept of a driving rain index. It will outline measurements carried out in the field by the author to determine a driving rain factor peculiar to the test site used for the calibration experiments and comments on deficiencies of this method.

Chapter 5 details the development and calibration of the accelerated weathering test method.

Chapter 6 presents the results of laboratory experiments into the effect of various wind-driven rain parameters on the erosion of earth wall specimens with the aim of providing a method of converting laboratory performance into expected field performance.

Chapter 7 details the field tests carried out over a period of two years to compare the performance of samples in the field with their performance in the accelerated weathering test.

Chapter 8 develops a model for predicting the performance of specimens in the field based on their performance in a spray test in the laboratory, and examines this model in relation to the data presented in Chapters 6 and 7. It also looks at the implications of this work in relation to the preparation of performance based standards.

Chapter 9 draws conclusions from the investigation and suggests areas for future study.

Chapter 2 Review of Previous Research into the Durability of Earth Walls

Previous research into the durability of earth walls has concentrated on

1. The development of tests to establish the erosion resistance of earth wall specimens and
2. Investigations into the effects of various material parameters on the erosion resistance of earth walls.

This Chapter will describe this research and analyse some of the data produced by other researchers in order to provide some insight into the various parameters that are relevant to the prediction of the erosion of earth walls.

2.1 Tests Relating to the Erosion Resistance of Earth Wall Specimens

The various test methods used in earth wall construction can generally be classified into three categories

1. Indirect Tests, where a test, which bears little or no relation to the degradation mechanisms, is carried out, such a test having been shown from experience to be a reasonably reliable predictor of the performance of the material under in-service conditions.
2. Accelerated Tests, where an attempt is made to model the in service degradation process, with the intensity of the degradation factors increased to compensate for the reduced time frame.
3. Simulation Tests, where an attempt is made to exactly model in-service conditions

Table 2.1 gives a breakdown of the more common tests used to evaluate the durability of earth wall specimens, based on the above criteria. Where various researchers have been involved only the general type of test (eg compressive strength) is listed.

Table 2.1 Classification of Durability Tests Relating to Earth wall Construction

Category	Source/Type	Indirect Tests	Accelerated Tests	Simulation Tests
Wire Brush Tests	ASTM D559 (1944)			
	CraTerre (Unpublished))			
Spray Tests	Cytryn (1956)			
	Wolfskill et al. (1970)			
	Reddy & Jagadish (1987)			
	Ola & Mbata (1990)			
	Bulletin 5 (1987)			
	Dad (1985)			
	Ogunye (1997)			
Drip Tests	Yttrup et al. (1981)			
	Swinbourne Uni. (1987)			
Permeability and Slake Tests	Webb et al. (1950)			
	Cytryn (1956)			
	N.M. Build. Code (1991)			
	Cartem (Unpublished)			
	Sun-Dried Bricks (1992)			
Strength Tests	Compressive Strength			
	Wet/Dry Strength Ratio			
Surface Hardness Tests	Penetrometer			
	Pendulum Schlerometer			
	Surface Pulloff			

2.1.1 Wire Brush Tests

2.1.1.1 ASTM D559 Wire Brush Test

The ASTM D559 test is probably the most widely recognised test for durability of cement stabilised earth and was developed following research into the use of soil-cement as a paving material. It was developed towards the end of the Second World War as ASTM D559 " Methods of Wetting and Drying Test of Compacted Soil-Cement Mixtures" (ASTM, 1944).

The test was developed "*to determine the minimum amount of cement required in soil-cement to achieve a degree of hardness adequate to resist field weathering*" (ASTM D559- Section 3).

In this test, stabilised soil is compacted in three layers at optimum moisture content in 102 mm diameter moulds to a height of 116 mm. Each layer is compacted with 25 blows of a 50 mm diameter rammer (weighing 2.5 kg) falling a distance of 300 mm.

Following compaction the specimens are stored for 7 days in an atmosphere of high humidity and then submerged in tap water for a period of 5 hours. The specimens are then placed in an oven at 71°C for 42 hours and removed. The specimens are then given two firm strokes on all areas with a wire scratch brush to remove all material loosened during the wetting and drying cycle. The wire brush is similar to a butchers brush and has 50 groups of ten bristles, each bristle being 50 mm by 1.6 mm by 0.46 mm. The firm stoke corresponds to a pressure of 13 Newtons and eighteen to twenty vertical brush strokes are required to cover the sides of the specimen twice and four strokes are required on each end. Twelve cycles of wetting and drying are carried out and the weight loss at the conclusion of the test determined as a percentage of the original dry weight.

This test is extensively used in the road construction field. The Portland Cement Association (1956) provides guidance as to the limits of soil loss considered acceptable for various types of soils in road construction, ranging from 7% for clayey soils to 14% for granular soils.

In South Africa Webb et al. (1950) carried out tests on stabilised pressed earth bricks and fired bricks using a modification of ASTM D559 and concluded that earth bricks made from suitable soils were equivalent to medium quality fired stock bricks. A summary of their results is shown in Table 2.2, where the 12 cycle value (consistent with the ASTM D559 requirement) has been linearly interpolated from the Webb et al. values for 10 and 15 cycles.

Table 2.2 Results of Webb et al. (1950)

Description of specimen	% Loss of Weight (Interpolated for 12 cycles)
Clayey soil with 6% cement	43
Clayey soil with 12% cement	23
Intermediate soil with 6% cement	21
Intermediate soil with 12% cement	3.4
Sandy soil with 6% cement	3.3
Sandy soil with 12% cement	0.5
Poor quality stock brick	5.5
Medium quality stock brick	0.6
Good quality stock brick	0

In 1958 Fitzmaurice carried out a comprehensive study on the condition of existing earth wall buildings for the United Nations (Fitzmaurice, 1958). In his detailed study of the properties of stabilised earth the ASTM D559 wire brush test for testing stabilised earth was employed.

Based on his observations regarding the condition of buildings, Fitzmaurice set out guidelines for the maximum weight loss that should be considered acceptable in relation to this test (Table 2.3).

Table 2.3 Weight Loss Limits Suggested by Fitzmaurice (1958)

Type of Development	Weight Loss	
	In any Climate	In Dry Climate (<500mm rain p.a.)
Permanent Buildings	< 5%	< 10%
Rural Buildings	<10%	< 10%

Although considered by Walker (1995) to be a severe measure of durability resistance for earth walls the wire brush test has the advantage of being an ASTM standard specifically relating to the durability of soil- cement mixtures. It was adopted for earth building standards in Kenya (UNCHS, 1989) and India (Indian Standard 1725, 1960), although recently the wire brush component has been omitted in tests in India (Reddy and Jagadish, 1995) .

The main disadvantage of the wire brush test is the length of time required to perform it (24 days) and the associated expense. Secondary problems are the possibility of variations in results due to inconsistent application of the brush pressure.

2.1.1.2 CraTerre Abrasion Test

CraTerre (Personal communication Vincent Rigassi) have developed an "abrasion" test for compressed earth blocks, which will be included in a new standard they are developing. Their test is a modification of ASTM D559 but does not involve any wetting. In their test a dry sample is brushed back and forth every second for 60 seconds, with the brush loaded with a 3 kg weight. The brush remains in the centre of the sample. An abrasion factor is then defined as the weight lost per unit area of surface. In this test procedure resistance to water is measured separately by a wet compression test.

2.1.2 Spray Tests

2.1.2.1 Cytryn Spray Test

In Israel Cytryn (1955) recognised that a test, which simulated the action of rain, was needed to test for resistance to the forces of driving rain. He developed a test, which involved a shower rose spraying water vertically onto specimens from a height of 250 mm. The water pressure was 50 kPa and the exposure time was 33 minutes. Cytryn adjusted the volume of water falling on the blocks to be equivalent to 7,500 mm of rain, which is about equal to 10 years of rainfall in Israel. Exact details of the test were not available, but if the spray were assumed to fall on a radius of 150 mm, the discharge rate of the spray would be around 4 l/min.

A block was considered to have passed this test if not more than two of its corners deteriorated during the test and if at the same time the surface erosion did not exceed 10 percent.

Cytryn does not give any details as to what constituted the deterioration of a corner nor of the method for determining surface erosion. It is assumed from his writing however, that the blocks were weighed following spraying and that the loss in weight was then expressed as a percentage of the original weight of the blocks. This test appears to be the forerunner of the three similar tests described below. Like these, it suffers from the fact that it was developed in a specific climate and the test procedure is not directly linked to climatic parameters.

2.1.2.2 Wolfskill Spray Test

A spray test developed by Wolfskill (1970) is used in the USA. It involves spraying water for 2 hours horizontally at the specimens through a 100 mm shower rose at a pressure of 140 kPa, with specimens placed 175 mm from the rose. According to Norton (1986) the results may be interpreted as follows for unstabilised surfaces.

" - Pitting 6-12 mm deep is acceptable for use in areas with less than 500mm rainfall p.a.

- Pitting 0-5 mm is acceptable for use in areas with 500 to 1250mm rainfall p.a.

- In areas with rainfall higher than 1250mm p.a. there should be no pitting"

For stabilised soils Norton recommended spraying for 6 hours, with the results interpreted as above. There appears to be no logical reason why stabilised soils should be sprayed for longer, other than the possible linkage of stabilisation with a more stringent durability requirement. This test was used by Lunt (1980) to test two Ghanaian soils, stabilized with 6% lime, compressed at varying pressures.

2.1.2.3 Reddy and Jagadish Spray Test

The Wolfskill test was adapted by Reddy and Jagadish (1987) to test pressed soil blocks in India. In their case a shower rose was held a distance of 175 mm from the specimens, which were 305 mm by 144 mm in dimension. Water was sprayed horizontally onto the specimens at a pressure of 70 kPa through 226 holes with an average diameter of 1.15 mm.

The shower rose had a diameter of 90 mm. Reddy and Jagadish quoted a hole density of 3.2 per cm^2. No figures for discharge are quoted in their paper but they noted that in one minute the amount of water discharged is equal to a precipitation of 566 mm. If it is assumed that this precipitation is over an area of 144 mm diameter then the resultant discharge is around 9 l/min.

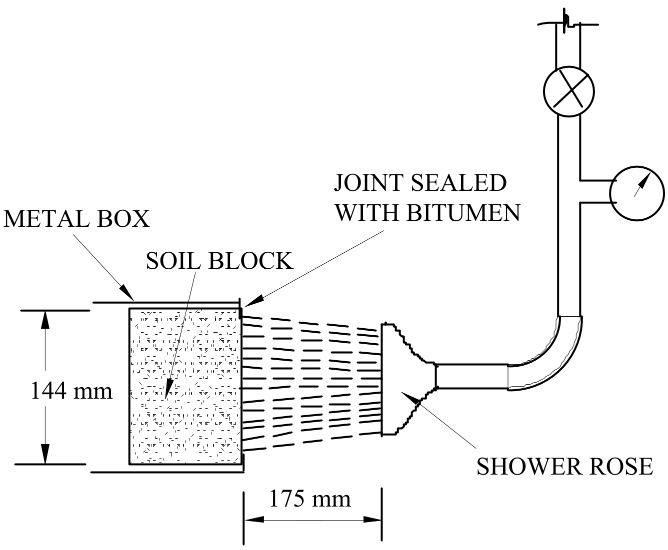


Figure 2.1 Details of Reddy and Jagadish Spray Test

Reddy and Jagadish defined the relative erosion of test specimens as the volume of soil removed divided by the volume of water impinging on the specimens.

The volume of soil removed was then defined as the average depth of erosion multiplied by the eroded area of the block. The volume of water impinging on the specimen was then defined as the precipitation rate (566mm/min) times the duration of the test times the area of water impact.

On the basis that the eroded area of the block is equal to the impact area the above relationships enables the relative erosion to be expressed as an erosion ratio (ER), where the ER simply relates the average depth eroded per minute to the precipitation per minute (566 mm/min).

$$ER = \frac{\text{Average depth of erosion per minute (mm)}}{566} \qquad \text{.........}(2.1)$$

Equation 2.1 assumes that erosion is linearly proportional to spray intensity and duration of spray.

Reddy and Jagadish (1987) found that the majority of specimens were completely eroded in a period of 2 hours with their test. They conducted tests on 5 different unstabilised Red Soil types and found ER's varying from 0.00292 to 0.03887. The average depth of erosion for the latter specimen (RS7) was 22 mm and the test was carried out for a period of 1 minute.

Reddy and Jagadish then built an experimental wall using the RS7 soil and exposed it to the weather for a period of 3 years, during which time the total rainfall was 2330 mm. At the end of this period the average depth of erosion in the test wall was 28.3 mm, giving a field ER of 0.012, compared to the laboratory value of 0.039. They explained this difference as follows

"*The higher value of erosion ratio in the laboratory test is understandable, since the rate of precipitation in the laboratory spray is approximately hundreds of times higher than the highest precipitation rate in any rain. It is also possible that more than half the precipitation is caused by low intensity rains which hardly cause any erosion. The laboratory test is hence decidedly more severe than rain erosion in the field and can be regarded as a very conservative indicator of the erosion behaviour of mud brick walls*."

They also conducted tests on pressed earth soil blocks made from red soil stabilised with 5% cement. These were exposed to the spray test for a period of 120 minutes with very little erosion being observed, "*A few small pits/patches of less than 1 mm depth are seen on the faces of the soil-lime and soil-cement blocks using red soil RS3*"

2.1.2.4 Ola & Mbata Spray Test

Ola and Mbata (1990) sprayed water vertically 140 mm onto specimens using a 100 mm shower rose for a period of 3 hours. They sprayed cement stabilised specimens at five different pressures, 40 kPa, 150 kPa, 250 kPa, 350 kPa and 450 kPa. Brick sizes were 240mm by 100mm by 80mm.

Ola and Mbata quoted rates of discharge varying from 4.16 l/min at a pressure of 40 kPa to 46.30 l/min at a pressure of 450 kPa (8.33 m^3 in 3 hours). The discharges were considered " *adequate to generate the varying rainfall rates observed in the tropics and other parts of the world*". Assuming a target area of around 240 cm^2 the flow rates used correspond to precipitation depths of around 30 to 350 metres, the lower value being equivalent to an annual rainfall of 600 mm over a 50 year period, and the upper value being equivalent to an annual rainfall of 7000 mm over the same period.

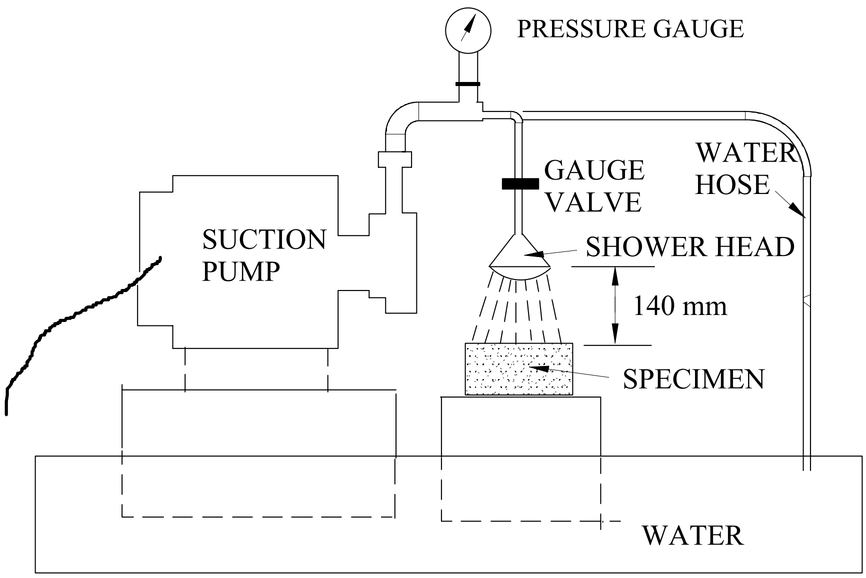


Figure 2.2 Ola and Mbata Spray Apparatus (Ola and Mbata, 1990)

The results showed that weight loss increased with increasing spray pressure and decreased with increasing specimen compaction pressure and/or increasing cement content. In all cases of stabilised specimens weight loss was less than 1%. For the specimens compacted at 1 MPa and sprayed at 450 kPa the measured mass loss of 0.98% represents a loss of approximately 40 g or 0.56 kg/m^2/hour or 0.28 mm/m^2/hour or 0.1 mm/metre of rainfall.

Analysis of their results for the 2 MPa specimens shows that as a first approximation the percentage mass loss can be approximated as a constant times the volume of water impacting the specimen (Coefficient of Variation ≈ 20-30%). Further accuracy is obtained by plotting the erosion per unit volume versus the spray velocity (Figure 2.3).

As can be seen from Figure 2.3 this mass loss per unit volume of impacting water decreases with increasing spray velocity.

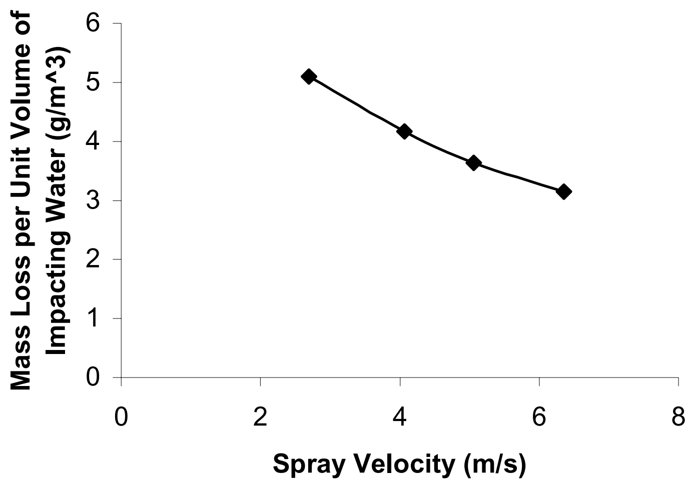


Figure 2.3 Mass Loss vs Spray Velocity (Ola and Mbata, 1990)

If the mass loss per unit volume is plotted against the inverse of the square root of the impacting velocity (Figure 2.4) there is an extremely good linear correlation (R^2 = 0.99). The slope of the line varies depending on the compaction pressure but the exponent is fairly consistent for all the tests. This indicates that there might be a simple relationship between erosion per unit volume of water and the inverse of the square root of the spray velocity (v), with the material factors being subsumed in a single multiplying factor.

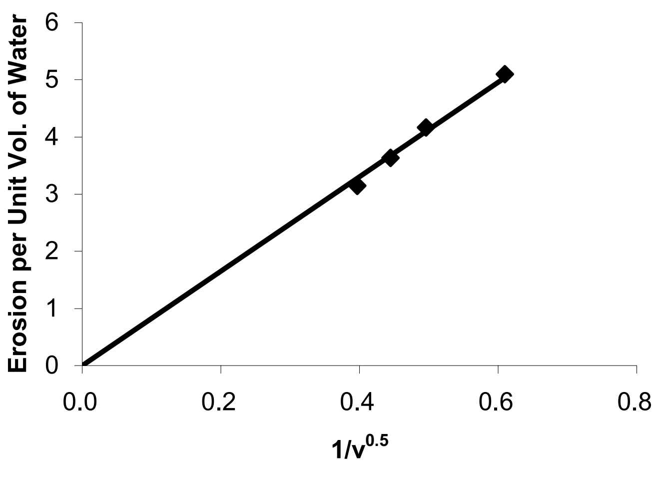


Figure 2.4 Erosion per Unit Volume vs. $\frac{1}{\sqrt{v}}$

2.1.2.5 Bulletin 5 Spray Test

In response to an increased interest in earth construction in the 70's the Commonwealth Experimental Building Station in Australia developed a refined version of the spray test (Schneider, 1981). This test is further referred to herein as the "Bulletin 5" spray test as that is the name of the document in which it is contained.

This spray test is called up in the Building Code of Australia and a modified version was included in the New Zealand Code of Practice on earth wall buildings (NZS 4297,1998).

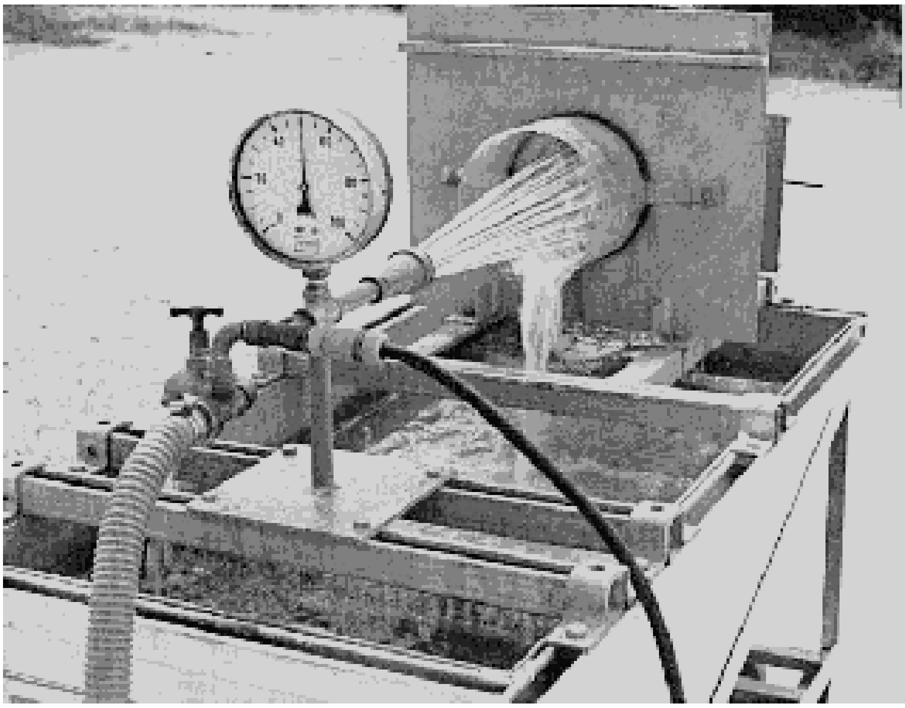


Figure 2.5 Australian "Bulletin 5" Spray Test (Schneider, 1987)

The Bulletin 5 spray test involves water being sprayed horizontally out of a special nozzle at a pressure of 50 kPa. The sample is placed 470 mm from the nozzle and after an hour the sample is examined. The depth of erosion is determined using a 10 mm diameter rod. The impact area is within a circle of 150 mm diameter. The nozzle has 35 holes each of which is 1.3 mm in diameter. The total cross-sectional area of flow is therefore 46.5 mm^2 . Flow pressure is 50 kPa, which would give a theoretical exit velocity of 10.0 m/sec.

Measurements carried out indicate a discharge of 29.6 l/min for this test which yields a total volume of water in the one hour test of approximately 100 metres or approximately 85 years rainfall in Sydney. The corresponding jet velocity of 9.9 m/s, based on the above cross-sectional area, indicates very little head loss through the nozzle.

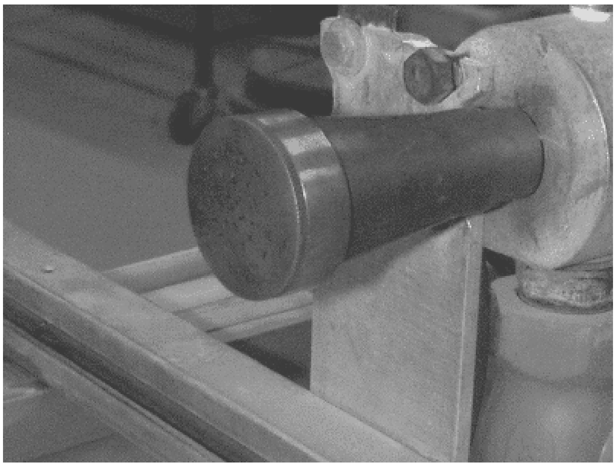


Figure 2.6 Bulletin 5 Nozzle

The maximum allowable erosion is 60 mm per hour. Frencham (1982) reported that "*The present thinking is that soils having an erosion rate of 0.5 mm/minute* [30 mm total] *for the duration of the test are beyond doubt; those having a rate between 0.5 and 1.5 need further evaluation; and those having rates in excess of 1.5 are either unsuitable or need stabilisation to be made suitable.*" Such thoughts do not appear in Bulletin 5 and do not seem to coincide with the opinion of many that 60 mm max erosion is too severe.

The kinetic energy associated with the nozzle is approximately 5000 MJ/m^2. To obtain some idea of the relevance of the Bulletin 5 spray test, this value can be compared to the value for the annual kinetic energy of rainfall obtained by using the formula of Morgan et al. (1984) in which kinetic energy is related to annual rainfall.

$$KE\ (J/m^2) = \text{Annual Rainfall (mm)} \times K \qquad \text{..........}(2.2)$$

Assuming K = 21 $J/m^2/mm$, as suggested by Morgan for temperate climates, and an annual rainfall of 1200 mm, gives an annual kinetic energy of around 25 MJ/m^2. Assuming further that the test should relate to a 50-year life span then the total kinetic energy over those 50 years would be 1250 MJ/m^2. If this were then related to a limiting erosion of 15 mm then the corresponding kinetic energy for a limiting erosion of 60 mm (that stipulated in the Bulletin 5 test) would be 5000 MJ/m^2 , which is consistent with the Bulletin 5 test (assuming of course that all the kinetic energy of the rain was directed at the earth wall).

2.1.2.6 Dad's Spray Test

As part of his research work into cement stabilised soil Dad (1985) developed a spray test based on one developed by Meyer and McCune at Purdue University for soil erosion. In this test a particular 2.5 mm diameter Veejet nozzle (No 80100) was placed vertically above a specimen, which was aligned at an angle of 30 degrees to the falling spray of water. (Veejet nozzles are manufactured by Spraying Systems Company in Illinois, USA and are typically used for washing coal on a conveyor. They produce a flat elliptical spray pattern, with lower intensities at the ends). Dad found that using a drop height of 2.45 metres and a nozzle pressure of 42 kPa he was able to simulate the terminal velocity of most raindrops.

The cured test specimens were placed at different positions on a grating below the spray, depending upon whether a high intensity (3125 mm/hour) or low intensity (145 mm/hour) rainfall was being simulated. To simulate the annual rainfall in Bangladesh (3500 mm/year) over a 25-year period, specimens were continuous spraying for 35 hours at a high intensity location and 30 days at a low intensity location. At high intensity, spraying continued for 12 hours after which the specimen was removed and oven dried at 60° C for 24 hours and then this cycle was repeated.

Some of the conclusions of his work were

- Cement content and compaction pressure were the two most important variables for determining durability
- The effect of cement content was practically linear.
- Spraying at an angle of 90 degrees to the block face produces about 30% more erosion than at 30 degrees.
- There was a small difference in erosion between horizontal and side faces
- There was a similar magnitude of erosion in the high intensity test compared to the low intensity test, with the high intensity test being marginally higher.

Figure 2.7 illustrates the variation in erosion with compaction pressure and spray intensity. Dad suggested that the high intensity test should be used because of its much shorter duration (35 hours).

- Erosion increased with time but at a marginally increasing rate, especially towards the end of the test.

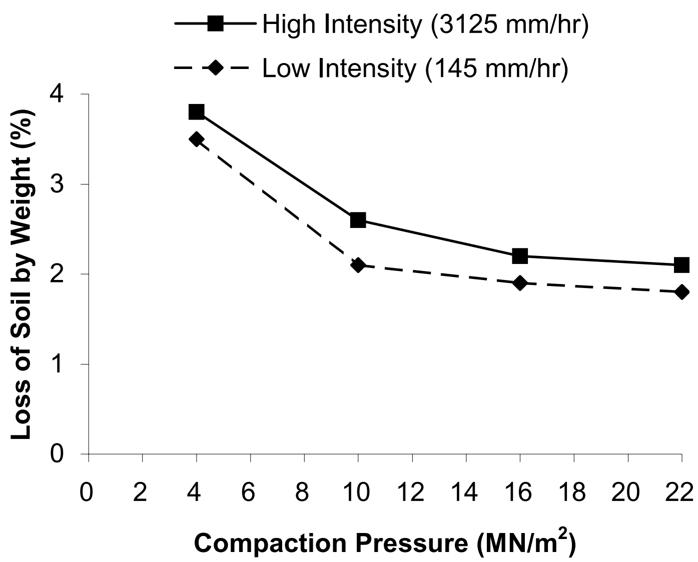


Figure 2.7 Effect of Spray Intensity on Loss of Weight (Dad, 1985)

2.1.2.7 Ogunye's Spray Test

Ogunye (1997) followed on from the work of Dad using a simulated spraying chamber approximately 1 metre square. He also apparently used a Veejet 80100 (6.4 mm jet diameter) and experimented with various pressures and drop heights. His aim was to simulate rainfall of 150 mm/hr and to do this he found that he needed to spray at a pressure of 50 kPa with the nozzle suspended 2000 mm above the specimens, which were placed on a sloping rack. Details of his test apparatus are given in Figure 2.8.

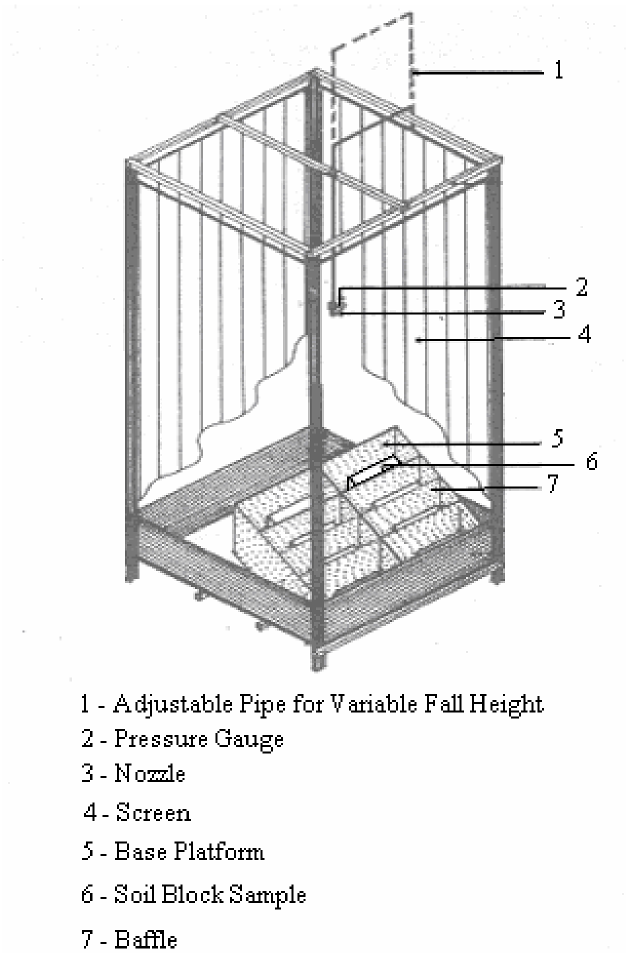


Figure 2.8 Ogunye Spray Test Set-up (Ogunye, 2000)

The sloping rack contained "boxes" for eight specimens and the angle was adjustable, although in his tests an angle of 30 degrees was adopted. Specimens were painted on all sides, except the exposed face, with a heat resistant paint. Specimens were sprayed for a total of 120 hours and rotated at 15-hour intervals to offset any variation in intensity produced by the VeeJet spray pattern. The time of exposure and intensity of rainfall was chosen to reflect the amount of rain experienced in tropical Nigeria.

From data that appeared in his work it seems that the discharge was around 2.3 l/min giving a nozzle velocity of 1.2 m/s, which equates to an impact velocity of around 6.5 m/s. This impact velocity would correspond to a drop size of around 2 mm.

Ogunye used his test to examine the change in various parameters (eg wet strength) with weight loss according to his test procedure for five artificial soils, made of combinations of sand, silt and clay, ranging from a sandy loam (Soil 1) to a clay loam (Soil 2). The soils were stabilized with cement (6, 8 and 10%), lime or lime/gypsum. Weight losses for the 120-hour tests ranged from 0.14 to 5.82%, with around 70% of the specimens having weight losses less than 1%.

2.1.2.8 Zavoni et al. Spray Test

Studies carried out by Zavoni et al. (1988) into the properties of stucco compositions applied to adobe structures at the Catholic University of Peru used a simple oscillating lawn sprinkler to simulate rain on test panels. In the third series panels were subjected to 2 hours of daily simulated rain for a 15-day test period. They point out that in their opinion this test was much more severe than normal rainfall. Their results are particularly interesting in that they showed a gradual fall off in the rate of weight loss with hours of rain, the graph showing excellent agreement with an MMF growth function. Their results are shown in Figure 2.9.

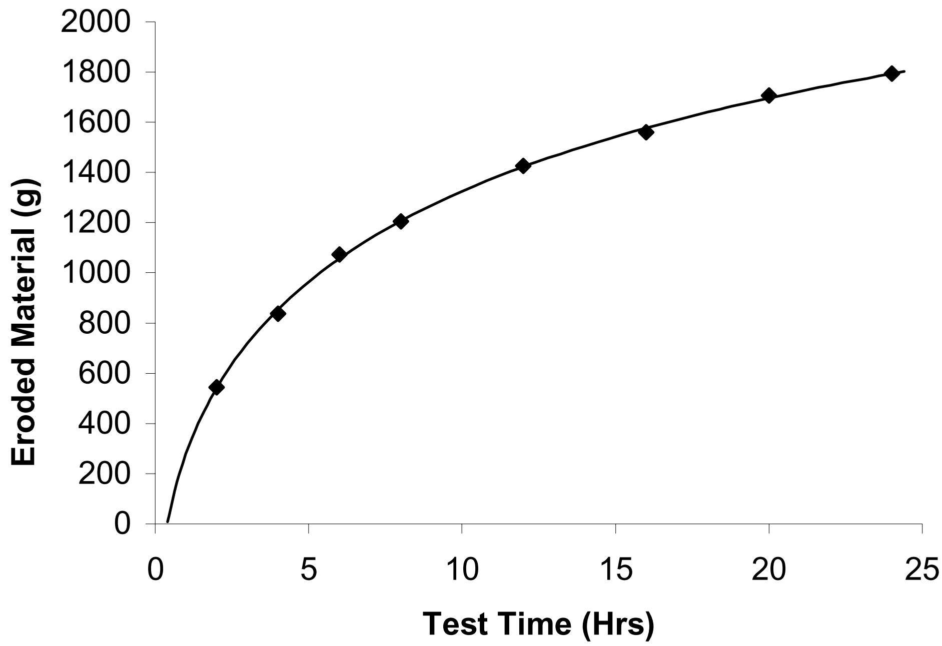


Figure 2.9 Variation of Erosion with Time (Zavoni et al., 1988)

2.1.3 Drip Tests

2.1.3.1 Yttrup Drip Test

Yttrup, Diviny and Sottile (1981) developed the first drip test at Deakin University. Their motivation was to devise a simple test that could be used by adobe owner-builders to determine the suitability of their soil. The test involves releasing 100 ml of water in the form of drops onto sample bricks, which are inclined at an angle of 27 ° from the horizontal. Following the test the pitting depth is recorded and the "Depth of Pitting" is taken as the average pitting depth for both sides of the sample.

According to Morris (1994) this test produced water drops of around 6 mm with quite varying frequency. On average he found that 833 drops fell over a period of around 60 minutes (approximately 14 drops per minute). The theoretical velocity of the drops is 2.8 m/s and the kinetic energy 0.44 mJ per drop (Total kinetic energy = 833 × 0.44 = 0.37J). On the basis that each drop impacts on an area of 25 mm by 25 mm this equates to a kinetic energy of 0.6 MJ/m^2

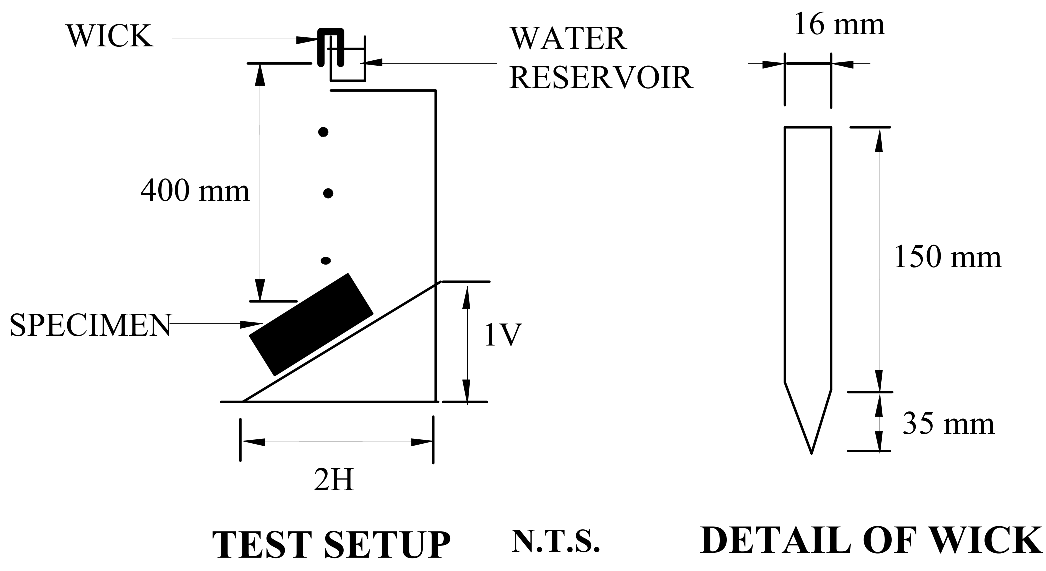


Figure 2.10 Yttrup Drip Test Set-up (1981)

Frencham (1982) developed the approach further and related the depth of pitting following the test to an Erodibility Index based on a correlation of drip test results with the observed performance of 20 buildings in the Western District of Victoria, which have existed for periods between 60 and 120 years. He categorised these buildings into four categories : Non Erodable, Slightly Erodable, Erodable and Very Erodable based on their surface appearance. Samples of each category were subjected to the drip test and the results were then used to define four classifications of "Erodibility Indexes", as shown in Table 2.4.

Table 2.4 Classification of Erodibility According to Yttrup Drip Test

Erodibility Index E_I	Pitting Depth (mm)	Erosion Category
1	D = 0	Non Erodable
2	0 < D < 5	Slightly Erodible
3	5 < D < 10	Erodable
4	D > 10	Very Erodable

The rainfall in this area averages around 500 mm per year. It appears that samples were taken from the least exposed areas of the buildings: "*the east wall was used as a source of the sample bricks …. because of its minimal exposure to adverse conditions* " and the buildings had little or no eaves overhang.

Frencham also proposed a formula to take into account differing wall exposures and rainfall than that experienced by the sample bricks used to calibrate the Erodibility Index. For differing exposure conditions he proposed an Exposure Factor (E_x), which was derived intuitively from the observed effects of weathering. Values for exposure factors are given in Table 2.5.

Table 2.5 Exposure Factors E_x (Frencham, 1982)

Terrain Category	Walls exposed to prevailing winds	Other walls
1. (Coastal, very exposed)	2	1
2. (Rural)	1	0
3. (Suburban Area)	0	0

For differing rainfall rates Frencham proposed the use of a Rainfall Factor R_F, which is zero if the rainfall is less than 520 mm and 1 if the rainfall was greater than 520 mm.

Frencham combined the above two factors with the Erodibility Index (E_I) of a test block to give a "Wall Erodibility Index" (E_{WI}) which was meant to give a guide to the actual performance of an unprotected wall in a specific location. The Wall Erodibility Index was defined as follows.

$$E_{WI} = E_I \text{ (Sample)} + \text{Exposure Factor} + \text{Rainfall Factor} \qquad \text{……….(2.3)}$$

Frencham suggested that soil samples and locational factors which produce a Wall Erodibility Index greater than 4 imply that the proposed material is not suitable for use without stabilisation, i.e. the soil is not suitable in its present form.

Frencham further proposed relating Erodibility Indices as determined above to the expected loss of structural wall thickness (Table 2.6)

Table 2.6 Relationship between Wall Erodibility Index and Loss of Wall Thickness

Wall Erodibility Index	Expected Loss in Wall Thickness
1	0 mm
2	10 mm
3	25 mm
4	50 mm

2.1.3.2 Swinburne Accelerated Erosion Drip Test

The Swinburne Accelerated Erosion Test (SAET) was devised in 1987 by a group of final year Civil Engineering students at the Swinbourne University of Technology. In their study of the Yttrup drip test they concluded that the resultant pitting depths were too small to be accurately measured. They developed a similar test but with a continuous jet of water rather than the individual drops used in the Yttrup drip test. The head of water above the brick face is also significantly higher than with the Yttrup drip test. In the SAET test a continuous jet of water is discharged via a 5mm I.D. tube for a period of 10 minutes with a constant head of 1500mm. Figure 2.11 is a sketch of the SAET test. According to the Earth Building Association of Australia (EBA, 2001) discharge from this test is approximately 1 l/min (17.7 ml/s) with a kinetic energy of 156 J over the duration of the 10-minute test (0.26 J/s).

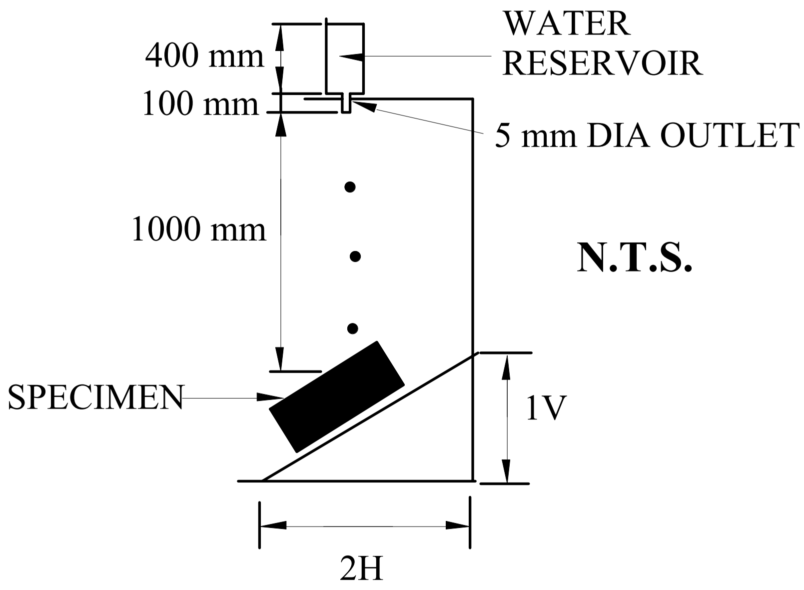


Figure 2.11 SAET Test

Weisz et al (1995) proposed the following classification of mud bricks based on the SAET drip test

Table 2.7 SAET Drip Test Classification

Classification	Pitting Depth (mm)
Excellent	$0 < D \leq 10$
Good	$10 < D \leq 20$
Fair	$20 < D \leq 30$
Poor	$D > 30$

2.1.3.3 Comparison Between Drip Tests and Bulletin 5 Spray Test

Weisz et al. (1995) collected sample bricks from three sites in Victoria. 19 of the samples were adobe bricks (from 2 sites) and the remaining 9 were pressed earth bricks from the remaining site. They then subjected them to the above three tests. It appears that the drip tests were applied to the two side faces and the spray test to the flat face, although the latter is not clear in their paper. To avoid premature wetting each brick was first tested by the Yttrup drip test, then by the SAET drip test and finally by the Bulletin 5 spray test.

It appears that the pressed earth bricks (Balnarring) were the weakest and in some cases eroded right through before the 60 minutes was up in the spray test. In this case the pitting depth was calculated based on the average rate of erosion. In some cases the values for the Yttrup drip test were very small, and in this case an arbitrary value of 0.5 mm was assigned to these bricks.

Using regression analysis Weisz et al. derived the following relationships between the tests

Yttrup Drip Test Pit Depth = 0.1312 × SAET Drip TestPit Depth (r = 0.78)…..….(*2.4*)

Bull 5 Spray Test Pit Depth = 5.29 × SAET Drip Test Pit Depth (r = 0.93)….…(*2.5*)

Bull 5 Spray Test Pit Depth = 37.42 × Yttrup Drip Test Pit Depth (r = 0.90)……..(*2.6*)

The correlations using the Yttrup drip test contained 15 tests where nominal 0.5 mm erosions appear to have been specified and the values for both the SAET and Bulletin 5 test were low for all the 19 adobe bricks. The values for the pressed earth bricks were much larger. The author carried out a regression analysis on these results only and, although the relationships above remained substantially the same, the correlation coefficients were significantly lower (eg. Bull 5 vs. SAET test r~0.5), when the nominal values were not included.

2.1.4 Permeability Criteria and Slake Tests

2.1.4.1 Webb et al.

Webb et al. (1950) measured the water absorption of soil cement blocks after soaking in water for 24 hours. Their results indicated a maximum weight gain of 24.4%, a minimum of 12.0% and an average of 16.9%. Despite these values they concluded, "O*n twenty-four hours immersion in water at room temperature, the dry specimens should preferably not gain more than 12% in weight, although some bricks with a higher absorption may be satisfactory* ". This seemingly stringent requirement appears to relate more to a need for moisture to remain in the mortar during laying, rather than for any consideration of durability, as the authors specifically refer to the wire brush test for this.

Webb et al. also simulated water absorption from mortar by laying specimens on wet felt and in this case both sandy soil and clay soil blocks absorbed less than 12.5% in a four-hour period.

2.1.4.2 Cytryn Immersion Test

As well as subjecting blocks to a spray test Cytryn (1955) also soaked them in water to determine their behaviour in a saturated condition. Blocks were left in water with 1/8 of their depth exposed for a period of 24 hours. The blocks were weighed after the test. Blocks were deemed to have passed this test if
"(*1) not more than two of its corners deteriorated, (2) if the weight loss of the material separated from the block during 24 hours did not exceed one percent of its dry weight, and (3) if immediately after the 24 hours period of immersion it was possible to lift the block out from the water by hand and to carry it away without damaging it.*" (Cytryn, 1955)

This test is significant because, although it was not considered by Cytryn to be a test for resistance against erosion, "*The block which passed successfully the accelerated weathering test usually also passed the immersion test*" (Cytryn, 1955). It can therefore be considered as a substitute for the spray test.

The amount of water absorbed by the blocks during Cytryn's tests varied from about 7% to 20% but Cytryn appears to consider the limit of 12% of Webb et al. (1950) as being an acceptable limit.

2.1.4.3 Soaking Test – New Mexico Building Code

Section 2412 of the New Mexico Building Code (1988) contains the following

"C. Classes of Earthen Construction

(1) *Stabilised Adobes. The term "stabilised" is defined to mean water resistant adobes made of soil to which certain admixtures are added in the manufacturing process in order to limit the adobe's water absorption. Exterior walls constructed of stabilised adobe and mortar require no additional protection. Stucco is not required. The test required is for a dried four-inch (4") cube cut from a sample unit and shall absorb not more than four percent moisture by weight when placed upon a constantly water saturated porous surface for seven (7) days. An adobe unit which meets this specification shall be considered "stabilized"."*

This test relates more to moisture absorption than to durability, as the majority of adobe buildings in this region are protected from driving rain by waterproof renders.

2.1.4.4 Cartem Soak Test

Cartem Products , manufacturer of the Elephant blockmaker, specify a slake test in their brochure. This test is described as follows

Five blocks selected at random should be tested by immersing them in water overnight for at least 12 hours, and then dried in the sun for a full day. This procedure must be carried out seven times. If the blocks then slake or fall to pieces this indicates that the mix must be modified or there is a fault with the stabiliser. (Cartem Brochure)

2.1.4.5 Sun-Dried Bricks Slake Test

Sun–Dried Bricks Ltd specify a modified slake durability test in their Information Bulletin #5.3 which is similar to the Cartem test. Their test involves 8 hours total immersion followed by 16 hours drying at 50 ° C. This cycle is repeated 5 times and the ratio of the dry weight before and after the test determined. Expressed as a percentage this ratio is called the Slake Durability and Sun-Dried Bricks use an arbitrary scale (Table 2.8) to determine the suitability of their bricks.

Sun-Dried Bricks indicate that this is a modified version of the slake durability index used in engineering geology, involving mechanical tumbling in a rotating mill. The validity of their arbitrary scale must therefore be questioned, as it involves no abrasion at all.

Table 2.8 Classification of Slake Durability

Slake Durability%	Durability
95-100	Extremely High
90-95	Very High
75-90	High
50-75	Medium
25-50	Low
0-25	Very Low

2.1.5 New Zealand Code

This standard was a result of a joint collaboration between Australia and New Zealand but the final documents were not adopted in Australia. The standards are NZS 4297:1998 "Engineering Design of Earthbuildings", NZS 4298:1998 "Materials and Workmanship and NZS 4299:1998 "Earth Buildings Not Requiring Specific Design".

Clause 3.2.1 of the Engineering Design section of the Standard states that, with regard to durability

"*An earth wall will be deemed to comply with the durability performance criteria if, provided that normal surface maintenance has been carried out, its thickness has not decreased by more than 5% nor by more than 30 mm at any point during the buildings life.*"

In an attempt to relate the material properties of earth buildings to their climatic environment the author proposed a modification to the limiting erosion depth in the Bulletin 5 spray test. This modification was contained in the initial draft document of the Code Committee BD/83, and involved defining a "Limiting Erosion Depth" which was dependant on climatic conditions. The formula proposed was

$$\text{Limiting Erosion Depth in mm} = k_1 \times k_2 \times k_3 \times 20 \qquad \ldots\ldots\ldots(2.7)$$

Where

k_1 = Rainfall Factor = $\dfrac{1200 \times 50}{w \times P_a}$

w = Serviceability Wind Speed for Building location (m/sec)

P_a = Annual Rainfall for building location (mm/yr)

k_2 = Wall Orientation Factor = 1.4 for walls not facing predominant wind driven rain

= 1 Elsewhere

k_3 = Eaves Factor = $1 + \left(\dfrac{2 \times b}{h} \right)$

b = eaves width (mm); h = height of wall to eaves (mm)

All of the above factors were based on the author's experience, with the main factor k_1 being based on the assumption that a limit of 20 mm erosion was appropriate for an annual rainfall of 1200 mm and a design wind speed of 50 m/s.

Following concerns from one member of the committee (Richard Walker) that this formula was too sensitive to rainfall a revised formula for k_1, suggested by Mr Walker was finally adopted. In this formula the cube root of the rainfall intensity is used when calculating k_1 (Equation 2.8).

$$k_1 = \text{Rainfall Factor} = \frac{10 \times 50}{\sqrt[3]{P_a} \times w} \qquad \ldots\ldots\ldots\ldots(2.8)$$

(Note that 10 is approximately the cube root of 1200)

There was considerable debate within the committee regarding the relative merits of the Bulletin 5 spray test vis-a–vis the Yttrup drip test. In the end it was decided to incorporate both the Yttrup Drip test and the Bulletin 5 spray test into the standard. This was achieved by changing the Limiting Erosion Depth to a "Limiting Erodibility Index" so that comparison could be made with the Yttrup "Erosion Indexes". The Limiting Erodibility Index was defined as follows

$$\text{Limiting Erodibility Index} = k_1 \times k_2 \times k_3 \qquad \ldots\ldots\ldots\ldots(2.9)$$

Using this approach a limiting erosion of 20 mm corresponds to a limiting erodibility index of 1.

Clause 3.2.2 states that *"Walls shall be considered satisfactory in terms of 3.2.1 above if the erodibility index of a sample (as determined in accordance with Appendices D or E of NZS 4298 is less than or equal to the Limiting Erodibility Index* [Equation 2.9] *determined in accordance with Appendix A of this Standard."* Appendices D and E specify Erodibility Indices for the Bulletin 5 spray test and the Yttrup drip test as shown in Tables 2.9 and 2.10.

Table 2.9 Erodibility Indices from Spray Erosion Test

Depth of Erosion (mm/hr)	Erodibility Index
<20	1
$20 \le D < 50$	2
$50 \le D < 90$	3
$90 \le D < 120$	4
$D \ge 120$	5 (Fail)

Table 2.10 Erodibility Indices from Yttrup Drip Test

Pit Depth (mm)	Erodibility Index
Erodibility Index of 1 can only be determined by spray test	1
$0 < D < 5$	2
$5 \le D < 10$	3
$10 \le D < 15$	4
$D \ge 15$	5 (Fail)

2.1.6 Strength Tests

2.1.6.1 Wet to Dry Strength Ratio

On the basis of work done by Winkler on stone testing the author (Heathcote, 1995) proposed using the ratio of wet to dry strength as a measure of the durability of earth buildings.

Following on from work by Tejmajer, Winkler (1985) proposed the use of an index of durability for building stones based on the ratio of wet to dry compressive or flexural strength. Winkler points out that " *the grain cement in sandstones appears to be a deciding factor*" and "*Clay minerals may form ……….resulting in a decrease of the durability and dry-to-wet strength ratios*". Winkler proposed an evaluation system based on varying ratios of wet to dry moduli of rupture, shown in Figure 2.12. By this figure a "fair" degree of durability is achieved with a ratio of wet to dry strength of 60%.

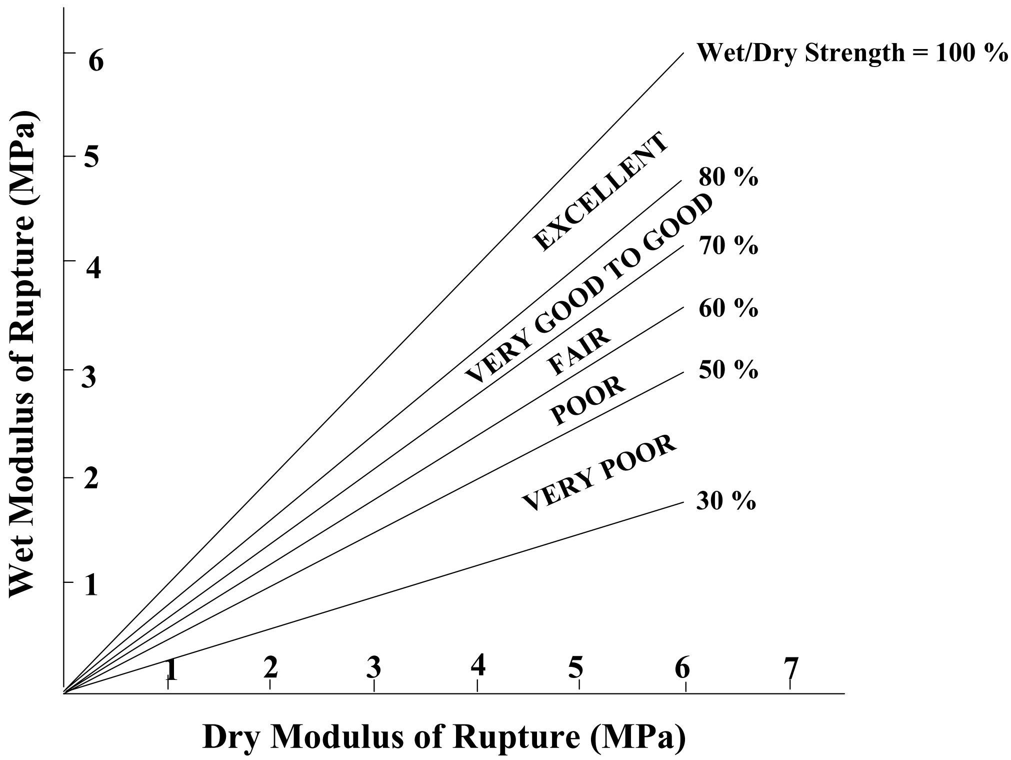


Figure 2.12 Winkler's Durability Criteria for Stone

Winkler (1985) concluded that the ratio of wet to dry strength was "*a good and rapid method of testing the durability of a stone for construction, if used with caution*"

Like many other porous materials the wet strength of earth walls is significantly lower than the dry strength. Lunt (1980) stated that "*the wet strength of a stabilised soil wall may be only one-third of its dry strength*". Jagadish and Reddy (1984) reported that "*a large number of studies have shown wet/dry strength ratios in the range of 0.25 to 0.35*".

Heathcote (1995) reported that stabilised soil samples which satisfied the spray test requirements of the de facto Australian standard (Bulletin 5) had ratios of wet to dry strength around 0.33. In the tests by Cytryn (1957) the ratio between saturated to dry (presumably air-dry) strength was about 40% for loess soils and 60% for a permeable sandy soil. Both these soils were stabilised with from 6 to 8% cement and easily passed the Cytryn spray test.

Tests conducted by Chadda (1956) in India show that for a clayey silt the ratio between wet and dry strengths was 0 for a cement content of 2% and increased to 0.41 for a cement content of 8%. For a sandy soil the ratio remained about 0.4 for all cement contents between 2% and 8%.

Tests by the Central Road Research Institute in India (Date Unknown) reported saturated to oven-dry ratios of 0.15 and 0.25 for soils which they considered needed to be stabilised.

The author evaluated data obtained from Walker (1995a), which shows that the durability of pressed earth specimens increases exponentially with an increase in the ratio of wet to oven dry strength, as shown in Figure 2.13.

Based on the Fitzmaurice criteria of a maximum of 5% weight loss (according to the wire brush test) a wet to dry strength ratio of the order of 0.8 (Upper Bound) would seem to be required based on the Walker data. For a limitation of 10% a wet/dry ratio of around 0.5 would seem reasonable.

Wolfskill (1970) proposed a minimum wet to dry strength ratio of 0.5 and this appears to have become part of the CraTerre specification for pressed earth bricks (CraTerre, 1989). The requirement for a wet to dry strength ratio of 0.5 was continued by

CraTerre/ENTPE (1996) but appears to be more related to the requirement for compressive strength than durability as this document introduces an additional requirement for abrasion resistance for blocks exposed to driving rain. The wet to dry strength ratio remains constant but the required abrasion resistance (as determined by their modified wire brush test) varies with exposure.

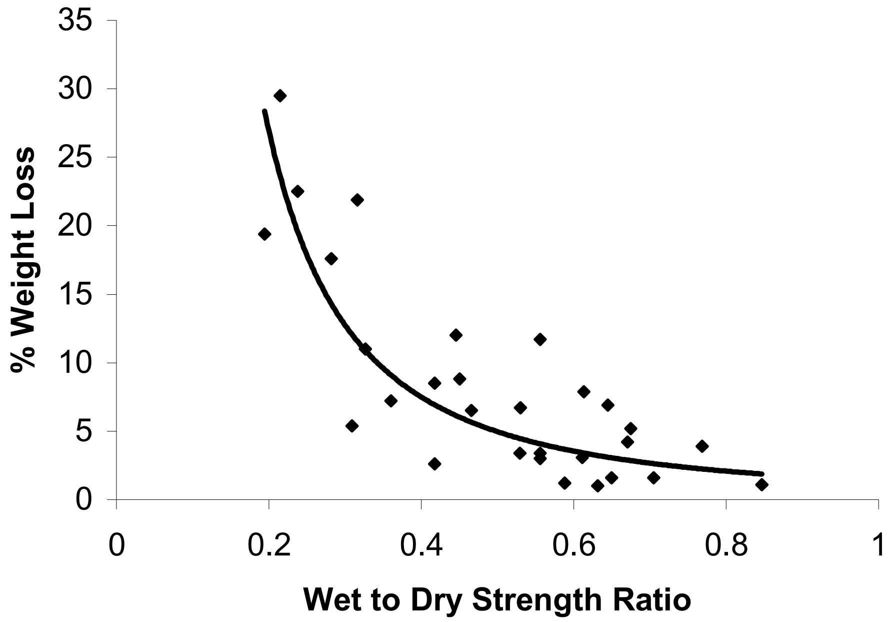


Figure 2.13 Weight Loss vs. Wet to Dry Strength Ratio

2.1.6.2 Correlation Between Compressive Strength and Durability

For a given soil there is usually an increase in strength and durability with increasing cement content. However across a range of soils there is no simple relationship between strength and durability. The Portland Cement Association (PCA, 1956) carried out compressive strength and "wire brush" durability tests on 1,188 samples with clay contents varying from 0-50%. They found considerable difference in the 7-day saturated compressive strengths of specimens which passed their durability criteria. A histogram of their results is shown as Figure 2.14.

From Figure 2.14 it can be seen that the mean saturated strength of specimens passing the "wire brush" test was around 2.5 – 3.0 MPa and that 95% of the specimens passing the "wire brush" durability test had a saturated compressive strength greater than 5.0 MPa.

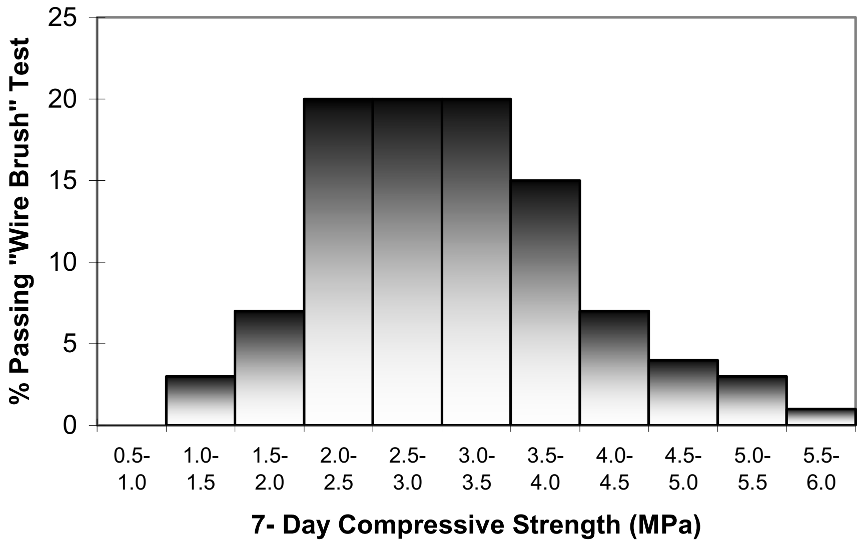


Figure 2.14 Relationship Between Strength and Durability (PCA, 1956)

Based on the PCA data it would not be possible to use compressive strength as a substitute for durability testing except to say that a specimen with a saturated compressive strength of greater than 5 MPa would most likely pass the “wire brush” test. However compressive strength may be used as a control for durability once the relationship between the “wire brush” test and strength has been established for a particular soil.

A plot of Walker's data (Walker, 1995a) for saturated compressive strength versus weight loss as per the wire brush test is shown in Figure 2.15. This figure shows a coefficient of determination (R^2) of 70%. , which means that 70% of the variation in weight loss can be explained by variations in saturated compressive strength. Although this is not conclusive the result does indicate a trend.

Crowley (1998) carried out unconfined compressive strength and Yttrup drip tests on five soils with clay contents varying from 19 to 65% and cement contents between 0 and 10%. For the compression tests the samples were oven dried and strengths varied from 0 –25 MPa. Crowley found no relationship between the two tests either as a whole or for individual soils. This may not be surprising given that durability must have a great deal to do with saturated properties and all his compressive tests were oven dry.

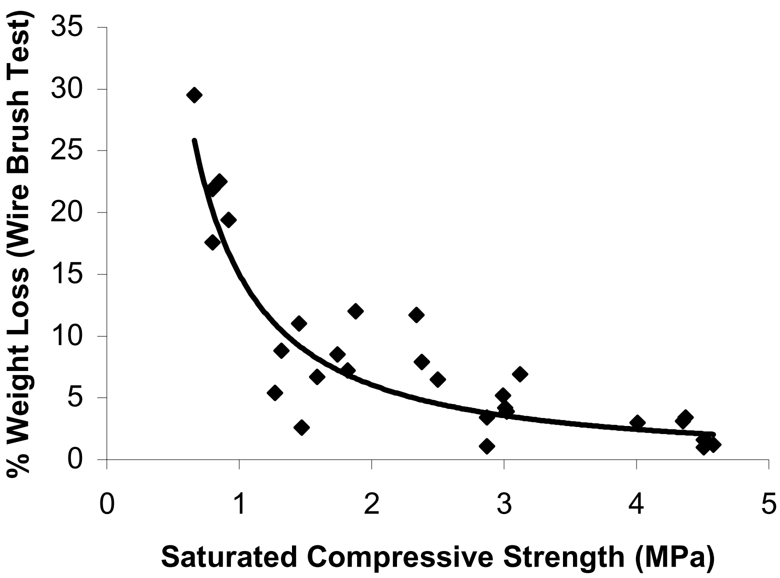


Figure 2.15 Saturated Compressive Strength vs. Erosion

2.1.7 Surface Strength Tests

2.1.7.1 Penetrometer Tests

Jagadish and Reddy (1984) used a penetrometer test as a measure of compressive strength, which can then be related to durability on the basis of the tests of the Portland Cement Association, presented in Section 2.1.6.2. They used a concrete testing penetrometer. Blocks were wetted by pouring water on the face of the bricks three times. When the water was absorbed by the bricks the penetrometer was pressed into the bricks until a pressure of 3.5 MPa was reached. This was repeated at 6 points on a brick and the average penetration recorded.

Jagadish and Reddy found a reasonable correlation between the average penetration and the dry compressive strength of the bricks measured in a compression testing machine. The strength reduced rapidly for penetrations greater than 1 mm with dry strengths less than 2 MPa after a penetration of 3 mm.

2.1.7.2 Pendulum Sclerometer

CraTerre have used a low strength pendulum sclerometer, used in testing concrete, for testing earth bricks. This apparatus works on a rebound principle, with the strength of the brick proportional to the angle to which the falling pendulum rebounds off the brick.

2.1.7.3 Surface Pulloff Tests

In 1997 the author proposed the use of a surface pull-off test using glued on bolts as an indicator of the erosion resistance of soil specimens. As part of a student project a series of 23 specimens were made with cement stabilised artificial soils containing various combinations of sand, fly ash (representing silt) and kaolin (representing clay). The heads of two 16 mm diameter bolts were then epoxied onto the sides of the specimens. When the epoxy had cured the specimens were wetted and the bolts pulled off using a spring balance attached to a loop welded to a 16 mm nut screwed onto the ends of the bolts. These specimens were then subjected to the standard Bulletin 5 spray test. The weight loss following the test was recorded and converted into an average loss in surface thickness over the spray area. The results, shown in Figure 2.16, show a reasonably good correlation between erosion resistance and the pulloff values.

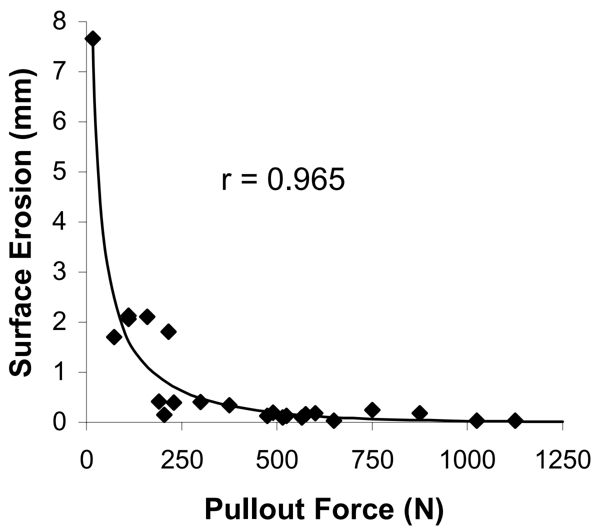


Figure 2.16 Graph of Average Surface Erosion vs. Pullout Force

2.2 Effect of Material Properties on the Erosion Resistance of Earth Walls

2.2.1 Soil Composition

The Universal Soil Loss Equation (USLE) has been widely used by conservationists in the United States to predict soil erosion and some similarity with the erosion of earth walls could be expected.

The USLE uses a soil erodibility factor K. The Agricultural Research service in the USA provides a nomogram for determining the value of K based on soil composition, structure and permeability (ARS, 1975). Should all these factors not be available then the ARS gives approximate values for K based on soil descriptions. Some of these values are given in Table 2.11, in increasing order of erodibility (higher K means more erosion).

Table 2.11 Soil Erodibility Factors (ARS, 1975)

Soil Description	Erodibility Factor (K)
Sand	0.05
Sandy Clay	0.14
Clay	0.13-0.29
Silty Clay	0.25
Sandy Loam	0.27
Sandy Clay Loam	0.27
Clay Loam	0.28
Silty Clay Loam	0.37
Silt	0.60

Quite obviously a pure silt or sand would not make a suitable earth wall, due to their lack of cohesion. What this table indicates is that a sandy clay or a clay would make the most durable material and that silt is less durable than sand when mixed with clay.

Evans (1980) notes that "*Soils with more than 30-35% clay are generally coherent and form stable soil aggregates which are resistant to raindrop impact and splash erosion*"

In general the type of soil used in earth wall construction is dependant to a large degree on the method of construction and whether or not stabilisers are to be used. For instance in Australia adobe bricks are rarely stabilised and typically have a relatively high proportion of clay. In some parts of the United States, however, adobes are made from silty sands with low proportions of clay, but are stabilised with bitumen. In most cases a sandy clay with a clay content less than 20% and greater than 5% would be considered suitable for pressed block or rammed earth construction. Silt is generally regarded as being deleterious in both unstabilised adobes and stabilised pressed earth blocks.

Erosion data for different soil types is more available for pressed earth blocks. The data of Cytryn (Cytryn, 1956) showed a markedly higher resistance for the 16% clay soil but is inconclusive for the other samples. Reddy and Jagadish (1987) determined their "Erosion Ratio" for 5 specimens of varying clay content If durability is defined as the inverse of their ER then there data can be plotted as shown in Figure 2.17. Although Reddy and Jagadish used this data to support an increase in durability with clay content the correlation is not good.

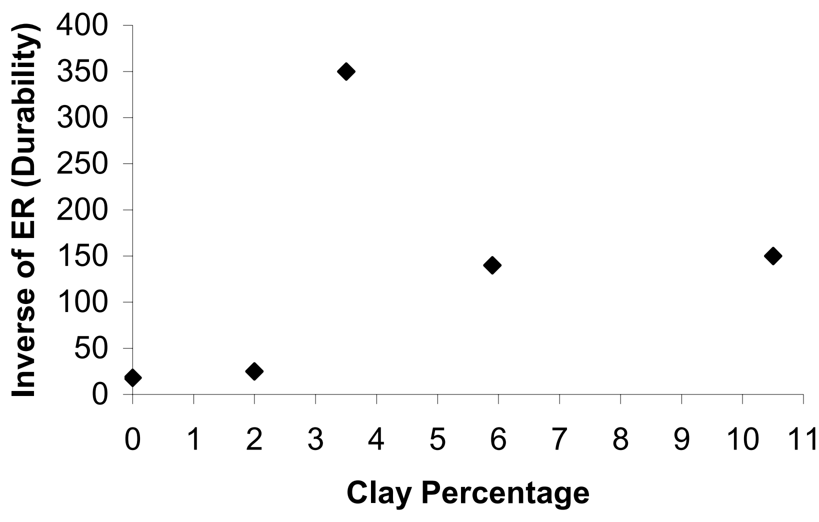


Figure 2.17 Durability vs. Clay Percentage (Reddy and Jagadish, 1987))

Crowley (1998) conducted drip tests on five soils with high clay contents. His results are shown in Figure 2.18. They show a consistent increase in durability with increasing clay content.

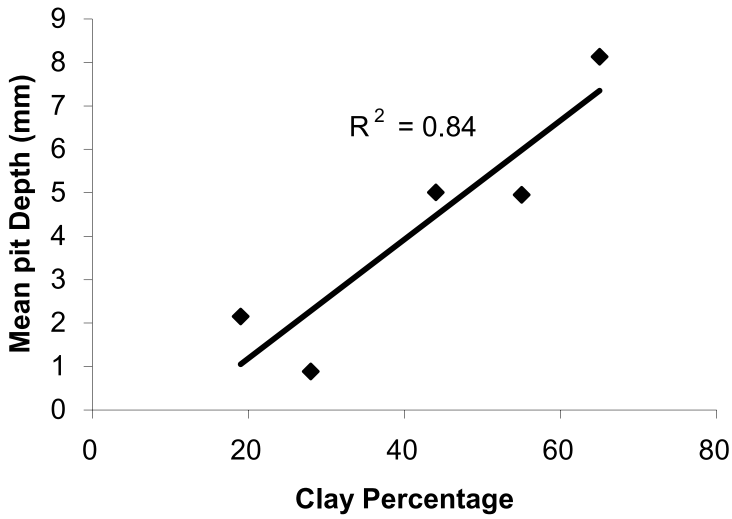


Figure 2.18 Erosion vs. Clay Content (Crowley, 1998)

2.2.2 Effect of Density

The effect of density on the erosion resistance of unstabilised earth has long been recognised. In Israel Cytryn (1957) manufactured pressed earth blocks using three different block presses and spayed them with water to determine their durability (for details of spray test see Section 2.1.2.1). He tested five different types of soils with approximately fifteen blocks per soil type (five each machine). His results for the Beisan soil (16% Clay) are plotted as Figure 2.19, in which the erosion time is the time taken for the water spray to penetrate the specimens. The results indicate an exponential increase in erosion with increasing density.

Jagadish and Reddy (1984) conducted spray tests on two unstabilised soils to determine the relationship between their "Erosion Ratio" and dry density. Their results for a "Red Soil" containing 6% clay is shown in Figure 2.20. The inverse of their "Erosion Ratio" has been used as an indicative measure of durability. The results show a similar relationship to that found by Cytryn.

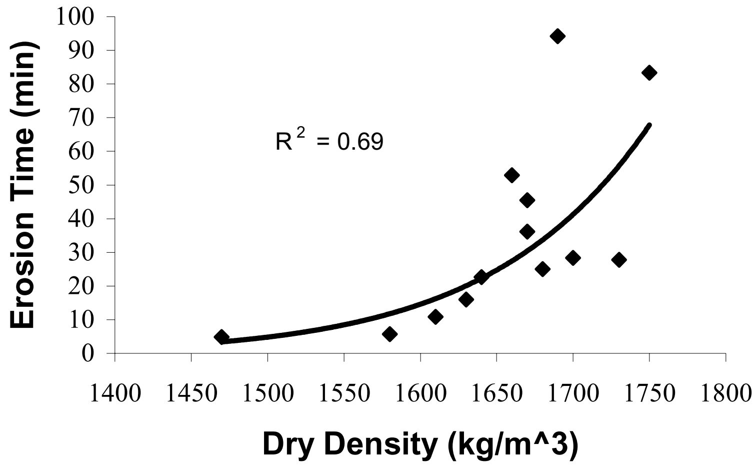


Figure 2.19 Relationship Between Erosion Resistance and Dry Density for Unstabilised Pressed Earth Blocks (Cytryn, 1956)

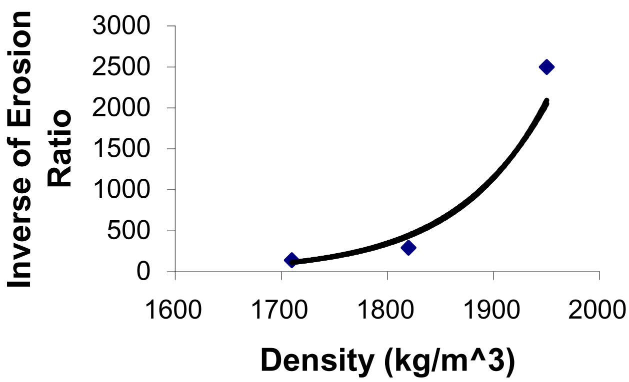


Figure 2.20 Relationship Between Durability and Dry Density (Jagadish and Reddy, 1984)

Tannous (1995) conducted experiments into the effect of density on durability under the author's directions. In these tests two different simulated soil compositions were used, one with a clay content of 5% and one with a clay content of 15%. No stabiliser was used. Forty specimens of varying density (20 per soil type) were subjected to the standard Bulletin 5 spray test and the time taken to penetrate the 60 mm thick specimens was taken as a measure of their durability. Figure 2.21 is a plot of the values for the soil containing 5% clay.

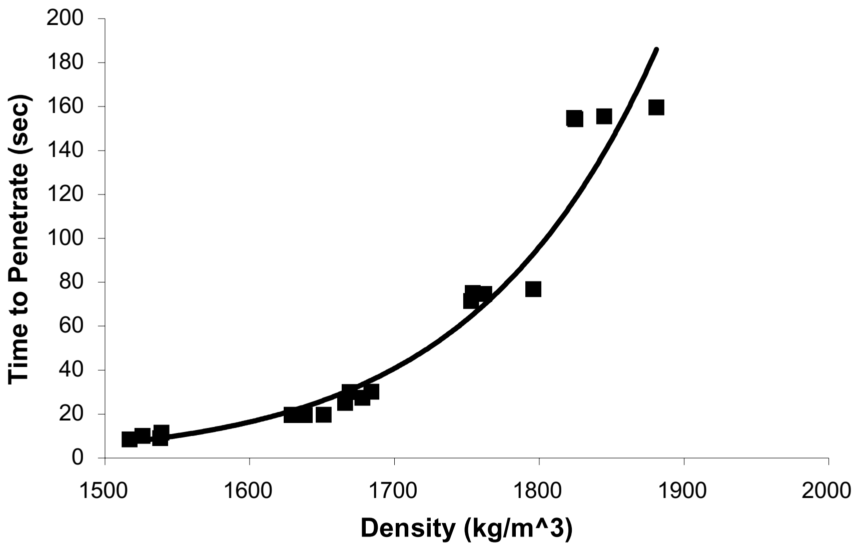


Figure 2.21 Variation of Erosion with Density (Tannous 1995)

Both the results of Reddy and Jagadish and Tannous indicate a significant increase in erosion resistance above a density of around 1800 kg/m^3.

Spence and Cook (1983) list a durability relationship between density and cement percentage based on testing of 16 Zambian soils by Spence. They stated that "*Since durability is strongly correlated with dry density, the cement content required for adequate stabilisation (less than 10 percent weight loss in the* (wire brush) *durability test) can be determined directly from the dry density of compacted blocks…. Soils giving compacted dry densities less than 1650 kg/m^3 are considered unsuitable, requiring more than 10 percent of cement to stabilise, which is usually uneconomical, while 5 percent is the minimum cement content recommended".*

Figure 2.22 is a plot of the data of Oskan & Al –Herbish (1995), Ngowi (1997) and Walker (1995a), which shows a significant increase in density with increasing cement content. Since an increase in density has a marked effect on durability it is possible that the increase in durability with increasing cement content is closely associated with the increase in density.

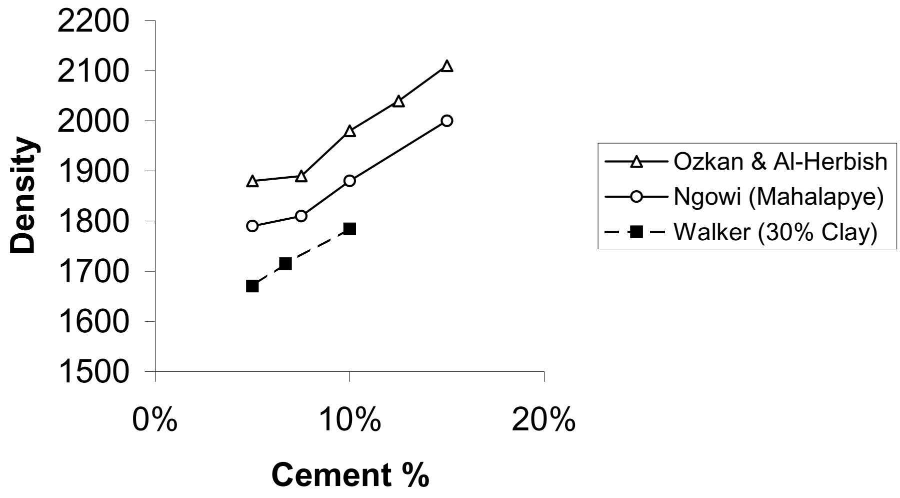


Figure 2.22 Variation in Density with Cement Content

2.2.3 Effect of Cement Content

The re-birth of pressed earth brick construction was largely stimulated by the work of Fitzaurice in the late 60's for the United Nations (Fitzmaurice, 1958). In his report Fitzmaurice examined unstabilised earth buildings in France and England and found that although there were many splendid examples of earth buildings more than 100 years old the maintenance costs were extremely high. He pointed out that as societies became more mechanised unstabilised earth walls became more uneconomical *"The labour cost in original construction might not be excessive, but the high maintenance cost was quite impractical."* (Fitzmaurice, 1958)

Fitzmaurice recognised the potential of cement stabilised earth construction based on research into stabilised soil roads in the 1930's. Sheets and Catton (1938) set out the basic principles of cement stabilised earth, which were established at that time. Fitzmaurice suggested that what was needed was a clear definition of stabilised soil walling as many partially stabilised walls "*inevitably have begun to decay and are often disfigured by many cracks within a few years of their completion*". He proposed that the term "stabilised soil walling" should be restricted "*to work of such quality that the walls will remain fully durable throughout the expected life of the building".* (Fitzmaurice, 1958)

Cytryn (1957) quotes instances of soils where reasonable stabilization has been achieved with cement contents as low as 2.5%. The ACI "State of the Art Report on Soil Cement" (ACI, 1991) suggests that for road pavements "*Cement requirements vary depending on desired properties and types of soils. Cement contents may range from as low as 4 to a high of 16 per cent by dry weight of soil. Generally, as the clayey portion of the soil increases, the quantity of cement required increases*."

The author has conducted many tests over a long period of time using various soils and has noted that for durability in a Sydney climate a minimum of 5% cement (by weight) stabilization should be considered, with the suitability of the soil being seriously questioned if more than 10% cement is required. "*Most soils can be stabilised with about 7.5% of cement compared to around 12% required in concrete blocks*" (Heathcote, 1991).

Figure 2.23 illustrates clearly the variation in erosion which can occur in a wall due to variations in stabilisation, and to a lesser extent by variations in source material. This photo was taken of a test building constructed at the University of Technology Sydney by the author in 1992.

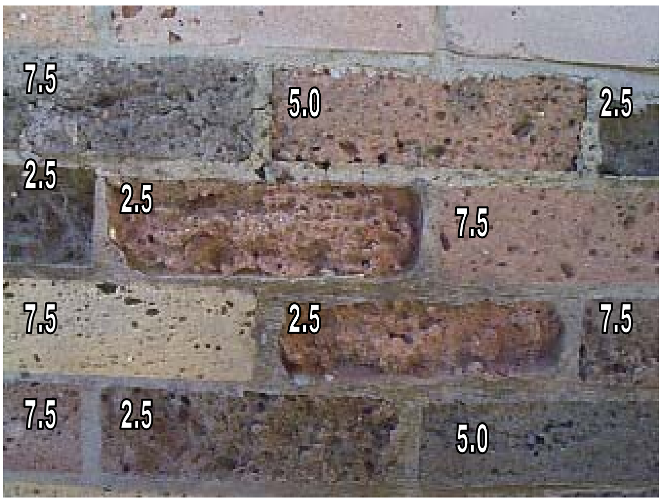


Figure 2.23 South Wall of Test Building at UTS

Bricks in this building were made from four different sources of material, each being different in colour, and stabilised with varying percentages of cement (shown in Figure 2.23). This figure shows a clear variation in erosion between the 2.5% and 7.5%

specimens, with some variation in the 2.5% stabilized specimens between the central red specimens and the outer black specimens.

Heathcote and Piper (1994) proposed that there is a minimum cement content for a particular soil below which the clay-cement skeleton cannot fully develop, and their tests on a particular soil showed this to be the case for cement contents less than 1%.

Herzog (1964) notes, "*one of the most significant aspects of soil cement strength is its durability under adverse climatic conditions. The semi-impervious skeleton structure with an almost impervious hardened cement core could be expected to hinder considerably the movement of water to and from the enclosed matrix. This is probably the main reason for the stability of clay cement under all weather conditions*" (Herzog, 1964).

The effect of cement on the durability of soil cement mixtures has been widely investigated in the road construction industry. For example Abrams (1959) conducted "wire brush" durability tests on two soils with varying cement contents. Soil No 1 (AASHO Group A-1) was a granular soil with minimal fines while Soil No 2 (AASHO Group A-6) was a clayey soil with about 35% passing the 200 sieve. The results for Soil No 1 are shown in Figure 2.24.

Ngowi (1997) carried out wire brush tests on two Botswana soils made into pressed earth blocks. The first soil (Mahalapye) was a clay soil with 48% clay content and 27% sand content whilst the second soil (Tsabong) was a sandy loam with 14.5% clay content and 63% sand content. His results for the Tsabong soil are plotted as Fig 2.25.

Both the Abrams and the Ngowi tests show extremely good correlation between cement content and weight loss as determined by the wire brush test. They show a definite power relationship with 95% confidence limits for the power factor of 1.11 – 4.28 for granular soils and 0.69 – 2.83 for clayey soils.

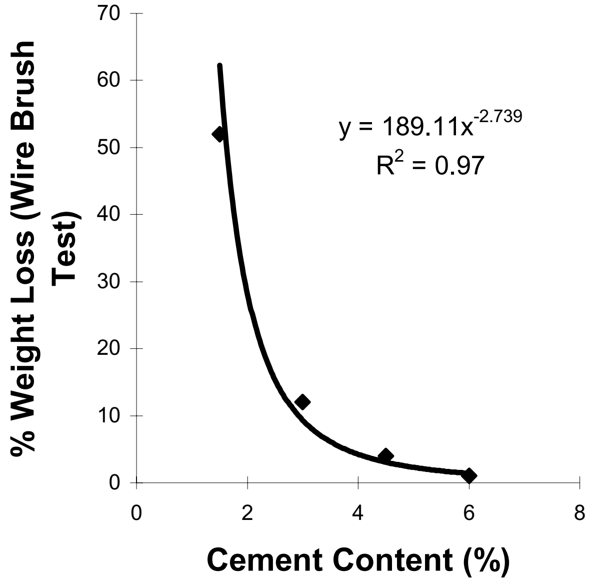


Figure 2.24 Effect of Cement Content on Durability (Abrams, 1959)

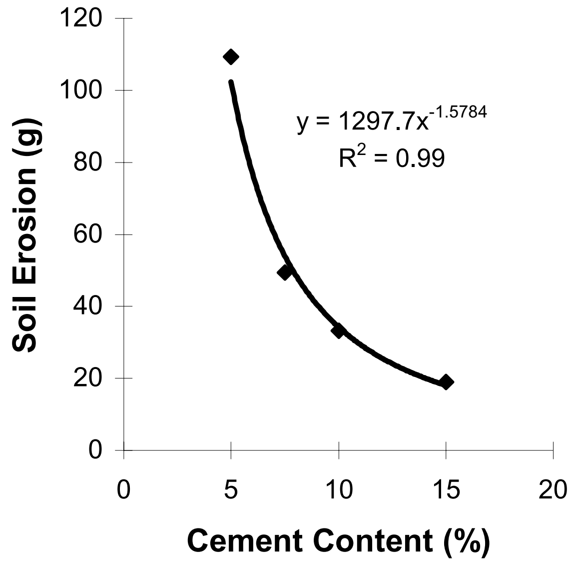


Figure 2.25 Effect of Cement Content on Durability (Ngowi, 1997)

2.2.4 Effect of Surface Coatings

In areas such as New Mexico in the USA, where protective coatings are commonly applied to the surface of earth walls, the question of resistance to driving rain is not appropriate. In these cases the question of durability relates more to the permeability of the wall and the effect moisture has on the strength of the wall.

Figure 2.26 Rammed Earth Panels in Sydney (1990)

Figure 2.26 shows a sample panel of rammed earth which was coated with stucco in 1948 (right hand side) and which was in remarkable condition in 1990. The left hand side panel had only paint protection and had eroded badly.

2.2.5 Effect of Age at Time of Testing

There is a lot of anecdotal evidence to suggest that the durability of earth walls increases with age, however there is not much experimental evidence to support this, other than limited work carried out by Patty (1936) and Eassey (1997).

Patty (1936) constructed twelve rammed earth test blocks using three different types of soils, a heavy clay soil (10% sand), a medium sandy soil (38% sand) and a very sandy soil (75% sand). These specimens were compression tested, with four blocks of each soil tested after six months, four after one year and four after two years.

These tests indicate approximately a 50% increase in compressive strength over a period of two years, regardless of the soil composition, and it could be expected that this increase would be similar with respect to weather resistance. However, Patty comments that the very sandy soil makes the best wall because of its resistance to the action of weathering and that the heavy clay soil, although marginally stronger (around 12%), is not suitable for rammed earth walls because of its tendency to slake.

Patty offers no explanation as to the cause of the observed increase in strength. A possible explanation would be that the increase in strength is due to a reduction in moisture content and related shrinkage, as it is known (Heathcote, 1991) that moisture content has a significant influence on compressive strength. Patty however chose an initial time of 6 months because "*the material is known to dry out to a constant weight within ninety days under laboratory conditions*" which would seem to rule out change in moisture content as a possible cause. In terms of the clayey soil it could possibly be explained in terms of a more favourable re-alignment of the clay particles over time or an increase in bond strength due to changes in the charges of clay particles but for the very sandy soil there appears to be no obvious explanation.

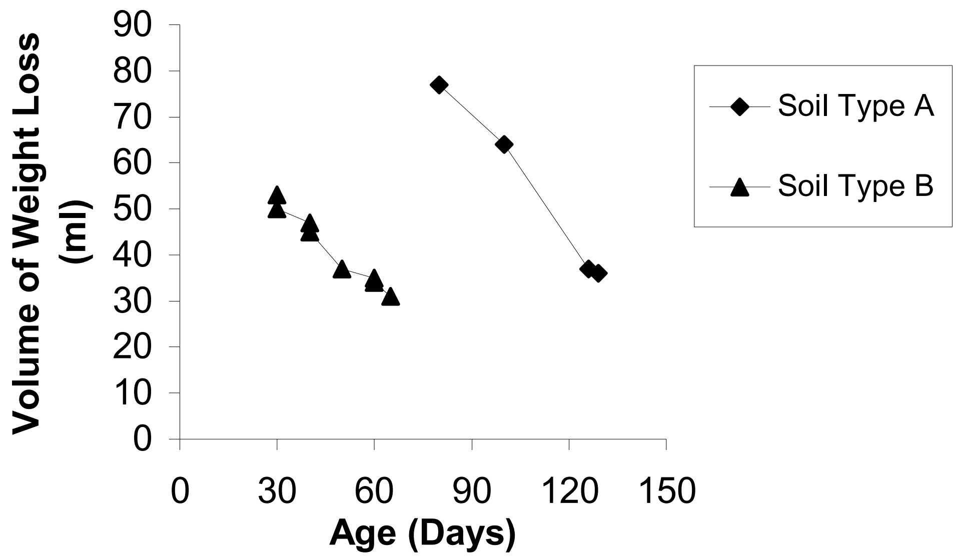


Figure 2.27 Variation in Spray Test Weight Loss with Age (Eassey, 1997)

Eassey (1997) conducted spray tests at different times on similar specimens made from two soil types and two cement contents. Soil Type A had 33% clay whilst Soil Type B had 9% clay. His results for the 3% cement content specimens are given in Fig 2.27 (the variation with age for Soil Type B – 6% was not plotted as the ages were too close)

2.3 Effect of Angle of Incidence of Water Drops

Eassey (1997) conducted limited tests to investigate the effect of spray angle on erosion under the direction of the author. He used a commercially available VeeJet nozzle inclined at angles of 30, 60 and 90 degrees to the face of specimens (Figure 2.28).

Figure 2.28 Angled Spray Jet (Eassey, 1997)

The specimens were made from two types of soil, a clayey sand (Soil A) and a sandy clay (Soil B). Four samples were tested for each soil and spray angle and the mass loss expressed as a ratio compared to the mass loss at zero degrees (E_{Normal}). The four results for each angle were averaged to produce the graph shown in Figure 2.29. Although there was considerable scatter in the results the results did indicate that for the clayey sand (Soil A) there was more erosion at an angle of incidence of 30 degrees compared to that for the spray impacting normal to the specimens (Angle of Incidence = 0 degrees).

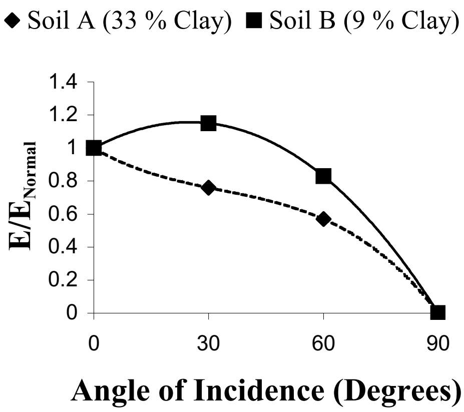


Figure 2.29 Effect of Impact Angle (Eassey, 1997)

2.4 Summary

- From the literature survey it appears that the test that is most strongly correlated with field performance is the wire brush test. However this test takes a long time to perform, does not replicate the action of rain and may be subject to operator variability.
- Various types of spray tests have been devised, but little work has been carried out in relating the performance of specimens in the spray test to performance in various climatic conditions.
- There are some indirect tests, such as the pullout test, which correlate reasonably well with spray or wire brush tests, which are in turn correlated with durability, but these are more of use as control tests to ensure consistent quality.
- Total rainfall simulation spraying would appear to offer a more accurate result but requires sophisticated equipment with tests taking a long time.
- Short duration spray tests are easier to perform and replicate some of the natural properties of rain.
- The drip tests appear to offer a quick guide to the suitability of bricks but their application to areas outside the area in which they were developed is questionable.
- Permeability, strength and Slake tests are a possible surrogate for erosion testing but do not replicate the action of rain
- There appears to be some increase in durability with age.
- On balance it appears that a spray test offers the best alternative for an accelerated test. It is easy to perform, simulates the action of driving rain, and acts over a reasonable area of a specimen, thus reducing the chance of testing minor weak spots.

Chapter 3 Theoretical Approaches to Erosion Due to Liquid Impact

3.1 Introduction

The surface of a material or body is said to be "durable" if it does not wear out or "erode". Erosion can be sub-divided into chemical erosion, caused by the chemical action of liquids on the base material, or physical erosion, caused by the mechanical wearing down of the base material due to the erosive actions of liquids or solids applying an erosive force to the base material. The "erosive force" involved in the physical erosion process may be a normal force, a shear force or in many cases a combination of normal and shear forces. The action of the erosive force leads to removal of the base material, which is then transported to another location.

This investigation concentrates on the physical aspects of the erosion process, in particular on the effect wind-driven rain has on "wearing down" the surface of earth walls.

In the case of the erosion of earth walls by driving rain, very little theoretical work has been carried out. The problem of the erosion of materials by liquid impact however is a general one that arises in many related fields of science. This Chapter will examine the theoretical work that has been done in these fields, in order to identify the nature and importance of the underlying parameters affecting the erosion process, and will examine how the theoretical work developed in these fields may be applied to the prediction of the erosion of earth wall in particular environmental conditions.

3.2 Background to Fields Involving Erosion by Liquid Impact

One of the oldest forms of erosion is that experienced in the area of physical geography, where the erosive power of streams have altered the shape of landscapes since time immemorial. On the coastline waves provide the dominant attacking force . Pressures created by breaking waves can cause tremendous stresses within cliff rocks leading to their ultimate degradation.

In more recent times one of the more adverse effects of civilisation has been the marked increase in land erosion due to rain falling on unprotected soils.

In materials technology the process of erosion of materials can be defined as the wearing away of surface material due to mechanical action, and this occurs in many cases where two materials rub against each other, eg erosion of brake pads. Where water is involved the dominant action is friction between the boundary water layer and the material. For example this occurs in the erosion of concrete on dam spillways. Where the erosive force is provided by a jet or spray of water the dominant action is a normal force leading to a failure in the material, sometimes accompanied by a shear stress along the face of the specimen as the water disperses. Such an occurrence is a problem in high speed aircraft passing through rain storms. This problem has been extensively studied and, although the velocities involved are significantly higher, is very similar to the situation of wind-driven rain on earth walls.

3.3 Liquid Erosion in the Field of Physical Geography

3.3.1 Stream Erosion

In the field of physical geography, physical erosion refers to the wearing effect of wind, moving water and ice on the land's surface. Stream erosion is one of the more noticeable land eroding processes and is one in which water velocity plays a major part.

Sale and Sale (1967) define five major sub-processes of erosion , of which hydraulic action or fluviraption is of major interest to this study. Hydraulic action, or fluviraption, "*includes all the mechanical methods carried out by the flowing water itself without the aid of rock . The impact and shearing force of the flowing water loosens and lifts particles, and may wedge loose fragments from concavities and joint cracks by hydraulic pressure.*

Fluviraption has little effect on firmly cemented bedrock but alone may be sufficient to erode weakly consolidated bedrock and residual overburden. The greater the turbulence and the higher the velocity, the greater the effect."

The principle factor influencing the "hydraulic" erosive capacity of a river is therefore the velocity of its flow, this determining the shear stress at the boundary between the water and the riverbed.

"*For erosion to occur the shearing stress of the mobile agent, running water in this instance, must be greater than the force of cohesion between the particles of the substrate*" (Sale and Sale, 1967)

Shear stresses at the river bed are proportional to the square of the boundary layer velocity, and using the classical equation of du Boys bed load transport can be written as

$$G \sim V_o^4 \times [1-(V_C/V_O)^2] \qquad \text{.........}(3.1)$$

where

G = Bed load transport per unit width of stream

V_O is the stream velocity and

V_C is the stream velocity at which transport begins.

Although this approach ignores the effect of turbulence it does indicate the marked dependence of bed-load transport on stream velocity, and introduces the idea of a critical velocity, below which there is no erosion.

Tweedie (1970) makes the point that, given that stream velocity is the predominant factor and that stream velocities are highest during periods of flooding, "*Flood conditions are thus most important in initiating the movement of bed load and most of the erosional work of the stream is done when it is in flood*" (Tweedie, 1970).

3.3.2 Coastal Erosion

The process of the erosion of beaches due to wave action has some interesting parallels with the erosion of vertical earth walls. Both processes involve a flux of water energy hitting a barrier at an angle and both have elements of an erosive mechanism and a transport mechanism.

A commonly used formula for the prediction of sand erosion along beaches is that proposed by the Coastal Engineering Research Centre in the USA (CERC, 1973). In essence the CERC formula looks at the flux of kinetic energy (wave power) of groups of waves approaching a shoreline at an angle ϕ_{br}, and travelling at a wave group celerity of $c \times n$ where

c =single wave celerity, or phase speed and

n = function of water depth

The Wave Power per unit crest length is equal to the wave Kinetic Energy times the wave group celerity ($c \times n$)

where

Kinetic Energy = $1/8 \times \rho \times g \times H^2$

ρ = Water density

g = Acceleration due to gravity and

H = Wave height

On the basis of model and prototype measurements the CERC came up with the following best-fit formula

$$\text{Sand Transport} = 0.014 \times H_o^2 \times K_{br} \times C_o \times \sin \phi_{br} \times \cos \phi_{br} \qquad \ldots\ldots\ldots(3.2)$$

where

H_o = Incident Wave Height

K_{br} = Wave Refraction Coefficient = b_o/b (Figure 3.1)

ϕ_{br} = Angle of wave relative to shoreline

C_o = Wave Group Velocity = $c \times n$

The CERC formula has been found to give acceptable results when applied in practical situations and is consistent with the more theoretically correct derivation given by Graaf (1978). The horizontal wave velocity at the sea bed in shallow water is directly related to the wave height, as is the bed shear stress, and therefore longshore erosion may be thought of in rough terms as being proportional to the square of the horizontal wave velocity at the sea bed.

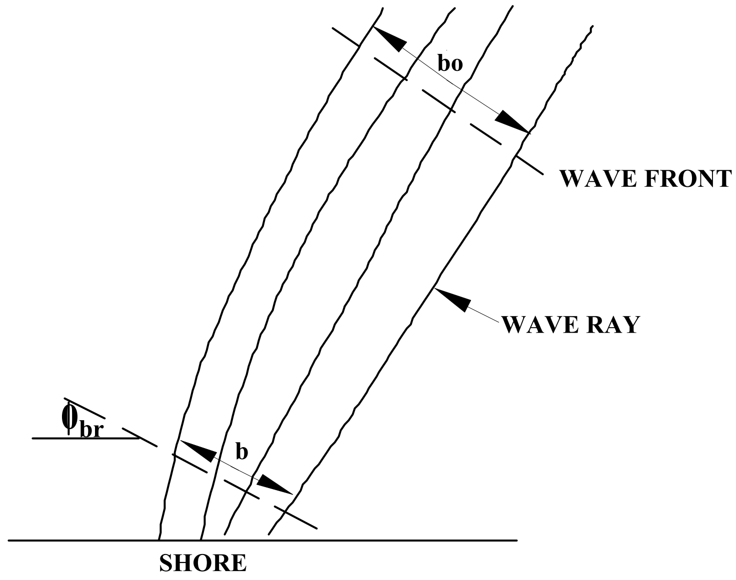


Figure 3.1 Beach Erosion Parameters

Bijker (quoted in Graaf, 1978) has proposed a variation of the bottom shear stress term in the Kalinske-Frijlink formula for bed load transport (under currents alone) to account for the instantaneous velocity caused by breaking waves. He split the total longitudinal sediment transport into a bed load and a suspended load component and his work showed that the waves acting primarily as a "stirring" agent, with the longshore current acting as the "transport" medium.

3.4 Soil Erosion

Soil erosion is a growing concern in the world. "*In the United States, an estimated 4,000 million tons of soil ….are lost from …. cropland each year*" " (Pimentel et al., 1995). With such a major problem it is not surprising that a great amount of research has been directed to the problem of soil erosion over the years. The erosion problem in soils has an obvious strong parallel with the erosion of unstabilised earth walls, and examination of research in this area can provide valuable clues to the erosion process in both unstabilised and stabilised earth walls.

In general a distinction is made in soil erosion between rill erosion and inter-rill erosion, although in the more commonly used Universal Soil Loss Equation (USLE) (to be discussed later) the two are treated as one for the purpose of calculating total soil losses over an area.

Rills are continuous channels of narrow width and shallow depth. Inter-rill erosion occurs when soil between rills is detached by impacting raindrops and is transported to rills by overland flow. On a simplified level erosion of soils due to rain involves detachment of soil particles due to rainfall impact and their transportation by overland flow. In general the velocity of overland flow is insufficient to generate large enough shear stresses to detach soil, however detachment of soil particles may occur in rill areas when the flow driven erosion mechanism is aided by turbulence from impacting raindrops.

Study on the effect of raindrops on the erosion of earth surfaces began with the work of Wollny in 1877 (Terry, 1998) and commenced in a more scientific manner with the seminal work of Laws in 1940 and Laws and Parsons in 1943.

3.4.1 Detachment Process

In terms of the connection between soil erosion and the erosion of earth walls it is in the area of the detachment of soil particles in the inter-rill area that is of major interest, more particularly the detachment of soil particles by raindrop impact. Detachment and transport of soil particles by raindrop impact is also described as splash impact.

Terry (1998) defined three main factors affecting splash detachment,
(i) raindrop erosivity, which depends on drop size, shape, and kinetic energy;
(ii) target characteristics, including soil texture and other geotechnical properties, antecedent moisture content, micro-topography, and especially the presence or absence of a water film; and
(iii) the behaviour of a water drop upon collision with a soil surface.

Terry identified five major components of soil erosion, of which aggregate breakdown and cratering are of interest. Aggregate breakdown occurs when the forces at the perimeter of raindrop impact break down the material into micro aggregates and primary mineral grains. Cratering occurs when soil particles and irregularities at the bottom and sides of the impact cavity are detached by shearing. According to Terry, soil resistance to cratering is determined by the shear strength of the soil, whilst aggregate breakdown occurs by dislodgement of material under high pressures.

3.4.2 Relationship Between Raindrop Size and Velocity

Laws (1940) identified kinetic energy as the primary factor in predicting soil erosion, and concluded that a knowledge of the relationship between drop size and drop velocity was therefore needed. Laws carried out experiments relating the two factors, and Gunn and Kinzer verified his work in 1949. Figure 3.2 shows the relationship between raindrop diameter and terminal velocity given by Ginn and Kinzer. Raindrop sizes greater than 6 mm appear not to occur in practice, with drops approaching this size breaking down into smaller drops.

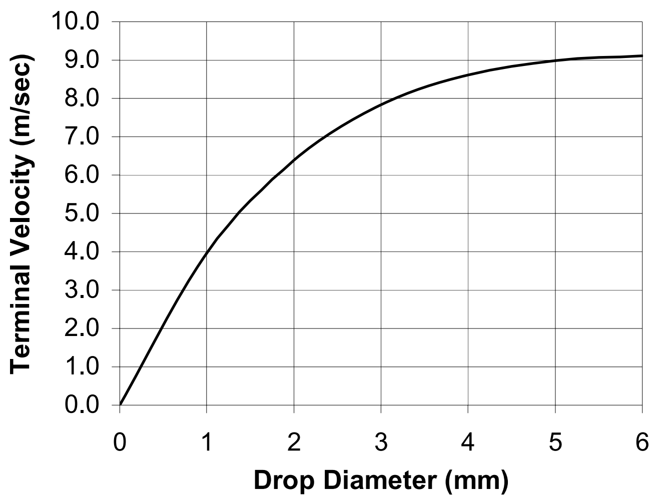


Figure 3.2 Terminal Velocities of Raindrops

3.4.3 Variation of Drop Size Distribution with Rainfall Intensity

A detailed knowledge of rain drop size distribution is needed to calculate the kinetic energy of storms. Laws and Parsons (1943) used a flour pellet method to determine the distribution of raindrop sizes within a given storm of intensity I (mm/hr) for storms in Washington D.C.

In 1948 Marshall and Palmer proposed an exponential drop size distribution (Equation 3.3) based on data measured in Ottawa by radar echoes.

$$N_d = 8000 \times \exp(-4.1 \times d \times I^{-0.21}) \qquad \text{……….}(3.3)$$

where

N_d = No of drops between d and d + δd ;

I = Rainfall Intensity (mm/hr) and

d = Raindrop diameter (mm)

Equation 3.3 is shown graphically in Figure 3.3. Marshall and Palmer obtained good agreement with the Laws and Parsons (1943) data except at lower drop sizes.

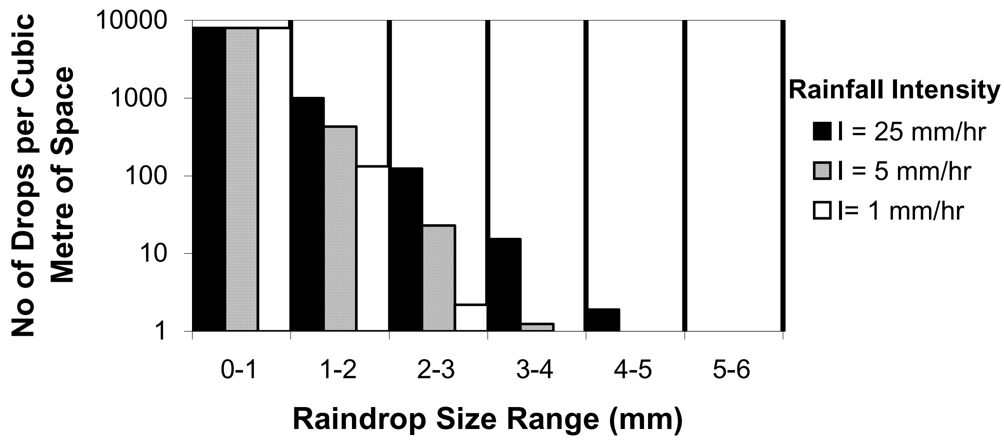


Figure 3.3 Variation of Drop Size Distribution with Rainfall Intensity

Using Equation 3.3 Marshall and Palmer showed that the mass of rain falling per cubic metre of airspace would be equal to $0.089 \times I^{0.84}$ grams/metre^3

Following up on the work by Marshall and Palmer and other researchers, Assouline and Mualem (1989) proposed a dimensionless drop size distribution which agreed fairly well with the reported measurements of five groups of researchers, Laws and Parsons (1943), Carter et al. (1974), Hudson (1965), Cataneo and Stout (1969) and Feingold and Levin (1986).

In their method the drop size distribution F(d*) is characterized as follows

$$F(d^*) = 1 - \exp(-0.71 \times d^{*3}) \qquad \text{.........}(3.4)$$

Where d* is a representative drop size equivalent to the drop diameter d divided by the centroidal drop size of the drop size distribution [$d_G(I)$]. According to Assouline and Mualem $d_G(I) = a \times I^b \times \exp(-c \times I)$ where a, b and c are regional characteristics.

For the Laws and Parsons data (Washington D.C.) Assouline and Mualem determined the values for a, b and c to be 1.314, 0.181 and 0.297 respectively, and with these values they obtained perfect correlation with the drop size distribution obtained by Laws and Parsons. Figure 3.4 shows the resultant distribution for various rainfall intensities using the method of Assouline and Mualem and the Laws constants.

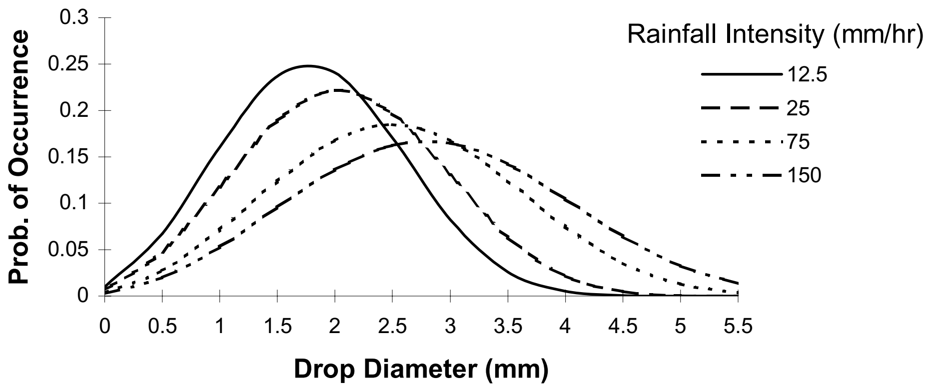


Figure 3.4 Rainfall Drop Size Distributions

3.4.4 Variation of Median Drop Diameter with Rainfall Intensity

Laws and Parsons (1943) also developed an equation between intensity and d_{50}, where d_{50} is the median drop diameter in mm and I is the rainfall intensity in mm per hr.

$$d_{50} = 1.24 \times I^{0.182} \qquad \text{.........}(3.5)$$

Figure 3.5 shows this relationship. It can be seen that d_{50} increases slightly with rainfall intensity but that an average value of 2.6 m/sec is a reasonable approximation over the range of commonly occurring rainfall intensities.

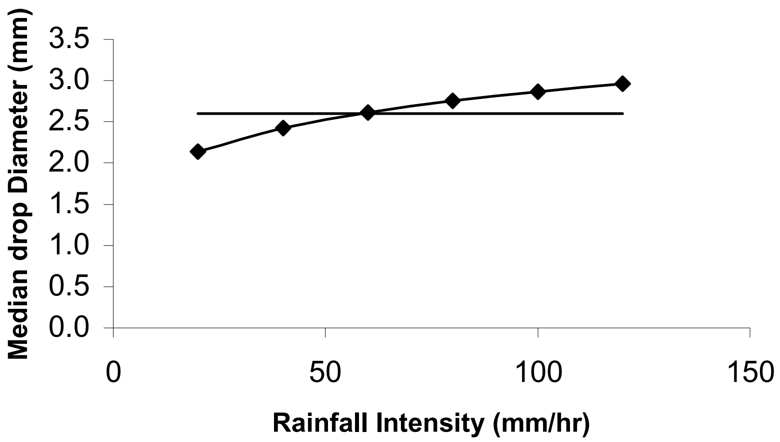


Figure 3.5 Variation of Median Drop Diameter with Rainfall Intensity

3.4.5 Other Parameters Affecting Soil Erosion

Laws was one of the first people to associate the kinetic energy of rainfall (= $\frac{1}{2}mv^2$) with soil erosion, but other parameters have also been investigated in the soil erosion field.

Cook (1936) identified raindrop velocity as the principle determinant of soil erosion and Horton (1940) regarded energy per mm of rain as the important property. Other researchers at the time came to slightly different conclusions with Neal and Baver (1937) identifying momentum per unit area as a property of rainfall. Ekern (1950) carried out tests on sandy soils and concluded as follows "*This experiment has shown that the erosive capacity of a falling mass of water depends on the energy per unit area of the individual drop. The kinetic energy of the falling drop determines the force of the blow that must be absorbed at each impact, while the horizontal area of the drop determines the amount of soil that must sustain that blow.*"

Rose (1960) related soil erositivity to raindrop momentum and Palmer (1963) used it as a theoretical model when investigating the influence of a water layer on impact forces. Elwell and Stocking (1973) analysed data from six plots of land in Rhodesia and found that total momentum explained between 85 % and 90 % of the variations between plots, but then goes on to conclude that "*total kinetic energy is the logical choice*" to give a "*rational explanation of the ability of rainfall to cause erosion*. As recently as 1985 Gilley and Finkner (1985) tested a wide range of relationships involving kinetic energy and momentum and concluded that kinetic energy per unit of drop circumference was the best fit to the available data.

Park et al (1983) calculated theoretical expressions for kinetic energy (proportional to $I^{1.16}$ and momentum (proportional to $I^{1.09}$) based on the Laws and Parsons raindrop distribution data and this small difference in exponents could perhaps explains the correlation between both kinetic energy and momentum and experimental results

3.4.6 Variation of Kinetic Energy with Rainfall Intensity

A major advancement in the field of soil erosion was made by Wischmeier and Smith in 1958 when they related rainfall kinetic energy to rainfall intensity, using the raindrop size distributions given by Laws and Parsons and the terminal velocities predicted using the terminal velocities measured by Laws (1941) and Gunn and Kinzer (1949).

Substituting mass and velocity of raindrops into the usual formula for kinetic energy Wischmeier and Smith (1958) derived Equation (3.6).

$$kE = 11.87 + 8.73 \times \log_{10}(I) \qquad \text{.........}(3.6)$$

where
kE = Kinetic Energy in J/m^2/mm of rain, and
I = Rainfall intensity in mm/hr

For normal values of I, Equation (3.6) can be replaced, to an accuracy less than 0.5%, by

$$kE = 15.375 \times I^{0.14} \qquad \text{……….}(3.7)$$

Using Equation (3.7) for kE, total kinetic energy (KE) can be expressed as follows

$$KE = kE \times I \times T = 15.375 \times I^{1.14} \times T \qquad \text{………..}(3.8)$$

where

KE = Total kinetic energy in J/m^2, and

I = Rainfall intensity in mm/hr

T = Duration of rainfall (hrs)

3.4.7 Variation of Total Kinetic Energy with Annual Rainfall

In Nigeria, Lal (Lal et al., 1994) related kinetic energy to rainfall amount as follows

$$KE\ (J/m^2) = 24.5 \times P_a + 27.6 \qquad \text{……….}(3.9)$$

Where P_a is the mean annual rainfall in mm, whilst in Zimbabwe, Elwell (quoted in Lal et al., 1994), gives KE for a season as approximately $18 \times P_a$.

Morgan, Morgan & Finney (1984) developed a method for predicting splash detachment rates based on kinetic energy where the total kinetic energy impacting the surface in one year is related to annual rainfall by the formula

$$KE = K \times P_a \qquad \text{……….}(3.10)$$

Where

KE = Total Kinetic Energy in J/m^2

P_a = Annual rainfall in mm

K = 21 J/m^2/mm for temperate climates

= 24 J/m^2/mm for tropical climates and

= 25 J/m^2/mm for strongly seasonal climates

Hudson (1971) used a value for K of 1.2 for temperate climates and 11.2 for tropical climates, on the basis that rainfall less than 25 mm/hr is neglected. Morgan (1986) questioned the use of a threshold intensity of 25 mm/hr proposed by Hudson, noting that it is rarely exceeded in Western Europe and that arbitrary thresholds of as low as 6 mm/hr have been used in Germany and that even 2.5 mm/hr may be more appropriate.

3.4.8 Relationship between Kinetic Energy and Soil Loss

Wishmeier and Smith (1958) recognized that kinetic energy alone was not the sole determinant of soil loss
"*It is apparent to the observer that two rainstorms of equal total amount falling on the same field and on comparable surface conditions often produce widely differing soil losses*". (Wishmeier and Smith, 1958)

They then examined a vast amount of data relating to the erosion of fallow fields, and on the basis of regression analysis concluded that "*The best single variable found for prediction of soil loss from cultivated fallow soil is the product of the total rainfall energy of a storm and its maximum 30–minute intensity. This product measures the interaction effect of the two rainfall characteristics* (KE and I). *It will be referred to as the* $E \times I$ *variable*". (Wishmeier and Smith, 1958)

The correlation coefficient for the EI variable was 88%. Other variables examined by Wishmeier and Smith were rainfall amount (42%), rainfall energy (62%), maximum 15 minute intensity (66%) and maximum 30-minute intensity (80%).

The EI_{30} (Kinetic Energy $\times$ I_{30}) component of storms forms the basis of the rainfall erosivity index (R) used in the Universal Soil Loss Equation (USLE -subsequently revised and called RUSLE), which is probably the most widely used and researched soil erosion formula in the world. The USLE predicts soil loss as a linear combination of the soil erodibility factor R and four other factors, a slope length factor, a slope gradient factor, a cropping management factor and an erosion control practice factor.

In the USLE method R is calculated by dividing rainstorms into specific intensity ranges, with the total kinetic energy calculated for the storm event based on the equation of Wishmeier and Smith. This value is then multiplied by the maximum 30-minute rainfall intensity for the storm and all EI_{30} values then added for the year. Storms are classified as events separated by periods of at least 6 hours with no rainfall. The units of R are in N/hr and are about 1.7 times higher than those obtained in English units (100 ft-tons/acre).(in./hr). English values of R typically vary from 50 to 500 for the eastern U.S. (Wishmeier and Smith, 1978)

Following studies by Carter et al (1974) and Hudson (1971) which showed that the median drop size does not continue to increase with rainfall intensities above 76 mm/hr, current recommendations are that a maximum value of 76 mm per hr be used when calculating kinetic energy and a maximum of 63 mm per hr is also recommended for the I_{30} component.

Recent work by Larson et al. (1997) has emphasized that correlation of traditional erosion models such as RUSLE are based on long-term average annual soil erosion and that "*examination of erosion events at a number of locations has shown that a large proportion of soil erosion over an extended time period occurs during a relatively few large storms*" (Larson et al., 1997)

3.4.9 Relationship between EI_{30} and Rainfall

In order to simplify the USLE method and to provide easily calculated values in a variety of areas the EI_{30} factor in the USLE has been correlated to many rainfall parameters (Mitchell and Bubenzer, 1980), including a very simple linear proportion (50% +/- 5 %) of annual rainfall amount derived by Roose (1977) in West Africa.

On the basis of Equation 3.8 it is possible to express the EI_{30} value as being proportional to $I^{2.14}$, since E is proportional to $I^{1.14}$ (Foster and Meyer (1975).

Because of the problem with data availability Richardson et al. (1983) suggested treating EI_{30} as a combination of a deterministic component, based on a representative rainfall period or rainfall "event" (in their case one day) and a random component in the following relationship

$$EI_{30} = a \times P_d^{\,b} + \varepsilon \qquad \text{.........}(3.11)$$

where a and b are constants and

EI_{30} = Daily EI_{30} value

P_d = Daily Rainfall in mm

ε = Random Component

The analysis they performed used the traditional formula for rainfall energy combined with the extreme assumptions of a) evenly distributed rainfall intensity over the rainfall "event' or b) rainfall intensity varying from zero to peak intensity over the period of the rainfall "event". Their studies showed that although the parameter "a" varied significantly from season to season and from location to location the parameter "b" was fairly constant at a mean value of 1.81, i.e. the erosivity index was proportional to the daily rainfall raised to a power of 1.81. They also found that the random component was not seasonally dependant and concluded that it was the "*result of the variation in rainfall intensity that can occur within an event of a given rainfall amount*." Richardson et al., 1983)

3.4.10 Soil Detachment Models

Ellison (1944) was probably the first person to study the mechanics of the detachment process in detail. He identified the major meteorological factors affecting the loss of soil due to raindrop splash as "*sizes of raindrops, intensity of rainfall, raindrop velocity, and wind direction and velocity*".

Ellison carried out 59 detailed experiments using artificial rainfall with splashed soil collected in soil samplers. Raindrop velocities were not terminal, but were varied from 3.65 to 5.85 metres per second, drop sizes of 3.5 mm and 5.1 mm were used, and rainfall intensities varied from 117 to 376 mm per hour. Ellison carried out a multiple regression analysis to derive Equation 3.12, which indicates a strong dependence of erosion on raindrop velocity.

$$\text{Rain splash Erosion} \propto v^{4.33} \times d^{1.07} \times I^{0.65} \qquad \ldots\ldots\ldots(3.12)$$

In his conclusions Ellison notes "*Formula (3)* [Equation 3.12] *indicates that only small changes in velocities of raindrops may cause large differences in quantities of soil carried by the splash*".

In the Morgan et al. method (Morgan et al., 1984) the rate of splash detachment is calculated as shown in Equation 3.13

$$F = K \times KE \times \exp^{(-0.05 \times P^*)} / 1000 \qquad \text{.........}(3.13)$$

where

F = Splash Detachment in kg/m^2

K = Soil Factor. Typical K values are 0.02 for clay, 0.3 for sandy loam and 0.7 for sand

KE = Kinetic Energy of Rainfall in J/m^2;

P* = Percentage Rainfall contributing to interception.

Assuming for example a sandy loam in a temperate climate with annual rainfall of 1000 mm/annum and P* = 25%

KE = 1000 × 21= 21,000 J/m^2 (from Equation 3.10)

And F = 0.3 × 21,000 × exp (-.05× 25) /1000 = 1.8 kg/m^2

The basic interrill detachment model given in Equation 3.14 forms the basis of many modern erosion models, including the WEPP model (Lane et al., 1989).

$$D^* = K \times I^2 \qquad \text{.........}(3.14)$$

where

D* = Detachment Rate in kg/m^2/hr

K = Soil Variable and

I = Rainfall Intensity in mm/hr

Park et al (1983) tested five types of soils and came up with exponents of I which varied from 1.6 to 2.1.

When multiplied by the storm duration (T), Equation 3.14 becomes

$$D = K \times I^2 \times T \qquad \text{.........}(3.15)$$

where

D = Detachment in kg/m^2

Foster et al (1985) view equation 3.15 as a combination of rainfall volume (I × T) and a "characteristic intensity" (I). "*Thus volume of rainfall, and maximum 30 – minute intensity are the two most important general measures of rainfall erositivity. These two variables were as good as EI for describing erosion from fallow plots*". (Foster et al., 1985)

3.4.11 Single Raindrop Detachment Models

More recently attention has been focused on single drop detachment data and raindrop size distributions combined with models based on the engineering properties of soils, for example the shear strength model of Nearing and Bradford (1985). In 1991 Sharma et al proposed a single drop detachment model as

$$D_d = k_d\,(ke - ke_o) \qquad \text{..........}(3.16)$$

where

D_d = Detachment of soil due to single raindrop (kg)

k_d = soil detachability coefficient (kg/J)

ke = kinetic energy of a single drop (J) = $2.613\times10^{-7} \times d^3 \times v^2$

d = Drop diameter in mm

v = Impact velocity in m/s

ke_o = threshold kinetic energy needed to initiate detachment (J)

The suggestion of a threshold kinetic energy (ke_o) has some parallels with Hudson's suggestion of a threshold rainfall intensity of 25 mm/hr (Hudson, 1971), below which no erosion takes place. Sharma et al measured values of ke_o ranging from "*0.1 mJ in low strength, low-clay soils to about 0.6 mJ for a high-strength clay soil*" (Sharma et al., 1993)

Sharma et al. (1993) took this single drop model and, applying the normalised raindrop size distribution function of Assouline and Mualem, developed a total detachability model as

$$D^* = k_d \times I \times (kE - kE_o) \qquad \text{............}(3.17)$$

where

D^* = Rate of raindrop detachment (kg/m^2/hr)

I = Rainfall Intensity in mm/hr

kE = Total Rainstorm Kinetic Energy (J/m^2/mm rain)

kE_o = Sum of kinetic energy of raindrops having a drop kinetic energy in excess of threshold kinetic energy (J/m^2/mm rain)

kE_o is calculated by dividing a storm into drop size classes and calculating the number of drops in each class size (Unit kinetic energy of a drop size class as per the method of Assouline and Mualem divided by the kinetic energy of a single drop). kE_o is then obtained by adding the kinetic energy of the drops having ke less than ke_o to the number of drops with ke greater than ke_o multiplied by ke_o.

Sharma et al. applied this model to 2 soils to compare it with erosion models of the form

$$D^* = K \times I^b \qquad \text{.........}(3.18)$$

They used measured values of k_d and values of ke_o arbitrarily varied between 0 and 0.5J. They concluded, "*If* (k)e_o *is not used in the single-drop detachment model, b is approximately equal to 1. Compared with b = 2 used in contemporary soil erosion models (Foster, 1982, Rose, 1985), values derived from the simulated data in this study range from 1.08 to 1.44*" (Sharma et al., 1993) and suggested that this difference may in fact be due to a non-linear interaction of individual raindrops rather than the linear assumption in their model.

3.4.12 Time Dependence of Soil Erosion

Some researchers have investigated the effect of variation in soil erosion with duration of rainstorm. Ellison (1944) observed a reduction in raindrop splash with time and noted that this appeared to be because "*the surface has become sealed and the loose particles above the plane of sealing have been carried away by erosional processes*"

According to Foster and Meyer (1975) "*Even for a constant rainfall intensity, the rate of particle detachment by raindrop impact is a time-dependent function. In some cases* *the rate increases rapidly in the beginning, reaches a peak, and then decays exponentially to a steady–state rate*" (Foster and Meyer, 1975).

Morgan (1986) implies that the momentum of impacting raindrops has a consolidating effect, and that this effect is "*best seen in the formation of a surface crust, usually only a few millimeters thick, which results from the clogging of the pores by soil compaction" It has been suggested by Young (1972) that this is associated with the dispersal of fine particles from soil aggregates or clods which are translocated to infill the pores….. Hillel (1960) explained crusting by the collapse of the soil aggregates on saturation*" (Morgan, 1986).

Agassi et al. (1985) showed that a seal did not form at low values of kinetic energy, but that at values of 23 $J/m^2/mm$ of rain (typical of temperate climates) a seal with a very low hydraulic permeability was formed. According to Agassi et al. (1994) dispersive soils (high ESP) are more susceptible to erosion, and this may be due to the fact that they do not form a seal.

3.4.13 Effect of Surface Water Layer

Another factor examined by researchers is the effect of the presence of a surface layer of water on soil detachment. Palmer (1963) concluded that for soil erosion "*Under certain conditions, a raindrop may increase its mass by some added virtual mass, because of the presence of a water layer. The resultant impact forces will then be greater than if the soil surface were bare."* (Palmer,1963)

Moss and Green (1983) studied the effect of surface flows on raindrop detachment of soils. They found that detachment (air splashing) increased strongly with drop diameter but fell rapidly as water depth increased. It fell to near negligible if only 2mm of water covered the surface. A similar conclusion was reached by Foster et al. (1985)

"*As water depth increases from zero to about 0.3 drop diameters, the forces increase (Mutchler and Hansen, 1970), but at greater depths the forces decrease. When water* *depth exceeds approximately 3 drop diameters, drop impact forces on the soil surface and subsequent soil detachment are negligible*." (Foster et al., 1985)

3.5 Erosion of Metals by Raindrops Impacting at High Speed

Erosion due to the impact of liquid droplets became a problem in the mid 1940's when it was noticed that paint and subsurface material was damaged by rain when planes flew at speeds in excess of about 150 m/s. The problem is a similar one to that occurring in steam turbines and missiles and has been studied over a long period of time.

3.5.1 Mechanics of the Impact Process

Although there is not a general theory for the behaviour of materials under the action of high-speed droplet impact, the action of drops has been widely studied by photographic means. Three distinct stages can be identified in the impact process, as shown in Figure 3.6, taken from Springer (1976)

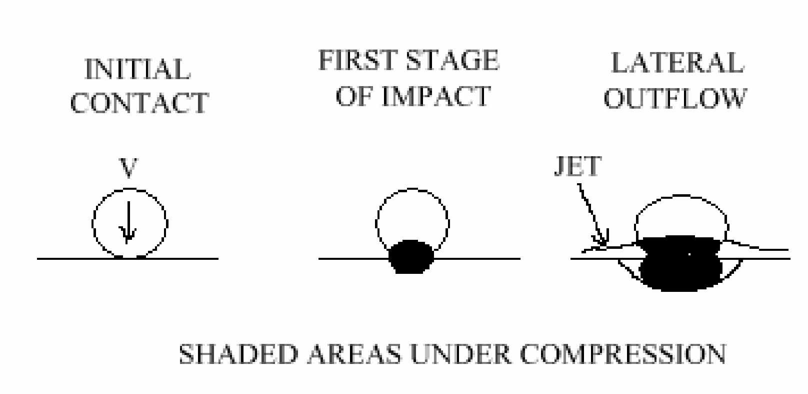


Figure 3.6 Three Stages in Impact Process

At the initial point of impact the droplet comes to a sudden stop, and quasi one-dimensional conditions prevail. Shock waves form and begin to travel up into the drop. Shock wave pressures are high and similar to those that occur in a "Water Hammer" situation. The average pressure in this situation is given by

$$p = \rho_0 C_0 v / 10^6 \qquad \text{.........}(3.19)$$

where

p = Shock wave pressure (MPa)

ρ_0 =Water density = 1000 kg/m^3

C_0 =Speed of Sound in Water = 1463 m/sec, and

v =Impact velocity (m/sec)

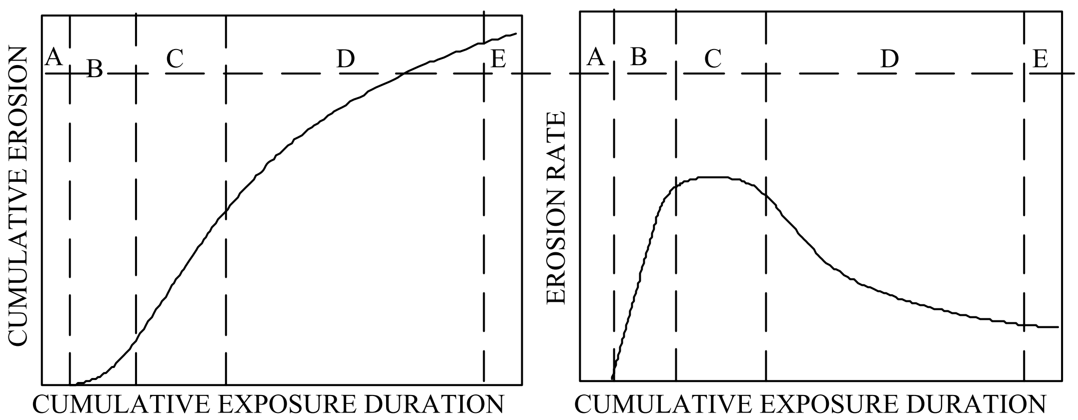
Engel (1955) showed that in the case of a water drop the water hammer pressure should be multiplied by a factor of approximately 0.45 to account for the spherical shape of the drop, giving an impact pressure of approximately 0.686 × v (MPa).

At the second stage the contact area increases and maximum pressure occurs at the periphery of the drop. According to Brundon and Rochester (1979) edge pressures in this case can be as high as 2.5 times those obtained in the first stage.

At the third stage the shock front detaches from the solid surface and the compressed liquid squirts out laterally with velocities much higher than the impact velocities. "*The jets interact with minute, existing surface flaws and may tear off bits of the surface or may widen cracks*" (Springer, 1976)

3.5.2 Effect of Duration of Loading

One of the most puzzling aspects of liquid drop erosion is the time dependence of the erosion process. This was recognized by Honegger in 1927. who showed the classic stages in the erosion process, shown in Figure 3.7



a)Total Erosion **b) Erosion Rate**

Figure 3.7 Characteristic Erosion vs. time Curves (Heymann, 1992)

In the first stage (A) there is no loss of material. This is referred to as the incubation period. In stage B erosion rate accelerates until it steadies off in Stage C. In Stage D there is a decreasing erosion rate leading to a terminal or final steady stage rate (E), if it occurs.

Honegger explained this as follows

"*As long as the surface is smooth, it offers no hold for the impinging drops of water and the water flows off on all sides. Therefore, erosion does not occur for some time. However, as soon as any roughness forms, erosion develops rapidly because the water penetrates the unevenness of the surface at a high pressure due to the impact, and acts very violently. Finally, when the erosion has attained a considerable depth, a layer of water adheres to the now completely roughened surface. This water dampens the impact of subsequent drops so that their destructive action is diminished. The specific erosion consequently decreases after a certain depth has been reached* " (Honegger, 1927, quoted in Bargmann, 1992)

Pouchot (1970) supported this theory "*It seems likely that after a small number of impacts that the water wets the specimen and a film of water develops on the surface. This can change, at least in principle, the maximum impact pressure and duration of impact from that resulting from the impact of a water drop on a dry surface*" (Pouchot, 1970)

Heyman (1992) said that the incubation and acceleration stages were easy to explain if one assumed a fatigue like failure mechanism, but noted that the theories to explain the deceleration phase were largely conjectural

"*Some have also been based on the statistics of the damage mechanisms, combined with changes in the surface properties brought on by erosion itself. Some are based on the topographical changes in the surface: as the surface is roughened, the surface area is increased, and more energy is needed to continue erosion. Also, liquid drops will now tend to impact on the peaks or the slopes of the roughened surface; in both cases the impact pressures may be reduced. Finally, the liquid retained in erosion craters has been supposed to cushion and protect the surface*" (Heymann, 1992)

3.5.3 Effect of Drop Size

The action of liquid droplets is treated separately in the literature from that of liquid jets as " *Rough comparisons of test data suggest that the erosion rate due to a continuous jet can be from one to five orders of magnitude lower than that due to the same quantity of liquid impinging at the same velocity but in the form of droplets*" (Heymann, 1992). According to Brunton and Rochester (1979) 2mm drops appear to have been adopted by most researchers as the "standard" size, and that erosion using drop sizes greater than 1 mm is independent of drop sizes.

3.5.4 Effect of Impact Velocity

Honegger (1927- in Brunton and Rochester, 1979) investigated the relationship between erosion damage and impact velocity for high strength alloys. He found evidence of a threshold velocity (v_c) of 125 m/sec, below which no significant erosion occurred, and found that mass loss was proportional to $(v-v_c)^{2.}$ Baker et al (1966- in Brunton and Rochester, 1979) found a relationship between erosion loss per square metre per unit volume of water and $(v - v_c)^{2.6}$.

Heymann (1992) rejects the concept of a threshold velocity and suggests that erosion is proportional to the 4th or 5th power of velocity. Hoff et al (1967 - in Brunton and Rochester, 1979) came up with the relationship $D = v^n$, where n ranged between 5 and 7 for the majority of metals, ceramics and polymers tested. Their tests were based on velocities up to 410 m/sec. Springer (1976) states that "*Experimental observations often indicate that the time rate of mass loss (dm/dt) varies approximately with the fifth power of the impact velocity.*"

3.5.5 Effect of Angle of Attack of Raindrops

Based on the work of others, Brunton and Rochester (1979) concluded, "*for smooth hard surfaces, the normal component of velocity determines the damage potential of the drop but that for roughened surfaces the tangential component becomes significant, especially for materials with low shear strength"* (Brunton and Rochester, 1979).

3.5.6 Theories Relating to the Erosion Process

Various theories have been proposed to explain the erosion process, none of which is widely accepted.

One of the earliest and more interesting approached to this problem was given by Mok (1962). Mok's work is based on the work by Brundon (1962) and Bowden and Field (1964).

Based on the available experimental results indicating the existence of a threshold velocity Mok relates the difference between the impact and threshold velocities to the number of cycles of stress before failure occurs. He then assumed a stress attenuation equation relating stress drop off with distance below the surface to arrive at the Equation 3.20, which he showed to be consistent with the experimental results available at that time.

$$dE/dt = a \times k \times d \times (v - v_c) \times Q / (\alpha \times C_0 \times n_o) \qquad \text{.........}(3.20)$$

where

dE/dt = Rate of mass of material lost
a = Constant depending on the properties of the rain and the material
k = parameter of proportionality used in the stress attenuation factor
d = Raindrop diameter
v = Raindrop velocity
v_c = Critical Raindrop velocity
Q = Mass of water impacting surface
α = exponent in stress attenuation equation
C_0= velocity of sound in water and
n_o = Number of impacts during the incubation period

Grouping together all the constant factors and assuming that n_o is a function of the material, Equation 3.20 can be expressed as

$$E = \phi \times Q \times (v - v_c) \times d \qquad \ldots\ldots\ldots(3.21)$$

where

E = Mass loss

ϕ = Material factor

Q, v, v_c, and d as for Equation 3.20

Thiruvengadam (1967) provided a theory based on his concept of "*erosion strength*", which he defines as the energy-absorbing capacity of the target material per unit volume under the action of erosive forces. The time dependency of the erosion rate is linked to a Weibull function and in general gives fair agreement with experimental rates for stainless steel, although it has been widely criticized on theoretical grounds (Adler, 1979)

Heymann (1970) adopted a statistical approach in which the erosion rate was assumed to be dependent on the lifetime of a layer of surface cells. His work showed that a "*rationalized erosion rate*" was proportional to the 5^{th} power of impact velocity.

Springer (1976) adopted a model based on a cumulative fatigue damage concept, where erosion was characterized by an incubation period and then a linear erosion rate period during which time the erosion rate was inversely proportional to the incubation period. According to his method the mass loss per unit time is approximately proportional to v^5. Adler (1979) has criticized Springers approach as a "*series of curve fitting routines for an experimental data base which involves a high degree of arbitrariness*".

Bargmann (1992) presented an erosion theory based on the statistical nature of the repetitive attack process. He assumed that the loss of material is a random variable, which takes on different values depending on the number of impacts on the target area. Whilst this approach would seem to have the potential for predicting erosion curves it does not appear to offer any practical guidance at this stage.

3.5.7 Standard Practice for Liquid Erosion Testing

The present state of the art in liquid impingement erosion testing for metals and ceramics is covered in ASTM G73-98 - Standard Practice for Liquid Erosion Testing. ASTM G73 does not specify a particular test apparatus but "*applies principally to those erosion test devices in which one or more specimens are attached to the periphery of a rotating disk or arm, and their circular path passes through one or more liquid jets or sprays, causing discrete impacts between the specimen and the droplets* "(Section 6.1), ASTM G73-98 does recognize that other liquid impact devices such as spray tests exist.

ASTM G73 classifies spray testing as "*distributed impact tests*" and sets out a procedure for representing the erosion resistance of a material in terms of a "Normalised Erosion Resistance" and a "Normalised Incubation period".

Specimens are required to be tested by the test apparatus, and by periodically halting the test, a cumulative mass loss versus cumulative time curve produced. Figure 4 of that standard (Reproduced in part as Figure 3.8) sets out the shapes of common erosion curves

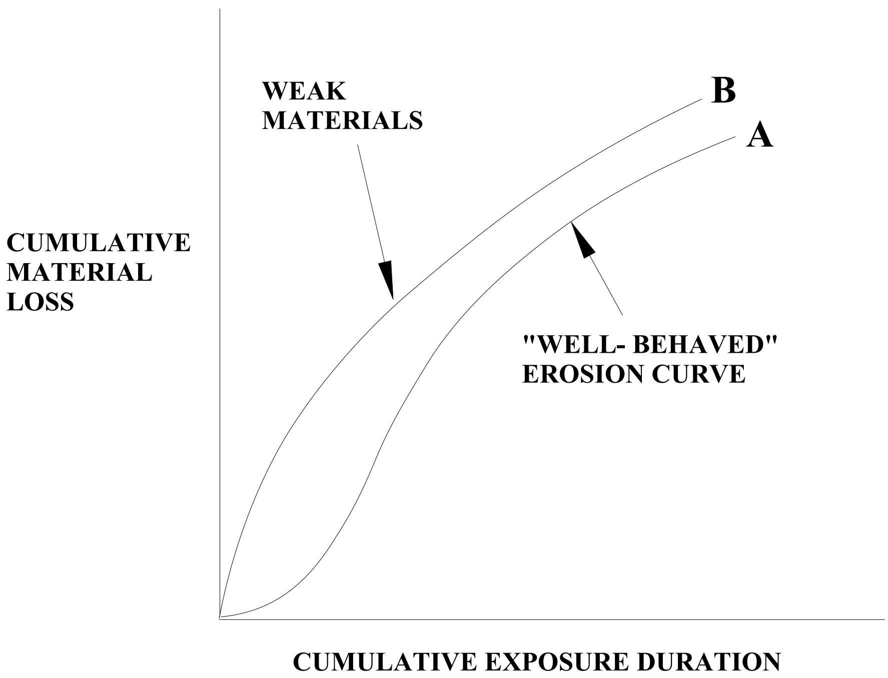


Figure 3.8 Figure 4 from ASTM G 73

Curve A is the commonly quoted curve for metals, being characteristically "S' shaped and having a distinct incubation period, during which time there is little or no erosion. According to ASTM G73 curve B may occur "*because the impact velocity is high enough so that each single impact removes material and no incubation period exists*" (Section 10.3.3). Type B curves were observed to be predominant in preliminary earth wall specimen tests, carried out by the author.

Section 10.3.4 shows how to define the maximum volumetric erosion rate (Q_e) based on the cumulative volumetric erosion versus time curve. For curves of type B where the maximum erosion rate occurs at the outset, Q_e is defined in Figure 3.9.

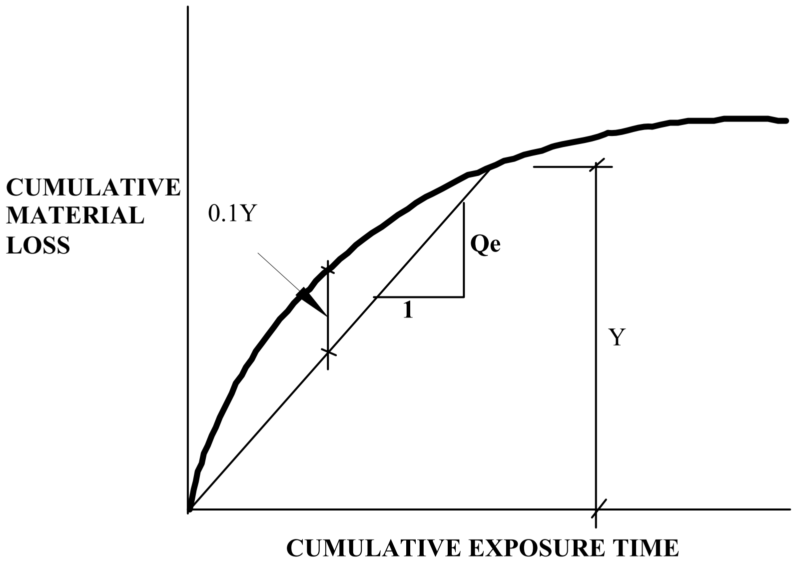


Figure 3.9 Calculation of Maximum Erosion Rate (Q_e)

ASTM G73 recognises the difficulty of specifying a definitive method for erosion resistance, instead relying on the comparative performance of materials

"*With the present state of the art, it is not possible to define "absolute" erosion resistance parameters, or even to identify the dimensions of such a parameter or the units in which it should be expressed. This comes from the lack of any accepted complete physical model for relating erosion performance to material parameters and major variables describing the impingement conditions. Therefore most investigators resort to comparative evaluations of different materials" (Section 10.1.1)*

For test results to be compared to a designated reference material similarly tested ASTM G73 defines a normalized erosion resistance $S_{ex/r}$ (Section 10.4.2) where

$$S_{ex/r} = Q_{er}/Q_{ex} \qquad \ldots\ldots\ldots(3.22)$$

where

Q_{er} = Maximum erosion rate for test material, and

Q_{ex} = Erosion rate for designated reference material.

Section 11 of the standard presents a formula for calculating the "Impingement Rate" of test apparatus in order "*to make quantitative comparisons between results from different impingement conditions, or to develop empirical models, or to verify theoretical predictions*". For a single number nominal value of spray angle, and for distributed impact tests, the impingement rate U_i is defined as follows

$$U_i = (\psi) \times v \times \mathrm{Cos}\varphi \qquad \ldots\ldots\ldots(3.23)$$

where

ψ = Spray Volume Concentration, and

v = Impact Velocity of Drops in m/s

φ = Angle of Impact relative to normal

For a given rainfall rate U_r, Ψ is given by Equation 3.24.

$$\Psi = \frac{U_r}{1.44\times10^7 \times d^{0.56}} \qquad \ldots\ldots\ldots\ldots(3.24)$$

where

U_r = Rainfall Intensity in mm/hr, and

d = Drop diameter in mm

Equation 3.24 comes from ASTM G73 and is based on a constant drop size. For the more general case of varying drop sizes a representative drop diameter $\bar{d}$ could be used. In this case the exponential term becomes a variable and, using the more normal designation for rainfall (I) instead of U_r, equation 3.23 becomes

$$U_i = K \times \frac{I \times (vCos\varphi)}{\bar{d}^{a}} \qquad \text{.........}(3.25)$$

where K and a are constants

In section 11.3 of ASTM G73 the "linear erosion rate (U_e)" is defined as the slope of the maximum cumulative volume erosion curve (Q_e) divided by the exposed area of Spray (A). The rationalized erosion rate is then defined as follows

$$R_e = U_e/U_i = Q_e/(U_i \times A) \qquad \text{.........}(3.26)$$

for a particular impingement rate and in Section 11.5.3 Re is used to define a severity index (F_e) for a particular test apparatus as follows

$$\log F_e = \log S_{er} + \log R_e - 4.80 \times \log v + 16.31 \qquad \text{.........}(3.27)$$

where

S_{er} ="Reference Erosion Resistance" of the reference material tested

3.6 Summary

Although some insight into the erosion of earth walls can be gleaned from work done in the fields of physical geology, such as the fact that most erosion occurs in times of major events, most of the experimental work applicable to the erosion of earth walls has occurred in the fields of soil erosion and in the erosion of materials due to horizontal impact with raindrops.

In the case of soil erosion the available research evidence can be summarized as follows

- Theories are based on kinetic energy in the main
- USLE equation most widely accepted, based on total rainfall kinetic energy (KE) times the I_{30} rainfall rate (EI_{30})
- Other theories attribute erosion rate to I^2, or total erosion to the volume of water impacting the surface times a representative rainfall intensity
- Total Erosion may also be thought of as proportional to the volume of water impacting the surface times the sum of the excess kinetic energy ($KE-KE_o$) during storms. Since E is approx proportional to I both of the above approaches should yield similar results.

- There is a direct link between the terminal velocity of the median raindrop size (and hence kinetic energy) and rainfall intensity through the relationships between v and d_{50} and d_{50} and I.
- When velocity was independent of rainfall intensity (as in the Ellison tests) there was a good correlation between erosion and the volume of impacting water times v^5
- There appears to be some time dependence but the evidence is not strong. Reduction of erosion with time appears to be linked to a decrease in surface porosity caused by sealing of the surface over time (crusting).
- There appears to be a nearly linear relationship between drop size and erosion rate.

On the evidence relating to the erosion of metals subject to horizontal raindrop attack the following conclusions can be made

- Erosion Rate is proportional to v^n, where n is approx 5, or $(v-v_c)^m$, where m is approx 2.5 and v_c is a critical impact velocity.
- There appears to be little variation in erosion rates with raindrop size for raindrops sizes greater than 1 mm.
- There is no relationship between I and v.
- There is a strong time dependency with possibly an incubation period.

Earth walls subject to attack by rainfall are harder than soils or beaches but softer than metals. The predominant erosive mechanism is similar however, being one of impacting liquid kinetic energy, with the volume of impacting water being a major component and the velocity of the water being the other. In the case of rainfall, drop size appears to also be a contributing factor.

Chapter 5 will examine the relationship between the volume of impacting water and rainfall intensity and wind speed. Chapter 6 examines the variation of erosion with impact velocity and drop size as well as developing a relationship for the effect of time dependency.

Chapter 4 Characterisation of Climatic Factors

4.1 Introduction

The original development of mud brick buildings was in Mesopotamia and Egypt. Annual rainfall in these areas does not exceed 400 mm and in Mesopotamia it is as low as 200 mm. Erosion by wind driven rain was therefore not a significant problem, and earth building is still common in Middle Eastern countries.

Over time mud brick construction extended to wetter areas of the world such as northern China, England, France, Mexico, Peru, Nigeria, South Africa and Australia. In general however, unless they are very well protected by overhanging eaves, unstabilised mud brick construction is unlikely to be found in areas where the annual rainfall is greater than 1000 mm.

Recently however, earth building has been extended to climates with annual rainfalls in excess of 1000 mm or sometimes unprotected earth walls have been used in areas of annual rainfall between 500 and 1000 mm. In these cases the resistance of walls to driving rain is a major problem.

This Chapter concentrates on the relationship between erosion in the field relative to erosion in an accelerated erosion test carried out in the laboratory. In order to relate the two, it is necessary to define the climatic conditions existing in the field. Since driving rain is the principal degradation mechanism, this Chapter will look at the defining characteristics of rainfall and wind, and will examine the relationship between the two. It will also examine the relationship between measured rainfall and wind speed and the amount of rain impacting on vertical surfaces.

4.2 Rainfall

4.2.1 Introduction

Precipitation occurs when masses of humid air are cooled below their dew point as they rise in the atmosphere. As condensation continues the water droplets in the clouds grow larger and heavier, until the atmosphere cannot support them and they precipitate.

Raindrop sizes during precipitation vary from around 1mm to 6mm falling with velocities up to around 9m/sec. The mechanisms, which produce rising air, can be divided into three types

- **Convectional** – heated air rises in convection currents. This is typical of hot periods in a day, for example a summer afternoon storm. The rain is usually short and heavy and sometimes accompanied by thunder and lightning. It is typical of equatorial and tropical areas at all seasons, and of continental interiors in middle and high latitudes in the summer season.
- **Orographic** – moist air forced to rise over higher ground. Whenever onshore winds from oceans are humid and warm in relation to the land barrier onto which they are blowing, the rainfall of this type will be particularly heavy. It is often more of a modifying factor to rain produced by one of the other two mechanisms.
- **Frontal** – Warm moist air mass forced to rise above cold. Can be either a cold front where an advancing cold air mass pushes warm air up or a warm front, where warm air lifts up whilst passing over a cold air mass. Mid-latitude cyclones in the southern hemisphere produce both cold and warm fronts at various times. Warm fronts are much slower moving than cold fronts and are rarely seen in Australia, where the predominant precipitation process is due to cold fronts. The approach of a cold front is usually preceded by thunder and lightning and the rain comes suddenly, is heavy and does not last long

Frontal air masses around the world are divided into four categories

1. Tropical (Warm)
2. Polar (Cold)
3. Continental (Dry)
4. Maritime (Moist)

On the east coast of Australia tropical maritime (mT) air masses coming from the north produce most of the rain in summer and polar maritime (mP) air masses coming from the south produce the rain in winter

In general, although rain can come from most cloud formations, high rates of rainfall generally only come from those clouds which extend high into the atmosphere, these being nimbostratus (layered rain cloud) and cumulonimbus (heaped rain cloud) (Horrocks, 1964). According to Fyall (1965), high rates of rainfall are more likely to be associated with cumulonimbus clouds of localized origin, but in some places the cumulonimbus activity may be widespread and give the appearance of continuous rain.

4.2.2 Seasonal and Spatial Variation

4.2.2.1 Annual Rainfall

Maximum annual rainfall varies all over the world, from zero in some places up to around 12,000 mm in others. Figure 4.1 indicates the distribution of annual rainfall around the world.

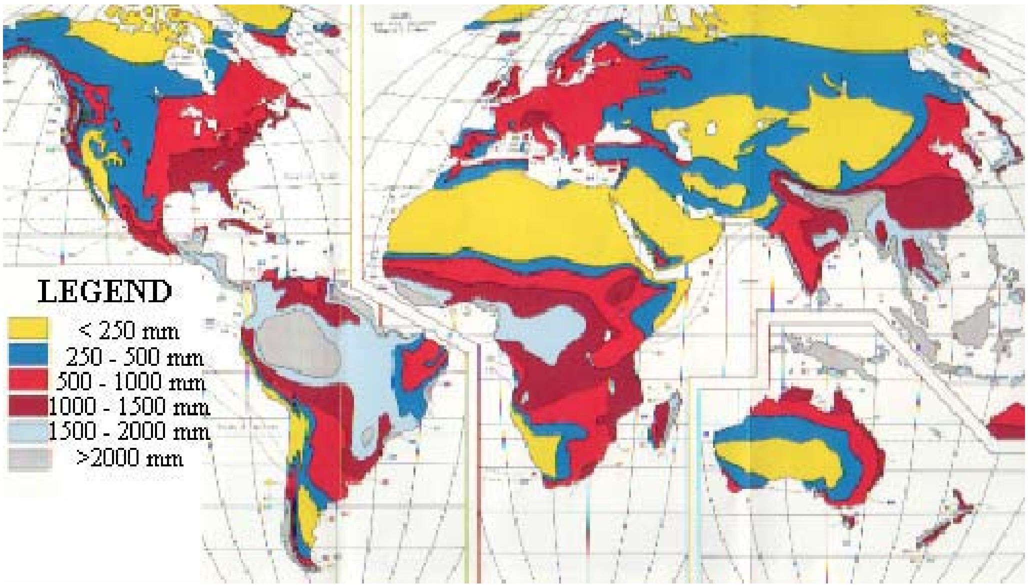


Figure 4.1 Generalised Map of Mean Annual Rainfall
Reproduced from Petterssen (1969)

Based on the historical performance of earth buildings it is possible to separate areas of the world into three regions according to their annual rainfall. These are

Region 1 – Rainfall less than 500 mm per annum – Little problem with erosion due to rain.

Region 2 – Rainfall between 500 m per annum and 1500 mm per annum – Erosion of unprotected earth walls due to rain needs consideration.

Region 3 – Rainfall greater than 1500mm per annum – earth wall construction not appropriate unless walls are well protected from rainfall by eaves or protective coatings.

4.2.2.2 Temporal Variation

The seasonal distribution of rainfall can vary significantly within a continent, as can be seen from Figure 4.2, in the case of Australia.

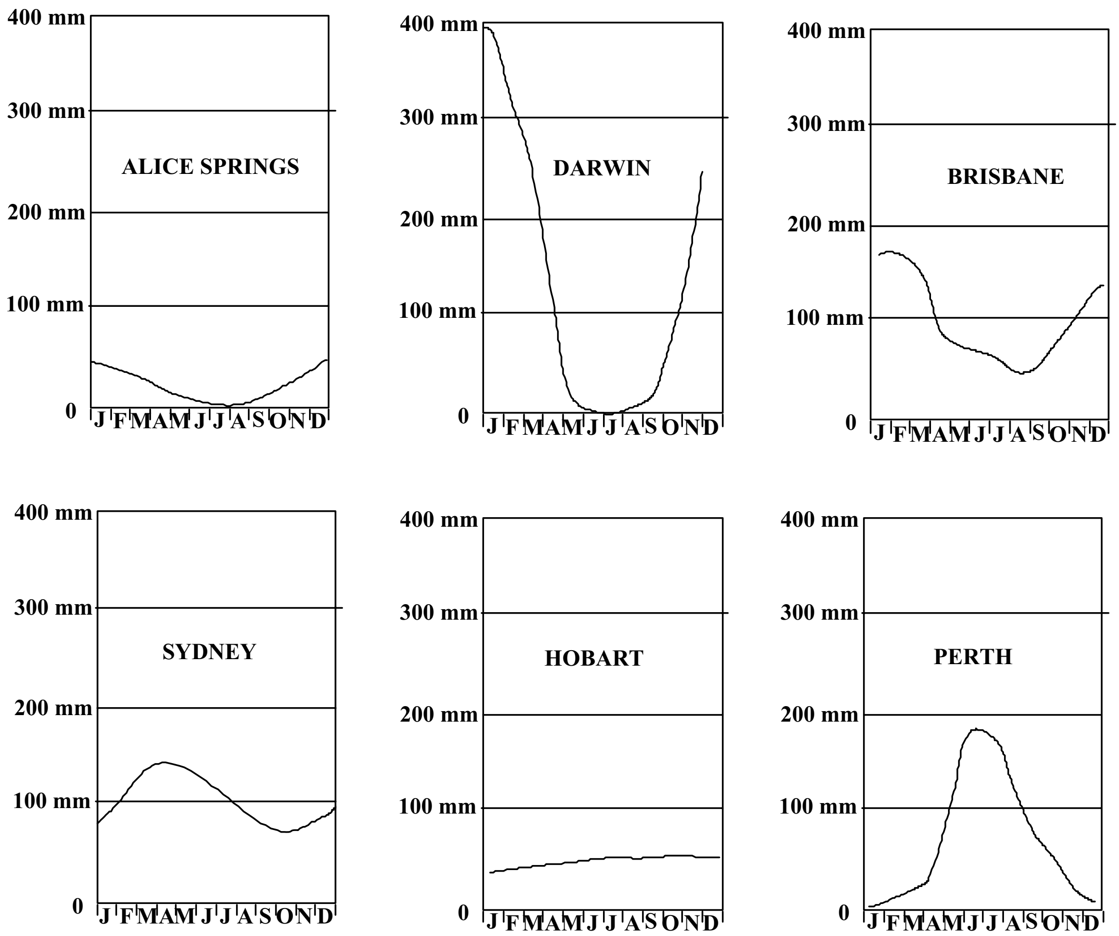


Figure 4.2 Seasonal Variation of Rainfall in Australia

Figure 4.2 shows that in the south-east of the continent (Sydney and Hobart) rainfall is more evenly spread throughout the year whereas in the north (Darwin and Alice Springs) and west (Perth) the rainfall is noticeably seasonal. In the case of NSW slightly higher rainfall rates can be expected in the first half of the year.

Individual rainstorms contribute widely differing amounts to the annual precipitation in all parts of the world. Riehl (1965) reported that for the average of 24 rainstorms that occur in Colorado every year, 50% produce over 75% of the total yearly precipitation, and 25% produce over 50% of the yearly precipitation. Jackson (1977) indicates that for Niugini for storms greater than 25 mm/hour the largest 25.4% of storms accounted for 77.8% of the rainfall.

4.2.2.3 Spatial Variation

In general rainfall is higher at low latitudes
"*In the lower levels of the atmosphere mean air temperatures vary broadly with latitude, and with the higher temperatures of low latitude are associated greater quantities of water vapour in the air for condensation and more powerful convection currents to produce it*"(Jennings, 1967)

During storms, areas affected by rain vary generally in accordance with the intensity of the rain, with intense storms occurring over small areas generally. According to Fyall (1965) in temperate climates rainfall of 2 mm/hr can be expected over distances of 800-1600 km (Type A). Rainfall of from 2 to 10 mm/hr can be expected over distances up to 250 km in extent by 15-30 km wide, generally associated with some convective activity (Type B). Fyall defines a Type C rainfall consisting of a band of rain 5 km wide having an intensity of 100 mm/hr, flanked on each side by 2.5 km wide bands having intensities of 40 mm/hr with areas further out from this (up to 15 km) having an intensity of 20 mm/hr. Fyall gives similar criteria for tropical climates.

4.2.3 Classification of Rainfall

4.2.3.1 Based on Intensity

According to Fyall (1965) rainfall can be classified according to intensity as follows

- Drizzle or light rain 0 – 2.5 mm/hr
- Moderate to heavy rain 2.5 – 12.5 mm/hr
- Tropical rain 12.5 – 25 mm/hr
- Thunderstorms Over 25 mm/hr

The average amount of rainfall per rain day is also used as a measure of the overall intensity of rainfall falling in an area. Jennings (1967) presented data for 1500 stations around Australia during the period 1911-1940 and found that the average amount of rainfall per rain day varied from around 5 mm per rain day at a latitude of 42 degrees south to around 15 mm per rain day at a latitude of around 10 degrees south. Jennings also found that on the coast of NSW the average amount of rainfall per rain day was lower than inland due to the higher incidence of days of light drizzle.

Another measure of the intensity of rainfall in an area is the number of thunder days per year. A thunder day is defined as a day in which thunder is heard, and therefore depends on the ability of the observer to hear the thunder.

4.2.3.2 Based on Drop Size

Raindrop size varies quite significantly with rainfall intensity, although the mean raindrop size (d_{50}) is fairly independent of intensity. Figure 4.3 shows for instance that at an intensity of 20 mm/hr 95% of the volume of rain has raindrops greater than 1 mm, 50% of the volume has raindrop sizes in excess of about 2.2 mm and only 5% of the volume has raindrop sizes greater than 4 mm.

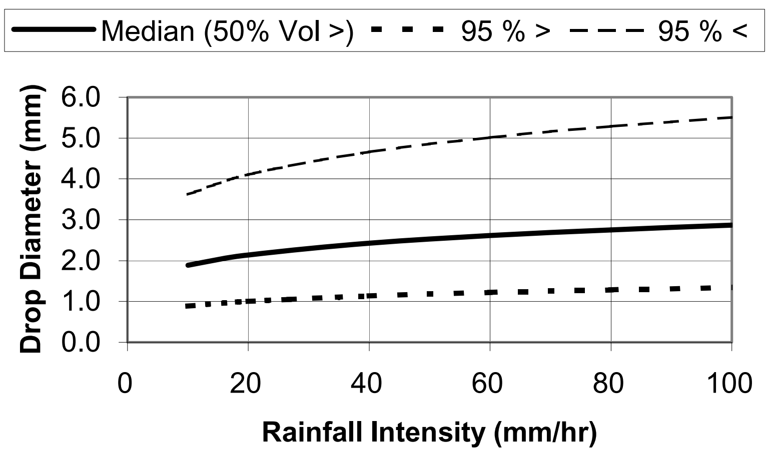


Figure 4.3 Raindrop Diameter vs. Rainfall Intensity (Laws and Parsons, 1943)

In terms of practical application of raindrop diameter to any theoretical model it must be remembered that rainfall data is normally measured in hourly intervals and that the variation in rainfall intensity during that period is not available. Although it could be expected that low hourly rainfall volumes are associated with fairly constant rainfall intensities (and vice versa) this is not necessarily the case. At the extremes it could be expected that the maximum rainfall intensity in an hour period vary between the recorded hourly rainfall and some value possibly six times higher than this. Given the potential associated variation in VMD it may not be possible to include the effect of drop diameter explicitly. Adopting a representative drop size of around 2.6 mm would seem to be the most practical solution at this stage.

4.2.3.3 Based on Volumetric Drop Concentration

Fyall (1965) gives the following expressions for the mass concentration of rain per unit volume

$$\text{Mass Concentration (gm/m}^3\text{)} = 0.278 \times \frac{\text{Rainfall Intensity (mm/hr)}}{\text{Terminal Velocity (m/sec)}} \quad \ldots\ldots\ldots(4.1)$$

If the terminal velocity is expressed as a function of rainfall intensity according to Lacy (1965) as $v = 4.505 \times I^{0.123}$, this expression becomes

$$\text{Mass Concentration (gm/m}^3\text{)} = 0.062 \times I^{0.877} \quad \ldots\ldots\ldots(4.2)$$

$$\text{Volume Concentration (l/m}^3\text{)} = 62 \times I^{0.877} \quad \ldots\ldots\ldots(4.3)$$

Springer (1976) gives the formula for number of raindrops per square metre per minute as

$$N = \text{Number of raindrops/m}^2\text{/min} = \frac{I \times 10^5}{\pi \times d^3} \quad \ldots\ldots\ldots(4.4)$$

where I is in mm/hr and d in mm

For example, for drops of 2.5 mm diameter falling at an intensity of 25 mm/hr then the number of drops per square metre per minute would be approximately 50,000, or approximately one drop per second over an area of 35 mm by 35 mm.

4.2.3.4 Based on Terminal Velocity of Raindrops

The terminal velocity of raindrops can be linked to the diameter of the raindrops using Stokes equation but inevitably the drag coefficient has to be determined from experimental work. Best (1950) studied the work of Laws (1941) and Gunn And Kinzer (1949) and their results are reproduced in Figure 4.4, together with the approximation made by Lacy (1976). Lacy does not specifically give this formula but it can be interpolated from the way he derives the expression for wind driven rain.

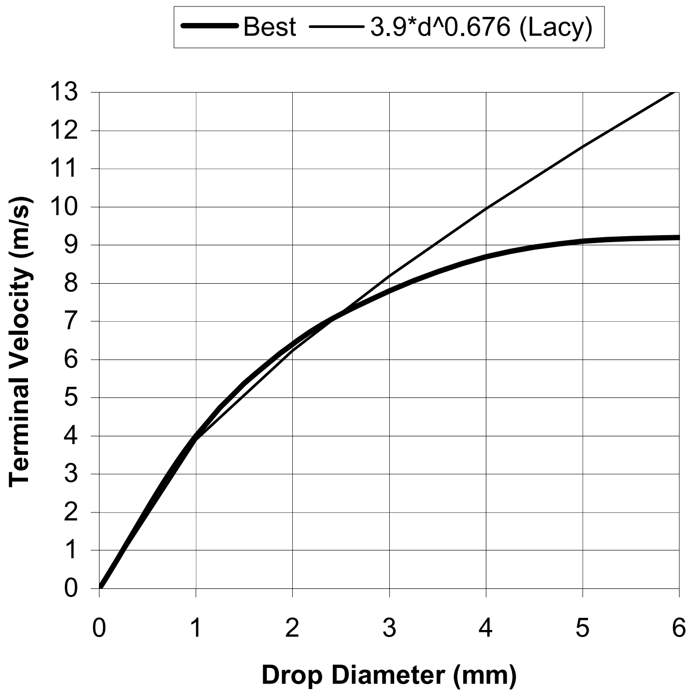


Figure 4.4 Terminal Velocities of Raindrops

Figure 4.4 indicates that in the region of the median drop sizes shown on Figure 4.3 (2-3 mm) the approximation used by Lacy is a good fit to the equation given by Best.

4.2.4 Rainfall Measurement

Measurement of rainfall can either be on a periodic basis (usually hourly or daily) or may be continuous. In the common case where hourly rainfall records are kept the recorded rainfall is the mean rainfall for the clock hour. In actual fact the rainfall rate is rarely constant for the whole hour and can vary up to greater than 6 times the mean hourly rate in some circumstances.

In the case of a float gauge, precipitation is continuously recorded until a maximum level is reached (Say 10 mm), upon which the gauge is emptied and the process repeated. The rainfall intensity at any one instance of time is therefore the slope of the recorded line.

Figure 4.5 shows a typical rainfall record from the station at the International Airport at Sydney, where the field testing for this investigation was carried out. The record is for the 20th February 2001. From this it can be seen that between 2 am and 3 am cumulative rainfall was 4.2 mm (9.6 – 5.4) and the rate (slope) was approximately constant. This means that the instantaneous rainfall intensity was approximately equal to the clock hour rainfall intensity, i.e., 4.2 mm/hr.

For the period between 1 am and 2 am it can be seen that the slope of the line increases exponentially, as would the instantaneous rainfall rate. For the first three quarters of an hour the rainfall rate was low (flattish slope) whilst for the last 15 minutes the slope approximates a slope of 18 mm/hr. This means that the total rainfall for the hour is therefore roughly $0.75 \times 0 + 0.25 \times 18 = 4.5$ mm (This can be compared with the actual recorded clock hour rainfall of 4.4 mm (5.4 –1)). The maximum 15-minute rainfall intensity is 18 mm/hr, or 4.3 times the clock hour intensity. Since the mean clock hour intensity is 4.4 mm/hr, 100% of the rainfall occurred at an intensity at least four times greater than the recorded clock hour intensity.

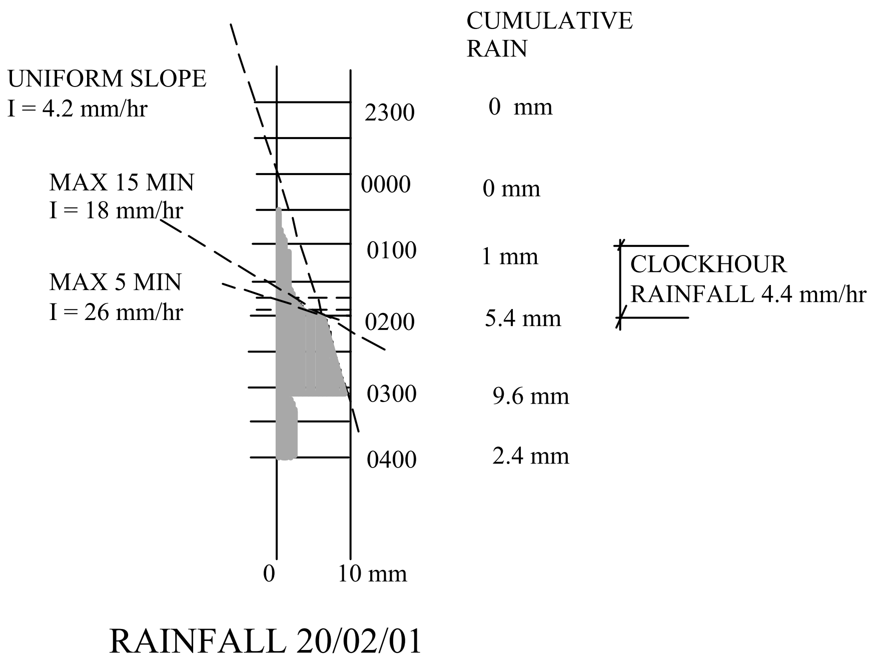


Figure 4.5 Variation of Rainfall Intensity With Time

For the last five minutes of the hour the slope is roughly 26 mm/hr, indicating that the maximum five-minute intensity for the hour is approximately 6.2 times the clock hour intensity.

Breihan (1940) examined the relation of hourly mean rainfall to actual intensities for various storms in the Mississippi Valley in the USA. In particular he examined 111 storms with clock hour intensities of greater than 12.5 mm/hour. His results are summarised in Figure 4.6.

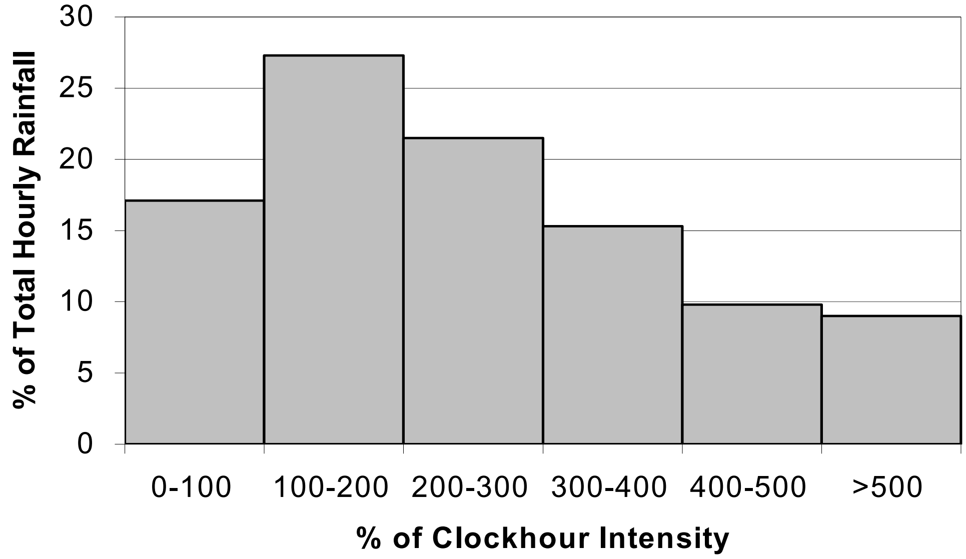


Figure 4.6 Temporal Variation of Clock Hour Rainfall Intensities (Breihan, 1940)

Breihan's results indicate that, for storms with clock hour intensities greater than 12.5 mm/hour and less than 25 mm/hour, 83% of the total rainfall in a clock hour occurred at intensities greater than the mean clock hour intensity and 50% of the total rainfall occurred at intensities greater than 225% of the mean clock hour intensity

Breihan also examined 30 storms with clock hour intensities greater than 25 mm/hour. For these storms 78% of the total rainfall in a clock hour occurred at intensities greater than the mean clock hour intensity and 50% of the total rainfall occurred at intensities greater than 190% of the mean clock hour intensity.

In general his results indicate that the lower the hourly clock rainfall the greater is the spread of values about the mean hourly value.

4.2.5 Effect of Varying Rainfall Intensities on Total Kinetic Energy

Rogers et al. (1967) have shown that, although rain gauges tend to mask short-term intensity fluctuations, this has very little effect on kinetic estimates for a storm. They calculated the kinetic energy of a 5-minute storm based on an average rainfall intensity and compared it with the kinetic energy based on each minute's intensity. They concluded "*Although there was an eightfold change in intensity during the 5-minute period, the summation of kinetic energy from each minute differed by less than 4% from the kinetic energy value based on the average intensity for the 5-minute period.*"

4.2.6 Rainfall at Test Site

All specimens used for field testing in this investigation were placed at the Bureau of Meteorology recording station at Sydney Kingsford Smith Airport, approximately 12 km south of the Sydney Harbour Bridge. The location of the field test site and that of the main recording station in Sydney at Observatory Hill is shown on Figure 4.7

The field test site is in flat terrain with the airport to the north and Botany Bay to the south. Observatory Hill, on the other hand, is located in a sheltered site in the heart of Sydney. The weather at this site is significantly influenced by its surroundings. It does however have a long history of weather recording.

Sydney's rainfall is principally produced by moist easterly airstreams in the summer months and drier westerly airstreams in the winter. Rainfall varies significantly from year to year with a mean annual rainfall of around 1200 mm. Rainfall occurs fairly uniformly around the year, with a late summer maximum, a secondary maximum in June and a minimum around August/September. Sydney experiences on the average about six major storms each year, although there is considerable variation from year to year.

The predominant rain producing mechanisms are

- Major storms – deep low-pressure systems in the Tasman Sea can produce strong winds and heavy rainfall along the NSW coast. Of particular significance are blocking high-pressure systems over the southern Tasman region. The associated low-pressure systems along the NSW coast can produce heavy rains, usually in autumn and winter.
- Thunderstorms – these often originate in the high ground to the west of Sydney and move eastward towards the coast. They mainly occur during the spring and summer months and produce localised heavy falls.
- Cold Fronts – not a major source of rainfall, but occasionally can produce prolonged heavy showers from a south-easterly direction.

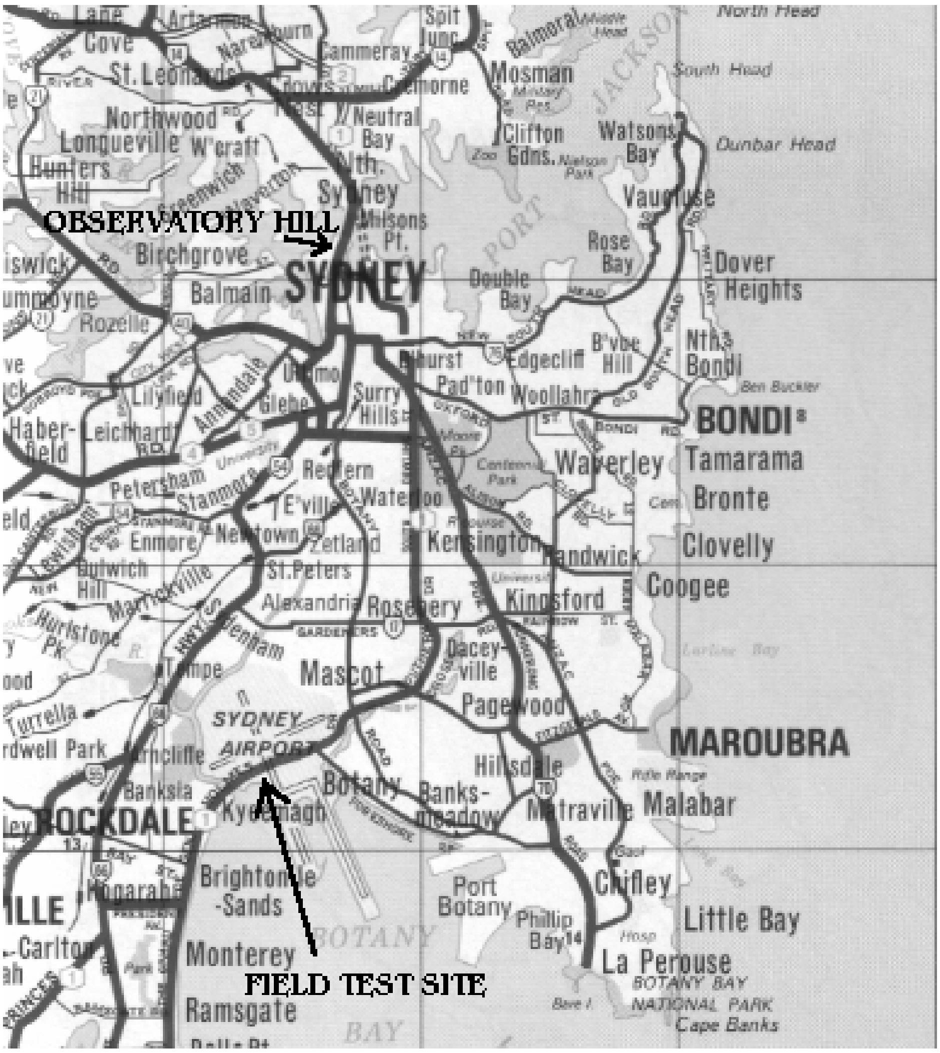


Figure 4.7 Location of Field Test Site

The author has examined just over six years of hourly rainfall records at Kingsford Smith Airport in Sydney for the period 1992 - 1998. The results are shown in Table 4.1.

Table 4.1 Variation of Rainfall Amount with Intensity

CLOCK HOUR RAINFALL (mm)	**<2.5**	**2.5 - 10**	**10 - 25**	**>25**
% OF OCCURRENCES	81.6	11.2	4.7	2.5
% OF RAINFALL AMOUNT	5	24	27	44

Of the 2303 hours of rain that fell in that period (Average of 366 per year) 18.4% of the hourly clock rainfall was greater than 2.5 mm/hr but accounted for 95% of the total rainfall amount for the period. 44% of the total rainfall was recorded for the 2.5% of occurrences where clock rainfall was greater than 25 mm/hour.

The Bureau of Meteorology (1979,p43) conducted a similar analysis for rainfall at Observatory Hill in Sydney for the period 1950 – 1959. Their analysis showed that on average there were 816 hours of rain per year with 19% of that rainfall being greater than 2.5 mm per clock hour. Although the average number of rain hours per year varies significantly from the authors analysis at Kingsford Smith Airport the percentage of rain hours in which rainfall was greater than 2.5 mm are very similar (18.4% vs. 19%).

4.3 Wind

4.3.1 Introduction

Without wind there would be no rain hitting vertical earth walls. Wind provides not only the means of re-directing rain onto vertical surfaces, but also provides additional energy to raindrops.

Wind speeds can be quoted in knots, metres per second, km per hour or in miles per hour. The following relationships between these units apply.

1 m/sec = 1.94 knots (≈ 2 knots) = 3.59 km/hr

1 knot = 0.52 m/sec = 1.85 km/hr (≈ 2 km/hr)

1 km /hour = 0.28 m/sec (≈ 0.25 m/sec)

1 mph = 0.45 m/sec

In general, wind speeds in this thesis will be quoted in m/sec.

Wind speeds can be categorised according to the Beauford scale, as shown in Table 4.2

Table 4.2 Categorisation of Wind Speeds

Beauford Number	**Description**	**Wind Speed (Knots)**	**Wind Speed (m/sec)**
0	Calm	<1	0 - 0.2
1	Light Air	1 - 3	0.3 – 1.5
2	Light Breeze	4 - 6	1.6 – 3.3
3	Gentle Breeze	7 – 10	3.4 – 5.4
4	Moderate Breeze	11 – 16	5.5 – 7.9
5	Fresh Breeze	17 – 21	8.0 – 10.7
6	Strong Breeze	22 – 27	10.8 – 13.8
7	Near Gale	28 – 33	13.9 – 17.1
8	Gale	34 – 40	17.2 – 20.7
9	Strong Gale	41 – 47	20.8 – 24.4
10	Storm	48 – 55	24.5 – 28.4
11	Violent storm	56 – 63	28.5 – 32.6
12	Hurricane	64 +	32.7 +

4.3.2 Spatial and Temporal Variation

All wind speeds given in weather reports are implied to mean the wind speed at a height of 10 m above the ground, and most recording stations standardise their equipment at this height.

Wind speeds at a height less than 10 metres can be substantially less than those recorded at weather stations. The actual values vary according to the terrain as determined by the following simplified equation (Laughlin, 1997)

$$\text{Wind Speed at Height x} = \text{Wind Speed at 10 m} \times \left(\frac{x}{10}\right)^{\alpha} \qquad \ldots\ldots\ldots(4.5)$$

where

α = Surface Friction Coefficient

= 0.10 (Smooth hard ground, lake, ocean)

= 0.14 (Short grass, natural surface)

= 0.40 (Urban areas with tall buildings)

For example where specimens are placed 1 metre above the ground with a friction coefficient of 0.14 wind velocities would be only 72% of those recorded at a height of 10 metres.

Wind speeds vary significantly over a clock hour, and recorded hourly values represent an average value, generally over the last 10 minutes of the hour. During that time gust wind speeds can be significantly higher than the average. In the situation where the surface friction coefficient is around 0.14 theoretical values of gust speeds are around 60% greater than the average wind speed recorded at a height of 10 metres.

4.3.3 Wind at Test Site

The Bureau of Meteorology measures both average and peak gust wind speeds at the test site. The anemometer is located adjacent to the runway at a height of 10 metres.

In general in Sydney easterly sea breezes (swinging to the north) are common in the summer months with westerly and north-westerly winds predominating in the winter. There are however considerable occurrences of wind emanating from other directions throughout the year.

Winds from the northerly sector tend to be stronger than those from the south, with the exception of the Southerly Buster in Summer, which has been known to produce gust speeds up to 80 knots (41 m/sec). This wind speed is in fact the 1 in a 100 year 3 second gust wind according to the draft Australian/New Zealand wind loading standard (DR 99419).

Dr 99419 also gives an indication as to the variation of wind strength with direction in Sydney, by means of wind direction multipliers (Table 4.3). These multipliers are for the coastal area of NSW around Sydney and indicate wind speeds from the southerly sector to be around 20% higher than the northerly sector.

Table 4.3 Wind Speed Multipliers for Sydney according to DR 99419

Compass Direction	Wind Speed Multiplier
N	0.80
NE	0.80
E	0.80
SE	0.95
S	0.90
SW	0.95
W	1.00
NW	0.95

Three-hourly wind records recorded at the test site for the period 1992 to 1998 were analysed (Figure 4.8). Of the 18,419 records (over a 6.3 year period) the average three hourly wind speeds recorded almost exactly 50% had wind speeds in excess of 4 m/s (approx 8 knots). This figure corresponds to a gentle breeze on the Beauford scale (Beauford No 3).

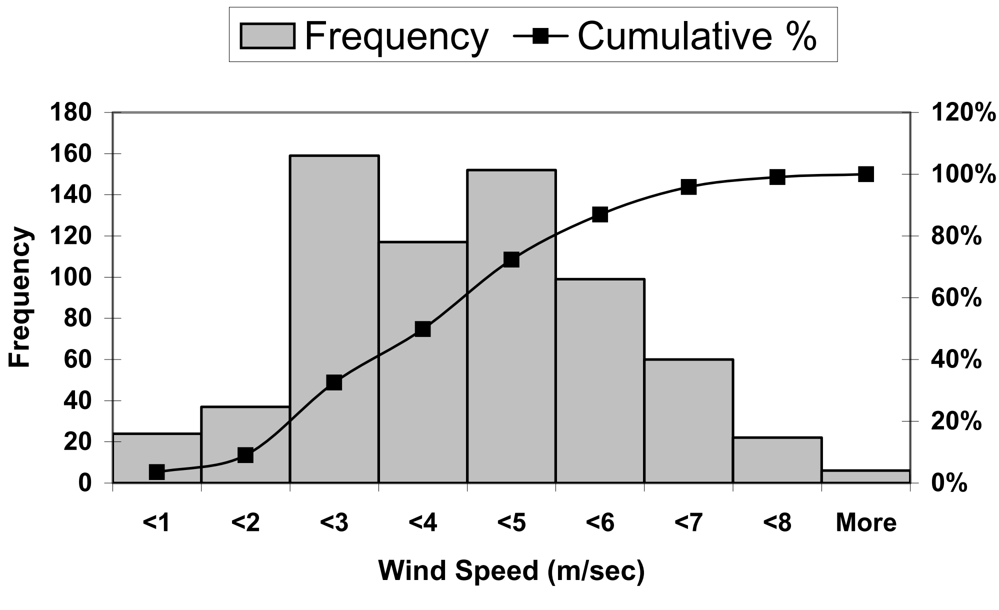


Figure 4.8 Frequency Distribution of Wind Speeds at Test Site (1992-1998)

Of the 50% of those wind speeds greater than 4 m/sec around 62% came from the southerly direction and 38% from the northerly direction. Average wind speeds for the winds above 4 m/sec were 6.6 m/sec for northerly winds and 7.2 m/sec for southerly winds (9.1% higher). The maximum hourly average wind speed during this period was 25.2 m/sec on the 31st August 1996.

For the same data 77% of the records showed a wind speed in excess of 2 m/sec (4 knots or light breeze on Beauford scale). Of these, 46% came from the northerly direction, with an average wind speed of 4.8 m/sec, and 54% from a southerly direction, with an average wind speed of 6.6 m/sec (37.5% higher).

4.4 Combinations of Wind and Rain

4.4.1 Introduction

There is no theoretical basis linking precipitation rates with wind speed at any given time. In order to produce some idea of the capacity of wind-driven rain to produce erosion it is necessary to resort to a statistical analysis of existing wind and rain records.

Disrud (1970) examined hourly rainfall and wind speed corresponding to each hour of rain recorded from local climatic data at Dodge City, Topeka, Winchita and Goodland, Kansas for the period July 1956 to July 1964. His results can be summarised as follows

Table 4.4 Wind speed Associated With Rain in Kansas (Disrud, 1970)

Location	**Mean Wind speed During Rain (m/sec)**	**Wind speed Exceeded Only 10% of the Time During Rain (m/sec)**
Dodge City	5	10
Goodland	5.5	10
Topeka	5.5	10
Wichita	5.5	11

Disrud found that there was little correlation between wind speed and rainfall and that "*wind speed accompanying rains could be predicted without regard to rainfall*"

The author carried out a similar analysis for rainfall at Sydney Kingsford Smith airport for the period October 1998 to September 1999 (Figure 4.9) and found, like Disrud, that there were large seasonal variations in wind speed associated with rain. For the period examined the mean wind speed during rain was 5.6 m/sec with a wind speed of 10.4 m/sec only exceeded 10% of the time. These values correspond very closely to those recorded by Disrud in Kansas (Table 4.4).

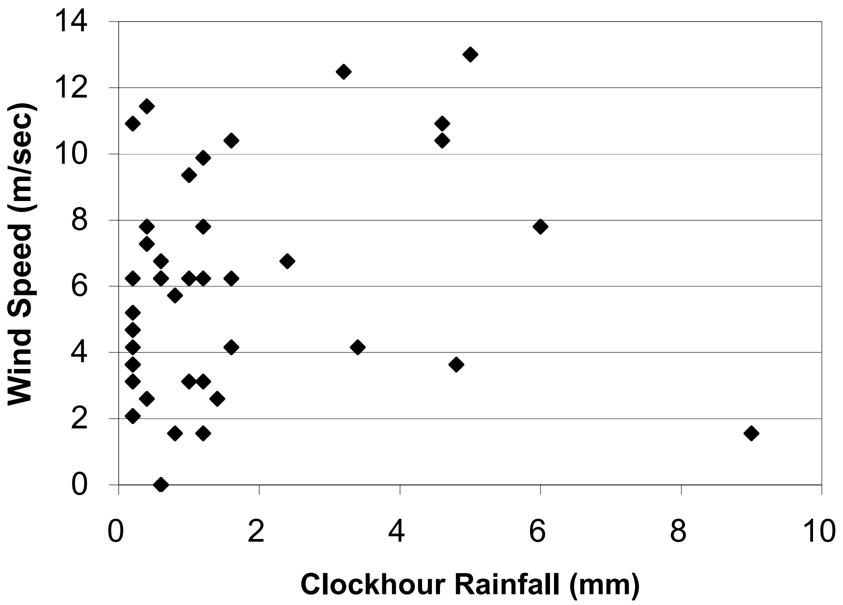


Figure 4.9 Variation of Average Wind speed with Rainfall (Oct'98-Sep'99)

Choi (1994) carried out a detailed analysis of extreme wind speeds at the test site (Sydney Airport) and concluded "wind speeds for higher rainfall intensities have lower values than those for smaller rainfall intensities."

Lacy (1977) measured mean wind speed during rain at Tredegar and these varied from 4.5 to 10.3 m/sec, with an average of 7.4 m/sec. He also carried out similar measurements at Garston, with mean wind speeds between 1.8 and 5.5 m/sec, with an average of 4.3 m/sec.

Murakami (1987) carried out a detailed study of wind speeds in 5 cities in Japan over the period 1961-1980. He found that the <u>maximum</u> wind speeds during rain (greater than 5 mm per hour), which were exceeded 50% of the time, varied between 8 m/sec and 10.6 m/sec. He also found that the <u>maximum wind</u> speeds during rain (greater than

5 mm per hour), which were exceeded 10% of the time, varied between 10.3 m/sec and 14.9 m/sec.

4.4.2 Combination of Wind and Rain at Test Site

It was not possible to associate wind speed with rainfall amounts for the test site records analysed by the author for the period 1992 – 1998, since rainfall amounts were recorded hourly and wind speeds 3 hourly. It is possible however to infer from this data the probability of winds greater than 4 m/sec being associated with hourly rainfall amounts greater than 2.5 mm. These values were chosen because they represent fairly low threshold levels of wind and rain and enable comparison to be made with extensive analysis carried out by the Bureau of Meteorology at the Observatory Hill site between 1950 and 1959.

Based on the data presented above it is possible to say that for any one hour of rainfall the probability of precipitation coming from the south and being greater than 2.5 mm, with an accompanying wind speed greater than 4 m/s (≈16 km/hr) is equal to 5.7% (0.184 (Pr. Rainfall > 2.5 mm/hr) × 0.50 (Pr. wind speed > 4 /s) × 0.62 (Pr. Wind from south). Similarly the probability of 2.5 mm of precipitation coming from the north is 3.5%.

These figures can be compared with those prepared by the Bureau of Meteorology at Observatory Hill for the period 1950 to 1959 which indicate that, for rain of intensity greater than or equal to 2.5 mm with wind speeds greater than or equal to 4m/sec, 5.9% of the average annual hours of rainfall (cf. 5.7%) came from a southerly direction and 2.6% (cf. 3.5%) from a northerly direction (Bureau of Meteorology, 1979).

In simple terms what this means is that if it is raining at the test site then there is only approximately a 6% chance that the rain will have an average intensity greater than 2.5 mm per hour and that the wind speed at the same time will be greater than 4 m/sec (8 knots) from a southerly direction. If specimens are orientated towards the south this means that if one adopts the above thresholds of rainfall intensity (2.5 mm per clock hour) and wind speed (4m/sec) then rainfall will be effective in causing erosion only 6% of the time.

4.5 Driving Rain Index

4.5.1 General Theory

In 1943-44 measurements by Chr. A.C. Neil (Reported in Lacy, 1965) indicated that wind driven rain was about 8% of the total rainfall at wind speeds less than 6 m/sec rising to nearly 40% at speeds of 10 m/sec. This means that the amount of rain striking a vertical surface varies according to the cube of the wind velocity, but takes no account of varying rainfall intensities.

In order to quantify the amount of rain impacting on a vertical surface Hoppestad (1955) introduced the idea of a "driving rain" index, which was the product of rainfall and the wind speed. Hoppestad produced maps of driving rain indices for Norway and this was followed up by Lacy and Shellard (1962) who produced similar maps for Great Britain. The unit of driving rain indexes is $m^{-2}sec^{-1}$. This early work by Lacy and Shellard was non-directional and assumed that there was a constant relationship between average annual wind speed and wind speed during rain.

Whilst these driving rain roses were a useful indication of the degree to which different facades were exposed to driving rain they did not directly indicate the amount of water impacting on the façade. Lacy (1965) developed a theoretical relationship between the two based on rainfall of a constant drop size passing through wind of a constant velocity. His relationship between the actual rainfall intensity (I), the measured rainfall intensity (I_m) and the rainfall intensity normal to a vertical surface (I_n) can be derived as shown in Figure 4.10 (b), where "v" is the terminal velocity of the raindrops and "u" is the wind speed. Mathematically

$$I_n = I \times \sin\theta$$

$$I_m = I \times \cos\theta$$

$$\text{Therefore } I_n = I_m \tan\theta$$

But since $\tan\theta = u/v$

$$I_n = I_m \times \frac{u}{v} \qquad \text{..........}(4.6)$$

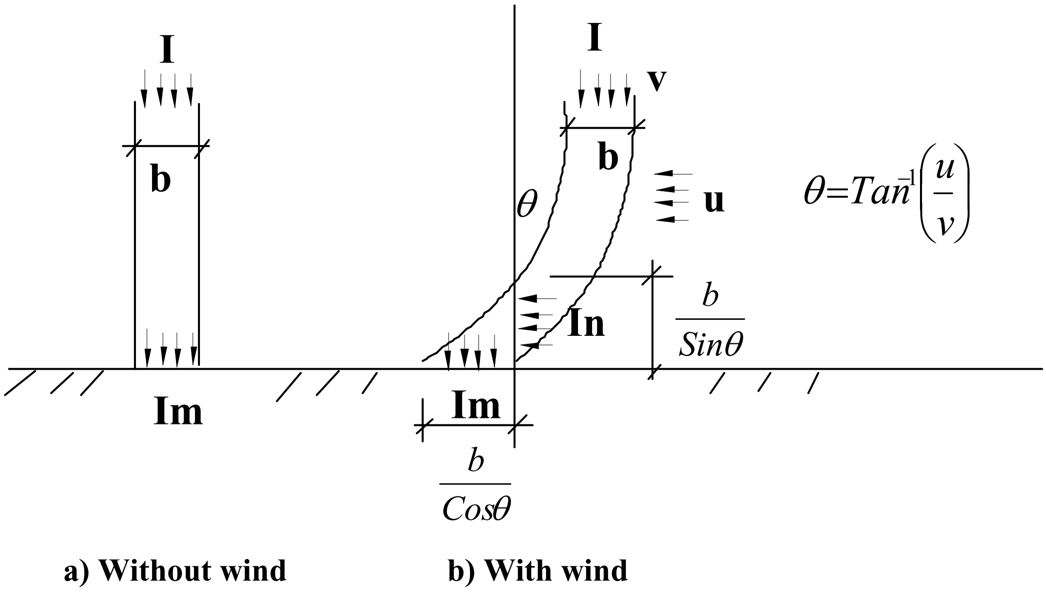


Figure 4.10 Relationship Between Measured and Normal Rainfall Intensity

Lacy then established a relationship between terminal rainfall velocity (v) and measured rainfall intensity (I_m) based on the following

1. The empirical relationship between rate of rainfall (I_m) and median drop size (d_{50}) developed by Laws and Parsons (1943)

$$d_{50} = 1.238 \times I_m^{0.182} \qquad \text{……….(4.7)}$$

2. A relationship between raindrop diameter and raindrop terminal velocity found by Best (1950), assuming uniform drop size

$$v = 3.9 \times d_{50}^{0.676} \qquad \text{……….}(\mathit{4.8})$$

Combining these two relationships we get

$$v = 3.9 \times d_{50}^{0.676} = 3.9 \times (1.238 \times I_m^{0.182})^{0.676} = 4.505 \times I_m^{0.123} \qquad \text{………..}(\mathit{4.9})$$

Substituting Equation 4.9 into Equation 4.6 gives the following relationship between the rainfall intensity normal to a vertical surface (Driving Rain) and the rate of rainfall measured on the ground for different wind velocities

$$I_n = 0.222 \times u \times I_m^{0.877} \qquad \text{……….(4.10)}$$

where

I_n = Rainfall intensity normal to vertical surface (mm/hr)

I_m = Measured vertical rainfall intensity (mm/hr)

u = Wind speed (m/sec)

This relationship is plotted as Figure 20 in Lacy's paper, which is reproduced here as Figure 4.11.

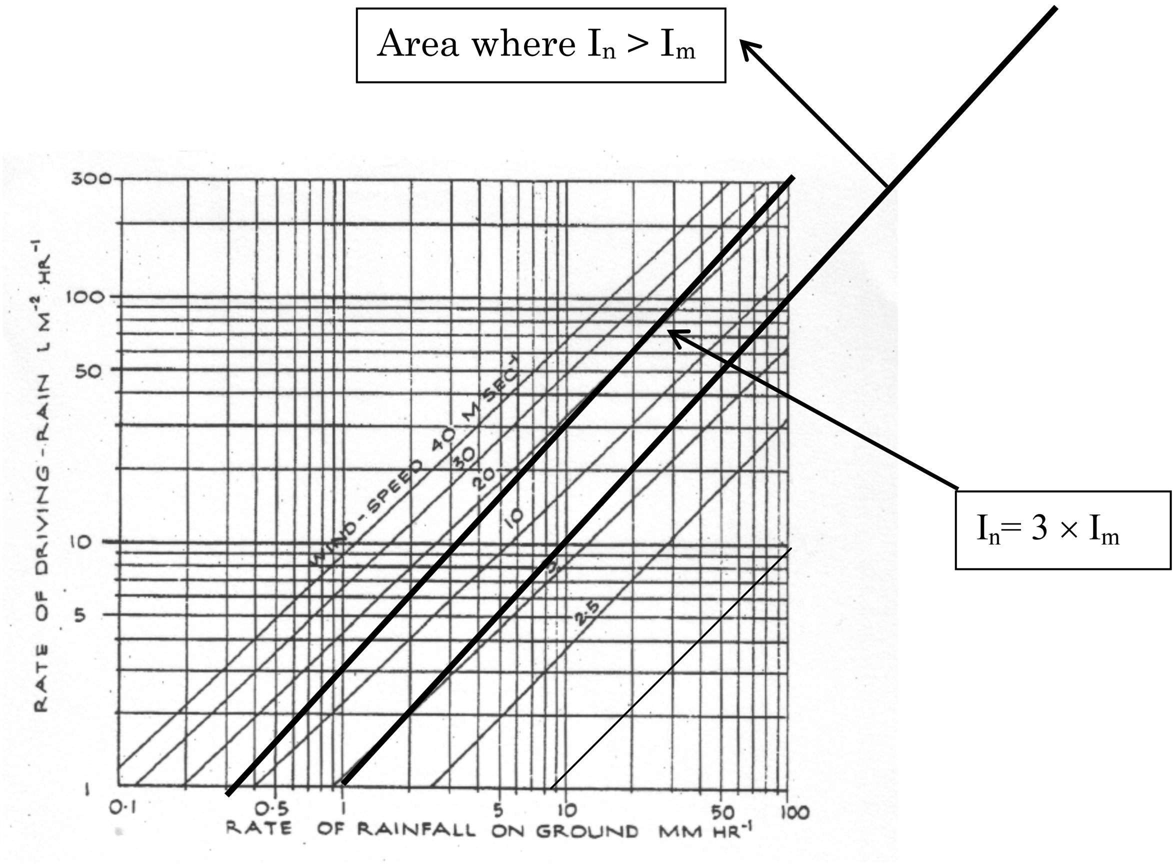


Figure 4.11 Relationship Between Driving Rain and Rainfall (Lacy, 1965)

Note that the driving rain (I_n) is greater than the measured rain (I_m) if the wind velocity (u) is greater than the raindrop terminal velocity (v) i.e. if θ is greater than 45°. The region in which this occurs is plotted on Figure 4.11 and occurs when the wind velocity is greater than about 5-10 m/sec for all rainfall intensities. Note also that for almost all rainfall rates the driving rainfall is at least 3 times the measured rainfall for wind velocities greater than 20 m/sec.

Equation 4.10 gives I_n in mm/hr with I_m in mm/hr and u in m/sec. If I_m is expressed in m/hr the factor become 222 instead of 0.222

For a rainfall rate of 50 mm/hr Equation 4.10 can be approximated by Equation 4.11, assuming I_m is expressed in metres

$$I_n = 137 \times u \times I_m \qquad \ldots\ldots\ldots(4.11)$$

For a rainfall intensity of 100 mm/hr a factor of 125 will give a good fit, and for 25 mm/hr the factor is 150. The multiplication factor will be referred to henceforth as the "Driving Rain Factor" (DRF) and the product of wind speed (u) and measured rainfall intensity (I_m) as the "Driving Rain Index" (DRI).

The volume of driving rain in an hour period per square metre of wall is equal to I_n so we can re-write Equation 4.11 as

Vol. of Driving Rain ($l/m^2/hr$) = DRF × Hourly Driving Rain Index (m^2/sec) …...(*4.12*)

If the total driving rain index for a period is defined as the sum of the hourly driving rain indices then Equation 4.12 becomes

Vol. of Driving Rain for Period (l/m^2)= DRF × Total DRI (m^2/sec) for period ….(*4.13*)

4.5.2 Driving Rain Factor (DRF)

Lacy, (1965), compared the values of driving rain (calculated using equation 4.10 (i.e. $I_n = 0.222 \times u \times I_m^{0.877}$) with the values of driving rain indices (Σ ($u \times I_m$) for 75 storms at Garston lasting 10 hours or more. He found that "*For these 75 storms, which occurred during the 16 years 1948-1963, the mean rate of rainfall on the horizontal was 1.18mm/h, the mean calculated driving rain in each storm was 7.67 mm and the mean driving –rain index 0.0373 $m^2 sec^{-1}$. From this it appears that a driving rain index of 1 m^2 sec^{-1} corresponds to 206 mm* [7.67/0.0373] *driving-rain on the vertical*". This corresponds to a driving rain factor of roughly 200, the value that is typically quoted.

However this was obtained from a case where the mean rainfall was only 1.18 mm/hr, which is very low. Putting I_m =1.18 directly into Equation 4.10 gives a DRF of 217, which is close to the 206 which was based on the summation of hourly records.

Henriques (1992) noted that Lacy's assumption of a factor of 206 was based on calculations rather than experiments. He also noted that if the 10 m high wind speed was used in Lacy's method the DRF would have to be correspondingly lower to account for the increase in wind speed with height. Using his transformation of wind speed with height, and assuming Lacy's calibration was carried out with wind speeds measured at 2 metres, a DRF of 200 becomes roughly 150.

Henriques carried out experiments using free standing and wall mounted gauges (Henriques, 1993) and came to the conclusion that

"- *the relation between the driving rain indices and the amount of water collected in free standing driving rain gauges was 1* m^2/sec *= 145 litres/*m^2/hr [DRF = 145]" (Henriques, 1993). *The correlation coefficient for this relationship was 0.91.*

These results were based on the standard 10 metre high recorded mean wind speeds. The total amount of rain during the experimental program was 680 mm and the mean wind speed was 4.5 m/sec.

In Henriques work all wind velocities were resolved in a direction normal to the gauge, with θ representing the angle of the wind to the normal. There was considerable scatter at low values of V Cos θ (Wind velocity resolved normal to gauge) when the analysis was separated into V Cos θ groupings. At a value of V Cos θ of 2 the regression relationship was 1 m^2/sec = 116 litres/m^2 or a DRF of 116. (Table 4.5)

The experiments of Henriques indicated that there was virtually no difference between hourly driving rain indexes based on mean wind speed over the hour and total hourly rainfall and the sum of indexes based on 5-minute intervals of rainfall and mean wind speed.

Table 4.5 Variation of DRF with Vcos θ (Henriques, 1993)

V×Cos θ	Driving Rain Factor	Correlation Coefficient	Occurrences
1	153	0.818	821
2	116	0.815	749
3	139	0.892	571
4	128	0.863	478
5	138	0.875	297
6	148	0.944	156
7	162	0.895	88
8	155	0.954	42
9	138	0.925	22
10	119	0.993	3
All	145	0.910	3227

Directional driving rain roses produced by Lacy in 1976 (Lacy, 1976) were based on hourly rainfall amounts and hourly mean wind speed. These indicated that in Great Britain the wind speed during periods of rain was higher than the average annual wind speed but that the ratio varied throughout the country. Prior and Newman (1988) note that driving rain indices based on mean hourly wind speed data and hourly rainfall rain can be up to 30% higher than those bases on mean annual wind speed and mean annual rainfall.

4.5.2.1 Driving Rain Indices at Test site

Hourly wind and rain records at the test site were obtained for the period October 1998 to October 2001.

Analysis of these records to determine the driving rain indices for each month of record was carried out on a spreadsheet. For every hour of rainfall the mean wind speed for that hour was recorded, resolved into compass octants, and multiplied by the mean wind speed for that hour. The totals for each month were then plotted as wind driven rain roses for each month of the period (Note that in Appendix D these are plotted in units of knot-m/sec whereas the sample shown in Figure 4.12 is in m^2/sec).

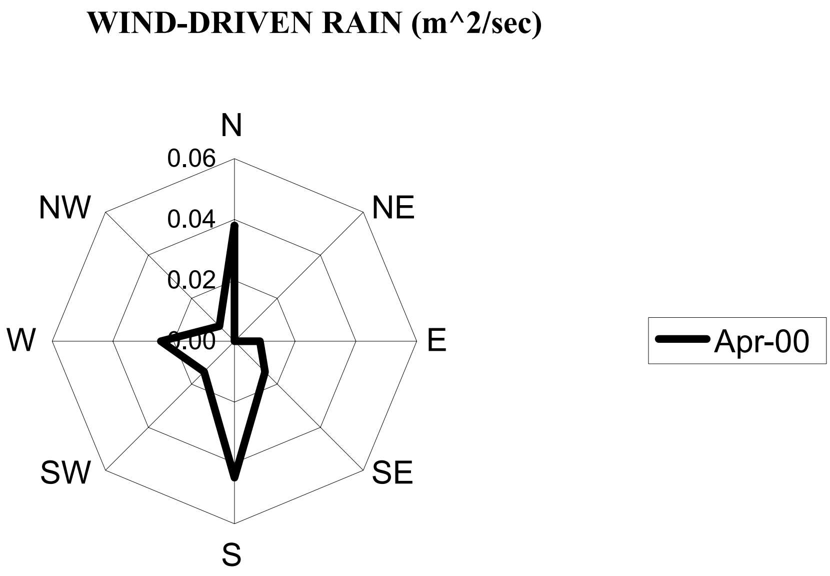


Figure 4.12 Sample of Wind-Driven Rain Rose

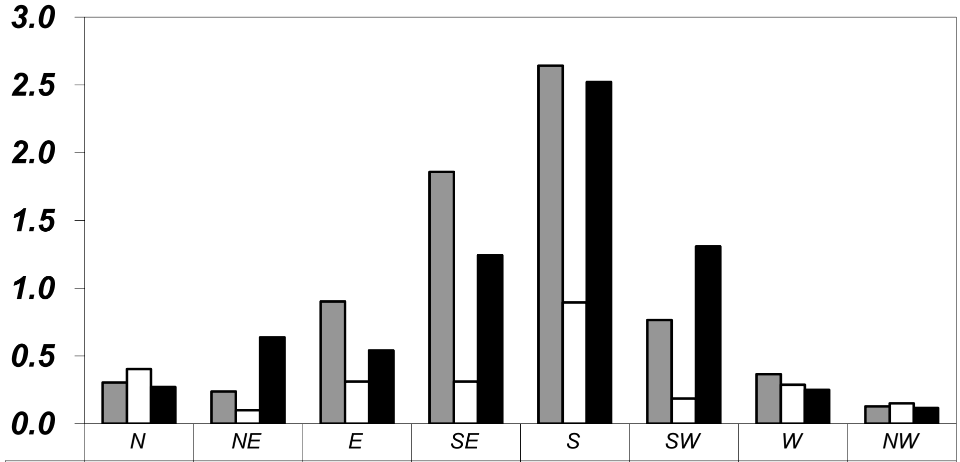
A summary of the wind driven rain indices for the three years of records is given in Table 4.6 with yearly graphs shown in Figure 4.13. Detailed monthly graphs are shown in Appendix B.

The results show that quite clearly the majority of wind-driven rain at the test site comes from the southern side. This was obvious during preliminary testing when some specimens were aligned north and some south. The specimens that were aligned to the north had insufficient erosion to measure accurately and from then on all specimens were aligned to the south.

Table 4.6 demonstrates that the driving rain index at the site varies from month to month, but generally reflects the tendency for higher rainfall to occur in the first half of the year. Values vary from a consistent low of less than 0.1 m^2/sec in September to a maximum of 0.933 in May (from the south). The latter corresponds to a value of around 150 litres/m^2 if a middle value DRF is assumed. Total values for the year (Figure 4.13) are highest from the south side and correspond to a maximum value of around 400 litres/m^2 per annum assuming a DRF of 150.

Table 4.6 Summary of Wind Driven Rain Indices Calculated for Site

Month	Max. W.D.R.	Comments
October	0.344 (S)	Max occurs from E, SE and S in 1999. Significantly greater values in 1999.
November	0.375 (NE)	Max occurs from E and NE in 2000. Significantly less in other years.
December	0.118 (N)	Fairly uniform (0.08 – 0.102) from south all years. Max in 1999 from N with zero in other years from this direction
January	0.765 (SE)	Strong values 1999 and 2001 from E, SE and S with minimal values from N, SW, W and NW all years
February	0.733 (S)	Minimal values from SW, W and NW all years. Low values N, NE and E. Values around 0.2 SE and S except for max of 0.733 from S in 1999.
March	0.838 (S)	Markedly higher values in 2000. Rest all fairly low except 0.38 from SE in 2000
April	0.598 (S)	Similar to January. Strong values in 1999 and 2001 from SE, S and SW quarters
May	0.933 (S)	Minimal values most years except for very high values from S and SW (0.625) in 2001
June	0.208 (S)	All values minimal except for W (1999) of 0.186 and max
July	0.478 (SE)	Values over 0.3 from E, SE and S in 1999. 0.2 from SW in 2001 and) 0.17 from W in 1999. Consistently minimal from N, NE and NW
August	0.212 (SW)	Low except for max (1999), 0.12 from SW in 2001 and 0.17 from S in 1999
September	0.157 (S)	Consistently very low except for maximum
Annual	2.643	Despite yearly variations shows significantly higher values from southerly directions



	N	NE	E	SE	S	SW	W	NW
Yr 1	0.304	0.236	0.903	1.858	2.643	0.764	0.365	0.128
Yr 2	0.403	0.099	0.309	0.309	0.895	0.185	0.288	0.149
Yr 3	0.270	0.636	0.539	1.242	2.522	1.307	0.248	0.117

Figure 4.13 Annual Wind Driven Rain Indices (Oct. '98 – Oct. '01)

4.5.2.2 Calibration of Driving Rain Index

In order to correlate the performance of the specimens in the field with those in the laboratory the amount of water impacting the specimens needed to be determined based on the driving rain index for the period of exposure of the specimens. It was therefore necessary to install a rainfall collector at the test site to determine the driving rain factor relevant to the site.

The collector consisted of a "periscope" made out of 150mm diameter PVC pipe (Figures 4.14 and 4.15). The inlet was aligned perpendicular to the south at the level of the specimens. Leading from the entrance pipe was a 90° bend attached to a length of pipe that reached the ground. The bottom of the pipe was sealed. The water that collected in the pipe was collected periodically (every one to two months) and emptied into a graduated flask. The amount of water collected was then recorded in litres. The rain and wind records collected during the recording period were analysed on a spreadsheet to determine a driving rain factor for the period of record.

Figure 4.14 Overall View of Experimental Frame

Figure 4.15 Close up view of "Periscope" Rain Collector

Each 100 ml of rain collected in the collector corresponded to 5.66 mm of wind driven rain (inlet diameter was 150 mm). I_n was then calculated by multiplying the amount of rain collected in ml by 0.0566. I_m was taken from the sum of the recorded rainfall records for the period.

The driving rain index was taken by summing the product of the hourly wind speed in m/sec by the hourly rainfall in m/sec, with the wind speed resolved normal to the face of the collector. A factor was applied to change the wind speed from knots to m/sec and to change the rainfall from mm to m. The driving rain factor was then obtained by dividing the driving rain (I_n) by the driving rain index

A total of 14 calibrations were attempted throughout the two-year period, but because of some difficulties (eg spilling water, too little rain) only 11 proved acceptable for analysis. The results of the analysis of these eleven samples are shown in Table 4.7, with the resultant values of DRF shown graphically in Figure 4.16. Full details of the analysis appear in Appendix C.

The analysis indicated driving rain factors between 50 and 179, with the mean DRF being 116. The standard deviation of the sample was 35 (COV = 31%) and the 95% confidence limits were 91 and 141.

The data was also analysed using a multiplicative factor for wind velocity and a power factor for rainfall but although some improvement in the coefficient of variation was possible (down to 29%) this slight improvement was not felt to be sufficient to warrant the more complicated analysis in future work.

The value of 116 is low compared to the mean value measured by Henriques (1993) for a free standing rain gauge (145) and the value of Lacy (Corrected for height = 150). It should be noted however that there was considerable variation in the DRF with wind velocity in the work of Henriques, with values varying from 84 to 170.

Table 4.7 Experimental Driving Rain Factors

Series No.	Period	I_n (mm) (A)	I_m (mm)	$\sum u \times I_m$ (m^2/s) (B)	Average Wind Speed (m/s)	Driving Rain Factor (A/B)
1	16/7/99 – 10/8/99	9.62	17.80	0.121	7.1	80
2	10/8/99 – 3/9/9	28.86	36.47	0.310	6.4	93
4	18/10/99– 16/11/99	54.5	45.03	0.426	8.2	128
6	15/01/00-23/3/00	222.7	132.2	1.270	8.3	179
8	14/8/00-12/10/00	11.32	16.58	0.119	6.1	95
9	12/10/00-17/11/00	9.91	18.80	0.111	4.9	89
10	17/11/00-7/12/00	13.02	17.29	0.144	7.0	90
11	15/2/01-13/3/01	37.94	23.09	0.266	6.0	143
12	13/3/01-11/4/01	18.4	45.90	0.369	7.6	50
13	11/4/01-16/5/01	150.1	216.3	1.581	8.4	95
14	16/5/01-13/6/01	59.46	46.36	0.364	7.2	163

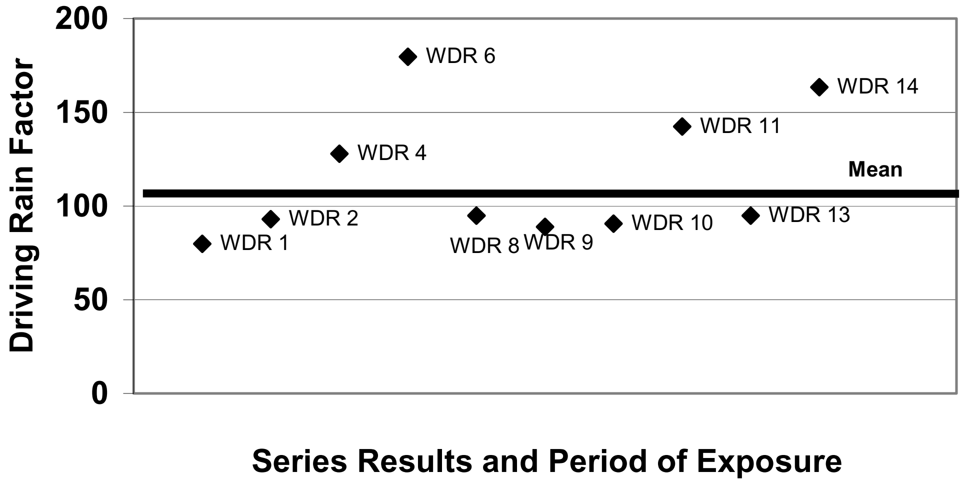


Figure 4.16 Wind Driven Rain Factor for Test Results at Site

Possible reasons for the significant variation in values for DRF were

- Evaporation from tube – no allowance or measurement of evaporation was made but in general it appears that there is no discernible seasonal trend in DRF's.
- Rain splash from entrance to the collector (dependent on wind strength and direction). This could be significant but is difficult to measure.
- Error in resolving driving rain normal to collector face. This error varies depending on incident wind angle and is felt to contribute most of the variation, although no proof of this is available. For this study the traditional method used to determine the amount of driving rain impacting a vertical surface using wind velocity times Cos θ will be used, where θ is the angle relative to the normal.
- Errors though variations in drop size distribution. Again this is thought to be significant but no easy method is available to account for this.
- Variations between wind speed at recording station and wind speed at test site – although both are located at the airport the wind speed recorder is located a reasonable distance from the test site and variations in wind speed could be expected.
- Variations in "catch" with gust wind speed. The DRF is based on mean wind speeds and gust speeds can be significantly greater. Heavy rains are often accompanied by gusts and this could affect results.

The results indicate that the average wind speed during rain was relatively similar for all 11 periods of exposure. The mean of the average wind speed for all tests was 7.0 m/s with the 95% confidence limits 6.26 to 7.74 m/s.

4.5.2.3 Correlation Between Recorded Rain And Measured Rainfall

The results also indicate a significant link between the measured driving rain (I_n) and the rainfall measured on the horizontal surface (I_m). A linear best-fit equation to the data is given in Equation 4.14.

$$I_n = 0.865 \times I_m \qquad \ldots\ldots\ldots\ldots\ldots (4.14)$$

This relationship is plotted in Figure 4.17 along with the 95% confidence intervals. The relationship has a coefficient of determination (r^2) of 68%, meaning that 68% of the variation in measured rain striking a vertical surface can be explained by a variation in the measured vertical rain.

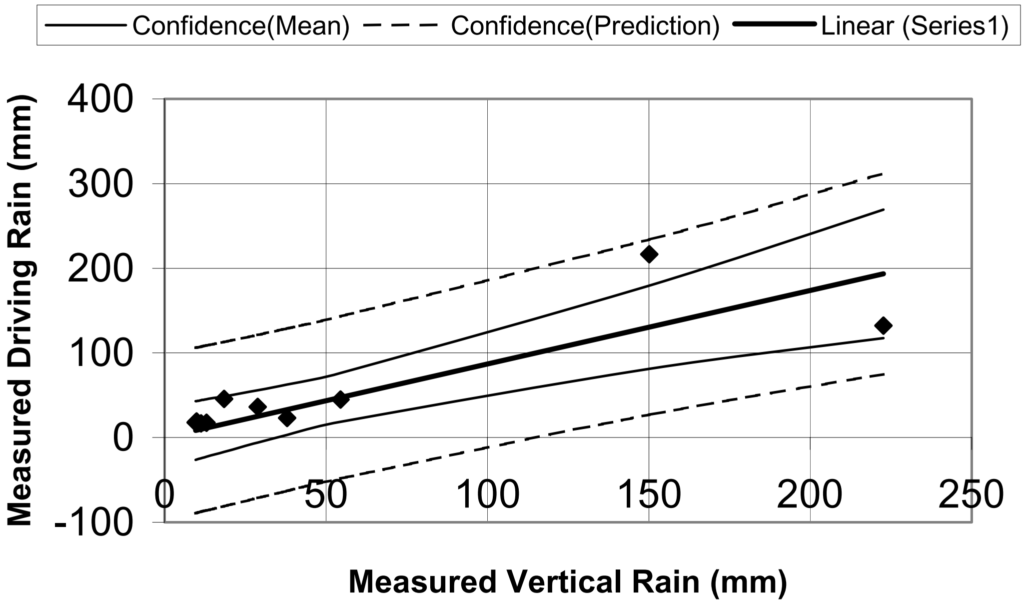


Figure 4.17 Relationship Between Measured Driving Rain and Measured Vertical Rain

4.5.2.4 Variation of Wind-Driven Rain Over Wall Surfaces

The issue of the variation in driving rain over wall surfaces is not considered in this investigation, although the work of Lacy (1965), Newman, Henriques (1993) and Atkinson and Snape (1999) will be briefly discussed here.

Lacy (1965) noted, "*It seems clear therefore that the edges of a building must collect more rain than the rest of the wall.*" He measured driving rain on a two-storey building at Garston, and found that the most exposed walls received only about 25% of the driving rain computed from freestanding gauges. At Cefn Golau Lacy (1977) found that for the west wall of a building the driving rain on the wall was roughly 50% of that measured in a freestanding rain gauge facing west.

Newman (1987) presents the result of work carried out at the BRE into the distribution of driving rain on a gable wall. It is not clear, but this may be the same wall quoted by Lacy. Newman's Figure 10 is reproduced here as Figure 4.18. These figures indicate that the "catch" of a wall can be as low as 19% of that of a free standing rain gauge and that at the extremities of wall values can be about 3 times that amount.

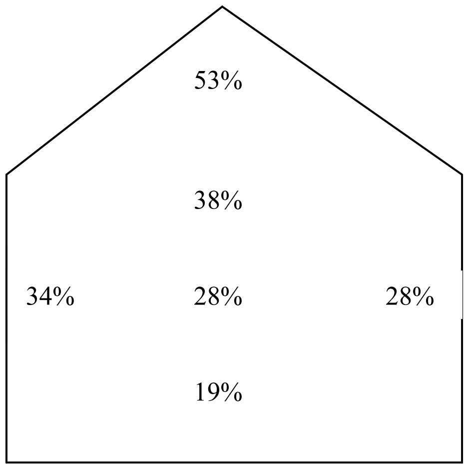


Figure 4.18 Experimental Catch Ratios on Gable End Wall (Newman, 1987)

Henriques (1993) also measured driving rain indices based on rainfall collected in gauges mounted on a two storey building façade. His measurements show that the amounts of water collected on a wall were 58% of the amounts collected in a free standing driving rain gauge. His preliminary results, based on gauges spread about two walls, was that there was a significant variation in driven rain distribution over the walls. His results showed that the rainfall at the top of the walls was 4.6 times that in the centre.

Atkinson and Snape (1999) developed a method of mapping rainfall distribution on facades using rainfall characteristics, but this method is still largely developmental.

4.6 Summary

The erosion of unprotected earth walls appears to be a problem in regions where the annual rainfall is in excess of around 400mm. The first step in predicting erosion is to estimate the amount of driving rain striking a vertical surface based on the wind and rain records relevant to the site.

Rainfall at the site will occur with varying intensity. Typically clock hour intensities will be up to 6 times the five minute intensity, but kinetic energy calculations would seem to indicate that using clock hour values of rainfall will not result in a significant loss of accuracy and even using annual values would appear to underestimate the true value by less than 30% (Prior & Newman, 1988).

Similarly wind is a stochastic process and gust speeds of up to 60% greater than the mean wind speed can be expected in a clock hour period. Whilst this may significantly affect the short-term volume of water impacting a surface it is felt that in the long term the use of mean wind speeds will be adequate for prediction purposes.

As a first approximation, the amount of rain striking a vertical surface can be correlated with the product of the mean annual rainfall and the mean wind speed during rain. Mean wind speeds during rain in the experimental work carried out by the author were around 7 m/sec and this is similar to values obtained both in America and England. Since this mean wind speed is relatively constant for a given site there is therefore a reasonable relationship between rain impacting a vertical surface and rain falling on the ground. In the case of the experimental work presented here rain striking the south facing specimens was found to be approximately 87% of the rainfall measured on the ground.

A better method of calculating the amount of rain striking a vertical surface is to use a driving rain index, largely pioneered by Lacy, based on hourly wind and rain records. This is the method adopted in British Standard BS 8104 "Methods of Assessment of Exposure to Wind-Driven Rain". This method involves summing the product of hourly rainfall times wind speed resolved normal to the surface. The result is normally expressed on an annual basis, with driving rain indices of 3- 7 m^2/sec/yr being considered as moderate exposure, with values greater than 7 m^2/sec/yr being considered severe.

In this study rain records at the test site near Sydney's International Airport were collected for a three-year period with annual Driving Rain Indices close to the severe range. Monthly results indicated a strong emphasis on wind driven rain from the southerly direction.

According to Lacy the amount of water impacting a vertical surface can be related to the driving rain index by means of a Driving Rain Factor, which varies dependent on what height the wind speed is measured. Lacy quotes a DRF of 200, and this value is adopted in BS 8104 with a correction for height.

The author placed a rain collector at the test site to measure wind driven rain and derived DRF's of between 90 and 150, with a mean value of 116. This should be compared with the value of Lacy, which when corrected for height gives a value of 145 at the test site, since the specimens are roughly 1 metre off the ground. As the results of Henriques indicate, there is expected to be considerable scatter about this value.

In view of the fact that evaporation may have been a factor and the fact that wind speed was not measured directly at the site it is felt that a factor at the upper end of the range (more in line with Henriques) might be more realistic. A Driving Rain Factor of 150 will therefore be assumed in this investigation when relating fieldwork to laboratory testing.

Chapter 5 Laboratory Simulation of Wind Driven Rain

5.1 Introduction

One of the primary aims of this thesis is to develop a methodology whereby the in-situ performance of earth walls can be predicted based on accelerated laboratory tests combined with a characterization of the climatic conditions relevant to the particular site where a building is to be built. The previous chapter has dealt with the characterization of climatic conditions. This chapter will deal with the development of the accelerated weathering test used in the experiments presented in later chapters.

Table 2.1 classifies existing tests into either simulation, accelerated or indirect tests. The classification of the drip tests deserves comment. Whilst in principle the Yttrup test mimics the action of a drop of rain on an inclined surface, the absence of turbulence, the low impact velocity and the higher than average drop size mean that the test is more of an indirect test than an accelerated test. Similar argument applies to the Swinbourne test, only in this case there is no drop at all. One of the biggest drawbacks of these tests is the localized nature of the impact, and varying results could be expected within relatively close distances.

Full simulation tests have been developed by Dad (1985) and Ogunye (1997) based on the work done in the area of soil erosion. Whilst this work is commendable the tests take a long period of time, of the order of two weeks, and the extent that they simulate rain is open to debate. For example there is no variation of intensity, raindrop size or angle of impact during the test period.

In view of the above it was felt desirable to pursue the option of a modified spray test which could be performed in a short period of time, but which would offer some advantages over previous spray test methods, these being

1. Simulation of rain drops rather than a steady jet
2. Introduction of some turbulent action.

5.2 Rainfall Simulation in the Field of Soil Erosion

Simulation of the erosive effects of rain has long been a problem in soil erosion, and many attempts have been made to produce the ideal rain simulator. Hall (1970) listed three fundamental problems encountered in designing a rainfall simulator, namely:

1. *The control of application rates in both space and time.*
2. *The reproduction of drop size distributions observed in different intensities of natural rainfall at the corresponding application rates.*
3. *The reproduction of the terminal velocities of natural rainfall.* (Hall, 1970)

Tossel et al. (1987) expanded this list to 10 problems (characteristics required of a rainfall simulator) as follows

"1. Drop-size distribution similar to natural rainfall given comparable rainfall intensities.
2. Drop impact velocity approximating terminal velocity of natural raindrops.
3. Rainfall intensity representing the geographical region where studies are to be conducted.
4. Uniform rainfall over the study area.
5. Energy characteristics corresponding to natural rainfall for comparable intensities.
6. Rainfall intensity continuous over the storm event.
7. Storm pattern reproduction.
8. Sufficient area of coverage.
9. Drop impact angle near vertical.
10. Site to site portability." (Tossel et al., 1987)

A common feature of many of the early attempts to simulate rain was the use of commercial nozzles. With little available information on drop size distribution, simulation was reduced to reproducing the rainfall intensity typical of the area. Following the experiments by Laws in 1940 (Laws,1940), in which he showed that erosion could in some cases be proportional to the cube of the raindrop diameter

(1200% increase for increase in average drop size from 1 mm to 2.25 mm), there was more focus on reproducing the drop size distribution in rainfall simulators.

Early attempts by the Soil Conservation Service in the US involved spraying water with special nozzles (Type F) up 3 metres into the air. However, as can be seen from Figure 5.1 (Hall, 1970), to achieve the terminal velocity of most raindrop sizes the spray would have to reach a height of around 10 metres. Quite obviously this was impractical and recent efforts in rainfall simulation (eg Tossell et al., 1987) have centred around using sprinkler nozzles under pressure, producing drop velocities similar to the terminal velocities of rain drops and rain drop size distributions typical of the intensity required.

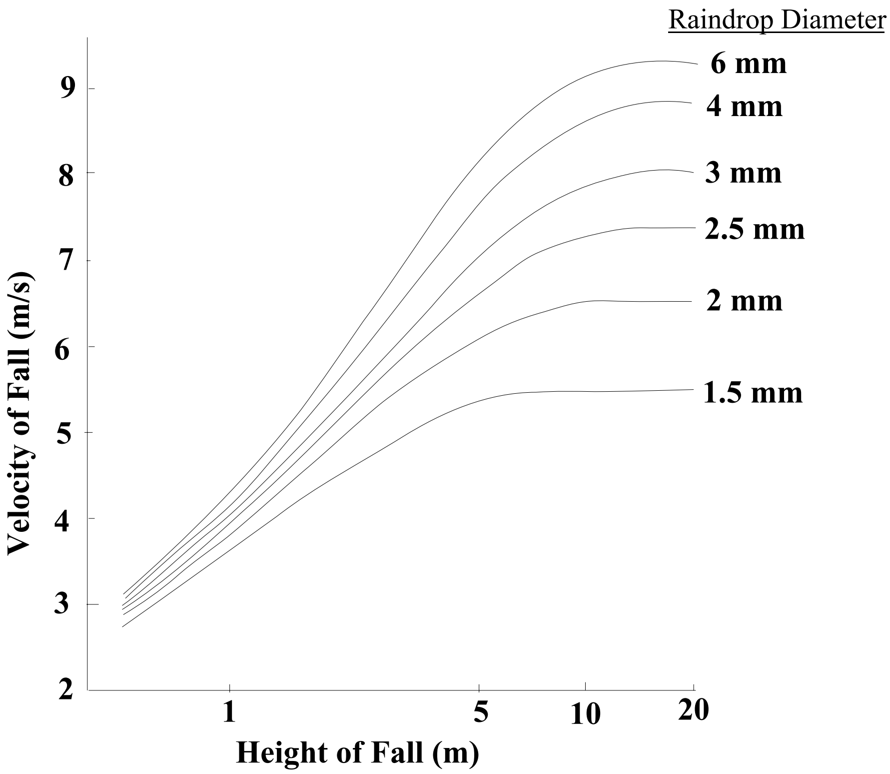


Figure 5.1 Required Fall Heights to Achieve Terminal Velocity (Hall, 1970)

5.3 Differences Between Soil Erosion Testing and Testing for Earth Wall Durability

The three problems mentioned by Hall (1970) reflect the general dependence of soil erosion on three parameters, viz, rainfall intensity, drop size and the terminal velocity of rain drops, or as expressed mathematically

Soil Erosion = f (Rainfall Intensity, Drop Size, Terminal Velocity) ……….(*5.1*).

In the case of soil erosion the angle at which the drops hit the ground appears to be relatively insignificant in relation to these three parameters, whereas in the case of earth wall erosion the angle at which the raindrops strike the wall is of major significance. Firstly, it is an indicator of the intensity of rain striking the wall, secondly, it is an indicator of the impact velocity of the rain drops striking the wall and thirdly, there is some evidence (examined in Chapter 6) which suggests that there is a direct link between impact angle and erosion, other things being equal. The angle at which the raindrops strike a wall (θ) is dependent on the terminal velocity of the raindrops (v) and the wind speed (u), and varies both temporally and spatially during a storm. This angle can vary from 0° in the case where there is no wind, to angles of around 70°.when the wind speed is around 15 m/s.

During a given storm the intensity, raindrop size, impact angle and impact velocity all change with time, making it difficult to simulate in a simple test. For that reason it is necessary to use "representative" values of these variables. In addition there is evidence to show that this erosion is a function of time, at least in laboratory testing.

In order to speed up (accelerate) test times one or more of the above non-material factors must be amplified. In the case of spray testing this is usually spray intensity.

5.4 Accelerated Testing

Bearing in mind that the life of a building is usually in excess of 50 years it is obvious that time is the most crucial element in the erosion of earth walls. For practical reasons any testing must be carried out within a much shorter time frame than the life of a building. Such testing is referred to as "accelerated" testing. Shortening the time frame however has to be accompanied by an increase in the intensity of the degradation factors, and the choice of a suitable test will often lie in the decision as to how much intensification is possible without altering the degradation mechanism.

ASTM E632 (1982) sets out a standard practice for "*developing accelerated tests to aid prediction of the service life of building components and materials*". ASTM E632 recognises the difficulty of developing accelerated ageing tests to predict long-term in-situ performance but notes that despite these shortcomings, they are used to provide needed durability data. Some of the shortcomings it identifies are

"3.1.1 The degradation mechanisms of building materials are complex and seldom well understood,
3.1.2 The external factors that affect performance are numerous and difficult to quantify, so that many existing accelerated procedures do not include all factors of importance and those included seldom relate quantitatively to in-service exposure, and
3.1.3 The materials are often tested in configurations different from those used in-service. "(ASTM E632, 1982)

ASTM E632 defines a test in which building components are subjected to accelerated degradation factors as an "accelerated ageing test", and defines four procedures for developing predictive service life tests. They are

Stage 1 – Problem Definition – this involves setting out what the test should do and the degradation factors that should be included in the ageing test.

In this investigation the aim is to formulate an accelerated ageing test which will predict the performance of earth wall specimens subjected to wind-driven rain in the field. At this stage the prediction is limited to field specimens placed in a test rack. Later on this work will be extended to the prediction of the performance of earth walls in buildings.

The only degradation factor considered in this investigation will be wind-driven rain. Although it is recognized that factors such as acid rain or sulphate attack may be additional factors, which could contribute to the erosion of earth walls, such factors are not covered in this investigation.
The last stage in problem definition is to postulate how the degradation characteristics of in-situ performance can be induced by an accelerated ageing test. The assumption in this investigation is that an accelerated spray test will provide an adequate representation of the in-situ resistance of earth walls to driving rain.

Stage 2 – Pre-Testing –The aim of pre-testing is to confirm the effect of degradation factors on the degradation mechanisms. In this investigation the degradation factor, wind-driven rain, has many characteristics as indicated in Chapter 4, and the testing carried out in Chapter 6 will examine the extent to which changes in these characteristics effect the degradation mechanism.

Stage 3 – Testing - Testing involves the comparison of the degradation obtained by both in-service and the accelerated ageing test. Chapter 7 will present the results of three years of field testing of samples that were subjected to accelerated spray testing prior to placement in the field.

Stage 4 – Interpretation and Reporting of Data – this involves the development of a mathematical model of degradation, using this model to compare the performance of in service tests with the accelerated ageing tests. This will be presented in Chapter 8.

5.5 Selection of Laboratory Test

Soon after commencing research into the behaviour of earth walls in 1988, the author had a spray testing rig built at UTS according to the Bulletin 5 specifications dealt with previously. At that time (and to this day) all earth wall buildings were required by the Building Code of Australia to be tested using the standardised rig given in Bulletin 5. The nozzle was purchased from the National Building Technology Centre who publishes Bulletin 5. A photo of the test setup is shown in Figure 5.2 and a close-up of the nozzle is given in Figure 2.6.

The test rig consists essentially of a plastic bath, which is divided into two sections by a Perspex weir. The specimens are mounted behind a thin steel plate and are exposed to the spray through a 150 mm diameter hole. The pump has a capacity of 400 W and an oil filled pressure gauge, reading to 180 kPa, measures the pressure immediately adjacent to the nozzle. The special Bulletin 5 nozzle is placed on a cross bar, with the end located 470 mm from the face of the specimens.

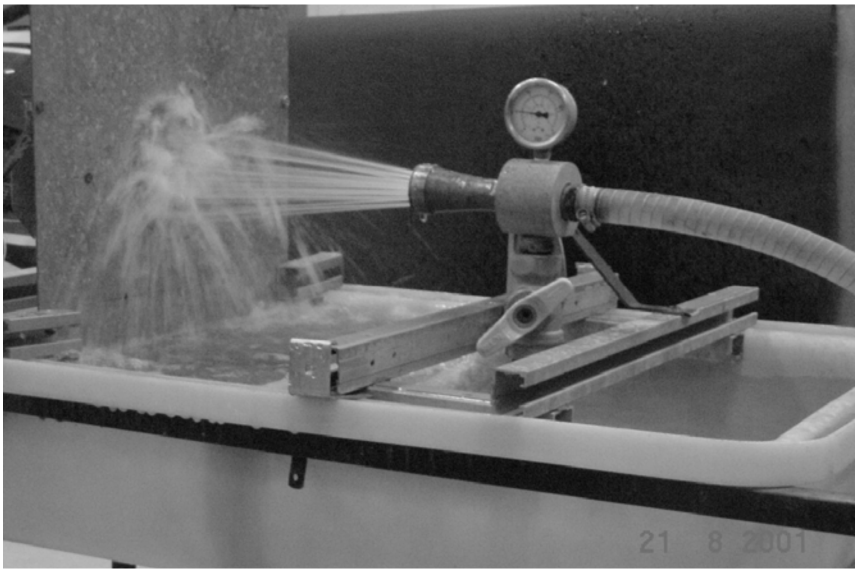


Figure 5.2 UTS Spray Test Rig with "Bulletin 5" nozzle

Water is then pumped through the nozzle onto the specimens, with the return water flowing over the weir into the first chamber, and then out though a discharge pipe. Filter cloth is draped over the weir to reduce transfer of sediment into the first chamber. The outlet also has a strainer fitted to reduce sediment being recycled. Figure 5.3 shows the spray impacting a specimen

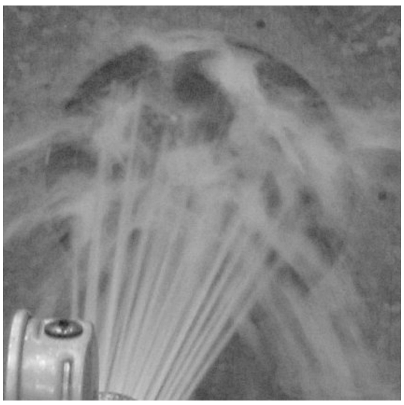


Figure 5.3 Spray Pattern of Bulletin 5 Nozzle

The Bulletin 5 test delivers water at a flow rate of around 30 litres /minute at a velocity of around 10 m/s. This is equivalent to about 85 years of Sydney's rainfall in a period of one hour.

Following extensive testing with this set-up it was felt that the standard nozzle did not adequately model the impact process of driving rain. The nozzle has a number of individual jets, which work independently, and produce a series of bored holes in weak samples, as seen from Figure 5.4. In addition the holes clogged up frequently and required frequent changing of water.

It was also felt that the fact that natural rain was by nature turbulent, and was composed of drops rather than water jets, necessitated the adoption of a new test if correlation was to be made between field and laboratory results.

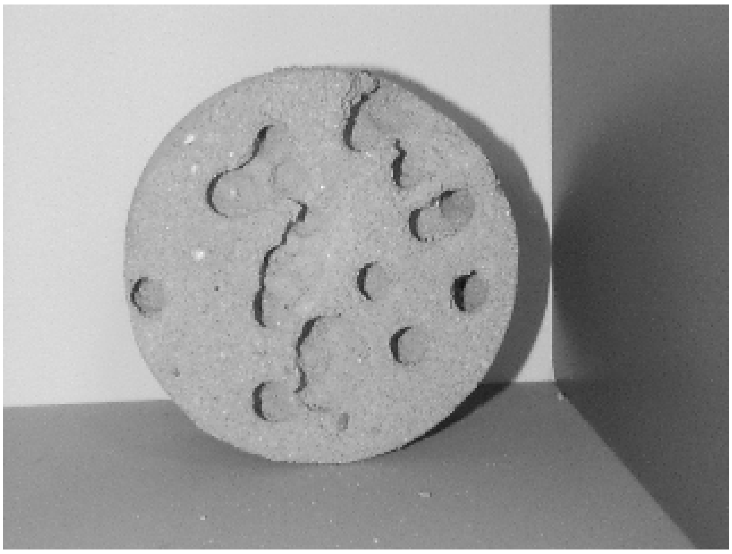


Figure 5.4 Weak Specimen showing Series of Bored Holes

The requirements for a new test were that it should

- be relatively inexpensive
- have a relatively narrow angle of spray
- be replicable
- be able to reproduce drop sizes of the order of those experienced during rain
- have drop velocities of the order of the impact velocity of raindrops

- be simple to set up and
- not take long to perform

In the end, after much experimentation, it was decided that a spray test based on the Bulletin 5 apparatus was the most practical, but using a nozzle which produced a turbulent spray pattern.

Spraying Systems Co were approached with the above criteria and they suggested their "Fulljet" narrow angle spray nozzles. These nozzles consist of a single bore with a rotating internal vane inside which produces drops of the order of 1-3 mm diameter.

Figure 5.5 shows a cross section through a nozzle shown in the Spraying Systems brochure.

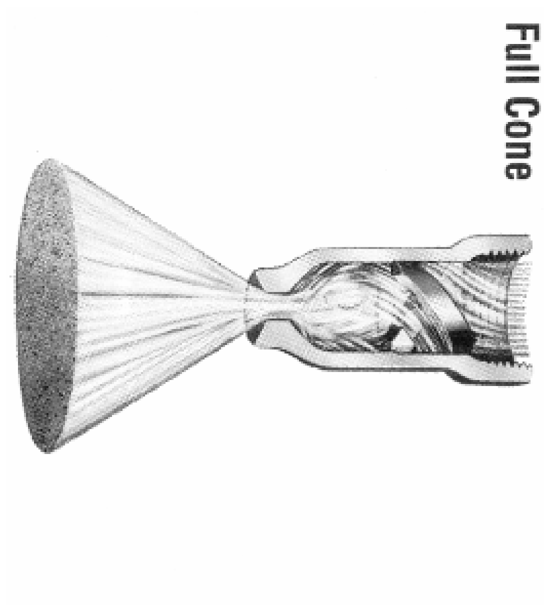


Figure 5.5 Diagrammatic View of VeeJet Nozzle

The 15 degrees spray angle nozzles were chosen with the spray diameter (125 mm) slightly less than the Bulletin 5 template (150 mm diameter) at a distance of 470 mm.

The above configuration was used in the initial set of testing. With later tests however, the distance between the nozzle and the specimens was reduced to 340 mm to ensure all of the water impacted the specimens. This reduced the impact area to a 90 mm diameter, which in general leads to erosion craters of around 120 mm diameter. Within that 120 mm diameter the intensity could be expected to vary significantly, but for comparison purposes only the average intensity over the whole area will be referred to in this thesis.

Four nozzle diameters were purchased, 3.2 mm (model 1530), 4.4 mm (Model 1550), 5.6 mm (Model 1590) and 7.5 mm (Model 15150). They have a quoted velocity efficiency of 94 % at 140 kPa. Initially only the first three nozzles were used, but in order to examine the effect of drop size a further nozzle (15150) was ordered.

In general drop sizes for these nozzles depend on

1. Nozzle size – an increase in flow rate will increase the drop size, for a constant pressure.
2. Pressure – an increase in pressure will reduce the drop size.

Volume Median Diameters (VMD's) for the nozzles, supplied by Spraying Systems Co, are given in Table 5.1. The VMD is a value where 50% of the total volume of liquid sprayed is made up of drops with diameters larger than the median value and 50% smaller

Table 5.1 Drop Sizes for Nozzles

Nozzle No	Pressure (kPa)	VMD (mm)	Pressure (kPa)	VMD (mm)
1530	70	1.10	150	0.97
1550	70	1.13	150	1.00
1590	70	1.16	150	1.03
15150	70	2.45	Not Available	Not Available

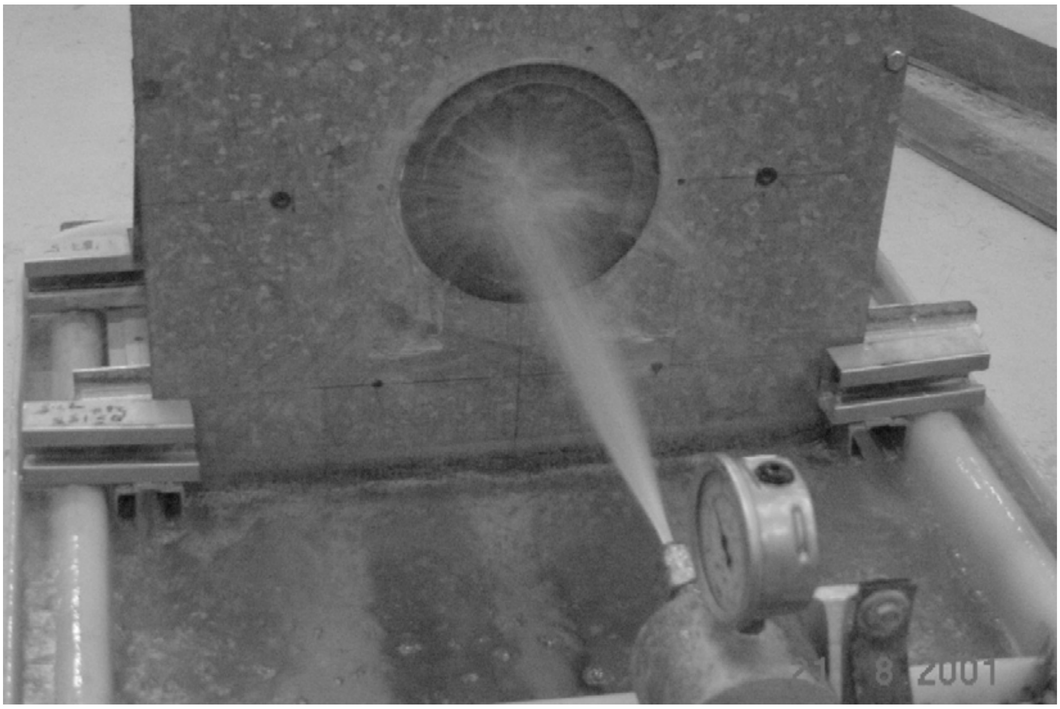


Figure 5.6 View of Test Rig with "VeeJet" Nozzle

5.6 Nozzle Calibration

All nozzles, together with the Bulletin 5 nozzle, were calibrated in order to quantify their discharge rates and to determine nozzle exit velocities.

5.6.1 Spray Volumes – Full Spray Impact

In the cases where the full impact of the spray impinged on the specimen spray volumes were measured by discharging 9.3 litres of water through the spray directly into a measuring bucket, and measuring the time taken. The results of these tests are given in Table 5.2. Due to turbulence in the bucket noticeable variations in discharge rates were observed, and at least three readings were averaged to produce the figures below. It is to be expected that more accurate calibration of the nozzles, by measuring discharge over bigger volumes, would result in less variation, although in general the values given below are fairly close to those quoted in the Spraying Systems brochure.

Table 5.2 Discharge Rates in Litres per minute

	Nozzle Diameter (mm)				
Pressure	1530	1550	1590	15150	Bulletin
(kPa)	3.2 mm	4.4 mm	5.6 mm	7.5 mm	5 Nozzle
50		8.4	15	30.9	28.6
70		9.5	17.1	33.4	35
80	5.5				
90				35.5	37.5
100	6	11			
115	6.4				
120			20.7		
130	6.8	12.7	21.9		

Best-fit lines were fitted to this data on the basis that the discharge was proportional to the square root of the spray pressure. Velocity efficiencies were then calculated based on the cross sectional area of the nozzles and the equation for velocity v (m/sec)= 1.414 $\sqrt{}$ Pressure (Table 5.3). The correlation coefficient and velocity efficiency for the 7.5 mm nozzle is distorted because only three values were used and the value for velocity efficiency for the Bulletin 5 nozzle is probably affected by the fact that all hole diameters were assumed to be the same. The velocity efficiencies for the other three nozzles are in line with the manufacturers data.

Table 5.3 Best Fit Flow Rate Lines

NOZZLE DIA	**BEST FIT LINE**	**VEL. EFFIC.**	**CORR. COEFF.**
3.2 mm	Discharge (l/min) = 0.6 × √ Pressure (kPa)	88%	0.99
4.4 mm	Discharge (l/min) = 1.12 × √ Pressure (kPa)	88%	0.99
5.6 mm	Discharge (l/min) = 1.96 × √ Pressure (kPa)	94%	0.96
7.5 mm	Discharge (l/min) = 3.97 × √ Pressure (kPa)	106% *	0.44*
Bulletin 5	Discharge (l/min) = 4.05 × √ Pressure (kPa)	103%*	0.97*

In general a linear fit provided a better correlation than the power fit above, within the range of pressures tested, and therefore linear equations were used to “fill in” the values on the discharge tables (Table 5.4).

Table 5.4 Variation of Spray Rates (Litres/Min) with Spray Pressure

	Nozzle	**Diameter**	**(mm)**		
Dia.	**3.2**	**4.4**	**5.6**	**7.5**	**Bulletin 5**
Pressure	**Q (l/min)**	**Q (l/min)**	**Q (l/min)**	**Q (l/min)**	**Q (l/min)**
50	4.7	8.4 (8.4)	15.2 (15.0)	31.0 (30.9)	28.6
60	5.0	8.9	16.0	32.1	
70	5.2	9.4 (9.5)	16.8 (17.1)	33.3 (33.4)	
80	5.5 (5.5)	10.0	17.6	34.4	
90	5.8	10.5	18.5	35.6 (35.5)	
100	6.0 (6.0)	11.0 (11.0)	19.3	36.7	
110	6.3	11.6	20.1	37.9	
120	6.5	12.1	20.9 (20.7)	39.0	
130	6.8 (6.8)	12.6 (12.7)	21.8 (21.9)	40.2	

* Note that measured values are shown in brackets

5.6.2 Spray Velocities

Based on the above values for discharge continuity considerations (Velocity = Discharge / Nozzle Area) were used to develop a table relating spray velocities to spray pressures ranging from 40 to 130 kPa. The resultant velocities are shown in Table 5.5 and reflect the head loss through the nozzles.

5.6.3 Spray Volumes – Partial Spray Impact

In some of the experiments (series V1 – Chapter 6) the larger distance of 470 mm between nozzle and specimens was used and the specimens were only subject to the middle 100 mm diameter of the spray so that 3 sprays could be carried out on one face of a Cinva Ram block. In this case it was assumed that the spray velocities were the same as given above but testing was carried out to determine the amount of water impacting on the specimens. This was done by gluing on a funnel to the back of the 100mm holes and recording the amount of water passing through in a certain time. The results of these tests were variable (Figure 5.7) and indicated that the greatest flow was achieved with the 4.4 mm nozzle rather than the larger 5.6 mm nozzle. This was attributed to the varying spatial variation of the sprays. For the purpose of analysing test results in these cases discharges were read directly off Figure 5.7.

Table 5.5 Variation of Spray Velocity with Spray Pressure

	Nozzle	Diameter	(mm)		Bulletin
Dia.	**3.2**	**4.4**	**5.6**	**7.5**	**5**
Pressure	**v (m/sec)**	**v (m/sec)**	**v (m/sec)**	**v (m/sec)**	**v (m/sec)**
50	9.8	9.2	10.3	11.7	9.9
60	10.3	9.8	10.8	12.1	
70	10.8	10.3	11.4	12.5	
80	11.4	10.9	11.9	13.0	
90	11.9	11.5	12.5	13.4	
100	12.5	12.1	13.1	13.9	
110	13.0	12.7	13.6	14.3	
120	13.5	13.3	14.2	14.7	
130	14.1	13.8	14.7	15.2	

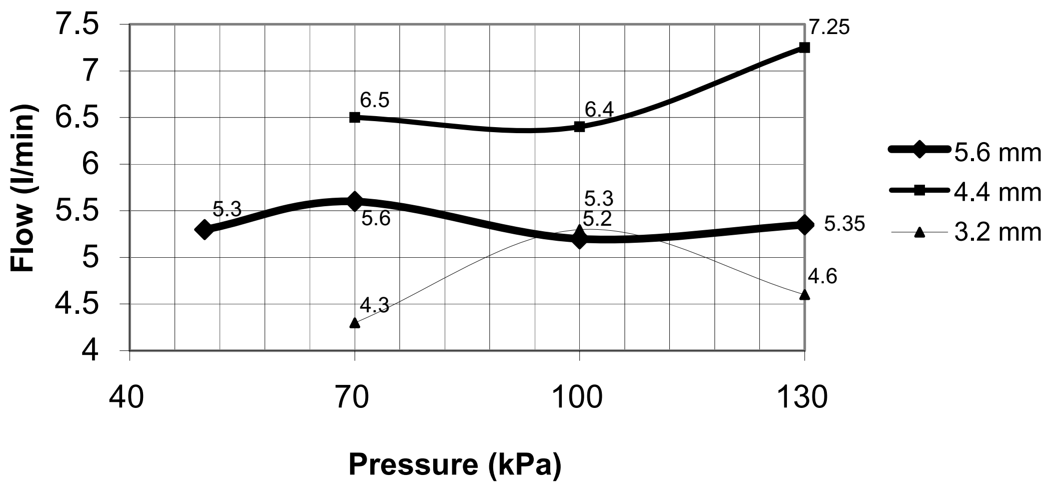


Figure 5.7 Flow Rates through 100 mm Opening

Chapter 6 Incident Rainfall Characteristics and Their Laboratory Simulation

6.1 Introduction

The assumption made in this investigation has been to assume that the behaviour of climatic variables in the field can be represented by their behaviour in the laboratory. It would be highly desirable to directly measure in the field the effect rainfall variables have on the erosion of specimens. This is impractical however, as storms comprise of a variety of raindrops approaching at different angles and with different impact velocities, depending on wind strengths and rainfall intensity. The best that can be done is to keep as many of the secondary variables as possible constant, and to examine the effect primary variables have on erosion, and this can only be done in a laboratory.

In choosing what variables to examine resort was made to the previous work done on soil erosion and on the erosion of aircraft by impacting rain (Chapter 3)

In Chapter 3 it was suggested that the main variables effecting erosion were

- Impacting volume of rain (Q)
- Impact drop velocity (v)
- Angle of impact of drops (φ)
- Raindrop diameter (d)
- Time, in the form of a function f(t)

It was shown in Chapter 4 that the volume of impacting water on earth walls (Q) could be related to the driving rain index, which is a product of the hourly rainfall intensity and the wind speed. In general it will be assumed that there is a linear relationship between erosion and impacting volume of water. Results will therefore be expressed in terms of erosion per unit volume of impacting water (E/Q). If there is any time effect then this will be incorporated in the time function (f(t))

This Chapter will examine the effect of the remaining variables in the laboratory, as well as looking at other secondary variables, such as antecedent moisture content, in order to provide a predictive equation that can be used to compare the performance of specimens in the laboratory with specimens in the field (Chapter 7).

In view of the fact that a comparison was to be made between field and laboratory results, it was felt preferable to compare the effects of these variables in terms of erosion (grams) per unit area of surface per unit volume of impacting water (litres). As impact area was not a variable in the tests the results are generally expressed in grams/litre of impacting water.

6.2 Effect of Time

The effect of time is obviously a major influence on the erosion of earth walls, both in the field and in the laboratory. For a constant rainfall intensity or water jet velocity the volume of water impacting a surface is linearly related to the exposure time, and from the work done in soil erosion, erosion was linearly related to the volume of impacting water. The initial assumption made by the author was therefore that erosion in the laboratory would be linearly dependent on the volume of impacting water.

It became apparent however, following the initial series of field tests, that the erosion of specimens in the field per unit volume of impacting water was much greater than occurred in the laboratory. The erosion mass of specimens in the field for the first series of field tests (Series A – see Chapter 7) was, by co-incidence, similar to that for the specimens tested in the laboratory, and yet the volume of impacting water was much greater in the laboratory tests. This is illustrated in Figure 6.1, where the ratio of the field erosion per litre of impacting water to the spray test erosion per litre of impacting water is plotted against the duration of the laboratory tests.

It was clear from the results that there were other factors involved in the difference between field and laboratory tests besides time, as the lowest ratio between field and laboratory results was 5.7 for the 3% specimen. However what was of most interest was the fact that that this ratio increased dramatically with time of exposure in the spray test, up to around 1600, leading to the conclusion that there was possibly a time effect involved in the continual spraying of specimens.

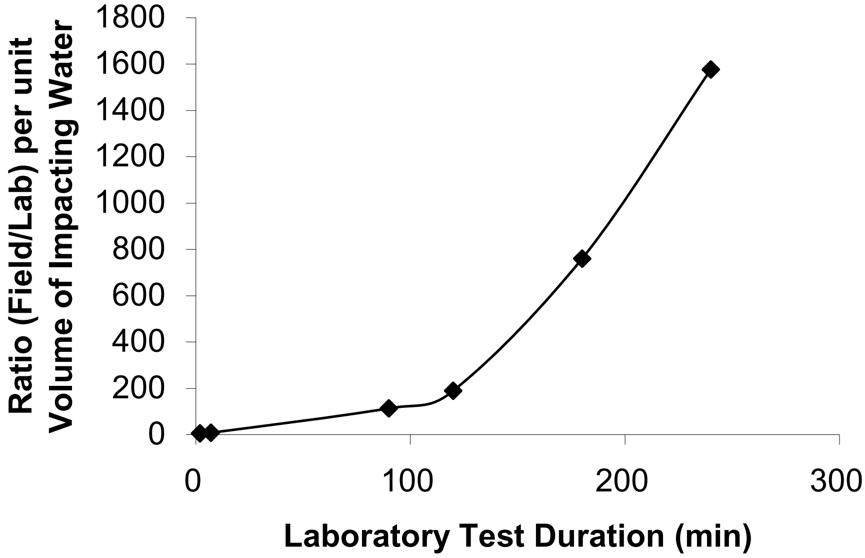


Figure 6.1 Variation of Erosion per Unit Volume of Water with Time

6.2.1 Analysis of Experimental Results of Adams

Adams (1998) carried out experiments into the effect of duration of loading on the erosion of cement stabilised pressed earth bricks under the direction of the author. In these tests bricks were made from sandy loam with around 3% cement content in a Cinva Ram brick press. Five bricks were tested. Four of these were separately tested on the top, bottom and side faces of the bricks whilst the fifth was tested on the top and bottom only. The low cement content was deliberately chosen so that erosion amounts would be measurable. A wire was cast in and the specimens were then hung from a laboratory balance over the impact area of the author's standard spray testing apparatus. A photo of one of the bricks being tested on a side face is shown in Figure 6.2.

Prior to starting the test the specimens were soaked until they were of a constant weight (i.e. saturated). During the test the change in weight was then recorded at regular intervals. The results indicated a high initial erosion rate, which decreased with time. The magnitude of the erosion varied between bricks made from different batches, as well as between various faces of the same bricks, as can be seen from the results, shown in Figures 6.3, 6.4, and 6.5.

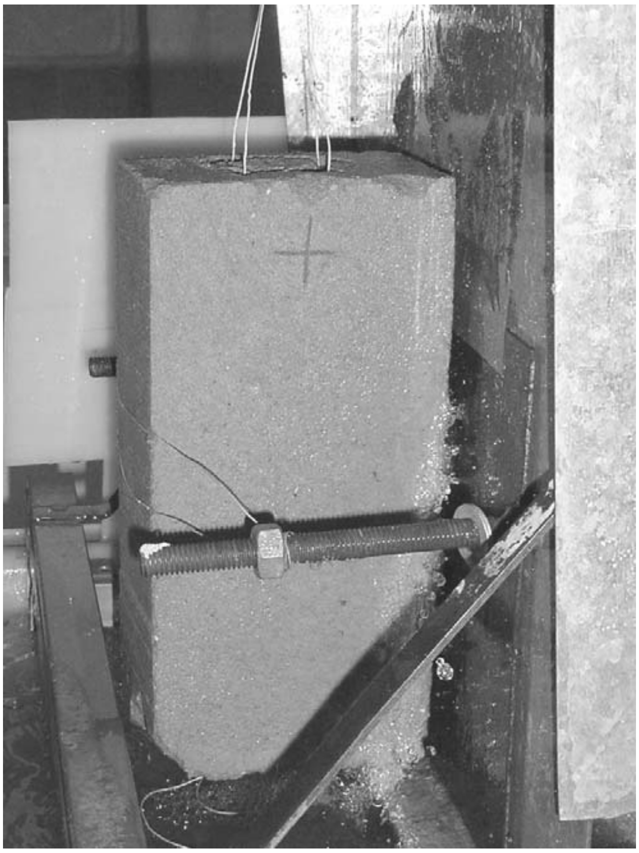


Figure 6.2 Test Set-up (Adams)

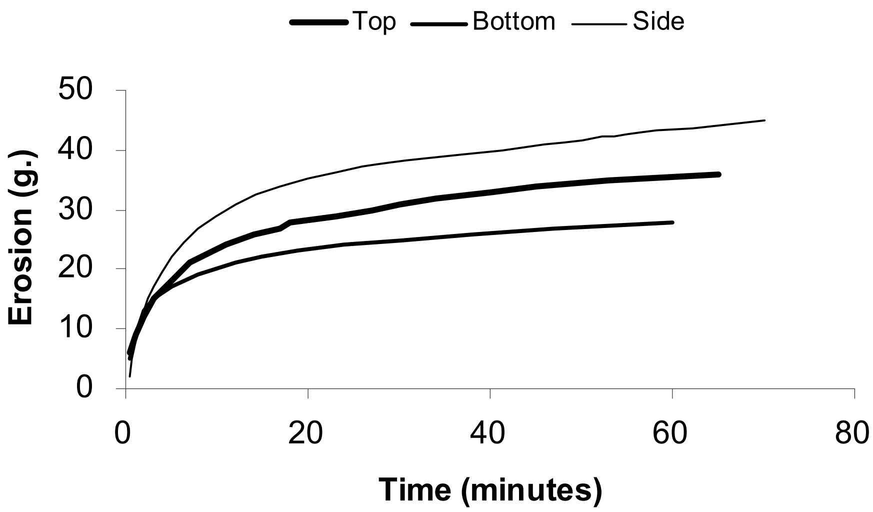


Figure 6.3 Adams Erosion vs. Time Data for Batch 1

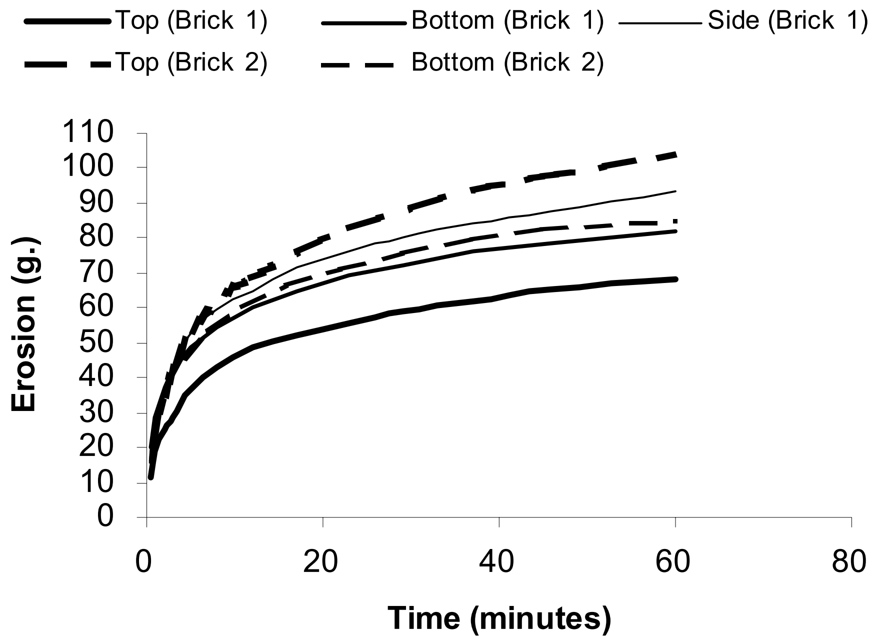


Figure 6.4 Adams Erosion vs. Time Data for Batch 2

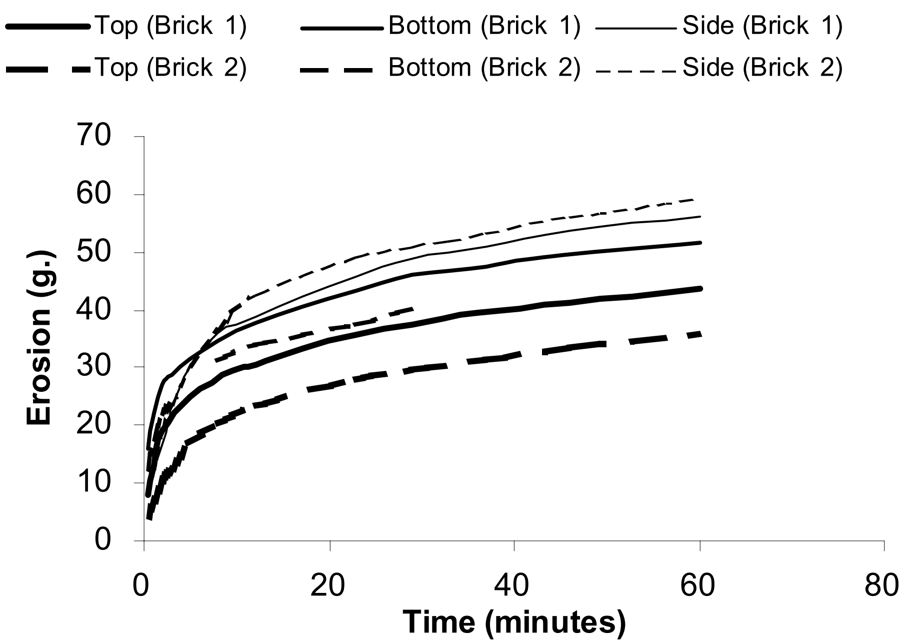


Figure 6.5 Adams Erosion vs. Time Data for Batch 3

The erosion of the specimens at 60 minutes varied from around 28 grams to 105 grams but in general the shape of the curves were fairly consistent, confirming the authors hypothesis that the erosion rate would decrease with time. The factors most probably responsible for the variation in the 60 minute erosion, given that samples were mixed from the same soil source and had the same cement content, were the degree of compaction which varies from face to face and from block to block, and possibly on the degree of curing.

In order for these curves to be useful in converting values of erosion measured at different periods of time to a common time frame, and to relate instantaneous erosion rates which might occur in the field with erosion amounts measured over longer periods in the laboratory, it was necessary to represent these curves in a dimensionless manner.

Initial attempts to derive dimensionless erosion vs. time curves assumed a logarithmic curve, with erosion and time normalised to a 30 minute time frame (Figure 6.6).

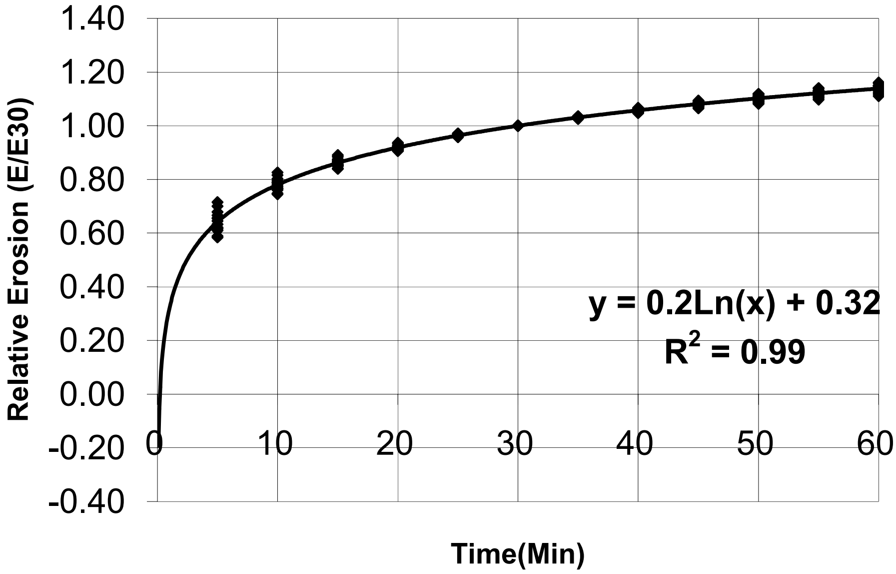


Figure 6.6 Relative Erosion vs. Time (Heathcote & Sri Ravindrarajah, 2000)

By making an assumption that erosion in the field was dependent on the 5 minute erosion rate it was possible to adjust the field and laboratory results of the Series A tests (presented in Chapter 7) to a common time frame of 30 minutes. In doing so a linear relationship between field and laboratory results were generated for the 3%, 4% and 5% cement content specimens (Figure 6.7).

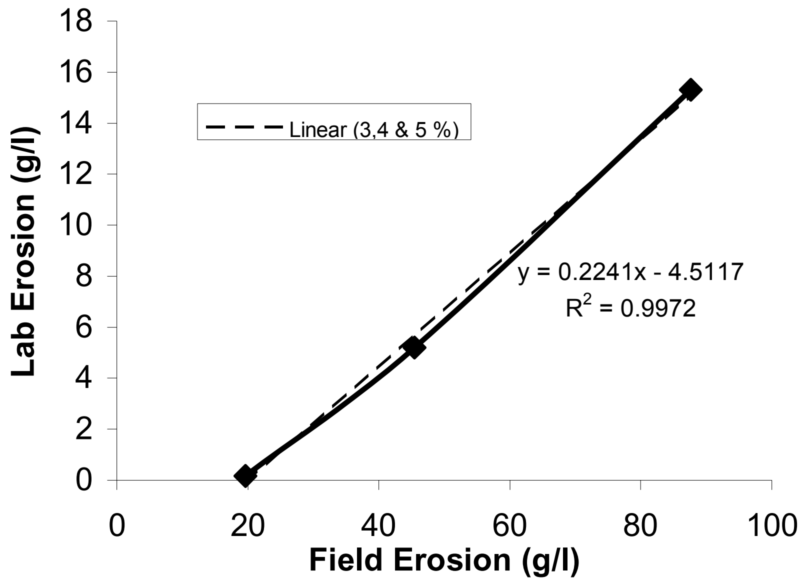


Figure 6.7 Variation Between Laboratory and Field Erosion(Heathcote & Sri Ravindrarajah, 2000)

Although Figure 6.7 was used to explain most of the variation between erosion per unit volume for the lower cement contents, it was felt that it was not sufficiently accurate at the lower end of the time scale because of the inability of the logarithmic function to predict a zero incubation period. In addition it was felt that a 60-minute reference period was probably more appropriate, as it is the normal test period for the Bulletin 5 spray test and it is the time when the erosion rates in the Adams tests are reasonably stable.

Since the shape of the Adams data is characteristic of growth curves various growth models were tried to represent the time function, including a simple saturation growth model [$y = \frac{a \times x}{(b + x)}$] .In the end an MMF (Morgan – Mercer – Flodin) sigmoidal growth model [$y = \frac{\left(a \times b + c \times x^d\right)}{\left(b + x^d\right)}$] was adopted as it provided an excellent fit to the data. Sigmoidal growth curves are a subset of the Growth Family of curves, and are commonly used in a wide variety of applications such as biology, engineering and economics. These curves start at a fixed point and increase their growth rate monotonically to reach an inflection point. After this, the growth rate approaches a final value asymptotically (CurveExpert, 1995).

The MMF model is based upon the hyperbolic function and has the form, expressed in terms of the erosion problem, of

$$\frac{E}{E_{60}} = \frac{\left(a \times b + c \times \left(\frac{t}{t_{60}} \right)^{d} \right)}{\left(b + \left(\frac{t}{t_{60}} \right)^{d} \right)} \qquad \text{……….}(6.1)$$

Where

E= Erosion at any time t

E_{60}= 60 minute erosion

t_{60} = 60 minutes

a, b, c & d are constants.

Note that if t = ∞ then f (t) = c.

A negative value for f(t) at t=0 is indicative of an incubation period (t_i) where

$$t_i = \left(\frac{-a \times b}{c} \right)^{\frac{1}{d}} \times t_{60} \qquad \text{……………..}(6.2)$$

Using all the data points collected by Adams a non-dimensional MMF graph relating erosion to time was determined using the CurveExpert program. It is presented as Equation 6.3, which is plotted in Figure 6.8 along with the base data. The best-fit line has a high coefficient of determination (98.8%), and indicates that in the long term the maximum erosion will be 82% greater than the 60-minute erosion. Equation 6.3 indicates an incubation period of around 1/10th of a second.

$$\mathrm{E} = \frac{\left(-0.215 + 1.813 \left(\frac{t}{t_{60}} \right)^{0.343} \right)}{\left(0.602 + \left(\frac{t}{t_{60}} \right)^{0.343} \right)} \times E_{60} \qquad \text{……….}(6.3)$$

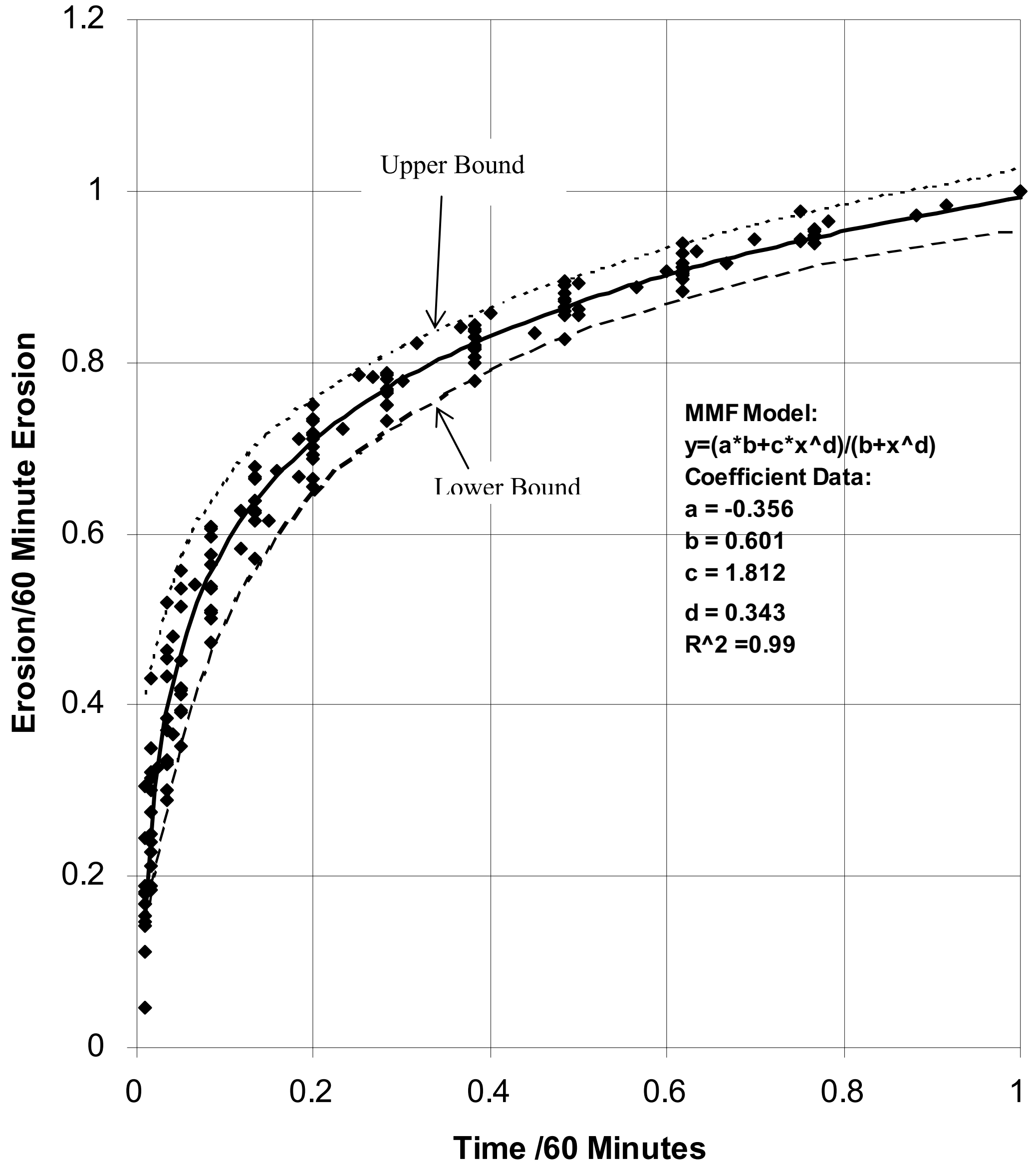


Figure 6.8 Non-Dimensional Erosion Curve

Upper and Lower bounds to the data were manually drawn and fitted to MMF functions using the CurveExpert program. The resultant equations are shown as Equations 6.4 and 6.5.

$$E = \frac{\left(5.577 \times \left(\frac{t}{t_{60}}\right)^{0.224}\right)}{\left(4.433 + \left(\frac{t}{t_{60}}\right)^{0.224}\right)} \times E_{60} \qquad \ldots\ldots\ldots(6.4)$$

$$E = \frac{\left(1.236 \times \left(\frac{t}{t_{60}}\right)^{0.706}\right)}{\left(0.294 + \left(\frac{t}{t_{60}}\right)^{0.706}\right)} \times E_{60} \qquad \ldots\ldots\ldots\ldots(6.5)$$

As an example of how Equation 6.3 may be used, assume that a spray test is carried out for only 20 minutes, with an erosion value of 48 grams, and you wish to find the 60 minute value.

Since $t_{20}/t_{60} = 0.33$

Then $E_{20} = 48$ mm = $(-0.215 + 1.812\times 0.33^{0.343})/(0.602+0.33^{0.343}) \times E_{60}$

$E_{60} = 48/0.8 = 60$ mm

6.2.2 Comparison with the results of Zavoni et al.

The results of Zavoni et al. (1988) were presented in Section 2.2.8 of Chapter 2, in which it was indicated that the rate of erosion of their samples when subjected to a water spray followed the shape of a MMF growth curve almost exactly. The graph of their results is reproduced as Figure 6.9 for completeness.

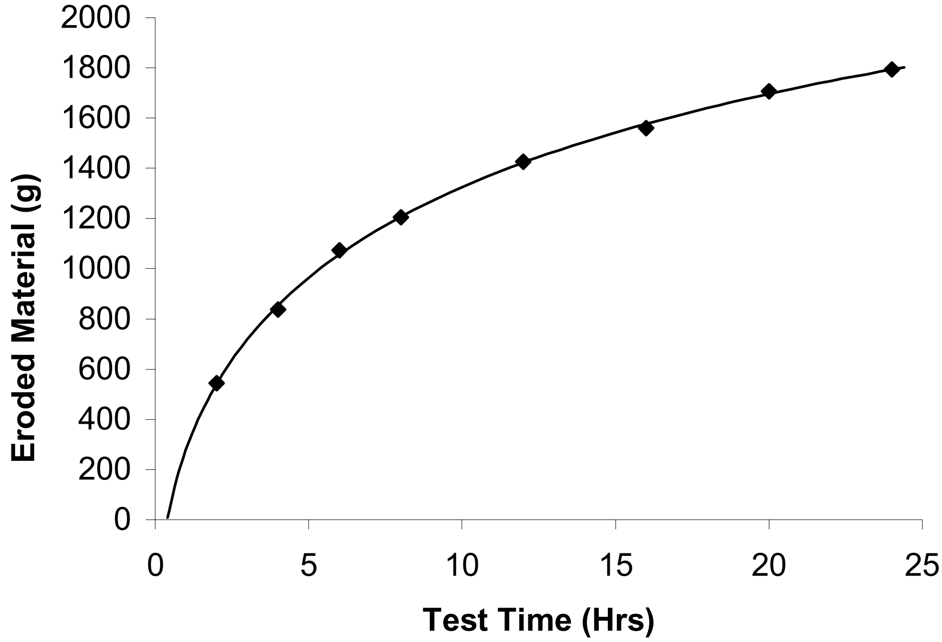


Figure 6.9 Variation of Eroded Material with Time (Zavoni et al., 1988)

It is not possible to compare the shape of this curve with that shown in Figure 6.8 because of the differing spray mechanisms. However the results of Zavoni et al. fit an MMF curve almost exactly ($r^2 = 0.999$) and lends weight to its use in defining the time function f(t).

6.2.3 Comparison with the Results of Dad

In his experiments Dad (1985) looked into the effect of duration of loading on the erosion of a clay specimen in his test rig. This specimen was compacted at 4 MPa and was subjected to high intensity rainfall (3125 mm/hr) with the sample inclined at an angle of 30 ° to the horizontal. His experiments involved simulating the volume of rainfall impacting a specimen over a 25-year period. For a particular clay soil he measured the weight loss corresponding to simulated periods of 5 years, 10 years, 20 years and 25 years. His results indicate an initial weight loss of around 1.5% within the first five years with a further 0.7% occurring linearly over the next 10 years, increasing exponentially to around 3.8% at 25 years. Figure 6.10 shows his data points graphically, these being scaled off.

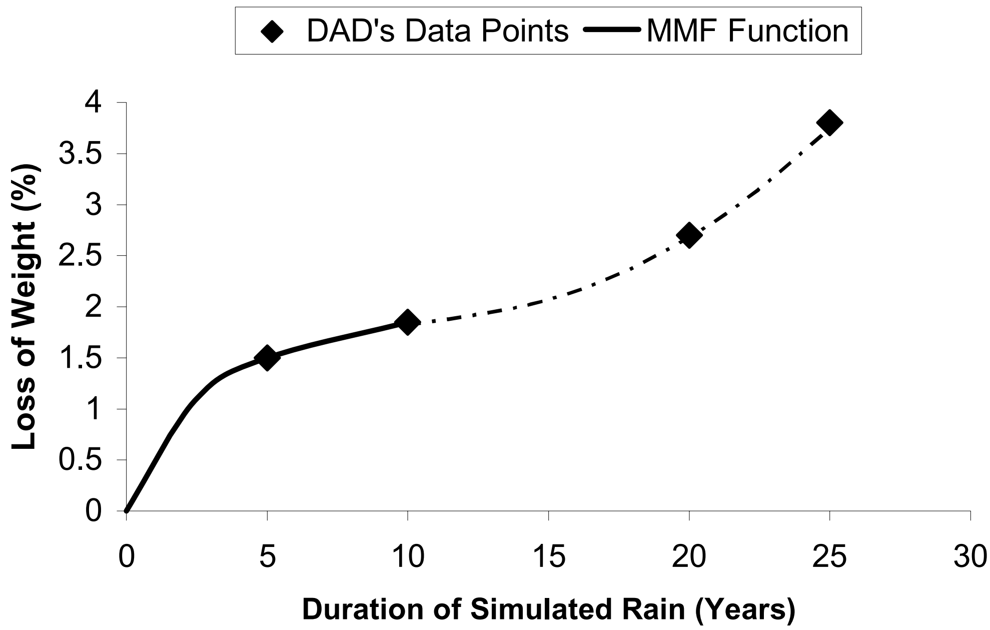


Figure 6.10 Variation of Weight Loss vs. Time

Dad notes that an increase in erosion rate with time is to be expected because "*once the surface of the block is broken away, a greater surface area of soil is exposed which is increasingly vulnerable to further erosion*"

Dad's results indicate a constant erosion rate with time after an initial sharp increase, in contrast to the decreasing rate given above. The difference may be attributable to a difference in time frame. The Adams tests indicate a decreasing erosion rate up to about one hour whilst Dad's first point for a simulated 5 years of rain occurred after 7 hours of spraying. Since both storms and accelerated spray tests occur mainly within a one to two hour time frame the duration of the accelerated test will be an important consideration in any correlation between field and laboratory performance.

6.2.4 Implication for Laboratory Testing

Figure 6.11 shows the volume of water impacting the surface as a proportion of the 60-minute volume (straight line) superimposed on Figure 6.8.

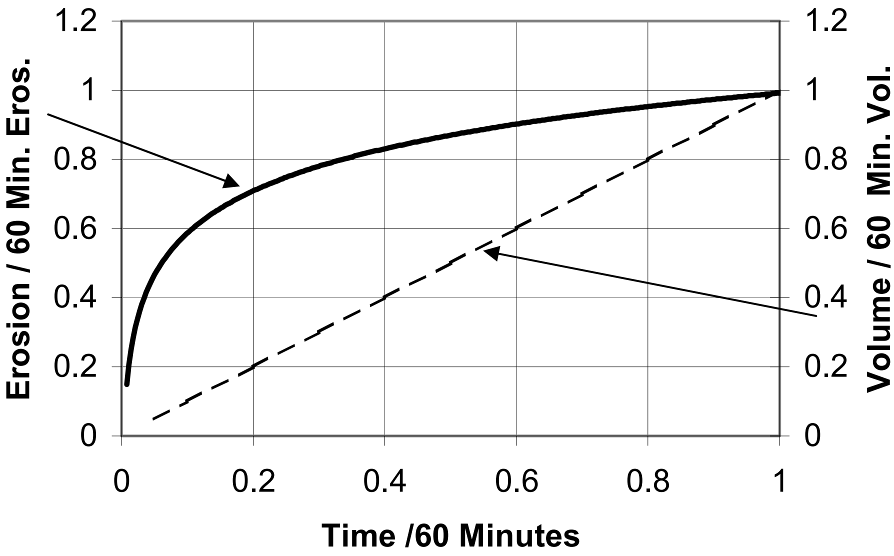


Figure 6.11 Non-Dimensional Volume of Water Curve

Dividing the erosion curve by the volume curve gives a non-dimensional representation of the erosion per unit volume of impacting water (Figure 6.12). The equation for this graph can be derived as follows.

From Equation 6.1

$$E = \frac{\left(-0.215 + 1.812\left(\frac{t}{t_{60}}\right)^{0.343}\right)}{\left(0.602 + \left(\frac{t}{t_{60}}\right)^{0.343}\right)} \times E_{60} \qquad \text{……….}(6.6)$$

And since

$$Q = \frac{t}{60} \times Q_{60} \qquad \text{……….}(6.7)$$

Then

$$\frac{E}{Q} = \frac{E_{60}}{Q_{60}} \times \mathrm{f(t)} \qquad \text{………..}(6.8)$$

where

$$f(t) = \frac{\left(-0.215 + 1.812\left(\frac{t}{t_{60}}\right)^{0.343}\right)}{\left(0.602 + \left(\frac{t}{t_{60}}\right)^{0.343}\right)} \times \frac{60}{t} \qquad \text{……….}(6.9)$$

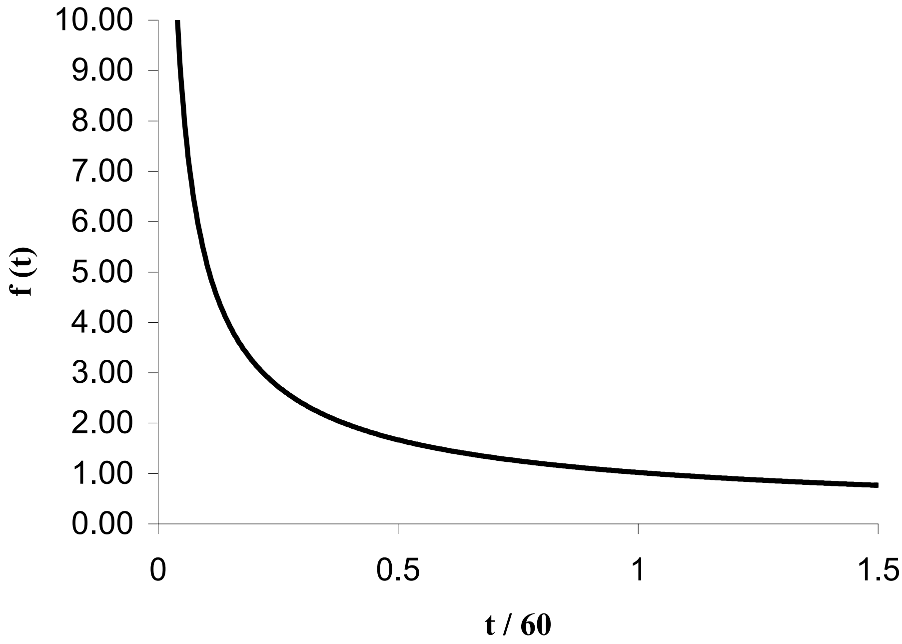


Figure 6.12 Graph of f(t)

Figure 6.12 indicates that if a specimen is tested for 6 minutes (0.1×60) then the effective erosion per unit volume of impacting water is 5.75 times that if it were tested for 1 hour or roughly 11 times if it were tested for 2 hours.

6.2.5 Implication for Field Testing

In the field erosion rates will vary significantly during a storm. For that reason it is necessary to adopt a representative period for a storm which is indicative of an average erosion rate during the storm. In general most erosion occurs during short periods of high rainfall intensity (Chapter4) and therefore it could be expected that a representative rainfall period of 5 minutes would not be unreasonable. For a representative period of 5 minutes

$$\frac{E}{Q} = 6.5 \times \frac{E_{60}}{Q_{60}}$$

This means is that in the initial stages of a storm the erosive capacity per litre of water is approximately 6.5 times that which would occur in a laboratory test conducted for a period of 60 minutes. For a representative period of 1 minute the factor would be 16.2.

6.2.6 Effect of Erosion on Different Faces

Although not a primary aim of this work it is informative to look at the variation in erosion rates in relation to the surface being sprayed.

Although the bricks made by Adams were from the same soil, erosion masses at 60 minutes varied from 36 to 104 grams on the top face, from 28 to 85 grams on the bottom face, and from 45 to 94 grams on the side. Of the 14 tests, 4 bricks were tested on the top, bottom and side and 1 was tested on the top and bottom only.

The mean variation between results on the top and bottom faces was 23%. Taking the worst of the top and bottom faces compared to the side face indicated a mean variation of 47% with higher results being recorded on the side faces.

These results indicate that the erosion on the side face of a brick could be significantly higher than on the tested face, which is generally either the top or the bottom face.

6.3 Effect of Drop Velocity

6.3.1 Theoretical Considerations

Previous research into aircraft erosion presented in Chapter 3 indicated that at high speed erosion of metals was proportional to velocity raised to the 5th power or if a threshold velocity was assumed then erosion minus the threshold velocity was proportional to velocity raised to the power of 2.5.

Most work in the area of soil erosion relates soil erosion to kinetic energy, or in some cases to momentum. In the case of momentum, if raindrop diameter is independent of impact velocity, then erosion per unit volume of rainfall will be proportional to velocity. In the case of kinetic energy it will be proportional to velocity squared.

Based on the above it would seem likely that velocity would effect erosion somewhere between the 1st and 5th power. If one assumes that there is no threshold velocity and that kinetic energy is the criteria, then an exponent of 2.0 to 2.5 would seem to be indicated.

6.3.2 Experimental Program

In order to investigate the effect of drop velocity on erosion seven different series of tests were carried out. These tests were done at varying intervals during this study and involved soils of differing composition. As the study progressed and the need for a better correlation between velocity and erosion was established, the tests became more focused in detail.

6.3.2.1 First Series

The first series involved spraying three circular areas on the same face of three Cinva Ram pressed blocks for a period of 30 minutes. These tests were carried out with various water pressures and nozzle sizes in the belief that a single relationship of the form $E = K \times p^a \times d_n^b$ could be established directly from three tests on the same face of a specimen, with p = Water Pressure (kPa) and d_n = Nozzle Diameter (mm),

It was felt at this stage that there was a direct relationship between drop size and nozzle diameter. This exercise proved to be inconclusive but the individual results for each of the three blocks, Z2, Z3 & Z4 are given here to show the general variation of erosion with impact velocity. Not surprisingly, the higher the impact velocity the greater the erosion.

A photo of one of the test specimens is given in Figure 6.13. The blocks were made of an artificial soil comprising Washed Sand, Kaolin (Clay) and a Flyash (Meant to replicate Silt). Because smaller holes were used to accommodate three holes on the face of a Cinva Ram brick it was necessary to calibrate flow rates for all three nozzles (See Chapter 5). Each test area was sprayed for a period of 30 minutes.

Figure 6.13 - Photo of one Specimen in Initial Series of Tests

The results of the erosion tests are given in Table 6.1 and Figure 6.14. Jet velocities and spray rates were computed from the data given in Chapter 5.

Table 6.1 Series 1 Test Results

SAMPLE NO	WATER PRESSURE (kPa)	CALCULATED JET VELOCITY (m/sec)	VOLUME OF WATER (l/min)	NOZZLE DIA. (mm)	EROSION VOLUME (ml)
Z2	50	9.4	5.3	5.6	8
Z2	103	13.25	5.3	3.2	13.5
Z2	130	14.1	7.3	4.4	13
Z3	50	9.4	5.3	5.6	7
Z3	100	13.1	5.3	3.2	18
Z3	110	12.9	6.6	4.4	24
Z4	50	9.4	5.3	5.6	30
Z4	110	13.6	5.2	3.2	32
Z4	130	14.1	7.3	4.4	46

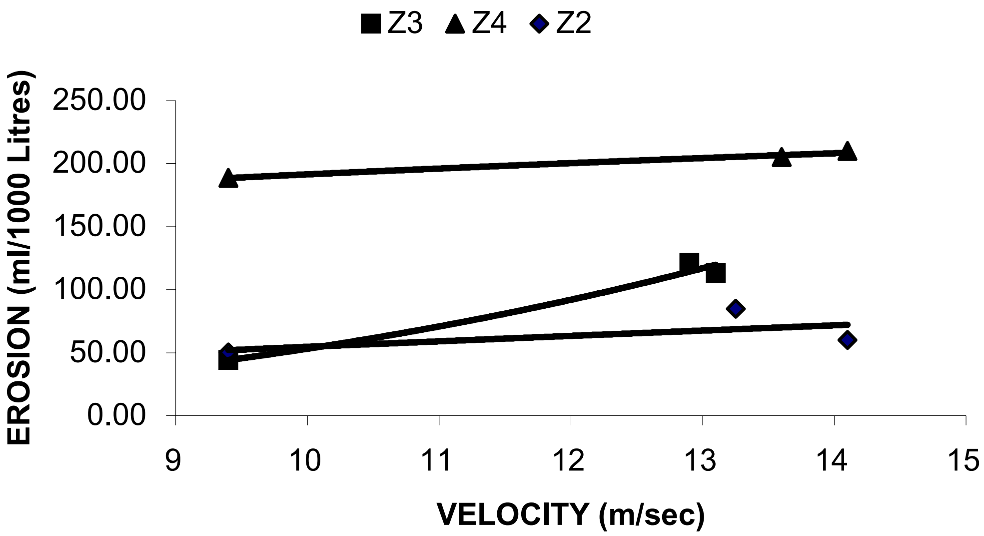


Figure 6.14 Variation of Erosion with Velocity (Series 1)

6.3.2.2 Second Series

The second series of tests (Series 2) were carried out on a silty sand material made into blocks using the Cinva Ram. These had 5% cement added and were subsequently cut into two with opposite faces being subjected to varying spray pressures. In all the tests the 4.4 mm nozzle was used and blocks were subjected to the full spray. The amount of spraying time was varied between 60 and 120 minutes to give measurable results and the erosion results were adjusted to a 60 minute time frame in accordance with Equation 6.3.

Measurement of the volume of eroded material was carried out by pouring water into the erosion crater and measuring the amount of water required to fill them. Initially oil was poured into the erosion craters as it was felt that the water would be absorbed too quickly but in fact after spraying the blocks were saturated and, if the measurements were done quickly, no measurable loss in accuracy was found when water was used instead of oil.

Figure 6.15 Split Blocks Following Testing

The results of the Series 2 tests are shown below together with the calculated values of velocity exponents. These velocity exponents have been calculated as follows.

1. Measured erosion values were corrected to 60-minute erosion values using the non-dimensional formula given in Section 6.2.
2. Spray rates were obtained from Chapter 5.
3. The 60-minute erosion values were then divided by the impacting water volume (Spray rate × Time) to get erosion rates per unit volume of eroded material
4. For each sample, the natural log of the ratio of the two values determined above was then divided by the natural log of the ratio between the two spray rates (Since the same nozzle was used the spray rates are proportional to the impact velocities). This is then the velocity exponent.

Table 6.2 Series 2 Test Results

Series 2							
Sample No	Pressure (kPa)	Time (min)	Erosion (E) (ml)	E_{60} (ml)	Spray Rate (l/min)	E_{60}/Q (ml/l)	Velocity Exponent
1	70	120	10	9	9.5	0.008	
	130	120	47	42	12.7	0.028	5.33
2	70	60	20	20	9.5	0.036	
	130	60	90	90	12.7	0.118	5.18
3	70	60	25	25	9.5	0.044	
	130	60	35	35	12.7	0.046	1.16
4	70	120	10	9	9.5	0.008	
	130	120	25	22	12.7	0.015	3.16
5	70	60	15	15	9.5	0.026	
	130	60	20	20	12.7	0.026	0.99
6	70	60	10	10	9.5	0.018	
	130	60	15	15	12.7	0.020	1.40
7	70	120	15	13	9.5	0.012	
	130	120	25	22	12.7	0.015	1.76
8	70	60	20	20	9.5	0.035	
	130	60	30	30	12.7	0.040	1.40
9	70	60	45	45	9.5	0.079	
	130	60	55	55	12.7	0.072	0.69
10	70	60	20	20	9.5	0.035	
	130	60	30	30	12.7	0.039	1.40

A summary of a statistical analysis of the Series 2 data is given in Table 6.3 below.

Table 6.3 Descriptive Statistics – Velocity Exponents - Series 2

Mean	2.25
Standard Error	0.54
Standard Deviation	1.72
Sample Variance	2.95
Range	0.69 – 5.33
Count	10
Confidence Level (95.0%)	1.23

6.3.2.3 Third Series

Extra data for 70 kPa and 130 kPa were obtained from the specimens cast for exposure in the field tests at the airport. These blocks were sprayed using the 4.4 mm dia. nozzle. Although the 70 kPa and the 130 kPa in this case were on different blocks these blocks were of the same material and were compacted to roughly the same density.

Table 6.4 Series 3 Test Results

Series 3							
Sample No	Pressure (kPa)	Time (min)	Erosion (E) (ml)	E_{60} (ml)	Spray Rate (l/min)	E_{60}/Q (ml/l)	Velocity Exponent
1	70	15	89	119	9.5	0.84	
	130	15	105	141	12.7	0.74	0.57
2	70	120	21	19	9.5	0.02	
	130	120	55	49	12.7	0.03	3.32

6.3.2.4 Fourth Series

A fourth series of tests was then carried out at pressures of 70 kPa and 110 kPa using the larger 5.6 mm nozzle (130 kPa was not possible with this nozzle). The results appear in Table 6.5. Note that in this case (as for Series 5,6 & 7) erosion values were obtained by drying and re-weighing the specimens, and are therefore expressed in terms of mass rather than volume.

Table 6.5 Series 4 Test Results

Series 4							
Sample No	Pressure (kPa)	Time (min)	Erosion (E) (mg)	E_{60} (mg)	Spray Rate (l/min)	E_{60}/mg	Velocity Exponent
1	70	37	55	60	16.8	0.10	
	110	30	83	95	20.1	0.16	2.53
2	70	56	83	84	16.8	0.09	
	110	45	96	101	20.1	0.11	1.03
3	70	56	100	101	16.8	0.11	
	110	45	131	138	20.1	0.15	1.73
4	70	56	97	98	16.8	0.10	
	110	45	123	130	20.1	0.14	1.55
5	70	56	56	57	16.8	0.06	
	110	45	144	152	20.1	0.17	5.49

6.3.2.5 Fifth Series

Tests were also carried out using the 5.6 mm nozzle on two unidentified soils. The results of these are designated as Series 5.

Table 6.6 Series 5 Test Results

Series 5							
Sample No	Pressure (kPa)	Time (min)	Erosion (E) (g)	E_{60} (g)	Spray Rate (l/min)	E_{60}/Q (g/l)	Velocity Exponent
1	60	84	15	14	9.5	0.02	
	110	60	21	21	12.7	0.03	1.35
2	60	42	50	53	9.5	0.13	
	110	30	102	117	12.7	0.31	2.69

6.3.2.6 Sixth Series

Series 6 specimens were made from a sandy loam (Marrickville soil) with approximately 3% cement. They were tested using the 5.6 mm nozzle. The 110 kPa specimens were sprayed for 30 minutes whilst the 60 kPa specimens were sprayed for 42 minutes.

Table 6.7 Series 6 Test Results

Series 6							
Sample No	Pressure (kPa)	Time (min)	Erosion (E) (g)	E_{60} (g)	Spray Rate (l/min)	E_{60}/Q (g/l)	Velocity Exponent
1	60	42	39	42	9.5	0.10	
	110	30	62	71	12.7	0.19	1.83
2	60	42	24	26	9.5	0.06	
	110	30	50	57	12.7	0.15	2.76
3	60	42	41	44	9.5	0.11	
	110	30	73	83	12.7	0.22	2.22
4	60	42	18	19	9.5	0.05	
	110	30	56	64	12.7	0.17	4.14
5	60	42	40	43	9.5	0.11	
	110	30	59	67	12.7	0.18	1.57
6	60	42	37	40	9.5	0.10	
	110	30	67	77	12.7	0.20	2.28

6.3.2.7 Seventh Series

Series 7 specimens were made from a "Brickies" sand, which could be described as a clayey sand. The 110 kPa specimens were sprayed for 10 minutes and the 60 kPa for 14 minutes. They were stabilized with 3% cement and tested using the 5.6 mm nozzle.

Table 6.8 Series 7 Test Results

Series 7							
Sample No	**Pressure (kPa)**	**Time (min)**	**Erosion (E) (g)**	**E_{60} (g)**	**Spray Rate (l/min)**	**E_{60}/Q (g/l)**	**Velocity Exponent**
1	60	14	43	59	9.5	0.44	
	110	10	71	106	12.7	0.83	2.03
2	60	14	45	61	9.5	0.46	
	110	10	79	118	12.7	0.93	2.25
3	60	14	39	53	9.5	0.40	
	110	10	80	119	12.7	0.94	2.78
4	60	14	49	67	9.5	0.50	
	110	10	66	98	12.7	0.77	1.33
5	60	14	42	57	9.5	0.43	
	110	10	91	136	12.7	1.07	2.97
6	60	14	30	41	9.5	0.31	
	110	10	74	110	12.7	0.87	3.42

6.3.3 Analysis of Experimental Results

A descriptive statistical analysis was carried out on the velocity exponents determined from Series 2 – Series 7 using the Excel Spreadsheet Data Analysis function. The results were as follows

Table 6.9 Descriptive Statistics –Velocity Exponents - Series 2–7

Mean	2.33
Standard Error	0.24
Standard Deviation	1.31
Sample Variance	1.72
Range	0.57 – 5.49
Count	31
Confidence Level (95.0%)	0.48

In this case there were 31 data points and the mean (2.33) was similar to that obtained for the 10 data points in Series 2 (Table 6.2). The 95% confidence limit on the mean (1.85 – 2.81) was much narrower than for Series 2 alone (1.02 – 3.48) reflecting the greater number of data points.

Figure 6.16 shows a Scatter Diagram of the data set including the possible outliers. A Box plot of the data shows that 50% of the velocity exponents lie in the range 1.4 – 2.88 with 3 possible (out of 31) outliers over 5. (When these 3 outliers are removed the mean velocity exponent drops from 2.33 to 2.01).

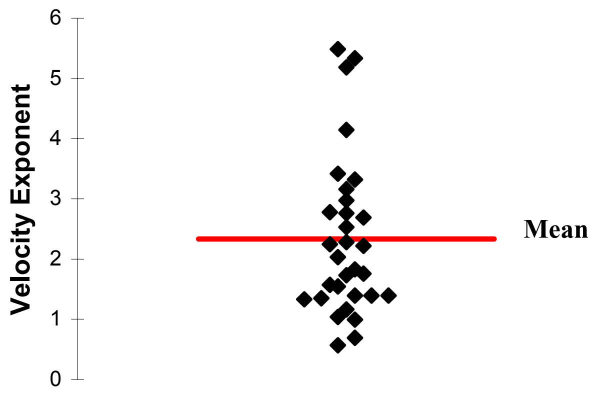


Figure 6.16 Scattergram of Velocity Exponents

A single factor ANOVA analysis was performed on Series 2, Series 4, Series 6 and Series 7 to see whether there was any appreciable difference between the series. As can be seen from Table 6.10 the results indicate that we can be almost 100% (P =98.5%) certain all the series come from the same population.

Table 6.10 Single Factor ANOVA Analysis – Series 4,6 & 7

SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
Series 2	10	22.45	2.25	2.95		
Series 4	5	12.34	2.47	3.15		
Series 6	6	14.80	2.47	0.84		
Series 7	6	14.78	2.46	0.56		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.303	3	0.101	0.050	0.985	3.028
Within Groups	46.09	23	2.004			
Total	46.39	26				

A separate analysis of Series 4,6 & 7 was carried out and this revealed a velocity exponent of 2.5 (Table 6.11), which indicates that the average for all the series (2.33 – Table 6.9) is influenced to a large extent by the Series 2 data. Given that in that Series the erosion volumes were small and the measurement method subject to some possible errors the value of 2.5 for the velocity exponent would seem appropriate.

Table 6.11 Descriptive Statistics – Velocity Exponents - Series 4,6 & 7

Mean	2.5
Standard Error	0.3
Median	2.2
Standard Deviation	1.1
Sample Variance	1.2
Range	1.0 – 5.5
Sum	41.9
Count	17.0
Confidence Level (95.0%)	0.6

6.3.4 Comparison with Ola and Mbata Results

Ola and Mbata (1990) carried out tests using a water spray at different pressures (See Chapter 3). They concluded that weight loss increased significantly with increase in the terminal velocity of the water jets. However if the erosion is expressed in terms of weight loss per volume of impacting liquid their results indicate a velocity exponent of –0.5. This result should be treated with some caution however, as the percentage loss of material in most tests were less than 1%, and there is also possibly a jet size effect.

6.4 Effect of Drop Diameter

6.4.1 Drop Size Distribution

In any storm there is a range of rainfall intensities, and within each intensity there is a range of drop diameters, varying from zero to around 6 mm. In general a drop size of 7 mm appears to be a limiting size above which drops become unstable and break up into smaller droplets (Hudson, 1963).

The drop size distribution given in Figure 6.17 has been described in Chapter 3.

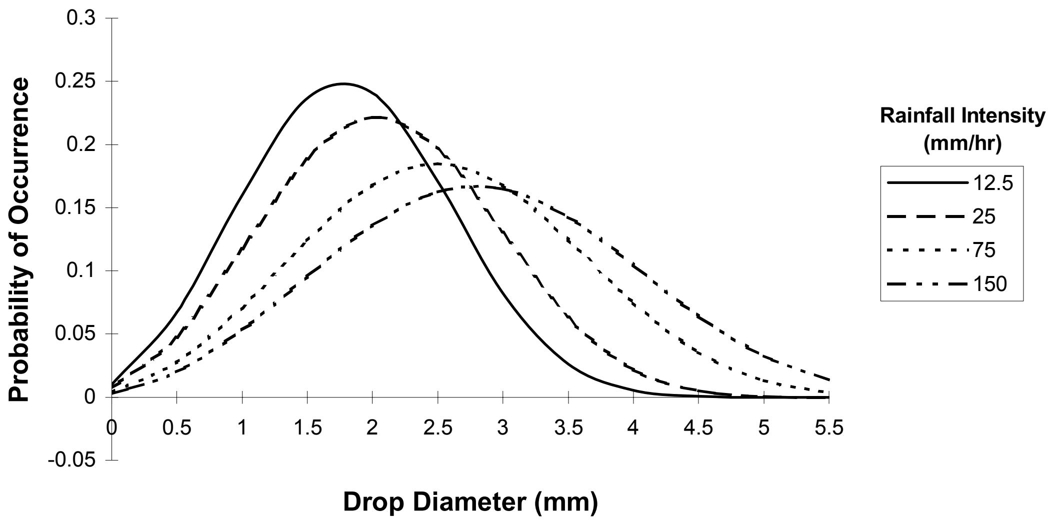


Figure 6.17 Drop Size Distribution for Washington based on formula by Assouline and Mualem (1989)

Springer (1976) suggested that because of the difficulty in simulating actual drop size distributions a characteristic drop size should be used in simulated erosion tests. One of the characteristic drop sizes he suggests is the VMD (Volume Median Diameter) defined as the raindrop diameter for which 50% of the rainfall has a diameter greater than and 50% less than. VMD's for the data shown in Figure 6.17 can be approximated to an acceptable degree of accuracy by the Equation 6.10.

$$\text{VMD (mm)} = I^{0.2} \qquad \ldots\ldots\ldots\ldots(6.10)$$

where I is in mm/hr

Due to the varying intensity of rainfall during a storm, and bearing in mind the fact that below a rainfall intensity of 12.7 mm there is unlikely to be any significant erosion, and above 100 mm/hr unlikely to occur very often, it is possible to adopt a s "representative" drop diameter of somewhere between 1.73 and 2.67. In this study a mean of these two, 2.2 mm. will be assumed for rainfall in the field when comparing with laboratory results.

6.4.2 Theoretical Considerations

The case for the influence of drop size on erosion of earth walls would appear to centre around the fact that smaller drops have less kinetic energy per unit impact area than do larger drops, and are therefore less effective in removing material.

On this basis the amount of material moved by drops travelling at the same velocity would be directly proportional to the drop diameter (Volume/Area ~ d). According to Gilley and Finkner (1985), kinetic energy per unit of drop circumference also fits the available data on soil erosion very well , and in this case the amount of material removed would be proportional to d^2 (Volume/ Perimeter ~ d^2).

However, for a given volume of rainfall [Intensity (I) × Time (T)] there are more small drops than there would be large, as shown in Equation 6.11, taken from Springer (1976)

$$q = \text{Number of raindrops/m}^3 \text{ rain} = \frac{530.5 \times \mathrm{I}}{v \times \mathrm{d}^3} \qquad \ldots\ldots\ldots(6.11)$$

where

I = Rainfall Intensity (mm/hr)

v = Drop velocity (m/sec)

d = Drop diameter (mm)

Since the total volume of material removed per unit volume of rainfall is equal to the amount removed per drop times the number of drops per unit volume the amount of erosion per unit of impacting rain could be expected to be proportional to d^n , where n = -1 or –2 , depending on which assumption you make (K.E./Unit area or K.E./unit circumference.

6.4.3 Experimental Investigation

In order to investigate the effect of drop size on erosion rates tests were carried out using spray nozzles with different drop sizes. The supplier of the nozzles used in testing was approached for data regarding their nozzles. It was decided to test using two different nozzles having significantly different median drop sizes but with the same drop velocity (12.7 m/s). The nozzles selected were

FullJet Narrow Angle Spray (Model Number 1550) with nozzle diameter of 4.4 mm and VMD of 1.1 mm at 110 kPa (Discharge = 11.6 litres per minute).

FullJet Narrow Angle Spray (Model Number 15150) with nozzle diameter of 7.5 mm and VMD of 2.5 mm at 75 kPa (Discharge = 33.9 litres per minute)

A series of 6 specimens were prepared with 3% cement content using a sandy clay soil. Specimens were compacted in 150 mm diameter moulds to a thickness of roughly 90 mm and to a density of around 1750 kg/m^3. After curing for about a month the specimens were cut in half, with opposing faces sprayed at with different nozzles with the same volume of water (i.e. the specimens sprayed with the smaller 1550 nozzle were sprayed for 33.9 /11.6 = 2.9 times as long as the 15150 specimens. Spraying was continued until there was measurable erosion and then the specimens were dried and weighed and the erosion loss recorded. The results were corrected to the standard 60-minute erosion value using Equation 6.3 and then divided by the discharge volume applicable to 60 minutes of operation of that particular nozzle. The results are presented in Table 6.12

Table 6.12 Experimental Results – Drop Size Effect

	1550 Nozzle					
Specimen Number	**Spray Time (min)**	**Erosion (g)**	**60 Min Erosion (g.)**	**60 Min Volume (litres)**	**Erosion (mg/litre)**	**VMD (mm)**
1	58	49	50	630	79	1.1
2	120	74	67	630	106	1.1
3	120	73	66	630	104	1.1
12	120	70	63	630	100	1.1
13	120	79	71	630	113	1.1
14	120	75	67	630	107	1.1
	15150 Nozzle					
Specimen Number	**Spray Time (min)**	**Erosion (g)**	**60 Min Erosion (g.)**	**60 Min Volume (litres)**	**Erosion (mg/litre)**	**VMD (mm)**
1	20	50	63	1962	32	2.5
2	42	78	84	1962	43	2.5
3	42	62	67	1962	34	2.5
12	42	98	105	1962	54	2.5
13	42	67	72	1962	37	2.5
14	42	85	91	1962	47	2.5

The results for each nozzle were then expressed as a drop size exponent in the manner carried out for the velocity experiments. Figure 6.18 shows the results in tabular form together with a Scattergram.

Specimen Number	Drop Diameter Exponent
1B	-1.14
2B	-1.15
3B	-1.42
4B	-0.79
5B	-1.42
6B	-1.06

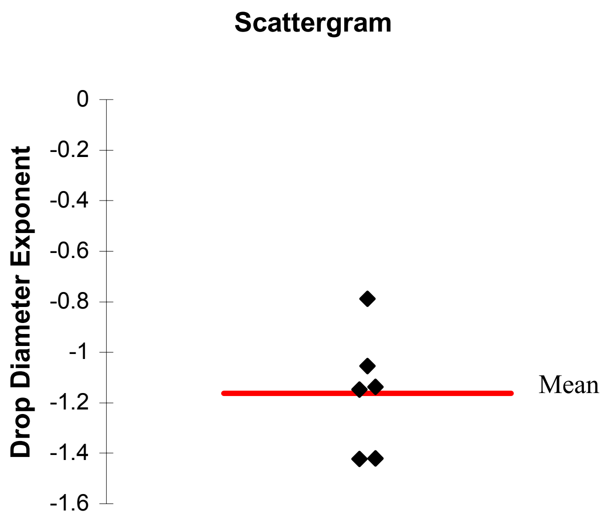


Figure 6.18 Variation of Drop Diameter Exponent

A statistical analysis of the above data revealed a mean exponent of **-1.16** with 95% confidence limits of 0.91 and 1.41.

6.5 Angle of Incidence of Water Drops

Earth walls differ markedly from earth on the ground in respect to their orientation with respect to falling rain. Indeed if rain falls vertically there will be no rain hitting vertical surfaces and thus no opportunity for surface erosion. For erosion to occur the rain must strike the wall at an angle. The action of wind on falling raindrops provides the mechanism by which this horizontal component is achieved. The wind has two effects

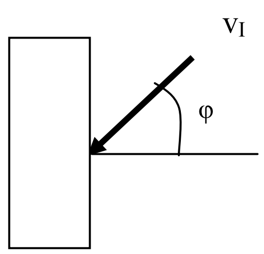
1. It increases impact velocity
2. By inclining the raindrops away from a normal to the surface there is a combination of normal and shear forces on the surface, with a potential for increased erosion.

6.5.1 Effect on Impact Velocity

A simple approach to determining the effect of wind on impact velocity is to assume a vector addition of terminal raindrop velocity and wind velocity. Caldwell and Elliott (Quoted in Lyles, 1977) "*concluded from a numerical investigation that raindrops falling through a logarithmic wind profile arrive at the surface retaining most of their horizontal speed*" Lyles (1977) concludes that little error would occur if the wind speed adopted were the wind speed at heights of 10 to 50 metres.

Using this approach, if a 2 mm diameter raindrop falls at 6.5m/sec in a wind of 9m/sec the resulting velocity will be 11.1 m/sec and the resulting kinetic energy would be $(11.1/6.5)^2$ or 2.92 times that of the same droplet falling in still air.

6.5.2 Effect of Angle of Incidence (φ)



Previous research into the erosion of metals by liquid impact (Section 3.5.5) determined that, for smooth hard surfaces, the damage potential of individual drops was dependent on the normal component of impact velocity, i.e.

$$E = f(v_I \times \text{Cos } \varphi) \qquad \text{.....................(6.12)}$$

where

E = Erosion

v_I = Incident raindrop velocity

φ = Angle of Incidence

In the case of raindrops striking a vertical wall under the action of wind the horizontal component of velocity is due to wind and Equation 6.12 becomes

$$E = f(u) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6.13)$$

where u = Wind speed

Brunton and Rochester (1979) stated however that, for roughened soft materials, the tangential component of impact velocity could become significant due to the shearing action of the lateral jets of water. To the author's knowledge no work has been done on this aspect for earth wall specimens, except for limited experiments carried out by Eassey (Eassey,1997).

Eassey's work showed that it is possible to get slightly more erosion in some cases when the angle of incidence is around 30 degrees, similar to that observed by Ruff and Wiederhorn (1979) for brittle materials subject to solid particle impact. For angles of incidence around 45 degrees however there was little difference in the observed erosion compared to that at 90 degrees for a sandy soil, indicating that for this soil and impact angle the kinetic energy of the drops determines the amount of erosion.
The problem is a complex one, as during any storm there will be a range of impact angles occurring in combination with varying raindrop sizes. For this investigation it is assumed that the erosion of specimens in the field is a function of impact raindrop speed only.

6.6 Thickness of Liquid Film

6.6.1 Experimental Investigation

In order to investigate the effect of a water layer on erosion the author purchased a solenoid which allowed the water spray to be intermittently applied, thus allowing time for water to flow from the surface. The solenoid allows the spray to be applied for a minimum of 2 seconds, and then stopped for a maximum period of 30 seconds, at which time it would be re-applied for another 2 seconds etc. It was felt that, if the water layer were a significant factor, such a test would indicate significant differences in erosion.

Preliminary testing was carried out with this apparatus using the 4.4 mm nozzle with a spray period of 1 second and a non-spray period of 10 seconds. The spray velocity and volume of water sprayed was kept constant. These tests indicated that there was very little difference between spraying samples intermittently and spraying them continuously. It was therefore concluded that the effect of a water layer on the surface was minor, and further tests were not carried out.

6.7 Effect of Water Spray on Material Properties

It is well known that sulphates are deleterious to soil cement Sherwood (1962) showed that sulphates attack the clay proportion of the soil, rather than the cement, and therefore sulphate-resisting cement is of little use. Bearing this in mind, and the fact that the author's field samples were located close to the sea (Botany Bay), the author resprayed test samples that had been exposed to the weather for a period of 10 months. The previously sprayed surfaces were ground smooth and then resprayed under the same original conditions. Two types of soils were used, roughly described as a sandy clay and a clayey sand. The results of the tests are shown in Fig 6.19.

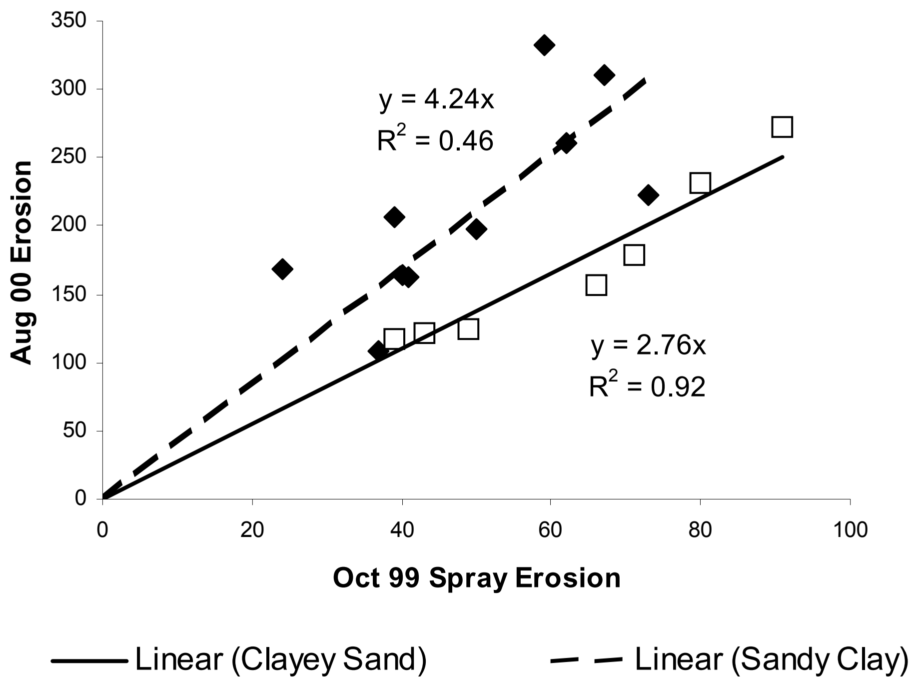


Figure 6.19 Variation of Spray Erosion with Time

For the clayey sand soil the difference in post and pre exposure spray erosion values was around 2.8 whilst for the sandy clay soil the difference was about 4.6. These values are consistent with the attack of the clay particles by sulphates in the air. The correlation for the clayey sand was very good but there was considerable scatter in the data for the sandy clay.

These results indicate a large decrease in erosion resistance over the ten month period, but must be treated with caution however, as grinding of the surfaces may have possibly led to an initial increase in the erosion rate over that which would have occurred with the smooth faced specimens in the original spray tests. Until further testing is carried out it would seem prudent to allow a greater margin of safety for specimens exposed to possible sulphate attack.

6.8 Effect of Moisture Condition of Specimens

6.8.1 Effect of Wetting and Drying

To investigate the effect of wetting and drying on the erosion of specimens a set of six specimens were made from a sandy clay with a cement content of 3%. These six specimens were then cut in two after 28 days and oven dried. One half of each specimen was then sprayed using a 4.4 mm nozzle for a period of two hours (Continuous). The other half was sprayed for half an hour, the specimen was then removed and oven dried at 60 degrees Centigrade, this being one cycle. Four cycles comprising 2 hours of spraying was carried out on these specimens. Average values are graphically represented in Figure 6.20, normalized to the 30-minute erosion. Spray pressure in all cases was 90 kPa.

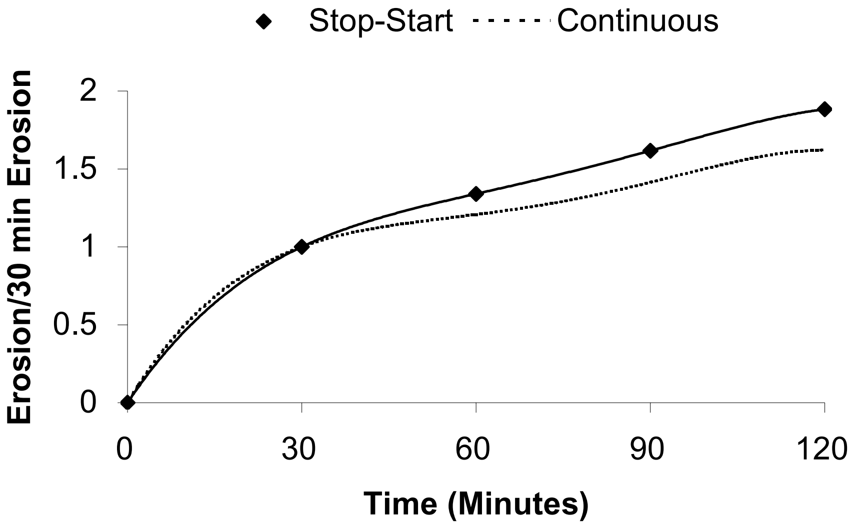


Figure 6.20 Variation of Spray Erosion with Wetting and Drying

Figure 6.20 demonstrates that over a two-hour spraying period the increase in erosion with alternate wetting and drying is around 18% over that when the specimen is continuously sprayed. Results for individual specimens are given in Table 6.13.

Table 6.13 Experimental Results –Effect of Wetting and Drying

Specimen	Initial Dry Weight (g)	Dry Weight After 30'	Weight loss (g)	Dry Weight After 60'	Weight loss (g)	Dry Weight After 90'	Weight loss (g)	Dry Weight After 120'	Weight loss (g)	Ratio
4A	1244	1190	54	1174	70	1158	86	1142	102	1.21
4B	1331							1247	84	
5A	1261	1210	51	1186	75	1161	100	1142	119	1.37
5B	1270							1183	87	
6A	1255	1196	59	1178	77	1160	95	1149	106	1.22
6B	1302							1221	81	
7A	1295	1252	43	1238	57	1230	65	1217	78	0.96
7B	1257							1184	73	
8A	1314	1250	64	1232	82	1221	93	1209	105	1.43
8B	1224							1138	86	
9A	1300	1248	52	1229	71	1218	82	1205	95	1.13
9B	1237							1130	107	

6.8.2 Effect of Antecedent Moisture Conditions

Following on from the above an investigation was made into the effect of the antecedent moisture content on erosion. In these tests the Marrickville soil was sprayed using the 4.4 mm nozzle for an hour with half of the specimens sprayed at 110 kPa and half at 70 kPa. Spraying was stopped at 7, 15, 22 and 60 minutes and the specimens dried and re-weighed. One set of specimens (G7B, G8B etc) was saturated at the outset and each time the spraying was stopped for re-weighing. Table 6.14 lists the results.

The results show that the erosion of samples that were initially dry is roughly 1.5 times that if the samples were initially wet. There seems to be a trend for this ratio to increase with time, especially for the specimens sprayed at 110 kPa, but the 7-minute ratio for that pressure appears to be an outlier. The three remaining ratios at 110 kPa average out at around 1.5 but there still is a trend to increase with time.

Table 6.14 Experimental Results – Antecedent Moisture Conditions

Time (Minutes)	0	7	15	22	60	Average Ratio Dry/Wet
Specimen	Weight Loss (g)					
110 Dry	0	27	29	39	63	
110 Wet	0	30	22	27	38	
Ratio Dry/Wet		0.90	1.32	1.44	1.66	1.33
70 Dry	0	13	25	27	35	
70 Wet	0	9	17	17	22	
Ratio Dry/Wet		1.44	1.47	1.59	1.59	1.52

6.9 Conclusions

This Chapter has examined the effects of various climatic parameters on the erosion of laboratory specimens.

- With respect to duration of loading its has been demonstrated that the erosion rate decreases with time of exposure, the shape of the erosion curve being similar to that of a MMF growth curve. A non-dimensional representation of that relationship was developed based on the experimental data of Adams.
- With respect to the effect of impact velocity on erosion it has been shown that the mean velocity exponent is around 2.5, but that the 95% confidence limits

range from 1.9 to 3.1, and that values as high as 5.5 or as low as 1.0 have been recorded.

- With respect to the effect of drop diameter it has been shown that erosion per unit volume of impacting water is inversely proportional to the median drop diameter raised to the power of 1.2.
- It has been shown that the more inclined raindrops are to the horizontal, the greater is the impact velocity and that angle of impact may have an additional erosive effect due to the development of radiating shear forces.
- Although only based on limited observation and preliminary testing it is felt that the effect of a layer of water on the surface of vertical elements is small.
- There is some evidence that sulphates in the air may attack the clay particles in earth walls and reduce their resistance to driving rain.
- The effect of continual wetting and drying of specimens has been shown to increase erosion by around 20% in the spray test over a two-hour period.
- The effect of initial moisture conditions indicates that samples that are originally dry prior to spraying eroded significantly more (30-50%) over a 1-hour period with possibly a greater increase expected over time.

Chapter 7 Field Testing of Earth Wall Specimens

7.1 Introduction

This Chapter presents the base field and laboratory data for eight series of tests, which were carried out by the author over a three-year period, commencing October 1998. These tests were carried out to determine whether the performance of specimens in the field could be accurately predicted based on performance of specimens in the laboratory. In order to investigate this, cylindrical samples were prepared and cut in half, so that one face could be tested in the laboratory, with the other face being exposed to the elements at the test site.

Chapter 6 identified the four major parameters affecting the resistance of earth wall to driving rain, viz.

- Material composition (Soil type, compaction, stabiliser proportion etc.)
- Quantity of impacting water
- Velocity of water particle impact
- Drop diameter.

Control of the effect of material composition was achieved by subjecting identical faces of the specimens to both the laboratory spray testing and the field exposure. The other three parameters were measured in the case of the laboratory specimens, or determined from climatic data in the case of field tests.

Chapter 8 will develop a theoretical model based on the underlying relationships of the three parameters, developed in Chapter 6, and will calibrate that model based on the results presented in this Chapter.

7.2 Location of Field Test Specimens

In order to correlate the field performance of specimens with wind and rain records it was necessary to locate the specimens as close as possible to an automatic weather recording station. There are only six Bureau of Meteorology weather stations in the Sydney area that provide automatic hourly collection of wind and rain data. For ease of access the station at the southern end of the main runway of Sydney's International Airport was chosen. This site has an unobstructed fetch to the south and as the majority of the wind driven rain was expected to come from the south the test rig was oriented to face south. Because of its structure exposure of specimens to the north was also possible.

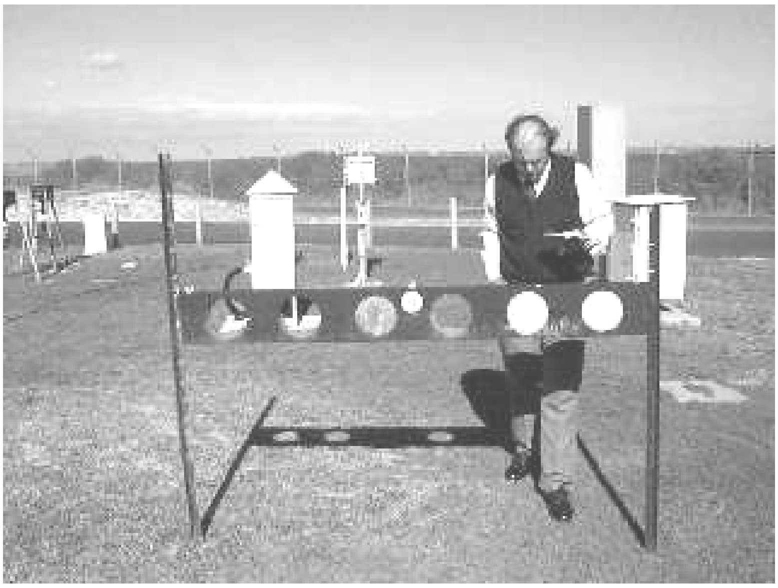


Figure 7.1 Author Inserting Samples into Initial Test Rack

The site is operated by the Sydney Airport Meteorology Office of the Bureau of Meteorology of the Commonwealth of Australia and is site number 066037 in their network of sites. The observation station was opened in 1929 and is situated at Latitude 33°56'28"S and Longitude 151°10'21"E. The wind frequency recorder is situated along the runway extending into Botany Bay at a height of 10 metres. The average annual rainfall for the site over this period is 1100 mm.

Rainfall records are logged at hourly intervals and include maximum and minimum hourly temperatures, relative humidity and dewpoint in addition to the rainfall in mm over the hourly period. The maximum hourly rainfall recorded during the three years of records collected and analysed was 41 mm on the 23rd January 1999. According to ARR (1977) this would translate into a possible 6-minute rainfall intensity of 127 mm/hr (K_m = 3.1).

Wind records indicate the 10-minute average wind speed and direction as well as the hourly maximum wind speed and the time at which it occurred. According to Cook (1985) empirical relationships have determined that the maximum hourly gust speed is around 1.6 times the mean hourly wind speed. A limited analysis of the recorded wind records was made for the second half of 1999 for the cases where wind coincided with rainfall. This revealed a significant scatter in the ratios between maximum gust speed and mean hourly 10-minute average but the means for each month were consistently around 1.75 to 2.0. Further analysis of the wind speeds at the airport is contained in Choi (1994)

7.3 Analysis of Field Climatic Data

Appendix D contains a detailed analysis of the climatic data obtained for each series of field tests. The output of both the rainfall and wind records appear on computer printouts at the weather station. These were photocopied and the relevant wind and rain records extracted manually each month before being entered into a spreadsheet for analysis. The compass direction of the wind was resolved into an angle relative to the direction the specimens faced i.e. south. This angle was called “phi”. The effective rain hitting the specimen was then calculated as the rainfall times the cosine of “phi”. For wind directions from the northerly direction phi was put at 90 degrees, thus excluding rainfall from that direction (Cos 90 degrees =0). The effective rain in metres was then multiplied by the wind speed in m/sec to give a value for wind driven rain in m^2/sec. In addition to this the wind data was separated into eight quadrants in the spreadsheet and combined with the rain data to yield driving rain in knot mm. These values were then plotted as a "Wind-Driven Rain" rose.

7.4 Preparation of Test Specimens

Initial testing in the laboratory was carried out using specimens pressed in a Cinva Ram hand press. It soon became apparent that with this machine there was a wide variation in the density of bricks produced, and as the initial investigations were to focus on the effect of cement content on durability (Series A and B) it was necessary to find some way of producing specimens with the same density.

In the Series A and B tests 150 mm diameter PVC pipes were used as moulds. Subsequently a concrete cylinder mould was used instead of the PVC piping. A 60 mm thick steel ram was made which fitted neatly inside the concrete cylinder and the required compaction force was applied using a manually operated hydraulic ram.

Mixes were initially batched using a small "dough" mixer but when this broke hand mixing was resorted to. Convenient amounts of material were weighed and then the required percentage of cement was mixed in with enough water to make the specimens amenable to handling after pressing. In the initial series of tests (Series A) the soil was batched oven dry as an attempt was made to more accurately investigate the effect of cement content. Later samples were batched air dry as the principal aim was to obtain correlation between field and laboratory tests. For each series of tests one batch of soil was prepared and then a set amount of mix was carefully weighed (around 3kg) and placed in the mould and compacted to a certain thickness. In this way the density of each series of tests was kept the same. Table 7.1 shows the results of a typical batch of specimens produced in this manner. In this case the mean dry density was 1830 kg /m^3 and the Coefficient of Variation was less than 1% (0.86%).

Specimens were cured under plastic in the laboratory for 28 days before being testing commenced

Table 7.1 Typical Dry Density Measurements for a Sample Batch

Specimen	Mass (g)	Diameter (mm)	Thickness (mm)	Density (kg/m^3)
M6	2608	153	77	1840
M7	2631	153	79	1815
M8	2613	153	77	1845
M9	2592	153	77	1830
M10	2603	153	77	1840
M11	2612	153	77	1845
M12	2626	153	78	1830
M13	2623	153	78	1830
M14	2614	153	79	1800

In order to correlate field and laboratory results all specimens were cut in half using a brick saw (water was used to cut down the dust). One of the cut faces was then subjected to the spray test and the other face was exposed to the weather. This meant that the faces exposed to the weather and to laboratory testing were as close as possible to being identical.

Samples were then oven dried and weighed. The spray faces were then sprayed immediately and the field specimens placed in the field.

7.5 Series A Tests (15th October 1998 - 3rd March 1999)

The test program involved mixing samples of a sandy loam with various percentages of off-white cement. Off–white cement was chosen because the specimens were to be visible to the public and it was felt that the more earthy look achieved with off-white cement would be more attractive. Soil containing these cement contents was compressed into 120 mm sections of PVC (Polyvinyl Chloride) drainage pipes.

Curing of specimens was by means of covering with plastic sheeting. Following curing for 28 days the sections of pipe were cut in half, each section being 60 mm thick. One of the cut faces was then tested in the spray test apparatus (Figure. 5.6) whilst the other face was installed in a test rack, which was located adjacent to the main runway at the test site (Figure 7.1). In all there was a total of 12 specimens, 6 of which were tested in the laboratory and 6 in the field

The laboratory specimens were tested in the spray test apparatus using the 4.4 mm nozzle at a pressure of 100 kPa. They were left in the test apparatus for varying lengths of time (Table 7.2). This was necessary in order to achieve erosion volumes that were measurable. For instance in the case of the specimen with 3% cement content, the test was stopped after 2 minutes because of severe erosion. On the other hand in the case of the 7 and 8% specimens the test was allowed to continue for a considerable length of time because of the low erosion rates. Following conducting spray testing the samples were oven dried and re-weighed to obtain the weight loss during the test.

Table 7.2 Series A Spray Testing Results

CEMENT CONTENT (%)	EXPOSURE TIME (minutes)	VOLUME OF WATER (litres)	SPRAY VELOCITY (m/sec)	WEIGHT LOSS (grams)
3	2	22	12.3	336
4	7	78	12.3	405
5	90	999	12.3	170
6	120	1332	12.3	61
7	180	1998	12.3	15
8	141	1565	12.3	4

The field specimens were inserted in the test rack shown in Figure 7.1. This rack was oriented due south and was placed adjacent to the runway at the test site from 15th October 1998 to the 3rd March 1999. The back of the rack was covered with a rigid plastic sheet to ensure that only the south face was exposed to the weather.

The wind and rain records were collected every month and analysed (See Appendix D) to produce a wind-driven rain rose (Figure 7.2) for the sample exposure period. The wind driven rain index used in this rose is the sum of the hourly rainfalls in mm times the corresponding wind speed in knots. It is clear from Figure 7.2 that the majority of the wind-driven rain during the period of sample exposure came from the south and southeast quadrants.

During the 139 days of exposure rain fell for 264 clock hours, representing 7.9% of the total clock hours for the period, or in other words an average of 1.9 rain hours per day. Most of the rain that fell (76%) had clock hour rates less than 2 mm (Figure 7.3). However 77% (403 mm) of the 524 mm of rain occurred at clock hour intensities greater than 2 mm, which means that 24% of the rainfall accounted for 77% of the rainfall. This means that the majority of the rain volume fell in less than 2% (24% × 0.079) of the time.

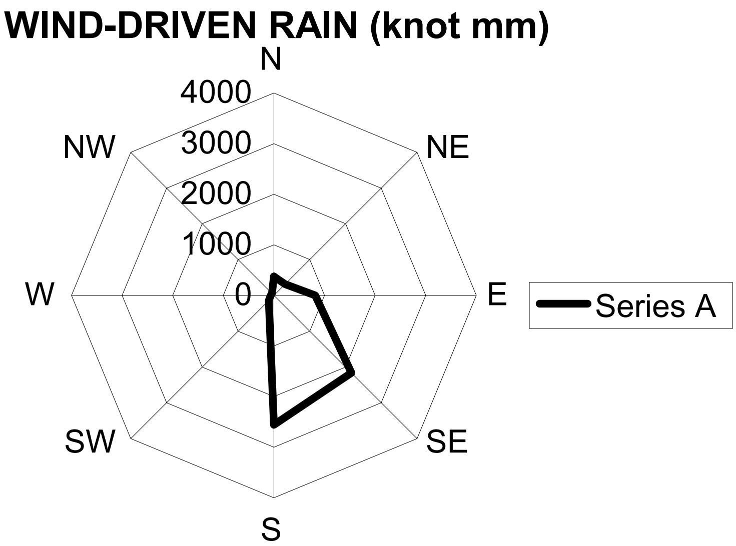


Figure 7.2 Wind Driven Rain Rose for Series A

An average wind speed of around 6m/sec was experienced during periods of rain and the maximum clock hour rainfall was 41 mm.

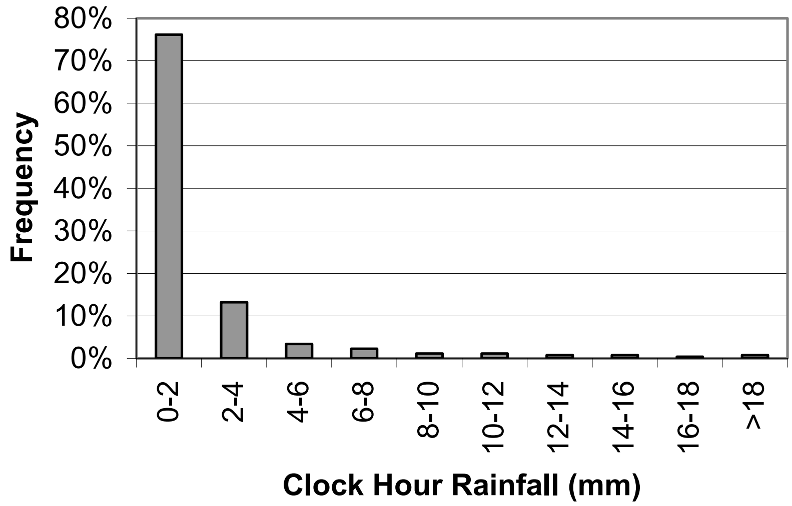


Figure 7.3 Frequency of Rainfall during Exposure Period (Series A)

The field samples were arranged in order of cement content and following the above period of exposure they were returned to the laboratory where they were oven dried and re-weighed. Figure 7.4 shows the erosion of the specimens, with specimens arranged in order with 3% on the left and 8% on the right.

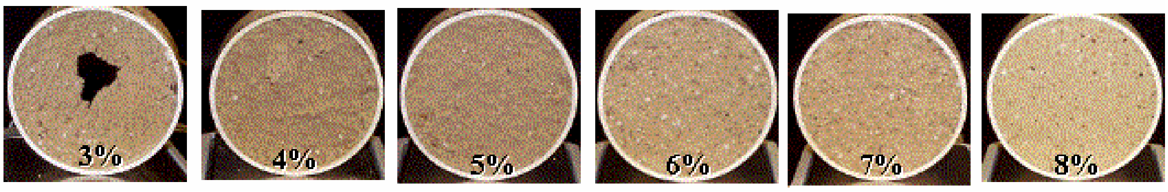


Figure 7.4 Test Specimens after Field Exposure

Figure 7.5 shows the 4% cement specimen being weighed and illustrates the degree of erosion that was achieved during the field exposure. In general the erosion profile was reasonably uniform across the surface of specimens.

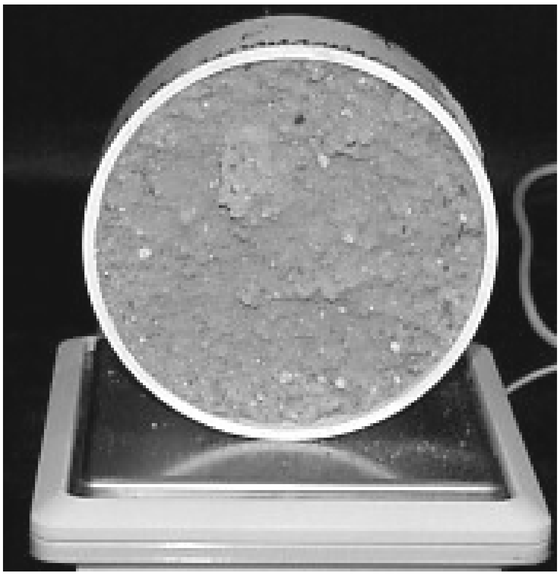


Figure 7.5 4% Cement Test Specimen Being Weighed After Period of Exposure

The loss in weight of each specimen is given in Table 7.3.

Table 7.3 Series A Field Testing Results (After 4.5 months)

CEMENT CONTENT (%)	DRIVING RAIN (m^2/sec)	AVERAGE WIND VELOCITY (m/sec)	WEIGHT LOSS (grams.)
3	2.14	6.14	662
4	2.14	6.14	343
5	2.14	6.14	148
6	2.14	6.14	66
7	2.14	6.14	43
8	2.14	6.14	31

7.6 Series B Tests (5th March 1999 – 7th July 1999)

Series B Tests consisted of the Series A specimens exposed to the weather for a further period of around 4 months (5/3/99 –7/7/99). Since the 3% cement content specimen had practically disintegrated it was replaced by a spare 5% specimen.

The distribution of rainfall during this period was similar to that which occurred for Series A, with most of the wind driven rain coming from the south (Figure 7.6). Of the

273 clock hours of rain that fell over the 124 days clock hour rates less than 2 mm occurred 82% of the time (Figure 7.7). Rainfall rates greater than 2 mm per hour accounted for 66% of the total volume of 381 mm. The average wind velocity during rainfall was 5.67 m/sec and the maximum clock hour rainfall was 18.4 mm.

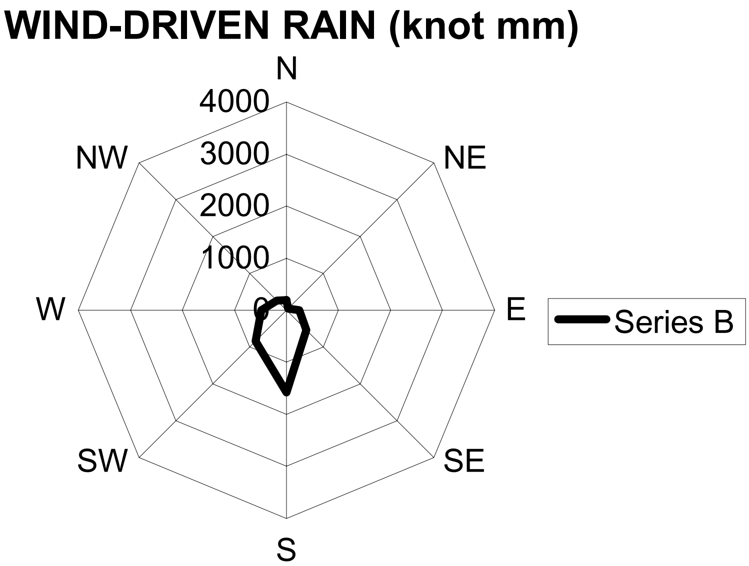


Figure 7.6 Wind Driven Rain Rose for Series B

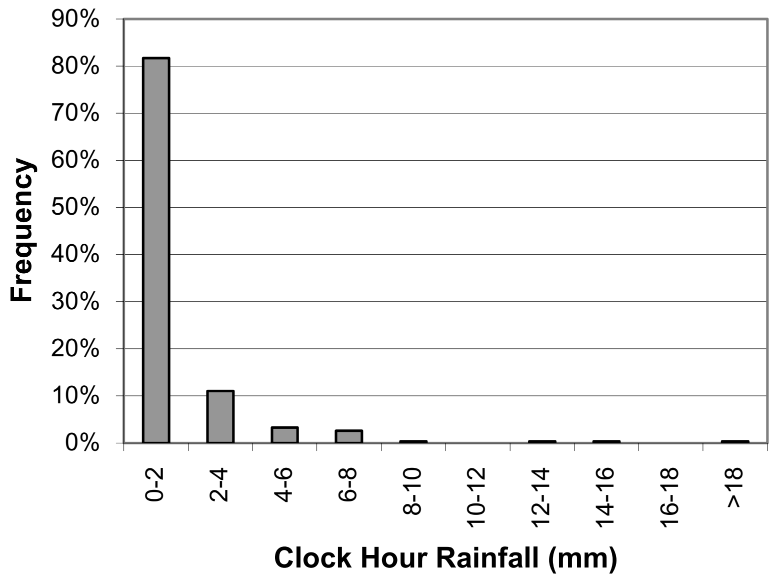


Figure 7.7 Frequency of Rainfall during Exposure Period (Series B)

Weight losses for the specimens during the period of exposure are given in Table 7.4.

Table 7.4 Series B Field Testing Results (After 4 months)

CEMENT CONTENT (%)	DRIVING RAIN (m^2/sec)	AVERAGE WIND VELOCITY (m/sec)	WEIGHT LOSS (grams.)
New 5	1.36	5.67	71
4	1.36	5.67	204
5	1.36	5.67	97
6	1.36	5.67	35
7	1.36	5.67	31
8	1.36	5.67	8

7.7 Series C Tests (7th July 1999 – 30th November 1999)

A completely new test rig was made for the Series C tests to make it easier to remove specimens for regular weighing. A photo of the rig appears below. The Series C tests comprised six specimens in the bottom row of the new test rig shown in Figure 7.8.

Figure 7.8 New Test Rack Placed at Airport in July 1999

The specimens were placed at the airport on the 7th July 1999. They consisted of specimens made from soil sourced from two sites (Belrose and Chatswood) with cement contents of 4%, 6% and 8%. As at the end of November 1999 very little erosion had occurred and the specimens were therefore removed.

Details of the spray test results (5.6 mm Nozzle) for these specimens are given in Table 7.5.

Table 7.5 Series C Spray Testing Results

SPEC. ID	SPRAY PRESSURE (kPa)	EXPOSURE TIME (minutes)	VOLUME OF WATER (litres)	SPRAY VELOCITY (m/sec)	WEIGHT LOSS (grams)
C4	70	60	570	10.3	23
B4	70	60	570	10.3	11
C6	70	60	570	10.3	8
B6	70	60	570	10.3	8
C8	70	60	570	10.3	5
B8	70	60	570	10.3	3

As for Series A and B the majority of wind-driven rain during the period of sample exposure came from the south (Figure 7.9).

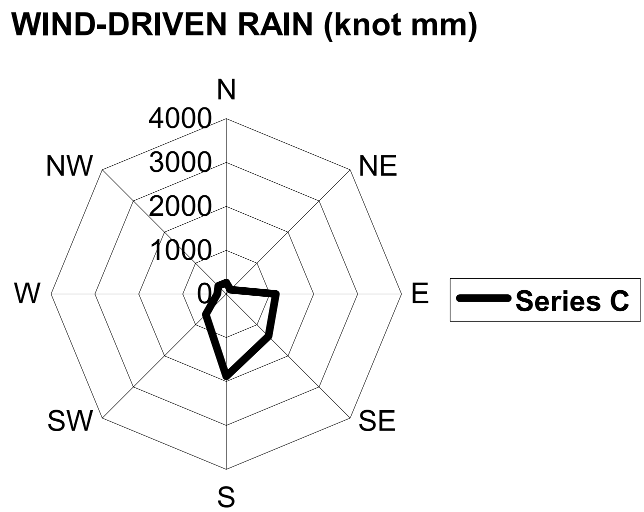


Figure 7.9 - Wind Driven Rain Rose for Series C

Of the 146 days these specimens were at the airport it rained for 6.7% of the clock hours (234 hours), producing a total of 416 mm of rain. Rainfall less than 2 mm per clock hour occurred 75% of the time (Figure 7.10) and the remaining 25% of the time produced 74% of the total volume of rain. Average wind speed was 6.27 m/sec and max clock hour rainfall was 16.8 mm.

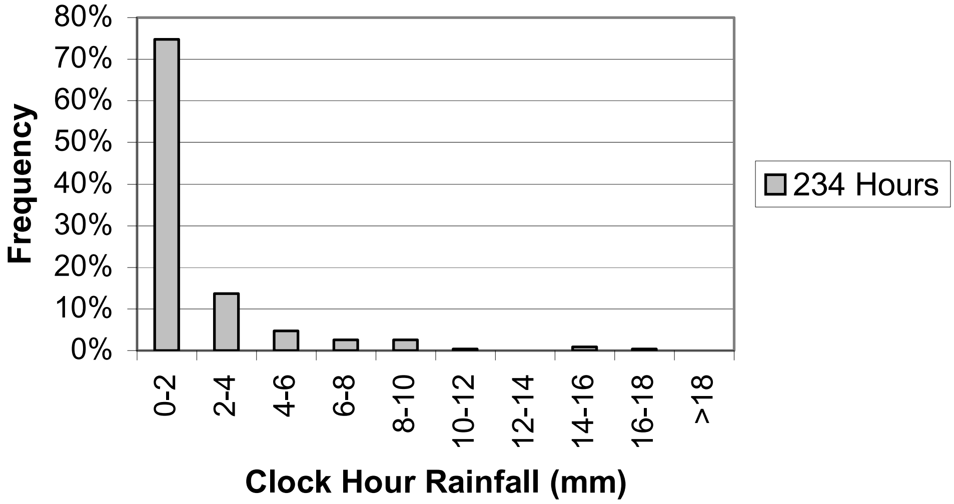


Figure 7.10 Frequency of Rainfall during Exposure Period (Series C)

Field results for the specimens are shown in Table 7.6.

Table 7.6 Series C Field Testing Results (After 4.5 months)

SPECIMEN NO	DRIVING RAIN (m^2/sec)	AVERAGE WIND VELOCITY (m/sec)	WEIGHT LOSS (grams)
ALL	1.78	6.27	Negligible

7.8 Series D Tests (20th August 1999 - 6th July 2000)

Five specimens were placed on the top row of the new rack on the 20th August 1999. Once again erosion was slow and three of these were removed on the 17th December 1999. The three specimens that were removed had been made from a clayey sand with around 4% cement content. The two remaining specimens had been made from a clayey soil (sourced from Chatswood) stabilized with 3% cement. Details of the spray test results (5.6 mm Nozzle) for these specimens are given in Table 7.7.

Table 7.7 Series D Spray Testing Results

SPEC. ID	SPRAY PRESSURE (kPa)	EXPOSURE TIME (minutes)	VOLUME OF WATER (litres)	SPRAY VELOCITY (m/sec)	WEIGHT LOSS (grams)
C1	70	15	252	10.3	89
C2	130	15	327	14.1	105

As for Series A and B the majority of wind-driven rain during the period of sample exposure came from the south (Figure 7.11).

Of the 321 days these specimens were at the airport it rained for 6.33% of the clock hours (488 Hours), producing a total of 651 mm of rain. Rainfall less than 2 mm per clock hour occurred 81% of the time (Figure 7.12) and the remaining 19% of the time produced 64% of the total volume of rain. Average wind speed was 5.97 m/sec and max clock hour rainfall was 16.8 mm.

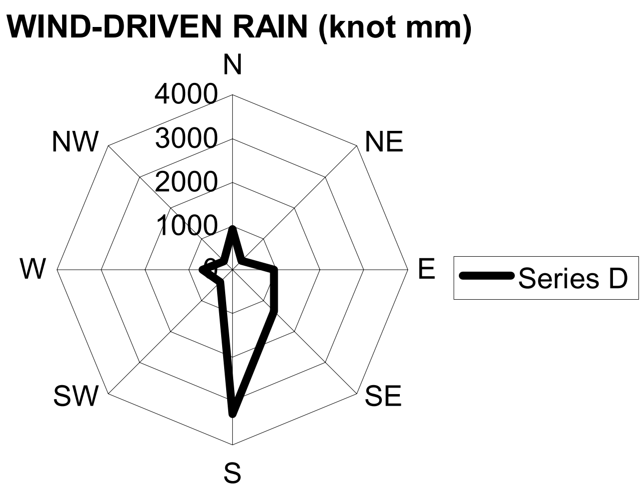


Figure 7.11 - Wind Driven Rain Rose for Series D

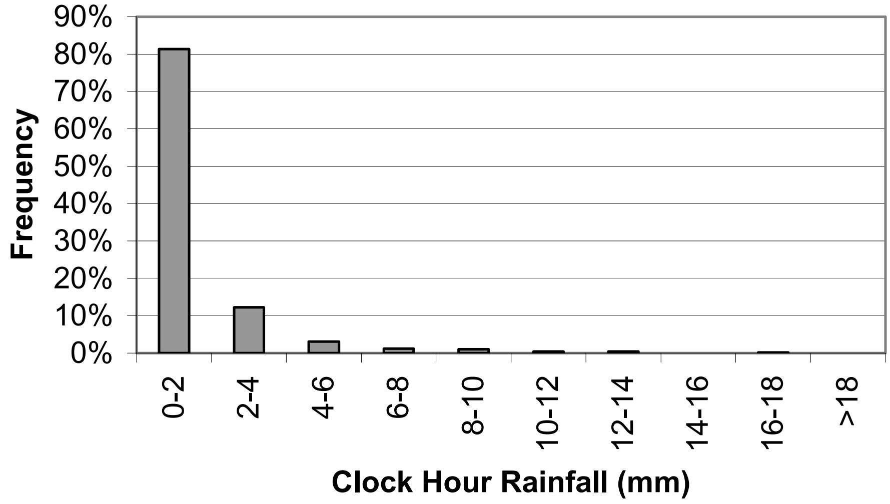


Figure 7.12 Frequency of Rainfall during Exposure Period (Series D)

Field results for the two specimens are shown in Table 7.8.

Table 7.8 Series D Field Testing Results (After 10.5 months)

SPECIMEN NO	DRIVING RAIN (m^2/sec)	AVERAGE WIND VELOCITY (m/sec)	WEIGHT LOSS (grams)
C1	2.42	5.97	112
C2	2.42	5.97	152

7.9 Series E Tests (30th November 1999 – 6th June 2000)

Series E tests involved samples previously used as part of the spray tests to examine the effect of velocity on erosion in the laboratory. Specimens 1 to 6 were made from a sandy loam overburden material sourced from an excavation site at Belrose This soil was used to make pressed earth blocks for a student project at Marrickville in Sydney. Specimens 7 to 11 were made using a "Brickies" sand, i.e., a fatty sand used for laying bricks.

Four of the specimens (Specimen numbers 1, 2, 11 & 9) were placed on the bottom row on the 30th November 1999. The remaining five, 2 on the bottom row (Nos 3 & 7) and three on the top row (Nos 5,6 & 10) were placed on the 17th December 1999.

All the specimens had been previously spray tested using the 5.6 mm nozzle as part of the laboratory tests into the effect of varying velocity on erosion. The results of the spray testing are given in Table 7.9.

Table 7.9 Series E Spray Testing Results

SPEC.ID. / EXP.FACE	SPRAY PRESSURE (kPa)	EXPOSURE TIME (minutes)	VOLUME OF WATER (litres)	SPRAY VELOCITY (m/sec)	WEIGHT LOSS (grams)
Marrick ville					
1B/South	60	42	676	10.9	39
2B/South	60	42	676	10.9	24
3B/South	60	42	676	10.9	41
5B/South	60	42	676	10.9	40
6B/South	60	42	676	10.9	37
Brickies Sand					
7B/South	60	14	225	10.9	43
9B/South	60	14	225	10.9	39
10B/South	60	14	225	10.9	49
11B/South	60	14	225	10.9	42

Analysis of the climatic data for the exposure period illustrated once again the predominance of driving rain from the southerly sector (Figure 7.13).

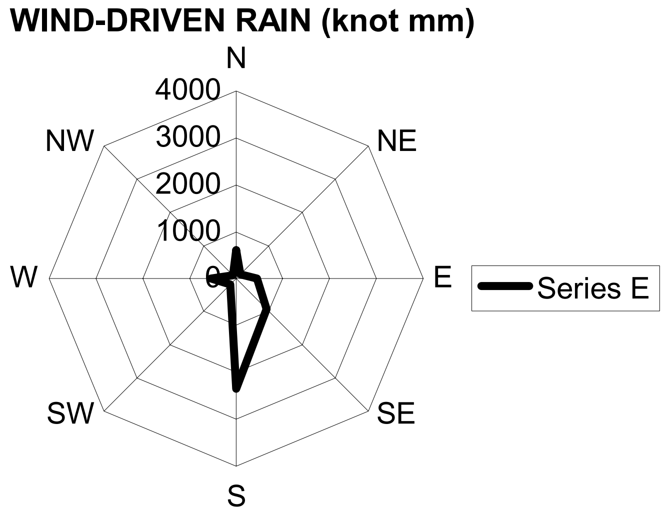


Figure 7.13 - Wind Driven Rain Rose for Series E

The specimens were subjected to 415 mm of rain over a period of 330 clock hours. The latter time represented 6.8% of the total of 202 days of exposure. 83% of the time when rain occurred it was less than 2 mm per clock hour (Figure 7.14), with the maximum clock hour rainfall being 12.4 mm. 63% of the volume of rainfall during this time was caused by the remaining 17% of the rain greater than 2 mm per clock hour. Average wind speed was 6.02 m/sec.

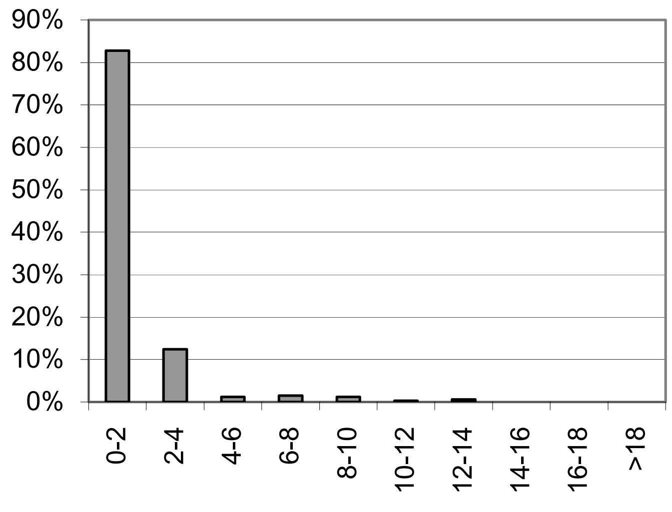


Figure 7.14 Frequency of Rainfall during Exposure Period (Series E)

Erosion of these specimens was slow and the average erosion depth over most of the specimens was only about 1.5 mm. This was most probably due to their higher cement content of around 4 %. They were removed on the 6th June 2000. Field test results are shown in Table 7.10.

Table 7.10 Series E Field Testing Results (After 6 months)

SPEC.ID	DATE PLACED	DRIVING RAIN (m^2/sec)	DATE REMOVED	INITIAL DRY WEIGHT (grams)	FINAL DRY WEIGHT (grams)	WEIGHT LOSS (grams)
M'Ville						
1	30/11/9	1.65	6/7/2000	1221	1201	20
2	30/11/9	1.65	6/7/2000	1174	1135	39.
3	17/12/9	1.65	6/7/2000	1193	1154	39
5	17/12/9	1.65	6/7/2000	1134	1102	32
6	17/12/9	1.65	6/7/2000	1217	1171	46
Brickies Sand						
7	17/12/9	1.65	6/7/2000	1219	1176	43
9	30/11/9	1.65	6/7/2000	1203	1181	22
10	17/12/9	1.65	6/7/2000	1201	1173	28
11	30/11/9	1.65	6/7/2000	1202	1152	50

7.10 Series FB (14th August 1999 – 13th March 2001)

A new set of specimens with 3% cement were made out of a clayey sand and were placed in the bottom row on the 14th August 2000.

The opposite faces of the specimens were sprayed using the 1550 (4.4 mm) nozzle at a pressure of 70 kPa for 60 minutes. The results of the spray tests are given in Table 7.11.

In general wind driven rain during the period of exposure was more to the east (Figure 7.15) than in the previous series of tests.

Table 7.11 Series FB Spray Testing Results

SPECIMEN NO	EXPOSURE TIME (minutes)	VOLUME OF WATER (litres)	SPRAY VELOCITY (m/sec)	WEIGHT LOSS (grams)
6A	60	570	10.5	69
7A	60	570	10.5	75
8A	60	570	10.5	58
9A	60	570	10.5	64
10A	60	570	10.5	78
11A	60	570	10.5	54

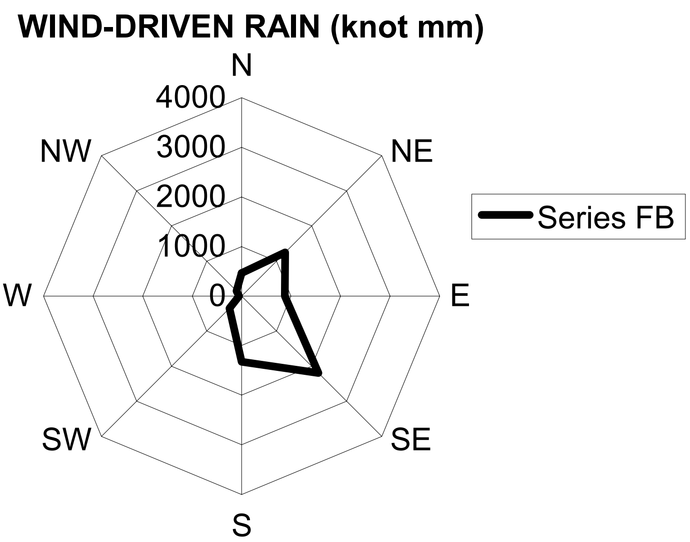


Figure 7.15 - Wind Driven Rain Rose for Series FB

Of the 211 days these specimens were at the airport it rained for 5.85 % of the clock hours (296 Hours), producing a total of 546 mm of rain. Rainfall less than 2 mm per clock hour occurred 78% of the time (Figure 7.16) and the remaining 22% of the time produced 73% of the total volume of rain. Average wind speed was 5.97 m/sec and max clock hour rainfall was 37 mm.

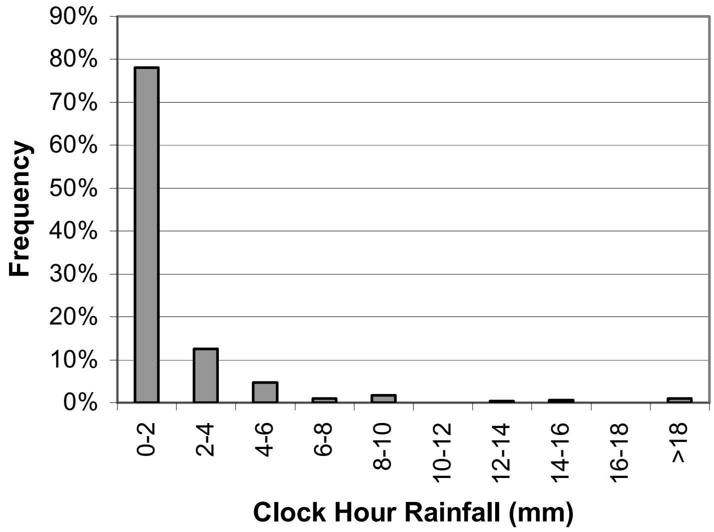


Figure 7.16 Frequency of Rainfall during Exposure Period (Series FB)

Field results for Series FB are given in Table 7.12

Table 7.12 Series FB Field Testing Results (After 7 months)

SPEC NO	WEIGHT 14/8/2000 (grams)	WEIGHT 13/3/01 (grams)	WEIGHT LOSS (grams)	DRIVING RAIN (m^2/sec)	AVERAGE WIND VELOCITY (m/sec)
6B	1291	1222	69	1.64	5.97
7B	1160	1093	67	1.64	5.97
8B	1274	1211	63	1.64	5.97
9B	1275	1189	86	1.64	5.97
10B	1287	1247	40	1.64	5.97
11B	1241	1179	62	1.64	5.97

7.11 Series FT (6^{th} July 2000 – 16^{th} May 2001)

The opposite faces of the top row specimens were spray tested using the 1590 (5.6 mm) nozzle for a period of 30 minutes at a pressure of 70 kPa. Results are given in Table 7.13.

Table 7.13 Series FT Spray Testing Results

SPECIMEN NO	EXPOSURE TIME (minutes)	VOLUME OF WATER (litres)	SPRAY VELOCITY (m/sec)	WEIGHT LOSS (grams)
1A	30	504	11.5	92
2A	30	504	11.5	62
3A	30	504	11.5	75
4A	30	504	11.5	72
5A	30	504	11.5	77

Quite heavy wind-driven rain occurred during the period of exposure, mainly from the south and southeast quarters (Figure 7.17).

Of the 344 days these specimens were at the airport it rained for 5.5% of the clock hours (455 Hours), producing a total of 883 mm of rain. Rainfall less than 2 mm per clock hour occurred 75% of the time (Figure 7.18) and the remaining 25% of the time produced 75% of the total volume of rain. Average wind speed was 6.30 m/sec and max clock hour rainfall was 37 mm.

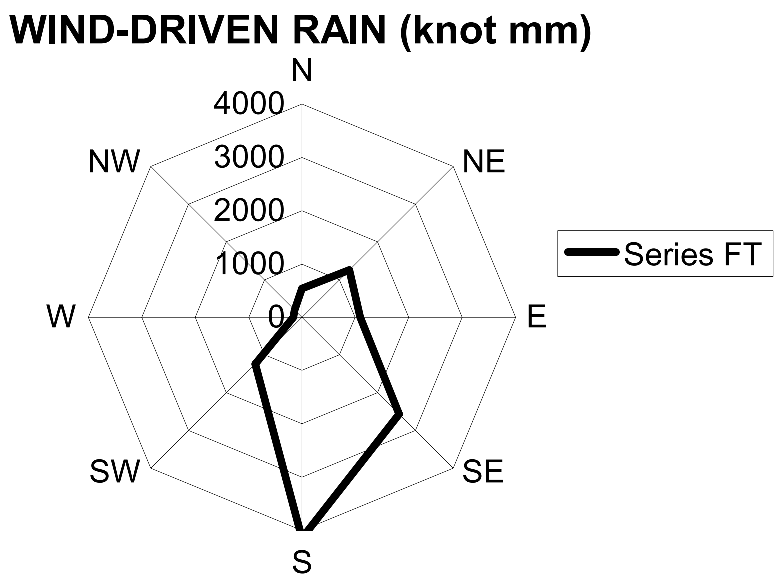


Figure 7.17 - Wind Driven Rain Rose for Series FT

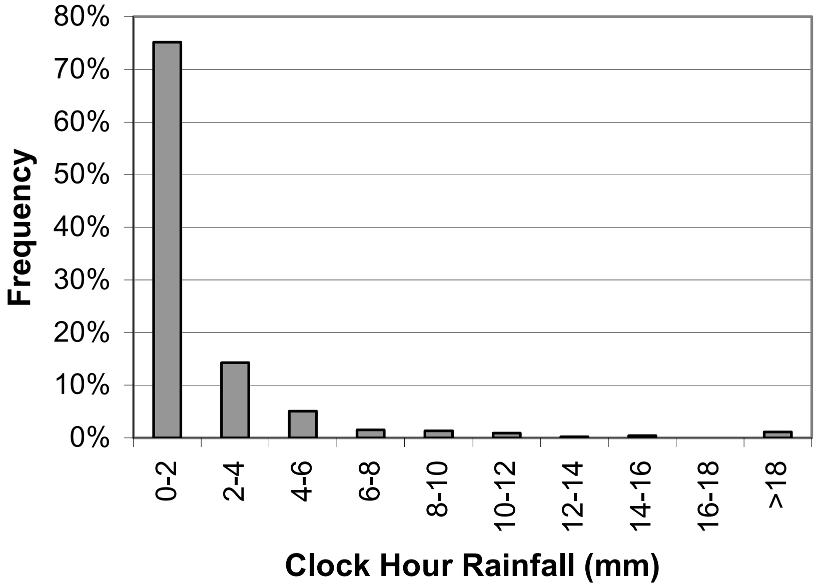


Figure 7.18 Frequency of Rainfall during Exposure Period (Series FT)

Field results for Series FT are given in Table 7.14.

Table 7.14 Series FT Field Testing Results (After 10 months)

SPEC NO	WEIGHT 6/7/2000 (grams)	WEIGHT 16/05/2001 (grams)	WEIGHT LOSS (grams)	DRIVING RAIN INDEX (m^2/sec)	AVERAGE WIND VELOCITY (m/sec)
1B	1377	1291	86	3.61	6.3
2B	1579	1509	70	3.61	6.3
3B	1416	1336	80	3.61	6.3
4B	1473	1392	81	3.61	6.3
5B	1440	1357	83	3.61	6.3

7.12 Series G (16th May 2001 – 10th December 2001)

Six specimens made from the Marrickville soil were placed in the bottom row of the test rig on the 16th May 2001. The opposite faces of specimens were spray tested using the

1550 (4.4 mm) nozzle for a period of 60 minutes with varying pressures. The results appear as Table 7.15.

Table 7.15 Series G Spray Testing Results

SPECIMEN NO	PRESSURE (kPa)	VOLUME OF WATER (litres)	SPRAY VELOCITY (m/sec)	WEIGHT LOSS (grams)
G1A	70	570	10.3	30
G2A	70	570	10.3	25
G3A	70	570	10.3	24
G4A	70	570	10.3	24
G5A	120	726	13.3	36
G6A	120	726	13.3	44

Wind-driven rain was again predominantly from the south, as can be seen from Figure 7.19.

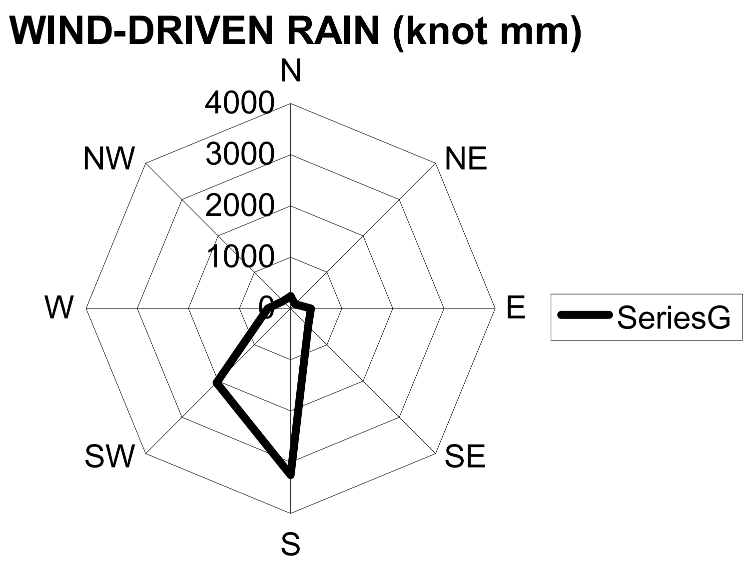


Figure 7.19- Wind Driven Rain Rose for Series G

Of the 208 days these specimens were at the airport it rained for 7.9% of the clock hours (392 Hours), producing a total of 512 mm of rain. Rainfall less than 2 mm per clock hour occurred 83% of the time (Figure 7.20) and the remaining 17% of the time produced 60% of the total volume of rain. Average wind speed was 7.41 m/sec and max clock hour rainfall was 11.8 mm.

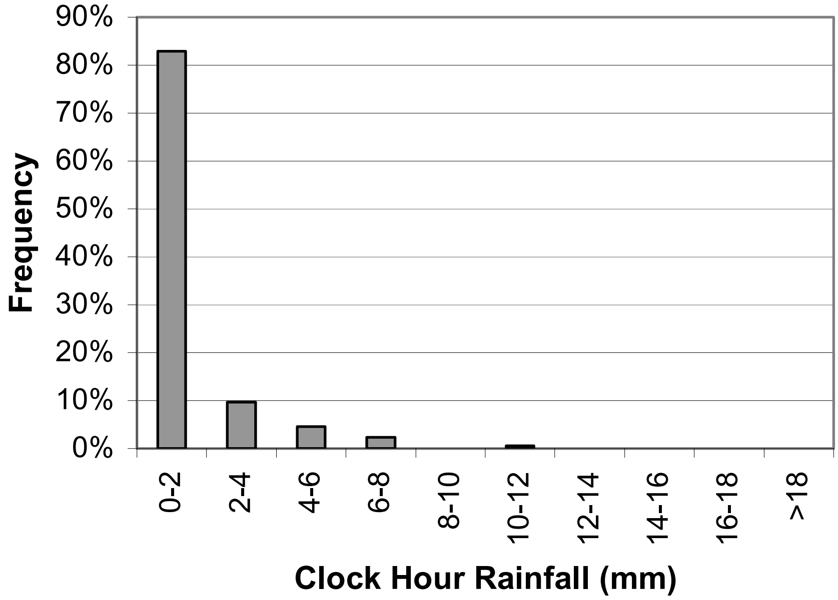


Figure 7.20 Frequency of Rainfall during Exposure Period (Series G)

Weight losses during the period of exposure are given in Table 7.16.

Table 7.16 Series G Field Testing Results (after 7 months)

SPEC NO	WEIGHT 16/5/2001	WEIGHT 10/12/2001	WEIGHT LOSS (grams)	DRIVING RAIN INDEX (m^2/sec)	AVERAGE WIND VELOCITY (m/sec)
G1B	1026	1007	19	2.67	7.41
G2B	1024	1010	14	2.67	7.41
G3B	1129	1113	16	2.67	7.41
G4B	1014	995	19	2.67	7.41
G5B	1107	1084	23	2.67	7.41
G6B	1109	1090	19	2.67	7.41

7.13 Summary

In general weight losses of specimens during spray testing varied quite significantly with cement content, soil type, nozzle diameter, spray pressure and duration of exposure to the spray. Nozzle diameter and spray pressures were deliberately varied to test their effect in relation to performance in the field.

The climatic data, on the other hand showed considerable consistency during the three years of testing, with the predominant wind-driven rain coming from the south or southeast. Table 7.17 summarises some of the climatic factors during each series of tests.

Average hourly rainfall during periods of rain was around 1.67 mm (+/- 0.33 mm) and in almost all cases the average wind speed during rain, with the exception of Series G, varied little from a value of 6 m/sec. The average Driving Rain Index per hour of rainfall was 0.0065 m^2/s (+/- 0.0015m^2/s), which equates to around 1 litre/m^2/hr if a Driving Rain Factor of 150 is assumed.

Table 7.17 Summary of Climatic Conditions

Series	% Time Rainfall	Average Hourly Rainfall (mm)	% Vol of Rain for Rainfall > 2 mm/hr	DRI	DRI /Hr of Rain (m^2/s)	Average Wind Speed (m/s)
A	7.9	1.98	77	2.14	0.0081	6.00
B	9.2	1.40	66	1.36	0.0050	5.67
C	6.7	1.78	74	1.78	0.0076	6.27
D	6.3	2.03	64	2.42	0.0050	5.97
E	6.8	1.26	63	1.65	0.0050	6.02
FB	5.9	1.84	73	1.64	0.0078	5.97
FT	5.5	1.94	75	3.61	0.0079	6.30
G	7.9	1.31	60	2.67	0.0068	7.41

Chapter 8 Evaluation of Experimental Data.

8.1 Introduction

The central premise of this investigation is that the durability of earth walls in the field can be accurately predicted by the performance of test specimens in the laboratory.

Chapter 7 presented the results of field tests on specimens whereby matching halves of specimens were exposed to weather in the field and to the spray test.

This Chapter will develop a theoretical model of the erosional behaviour of earth walls based on the work presented in Chapters 3, 4 and 6, and test its applicability using the data presented in Chapter 7. A methodology will then be presented detailing how such a model might be used in practical situations.

8.2 Theoretical Considerations

8.2.1 Determination of Field Erosion Model

It was demonstrated in Chapter 6 in the spray tests that the erosion of specimens due to impacting water droplets per unit volume of impacting water is equal to the 60 minute erosion per unit volume multiplied by a time function as follows

$$\frac{E}{Q} = \frac{E_{60}}{Q_{60}} \times f(t) \qquad \text{.........}(6.8)$$

where

E = Erosion of specimens at time t (g)

Q = Quantity of water impacting specimens at time t (l)

E_{60} = 60 minute spray erosion (g)

Q_{60} = 60 minute spray volume (l)

f(t) = Time function as per Equation 6.9

The ratio $\frac{E_{60}}{Q_{60}}$ is the relative erosion per unit volume of impacting water for a 60 minute duration of liquid impact. It is a function of the material properties.

f(t) indicates the variation of erosion with time and is based on the work presented in Chapter 6. The fact that f(t) is reasonably consistent over such a large range of final erosions (28g to 104g) lends support to its consistency, although more testing could be carried out by others to confirm the general validity of this statement. For the sake of this presentation however, f(t) will be assumed to be independent of material properties.

Equation 6.8 assumes a constant impact velocity (v) and drop diameter (d). It was shown in Chapter 6 however that, as a best approximation, $\frac{E}{Q}$ can be assumed to be proportional to $v^{2.5}$ and $d^{(-1.2)}$.

Adopting a reference value of d* for drop diameter and v* for impact velocity, Equation 6.5 can therefore be expanded to

$$\frac{E}{Q} \propto \frac{E_{60}}{Q_{60}} \times f(t) \times \left(\frac{v}{v^*}\right)^{2.5} \times \left(\frac{d^*}{d}\right)^{1.2} \qquad \text{……….}(8.1)$$

This equation is assumed to apply equally as well to the spray tests as to the field tests. Therefore

$$\frac{E_{Lab}}{Q_{Lab}} \propto \frac{E_{60}}{Q_{60}} \times f(t_{Lab}) \times \left(\frac{v_{Lab}}{v^*}\right)^{2.5} \times \left(\frac{d^*}{d_{Lab}}\right)^{1.2} \qquad \text{……….}(8.2)$$

and

$$\frac{E_{Field}}{Q_{Field}} \propto \frac{E_{60}}{Q_{60}} \times f(t_{Field}) \times \left(\frac{v_{Field}}{v^*}\right)^{2.5} \times \left(\frac{d^*}{d_{Field}}\right)^{1.2} \qquad \text{……….}(8.3)$$

where

t_{Field} = Representative storm duration, reflecting the fact that the erosion rate during storms is not constant in the field.

t_{Lab} = Exposure time in spray test (min)

v_{Field} = Representative impact velocity of raindrops in the field

d_{Field} = Representative raindrop diameter in the field.

E_{Field} = Erosion of specimens in the field (g)

Q_{Field} = Volume of water impacting specimens in the field (l)

Equating Equations 8.2 and 8.3 yields

$$E_{Field} \propto Q_{Field} \times \frac{E_{Lab}}{Q_{Lab}} \times \frac{f(t_{Field})}{f(t_{Lab})} \times \left(\frac{v_{Field}}{v_{Lab}} \right)^{2.5} \times \left(\frac{d_{Lab}}{d_{Field}} \right)^{1.2} \quad \ldots\ldots\ldots(8.4)$$

but $$\frac{E_{60}}{Q_{60}} = \frac{E_{Lab}}{Q_{Lab}} \div f(t) \quad \ldots\ldots\ldots\ldots\ldots..(6.8)$$

Therefore

$$E_{Field} \propto Q_{Field} \times \frac{E_{60}}{Q_{60}} \times f(t_{Field}) \times \left(\frac{v_{Field}}{v_{Lab}} \right)^{2.5} \times \left(\frac{d_{Lab}}{d_{Field}} \right)^{1.2} \quad \ldots\ldots\ldots(8.5)$$

or

$$\mathbf{E_{Field} = K \times E^*} \quad \ldots\ldots\ldots(8.6)$$

where

E_{Field} = Predicted Field Erosion (g)

K = Proportionality Constant

$$E^* = Q_{Field} \times \frac{E_{60}}{Q_{60}} \times f(t_{Field}) \times \left(\frac{v_{Field}}{v_{Lab}} \right)^{2.5} \times \left(\frac{d_{Lab}}{d_{Field}} \right)^{1.2} \quad \ldots\ldots\ldots.(8.7)$$

Equation 8.6 will form the basis for the prediction of field performance of the test specimens in Chapter 7 based on their spray test results. The ratio $\frac{E_{60}}{Q_{60}}$ is dependent on the material properties and will be referred to as a "Material Factor"

8.2.2 Alternative Derivation of Model

Equation 8.1 forms the basis of Equation 8.5 and can be derived in another way, using the formula for impingement rate presented in ASTM G73 (1998), which is outlined in Section 3.5.7 of this investigation.

If one assumes that the rate of erosion is dependent on the impingement rate (U_i), a material factor F_m, and a function of the impacting velocity (v), and varies over time according to some function f'(t), then Equation 8.8 can be postulated

$$\partial e/\partial t = U_i \times F_m \times f(v) \times f'(t) \qquad \ldots\ldots\ldots.(8.8)$$

where

$\partial e/\partial t$ = Rate of Erosion with respect to time

U_i = Drop Impingement Rate = $K \times \dfrac{I \times \left(\bar{v}\, Cos\theta\right)}{\bar{d}^{\,a}}$ [Equation 3.25]

I = Rainfall or Spray intensity

$\bar{d}$ = Representative drop diameter

θ = Angle of impact of raindrops relative to normal

$\bar{v}$ = Representative impacting drop velocity and

a = Constant

Assuming that $f(v) \propto \bar{v}^{\,b}$, and E = Total Erosion = ∫∂e/∂t.dt, equation 8.8 becomes

$$E \propto F_m \times \frac{I \times \bar{v}^{\,b} \times \left(v \times Cos\theta\right) \times \int f'(t)dt}{\bar{d}^{\,a}} \qquad \ldots\ldots\ldots.(8.9)$$

Furthermore, assuming that the volume of water impacting a vertical surface over a certain time (t) is a linear function of the driving rain index [I × u or I × ($\bar{v}$ × Cosθ)], times t ,i.e.

$$Q = I \times \bar{v} \times \cos\theta \times t \qquad \text{.........}(8.10)$$

then erosion per unit volume of impacting water can be expressed as

$$\frac{E}{Q} \propto F_m \times \frac{\bar{v}^{\,b}}{\bar{d}^{\,a}} \times f(t) \qquad \text{.........}(8.11)$$

Where

E = Total erosion

Q = Volume of impacting water

F_m = Material Constant

$\bar{v}$ = Representative impacting water velocity

b = Constant = 2.5 from Chapter 6

θ= Angle of impact

$\bar{d}$ = Representative drop diameter

a = Constant = 1.2 from Chapter 6

$f(t) = \frac{\int f'(t)dt}{t}$ From Equation 6.6 since $E = \int \partial e/\partial t.dt$

Equation 8.11 is identical to Equation 8.1 if the material constant is defined as $\frac{E_{60}}{Q_{60}}$, and essentially says that the erosion of earth walls is proportional to the quantity of water impacting the wall, times a material factor, times an intensity factor (which depends on impact angle, impact velocity and drop diameter), and varies with duration of impact according to a function f (t).

8.2.3 Determination of Impacting Water from Field Data

Chapter 4 sets out how Q_{Field} may be calculated from the measured rainfall intensity and the wind velocity through the use of a Driving Rain Index. In summary

$$Q_{Field}\ (l) = \text{Driving Rain Factor} \times \text{Driving Rain Index}\ (m^2/sec) \qquad \ldots\ldots\ldots(8.12)$$

A Driving Rain Factor of 150 will be assumed in this investigation based on the measurements carried out at the site as presented in Chapter 4.

8.2.4 Choice of Representative Raindrop Diameters

From the tests carried out by the author, presented in Chapter 6, erosion per unit volume of impinging water is inversely proportional to the median drop diameter raised to the power of 1.2.

The median drop size assumed in spray testing (d_{Lab}) is 1.1 mm for the 1550 (4.4 mm) nozzle and 2.5 mm for the 15150 (5.6 mm) nozzle.

The representative raindrop diameter in the field during a storm (d_{Field}) will vary roughly from 1 to 6 mm. From Figure 3.5 it can be seen that the average mean raindrop velocity over the normal range of rainfall intensities is around 2.6 mm, and therefore this value will be used in any subsequent analysis.

8.2.5 Determination of Representative Impact Velocities

From the tests carried out by the author, outlined in Chapter 6, erosion per unit volume of impinging water is proportional to impact velocity raised to the power of 2.5.

The spray velocity in the laboratory tests (v_{Lab}) is determined from the flow rate of the nozzle at the pressure of testing as outlined in Chapter 5.

In the field it was assumed that the representative impinging velocity (v_{Field}) is a vector addition of the gust wind velocity at the height of the test specimens (1 metre) for the test period and a representative raindrop velocity. The gust wind velocity was taken as

60% greater than the mean 10 metre wind velocity in accordance with Section 4.3.2. A representative raindrop velocity of 7.2 m/sec was used based on the assumed mean raindrop size of 2.6 mm. Therefore

$$v_{Field} = \sqrt{(7.2^2 + (1.6 \times \text{Mean Wind Speed for Test Period})^2)} \quad \ldots\ldots\ldots.(8.13)$$

8.2.6 Choice of Representative Storm Duration (t_{Field})

The erosion rate is the slope of the erosion versus time curve, and will vary significantly during a storm. In general the highest rainfall intensities occur over a short period of time, and normally a 5 minute intensity is taken for stormwater design purposes. Figure 8.1 indicates the variation in relative rainfall intensity (relative to 5 minutes) versus storm duration for a 20-year storm in Sydney.

If one assumes that the predominant erosion occurs during the upper third relative rainfall intensity (y = 0.67) then a representative storm duration of around 20 minutes is indicated. This value corresponds to an average erosion rate equal to that 10 minutes after a storm commences.

The choice of a representative storm duration is nor critical to the model presented in Equation 8.6, as this equation assumes it will be consistent across all storms. Any error in the assumption of t_{Field} therefore will only effect the proportionality constant (K), and a value of 20 minutes was adopted as a "best guess" estimate, yielding a value of 2.39 for $f(t_{Field})$.

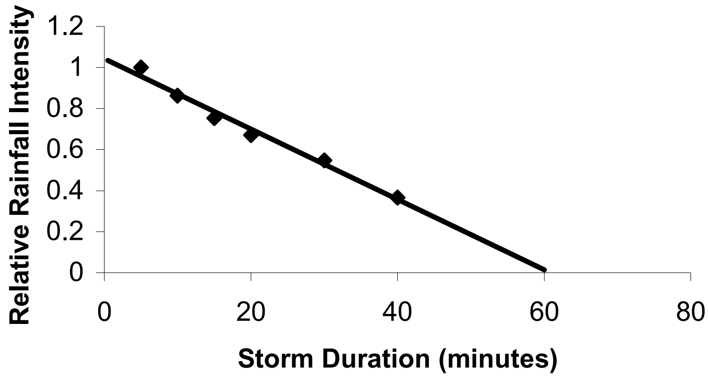


Figure 8.1 Relative Rainfall Intensity versus Storm Duration

8.3 Model Verification

In order to test the theoretical model presented as Equation 8.6, reference will be made to the field tests outlined in Chapter 7, whereby matching halves of specimens were subjected to both laboratory and field testing.

8.3.1 Effect of Volume of Impacting Water

One of the central propositions of this investigation is that, all things being equal, the erosion of specimens in the field is proportional to the volume of impinging rain as determined by the driving rain index. This is reflected in Equation 8.5, which, assuming a constant representative storm duration, constant material properties and constant mean field and laboratory impact velocities and drop sizes, reduces to

$$E_{Field} \propto Q_{Field} \qquad \text{.........}(8.14)$$

The assumption regarding a constant $f(t_{Field})$ assumes that increased rainfall will be associated with more rainfall events, and that the representative storm duration will be the same in all these events.

In order to test Equation 8.14 the specimens used in Series A tests were subjected to a further period in the field (Series B) to see whether there was any correlation between the erosion in both cases and their respective driving rain indices. From Chapter 7 it can be seen that the average wind speed during the periods of exposure was reasonably similar, and therefore the effect of wind speed will be small, as would the effect of any variation in raindrop size. Since the same specimens were used $\frac{E_{60}}{Q_{60}}$ will obviously be the same in both Series as well. Therefore, in accordance with Equation 8.5

$$(\frac{E_{Field}}{Q_{Field}})^{A} = (\frac{E_{Field}}{Q_{Field}})^{B} \qquad \text{...........}(8.15)$$

Figure 8.2 shows a plot of the weight loss per unit of driving rain for Series A and Series B. The best fit linear curve shows that the data fits Equation 8.15 to within 5 %.

The Pearson Correlation Coefficient (r) for the two series is 0.99, indicating an extremely high degree of correlation between the weight loss in the field and the driving rain index.

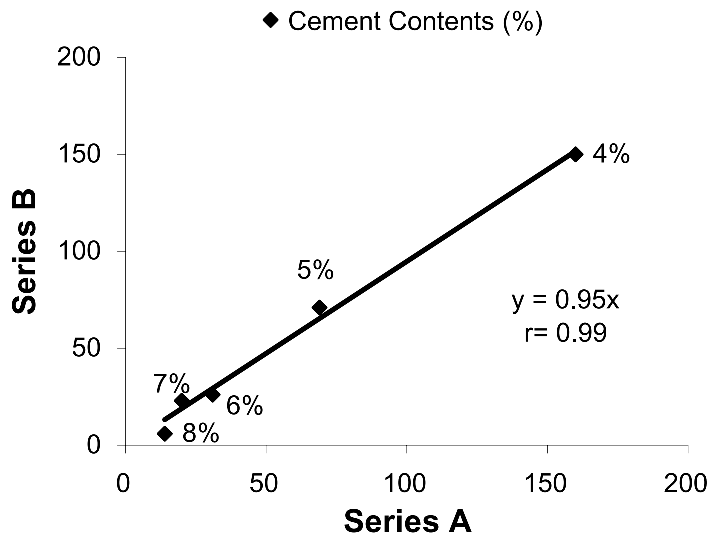


Figure 8.2 Weight Loss per unit of DRI

Based on these results it is apparent that, as assumed, weight loss is linearly related to the volume of impacting water.

8.3.2 Effect of Material Factor

In Equation 8.5 the material factor is defined as $\frac{E_{60}}{Q_{60}}$.

The Series A test was initially set up to investigate the effect of material properties on erosion. Since in this case we can assume that field and laboratory conditions are the same for all 6 specimens, Equation 8.6 reduces to

$$E_{Field} = K \times Q_{Field} \times \frac{E_{60}}{Q_{60}} \qquad \text{.........}(8.16)$$

or

$$\frac{E_{Field}}{Q_{Field}} = K \times \frac{E_{60}}{Q_{60}} \qquad \text{.........}(8.17)$$

Note that the specimens were sprayed for different lengths of time so the laboratory erosions (E_{lab}) have to be converted to 60-minute values (E_{60}) using equation 6.3.

Equation 8.17 is plotted in Figure 8.3 for the various cement contents in the Series A data. It demonstrates a high degree of correlation between the two factors $\frac{E_{60}}{Q_{60}}$ and $\frac{E_{Field}}{Q_{Field}}$ (r = 0.96) with a factor of 1.39 for K. This factor presumably accounts for such factors as antecedent moisture conditions and variations in the angle of impact of raindrops in the field. Figure 8.3 indicates that the assumption of a linear relationship between erosion in the field and the material factor $\frac{E_{60}}{Q_{60}}$ is correct, at least for the soil used in this series of tests.

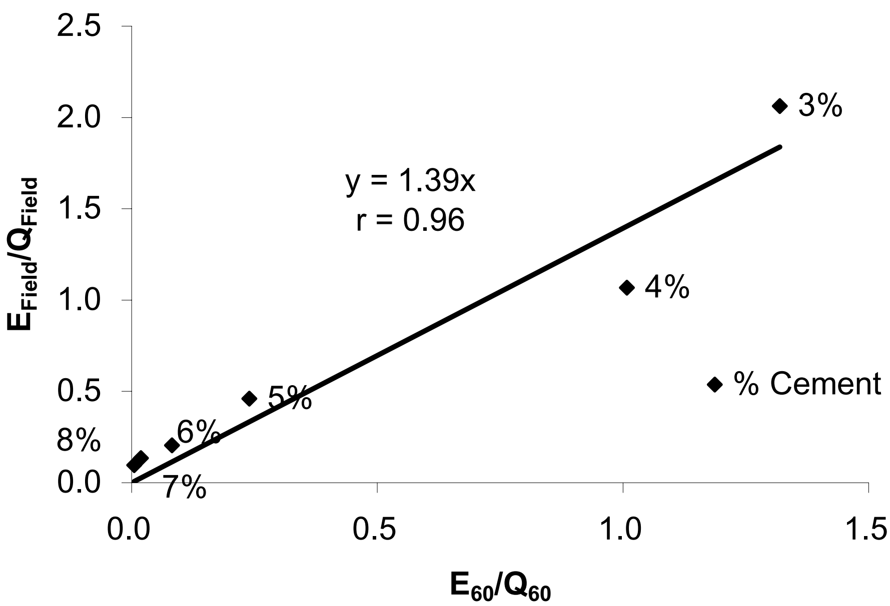


Figure 8.3 Relationship Between Field Erosion and Material Factor

The results of the Series A tests indicate that the material factor $\frac{E_{60}}{Q_{60}}$ is closely linked to the cement content of the specimens (Figure 8.4), as would be expected. Figure 8.4 indicates the strong effect cement content has on erosion. It indicates a marked increase in erosion (decrease in durability) for cement contents below 5%. The relationship for other soils may be different but generally this is a trend that could have been expected from previous work done by Heathcote and Piper (1994) which indicated a minimum cement content of 1% for stabilisation of earth walls.

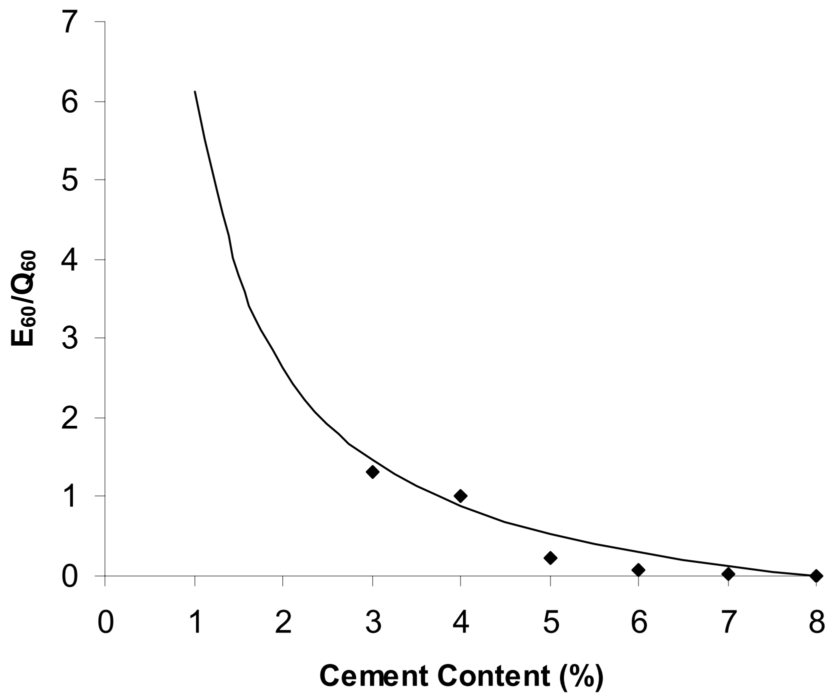


Figure 8.4 Relationship Between Cement Content and Material Factor

The relationship between cement content and E_{60}/Q_{60} shown in Figure 8.4 has the form

$$E_{60}/Q_{60} = \frac{7}{C} - 0.875 \qquad \text{..................}(8.18)$$

Where

C = Cement % by Mass

The Correlation Coefficient for this relationship (r) is 0.98.

8.3.3 Analysis of Series A, B, D, E, FB, FT and G Data

All of the data collected over the three-year period of testing (series A to G), with the exception of Series C, were analysed in accordance with Equation 8.6. The results are presented in Table 8.1 and plotted in Figure 8.5. The Series C results were excluded as the measured laboratory erosions were very small and the field erosions were negligible but not recorded.

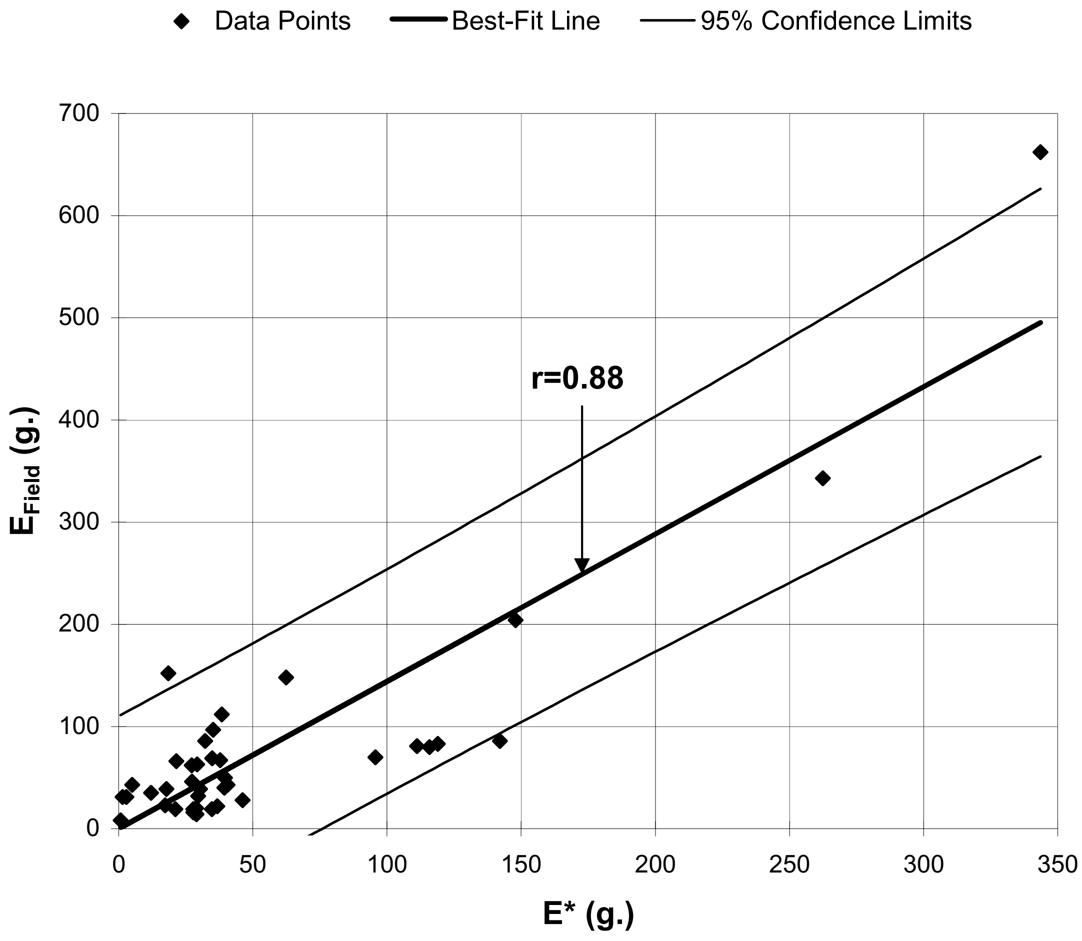


Figure 8.5 Variation Between E* and Measured Field Erosion

The best-fit linear equation for the results is

$$E_{Field} = 1.44 \times E^{*} = 1.44 \times Q_{Field} \times \frac{E_{60}}{Q_{60}} \times f\left(t_{Field}\right) \times \left(\frac{v_{Field}}{v_{Lab}}\right)^{2.5} \times \left(\frac{d_{Lab}}{d_{Field}}\right)^{1.2} \quad \ldots\ldots(8.19)$$

Table 8.1 Calculation of Predicted Erosion Values – All Series

Series	DRI	Q (litres)	V_{Field}	V_{lab} (m/s)	d_{50} (Lab)	E (Lab)	$t_{(lab)}$ (min)	K_1 (l/min)	E_{60}/Q_{60}	$(v_{Field}/v_{Lab})^{2.5}$	$(d_{Lab}/d_{Field})^{1.2}$	E_*	E_{Field}
A	2.14	321	6.14	12.1	1.125	336	2	11	1.331	1.02	0.37	381	662
A	2.14	321	6.14	12.1	1.125	405	7	11	1.017	1.02	0.37	291	343
A	2.14	321	6.14	12.1	1.125	170	90	11	0.242	1.02	0.37	69	148
A	2.14	321	6.14	12.1	1.125	61	120	11	0.083	1.02	0.37	24	66
A	2.14	321	6.14	12.1	1.125	15	180	11	0.019	1.02	0.37	6	43
A	2.14	321	6.14	12.1	1.125	4	141	11	0.005	1.02	0.37	2	31
B	1.36	204	5.67	12.1	1.125	405	7	11	1.017	0.90	0.37	163	204
B	1.36	204	5.67	12.1	1.125	170	90	11	0.242	0.90	0.37	39	97
B	1.36	204	5.67	12.1	1.125	61	120	11	0.083	0.90	0.37	13	35
B	1.36	204	5.67	12.1	1.125	15	180	11	0.019	0.90	0.37	3	31
B	1.36	204	5.67	12.1	1.125	4	141	11	0.005	0.90	0.37	1	8
D	2.42	363	5.97	11.4	1.125	89	15	16.8	0.119	1.13	0.37	43	112
D	2.42	363	5.97	14.7	1.125	105	15	21.8	0.108	0.60	0.37	20	152
E	1.65	247.5	6.02	10.8	2.48	39	42	16	0.044	1.31	0.94	32	20
E	1.65	247.5	6.02	10.8	2.48	24	42	16	0.027	1.31	0.94	20	39
E	1.65	247.5	6.02	10.8	2.48	41	42	16	0.046	1.31	0.94	34	39
E	1.65	247.5	6.02	10.8	2.48	40	42	16	0.045	1.31	0.94	33	32
E	1.65	247.5	6.02	10.8	2.48	37	42	16	0.041	1.31	0.94	30	46
E	1.65	247.5	6.02	10.8	2.48	43	14	16	0.061	1.31	0.94	45	43
E	1.65	247.5	6.02	10.8	2.48	39	14	16	0.056	1.31	0.94	41	22
E	1.65	247.5	6.02	10.8	2.48	49	14	16	0.070	1.31	0.94	51	28
E	1.65	247.5	6.02	10.8	2.48	42	14	16	0.060	1.31	0.94	44	50
FB	1.64	246	5.97	10.3	1.125	69	60	9.4	0.123	1.45	0.37	38	69
FB	1.64	246	5.97	10.3	1.125	75	60	9.4	0.133	1.45	0.37	42	67
FB	1.64	246	5.97	10.3	1.125	58	60	9.4	0.103	1.45	0.37	32	63
FB	1.64	246	5.97	10.3	1.125	64	60	9.4	0.114	1.45	0.37	36	86
FB	1.64	246	5.97	10.3	1.125	78	60	9.4	0.139	1.45	0.37	43	40
FB	1.64	246	5.97	10.3	1.125	54	60	9.4	0.096	1.45	0.37	30	62
FT	3.61	542	6.30	11.4	2.48	92	30	16.8	0.105	1.23	0.94	158	86
FT	3.61	542	6.30	11.4	2.48	62	30	16.8	0.070	1.23	0.94	106	70
FT	3.61	542	6.30	11.4	2.48	75	30	16.8	0.085	1.23	0.94	129	80
FT	3.61	542	6.30	11.4	2.48	72	30	16.8	0.082	1.23	0.94	123	81
FT	3.61	542	6.30	11.4	2.48	77	30	16.8	0.088	1.23	0.94	132	83
G	2.67	401	7.41	10.3	1.125	30	60	9.5	0.053	2.10	0.37	39	19
G	2.67	401	7.41	10.3	1.125	25	60	9.5	0.044	2.10	0.37	32	14
G	2.67	401	7.41	10.3	1.125	24	60	9.5	0.042	2.10	0.37	31	16
G	2.67	401	7.41	10.3	1.125	24	60	9.5	0.042	2.10	0.37	31	19
G	2.67	401	7.41	13.3	1.125	36	60	12.1	0.050	1.11	0.37	19	23
G	2.67	401	7.41	13.3	1.125	44	60	12.1	0.061	1.11	0.37	24	19

The correlation coefficient (r) for the relationship is 0.88 and the standard error of estimate is 54 g. The value for K represents a 44% increase over that predicted by theory (E*) and reflects the largely unknown factors such as antecedent moisture conditions, limitations due to varying drop sizes and velocities and variations in driving rain factors.

In general 95% of results lie within +/- 2 standard errors from the line of best fit, or in this case roughly 110 g from the line given in Equation 8.19. The confidence level of 110 g represents a loss in surface thickness of around 3.5 mm for the assumed 150 mm diameter specimen. This 110 g is related to the size of the specimens used in the tests, viz, 150 mm dia, and can be written in more general form as $6225 \times A_S$, where A_S is the face area of the specimens used in testing in square metres. (Note that $6225 \times \pi \times 0.075^2 = 110$)

A conservative estimator for field erosion can therefore be written as

$$E_{Field}(g) = 1.44 \times Q_{Field} \times \frac{E_{60}}{Q_{60}} \times f(t_{Field}) \times \left(\frac{v_{Field}}{v_{Lab}} \right)^{2.5} \times \left(\frac{d_{Lab}}{d_{Field}} \right)^{1.2} + (6225 \times A_S) \quad \ldots(8.20)$$

Note that both E_{Field} and E_{60} relate to the erosion of the same size units. This equation will give a predicted mean value of erosion that will be exceeded only 2.5 % of the time.

8.4 Sensitivity of Results

An analysis was carried out on the data given in Table 8.1 to see whether the velocity and drop size terms added significantly to the accuracy of the prediction of erosion using equation 8.6.

8.4.1 Effect of Drop Diameter Exponent

An analysis was carried out to determine the effect of the drop size exponent on the degree of the correlation between field and laboratory results, assuming a velocity exponent of 2.5. The results are presented in Table 8.2.

Table 8.2 shows that the best correlation is achieved when the drop size coefficient is zero, indicating that drop size has very little effect on the result. This result is probably effected to a large extent by the limited range of median drop sizes available with the nozzles used, coupled with the assumption of a constant median drop size in the field.

Table 8.2 Variation of Correlation Coefficient with Drop Size Exponent

Drop Size Exponent	**Correlation Coefficient (r)**
-1.2	0.94
-0.5	0.95
0	0.95
0.5	0.94
1.2	0.88

8.4.2 Effect of Velocity Exponent

Table 8.3 shows the effect on the correlation coefficient of varying assumptions for the velocity exponent, assuming a drop size exponent of zero.

Table 8.3 Variation of Correlation Coefficient with Velocity Exponent

Velocity Exponent	**Correlation Coefficient (r)**
-2	0.95
-1	0.96
0	0.96
1	0.95
2	0.95
2.5	0.95
3	0.94

8.5 Discussion

The best fit line between the actual field performance and the parameter E* given in Equation 8.19 is quite good (r= 0.88) and could form the basis for prediction in the area where the tests were carried out. The results should however be viewed in light of the following comments, and a large safety margin should be considered before adapting the methodology to other climatic regions.

- The factor K is higher than 1 indicating that erosion in the field is higher than that predicted from laboratory tests alone. This is thought to be principally due to the fact that in the field there will be continual cycles of wetting and drying. The limited results of experiments by the author, reported in Section 6.8 indicate that this could increase erosion by at least 50% and possible higher with time. Other factors such as the breakdown of the surface due to sulphate penetration is also a possible cause in this location, which is exposed to wind laden salts from the nearby sea, and the effect of drop size is unclear from the results.
- The factor K (1.44) is inextricably linked with the value of $f(t_{Field})$ assumed ($f(t_{Field})$= 2.39 for an assumed t_{Field} of 20 minutes). Although these two factors could be combined into one factor of 3.44 (1.44×2.39) retention of the $f(t_{Field})$ factor would emphasise the relationship between the assumed representative storm duration and particular site conditions. For instance t_{Field} could be much lower in areas where short duration storms are common and higher in areas where rainfall is more uniform. More research is needed in order to better clarify the definition and determination of a representative rainfall duration to be used in practical situations.
- The factor f(t) has been derived on the basis that the specimens were completely saturated. In practical situations specimens in the field will in many cases be dry before rainfall commences, and as indicated by the limited work done by the author and reported in Section 6.8, the form of f(t) will most likely be different in these situations. This should not however limit the usefulness of the approach presented here, as in practical situations the K factor would most probably be combined with the f(t) value to produce an overall multiplying factor for a given region.

- The approach presented herein has been based on testing involving identical “split-face” specimens, thus ensuring that the material properties and surface texture of the specimens tested in the laboratory, and those exposed in the field, are the same. It is therefore independent of these properties but does require that in practical situations the specimens to be tested in the laboratory will need to be as near as possible identical with the units constructed in the field. This means that they would need to have the same material composition, same amount of stabiliser and be compacted in the same manner as the tested specimens . In most situations this should be possible but surface texture and plane of compaction could be important variables which could lead to inaccuracies in the predicted outcome if the field and laboratory units differ significantly.
- The coefficient of determination for the data in Figure 8.5 (R^2 = 0.77) indicates that roughly 80% of the variation in field performance can be attributable to the variation in E*. There are however significantly more data points in the region of E* less than 50 grams. The percentage variation of results in this region is coming off a low base, and reflects the errors involved in measuring such small amounts of erosion. It will not be significant in practical situations as the erosions predicted in this area will be much less than those allowed in normal situations.
- As can be seen from Table 8.3, in the case of the experiments carried out by the author, the correlation between the predicted field performance of specimens and their actual performance is relatively insensitive to variations in assumed velocity exponent. However it must be emphasised that the difference between the laboratory spray velocities and the calculated impact velocities in the field was only around 25 % for all the series of tests, and the effect of differing laboratory and field velocities could become more important if this difference was much greater.
- The assumed drop size exponent of 1.2 produced a worse result than assuming a value of -1.2, indicating that erosion was directly proportional to drop size rather than inversely proportional as assumed. However the tests carried out in Chapter 6 all indicated a negative exponent. One explanation for this result might be that the predicted greater erosion capacity per unit volume of water for

smaller drops is a result of the cumulative effect of many impacts and that at a lower number of impacts, such as found in a storm, the effect is not as great. Clearly this is an area that needs further examination, but in the interim it appears that in the case of the experiments carried out drop size has little if any effect on the accuracy of the predicted field erosions.

On the basis of the sensitivity analysis carried out in Section 8.4, the accuracy of Equation 8.19 could be improved by the omission of the drop size and velocity terms. If both the drop size and velocity terms are omitted from the analysis, $f(t_{Field})$ is subsumed in K, and 150 mm dia specimens are assumed, then the relationship between field and laboratory performance takes the form of Equation 8.21, with the correlation coefficient being 0.96 . The results are shown in Figure 8.6.

$$E_{Field}(g) = 1.38 \times Q_{Field} \times \frac{E_{60}}{Q_{60}} + / - 80 \qquad \ldots\ldots(8.21)$$

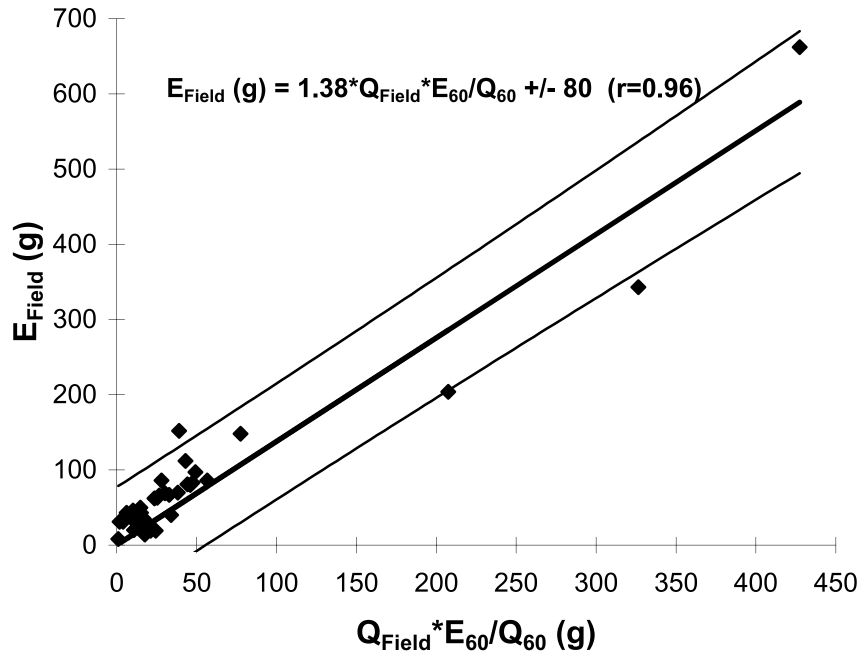


Figure 8.6 Variation Between E_{Field} and Q_{Field}*E_{60}/Q_{60}

8.6 Implications for Codification

Performance based codes require proof that the performance limits set by the codes are not exceeded. In the case of the durability of earth walls a performance limit expressed in terms of maximum permitted loss in wall thickness over the lifetime of the structure would seem to be appropriate.

Equation 8.21 is set out in terms of mass loss for a specimen diameter of 150 mm. In the more general context of predicting wall erosion as a mass loss per square metre of wall surface the confidence level needs to be expressed as a mass loss per square metre and the volume of impacting water needs to be re-defined in terms of a volume of water impacting per square metre of wall. The upper bound to Equation 8.21 can then be re-written as

$$E_{Field}*(kg/m^2) = \left(1.38 \times Q_{Field}* \times \frac{E_{60}}{Q_{60}} + \frac{80}{A_S}\right)/1000 \qquad \ldots(8.22)$$

Where

E_{Field}* = Predicted Field Erosion (kg/m^2 of wall area)

A_s = Area of Spray Specimen (m^2)

Q_{Field}* = Impacting Volume of Water on Vertical Surface in the Field (l/m^2)

E_{60} = 60 Minute Spray Erosion (kg)

Q_{60} = 60 Minute Spray Volume (l)

The following will set out how Equation 8.22 could be used to predict the "average" performance of a certain wall in a specific climatic region. It is not meant to be a definitive methodology but rather an indication of how Equation 8.22 might be applied in practice.

The first step would be to obtain a sample of the wall, constructed in a manner that reflects the actual construction of the wall. This sample (or samples) would then be tested in the spray test outlined in Chapter 5 for a period of 1 hour. Assume for argument sake that the resulting erosion of a 150 mm diameter specimen after 60 minutes is 300 grams, using a 1550 nozzle at 70 kPa (Discharge rate 9.5 litres per minute).

In that case $E_{60}/Q_{60} = 300/(60\times9.5) = 0.53$ g/litre.

In order to get Q_{Field} it is necessary to look at the worst exposed wall. Assuming that the building is to be located at the test site it can be seen from Chapter 4 that the predominant driving rain in this case comes from a southerly direction and represents approximately 60% of the yearly driving rain.

As an approximation the amount of driving rain impacting the wall over a fifty year period could be calculated using the annual rainfall (say 1.2 m), an average wind speed during rain (say 7m/sec) and a DRF of 150 as follows

$Q_{Field}* = 50 \text{ Years}\times (150\times1.2\times7) \times60\% = 37{,}800 \text{ litres/m}^2$

Applying this to Equation 8.22 yields

$$E_{Field}*(kg/m^2) = \left(1.38\times37{,}800\times0.53+\frac{80}{\pi\times0.075^2}\right)/1000$$
$$= 32 \text{ kg/m}^2$$

Assuming the wall has a density of 1850 kg/m^3 this equates to a wall thickness loss of 18 mm over a fifty year period.

Note that this value is only representative of the average erosion that could be expected in a wall at the height the specimens were placed in these experiments, i.e. 1 metre. To apply this methodology to a performance based code various safety factors would need to be developed to make this value representative of the maximum expected erosion , taking into account the local micro-climate and the physical characteristics of the wall surface and the structure as a whole.

Chapter 9 Conclusions and Recommendations for Further Research

9.1 Conclusions

This investigation has examined the issues surrounding the durability of earth walls. In particular a method was developed whereby the resistance of such walls to the erosive effect of driving rain can be reasonably predicted based on laboratory tests and an assessment of climatic site conditions.

Previous approaches to determining the performance of earth walls have been on the basis of testing specimens in various accelerated tests. All of these tests are empirical and are based on little or no correlation with in-situ performance. In some cases, correlation between field and laboratory performance has been extrapolated to other geographic areas with significantly different climatic conditions. Where adjustments for climatic conditions have been specifically made, such as that proposed by the author for the New Zealand Code on Earth Building, these have been based on subjective judgments rather than on objective principles.

In order to provide a scientific basis for predicting the in-situ durability of earth walls, the author carried out laboratory testing to investigate the effect of various climatic parameters, developed a theoretical model relating field to laboratory erosion, and then confirmed the suitability of the model based on extensive field test results.

Based on this work the following conclusions can be made

- The erosion of earth walls due to driving rain is proportional to the amount of rain impacting the vertical surface (Driving Rain).
- The volume of driving rain impacting a vertical surface is approximately equal to the sum of the hourly driving rain indices (Vertical rain × Mean hourly wind speed) times a wind-driven rain factor. A value of 150 was determined for the driving rain factor at the test site based on extensive field correlation between rain recorded using a specially constructed horizontal rain gauge, and the

amount of vertical rain recorded at the meteorological station located at the test site.

- The volume of driving rain varies significantly with compass direction. Based on data collected at the test site the predominant direction of driving rain in Sydney is from the south.
- Average wind speed during rain at the test site was around 7 m/sec, with 10 m/sec exceeded only about 10% of the time.
- Traditional spray tests for durability do not adequately model the action of wind-driven rain, especially in weak materials. The modified spray test developed by the author produces real drops with a turbulent action.
- The performance of various materials is directly proportional to their erosion in the modified spray test, per unit volume of impacting water. The erosion of specimens decreased markedly with cement contents above 4%.
- The erosion of specimens subjected to water drop impact increases at a decreasing rate with time. The shape of the erosion versus time curve is reasonably constant for all materials when presented in a non-dimensional form such as Equation 6.1. A MMF growth curve gave the best fit to the available data.
- Laboratory testing indicated that the amount of erosion due to driving rain per unit volume of impacting water is proportional to drop impact velocity raised to the power 2.5.
- Laboratory testing indicated that the amount of erosion due to driving rain per unit volume of impacting water is inversely proportional to drop size raised to the power 1.2.
- The moisture content of the specimens prior to drop impact effects the erosion of earth walls but can probably be allowed for by an increase in the proportionality constant.

An empirical equation developed by the author (Equation 8.6) was shown to be able to predict with acceptable accuracy the performance of test samples placed at the test site over a three-year period, based on the calculation of volume of impacting rain and the performance of identical (split face) specimens in the modified spray test developed by the author. Such an equation could form the basis for the determination of the performance of earth walls, and provide a basis for a limit state design of earth walls, whereby walls could be specifically designed to meet the erosional environment in which they are to be located.

9.2 Recommendations for Future Research

This thesis has examined many issues relating to the resistance of earth walls to wind-driven rain and has derived a basic methodology for the prediction of in-situ performance based of accelerated laboratory testing. Of necessity however large scale testing of all of the factors involved was not possible and much work is still to be done to confirm many of the preliminary findings presented herein. Some of the major areas in which further research work is needed are –

- Correlation between field and laboratory results has only been identified for one test site, because of the extensive time required (3 years of field testing was carried out). Further tests at other sites are needed to confirm the validity of the predictive methodology presented here. In particular further study is needed to obtain a better relationship between the representative storm duration (t_{Field}) and local climatic conditions.
- Although an attempt was made to vary the composition of soils used in order to generalise the results further work could be done in looking at the various parameters with respect to identifiable soil properties, such as clay content, clay type and plasticity index. In particular the shape of the f(t) function needs to be confirmed for other soil types.
- Although correlation of the field results with the laboratory results failed to improve with the addition of the velocity term, this may be due to the closeness of the field and laboratory velocities in the tests. Further field testing based on samples sprayed at lower velocities is needed to determine the significance of the omission of the velocity term in Equation 8.21.
- Further work is needed to investigate the effect of drop size, possibly using single drops of varying diameters.
- The effect of wetting and drying in the field has been subsumed in the value for K determined in Chapter 8. Further work relating this to climatic parameters would be desirable.

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Chapter 10 References

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Appendix A Monthly Driving Rain Indices at Test Site

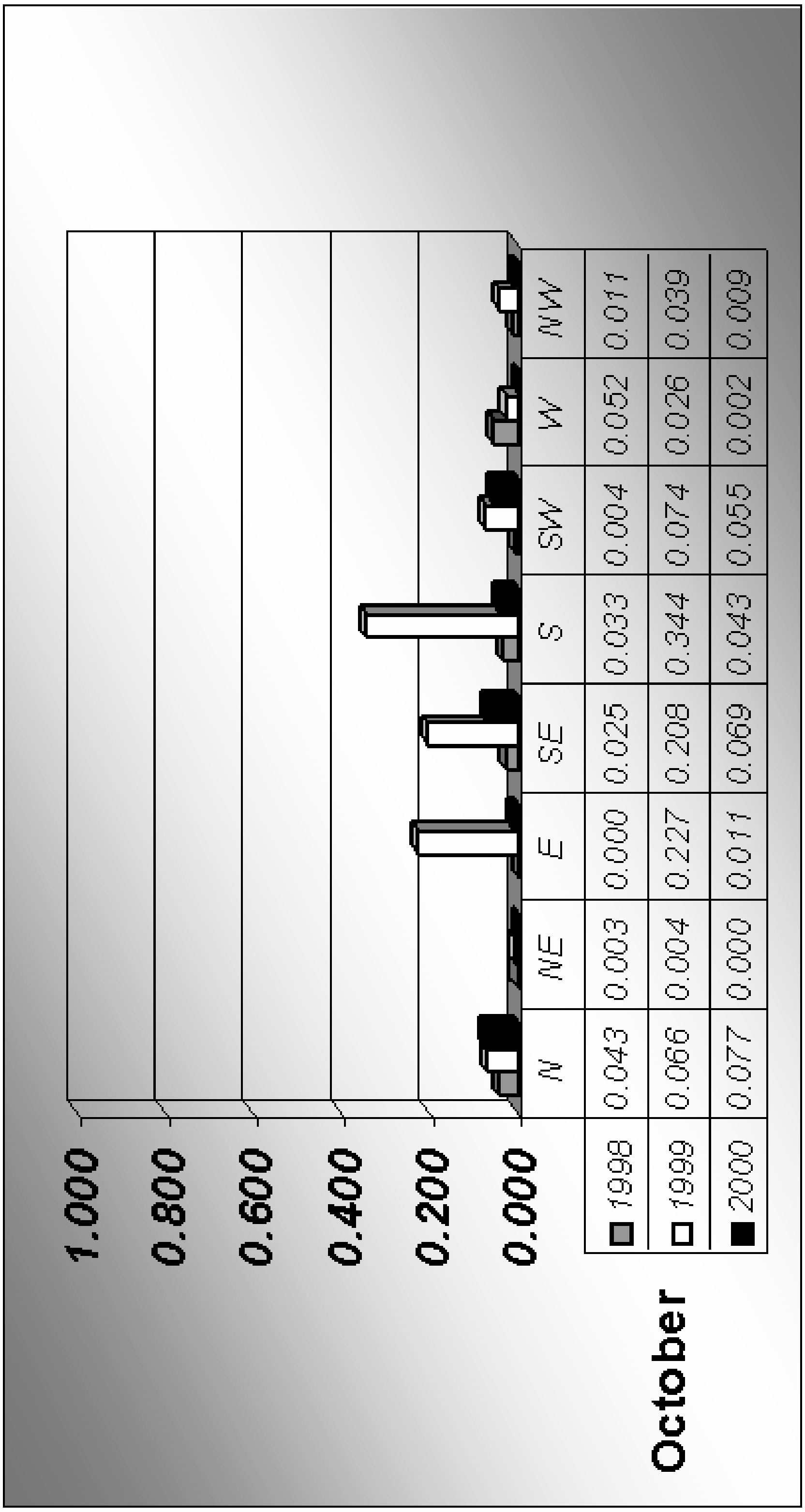

Figure A.1 October Wind Driven Rain Indices

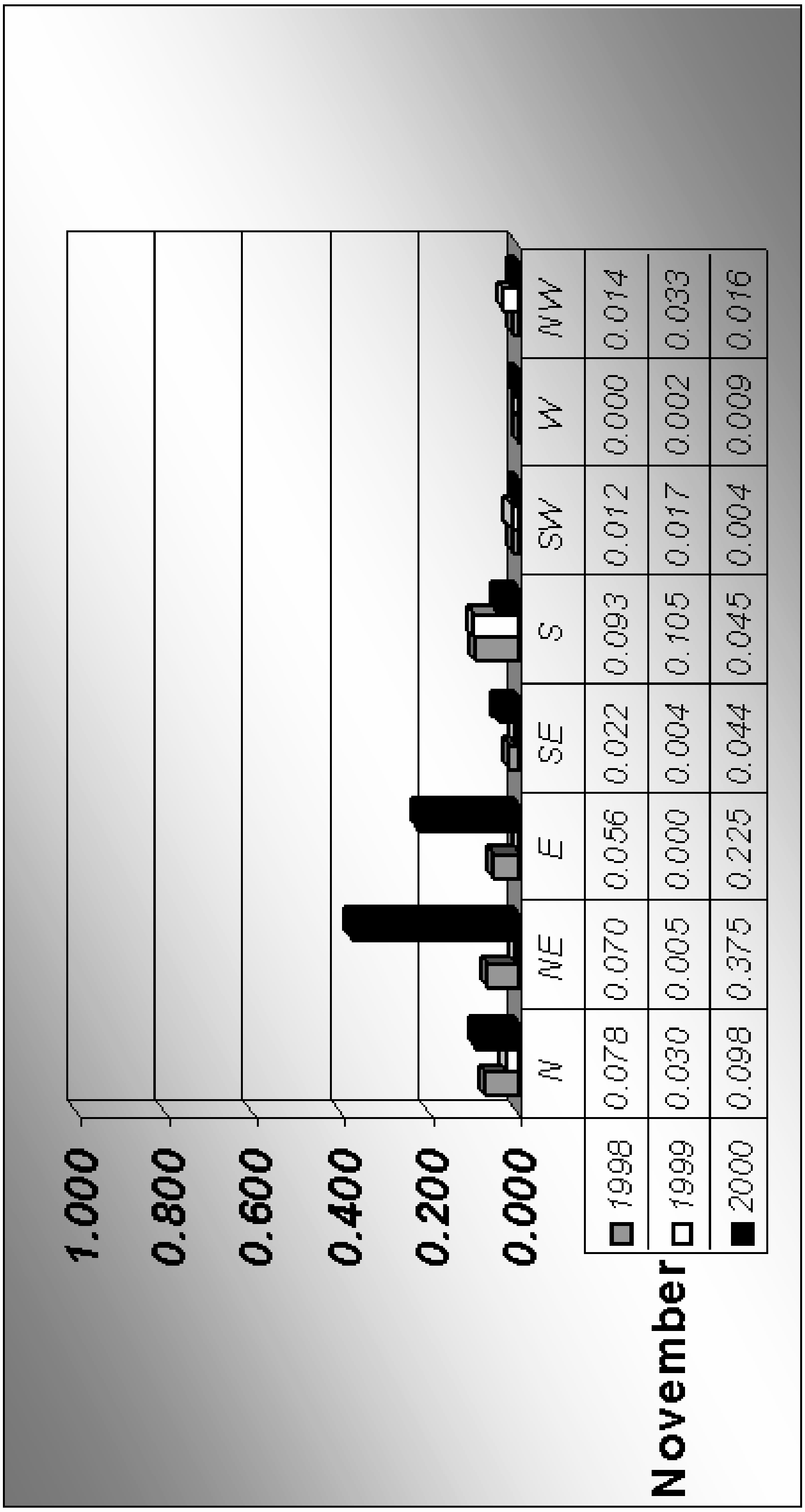

Figure A.2 November Wind Driven Rain Indices

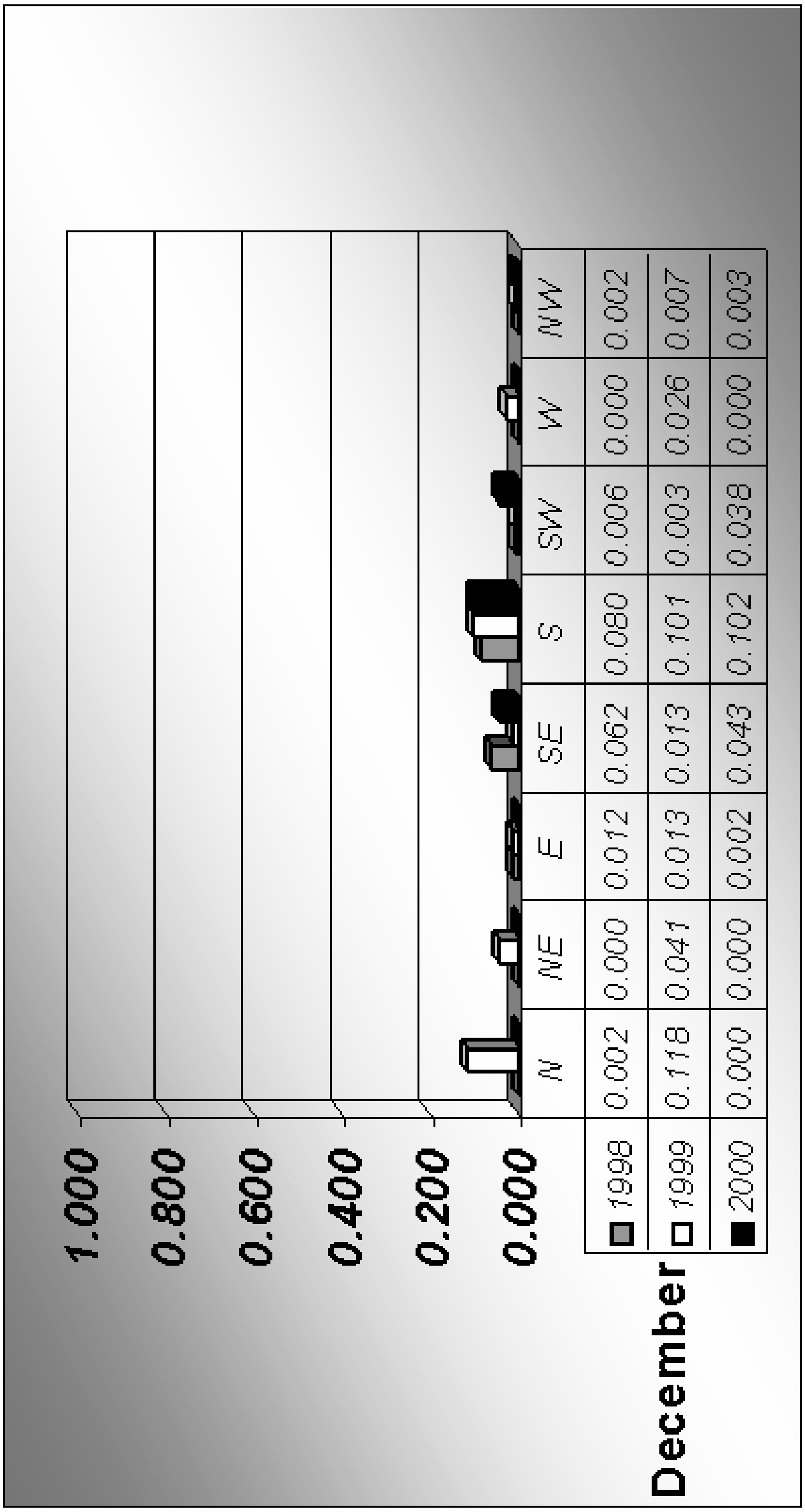

Figure A.3 December Wind Driven Rain Indices

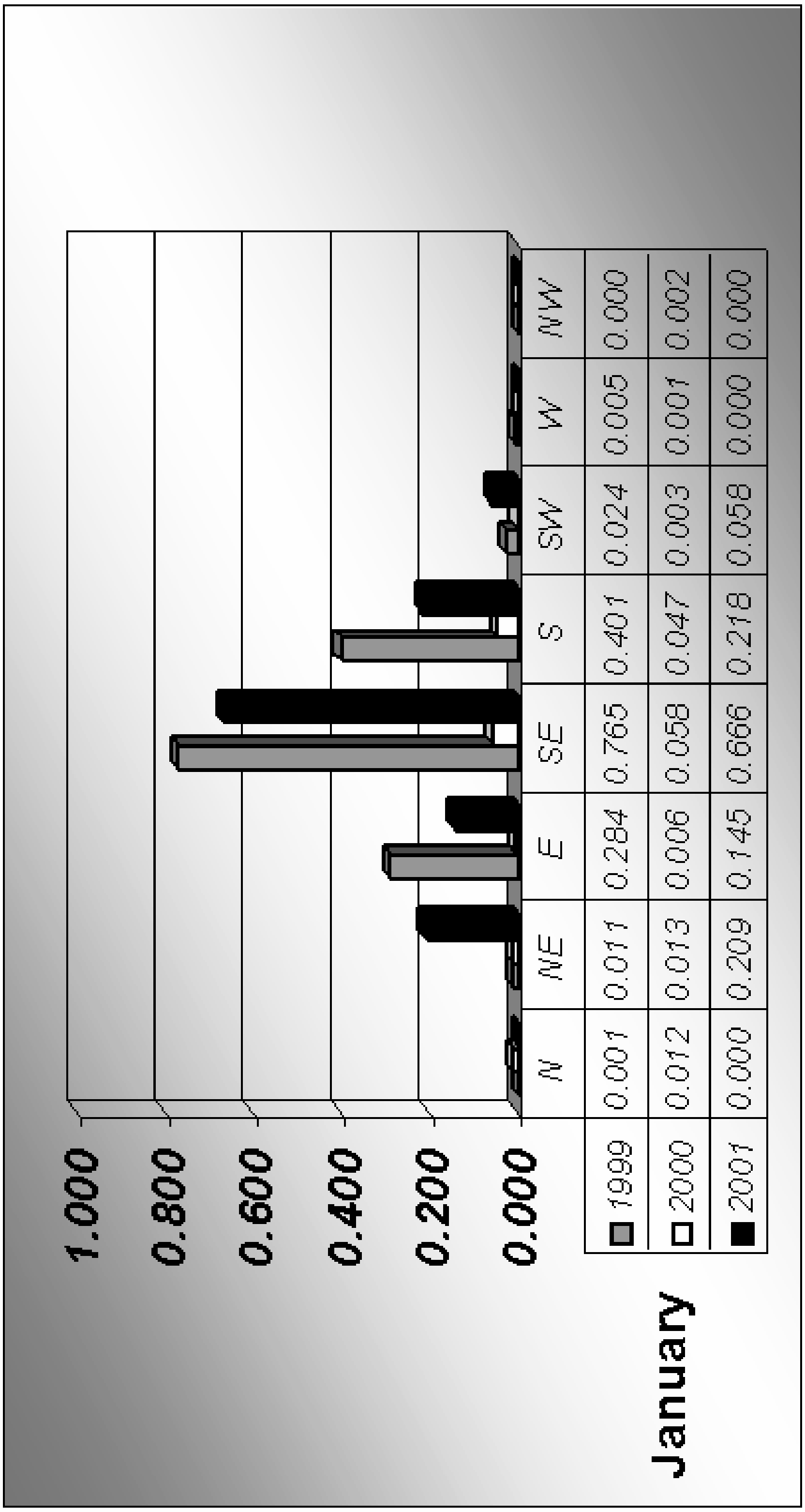

Figure A.4 January Wind Driven Rain Indices

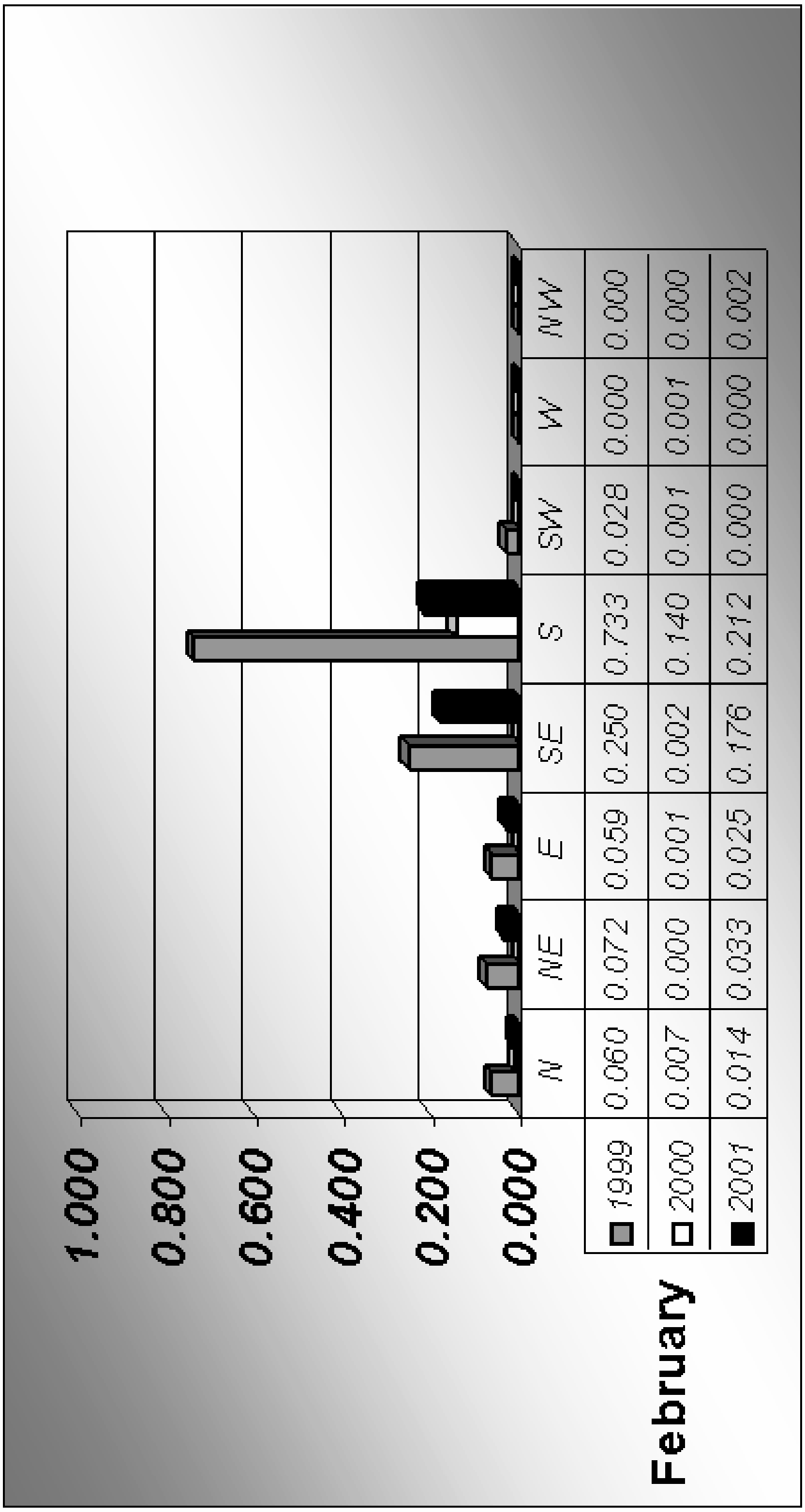

Figure A.5 February Wind Driven Rain Indices

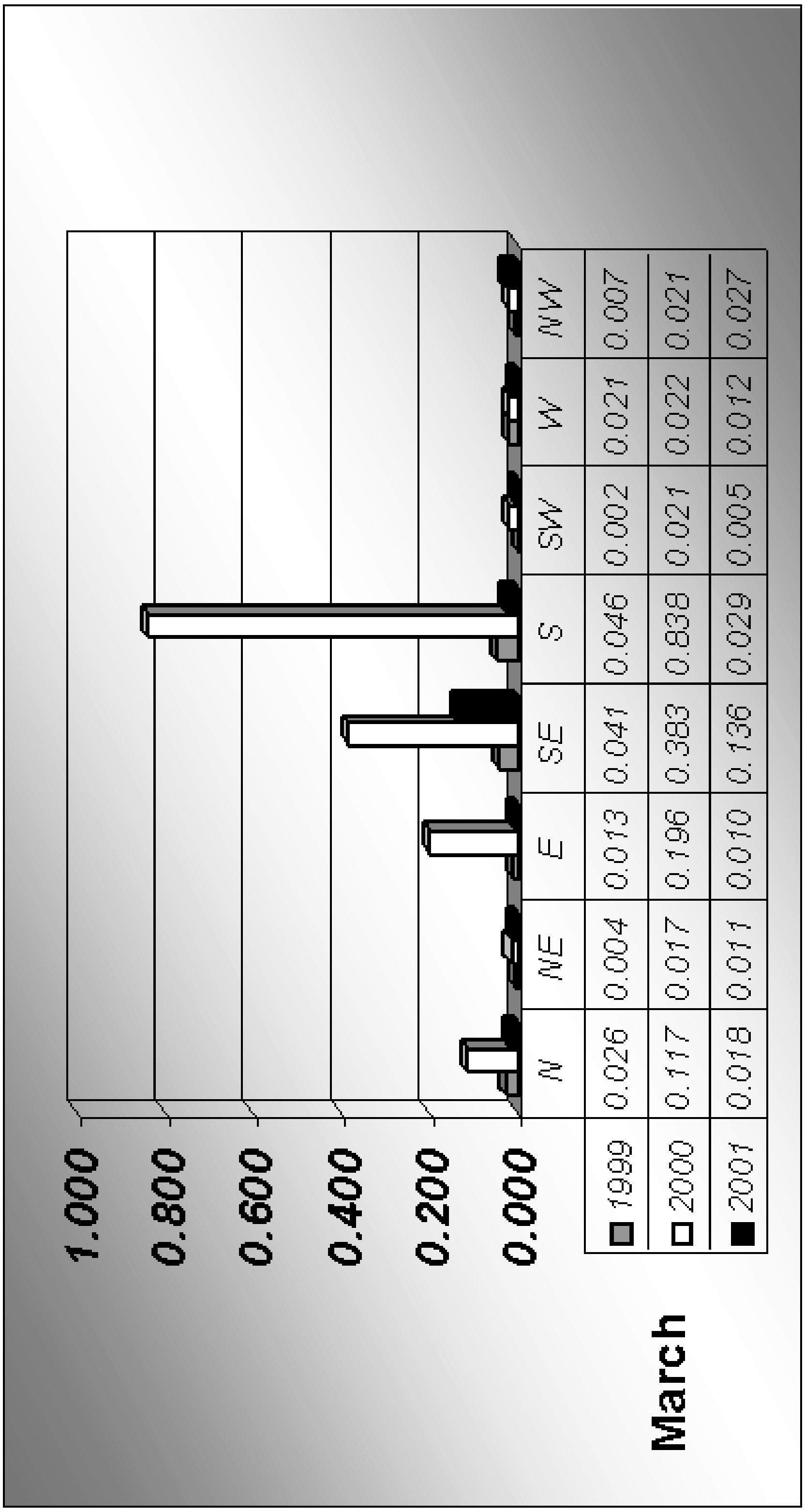

Figure A.6 March Wind Driven Rain Indices

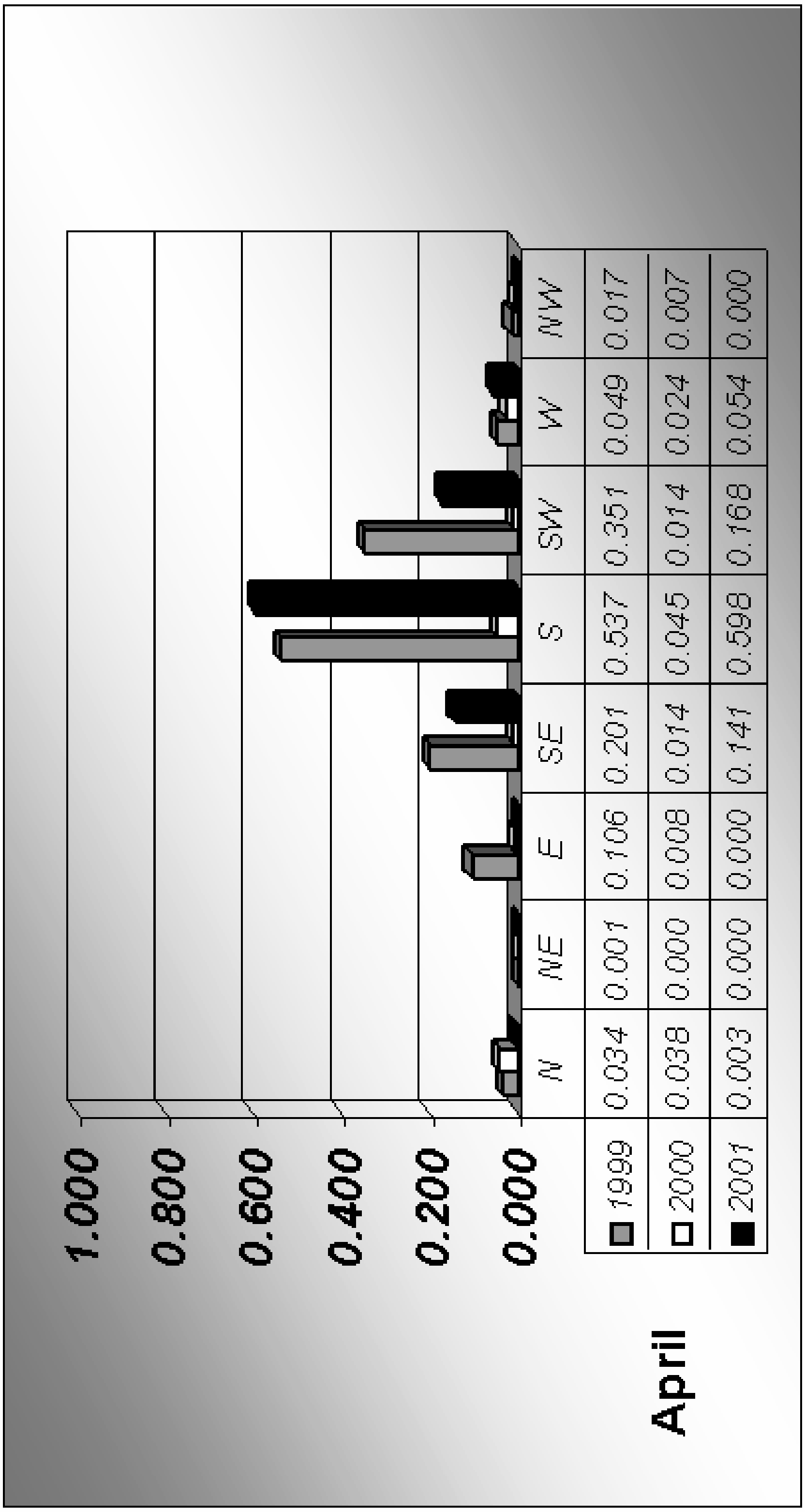

Figure A.7 April Wind Driven Rain Indices

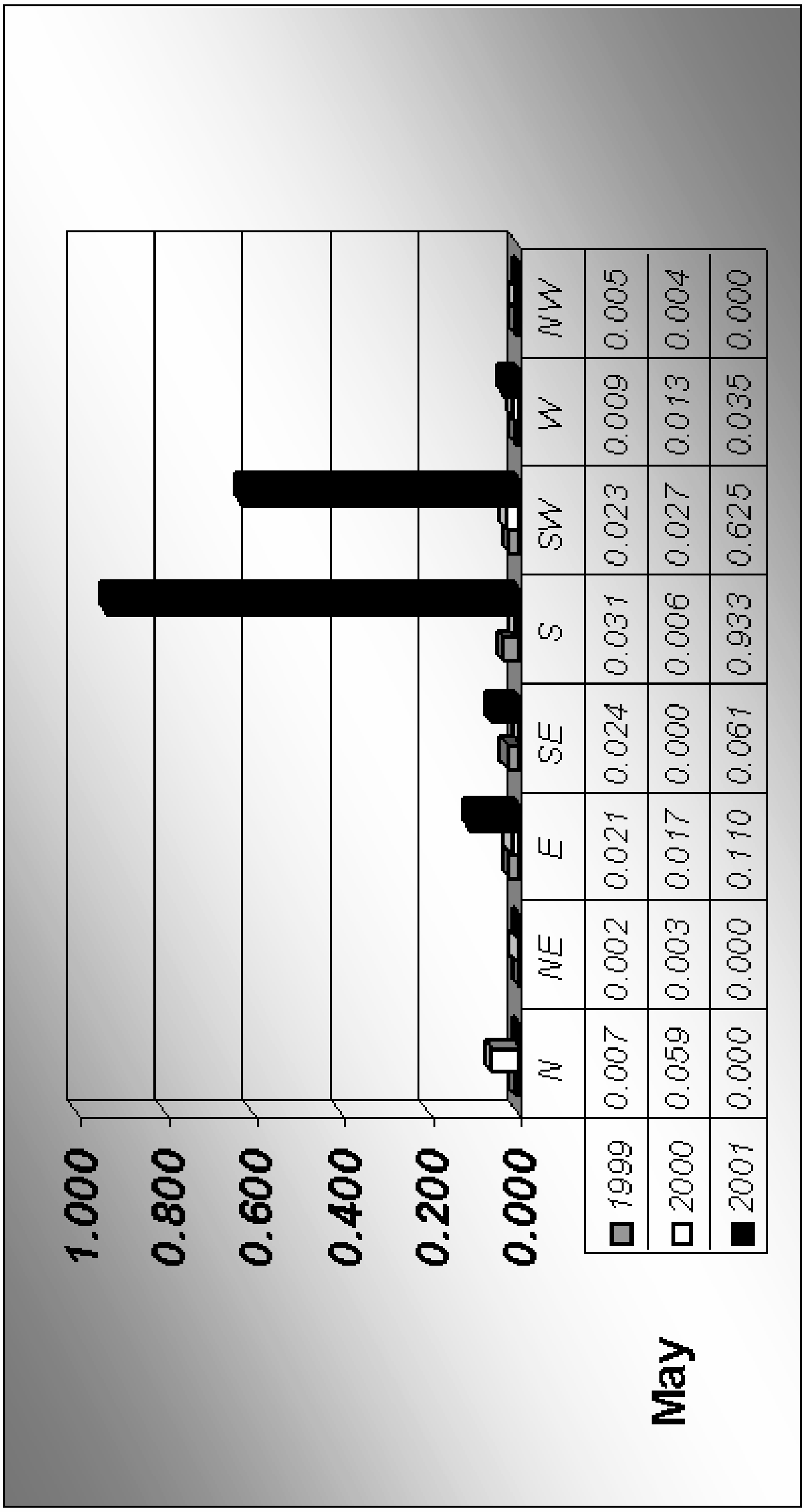

Figure A.8 May Wind Driven Rain Indices

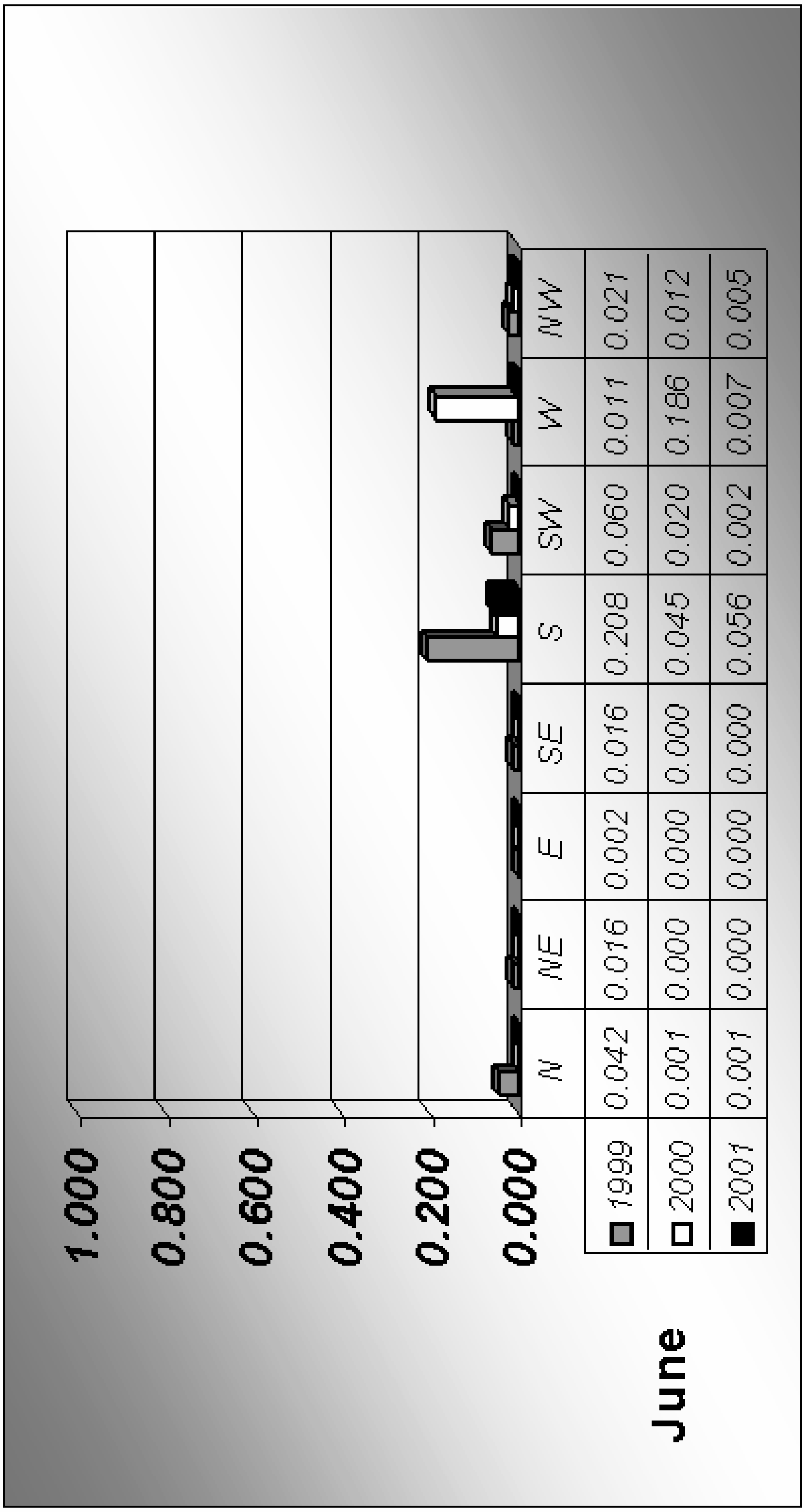

Figure A.9 June Wind Driven Rain Indices

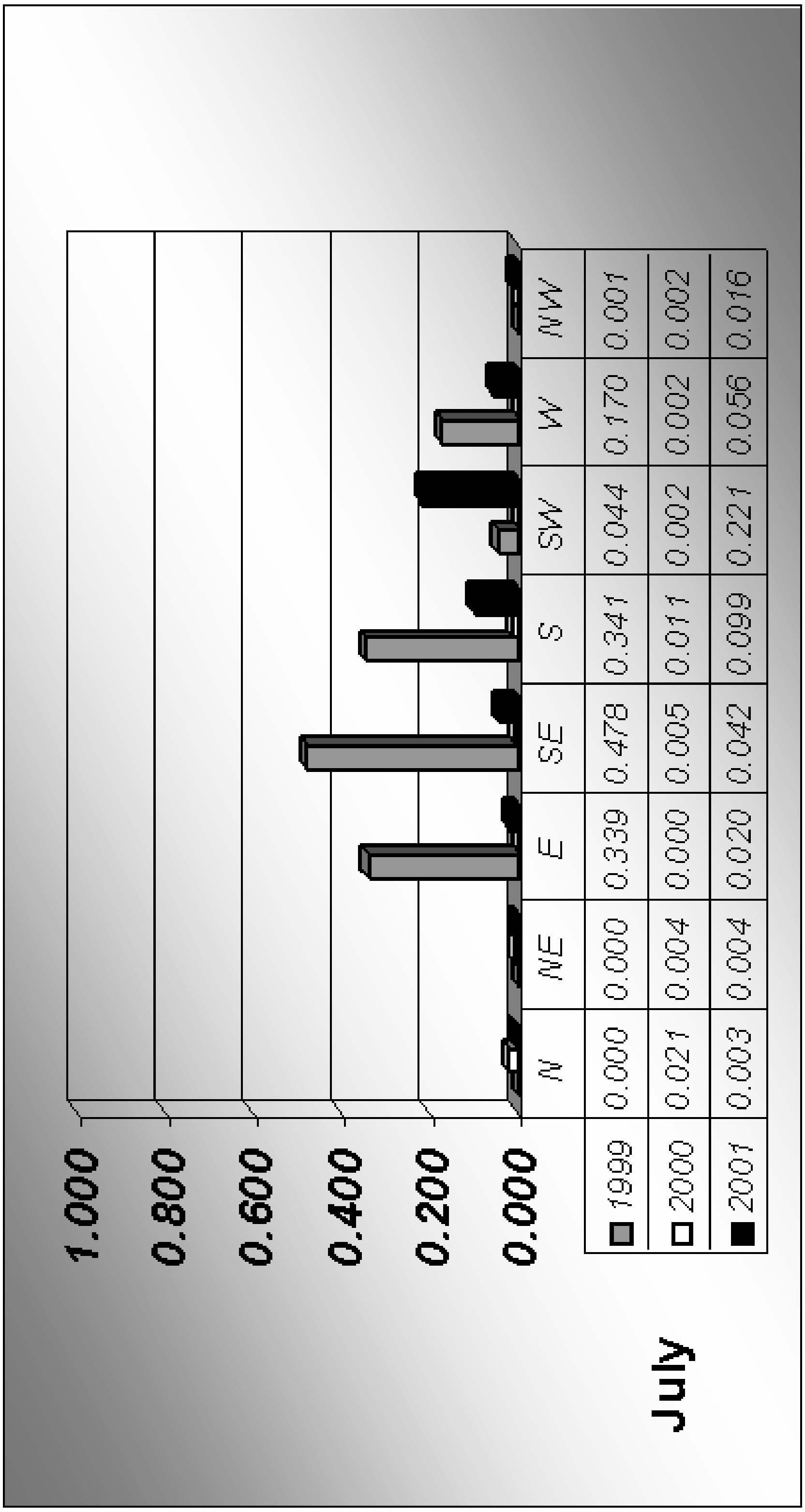

Figure A.10 July Wind Driven Rain Indices

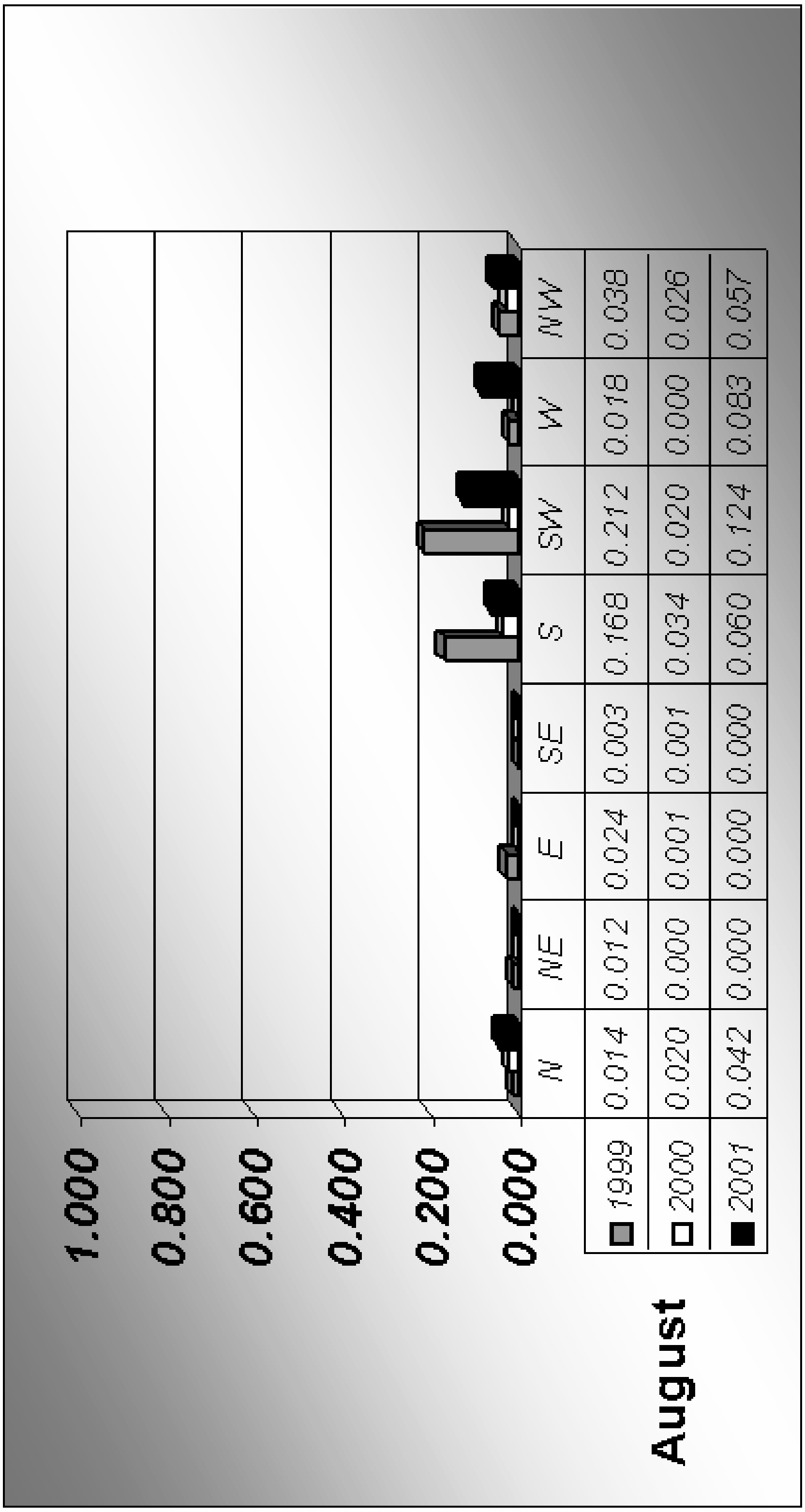

Figure A.11 August Wind Driven Rain Indices

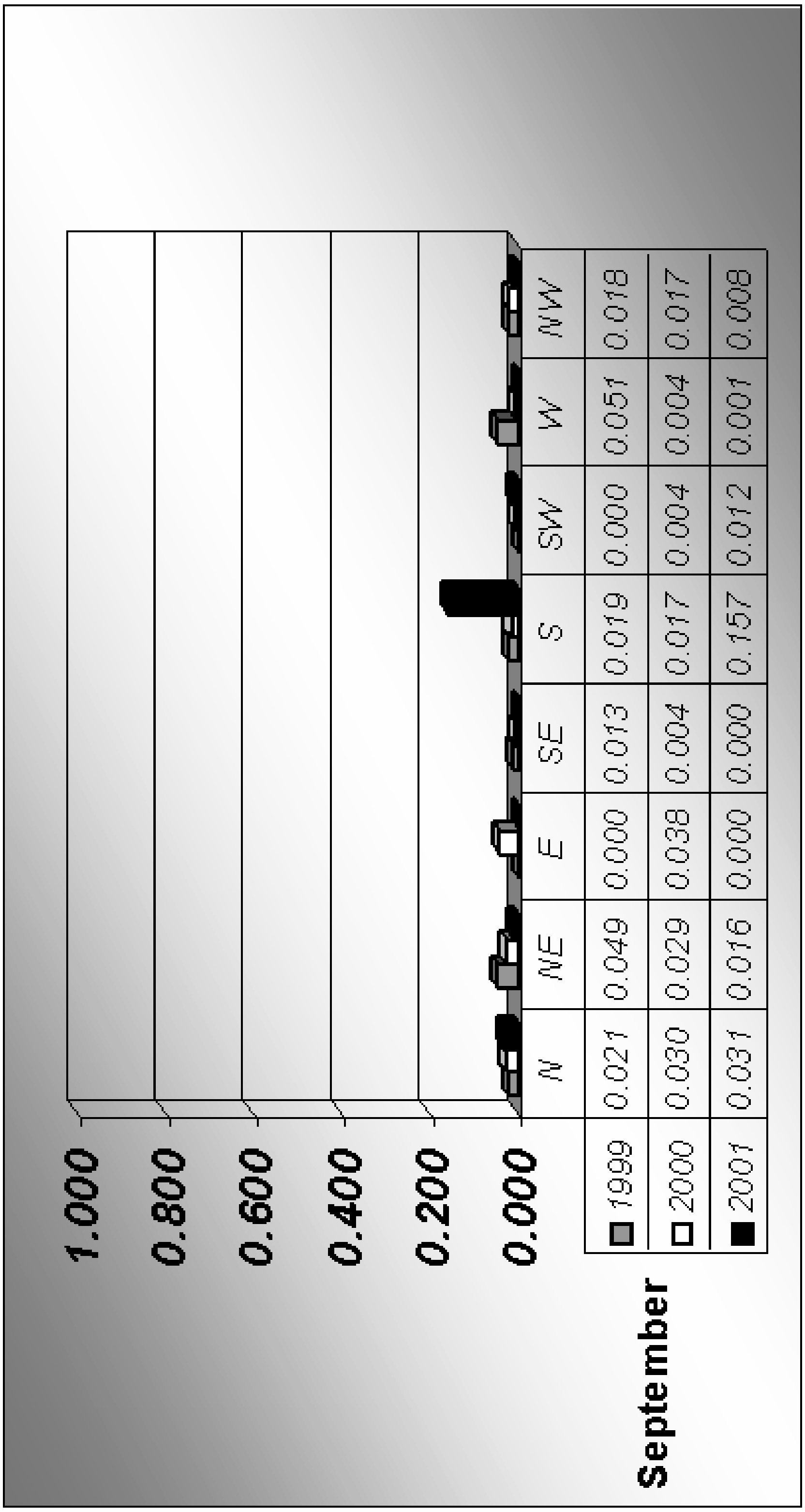

Figure A.12 September Wind Driven Rain Indices

Appendix B – Analysis of Driving Rain Field Data

	Wind-Driven Rain 1 16/7/99 - 10/8/99 - 170 ml =9.62 mm of wind blown rain										
MONTH	**DATE**	**TIME**	**RAINFALL**	**TIME**	**Direction**	**WIND(kn)**	**Max Wind Speed**	**Phi**	**Effective Southerly Rain**	**Wind Driven Rain**	**Aver South Wind**
July	25	11	0.6	11	188	17	27	8	0.59	5.2	17
	25	12	1.2	12	201	18	27	21	1.12	10.4	18
	25	13	0.4	13	162	25	32	18	0.38	4.9	25
	25	15	0.2	15	178	17	36	2	0.20	1.7	17
	25	19	0.2	19	161	20	32	19	0.19	1.9	20
	25	21	0.2	21	168	22	26	12	0.20	2.2	22
	25	22	0.4	22	160	17	23	20	0.38	3.3	17
	25	23	2.6	23	141	10	21	39	2.02	10.4	10
	25	0	0.4	0	160	13	24	20	0.38	2.5	13
	25	1	0.4	1	163	16	21	17	0.38	3.2	16
	25	2	0.6	2	103	14	22	77	0.14	1.0	14
	25	3	0.4	3	146	10	15	34	0.33	1.7	10
	25	7	0.2	7	68	7	18	90	0.00	0.0	
	26	12	0.8	12	129	14	18	51	0.50	3.6	14
	26	19	0.4	19	222	7	14	42	0.30	1.1	7
	26	21	1.6	21	220	6	14	40	1.23	3.8	6
	26	22	0.2	22	106	0	12	74	0.06	0.0	0
	26	23	0.2	23	329	5	9	90	0.00	0.0	
	31	20	1.2	20	204	16	34	24	1.10	9.0	16
	31	21	0.2	21	189	22	35	9	0.20	2.2	22
	31	22	0.2	22	201	21	33	21	0.19	2.0	21
	31	23	0.6	23	221	14	25	41	0.45	3.3	14
	31	0	1	0	236	12	16	56	0.56	3.5	12
	31	1	3.2	1	199	15	25	19	3.03	23.4	15
	31	2	0.6	2	198	16	27	18	0.57	4.7	16
August	3	13	0.4	13	116	4	7	64	0.18	0.4	4
	6	13	0.6	13	161	15	22	19	0.57	4.4	15
	6	14	0.2	14	176	16	25	4	0.20	1.6	16
	6	18	0.4	18	169	10	15	11	0.39	2.0	10
	6	19	2.8	19	225	7	14	45	1.98	7.1	7
	6	20	0.2	20	95	0	14	85	0.02	0.0	0
	6	8	0.2	8	322	4	6	90	0.00	0.0	
						6.6625			17.80	0.121	7.1
									6.8		
			0.121 m^2/sec = 9.62 mm								
			1m^2/sec = 80 mm								

Appendix C – Analysis of Field Erosion Climatic Data

																		373475
						Average (m/sec)		**SERIES A**	**Total**									
	Totals		**524**	**405**		**6.14**	**12747**	**273**	**2.14**	**371**	**307**	**816**	**2161**	**2557**	**139**	**63**	**53**	
Month	**Date**	**Time**	**Rainfall**	**Rainfall>2 mm**	**Direction**	**WIND(kn)**	**Phi**	**Effective Rain South Face (knot.mm)**	**Wind Driven Rain South Face (m2/sec)**	**N**	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	
October	19	17	1	0	304	6	90	0.00	0.0000								6	0
October	19	18	0.4	0	314	7	90	0.00	0.0000								3	0
October	21	21	0.6	0	137	7	43	0.44	0.0016				4					56
October	21	22	0.6	0	122	5	58	0.32	0.0008				3					21
October	21	23	0.2	0	53	3	90	0.00	0.0000		1							0
October	26	15	4.2	4.2	7	18	90	0.00	0.0000	76								1
October	26	16	0.4	0	13	11	90	0.00	0.0000	4								0
October	26	17	1.6	0	317	8	90	0.00	0.0000								13	0
October	26	3	0.4	0	192	12	12	0.39	0.0024					5				186
October	26	4	3.6	3.6	276	15	90	0.00	0.0000							54		0
October	26	5	0.4	0	47	12	90	0.00	0.0000		5							0
October	26	7	0.4	0	353	8	90	0.00	0.0000	3								0
October	31	19	0.2	0	155	23	25	0.18	0.0021				5					622
October	31	20	0.6	0	157	24	23	0.55	0.0068				14					2178
October	31	21	1	0	152	21	28	0.88	0.0095				21					2262
October	31	22	1.8	0	180	22	0	1.80	0.0204					40				5354
October	31	3	0.2	0	205	19	25	0.18	0.0018						4			338
November	1	19	0.4	0	170	24	10	0.39	0.0049					10				1554
November	1	0	0.2	0	188	25	8	0.20	0.0025					5				893
November	1	1	0.2	0	183	22	3	0.20	0.0023					4				594
November	1	2	0.8	0	220	15	40	0.61	0.0047						12			554
November	1	9	0.4	0	199	16	19	0.38	0.0031					6				415
November	2	10	0.2	0	198	19	18	0.19	0.0019					4				355
November	2	16	0.2	0	177	19	3	0.20	0.0020					4				372
November	2	17	0.2	0	165	17	15	0.19	0.0017					3				255
November	2	18	0.2	0	172	19	8	0.20	0.0019					4				369
November	6	19	0.2	0	158	12	22	0.19	0.0011					2				88
November	7	23	10.8	10.8	2	11	90	0.00	0.0000	119								0
November	7	0	0.8	0	323	10	90	0.00	0.0000								8	0
November	7	1	0.4	0	312	7	90	0.00	0.0000								3	0
November	7	9	0.6	0	316	5	90	0.00	0.0000								3	0
November	8	10	0.4	0	332	4	90	0.00	0.0000								2	0
November	8	17	1.2	0	159	16	21	1.12	0.0092					19				1230
November	8	18	0.6	0	161	16	19	0.57	0.0047					10				623
November	8	19	0.2	0	156	16	24	0.18	0.0015				3					201
November	12	10	1	0	178	4	2	1.00	0.0021					4				46
November	12	11	1.6	0	174	10	6	1.59	0.0082					16				467

November	12	12	0.6	0	151	8	29	0.52	0.0022				5					90
November	12	13	0.6	0	148	6	32	0.51	0.0016				4					47
November	12	14	1.2	0	111	6	69	0.43	0.0013			7						40
November	12	15	3.8	3.8	82	5	90	0.00	0.0000			19						0
November	12	16	0.8	0	42	9	90	0.00	0.0000		7							0
November	12	21	0.4	0	22	12	90	0.00	0.0000	5								0
November	12	0	0.4	0	357	7	90	0.00	0.0000	3								0
November	12	1	2.2	2.2	4	4	90	0.00	0.0000	9								0
November	12	2	0.6	0	16	14	90	0.00	0.0000	8								0
November	12	3	0.2	0	13	15	90	0.00	0.0000	3								0
November	17	4	0.8	0	164	24	16	0.77	0.0095					19				3033
November	17	5	0.2	0	170	27	10	0.20	0.0027					5				1144
November	17	7	0.2	0	162	29	18	0.19	0.0028					6				1401
November	18	18	1.2	0	163	21	17	1.15	0.0124					25				2940
November	18	19	0.6	0	150	21	30	0.52	0.0056				13					1331
November	18	20	0.6	0	147	28	33	0.50	0.0073				17					3297
November	18	6	0.2	0	165	14	15	0.19	0.0014					3				143
November	18	7	0.2	0	171	14	9	0.20	0.0014					3				146
November	19	4	0.2	0	213	12	33	0.17	0.0010						2			80
November	19	7	0.8	0	211	12	31	0.69	0.0042						10			327
November	19	8	0.2	0	200	13	20	0.19	0.0013					3				112
November	23	15	0.6	0	166	13	14	0.58	0.0039					8				347
November	23	16	2.6	2.6	186	6	6	2.59	0.0080					16				241
November	23	17	2.8	2.8	328	3	90	0.00	0.0000								8	0
November	23	18	0.2	0	118	6	62	0.09	0.0003				1					9
November	23	20	7	7	48	12	90	0.00	0.0000		84							0
November	23	4	0.2	0	324	5	90	0.00	0.0000								1	0
November	25	11	0.6	0	104	7	76	0.15	0.0005			4						18
November	25	20	3.6	3.6	91	12	89	0.06	0.0004			43						30
November	25	23	5.6	5.6	92	6	88	0.20	0.0006			34						18
November	25	9	2.2	2.2	38	14	90	0.00	0.0000		31							0
November	26	10	3	3	23	4	90	0.00	0.0000		12							0
November	26	11	1.8	0	134	0	46	1.25	0.0000				0					0
November	26	12	0.4	0	339	0	90	0.00	0.0000	0								0
November	27	1	0.4	0	320	7	90	0.00	0.0000								3	0
November	27	2	0.6	0	2	6	90	0.00	0.0000	4								0
November	27	3	0.2	0	288	0	90	0.00	0.0000							0		0
December	4	0	0.4	0	158	18	22	0.37	0.0034					7				584
December	4	2	0.4	0	136	17	44	0.29	0.0025				7					380
December	4	3	3.8	3.8	155	16	25	3.44	0.0284				61					3780
December	4	4	0.2	0	148	17	32	0.17	0.0015				3					224
December	4	5	0.4	0	164	15	16	0.38	0.0030					6				348
December	5	0	1.4	0	142	4	38	1.10	0.0023				6					51
December	5	1	0.6	0	173	13	7	0.60	0.0040					8				355
December	7	4	0.2	0	157	13	23	0.18	0.0012				3					110

December	8	10	1.6	0	126	3	54	0.94	0.0015				5					29
December	8	11	2.2	2.2	105	1	75	0.57	0.0003			2						5
December	8	12	0.2	0	156	1	24	0.18	0.0001				0					2
December	14	16	7.4	7.4	179	7	1	7.40	0.0267					52				941
December	14	17	1.8	0	87	12	90	0.00	0.0000			22						0
December	14	18	0.2	0	67	4	90	0.00	0.0000		1							0
December	14	5	0.2	0	182	22	2	0.20	0.0023					4				594
December	14	6	0.2	0	191	17	11	0.20	0.0017					3				259
December	14	7	0.4	0	194	15	14	0.39	0.0030					6				351
December	14	8	0.2	0	194	14	14	0.19	0.0014					3				143
December	15	12	0.2	0	209	11	29	0.17	0.0010						2			66
December	15	14	0.2	0	186	16	6	0.20	0.0016					3				218
December	15	4	0.2	0	198	13	18	0.19	0.0013					3				113
December	16	23	0.4	0	59	0	90	0.00	0.0000		0							0
December	16	4	0.2	0	160	0	20	0.19	0.0000					0				0
December	16	5	0.2	0	216	5	36	0.16	0.0004						1			11
December	16	6	0.4	0	287	0	90	0.00	0.0000							0		0
December	16	7	0.2	0	194	0	14	0.19	0.0000					0				0
December	18	11	1.4	0	165	18	15	1.35	0.0125					25				2130
December	18	0	0.2	0	179	9	1	0.20	0.0009					2				45
December	18	1	3.6	3.6	192	8	12	3.52	0.0145					29				601
December	18	2	0.4	0	211	6	31	0.34	0.0011						2			32
December	18	3	0.6	0	118	9	62	0.28	0.0013				5					64
December	18	4	0.4	0	156	5	24	0.37	0.0009				2					24
December	20	21	1.2	0	316	3	90	0.00	0.0000								4	0
December	20	23	0.2	0	213	9	33	0.17	0.0008						2			38
December	20	0	0.8	0	229	4	49	0.52	0.0011						3			24
December	20	9	0.2	0	175	19	5	0.20	0.0019					4				372
December	23	7	0.6	0	18	6	90	0.00	0.0000	4								0
December	23	8	0.2	0	4	5	90	0.00	0.0000	1								0
December	23	9	0.2	0	215	3	35	0.16	0.0003						1			5
December	30	5	0.2	0	129	10	51	0.13	0.0006				2					37
December	31	11	2	2	129	12	51	1.26	0.0078				24					600
December	31	12	0.2	0	140	12	40	0.15	0.0009				2					73
January	14	11	0.4	0	139	19	41	0.30	0.0030				8					563
January	14	13	0.6	0	169	17	11	0.59	0.0052					10				778
January	14	14	0.4	0	185	11	5	0.40	0.0023					4				150
January	19	22	1.8	0	183	18	3	1.80	0.0167					32				2831
January	19	23	1.4	0	177	15	3	1.40	0.0108					21				1265
January	19	0	1.2	0	169	12	11	1.18	0.0073					14				561
January	19	1	2	2	178	13	2	2.00	0.0134					26				1192
January	19	2	0.2	0	162	12	18	0.19	0.0012					2				91
January	19	5	1.6	0	178	19	2	1.60	0.0156					30				2982
January	19	6	0.8	0	180	20	0	0.80	0.0082					16				1754
January	19	7	0.8	0	184	22	4	0.80	0.0090					18				2374

January	19	8	0.2	0	169	23	11	0.20	0.0023					5				674
January	19	9	0.4	0	168	24	12	0.39	0.0048					10				1543
January	20	11	0.2	0	155	20	25	0.18	0.0019				4					397
January	20	12	3.2	3.2	165	20	15	3.09	0.0318					64				6778
January	20	13	0.8	0	164	23	16	0.77	0.0091					18				2641
January	20	14	0.2	0	170	22	10	0.20	0.0022					4				586
January	20	22	0.2	0	184	16	4	0.20	0.0016					3				219
January	20	8	4.8	4.8	190	19	10	4.73	0.0463					91				8815
January	20	9	10.2	10.2	131	19	49	6.69	0.0655				194					12480
January	21	10	2	2	110	18	70	0.68	0.0063			36						1078
January	21	11	1.8	0	120	24	60	0.90	0.0111				43					3550
January	21	13	3.8	3.8	123	20	57	2.07	0.0213				76					4539
January	21	14	14.4	14.4	169	14	11	14.14	0.1019					202				10437
January	21	15	8	8	177	16	3	7.99	0.0658					128				8768
January	21	16	0.6	0	152	17	28	0.53	0.0046				10					699
January	21	17	0.2	0	153	16	27	0.18	0.0015				3					196
January	21	19	0.6	0	158	14	22	0.56	0.0040					8				411
January	21	20	6.6	6.6	118	14	62	3.10	0.0223				92					2288
January	21	21	2.2	2.2	132	8	48	1.47	0.0061				18					251
January	21	22	0.2	0	130	14	50	0.13	0.0009				3					95
January	21	23	1.6	0	100	13	80	0.28	0.0019			21						166
January	21	0	0.4	0	84	10	90	0.00	0.0000			4						0
January	21	1	0.2	0	115	5	65	0.08	0.0002				1					6
January	21	5	0.4	0	122	11	58	0.21	0.0012				4					80
January	21	7	28.8	28.8	113	10	67	11.26	0.0580				288					3302
January	21	8	17.4	17.4	112	13	68	6.52	0.0436			226						3889
January	21	9	0.8	0	120	14	60	0.40	0.0029				11					295
January	22	10	0.2	0	134	17	46	0.14	0.0012				3					183
January	22	11	0.2	0	129	18	51	0.13	0.0012				4					198
January	22	14	1.6	0	117	15	63	0.73	0.0056				24					657
January	22	17	0.2	0	121	12	59	0.10	0.0006				2					49
January	22	18	2.6	2.6	71	9	90	0.00	0.0000			23						0
January	22	19	1.6	0	102	10	78	0.33	0.0017			16						98
January	22	3	13.2	13.2	0	0	90	0.00	0.0000	0								0
January	22	4	12	12	0	0	90	0.00	0.0000	0								0
January	22	5	1.2	0	40	3	90	0.00	0.0000		4							0
January	23	11	0.2	0	22	8	90	0.00	0.0000	2								0
January	23	6	3	3	44	5	90	0.00	0.0000		15							0
January	23	7	1.8	0	131	15	49	1.18	0.0091				27					1068
January	23	8	41	41	132	16	48	27.44	0.2261				656					30112
January	23	9	14.4	14.4	92	15	88	0.50	0.0039			216						456
January	27	2	1.4	0	172	12	8	1.39	0.0086					17				661
January	27	3	3.8	3.8	219	7	39	2.95	0.0106						27			376
January	27	4	0.2	0	356	0	90	0.00	0.0000	0								0
January	27	8	0.4	0	25	7	90	0.00	0.0000		3							0

January	29	10	0.2	0	165	3	15	0.19	0.0003					1				6
January	29	1	2.4	2.4	173	15	7	2.38	0.0184					36				2155
January	29	2	0.6	0	193	12	13	0.58	0.0036					7				279
January	29	3	3.4	3.4	247	6	67	1.33	0.0041						20			124
January	29	4	0.4	0	180	4	0	0.40	0.0008					2				19
January	31	2	0.2	0	106	13	74	0.06	0.0004			3						33
January	31	6	0.2	0	84	10	90	0.00	0.0000			2						0
January	31	7	1.8	0	290	5	90	0.00	0.0000							9		0
January	31	8	3.8	3.8	330	0	90	0.00	0.0000								0	0
February	1	10	2	2	100	13	80	0.35	0.0023			26						207
February	1	12	1.6	0	23	5	90	0.00	0.0000		8							0
February	1	13	2.4	2.4	33	5	90	0.00	0.0000		12							0
February	1	14	0.4	0	10	10	90	0.00	0.0000	4								0
February	1	15	0.4	0	100	5	80	0.07	0.0002			2						5
February	1	16	9	9	10	9	90	0.00	0.0000	81								0
February	1	17	0.6	0	12	6	90	0.00	0.0000	4								0
February	1	18	0.4	0	348	1	90	0.00	0.0000	0								0
February	1	1	0.4	0	120	6	60	0.20	0.0006				2					19
February	1	2	0.6	0	133	5	47	0.41	0.0011				3					27
February	1	6	0.2	0	314	0	90	0.00	0.0000								0	0
February	2	23	4.8	4.8	134	11	46	3.33	0.0189				53					1255
February	2	1	0.4	0	29	9	90	0.00	0.0000		4							0
February	2	2	1.8	0	67	0	90	0.00	0.0000		0							0
February	2	5	0.6	0	55	2	90	0.00	0.0000		1							0
February	4	20	1	0	140	10	40	0.77	0.0039				10					225
February	4	21	0.2	0	160	10	20	0.19	0.0010					2				55
February	4	0	1.4	0	100	8	80	0.24	0.0010			11						42
February	8	13	1	0	165	23	15	0.97	0.0114					23				3317
February	8	14	3	3	161	23	19	2.84	0.0336					69				9741
February	8	15	9	9	161	22	19	8.51	0.0964					198				25310
February	8	16	3	3	157	23	23	2.76	0.0327				69					9483
February	8	17	3.4	3.4	155	24	25	3.08	0.0381				82					12153
February	8	18	6.2	6.2	161	26	19	5.86	0.0785					161				30061
February	8	19	0.6	0	160	26	20	0.56	0.0075					16				2891
February	8	20	0.4	0	160	28	20	0.38	0.0054					11				2463
February	8	21	0.2	0	159	25	21	0.19	0.0024					5				842
February	8	22	0.6	0	160	24	20	0.56	0.0070					14				2224
February	8	23	1.2	0	164	24	16	1.15	0.0143					29				4549
February	8	0	1	0	162	23	18	0.95	0.0113					23				3266
February	8	1	4.6	4.6	157	21	23	4.23	0.0458				97					10846
February	8	2	1.8	0	160	15	20	1.69	0.0131					27				1530
February	8	3	3	3	155	19	25	2.72	0.0266				57					5071
February	8	4	2.8	2.8	355	4	90	0.00	0.0000	11								0
February	8	7	0.2	0	149	12	31	0.17	0.0011				2					82
February	9	10	0.2	0	76	10	90	0.00	0.0000			2						0

February	9	12	0.2	0	112	7	68	0.07	0.0003			1						10
February	9	13	2.2	2.2	68	7	90	0.00	0.0000			15						0
February	9	14	0.2	0	114	8	66	0.08	0.0003				2					14
February	9	16	1.6	0	45	9	90	0.00	0.0000		14							0
February	9	17	0.6	0	91	16	89	0.01	0.0001			10						12
February	9	20	0.4	0	78	13	90	0.00	0.0000			5						0
February	9	21	1.2	0	71	17	90	0.00	0.0000			20						0
February	9	0	2.6	2.6	67	14	90	0.00	0.0000		36							0
February	10	2	0.4	0	42	6	90	0.00	0.0000		2							0
February	10	9	5.4	5.4	33	6	90	0.00	0.0000		32							0
February	11	10	2.6	2.6	33	8	90	0.00	0.0000		21							0
February	12	22	0.4	0	52	11	90	0.00	0.0000		4							0
February	12	23	0.4	0	44	5	90	0.00	0.0000		2							0
February	12	1	0.6	0	24	0	90	0.00	0.0000		0							0
February	12	6	0.2	0	264	1	84	0.02	0.0000							0		0
February	24	10	3.4	3.4	180	6	0	3.40	0.0105					20				317
February	24	12	7.2	7.2	195	14	15	6.95	0.0501					101				5135
February	24	13	0.2	0	153	13	27	0.18	0.0012				3					106
February	24	15	0.4	0	197	6	17	0.38	0.0012					2				36
February	24	16	0.8	0	201	8	21	0.75	0.0031					6				128
February	24	17	2.2	2.2	190	16	10	2.17	0.0179					35				2378
February	24	18	4.4	4.4	217	11	37	3.51	0.0199						48			1323
February	24	19	0.4	0	170	14	10	0.39	0.0028					6				291
February	24	23	5.2	5.2	144	18	36	4.21	0.0390				94					6626
February	24	0	3.6	3.6	162	25	18	3.42	0.0441					90				15433
February	24	1	5.6	5.6	174	20	6	5.57	0.0574					112				12212
February	24	2	13.2	13.2	190	15	10	13.00	0.1004					198				11758
February	24	3	9.6	9.6	196	18	16	9.23	0.0855					173				14534
February	24	4	1	0	181	17	1	1.00	0.0088					17				1320
February	24	9	0.4	0	151	19	29	0.35	0.0034				8					652
February	25	4	1	0	196	14	16	0.96	0.0069					14				710
February	25	6	0.6	0	224	8	44	0.43	0.0018						5			74
February	25	8	2	2	195	16	15	1.93	0.0159					32				2120
February	26	12	1	0	176	6	4	1.00	0.0031					6				93
February	26	13	1.2	0	183	13	3	1.20	0.0080					16				715
February	26	5	0.2	0	198	14	18	0.19	0.0014					3				140
February	28	6	2.6	2.6	358	6	90	0.00	0.0000	16								0
February	28	7	3.2	3.2	83	5	90	0.00	0.0000			16						0
February	28	8	1.2	0	68	3	90	0.00	0.0000			4						0
February	28	9	3.2	3.2	154	0	26	2.88	0.0000				0					0
March	1	10	0.6	0	6	3	90	0.00	0.0000	2								0
March	1	11	1.4	0	19	10	90	0.00	0.0000	14								0
March	1	18	1	0	98	10	82	0.14	0.0007			10						41
March	1	19	0.6	0	90	10	90	0.00	0.0000			6						0
March	1	20	0.8	0	70	12	90	0.00	0.0000			10						0

March	1	21	0.4	0	55	12	90	0.00	0.0000		5							0
March	1	22	0.2	0	42	15	90	0.00	0.0000		3							0
			523.8							371	307	816	2161	2557	139	63	53	
										N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**	
			2															
			4															
			6															
			8															
			10															
			12															
			14															
			16															
			18															
			20															
			########		3/03/1999													
		Rain %			139	3336	7.9%											

Bin	*Frequency*
0-2	76%
2-4	13%
4-6	3%
6-8	2%
8-10	1%
10-12	1%
12-14	1%
14-16	1%
16-18	0%
>18	1%
	1
50	2
More	0