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ERODIBILITY OF CEMENTED MATERIALS

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SINOPSIS

Die gebruik van gestabiliseerde lae is 'n kosteffektief in padkonstruksie. Sekere materiale is egter meer erodeerbaar as ander en moet derhalwe vir erodeerbaarheid en/of duursaamheid getoets word. 'n Erosie Toets is in 1989 ontwikkel om die erodeerbaarheid te kwantifiseer. Hierdie verslag bespreek die huidige gebruik van erosie toetsing en duursaamheidstoetsing in Suid Afika. Hierdie verslag bespreek verder die resultate van 'n herhaalbaarheid en herproduseerbaarheidstudie wat is gedoen om die akkuraatheid van die toets te bepaal. Die Erosie Toets is ook vergelyk met twee duursaamheidstoetse wat tans in gebruik in Suid Afrika is. Nuwe erosie-swigkriteria vir beide buigbare- en starplaveisels word voorgestel, gebaseer op die jongste inligting. Ten laaste word die ontwikkeling van die DW Erosie Databasis bespreek (disket aan binnekant van buiteblad). Gevolgtrekkings in verband met erosie en duursaamheidstoetsing word gemaak tesame met aanbevelings en voorstelle vir verdere navorsing.

SYNOPSIS

The use of stabilised layers is cost effective in road construction in South Africa. Some stabilised materials have however been found to be susceptible to erosion. To identify erodible materials the Erosion Test was developed in 1989. This report discusses the state-of-the-art of erosion testing in South Africa. The report presents the results of the repeatability and reproducibility study undertaken to determine the precision of the Erosion Test. The Erosion Test is then compared with the two durability tests currently used in South Africa. Based on information currently available, new criteria for the Erosion Test are proposed for flexible and rigid pavements. The use of the new Department of Transport Erosion database created as part of this report (disk on inside cover) is then discussed. Finally conclusions concerning erosion and durability testing are presented along with recommendations and suggestions for further research.

TREFWOORDE
KEYWORDS Erosion, stabilised materials, pavement, Erosion Test, Brush Test, pumping, Erosion database.

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DISCLAIMER

The views and opinions expressed in this report are those of the author and do not represent Department of Transport policy.

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SUMMARY

Stabilised layers have been used cost effectively in road construction in South Africa. Some stabilised materials have, however, been found to be susceptible to erosion. To identify erodible materials the Erosion Test was developed in 1989. This report discusses the state-of-the-art of erosion testing in South Africa.

The report presents the results of the repeatability and reproducibility study undertaken to determine the precision of the Erosion Test. The Erosion Test is then compared with two durability tests currently used in South Africa. Based on information currently available, new criteria for the Erosion Test are proposed for flexible and rigid pavements. The use of the new DoT Erosion Database created as part of this report (disk on inside cover) is then discussed. Finally, conclusions concerning erosion and durability testing are presented along with recommendations and suggestions for further research.

For erosion to occur in pavement layers traffic loading, the ingress and movement of water and materials susceptible to erosion must all be present. Erosion testing aims to identify erodible materials so that they may be avoided or correctly modified thereby preventing erosion failure. This is currently done in South Africa using the Erosion Test device, the mechanical or manual Wet/Dry Durability Test or the cycled or residual UCS.

In the Erosion Tests three rectangular specimens are submerged in water and covered with a rough neoprene membrane. A 17.775 kg wheel, with a bevelled rim, is then cycled 5000 times over the specimens to erode the surfaces. The depth of erosion is measured at 15 locations on the surface of each specimen. The Erosion Index (L) is the mean of the average depth of erosion for the three specimens.

The mechanical wet/dry durability measures the percentage material loss after 12 wet/dry cycles. As part of each cycle the cylindrical specimen is rotated at 60 rev/min for 50 cycles. A stationary, 2.25 kg brush erodes the specimen surface.

The manual wet/dry durability test is similar to the mechanical wet/dry durability test except the cylindrical specimen is smaller, it is eroded by hand brushing and Proctor as opposed to Mod ASSHTO compaction is used. Two brush strokes approximating 13.5N each are applied over the curved surface of the specimen between each wet/dry cycle.

Erosion testing simulates the grinding action of pavement layers in the presence of water pressure whereas the durability tests simulate the loss of cementation due to continued wet/dry cycles in a pavement.

The repeatability and reproducibility for the Erosion Test was determined to establish the test precision. Repeatability is the value below which the absolute difference between two single test results obtained with the same equipment on identical test material, under the same conditions, may be expected to lie with a probability of 95 %. Reproducibility is the value below which the absolute difference between two single test results obtained with the same equipment on identical test material, under different conditions, may be expected to lie with a probability of 95 %. The reproducibility variance is numerically greater than the repeatability variance over the same Erosion Test result range.

The precision of the Erosion Test can be considered poor at this stage. The repeatability and reproducibility values both exceed the erosion test result measured over the current erosion criteria ranges. The repeatability / reproducibility values are relatively high as they are quoted for single Erosion Test values and not for the Erosion Index (L) which is the average of three single test results. The high results have been attributed to the lack of experience with the test, natural material variance and the Mod ASSHTO method of compaction which it is suspected produces non-homogeneous specimens.

A study was also undertaken to compare the Erosion Test with the mechanical and manual wet/dry durability test. Mass loss from the durability test initially increased rapidly, against the Erosion Index (L), and then tapered off. The manual and mechanical wet/dry relationship was linear. The regression coefficients were all relatively poor.

Relationships between the various durability / erodibility tests and the different UCS tests were exponential with a negative exponent. Over an Erosion Index (L) limit of 0-2 mm, increased erodible potential correlated with a dramatic decrease in strength. The trend was similar for the durability vs strength comparisons.

Comparison of the Erosion UCS (determined from blocks sawn off the Erosion Test beam), the Cycled UCS (wet/dry cycled), the Residual UCS (CO_2 saturated) and the Standard UCS for cement stabilised materials showed good linear correlations with one another. With further research it may be possible to relate the different UCS values with constant factors based on linear regressions. These were, however, based on limited results.

For lime-stabilised materials there was no significant relationship between any of the different test results. Although the comparison was based on only six results it could indicate that the current tests give an unsatisfactory indication of erosion or strength potential of lime-stabilised materials.

Based on experience with the erosion test, the Erosion Test criteria have been updated for rigid and flexible pavements. It was decided to differentiate between the different pavement types as the stabilised layers in rigid and flexible pavements are subject to different forces and modes of erosion failure. Flexible pavements are subject more to crushing due to local deflections while rigid pavements are subject more to slab movement effects at the joints or cracks. The proposed new criteria are tabled below.

Summary Table 1: New failure criteria for C3/C4 materials in flexible pavements

Material	Traffic class	Erosion Index, L(mm)
C3 (Base)	E0-E2	≤ 2
C3 (Base)	E3-E4	≤ 1
C4 (Subbase)	E0-E2	≤ 5
C4 (Subbase)	E3-E4	≤ 3

Summary Table 2: Proposed new failure criteria for C3/C4 cemented materials in rigid pavements

Material	Pavement type	Erosion Index, L(mm)
C3 (Subbase)	Un-Doweled	≤ 1
C3 (Subbase)	Continuously reinforced	≤ 1.5
C3 (Subbase)	Dowel-jointed	≤ 1.5
C4 (Lower Subbase)	All concrete pavements	≤ 3

Because of the limited test results currently available, it is important to consider the proposed limits as guidelines when selecting materials. As more information is collected these limits will be further refined.

It is important at this stage to base decisions on both the Standard UCS criteria as laid done in TRH4:1985 and the erosion criteria proposed here.

Erodibility potential is a relatively new consideration in the selection of stabilised material. To build up experience of erodible and non-durable materials in South Africa, a DoT Erosion Database has been started and is distributed with this report. The database can be used to collect, store and process current and future erodibility and durability data as it becomes available.

1 INTRODUCTION

This Project Report discusses the work done to date on the development of the Erosion Test (ET) and the state-of-the art of erodibility of cemented road-building materials in South Africa. Included with this final report is a database system containing most of the current Erosion Test results available in South Africa.

Stabilisation of otherwise unsuitable road building material is a cost-effective method of road construction in South Africa. Heavy Vehicle Simulator (HVS) testing identified some stabilised materials that are, in the presence of water, susceptible to erosion. The Erosion Test (ET) developed by De Beer in 1989[1,2] is an attempt to simulate erosion failure of stabilised bases and subbases.

At present the Erosion Test (ET) for lightly cementitious materials has been specified in detail[1]. More research, however, is required before the test can be adopted as a standard test in South Africa. For example, to streamline the test, user-suggested modifications to the test procedure need to be taken into account. The repeatability and reproducibility of the test must be determined and realistic failure criteria must be proposed. The relationship between the ET and similar erosion tests needs to be established so that users can relate the ET results to their experience with erodible materials. To make use of current and future erodibility/durability test results, it will be useful to establish a national record of erodible materials in South Africa. To facilitate this, an Erosion Database was developed. It is discussed later in this report.

This report begins by describing the mechanisms of erosion failure in flexible and rigid pavements (Section 2). Section 3 gives a brief description and comparison of the different erosion and durability tests available. The repeatability and reproducibility study carried out to determine the precision of the ET device is presented in Section 4. Section 5 compares and evaluates relevant durability tests with the ET. Based on current research, the comparison studies and an analysis of existing erosion data, failure criteria for the ET are proposed for flexible and rigid pavements in Section 6. Section 7 discusses the design and use of the new Erosion Database. Finally, conclusions and recommendations concerning the ET and the Erosion Database are formulated and discussed in Sections 8 and 9.

2 EROSION FAILURE OF STABILISED MATERIALS

The erosion of pavements may be defined as the wearing down of material from the interface of pavement layers due to hydraulic and/or mechanical action under traffic loading and is associated with excessive pore water pressure within pavement layers or between layer interfaces and with erodible materials.

Erosion involves two processes: production of loose material and removal of this material. Depending on the pavement characteristics these processes occur in different ways and lead to different results. These differences need to be identified so they may be reflected in the failure criteria developed for the Erosion Test (ET).

2.1 EROSION FAILURE IN FLEXIBLE PAVEMENTS

In flexible pavements, traffic loading is carried by the supporting layers as opposed to the surfacing layer only. The surfacing has a relatively low permeability and acts as a seal to prevent the ingress of water into the supporting layers. The base may be constructed from a stabilised, granular or asphaltic material. The subbase is constructed from stabilised materials or natural gravels.

The deflection of a flexible pavement surface under traffic loading sets up potentially high local contact stresses between the asperities of aggregates of different layers. These high contact stresses can disturb particle cementation and lead to crushing or compressive failure of the aggregates producing "free fines" on weakly stabilised layers.

Water infiltrates the flexible pavement either through pavement shoulders, surface cracks or a rising watertable. With traffic loading, high pore water pressures build up in the pavement layers shifting the loose particles, potentially reducing densities and thus creating voids. The voids opened up by the material loss are filled by the surrounding material. This redistribution of material may lead to surface deformation if the void occurs in supporting layers or potholes and cracking if it occurs near to the road surface. The cracks so formed, increase the potential for water ingress into the pavement layers and accelerate the erosion process.

Stabilised subbase layers are also prone to thermal cracking due to excessive stabiliser content and fatigue cracking under traffic loading owing to low strength or poor support. Although the post-cracked phase is part of the pavement design,[3] if the cracking is severe or if fatigue cracks are opened on the surface, water may enter the pavement facilitating the erosion process. Water may wash away loose material around the cracked blocks under traffic loading. The blocks then begin to rock up and down under traffic loading, crushing aggregates and producing fines which are removed from the pavement under pumping. This process has been defined[1] as follows:

"Pavement pumping is the rapid release of a pressurised soil and water composition from a relatively high to a relatively low pressure potential, whereby subsurface material may be redistributed multi-directionally. Normally, the pressure is released vertically through pavement joints, cracks and edges".

Once water has entered a pavement, the erodibility of the materials used will determine the ability of the road to withstand deterioration. Erosion tests help to identify erodible material so that they may be avoided or correctly modified.

2.2 EROSION FAILURE IN RIGID PAVEMENTS

In concrete pavements, most of the traffic loading is carried by the concrete slab and relatively little stress is transferred to the subgrade. A rigid pavement, unlike a flexible pavement, is not subject to local deflections due to loading, instead slab sections deflect. Water infiltrates the pavement through joints or edges where it accumulates under curled slabs. As traffic loading deflects an approach slab, the accumulated water is pushed at high velocity towards the leave slab. The leave slab is then deflected very rapidly by the wheel load and the water is pushed back under the approach slab[4,5]. The high water velocities induce high shear stresses on the support surface layers redistributing material. This causes the formation of voids and a loss of slab support leading to corner and transverse cracking of the slabs.

3 COMPARISON OF CURRENT EROSION AND DURABILITY TESTS

To evaluate the Erosion Test (ET) for use as a standard test it is useful to compare it with other erosion tests such as the rotational shear, jetting and various brush tests. Each test is briefly described and compared in Table 1.

3.1 ROTATIONAL SHEAR TEST[6]

A specimen is held stationary inside a rotating cylinder filled with water. The specimen is connected through an end plate to a load cell to measure the resultant torque introduced on the specimen by the rotating water. The erosion is measured as the mass of material lost after each test. Figure 1a shows a diagram of the rotational test device.

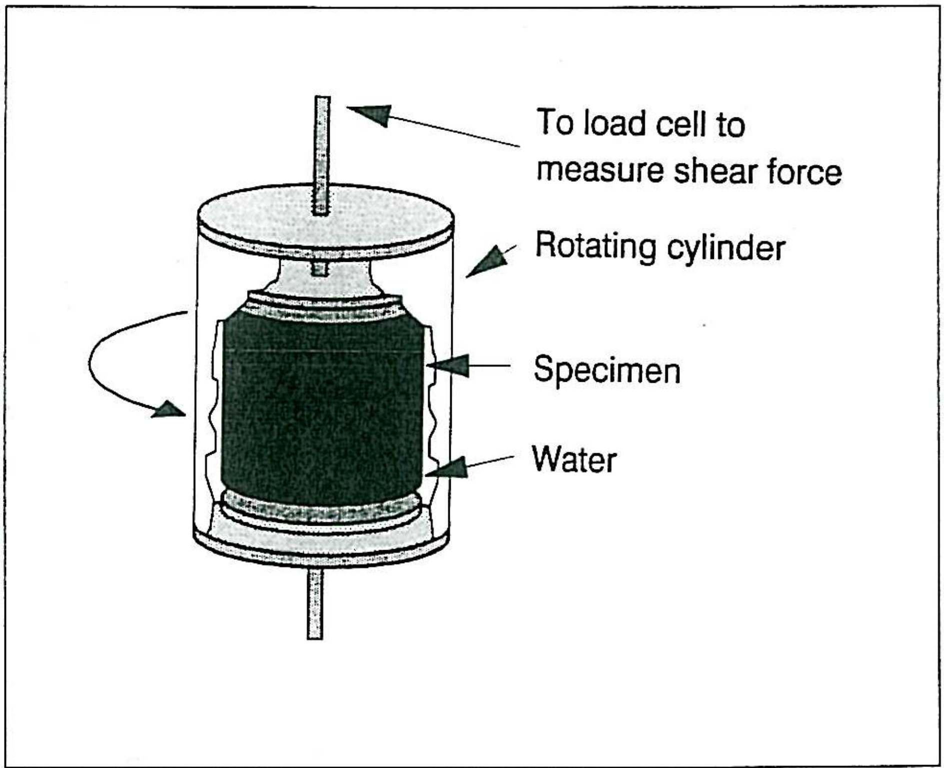

Figure 1a: The rotational shear device

3.2 JETTING TEST[6]

A pressured water jet, angled at 20 degrees to the horizontal, erodes the upper surface of the specimen. The shear stress applied is approximated by dividing the water force applied by the contact area. As with the rotational shear test erosion is measured by the amount of material lost after each test. Figure 1b shows the Jetting Test device.

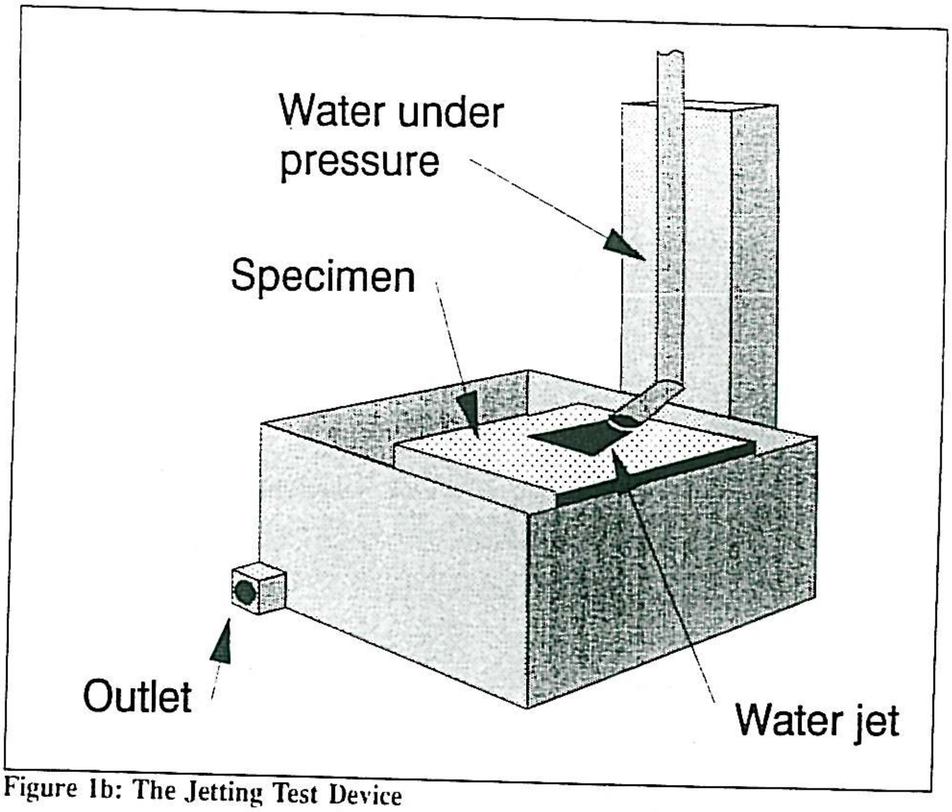

Figure 1b: The Jetting Test Device

3.3 BRUSH TESTS

A number of brush tests have been developed in different parts of the world. Most of the brush tests can be classified as durability tests. The brushing action removes particles loosened through wet/dry cycles and not through a pumping or grinding action. All use a brush to "erode" the sample surface and all measure the erodibility by mass loss. Brush and brush application differs from test to test.

3.3.1 Rotational brush test[7,8]

A 100 mm diameter, 1 kg, metal brush is mechanically rotated at 840 rev/min to erode the ends of the specimen surface. The device is shown in Figure 2a.

3.3.2 Mechanical brush test[9]

The test measures mass loss during of 12 wet/dry cycles. As part of each cycle a cylindrical specimen is rotated at 60 rev/min for 50 cycles. A stationary, 2.25kg brush erodes the specimen surface. The device is shown in Figure 2b.

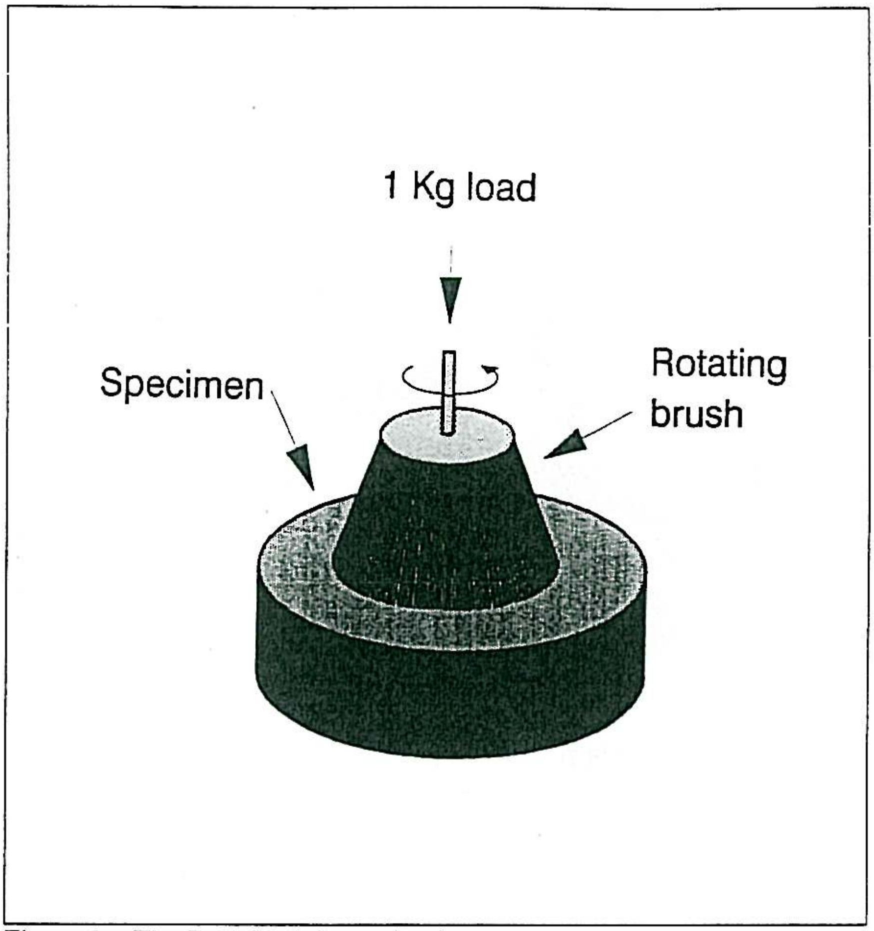

Figure 2a: The Rotational Brush Device

3.3.3 Manual brush test[10]

The test is similar to the mechanical brush test except that the cylindrical specimen is smaller and compacted using less effort. The specimen is eroded by hand brushing all surfaces using a specified wire brush. Two brush strokes are applied over the specimen surface between each wet/dry cycle. A brush stroke force of approximately 13.5N is applied by brushing the samples on a scale as shown in Figure 2c.

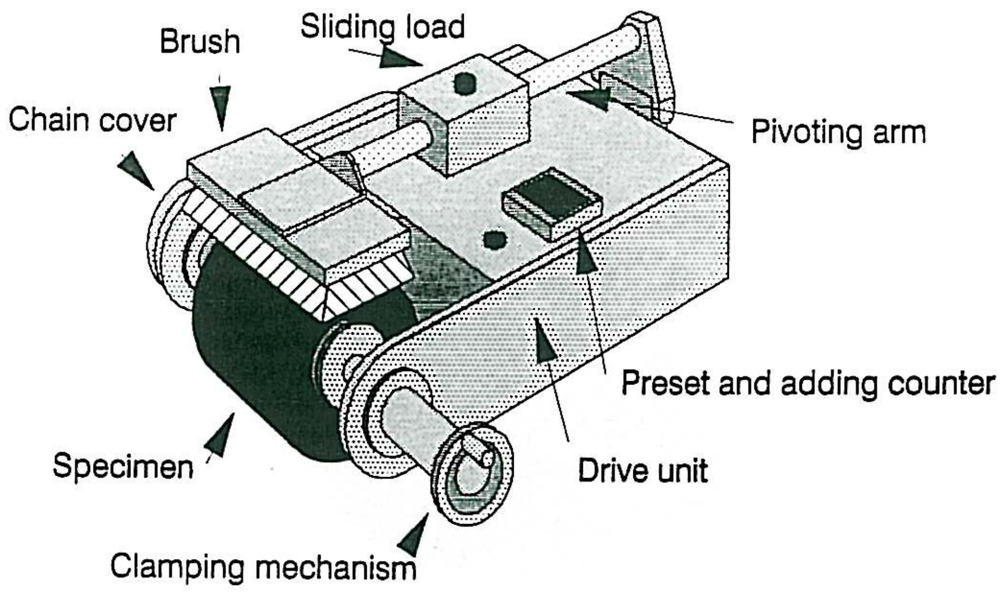

Figure 2b: The mechanical brush device

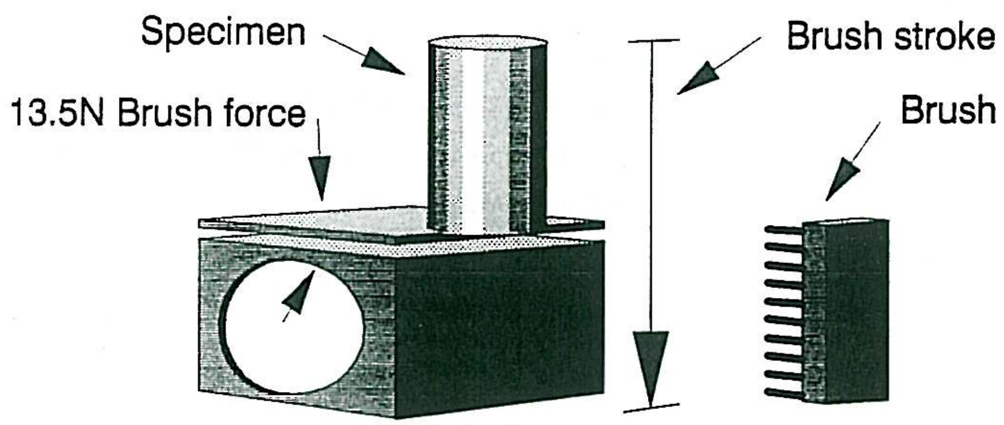

Figure 2c: Hand brushing method of the wet/dry durability test

3.4 EROSION TEST[1]

Three rectangular specimens are submerged in water and covered with a rough neoprene membrane. A 17,775kg wheel, with a bevelled rim, is then cycled 5000 times over the specimens to erode the surfaces. The depth of erosion is measured at 15 locations on the surface of each specimen and the Erosion Index (L) is considered the mean of the average depth of erosion for the three specimens. The device is shown in Figure 3.

3.5 EVALUATION OF EROSION TESTS

Different erosion tests are compared in Table 1. In the table the **Title** identifies the test. The **Country of origin** identifies the test origin so that particular influences can be identified. The **Date** indicates how long the test has been in use. The **Principle** on which the test is based identifies what assumptions the test is based on and thus the physical action the test tries to simulate. The test **Objective** determines what the test measures and the units of measurement used. The **Applicability and Advantages** covers areas where the particular test is suitable and has merit. **Limitations** identify weaknesses in the test procedure or results.

Considering Table 1, the following salient points can be noted:

- None of the tests evaluated is specified as a standard for evaluating erodibility in particular indicating that resistance to erosion is traditionally a secondary consideration. Currently, stabilised layers are specified according to Unconfined Compressive Strength (UCS) with durability tests performed only on specimens with borderline UCS results. Research has shown that erosion resistance can be improved by specifying higher compaction densities and UCS results thus negating the need for erodibility testing.

  In South Africa however, where relatively low stabiliser contents are used, some cases have occurred where materials with adequate strength (UCS) failed erodibility requirements[1].

- The shear and brush tests focus on different aspects of erodibility namely the effect of hydraulic shear stresses and the effect of aggregate abrasion. The Erosion Test (ET) simulates both of these phenomenon and is thus likely, with refinement, to provide a more realistic simulation of erodibility.

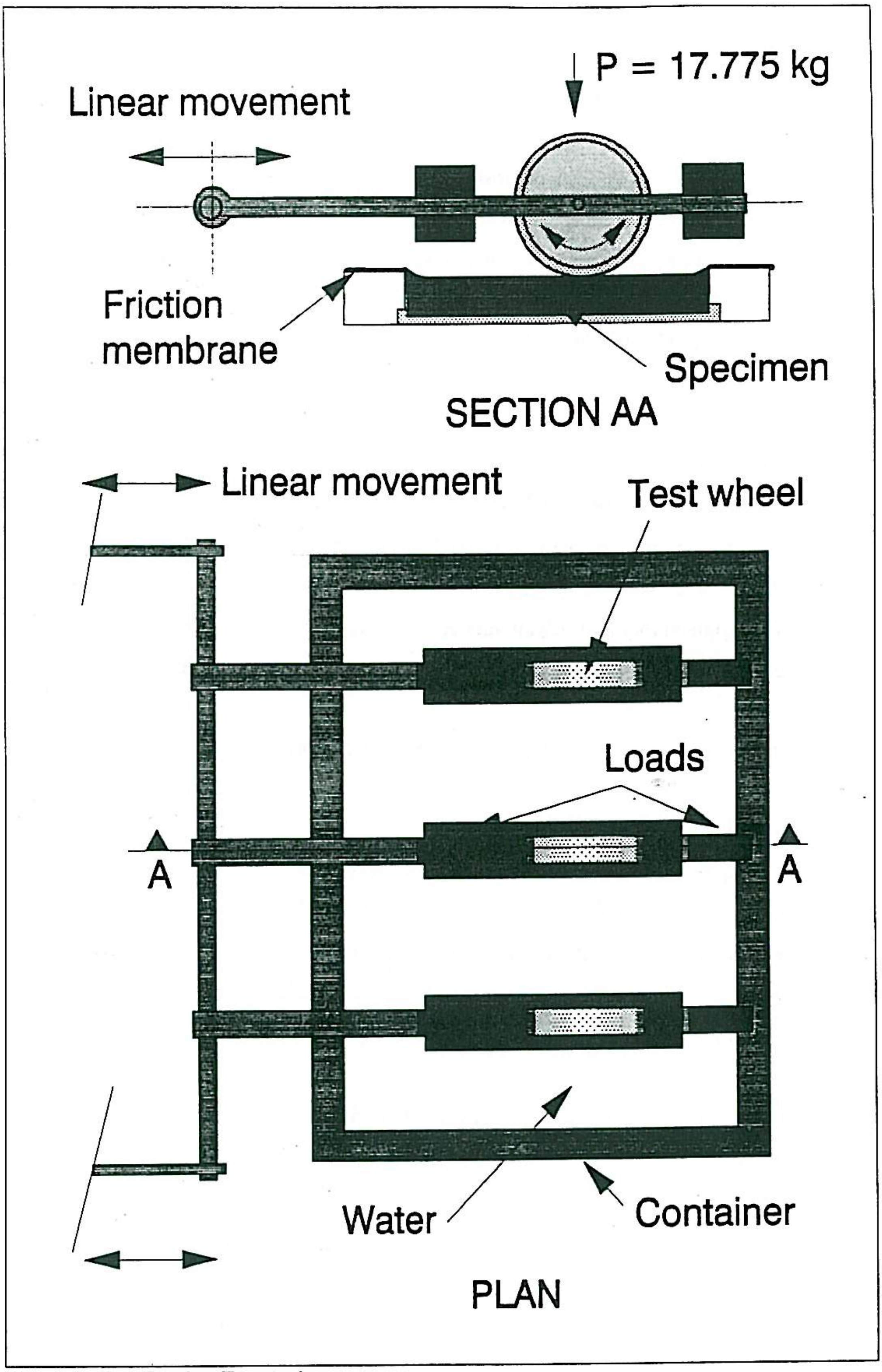

Figure 3: The Erosion Test device

- The critical shear stress (Tc) of the material has been correlated to wet/dry brush test results. Erosion Test results have shown no good correlation to the manual Wet/Dry brush test[1]. Because the test data was limited, more research would be required to confirm this result.

- The ET does not simulate weathering and carbonation effects at present because the specimen is not wet/dry cycled. Consideration can be given to a combination of carbonation and the Erosion Test to determine physical and chemical durability, and associated effects of carbonation on the erodibility of stabilised materials. This can be done by designing the experiment as such to incorporate aspects such as carbonation and wet/dry cycles.

The Erosion Test machine simulates traffic loading. With modifications it should be possible to use the machine for other road research. A number of possibilities have been identified, such as:

- Testing asphalt mix designs for rutting and stripping[12]. By heating the water in the machine, specimens can be tested at different temperatures. Ultra-violet lamps fitted to the machine could simulate environmental effects for fatigue testing, ageing, etc.

- Evaluating the effects of different Elastic Moduli ratios between pavement layers e.g. weak on stiff or stiff on weak, etc.

- Evaluating the effects of compaction-aid products and bitumen emulsion treated materials.

- Evaluating fatigue cracking of treated layers.

Table 1: Evaluation of current erosion tests

Title, country of origin and date developed	Principle	Objective	Applicability and Advantages	Limitations
Rotational shear test U.S.A., 1986[6]	Erosion occurs when the shear forces introduced by pressurised water on the layer under consideration exceed the critical shear stress level of the material	-To determine Tc, the critical shear stress of the material -To determine the quantity of eroded material	-The test can measure the shear stresses that cause erosion accurately. -It can be used on a diverse range of materials. -Tc has been correlated to the wet/dry brush test	-Only cohesive materials can be tested -Only takes water-induced shear stresses into account. -During the test, relatively large aggregates may come loose during testing which may not happen within the pavement. As the index is based on mass loss, this could lead to an incorrect interpretation of erodibility potential[1]
Jetting test FRANCE, 1979[7,8]	Similar to the Rotational Shear Test	Similar to the Rotational shear test	-The test can measure shear stresses on non-cohesive materials	-Same limitations as the rotational shear device concerning water induced stresses and large aggregates -Critical shear strength cannot be accurately determined because the shear stresses on the specimen are not uniform
Rotational brush test FRANCE, 1979[7,8]	Erosion occurs due to the abrasive action of the loaded pavement layers	-To measure the quantity of eroded material in g/m^2 -To calculate the erosion index (IE)	A design guide exists for the EI and rigid pavements so materials can be compared by their erosion index	-The reference material used to obtain the EI may be difficult to match in other countries -No correlation exists between other erosion tests -No body of information outside France

Table 1 (continued): Evaluation of current erosion tests

Title, country of origin and date developed	Principle	Objective	Applicability and Advantages	Limitations
Mechanical brush test S.A. 1988[9]	Wet/dry cycling reduces fines adhesion in the pavement layers. Erosion then occurs due to the abrasive action of the loaded pavement layers	-To measure the quantity of eroded material in g/m^2	-Improved reproducibility on the manual brush test due to mechanical brushing[9]	-Test duration 6 weeks -Because the mass of eroded material is measured, the test is susceptible to the same large aggregate loss errors as the rotational shear and jetting tests -Very little work carried out to date -Potential error in the mass loss results owing to local cemented surfaces produced during compaction
Manual Wet-dry brush test USA[11,23]	Similar to the mechanical wet-dry brush test	-To measure the quantity of eroded material in g/m^2	-A widely used test -Due to the wet/dry cycling the effect of carbonation can be determined	-Poor repeatability and reproducibility due to manual brushing technique used -The same mass loss and time disadvantages as the manual wet/dry brush test -Potential error in the mass loss results owing to local cemented surfaces produced during compaction
Erosion Test S.A.. 1984[1,2]	High contact stresses between the aggregates of pavement layers produce "free fines". Water then acts as a vehicle to remove these from the pavement leading to erosion.	-To measure the average depth of erosion (L) in mm -To determine strength parameters: the elastic modulus in bending. Strain at break; bending strength and Unconfined Compressive Strength	-More realistic modelling of erosion -Strength tests performed on the same sample -Relatively fast (8 days) -The test machine can be used for other tests, to study the effects of carbonation and wet/dry cycling.	-Cumbersome to make and handle specimens at present -The test machine is expensive -Limited test results available -At present the quick method cannot give any indication of natural carbonation, drying shrinkage or wet/dry cycling durability. With increased testing time these effects could be studied.

4 INVESTIGATION INTO THE PRECISION OF THE EROSION TEST

4.1 INTRODUCTION

Tests performed on presumably "identical materials" in presumably identical circumstances do not, in general, yield identical results. This is attributed to the unavoidable random errors inherent in every test procedure; the factors that may influence the outcome of a test cannot all be completely controlled. In the practical interpretation of test data, this variability has to be taken into account.

Many different factors (apart from error due to a lack of homogeneity of samples) may contribute to the variability of a test array. The variability will be larger when the tests to be compared have been performed by different operators and/or with different equipment than when they have been carried out by a single operator using the same instruments. Repeatability and reproducibility are used as extreme measures of variability.

To determine the precision limits of the Erosion Test method it was necessary to carry out a inter-laboratory repeatability/reproducibility study. This was done to the recommendation of International standard ISO 5725-1981 (E) - "Precision of test methods - Determination of repeatability and reproducibility by inter-laboratory tests[15]". However, owing to logistics and the limited number of participating laboratories the standard method could not be followed exactly. Deviation from the standard method is highlighted and explained where necessary.

4.2 OBJECTIVE

The principal objective of the investigation was to determine the repeatability (r) and reproducibility (R) of results from the Erosion Test performed using the Erosion Test machine (see Figure 3). A secondary objective was to receive constructive and objective criticism on the test method from the users so that the method could be improved if necessary and any problems with the apparatus resolved.

4.3 DEFINITIONS (ISO 5725-1981 (E)[15])

The repeatability (r) is the value below which the absolute difference between two single test results obtained with the same equipment on identical test material, under the same conditions (same operator, same apparatus, same laboratory, and a short interval of time), may be expected to lie with a probability of 95 per cent:

$$P(|d| \leq r)=0.95$$

where |d| = absolute difference in one laboratory

The reproducibility (R) is the value below which the absolute difference between two single test results obtained with the same method on identical test material, under different conditions (different operator, different apparatus, different laboratories and/or different time), may be expected to lie with a probability of 95 per cent.

$$P(|d| \leq R)=0.95$$

where |d| = absolute difference between laboratories

The terms repeatability and reproducibility refer to the precision or closeness-of-agreement of test results under different circumstances of replication.

4.4 DESIGN OF THE REPEATABILITY AND REPRODUCIBILITY STUDY

Five samples with a hand-brushed loss (test method A19 TMH1[11]) ranging from 3 to 100 per cent and Erosion Indices (L) from 0 to approximately 19 mm were selected for testing and these were sub-divided into sub-levels of 2, 4 and 6 per cent cement contents. Details of the materials used are shown in Table 2 with the grading curves in Figure 4.

All samples were prepared to TMH1[11] requirements by the CSIR (i.e. oversize crushed to pass 19mm), riffled to obtain 6 representative bulk samples and one of each was selected at random for distribution to the six participating laboratories. Also supplied to each laboratory was an adequate quantity of cement for the testing, obtained representatively from one pocket, thus ensuring uniformity and eliminating a possible source of bias.

The six participating laboratories were as follows:

- CSIR Division of Roads and Transport Technology (CSIR)
- Transvaal Provincial Administration (TPA)
- Natal Provincial Administration (Tested by Soils Design Laboratories in Pinetown for NPA)
- Department of Transport, Pretoria (DoT)

- Orange Free State Roads Department (OFS)
- Cape Provincial Administration (CPA)

It is recommended by ISO 5725-1981[15] that not less than 8 laboratories be used. However, it was not possible in this case as the cost of manufacturing the erosion machines is moderately high. The laboratories used are of the few highway laboratories in South Africa with good experience of testing stabilised materials which they do on a semi-routine basis for either quality control or research purposes.

Each laboratory was asked to perform the test on three replicates at each of three cement contents at the OMC and MDD supplied according to DRTT Erosion Test method[1]. Thus, for five material types, each laboratory was requested to compact three specimens at cement contents of two, four and six per cent. This gave rise to 15 different mean results.

As relatively few laboratories were used in the investigation, it would have been ideal to have increased the number of replicates to five at each cement content. This would, however, have significantly increased the material quantities being handled, the amount of testing and thus the cost.

The Erosion Test device erodes three samples simultaneously. It would have been useful to determine the repeatability / reproducibility for the Erosion Index (L) which is the average of the three samples but this would have trebled the work. It was thus decided to limit the laboratories used to six (6), materials to five (5) at three cement contents for the repeatability/reproducibility evaluation.

4.4.1 Comparison of the performance of the erosion machines

It was thought advisable to compare the performance of the erosion machines before starting the reproducibility study. It was supposed that should mechanical or electrical differences exist between them this would in turn have an effect on their performance vis-a-vis each other. Should such a discrepancy have existed it was thought advisable to quantify this at the outset so that correction factors could be applied to test results (if necessary). Two samples were tested at CSIR by all the machines that were to be used in the reproducibility study for the purposes of comparing the performance of the machines. One of the samples used was highly erodible whilst the other had a low erosion index (at the cement contents used).

4.5 ANALYSIS OF RESULTS

4.5.1 Comparison of machines

The results of the testing carried out for the purposes of comparing the performance of the various machines are given in Table 3. It can be seen from the test results that machine E gives values somewhat lower than the others. This trend, however, was not evident in the results of the reproducibility study and it was thus decided not to apply any correction factors to the test results produced by this machine. It was also evident from the results that the standard deviations were high. In some cases the standard deviation more than half the mean erosion (sample 12664, repetitions 1 and 2). This suggested that the repeatability/reproducibility of the test was relatively poor and thus the results of machine E could not statistically be considered outliers (see Table 10 where reproducibility and repeatability results are given).

4.5.2 Preliminary investigation of raw data from precision study

Table 4 contains all the test results from the six laboratories participating in the study. The cell means are given in Table 5 and the cell standard deviations in Table 6. A cell is defined as the results obtained by one laboratory for one sample at one cement content (i.e. sample 11390 tested at 2 % cement by laboratory 1 is considered to be a cell).

The Erosion Index could not be determined in some cases as the wheel on the erosion machine reached the end of its vertical travel before 5 000 repetitions had been completed (sample 11390, 2 and 4 % cement for most laboratories; sample 12664 2 % etc). This meant that these materials were highly erodible at the stabiliser contents used and would in all probability not be used for stabilised bases or subbases. These results were not used in the repeatability / reproducibility study. They are shown in Table 4 merely for information purposes.

Table 2: Properties of materials used in the repeatability/reproducibility investigation

CSIR sample number	Material type	LL	PL	PI	LS	Grading modulus (GM)	Gravel ICL (%)	OMC %*	MDD (kg/m^3)*
11390	Quartzitic sand, The Reeds	19	14	5	1,3	1,05	1,5	10,5	1954
11615	Sugar Dolerite, Ex. Devon - Delmas Rd.	37	28	9	6,5	2,39	3,0	10,0	2180
11616	Magaliesberg Quartzite Ex. Pretoria North - Britz Rd.	24	20	4	0,6	2,37	1,0	7,6	2120
11617	Calcrete Ex. Lichtenberg - Besiesvlei Rd.	21	12	9	4,2	1,89	1 - 2	7,8	2088
12664	Weathered Shale, Donkerhoek	29	16,5	12,5	6,6	1,51	3,5	12,3	1942

* Mod AASHTO compaction at 4% Ordinary Portland Cement

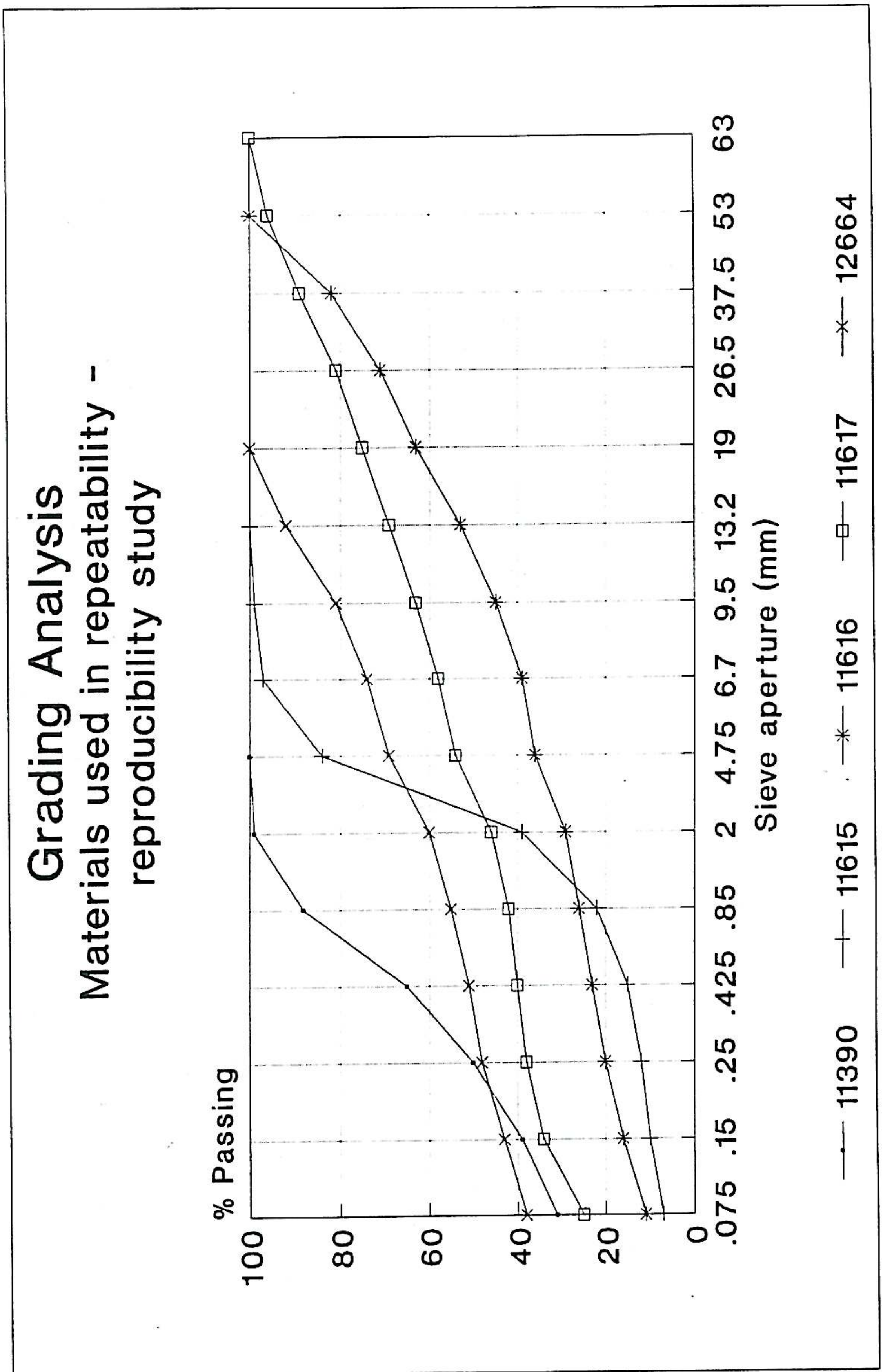

Figure 4: Grading analysis of materials used in the repeatability/reproducibility study

Table 3: Results from comparison of machines by CSIR

Sample	11390 (6% OPC) (Quartzitic sand)					12664 (4 %OPC) (Weathered shale)				
Specimen	1	2	3	Avg	Std dev	1	2	3	Avg	Std dev
Machine	Erosion Index Values - L (mm)									
A	12,2	7,9	13,7	11,3	3,0	1,9	4,0	2,4	2,8	1,1
B	9,4	10,7	14,1	11,4	2,4	2,0	1,1	1,2	1,4	0,5
C	13,2	11,0	12,7	12,3	1,2	1,4	1,4	1,7	1,5	0,2
D	15,0	10,1	12,6	12,6	2,5	0,3	1,4	0,9	0,9	0,6
E	8,1	8,6	9,0	8,6	0,5	0,9	0,9	0,6	0,8	0,2
F	15,4	8,3	10,4	11,4	3,6	0,7	2,1	1,8	1,5	0,7
Average	12,2	9,4	12,1	-----	-----	1,2	1,8	1,4	-----	-----
Std dev	3,0	1,3	2,0	-----	-----	0,7	1,1	0,7	-----	-----

Table 4: Original test results

Sample	11390 (Quartzitic sand)									11615 (Sugar dolerite)								
% OPC.	2			4			6			2			4			6		
Specimen	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
Lab	L (mm)									L (mm)								
1	**18,0**	**18,6**	**18,6**	**18,4**	**17,0**	**17,5**	**18,7**	**20,4**	**18,8**	7,6	5,2	6,6	2,1	5.4	4,4	7.7	4,8	3,7
2	**16,4**	**12,9**	**15,0**	12,8	13,1	8,7	5,3	7,8	8,1	7,2	6,5	13,4	2,0	2,2	2,1	0,5	2.2	1,5
3	**19,0**	**19,9**	**18,6**	**17,0**	**18,4**	13,3	10,6	8,6	8,9	6,1	11,2	1,6	0,1	0.2	0,2	0,1	0	0,3
4	**21,3**	**19,3**	**19,3**	**18,0**	**18,1**	**18,1**	16,9	**18,2**	17,7	0,3	0,9	0,9	0,1	0.2	0,1	0	0,1	0,1
5	17,8	17,5	15,4	17,3	19,7	17,8	16,2	14,8	12,7	6,0	4,5	4,3	4,2	0,6	1,1	1,6	0,7	0,6
6	16,7	17,2	18,7	18,3	18,7	19,2	14,8	14,3	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

- Underlined test results in bold were not included in the study - 5000 repetitions not attained
- Shaded blocks indicate a test done without the friction pad by error - not included in the study.
- N/A - Not available for the study
- OPC - Ordinary Portland Cement

Table 4(continued): Original test results

Sample	11616 (Magaliesberg quartzite)									11617 (Calcrete)								
% OPC	2			4			6			2			4			6		
Specimen	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c	a	b	c
Lab	L (mm)									L (mm)								
1	1,0	0,4	0,6	0,1	0,2	0,3	0,3	0,3	0,3	0,4	1,5	0,4	0,1	0,2	0,2	0,2	0,1	0,7
2	0,4	0,7	0,6	0,6	0	0,1	0,1	0,1	0	1,1	1,8	2,1	0,2	0,3	0,4	0,3	0	0,1
3	0,6	1,9	1,0	0,3	0,8	0,4	0,2	0,6	0,1	0,2	0,1	0,2	0	0,1	0,1	0,2	0,3	0,9
4	0,2	0,2	0,2	0,1	0,1	0,1	0	0,1	0	0,1	0,2	0,1	0,1	0,1	0,1	0,1	0	0
5	2,7	0,2	0,4	0,4	0,2	0,1	0,3	0,1	0,7	0,8	1,5	0,6	0,3	0,3	0,3	0,4	0	0,2
6	2,0	0,2	0,9	0,9	N/A	N/A	0,5	0,5	0,8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

- Underlined test results in bold were not included in the study - 5000 repetitions not attained
- Shaded blocks indicate a test done without the friction pad by error - not included in the study.
- N/A - Not available for the study
- OPC - Ordinary Portland Cement

Table 4 (continued): Original test results

Sample	12664 (Weathered shale)								
% OPC	2			4			6		
Specimen	a	b	c	a	b	c	a	b	c
Lab	L (mm)								
1	**12,1**	**12,9**	**17,6**	2,1	1,1	0,9	0,5	0,4	0,6
2	21,2	**34,5**	**26,4**	6,7	3,9	4,3	0,6	0,6	0,6
3	---	---	---	---	---	---	0,2	0,2	3,2
4	11,1	9,0	7,1	2,7	2,3	3,9	0,7	0,6	0,6
5	19,3	16,2	15,6	3,7	4,2	3,4	0,5	0,8	0,8
6	17,9	16,3	18,9	19,2	17,1	15,1	5,3	7,1	7,9

- Underlined test results in bold were not included in the study - 5000 repetitions not attained
- Shaded blocks indicate a test performed without the friction pad - not included in the study.
- OPC - Ordinary Portland Cement

--- Sample broke during preparation

Table 5: Cell averages (y)

Sample	11390			11615			11616			11617			12664		
% OPC	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6
Lab	L (mm)			L (mm)			L (mm)			L (mm)			L (mm)		
1'	#	#	#	6,47	3,97	5,40*	0,67	0,20	0,30	0,77	0,17	0,33	#	1.37	0.50
2	#	11,53	7,07	9,03	2,10	1,40	0,57	0,23	0,07	1,67	0,30	0,13	#	4,97	0,60
3	#	#	9,37	6,30	0,17	0,13	1,17	0,50	0,30	0,17	0,07	0,47	---	---	1,20
4	#	#	17,05	0,90	0,15	0,10	0,20	0,10	0,05	0,15	0,10	0,00	9,07	2,97	0,63
5	16,90	18,27	14,57	4,93	1,97	0,97	1,10	0,23	0,37	0,97	0,30	0,20	17,03	3,77	0,70
6	17,53	18,73	14,55	N/A	N/A	N/A	1,03	N/A	0,60	N/A	N/A	N/A	17,70	17,13*	6,77**

did not attain 5000 repetitions
--- sample broke during preparation

* Identified by Dixon's test as a straggler (see section 4.5.3)
** Identified by Dixon's test as an outlier (see section 4.5.3)

Table 6: Cell standard deviations (s)

Sample	11390			11615			11616			11617			12664		
% OPC	2	4	6	2	4	6	2	4	6	2	4	6	2	4	6
Lab	L (mm)			L (mm)			L (mm)			L (mm)			L(mm)		
1	#	#	#	1,21	1,69	2,07**	0,31	0,10	0,00	0,64	0,06	0,32	#	0,64	0,10
2	#	2,46	1,54	3,80	0,10	0,85	0,15	0,32	0,06	0,51	0,10	0,15	#	1,51	0,00
3	#	#	1,08	4,80	0,06	0,15	0,67	0,26	0,26	0,06	0,06	0,38	---	---	1,73**
4	#	#	0,80	0,00	0,10	0,00	0,00	0,00	0,10	0,10	0,00	0,00	2,00	0,83	0,06
5	1,31	1,27	1,76	0,93	1,95	0,55	1,39	0,15	0,31	0,47	0,00	0,20	1,99	0,40	0,17
6	1,04	0,45	0,5	N/A	N/A	N/A	0,91	N/A	0,17	N/A	N/A	N/A	1,31	2,05	1,33

did not attain 5000 repetitions

--- sample broke during preparation

** Identified by Cochran's test as an outlier (see section 4.5.3)

4.5.3 Statistical analysis of the results for the precision study

Determination of reproducibility involves three phases, namely

- a critical examination of the data in order to identify and treat outliers or other irregularities
- computation of preliminary values of r and R for each level separately
- establishment of final values r and R including the establishment of a relation between r, R and the mean if the analysis indicates that they are dependant on the mean.

Dixon's[15] and Cochran's[15] tests were applied to identify any statistically significant results in the raw data. Dixon's test is used to identify whether the highest or lowest values in a range are statistical acceptable (i.e within a 95 % confidence interval). Cochran's test is applied to variances in a group to determine if their spread is statistically acceptable. For both tests, results between a 1% and 5% significance level are called "stragglers" and those below a 1 % significance level are called "outliers" (see addendum to Table 7 and 8). A variance outside the 95 % confidence interval could indicate abnormal test results which have to be investigated.

Dixon's test was done to all samples at all cement contents in Table 5 (cell averages) to ascertain the acceptability of any seemingly low or high results from the laboratory tests. The outcome of this analysis and the probability levels are shown in Table 7.

From Dixon's test two stragglers and one outlier were discovered. The first straggler (Material 11615, 6 % OPC, Lab 1) is way above the average for its group. For this sample, the erosion at 6 % OPC is greater than the erosion at 4 % OPC. It was thus decided to reject this result. The second straggler (material 12664, 4 % OPC, Lab 6) and the outlier (material 12664, 6 % OPC, Lab 6) were rejected as they were way above the other results. No explanation was given for the high results from the laboratory involved.

Cochran's test was also applied to all the cell (all samples and cement contents) standard deviations (Table 6). The outcome is shown in Table 8. Material 11615, 6 % OPC, Lab 1 was detected as an outlier. This result had already been discarded after application of Dixon's test. Material 12664, 6 % OPC, Lab 3 was identified as an outlier. It was accepted because the range of values in the group were all relatively low.

Table 7: Dixon's test as applied to Table 5

Sample no	% Cement	Number of results	Dixon's test statistic, Q_{10}	Probability level, P (%)
11390	2	2	Insufficient data	
	4	3	0,936	P > 5
	6	5	0,248	P > 5
11615	2	5	0,496	P > 5
	4	5	0,490	P > 5
	6	5	0,755	1 < P < 5
11616	2	6	0,381	P > 5
	4	5	0,675	P > 5
	6	6	0,418	P > 5
11617	2	5	0,461	P > 5
	4	5	0,130	P > 5
	6	5	0,298	P > 5
12664	2	3	0,922	P > 5
	4	5	0,772	1 < P < 5
	6	6	0,888	P < 1

Where Q_{10} is the greater of:

$$\frac{Z(2) - Z(1)}{Z(H) - Z(1)}$$

$$\frac{Z(H) - Z(H-1)}{Z(H) - Z(1)}$$

Where Z(H) = A set of data, arranged in ascending order of magnitude, h = 1, 2, 3....H. In this case, H is the number of average test results for a material at a particular cement content.

Table 8: Cochran's test for maximum variance as applied to Table 6.

Sample no	% Cement	Number of results	Cochran's criterion, C	Probability level, P (%)
11390	2	2	insufficient data	
	4	3	0.769	P > 5
	6	5	0.335	P > 5
11615	2	5	0,579	P > 5
	4	5	0,569	P > 5
	6	5	0.804	P < 1
11616	2	6	0.581	P > 5
	4	5	0.506	P > 5
	6	6	0.466	P > 5
11617	2	5	0.453	P > 5
	4	5	0.581	P > 5
	6	5	0.467	P > 5
12664	2	3	0,413	p > 5
	4	5	0.543	P > 5
	6	6	0,925	P < 1

Where:

$$C = \frac{s^2 max}{\sum s_i^2}$$

s^2 max = the maximum standard deviation in a set

s_i = the standard deviation of a cell

Addendum to Tables 7 and 8

From ISO 5725-1981 (E)[15] the following limits should be applied to the probability P in Tables 6 and 7:-

P ≥ 5 %, that is, the test statistic is less than its 5 % critical value: the item tested is accepted as correct: the test is said to be statistically significant.

5 % > P ≥ 1 %, that is, the test statistic lies between its 5 % and 1 % critical values: the item tested is called a straggler and is marked with a single asterisk; the test is said to be statistically significant.

P < 1 %, that is, the test statistic is greater than its 1 % critical value: the item is called an outlier and is marked with a double asterisk; the test is said to be highly significant.

Critical values for Dixon's test.

Number of data in data set (H)	Significance level	
	5 %	1 %
3	0,970	0,994
4	0,829	0,926
5	0.710	0.821
6	0,628	0,740

Critical values for Cochran's test where the number of replicates is 3 (n = 3).

Number of laboratories(p)	Significance level	
	1 %	5 %
3	0,871	0,942
4	0,768	0,864
5	0,684	0,788
6	0,616	0,722

After rejection of the outliers and stragglers, the means (m), reproducibility (R) and repeatability (r) were computed (shown in Table 9) for the remaining results using the following equations.

S_1 is the sum of the cell averages.

$$S_1 = \sum \bar{y}_i \quad i=1,2,..,\text{no of laboratories}$$

S_2 is the sum of the squared cell averages.

$$S_2 = \sum \bar{y}_i^2 \quad i=1,2,..,\text{no of laboratories}$$

S_3 is the sum of the squared cell standard deviations (s_s).

$$S_3 = \sum s_i^2 \quad i=1,2,..,\text{no of laboratories}$$

s_r^2 is the known as the repeatability variance. It is the standard error associated with the test and is independent of operator or machine.

$$s_r^2 = \frac{S_3}{p}$$

where p = no of laboratories

s_L^2 is known as the between-laboratory variance and includes the between-operator and between-equipment variability.

$$s_L^2 = \frac{pS_2 - S_1^2}{p(p-1)} - \frac{s_r^2}{n}$$

m is the mean result for a set of test data after rejection of stragglers and outliers.

$$m = \frac{S_1}{p}$$

Repeatability (r) and Reproducibility (R) are calculated using the following formulas.

$$r = f\sqrt{2} \times s_r$$

$$R = f\sqrt{2} \times \sqrt{s_L^2 + s_r^2}$$

The coefficient √2 is derived from the fact that **r** and **R** refer to the difference between two single test results, and *f* is a factor whose value depends both on the number of test results available and on the error distributions assumed. If normal distribution is assumed, the number of test results is not too small, and if the probability level is 95 %, the factor *f* is taken as 1.96, Ref 15.

Table 9: Computed m, r and R after rejection of outliers and stragglers

Sample no	11390			11615			11616			11617		
Cement content %	2	4	6	2	4	6	2	4	6	2	4	6
No of laboratories (p)	2	3	5	5	5	4	6	5	6	5	5	5
S_1	---	48,5	62,6	27,6	8.4	2,6	4,7	1.3	1,7	3.7	0.9	1.1
S_2	---	817,5	852,5	188.2	24.1	2.9	4.5	0.4	0.7	4.4	0.2	0.4
S_3	---	7.9	9,2	39.8	6.7	1.0	3,3	0,2	0,2	0.9	0.0	0.3
S_r^2	---	2,6	1,8	8,0	1.3	0,3	0.6	0,0	0,1	0,2	0,0	0,1
S_l^2	---	15,4	16,5	6,2	2.1	0,3	0,0	0,0	0,1	0,3	0,0	0,0
Mean (m) in mm	---	16,2	12,5	5,5	1.7	0,7	0,8	0,3	0,3	0,7	0,2	0.2
Repeatability (r) in mm	---	4,5	3,8	7,8	3.2	1.4	2.1	0,6	0,5	1,2	0.2	0.7
Reproducibility (R) in mm	---	11,8	11,9	10.4	5.1	2,1	2,1	0,6	0,7	2,0	0.3	0.8

Table 9 (continued): Computed m, r and R after rejection of outliers and stragglers

Sample no	12664		
Cement content %	2	4	6
No of laboratories (p)	3	4	5
S_1	43,8	13,1	3,6
S_2	685,6	49,6	2,9
S_3	9,7	3,5	3,0
S_r^2	3,2	0,9	0,6
S_l^2	22,0	2,0	0,0
Mean (m) in mm	14,6	3,3	0,7
Repeatability (r) in mm	5,0	2,6	2,2
Reproducibility (R) in mm	13,9	4,7	2,2

4.5.3.1 Dependence of repeatability (r) and reproducibility (R) on the mean

From Table 9, **r** and **R** were plotted against mean (m) (Figures 5a and 5b) to determine whether the variables were dependant on the mean depth of erosion (m). Both graphs show a similar trend. There is a relatively sharp increase for low values and a flat increase for higher values. Owing to the limited data available, it was decided to approximate the reproducibility and repeatability results with linear functions.

Repeatability (r) vs Mean (m)

Repeatability is plotted against mean erosion result in Figure 5a. Repeatability increases with increased depth of erosion. The repeatability value increases rapidly initially and then tapers off.

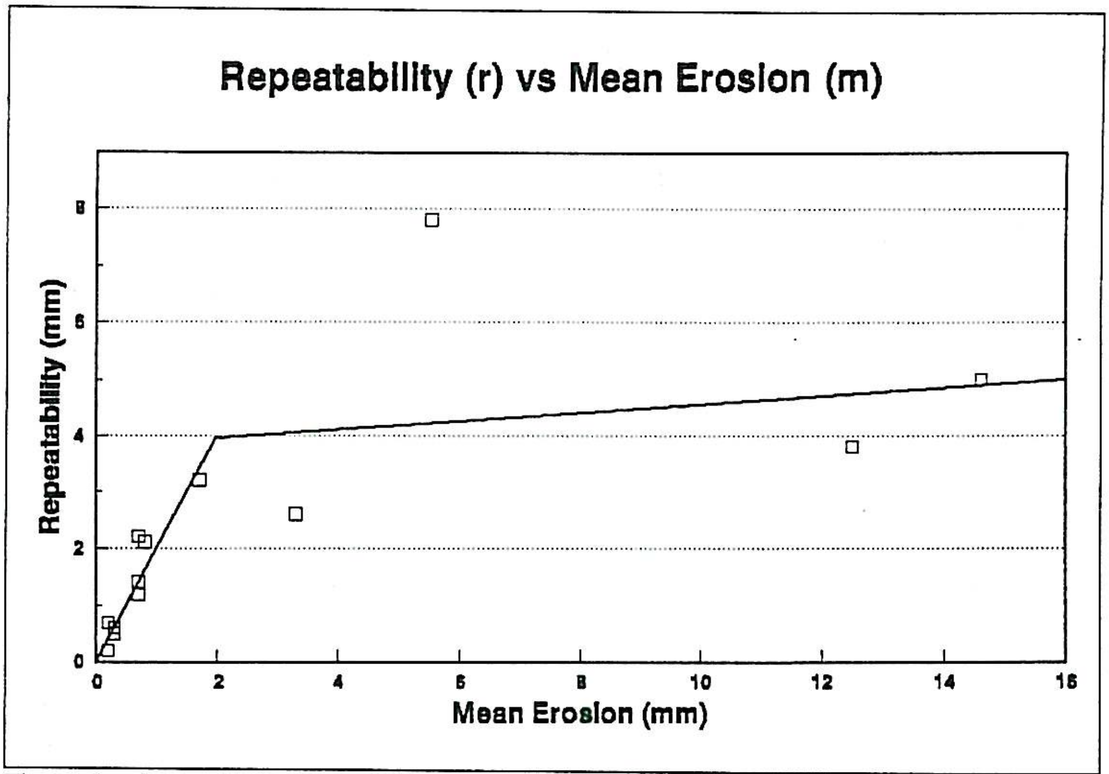

Figure 5a: Graph of repeatability vs mean for the Erosion Test

Reproducibility (R) vs Mean (m)

Figure 5b indicates a similar trend to the graph of repeatability vs mean (Figure 5a). Although the shape is similar, the reproducibility results have a higher range of values.

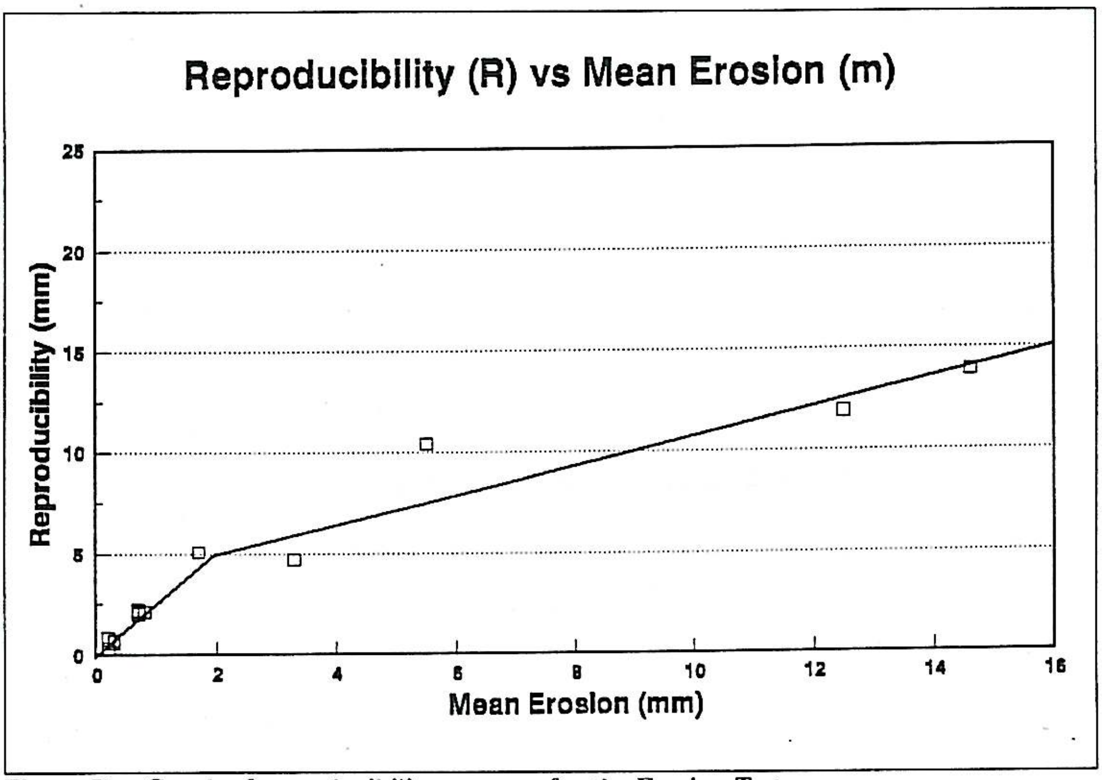

Figure 5b: Graph of reproducibility vs mean for the Erosion Test

From the linear approximations, the repeatability and reproducibility ranges are summarised in Table 10. The results have been quoted as ranges over the proposed erosion criteria ranges. Intermediate results can be found by interpolation.

TABLE 10: Estimates for R and r for different Erosion Test results

Erosion depth (mm)	r (mm)	R (mm)
From 0 to 2	0 - 4	0 - 5
From 2 to 16	4 - 5	5 - 15

r = repeatability

R = reproducibility

The difference between two single results found on identical test material by one analyst using the same apparatus within a short time-interval will exceed the repeatability, given in Table 10, on average not more than once in 20 cases with the normal and correct operation of the method.

The difference between two single and independent results found by two operators working in different laboratories on identical test material will exceed the reproducibility, given in Table 10, not more than once in 20 cases with the normal and correct operation of the method.

4.6 DISCUSSION OF REPEATABILITY AND REPRODUCIBILITY RESULTS

Based on the limited results given here, the repeatability and reproducibility of the test method may appear poor as both the reproducibility and repeatability results exceed the mean erosion measured. It is however important to bear the following in mind when viewing the results.

The repeatability and reproducibility results quoted here apply to a single test specimen out of the batch of three which actually defines the Erosion Index (L) and thus appear more strict. In reality the decision to accept or reject a material will be based on at least three results which allows determination of variance. Financially, it was not possible to increase the study to determine the repeatability / reproducibility results as this would have trebled the work. The results given here should be viewed as a starting point in determining the precision of the test and not final.

The Erosion Test is a new testing procedure with which the laboratories are not familiar. Most of the laboratories were involved with the Erosion Test for the first time when taking part in this exercise. It is plausible to assume that the repeatability and reproducibility figures will improve as experience is gained with the Erosion Test by laboratory staff. These include aspects such as sample preparation, compaction, test orientation and testing.

Owing to financial constraints the study was limited to six laboratories. The number of results was then reduced after removing outliers, stragglers and other unsuitable results. The study is thus based on few results.

Reproducibility variance is numerically greater than repeatability variance indicating that there is a greater variance in test results between laboratories than with the same laboratory. If it is assumed that the machines and materials are similar then this difference must be attributed to the execution of the test method. At present, the test method has been specified in detail[1] so it is unlikely that further refinement will improve the results. It is perhaps necessary to monitor execution of the test procedure to determine if the specified method is being executed as intended.

Yet another reason could be that the MOD AASHTO method of layer by layer compaction employed does not produce specimens that are homogeneous and it may be necessary to consider alternative methods of compaction such as the vibration table method. Indications at this time are that this method produces specimens that are more homogeneous, although this has as yet not been formally quantified. Research done by De Beer[1,2] indicated that increased compaction decreased the erosion potential.

4.7 DISCUSSION OF USER-SUGGESTED MODIFICATIONS TO THE EROSION TEST

Part of the reproducibility / repeatability study was aimed at improving the test procedure and the test device. A few improvements are suggested below.

- The Erosion Test device at present requires 5000 cycles which take approximately 85 minutes. Users suggested that the counter be linked to an automatic switch to turn the machine off when the required cycles are complete or a when a sample is completely eroded. This is technically possible but further investigation is required before this can be implemented.

- It is suggested that carrying handles be mounted on the compaction moulds for ease and safety when handling specimens.

- To increase the efficiency of the sample preparation / testing cycle it has been suggested that the machine be supplied with 9 compaction moulds.

- Some laboratories suggested that the erosion be done in the compaction mould to save time on mounting. A number of problems arise with this approach. Because the sample is contained the curing process would not be as efficient as the current method. It was found for Wet/Dry durability tests that the compaction process forms a thin, hard cemented layer on the specimen surface where it is in contact with the mould. This cemented layer might affect the test result. The top surface would not be suitable as it is usually uneven and weaker than the rest of the specimen.

5 COMPARATIVE STUDY OF THE EROSION TEST AND OTHER DURABILITY TESTS

5.1 INTRODUCTION

Investigations into stabilised base course failures have shown that many failures result from a cementation loss between the particles of the uppermost part of the layer. The durability of a stabilised layer is thus a major factor in the failure mechanism of stabilised base and subbase materials and is considered by many to govern the functional life of a pavement. In addition De Beer (1985)[16], Sampson (1988)[9], Netterberg[18] and others regard durability requirements to be of greater consequence than strength requirements, especially for fine grained weakly cemented materials. Several test methods are currently used to determine the durability characteristics of stabilised materials. The only test method, however, that is presently contained in specifications is the wet/dry hand brush test.

This section is primarily concerned with establishing whether any relationship exists between the Erosion Test method and the other test methods currently used to evaluate stabilised material durability. These tests are the mechanical wet/dry brush test, the hand wet/dry brush test, the standard unconfined compressive strength test (UCS), the cycled UCS test and the residual UCS test. The interrelationships between these test methods are also examined here.

The research discussed in this section is outside the project brief but was added to this study owing to its relevancy to the overall project. More research is, however, needed especially on the aspect of lime treated materials. The results in this section may serve to stimulate further research in this regard.

5.2 DESIGN OF CORRELATION STUDY

Five samples having Erosion Index values (L) ranging from 0.02 mm to 13.4 mm were selected for testing and these were stabilised with either 2, 4 or 6 % cement or lime depending on the material's plasticity characteristics. Details of the materials are shown in Table 11 and the grading curves in Figure 6. All samples were prepared to TMH 1[11] requirements and riffled to obtain sufficient representative material for the various tests.

For the purpose of this section a short description of all the test methods used in this study is given below.

TABLE 11: Properties of materials used in the correlation study

CSIR Sample No	Material type	LL	PL	PI	LS	Grading modulus (GM)	Gravel ICL (%)	OMC %	*MDD (kg/m³)
11615 c	Sugar Dolerite, Ex. Devon - Delmas Rd.	29	27	2	3,4	2,49	2,0	6,7	2114
11616 c	Magaliesberg Quartzite Ex. Pretoria North - Britz Rd.	24	20	4	0,6	2,29	1,5	8,6	2056
11617 c	Calcrete Ex. Lichtenberg - Besiesvlei Rd.	22	13	9	3,0	1,92	1	9,5	2017
12880 c	Weathered Basalt, Ex. Tuinplaas - Grecy Rd.	39	23	16	5,3	2,52	2,5	12,3	1942
12885 c	Weathered Diabase	26	14	12	5,7	0,91	1,5	12,3	1932

* (Mod AASTHO comp.,4% OPC)

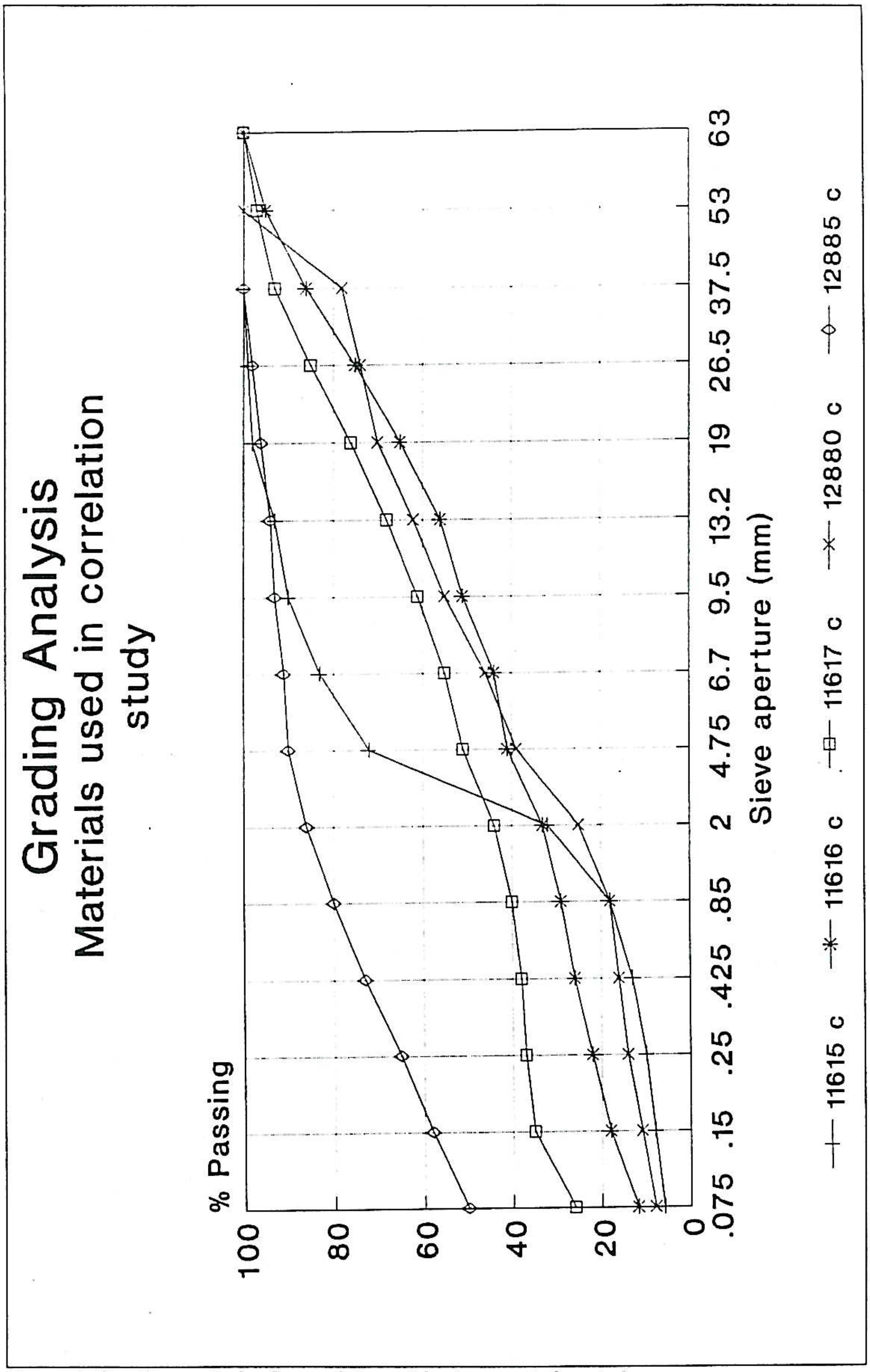

Figure 6: Grading analysis of materials used in the correlation study

5.2.1 Test methods

5.2.1.1 The wet-dry durability test for stabilised materials (hand brush)

This method is used to determine the soil-cement/lime losses obtained by repeated wetting, drying and hand brushing hardened soil-cement/lime specimens.

Specimens are prepared according to the appendix of TMH 1 method A19[11]. These are then cured for a period of 7 days at a relative humidity of 95 to 100 per cent. After curing the specimens are removed from the curing room and submerged in water at room temperature for a period of 5 hours. They are then placed in an oven at 71 °C for 42 hours. Thereafter the specimens are removed from the oven and given two firm strokes (a force of approx. 13,5 N is specified) on all surfaces with a wire scratch brush. The brush used is specified in the test method.

The procedure described above constitutes one cycle (48 hours) of the wet-dry durability test. The specimens are again submerged in water and the procedure repeated for 12 cycles. After 12 cycles the specimens are dried to constant mass at 110 °C and the mass loss after 12 cycles is determined.

5.2.1.2 The wet-dry durability test for stabilised materials (mechanical brush)

This method is essentially similar to the hand-brush method both in the preparation of specimens and the cycling of these specimens. The main difference is that the specimens are brushed by a machine especially designed for this purpose (Sampson 1988)[9]. the specimens placed in the machine are rotated at 60 revolution per minute whilst being brushed by a wire scratch brush loaded with 2.25 kg. Another important difference is that Proctor compaction is used in the hand-brush method whereas Mod AASHO compaction is normally used for the mechanical-brush method.

5.2.1.3 The determination of the unconfined compressive strength (UCS) of stabilised soils gravels and sands - standard method

This method determines the unconfined compressive strength of stabilised material by subjecting prepared specimens to an increasing load until specimen failure.

The unconfined compressive strength (UCS) of a stabilised material is defined as the load in kilopascals required to crush a cylindrical specimen 127,0 mm high and 152.4 mm in diameter to total failure at a rate of application of load of 140 kPa/s.

Mod AASHO specimens are prepared in accordance with the procedure described in the appendix to TMH 1 Method A14[11]. The specimens are then cured for seven days at a relative humidity of 95 to 100 per cent. After the curing period they are removed from the curing chamber and submerged in water at room temperature for four hours. After removal from the water the specimens are crushed to total failure in a compression testing machine.

5.2.1.4 The cycled unconfined compressive strength test (Cycled UCS)

This method is similar to the standard UCS test both in the preparation and crushing of specimens. The only difference is that the specimens are put through twelve wet-dry cycles as in the wet-dry durability brush test and after soaking for in water for four hours are crushed to total failure.

This method was developed for the purpose of determining whether "weathering" the material as in the wet-dry brushing test would have an effect on the unconfined compressive strength of stabilised material.

5.2.1.5 The residual unconfined compressive strength test (RUCS)

Again this method is similar to the standard UCS test, the only difference being that the specimens are saturated with carbon dioxide (CO_2) (24 hour saturation) before being soaked and crushed.

The carbonation of stabilised road layers has long been thought to be a problem (Netterberg)[19]. It is assumed that the stabilised material carbonates when coming into contact with CO_2 and this results in a partial or even complete loss of cementation of the treated layer with a large decrease in strength. To have some indication of the strength loss on carbonation the Residual Unconfined Compressive Strength Test was developed (adapted from De Wet and Taute (1985))[20].

5.2.1.6 The Erosion Test

The Erosion Test was developed to determine the Erosion Index (L) of cementitious materials using the Erosion Test device in which water-saturated beams of stabilised materials are tested under repeated loading and abrasion[1,2].

Material for this test is prepared according to TMH1 method A1[11]. Beams of stabilised material are made by compaction into specially designed compaction moulds using the Mod AASHO compaction hammer and static compaction in a press. The compaction effort usually ranges from 92 to 100 per cent Mod AASHO compaction . For this study 100 per cent Mod AASHO compaction was used for all samples.

The specimens are then placed in curing chambers specifically designed for this purpose and placed in an oven at 70 - 75 °C and allowed to cure for a period of seven days. After this the specimens are removed from the curing chambers, cut and mounted so that they may fit into the erosion testing machine.

The specimens are then placed in the Erosion Test machine for testing (see Figure 3). The testing machine consists of a loaded wheel running on a linear wheel track along the topside of the erosion specimen which is installed in a sealed container and is encased in gypsum in a smaller steel container. The large container is sealed at the top with a flexible neoprene membrane. Three friction pads are secured underneath the membrane and are in direct contact with the specimen. A loaded wheel runs on top of the membrane directly above the specimen.

The Erosion Index (L) is the depth of material eroded from the specimen and is determined by measuring the surface depth of the specimen both before and after erosion (5000 load repetitions) from a given datum point.

5.2.1.7 Other tests

Standard tests such as the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) (for both Proctor and Mod AASHO efforts), gradings, Initial consumption of lime (ICL) and Atterberg limits were also done on the material used in this section. All the test results are shown in Table 12.

Table 12: Correlation study test results

Sample	% Stab and type	OMC %		MDD (kg/m³)		ICL (%)		ICC (%)	Brush loss (%)		Erosion Index, L (mm)	UCS (kPa)			
		Mod	Proc	Mod	Proc	Std	NPA		Hand	Mech		Std	RUCS	Cyc	Eros
11615 c	2 OPC								100	60	13,4	1042	425	1316	870
	4 OPC	6,8	7,7	2114	1963	2,0	8,0	6,0	83	38	5,7	1371	782	1700	2060
	6 OPC								70	40	1,3	1289	823	2714	2630
11616 c	2 OPC								31	7	0,3	1042	987	2459	3910
	4 OPC	8,6	10,1	2056	2007	1,5	3,5	5,0	23	3	0,1	2467	2413	5551	6470
	6 OPC								4	4	0,1	3865	4167	8059	8640
11617 c	2 OPC								28	5	0,4	1069	823	1892	2080
	4 OPC	9,5	11,7	2017	1966	1,0	4,0	5,0	15	5	0,1	1974	1672	4194	4220
	6 OPC								13	2	0,04	2248	2577	6195	6580
12880 c	2 Lime								100	75	1,6	1453	768	55	1460
	4 Lime	11,3	15,3	1952	1910	2,5	6,7		100	20	0,1	1179	1151	2084	2830
	6 Lime								100	9	0,2	1234	1069	2083	2590
12885 c	2 Lime								24	12	10,5	261	329	713	630
	4 Lime	12,3	15,5	1932	1824	1,5	6,7		16	6	0,1	343	493	1658	1990
	6 Lime								9	3	0,3	274	631	2111	3330

5.3 DISCUSSION OF RESULTS OF THE CORRELATION STUDY

The coefficients of determination obtained should be considered of a tentative nature as they were obtained from a limited number of specimens. It was, however, not possible to carry out more tests because of financial and time constraints.

5.3.1 Cement stabilised materials

Material samples 11615 c, 11616 c and 11617 c were stabilised with various cement contents. The results of the regression analysis between the various tests are given in Tables 13a and 13b and Table 17.

5.3.1.1 Correlation of brush tests with the Erosion Test

Both the hand brush and machine brush wet/dry tests gave a good correlation with the Erosion Test. The correlation curves are given in the Appendices A1.1 to A1.3 and the correlation values are given in Table 13a.

The coefficients of determination (R^2) for the hand brush/ Erosion Test was 0,93. The formula that depicts the relationship between these two test is;

$$y\ (\textit{hand brush value}) = 55 + 17\ln(x)$$

where "x" is the Erosion Index, L.

This means that a cemented material having an Erosion Index of say 4 mm would have the approximate hand brush value of 79 % loss (78,6 = 55 + 17ln(4)).

The R^2 value for mechanical brush/Erosion Test was 0,91 and the formula giving the relationship between the two tests was;

$$y = 14{,}7x^{0{,}62}$$

This means that an Erosion Index of 1 mm would have an approximate mechanical brush loss value of 15 %.

Table 13a: Erodibility vs durability regression results for cement

Graph title	Reference figure	Equation	R^2
Mechanically brushed loss (y) vs Erosion Index (x)	A1.1	$y = 14.7\ x^{0.62}$	0.91
Hand brushed loss (y) vs Erosion Index (x)	A1.2	$y = 55 + 17\ \ln(x)$	0.93
Hand brushed loss (y) vs mechanically brushed loss (x)	A1.3	$y = 1.5\ x + 13$	0.94

Table 13b: UCS vs erodibility / durability regression results for cement

Graph title	Reference figure	Equation	R^2
Standard UCS (y) vs Erosion Index (x)	A2.1	$y = 1438\ x^{-0.15}$	0.45
Residual UCS (y) vs Erosion Index (x)	A2.2	$y = 981\ x^{-0.32}$	0.75
Cycled UCS (y) vs Erosion Index (x)	A2.3	$y = 2508\ x^{-0.28}$	0.76
Erosion UCS (y) vs Erosion Index (x)	A2.4	$y = 2567\ x^{-0.33}$	0.82
Standard UCS (y) vs hHand brushed loss (x)	A2.5	$y = 4427 - 785\ \ln(x)$	0.72
Residual UCS (y) vs hand brushed loss (x)	A2.6	$y = 11456\ x^{-0.66}$	0.83
Cycled UCS (y) vs hand brushed loss (x)	A2.7	$y = 10653 - 2067\ \ln(x)$	0.79
Standard UCS (y) vs mechanically brushed loss (x)	A2.8	$y = 2637\ x^{-0.22}$	0.37
Residual UCS (y) vs mechanically brushed loss (x)	A2.9	$y = 3481\ x^{-0.46}$	0.66
Cycled UCS (y) vs mechanically brushed loss (x)	A2.10	$y = 7275\ x^{-0.38}$	0.61

Present limits for durability are confined to those of Method A19[11] (hand brushing method) and are given in TRH 14 (NITRR, 1985)[21]. They are based on criteria developed in the USA. These limits state that the percentage loss of material should not exceed between 7 and 14 %, depending on the AASHTO material classification (AASHTO, 1961), after 12 wetting and drying cycles as follows:

< 14 per cent for soil groups A-1, A-2-4, A-2-5 and A-3;
< 10 per cent for soil groups A-2-6, A-2-7, A-4 and A-5;
< 7 per cent for soil groups A-6 and A-7.

Tentative limits for the mechanical wet/dry brushing durability test based on correlation studies between the mechanical and hand brush methods are given in Sampson and Paige-Green (1990)[24] as follows:

Stabilised material under concrete pavement - < 5%
Stabilised base - < 8%
Stabilised subbase - < 13%

Table 14 below gives the proposed erodibility criteria and the equivalent predicted hand brush and machine brush values calculated using the obtained relationships

TABLE 14: Predicted hand and machine brush values for proposed erodibility criteria

Layer	Traffic class*	Proposed Erosion Index L (mm)	Predicted hand brush loss (%) ($y=55+17\ln(x)$) $x \neq 0$	Predicted mechanical brush loss (%) ($y=14{,}7x^{0{,}62}$)
C3 (Base)	E0 - E2	≤ 2	≤ 67	≤ 23
C3 (Base)	E3 - E4	≤ 1	≤ 55	≤ 15
C4 (Subbase)	E0 - E2	≤ 5	≤ 82	≤ 40
C4 (Subbase)	E3 - E4	≤ 3	≤ 74	≤ 29

* Based on TRH4 (1985)[3]

It can be seen from Table 14 that materials considered satisfactory when applying the Erosion Test criteria are likely to be totally unacceptable when applying the current hand brush durability test criteria. For example, a stabilised material, used as a base course, with an Erosion Index value (L) of 0,2 mm would presumably have a 12 cycle hand brush loss of 27 per cent. This is not acceptable in terms of the current hand brush loss criteria given above.

It is important to note, however, that the limits for the hand brush test are considered very strict by several South African road authorities as they tend to reject material which is known to have performed well[22]. For this reason, the test and the limits tend not to be applied by road authorities. Nevertheless, it should be noted that no stabilised material known to have passed these strict wet/dry brushing criteria has given durability problems or failures (Sampson and Paige-Green, 1990)[24]. It should also be remembered that the hand brush durability test is carried out at a significantly lower density (i.e. Proctor compaction = approx. 95 % Mod AASHTO) than was the Erosion Test (100 % Mod AASHTO).

A comparison of the mechanical brush test limits and the Erosion Test criteria also indicates that stabilised materials that satisfy the Erosion Test criteria are unlikely to be acceptable where the brush test is concerned. An Erosion Index value (L) of for instance 5 mm will have an equivalent mechanised brush mass loss of 40 % (see Table 14) which is totally unacceptable in terms of the mechanical brush test limits (see page 44).

Erosion Index values of (L) 0,8 mm and below are considered acceptable in terms of the brush test criteria at least for subbase material whereas for the hand brush test only values below L = 0,1 are acceptable. A larger number of stabilised materials will thus satisfy the criteria of both the mechanical brush test and the Erosion Test than is the case with the hand brush test and the Erosion Test. This further strengthens the argument that the hand brush test limits are extremely severe and that this test method should be replaced by the mechanical brush test.

Both the specification limits for the Erosion Test and the mechanised brush test are of a tentative nature as they are derived from very limited performance related testing. There is thus much scope for improvement of the acceptance criteria of both tests. It is thus feasible to assume that these criteria will change as more performance related testing is done.

5.3.1.2 Correlation of unconfined compressive strength (UCS) testing with the Erosion Test

The correlation values for the various UCS tests and the Erosion Test are given in Table 13b.

The correlation value obtained between the Erosion Test and the standard UCS test was poor (R^2 = 0,45). It may be stated that no real correlation was expected between the two test methods, as the two tests measure different characteristics of the stabilised material. This is also seen with the correlation between the standard UCS and the mechanical brush test (R^2 = 0,37).

The correlation value (R^2) for the Residual UCS (RUCS)/Erosion Test was fairly good (R^2 = 0,75).

The formula that depicts the relationship between these two tests is:

$$y(RUCS\ value) = 981x^{-0,32}$$

where "x" is the Erosion Index, L

This signifies that a cemented material having an Erosion Index of say 3 mm (L = 3) would have an approximate RUCS value of 690 kPa (690 = $981x^{-0,32}$).

The R^2 value for cycled UCS/Erosion Test was 0,76 and the formula giving the relationship between the two test methods was:

$$y(UCSvalue) = 2508x^{-0,28}$$

Current practice in South Africa for UCS testing determines that the minimum design UCS strength after 7 days of curing is satisfied. The recommended minimum and maximum limits for the UCS of cemented materials given in TRH 14 (NITRR, 1985) are as follows (Table 15):

Table 15: Recommended UCS strength for stabilised materials

Material Classification	UCS (MPa)			
	100 % Mod AASHTO		97 % Mod AASHTO	
	max	min	max	min
C1	12	6	8	4
C2	6	3	4	2
C3	3	1,5	2	1
C4	1,5	0,75	1	0,5

Table 16 below gives the proposed erodibility criteria from this study and the equivalent predicted RUCS and Cycled UCS values calculated using the obtained relationships. The standard UCS is not included as the correlation between this test and the Erosion Test was very poor. It can be stated that for all practical purposes no correlation exists as far as this study is concerned.

Table 16: Predicted RUCS and cycled UCS values for proposed erodibility criteria

Layer	Traffic class*	Proposed Erosion Index, L (mm)	Predicted RUCS ($y=981x^{-0.32}$)** (kPa)	Predicted Cycled UCS ($y=2508x^{-0.28}$)** (kPa)
C3 (Base)	E0 - E2	≤ 2	≤ 786	≤ 2065
C3 (Base)	E3 - E4	≤ 1	≤ 981	≤ 2508
C4 (Subbase)	E0 - E2	≤ 5	≤ 586	≤ 1598
C4 (Subbase)	E3 - E4	≤ 3	≤ 690	≤ 1844

* Based on TRH4 (1985)[3]

** y = predicted UCS values; x = Erosion Index values.

It is evident when comparing Tables 15 and 16 that C4 and C3 materials conforming to the Erodibility criteria will, in all likelihood, not satisfy the RUCS strength requirements. For instance, an Erosion Index value of L = 5 mm for a C4 subbase material for the traffic class E0 - E2 will in all probability give a RUCS value of about 580 kPa whereas the UCS strength requirement is a minimum of 750 kPa (for Mod AASHTO compaction).

The Cycled UCS values may, on the other hand, exceed the maximum UCS requirements (Mod AASHTO) given in Table 15. For example, the maximum predicted Cycled UCS value for a C4 subbase (E3 - E4 traffic) is 1844 kPa whereas the maximum recommended UCS value for this material is 1500 kPa (see Table 15).

It must be remembered, however, that these values are based on fairly poor correlations. These observations can thus merely serve as guidelines at this stage.

5.3.1.3 Correlation of unconfined compressive strength (UCS) testing with the mechanical and hand brush tests

The results of the correlations are given in Table 13b and the correlation curves are given in Appendix A2.5 - A2.10.

The hand brush wet-dry test correlated fairly well with the various UCS tests. The best correlation was obtained for the Residual UCS (R^2 = 0.83) and the worst for the Standard UCS (R^2 = 0.72). The correlation value for the Cycled UCS/hand brush was R^2 = 0.79. These compare well with the correlations given by Sampson and Paige-Green (1990)[24] for the same test methods.

The Residual UCS (UCS method giving the lowest kPa values) versus hand brush (Figure A2.6 in Appendix) shows that materials satisfying the minimum UCS requirement for C3 material (1 MPa at 97 % Mod AASHTO) could have a wet/dry loss of approximately 40 per cent, which is totally unacceptable in terms of the current hand brush durability limits. Materials satisfying the minimum requirements of a C4 material are likely to give 100 per cent loss with 12 wetting and drying cycles which is also not acceptable. This again indicates that the specification limits for the hand brush test are far too severe.

It may alternately be stated that if the amount of stabiliser added is only sufficient to satisfy the C3 and C4 UCS requirements and not durability requirements, problems may be experienced with weakening and disintegration of surface layers. This may be part of the reason for many of the stabilised road layer failures that have recently been experienced[24].

Currently the hand brush test specifications appear to be too strict. Too much emphasis is also placed on satisfying strength criteria (Std UCS) and not enough consideration is given to material durability aspects for flexible pavements.

The correlation values for the various UCS test results and the mechanical brush wet/dry results were not as good as the correlation values obtained between the UCS tests and the hand brush wet/dry method. The reason for this is not clear. The wet/dry hand and machine brush tests are essentially the same, the differences being that in the hand brush test the specimens are brushed by hand whereas in the mechanical brush test the specimens are mechanically brushed; and in the hand brush test Proctor moulds and compaction are used whereas Mod AASHTO moulds and compaction effort are used in the mechanical brush test. These correlation values are contained in Table 13b and the correlation curves are given in the Appendix, Figures A2.8 - A2.10.

It is important to note that in many cases more stabiliser is required to satisfy material durability criteria than would be required if only strength criteria were considered. The additional initial cost may seem excessive cost but it could in the long run result in financial savings as future road failures are averted. There should be, however, a balance between the amount of stabiliser and shrinkage properties of the material in order to avoid excessive shrinkage and reflective cracking and durability and strength requirements.

5.3.1.4 Correlation of wet/dry brush test with the wet/dry mechanical brush test

The correlation value between the wet/dry hand brush test and the mechanical wet/dry test was relatively good as can be expected as these are essentially the same test (see Table 13a and Figure A1.3 in the Appendix).

5.3.1.5 Comparison of UCS results

In addition to the comparison between the different durability tests it was also possible to compare the Standard UCS, Erosion UCS, Cycled UCS and Residual UCS test results for the 9 cement specimens.

To establish if relationships exist between the different UCS tests, the results were plotted against each other and a regression carried out. The results gave R^2 values ranging between 0.84 to 0.97. This suggested a strong linear relationship between the different UCS tests. A second regression was then carried out for each set with the y intercept fixed at 0 to interrelate the different values. The results from the regression analysis are shown in Table 17 and the graphs in Appendix A3.

Table 17: Comparative UCS study regression results for cement

Graph Title	Ref fig	Normal regression		Regression with y intercept = 0		
		Equation	R^2	Equation	Std Err of estimated coefficients	R^2
Residual UCS (y) vs Standard UCS (x)	A3.1	y = 1.3x-676	0.96	y = 0.89x	0.06	0.89
Cycled UCS (y) vs Standard UCS (x)	A3.2	y = 2.4x-552	0.91	y = 2.14x	0.12	0.90
Erosion UCS (y) vs Standard UCS (x)	A3.3	y = 2.5x-412	0.84	y = 2.33x	0.17	0.83
Cycled UCS (y) vs Erosion UCS (x)	A3.4	y = 0.9x+73	0.96	y = 0.90x	0.03	0.96
Residual UCS (y) vs Erosion UCS (x)	A3.5	y = 0.5x-269	0.94	y = 0.41x	0.02	0.92
Residual UCS (y) vs Cycled UCS (x)	A3.6	y = 0.5x-295	0.97	y = 0.45x	0.02	0.95

The results indicate that comparatively, the Erosion UCS values are the highest followed by the Cycled UCS, Standard UCS and Residual UCS.

Because the R^2 values and the standard error of the x coefficient are reasonable for linear regressions, it may be possible with further research to relate the UCS tests with a multiplication factor. It would only be necessary perform one UCS test. Conversion between the different UCS tests can be done using the x-coefficients listed in Table 17 for a y-intercept set to zero. For example, an Erosion UCS = 4000 kPa is equal to a Standard UCS = 4000/2.33 = 1717 kPa. The error on the calculation is 4000/(2.33±0.17) i.e. between 1600 -1850 kPa. It is important to bear in mind that these relationships are based on 9 results and are the starting point for further investigations.

5.3.2 Lime stabilised materials

Material samples 12880 and 12885 were treated with lime and subjected to all the various tests. No satisfactory correlations were, however, obtained between any of the test methods. The best correlation obtained was between the wet/dry brush test and the wet/dry machine brushed test. This was, however, only a value of R^2 = 0.56 which may be considered very poor, or virtually no correlation.

The reason for this lack of correlation between the various tests is not apparent. Because of the importance of lime stabilisation to the roads industry this occurrence merits further investigation and should be researched.

5.4 SUMMARY OF COMPARATIVE STUDY

The regression values obtained should be considered of a tentative nature as they were obtained from a limited number of specimens.

- Correlations values between the two brush tests and the Erosion Test were fairly mediocre and suggested that brush test limits are too strict as materials passing Erosion Test criteria will fail the brush test. This is especially so for the manual wet/dry brush test.

- Correlation values between the various UCS tests and the wet/dry brush methods also indicate that the current specifications for manual brush loss are too stringent. It is inferred by the relationship between the UCS tests and the hand brush test that a C3 material satisfying minimum UCS requirements will have a brush loss of approximately 40 per cent, and 100 per cent for a C4 material. These findings and those of the correlations between the brush tests and the Erosion Test strengthen the existing premise that the manual brush test limits are extremely severe and that this test should be replaced by the mechanical brush test. It must also be remembered that both the specification limits for the Erosion Test and the Mechanised brush test are of a tentative nature as they are derived from a very limited number of performance related testing. There is thus much scope for improvement of the acceptance criteria of both tests. It is thus feasible to assume that these criteria will change as more performance related testing is done.

- UCS/Erosion Test correlation values suggest that C3 and C4-materials satisfying Erosion Test criteria will not satisfy UCS criteria when the Residual UCS test is used to evaluate the materials. However, maximum UCS 7-day criteria may be exceeded when the Cycled UCS is used, possibly because the cycled UCS has a curing period in excess of 28 days (approx. 6 weeks). The lowest UCS values are obtained using the RUCS method. It is thus recommended that this method be used to evaluate the stabilised material strength. This is a conservative approach which will ensure that if the material is subjected to wetting and drying or possibly detrimental carbonation in service, it will retain sufficient structural integrity to satisfy the original design UCS requirements.

- There were strong linear relationships between the Erosion UCS, the Cycled UCS, the Residual UCS and the Standard UCS based on the **cement** treated specimens. Comparatively the Erosion UCS values were the highest followed by the Cycled UCS, Standard UCS and Residual UCS. It is therefore recommended that the strength criteria should be based on the Residual UCS, thus ensuring that even if the material is subjected to wetting and drying or carbonation in service it will retain sufficient structural integrity to satisfy the original design requirement in terms of UCS. These findings support those of Sampson and Paige-Green (1990)[24].

- Where lime stabilisation was used no satisfactory correlations were obtained between any of the test methods. The reason for this is not apparent. Because of the importance of lime stabilisation to the roads industry this occurrence merits further investigation.

- It must be remembered, however, that the correlation values between the various test methods are in most cases based on fairly poor correlations. These observations can thus merely serve as guidelines at this stage.

6 EROSION TEST FAILURE CRITERIA

The ultimate goal of erosion testing is to establish criteria which can be used with confidence to select materials that will not fail prematurely under field conditions. Successful criteria will be able to differentiate between materials which will potentially cause erosion associated failure and those that will be acceptable.

Without complete field-related knowledge of erodible materials, it is necessary to establish criteria based on the theoretical causes of erosion, information available and engineering judgement. The criteria so established become the starting point. From there, as more information becomes available, the criteria can be refined. It is thus important not to consider the proposed Erosion Test failure criteria in isolation when making a decision to accept or reject a material. At least the UCS criteria should be adhered to.

The requirements for pavement erosion (see Section 2) were traffic load, the ingress and movement of water and material susceptibility to erosion. These need to be reflected in the Erosion Test failure criteria.

6.1 FLEXIBLE PAVEMENTS

In flexible pavements, the base layer is normally used to distribute the traffic load and transmit it to the subbase and subgrade layers. To avoid loss of support, the base is designed to be stronger than the subbase, and therefore requires a higher erodibility criteria than the subbase. Any water infiltrating the surface will affect the base first and any loss of base course material through erosion will potentially open up surface cracks faster than subbase erosion. It is thus important to specify more strict failure criteria for base layers than for subbase layers.

From the theoretical causes of erosion failure, simultaneous HVS and laboratory results[1] and experience with the test, the following criteria for flexible pavements are proposed in Table 18.

Table 18: Failure criteria for C3/C4 materials in flexible pavements

Material	Traffic class*	Erosion Index, L(mm)**
C3 (Base)	E0-E2***	≤ 2
C3 (Base)	E3-E4	≤ 1
C4 (Subbase)	E0-E2	≤ 5
C4 (Subbase)	E3-E4	≤ 3

* Based on TRH4(1985)[3]

** Erosion Index (L) = The average depth of erosion in mm measured from 15 measurements on 3 erosion specimens after 5000 load repetitions in the test device[1].

*** For the E0 - E2 traffic class the criteria is relaxed from 1 mm to 2 mm, compared with previously published criteria[1].

6.2 RIGID PAVEMENTS

Currently no comparative Erosion Test and field results exist on rigid pavements. A theoretical model was used here to formulate the erosion criteria. A typical concrete slab was analysed using loads at the slab edge where most erosion is expected[22]. The vertical stress for the worst case, an un-jointed concrete slab with no shear transfer, was calculated (24 kPa) and assigned the 1 mm limit. This stress correlates well with those measured by Robberts on a full-scale concrete pavement test[5]. Using 80 % shear transfer at the joints, edge stresses under dowel-jointed and continuously reinforced concrete pavements were calculated as 18 kPa. Although dowel-jointed pavements have higher shear transfer, 80 % was used to allow for cracking between joints. The 1 mm worst case limit was then multiplied by the ratio of edge stresses i.e. 1 x 24/18 = 1.5 mm. The C4 limit was assumed similar to the E3 - E4 category for flexible pavements. The criteria for cemented materials for rigid pavements is summarised in Table 19.

Table 19: Failure criteria for C3/C4 cemented materials in rigid pavements

Material	Pavement type	Erosion Index, L (mm)
C3 (Subbase)	Un-Doweled Jointed	≤ 1
C3 (Subbase)	Continuously reinforced	≤ 1.5
C3 (Subbase)	Dowel-jointed	≤ 1.5
C4 (Lower Subbase)	All concrete pavements	≤ 3

6.3 DISCUSSION OF CRITERIA

The erosion criteria for both flexible and rigid pavements are more differentiated than the wet/dry durability criteria (14 % mass loss specified for all cemented materials)[3]. The ultimate aim is to produce limits as exact as possible given the variance in road materials so that design and performance can be matched as closely as possible. The erosion criteria recognises different traffic groups and material classifications. Research has shown that although a material may be classified as a C3 or C4 material, based on UCS results, it may fail the erosion criteria[1]. It is therefore important to do more than one test for stabilised material selection. It is proposed here that at least both the UCS and the Erosion Test be done to select a proper durable material as is discussed in the previous section. It is foreseen that with more experience the erosion criteria will be further refined. At present the current criteria (Tables 11 and 12) are proposed to be used nationally.

7 THE EROSION DATABASE

7.1 INTRODUCTION

To facilitate the collection and comparison of existing and future erosion data, a user-friendly database system was created as part of this project. This section discusses how the database was developed, what information it contains, and how this information can be used now and in the future. A full program manual appears in Appendix B along with the program disk on the inside front cover of this report.

7.2 DATABASE DEVELOPMENT

The Erosion Database is a stand-alone computer program written in a database language which can be installed easily onto a hard disk. It allows users to locate groups of records and then print these from the database or import them into commercial spreadsheet for processing or printing. To ensure that the data base is user-friendly, the program is menu-driven and contains context sensitive help screens. The main menu screen is shown in Figure 7.

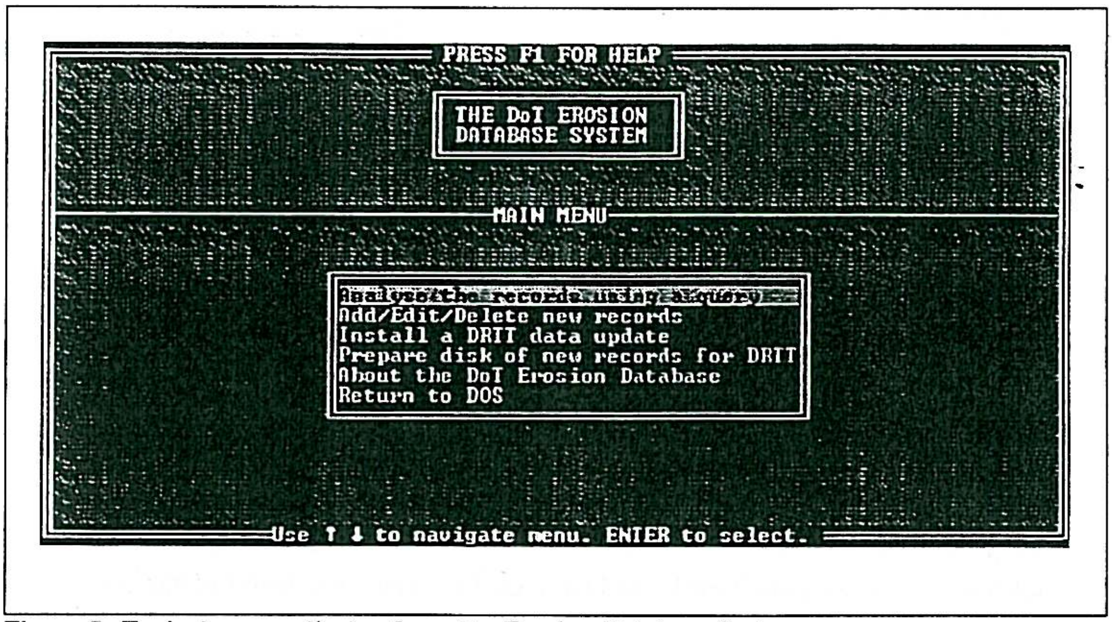

Figure 7: Typical screen display from the Erosion Database System

The database contains information on all aspects of erodibility. It is structured to provide information record identification, material properties, test results as well as field data and general comments on the material test. The following is a list of the fields (columns) in the database with an explanation of each.

A. RECORD IDENTIFICATION:

1. Information sender:

If a user identifies a record which is similar to the material under investigation, the organisation responsible for the original test can be contacted for more information if necessary.

2. Client:

If the information sender has no record of the results, a database user can contact the client for further comment on the test result and test situation.

3. Test reference number:

To allow the client or the information sender to identify the particular tests when requested.

4. Record date:

For further identification of the record.

5. Material Description:

Only a basic description is required. Instead of a detailed material description, material properties such as Grading Modulus and Optimum Moisture Content are included in the database so that similar materials can be located through these numerical fields and then the material descriptions compared. Previous databases which have attempted to reference materials on classification have not been successful. Accurate classification is difficult and too specific to locate groups of records.

6. Material Source:

The material source is included to identify the material tested further.

B. MATERIAL PROPERTIES:

Grading Modulus (GM), Maximum Dry Density (MDD), Optimum Moisture Content (OMC), Liquid Limit, Plastic Limit, Plasticity index:

Given the way database search operates, it is more effective to locate records using numeric fields rather than character fields. These numeric material properties fields allow users to locate records which are similar and then compare the physical classifications for similarities.

Stabilisers used:

This allows for three different stabiliser combinations to be included in the record.

Compaction and Curing:

Additional information which can be used for research purposes or as further identification.

C. TEST RESULTS:

The test result fields concentrate on durability testing but also include strength, lime/cement consumption, Heavy Vehicle Simulator (HVS) and field results.

Unconfined Compressive Strength (UCS), Carbonated UCS, Cycled UCS:

Each of these test results are recorded with their standard deviation for the test result and the number of tests in the group.

Manual Brush Test, Mechanical Brush Test, Erosion Test:

These test results also make provision for the average test result, the standard deviation and the number of test results involved.

Third point loading:

Although rarely performed on stabilised materials currently, the test was included for completeness.

Initial Consumption of Lime (ICL), Initial Consumption of Cement (ICC):

Used to determine the percentage stabiliser needed.

Carbonation:

A character field indicating the degree of carbonation.

Heavy Vehicle Simulator(HVS) / Field data:

Provides for field results and laboratory results to be included in the database when they occur.

Comment:

The comment field was included to allow unique observations to be noted about a batch of tests.

Because the above field list is extensive, the database can be used as a general materials test database as more information becomes available. The usefulness of the database will increase as the number of records increase. At present records have been collected from CSIR archives, the reproducibility/repeatability study, the durability test comparisons and various erosion results from local consultants.

Data collection for the database works as follows: CSIR will hold the master data file on behalf of Department of Transport. The program allows users to input their own records in tabular form. This information can then be sent back to CSIR via a floppy disk to allow the master data file to be updated. An update disk of new national records can be returned to users. An option selected from the program menu will then automatically update the master file on the users disk.

To encourage users to participate in data collection, it is envisaged that more functions be added to the original program. Users should be able to input their raw test results, for a variety of standard tests, and have the results processed and automatically stored to the database. The program could then print out a professional report for distribution to their client. Offering a reduction in user work load will encourage data collection as this is vital for database success. The program has been designed to add additional features at a later stage.

7.3 DEMONSTRATION OF THE DATABASE USING EXISTING RECORDS

The database was designed to achieve the following objectives:

- To provide a record of all durability and erodibility testing done to date in South Africa.
- To allow a user to match the properties of untested materials for comparison or reduction of testing.
- To allow different durability and erosion tests to be compared to establish relationships between the different tests and through this experience be able to refine erodibility and durability criteria.
- To determine the relationship between different test results such as UCS and Erosion.
- To determine the relationship between field experience and laboratory results.

As an example of the output, the following query was created to locate all lime stabilised, Erosion Test results in the database:

STABILISER CONTAINS "LIME" AND EROSION TEST > 0

A sample output is displayed in Figures 8a and 8b. The output in Figure 8a was printed directly from the program. Figure 8b was taken into a wordprocessing package and then printed. Both were printed on a laser printer. When printed from a word processor the output is neater than when printed directly from the program.

DoT EROSION DATABASE SYSTEM

QUERY OUTPUT

Material Description	Erosion Test (mm)
BEREA RED SAND	9.8
WEATHERED GRANITE	0.2
WEATHERED GRANITE	4.2
WEATHERED DOLERITE	3.4
WEATHERED DOLERITE	2.0
WEATHERED SANDSTONE	2.0
KAROO SANDSTONE	0.3
KAROO SANDSTONE	1.1
KAROO SANDSTONE	0.0
KAROO SANDSTONE	0.4
KAROO SANDSTONE	11.2
KAROO SANDSTONE	0.7
KAROO SANDSTONE	12.4
KAROO SANDSTONE	0.5
KAROO SANDSTONE	12.3
KAROO SANDSTONE	14.1
WEATHERED DOLERITE	2.2
WEATHERED DOLERITE	2.2
WEATHERED DOLERITE	3.8
WEATHERED DOLERITE	0.6
WEATHERED DOLERITE	0.1
WEATHERED DOLERITE	0.3
?	0.1
WEATHERED, DOLERITE	1.3
FERRICRETE, GRANOPHIER	0.5
WEATHERED BASALT	1.6
WEATHERED BASALT	0.1
WEATHERED BASALT	0.2
WEATHERED DIABASE	10.5
WEATHERED DIABASE	0.1
WEATHERED DIABASE	0.3

Figure 8a: Printed output from the Erosion Database

DoT EROSION DATABASE SYSTEM

QUERY OUTPUT

Material Description	Erosion Test (mm)	σ
BEREA RED SAND	9.8	3.5
WEATHERED GRANITE	0.2	0.2
WEATHERED GRANITE	4.2	0.0
WEATHERED DOLERITE	3.4	0.0
WEATHERED DOLERITE	2.0	0.0
WEATHERED SANDSTONE	2.0	0.0
KAROO SANDSTONE	0.3	0.2
KAROO SANDSTONE	1.1	0.3
KAROO SANDSTONE	0.0	0.0
KAROO SANDSTONE	0.4	0.1
KAROO SANDSTONE	11.2	0.8
KAROO SANDSTONE	0.7	0.1
KAROO SANDSTONE	12.4	1.2
KAROO SANDSTONE	0.5	0.3
KAROO SANDSTONE	12.3	0.8
KAROO SANDSTONE	14.1	1.8
WEATHERED DOLERITE	2.2	0.3
WEATHERED DOLERITE	2.2	0.2
WEATHERED DOLERITE	3.8	0.8
WEATHERED DOLERITE	0.6	0.2
WEATHERED DOLERITE	0.1	0.0
WEATHERED DOLERITE	0.3	0.1
?	0.1	0.0
WEATHERED, DOLERITE	1.3	0.9
FERRICRETE, GRANOPHIER	0.5	0.2
WEATHERED BASALT	1.6	0.0
WEATHERED BASALT	0.1	0.0
WEATHERED BASALT	0.2	0.0
WEATHERED DIABASE	10.5	0.0
WEATHERED DIABASE	0.1	0.0
WEATHERED DIABASE	0.3	0.0

Figure 8b: Database output printed from a wordprocessor

8 SUMMARY AND CONCLUSIONS

The following conclusions concerning the Erosion Test and the state of erosion testing in South Africa were drawn:

- Because the Erosion Test machine and test are relatively expensive and can only be performed by larger laboratories, it is unlikely that the test will replace other durability tests, but rather be used in conjunction with other tests.

- The repeatability and especially reproducibility of the Erosion Test method can be considered poor at this stage relative to the criteria established. This is partially because the results are quoted for a single test result and not the average of 3 test results which usually determine the Erosion Index (L). The relatively poor results have also been attributed to inexperience with the test procedure, natural material variability and the MOD AASHTO method of compaction which, it is suspected, produces non-homogenous samples. The present method of compaction is considered to be the prime reason for the high variability found with the Erosion Test results.

- Because the reproducibility and repeatability for single results is poor it is important to consider all three Erosion Test results and the variance before accepting or rejecting a material.

- The regression values obtained in the comparative study between the various durability test methods should be considered of a tentative nature as they were obtained from a limited number of samples.

  Correlation values between the two brush tests and the Erosion Test were low. It is suggested that brush test limits are too severe as materials passing Erosion Test criteria will fail the brush test. This is especially so for the wet/dry hand brush test.

  Correlation values between the various UCS tests and the wet/dry brush methods also indicate that the specifications for hand brush loss are too stringent. It is inferred by the relationship beween the UCS tests and the hand brush test that a C3 material satisfying minimum UCS requirements will have a brush loss of approximately 40 per cent and this figure will be 100 per cent for a C4 material. These findings and those of the correlations between the brush tests and the Erosion Test strengthen the existing premise that the hand brush test limits are extremely severe and that this test should be replaced by the mechanical brush test. It must also be remembered that both the specification limits for the Erosion Test and the mechanical brush test are of a tentative nature as they are derived from a very limited number of performance related tests. There is thus much scope for improvement of the acceptance criteria of both tests. It is thus feasible to assume that these criteria will change as more performance related testing is done.

UCS/Erosion Test correlation values suggest that C3 and C4 materials satisfying Erosion Test criteria will not satisfy UCS criteria when the Residual UCS test is utilised to evaluate the materials. However, maximum UCS 7 day criteria may be exceeded when the Cycled UCS is used, possibly because the cycled UCS has a curing period in excess of 28 days (approx. 6 weeks).

Where lime stabilisation was used, no satisfactory correlations were obtained between any of the test methods. The reason for this is not apparent. Because of the importance of lime stabilisation to the roads industry this occurence merits further investigation.

There were strong linear relationships between the Erosion UCS, the Cycled UCS, the Residual UCS and the Standard UCS based on the **cement** results. Comparitively the Erosion UCS values were the highest followed by the Cycled UCS, Standard UCS and Residual UCS. It is therefore recommended that rather than base the strength criteria on the 7 day UCS the Residual UCS or Cycled UCS be used depending on the material location in the pavement and the risk of strength loss due to carbonation. This will ensure that even if the material is subjected to wetting and drying or carbonation in service it will retain sufficient structural integrity to satisfy the original design requirement in terms of UCS. These findings are similar to those in Sampson and Paige-Green (1990)[24].

It must be remembered, however, that the correlation values between the various test methods are in most cases based on fairly poor correlations. These observations can thus merely serve as guidelines at this point.

- Because there is little comparative field and laboratory information available at this stage, the proposed criteria given here are based on experience and theoretical models. They must therefore be seen as guidelines when making decisions on the erodibility and durability potential of stabilised materials.

- Experience indicates the Erosion Test differentiates between C3 and C4 materials which is at present not possible with wet/dry durability tests. As more information becomes available, to obtain the optimum solution, the test will be able to discriminate between marginal materials.

- A DoT Erosion Database has been developed to reference, collect and analyse current and future erosion and durability test information. Because the database will rely on a wide range of laboratories to collect information, it is important that they are familiar with its use and are encouraged to use it.

- Users suggested improving the apparatus by installing a switch to turn of the device automatically after the maximum erosion or 5000 cycles have been reached. It was also suggested that handles be added to the compaction moulds to make them easier to carry and that nine moulds be supplied to allow the testing cycle to proceed uninterrupted.

- Because the Erosion Test device simulates traffic loading in the laboratory, it is possible that it could be used to evaluate and research other aspects of pavement design and performance such as the rutting and stripping of asphalt mixes, the cracking of treated layers or the effects of compaction-aid products on pavement layers.

9 RECOMMENDATIONS AND FURTHER RESEARCH

Based on the conclusions of this study, the following recommendations and suggestions for future research are made:

- Encourage more tests to be carried out on the Erosion machine to increase the amount of data and performance related experience.

- Carry out a follow-up reproducibility / repeatability study based on the Erosion Index (L), (3 results) as opposed to individual test results.

- Investigate the effect that different methods of compaction have on the variability of the Erosion Test (This is considered to be one of the main reasons for the high variability found in the Erosion Test results).

- Expand the comparative study to include more test results for cement and lime.

- Investigate the link between the different UCS values indicated here, on a wider range of materials.

- Check that a material satisfies both the Erosion Test criteria and the UCS criteria (TRH4:1985)[3] before accepting or rejecting it. Modification of the criteria may be needed, based on further research.

- To confirm the theoretical limits established to date for erosion testing, it will be useful to monitor field results in the future and be more aware of comparative field/laboratory studies especially in pavements that have failed owing to material susceptibility.

- Encourage record collection for the database by adding time-saving modules to the system and training users in its operation.

- Improve the Erosion Test by taking users suggestions into account.

- Investigate other uses for the Erosion Test device in pavement material evaluations to make it more economically viable.

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APPENDIX A1: GRAPHS OF EROSION TEST RESULTS VS DURABILITY TEST RESULTS

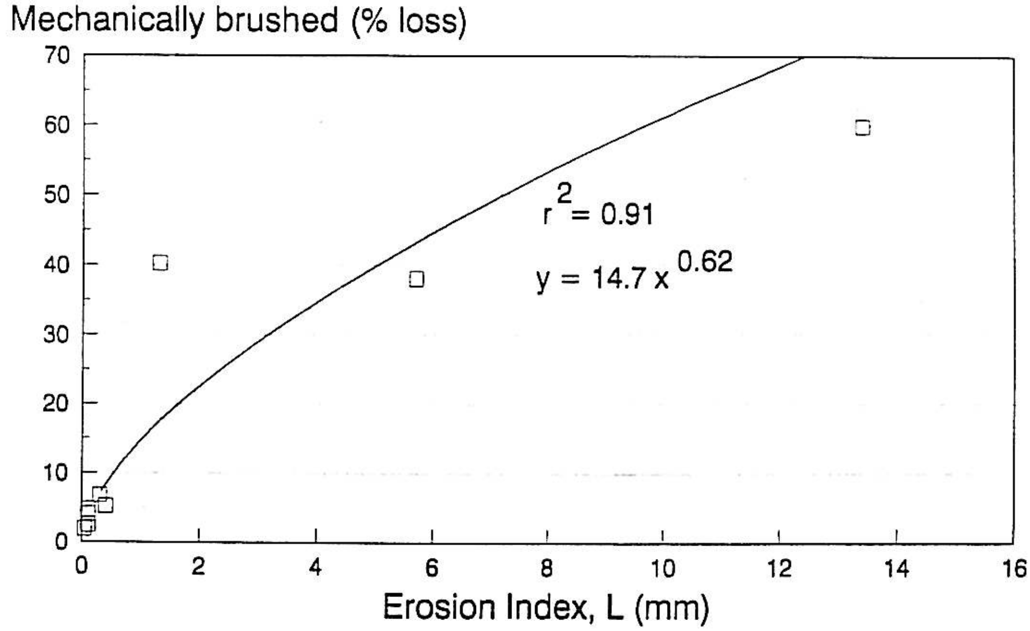

FIGURE A1.1: Mechanically brushed loss vs Erosion Index for the cement treated materials

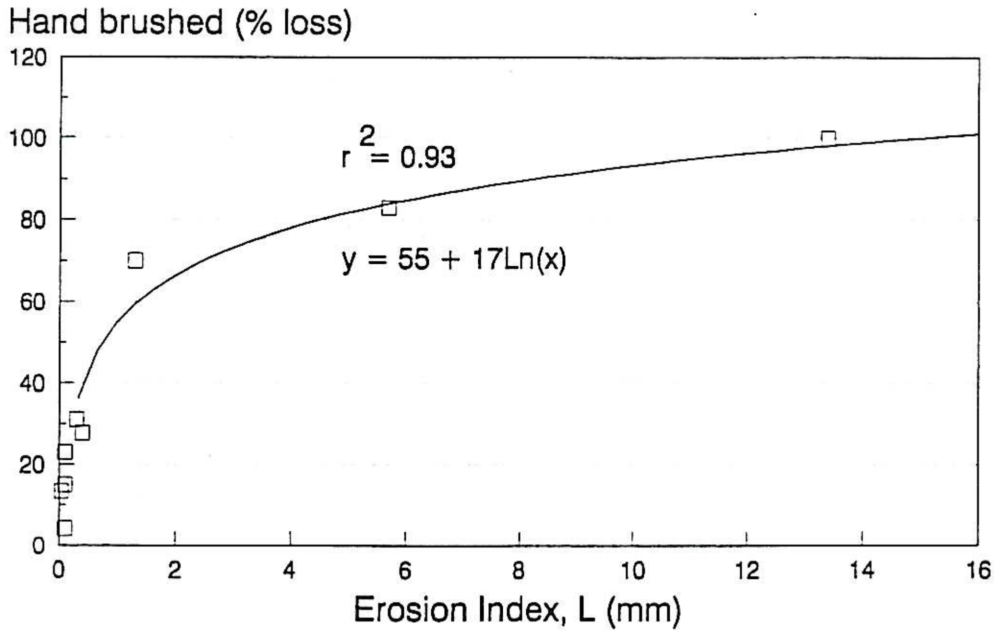

FIGURE A1.2: Hand brushed loss vs Erosion Index for the cement treated materials

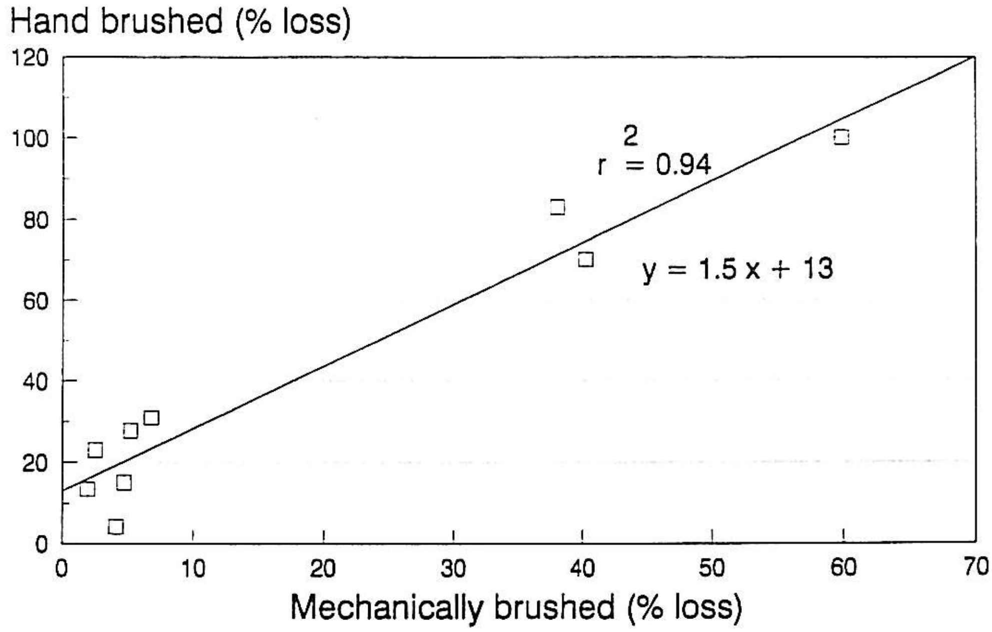

FIGURE A1.3: Hand brushed loss vs Mechanically brushed loss

for the cement treated materials

APPENDIX A2: GRAPHS OF EROSION AND DURABILITY TEST RESULTS VS UCS TEST RESULTS

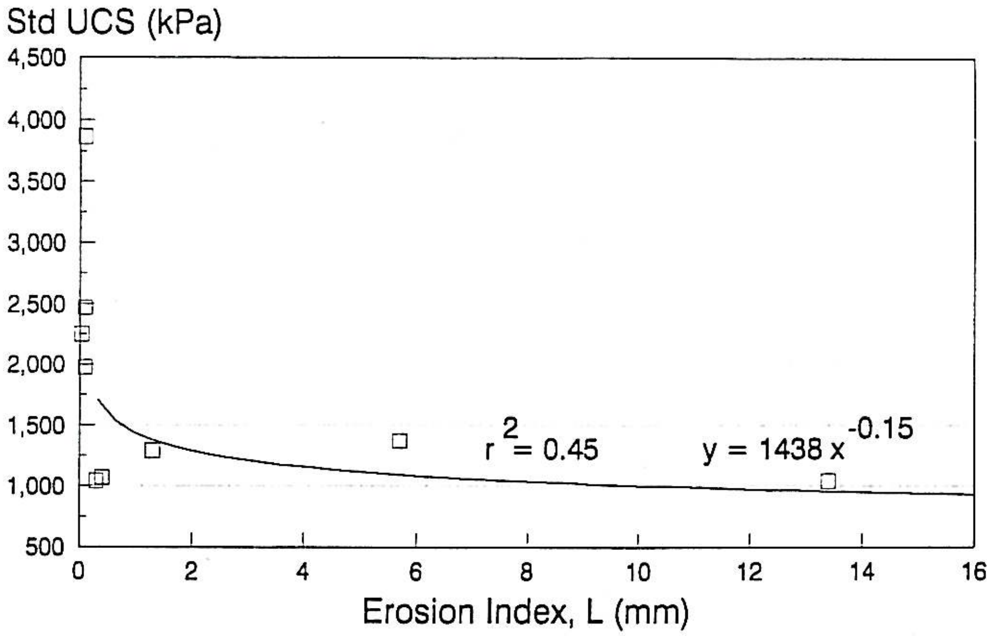

FIGURE A2.1: Std UCS vs Erosion Index for the cement treated materials

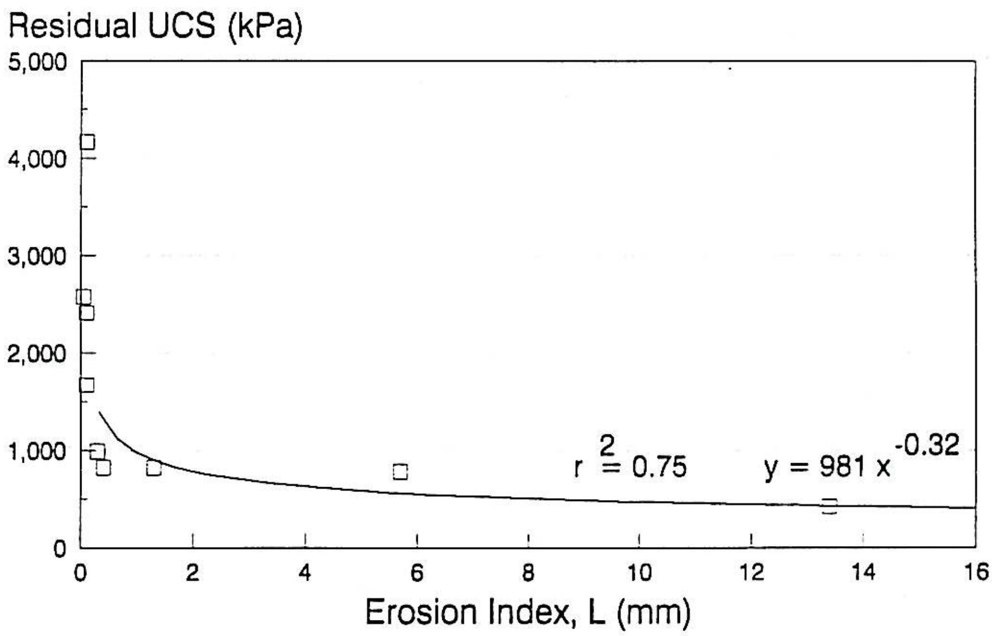

FIGURE A2.2: Residual UCS vs Erosion Index for the cement treated materials

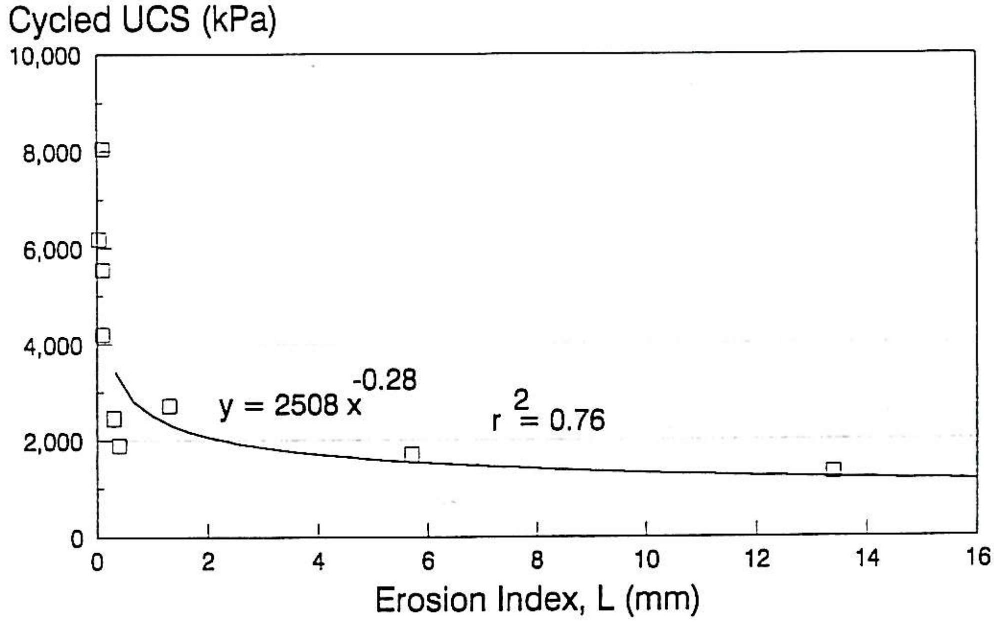

FIGURE A2.3: Cycled UCS vs Erosion Index

for the cement treated materials

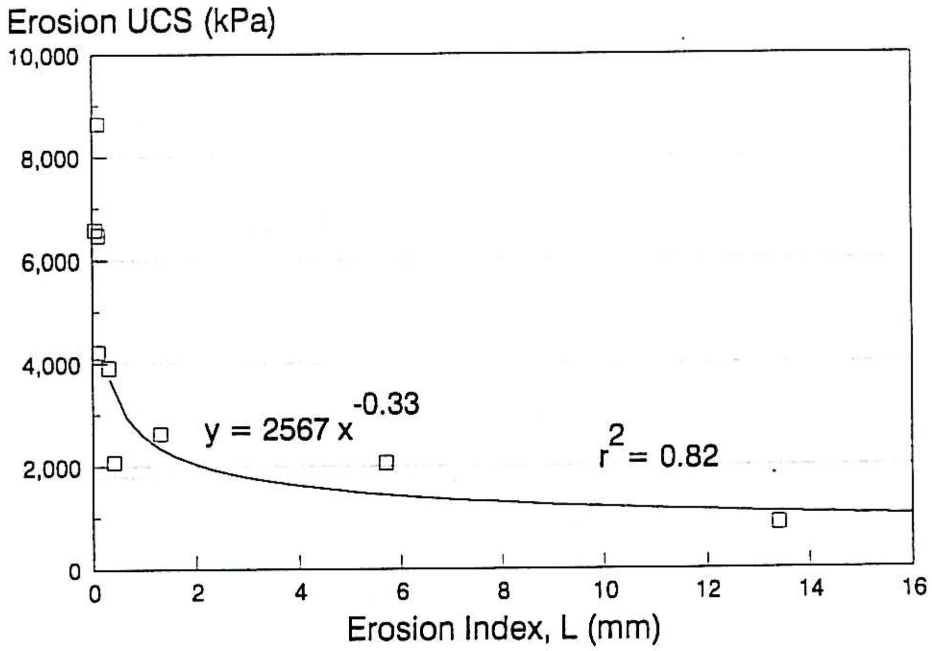

FIGURE A2.4: Erosion UCS vs Erosion Index

for the cement treated materials

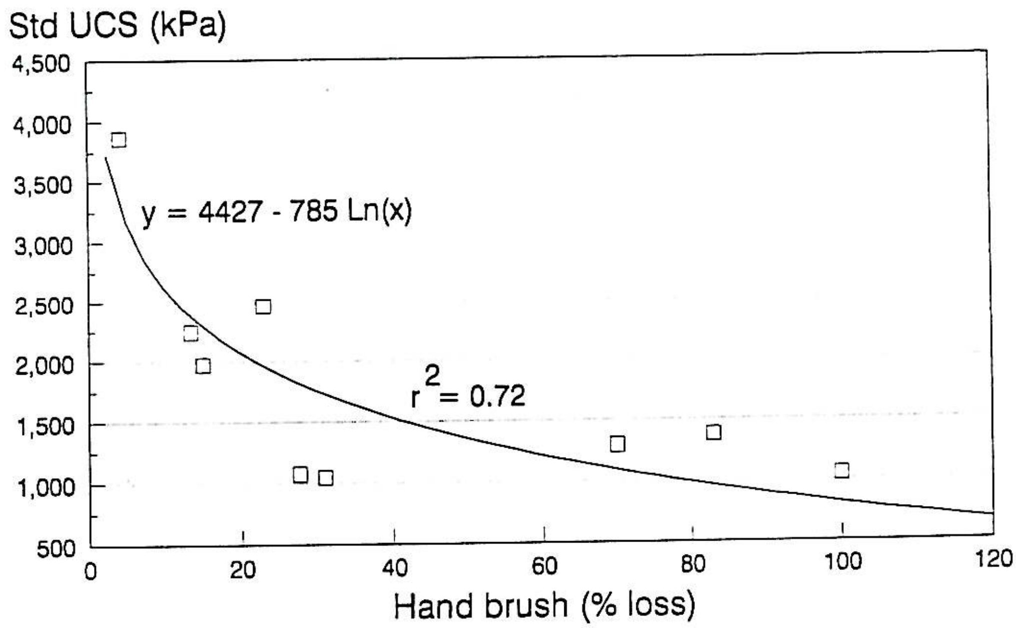

FIGURE A2.5: Std UCS vs Hand brushed loss for the cement treated materials

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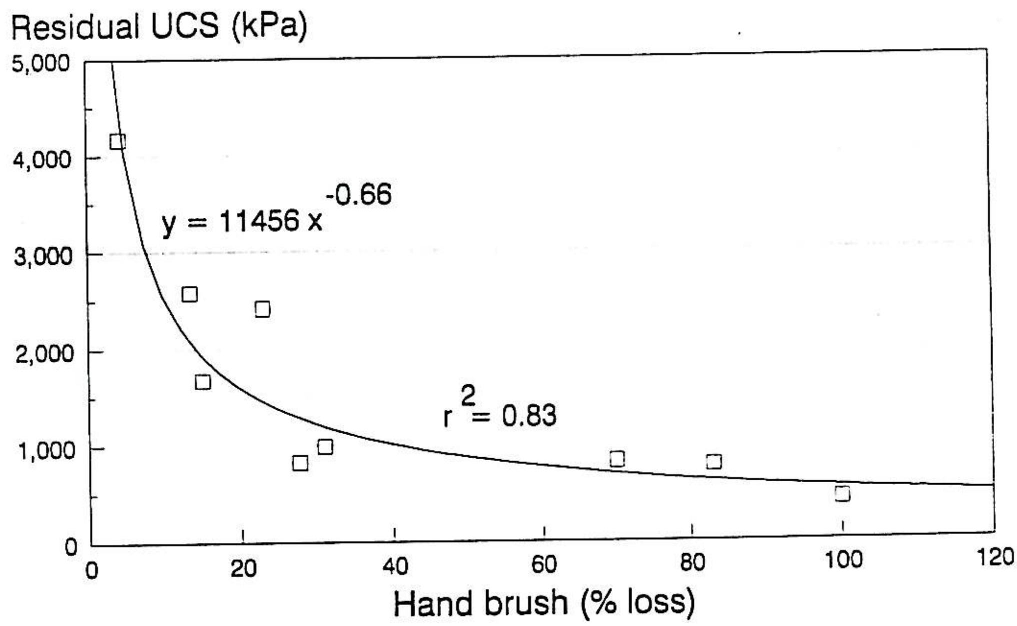

FIGURE A2.6: Residual UCS vs Hand brushed loss for the cement treated materials

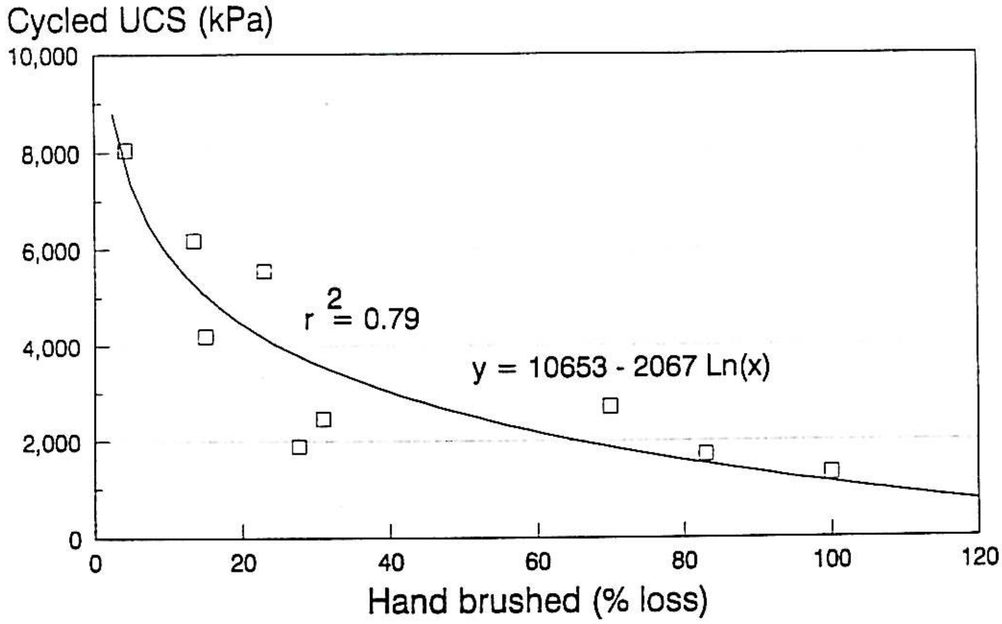

FIGURE A2.7: Cycled UCS vs Hand brushed loss for the cement treated materials

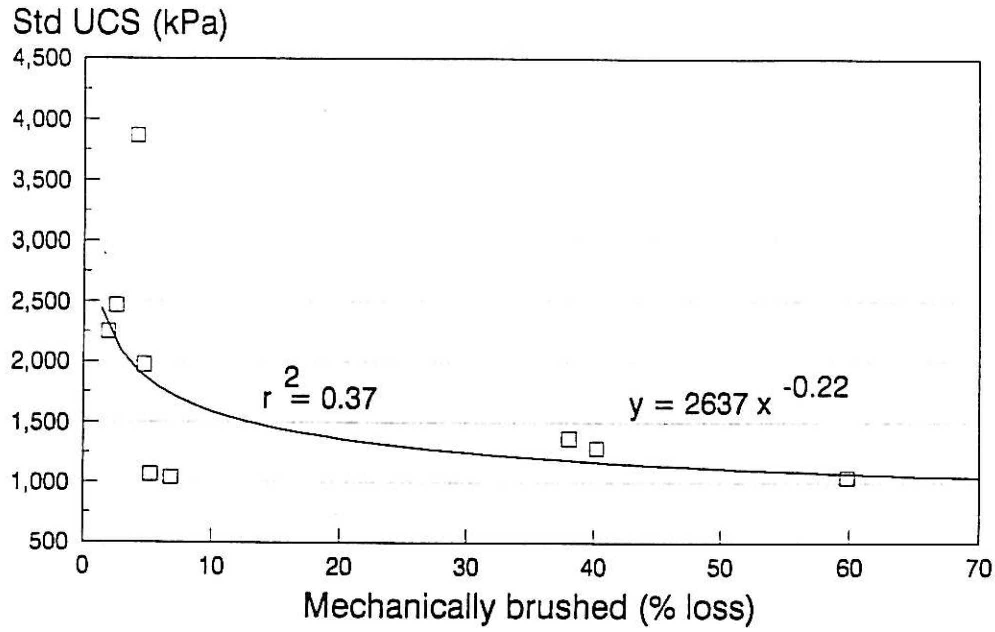

FIG A2.8: Std UCS vs Mechanically brushed loss for the cement treated materials

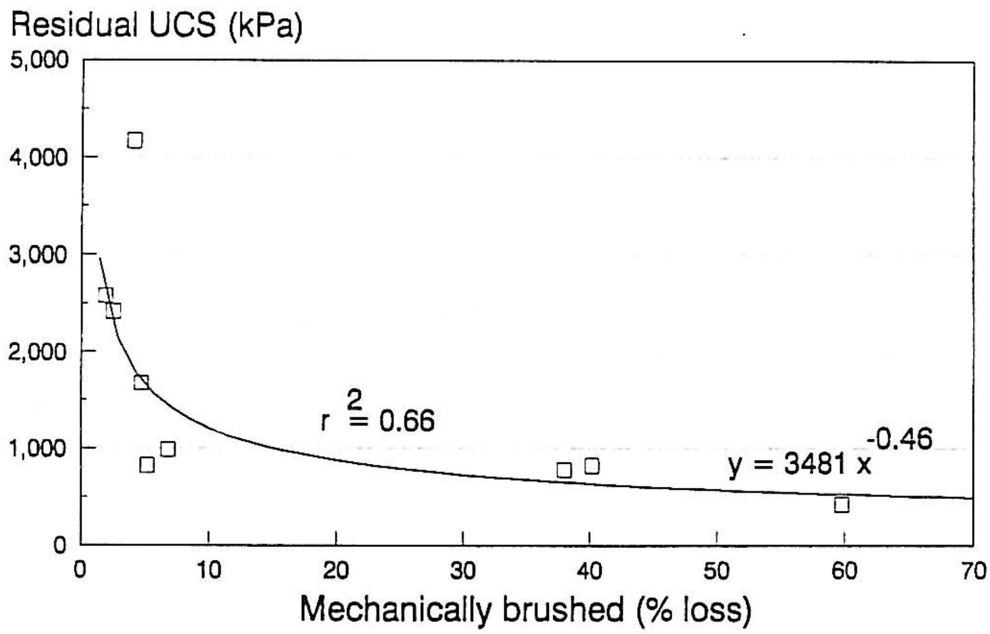

FIG A2.9: Residual UCS vs Mechanically brushed loss for the cement treated materials

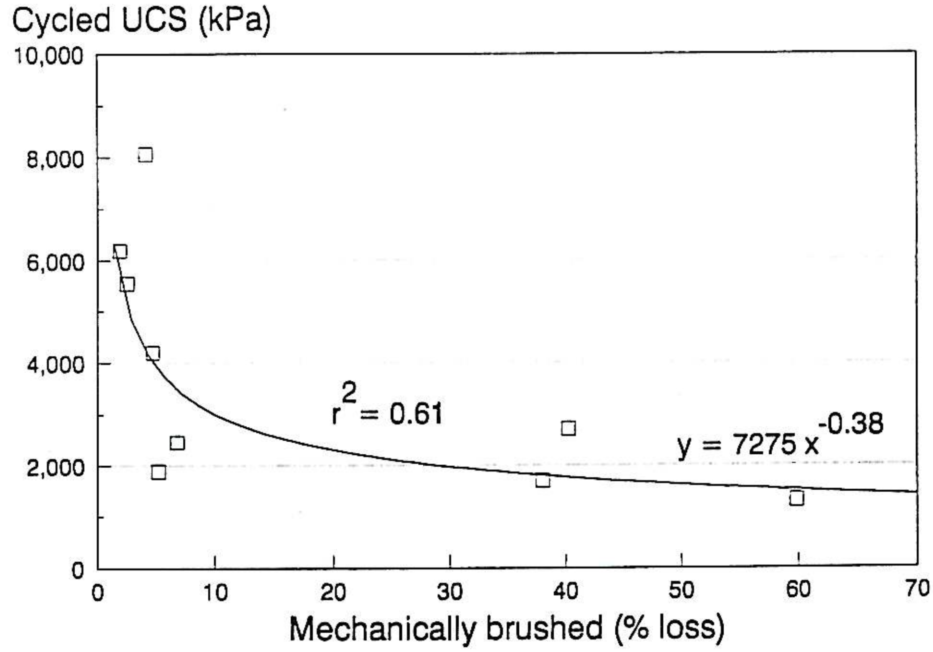

FIGURE A2.10: Cycled UCS vs Mechanically brushed loss for the cement treated materials

APPENDIX A3: GRAPHS OF THE UCS COMPARISONS

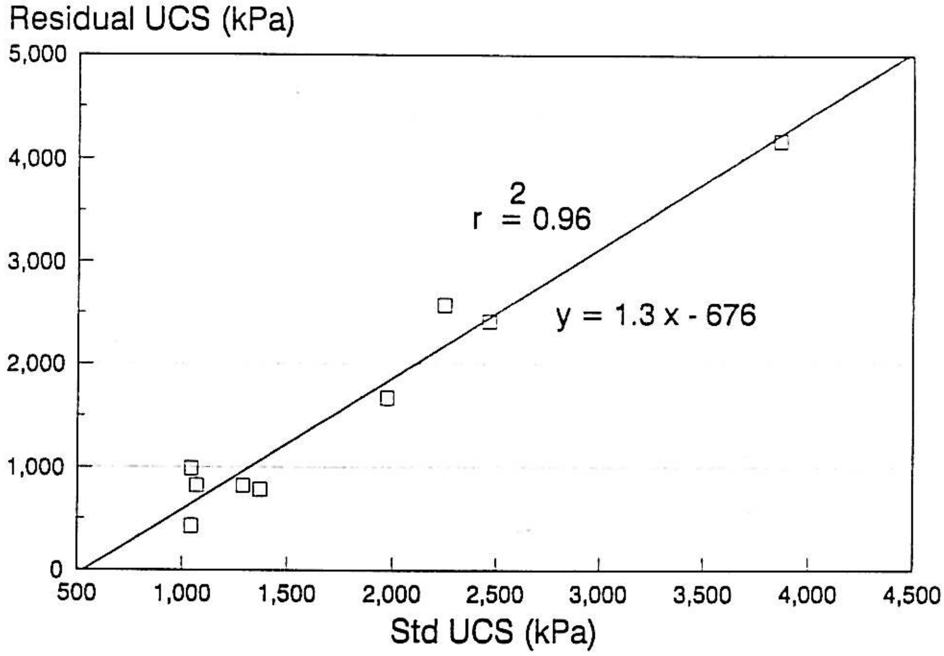

FIGURE A3.1: Residual UCS vs Std UCS for the cement treated materials

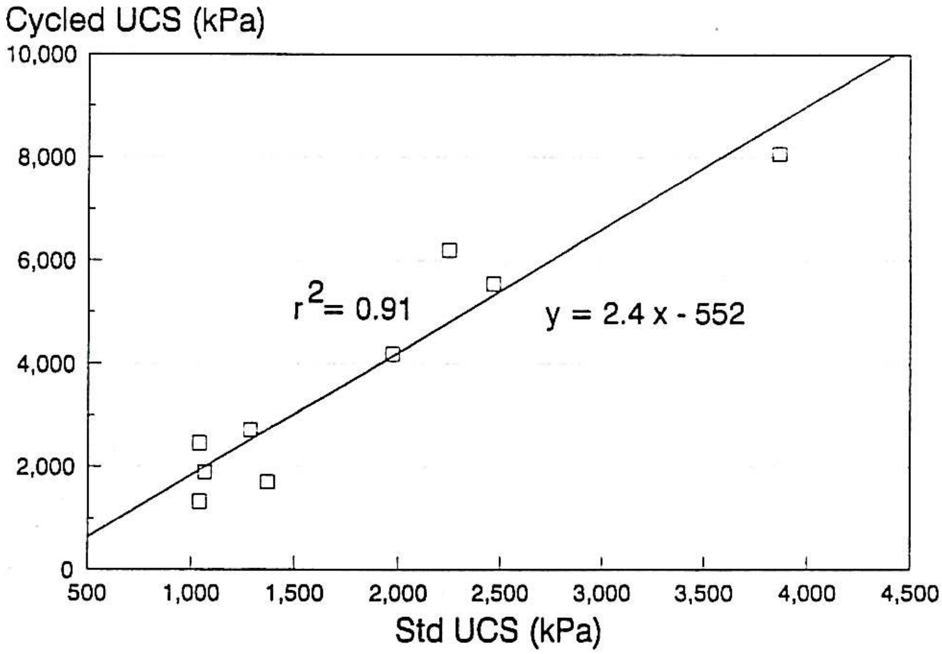

FIGURE A3.2: Cycled UCS vs Std UCS for the cement treated materials

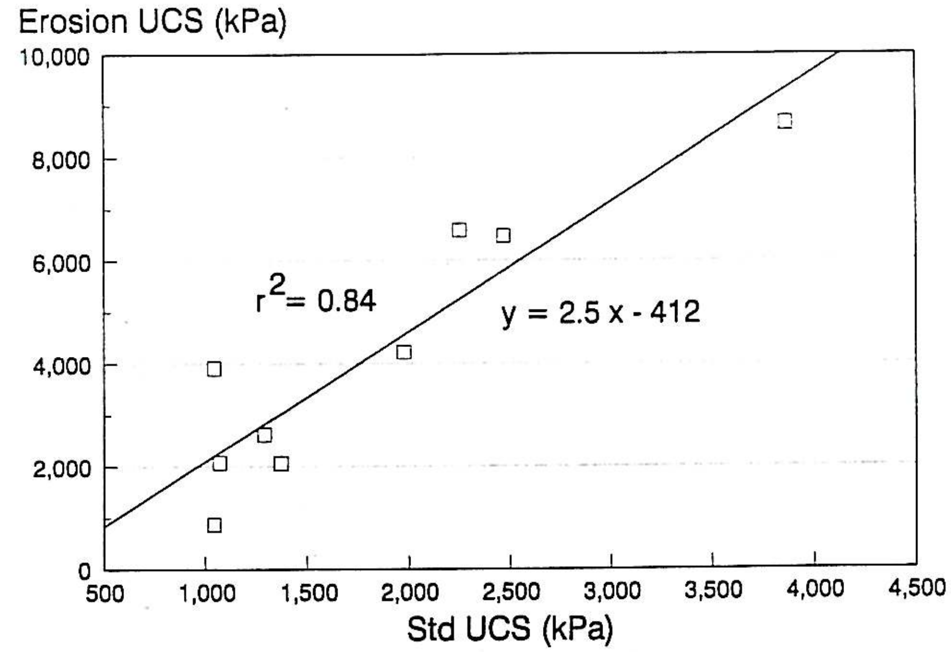

FIGURE A3.3: Erosion UCS vs Std UCS for the cement treated materials

---

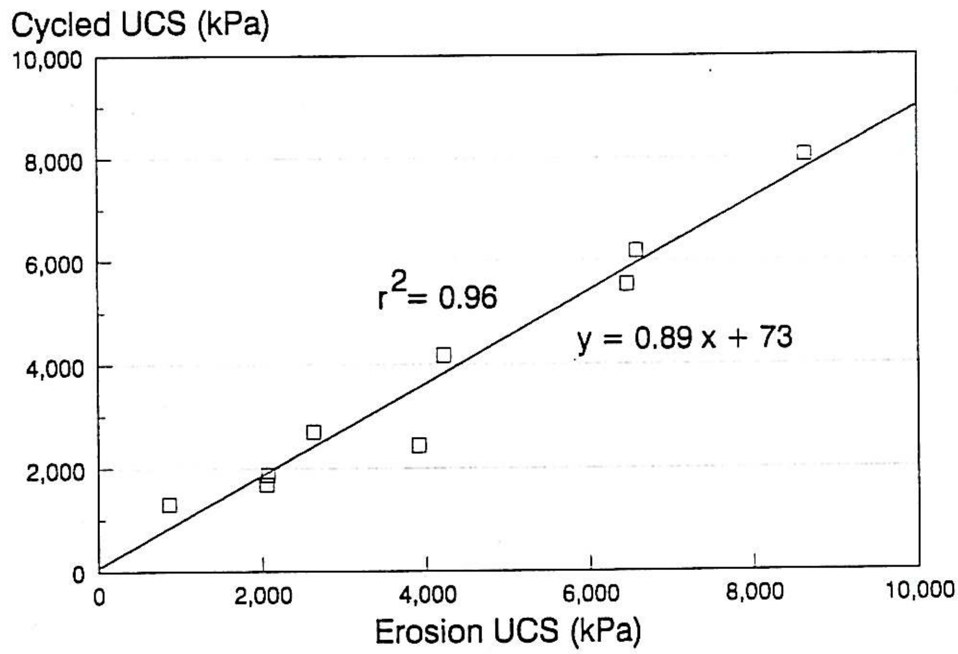

FIGURE A3.4: Cycled UCS vs Erosion UCS for the cement treated materials

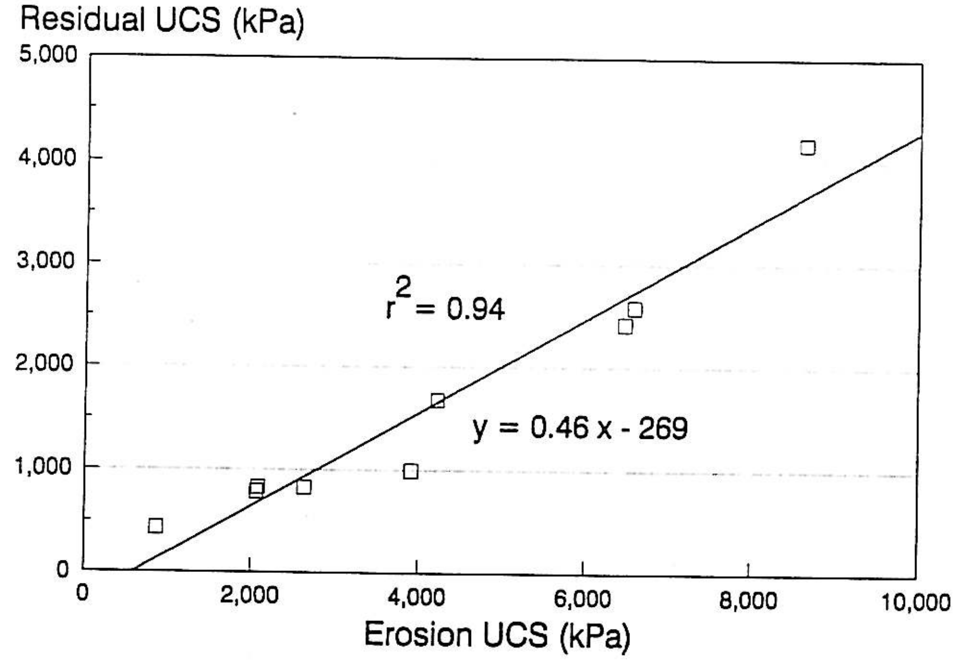

FIGURE A3.5: Residual UCS vs Erosion UCS for the cement treated materials

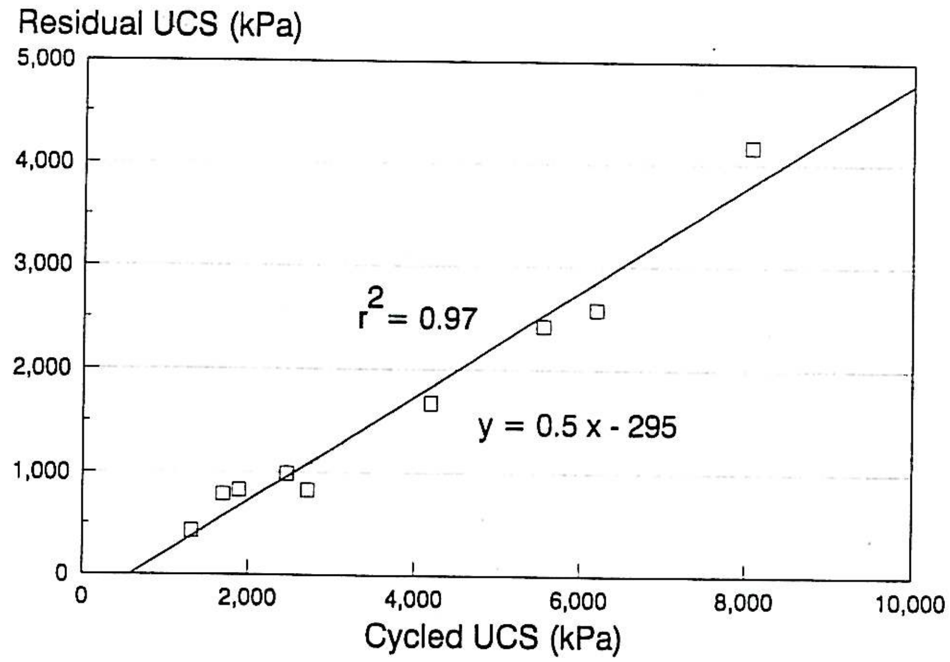

FIGURE A3.6: Residual UCS vs Cycled UCS for the cement treated materials

APPENDIX B: DoT EROSION DATABASE OPERATION MANUAL

THE DoT EROSION DATABASE MANUAL

INTRODUCTION

The DoT Erosion Database system is a computer program written as an addition to the Erodibility of Cemented Materials Report undertaken for the South African Roads Board (RR 91/167) by the Division of Roads and Transport Technology at the CSIR. The aim of the system is to collect data on erosion and durability testing undertaken in South Africa to gain further experience of erodible materials. As more data is collected, the system can be used in research to refine current durability testing criteria, it can track how materials in the field have performed over time and it can be used to investigate the relationships between durability and other material properties. For decision-makers it can be used as a check on new test results or in the place of additional testing.

This manual explains how the system is installed, how it is designed and how it is used.

INSTALLATION

The database requires the following hardware to execute:

- An AT286 or faster
- A hard disk with 1.5 Mb free disk space
- A 1.2 Mb floppy disk

To install the system:

- Insert the EROSION DATA BASE floppy disk into drive A.
- Type a:\INSTALL at the dos prompt and press ENTER

The installation program will create a directory on the hard disk called **C:\ERO** into which it will copy the program files. A batch file called EROSION.BAT will be copied into the root directory to allow the program to run from the root directory.

When the C:> prompt appears again, type **EROSION** to run the program.

PROGRAM DESIGN

The Erosion Database system is user-friendly and mostly self-explanatory. It is mainly menu driven ie the ARROW KEYS, ESCAPE and ENTER are the only keys necessary to control the program. If at any stage you require help, context sensitive help has been included into the program. To activate help press the F1 key.

Figure A1 shows the main features of each screen. The **instruction line** shows which menu is active or what the program is busy with. The **lower section** is used for data and menu display purposes. The last line indicates which keys are active on any particular screen.

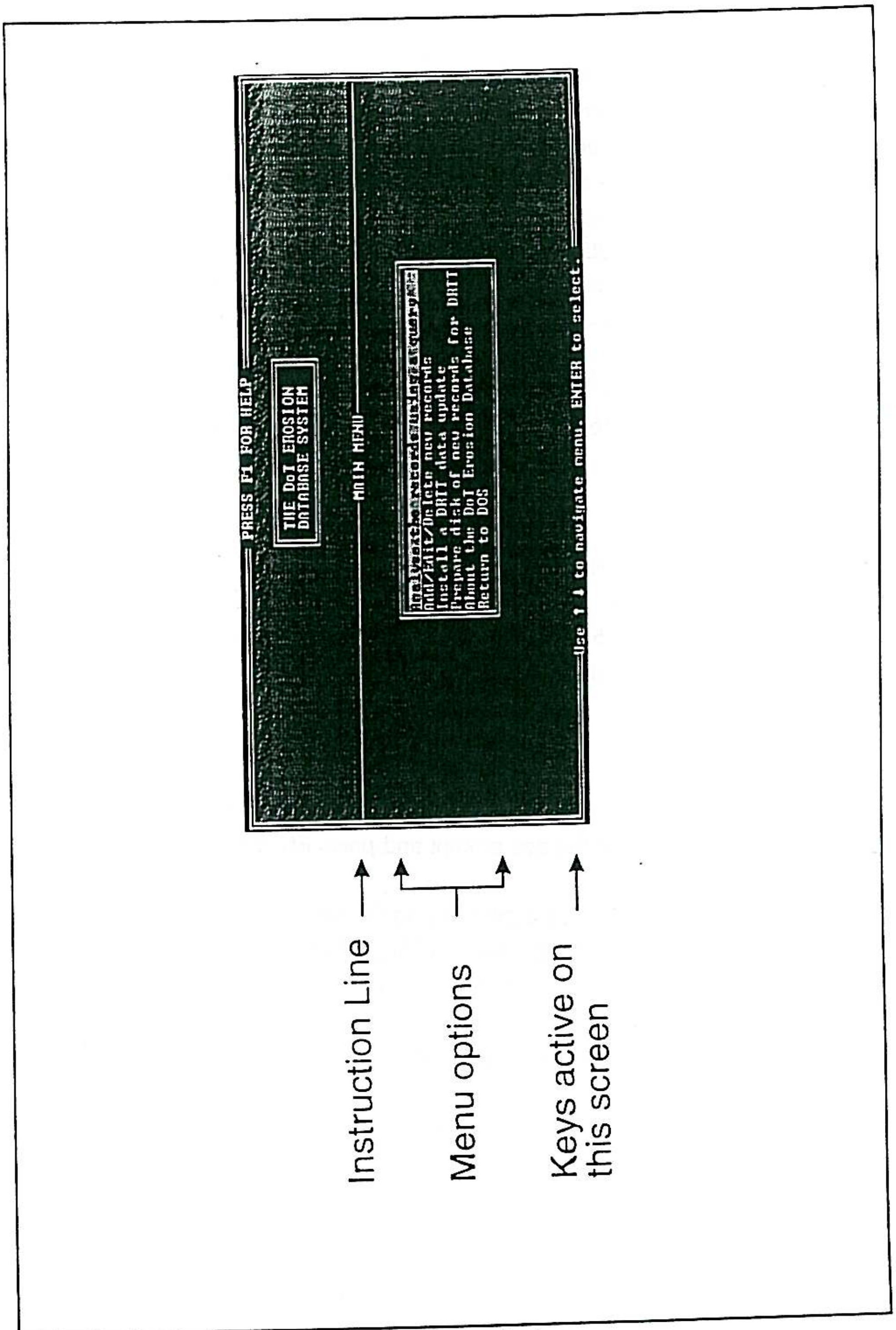

Figure A1: Typical Erosion Database screen display

The figure below is a diagrammatic layout of the program structure. Selecting a choice with the ARROW KEYS and pressing ENTER will take you to options lower down in the program. ESCAPE will bring you back up along the indicated paths in Figure A2.

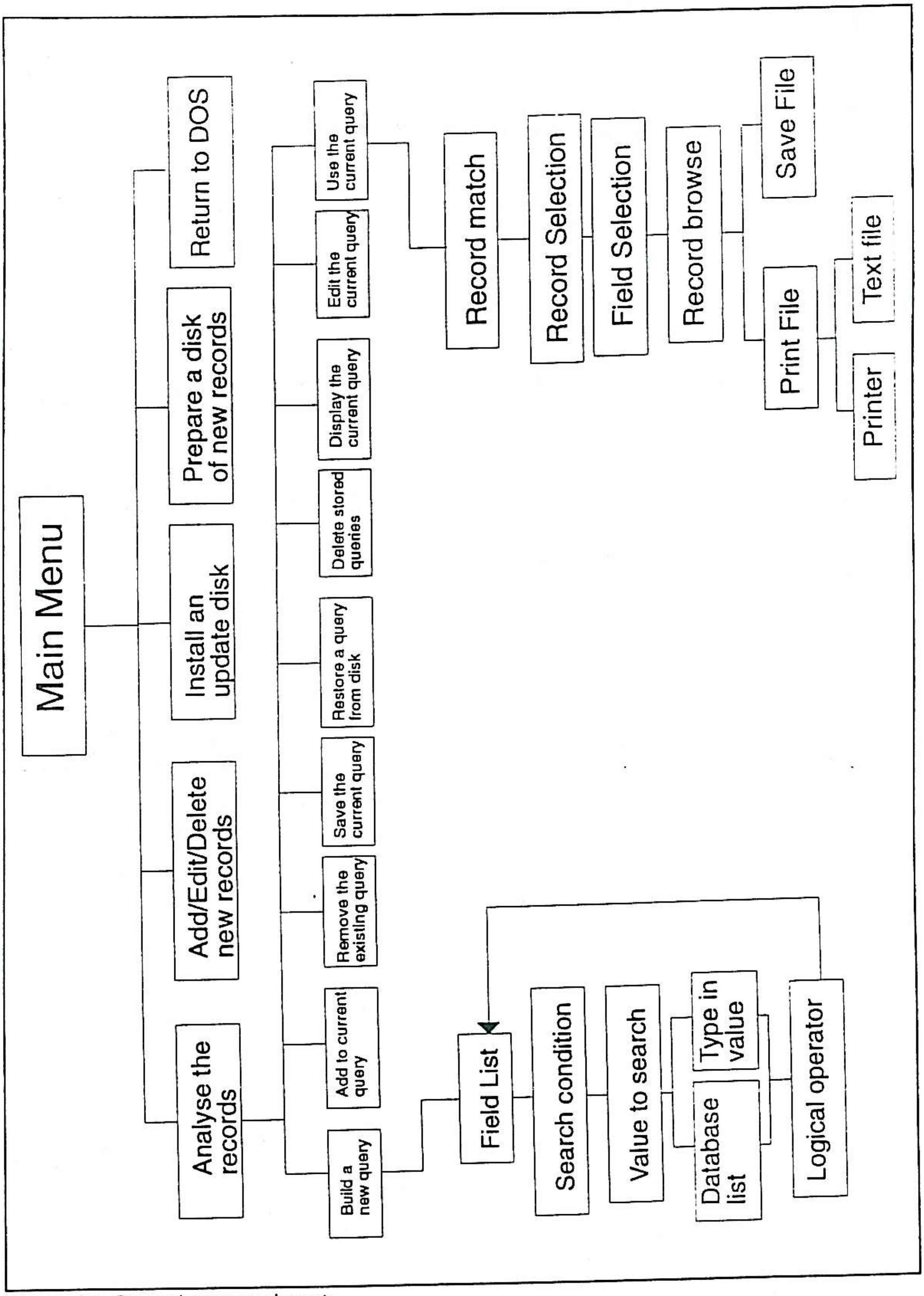

Figure A2: General program layout

NOTE : When operating the program it is impossible to destroy any of the DRTT master data file on your hard disk. Inadvertently pressing a key can always be corrected by pressing the ESCAPE key once. It is however possible to delete your own records which you have added in the ADD/DELETE/EDIT screen.

The following is a description of each of the options on the main menu. Indented sections refer to further choices made within each of these options. Refer to Figure B2 for a view of the program layout.

Analyse the records : This forms the main program body. It allows the user to locate records using a query condition. Once a group of records has been located they can be browsed. The user can then select records of particular interest from this group and print or save them to a file which can be imported into a spreadsheet package for further analysis.

> **Create a query to locate records :** By following the screen instructions it is possible to build up a query to locate records. Firstly the user is presented with a Field List (A field list contains some of the column headings in the database). A particular field is selected by moving the light-bar up and down using the arrow keys and pressing return on the field you wish to select. Next a list of operations will appear on the screen. An option is selected in the same way as before. The operations list is self-explanatory. After choosing the search condition you require, you can either extend the condition and follow the cycle again or choose "DONE" to end building the query. After creating the query you require you may use one of the other options on the "Create a Query menu".
>
> TIPS ON CREATING A QUERY.
> By knowing how the computer searches for records you will be able to locate the records you want easily. Because you can refine the list later, make your initial query as broad as possible. Once a search is complete browse the records. If there are too many records refine your query by adding to it. If you want all the records displayed select a query which is obviously true for records eg Grading Modulus(GM) ≥ 0 (The minimum is obviously 0 in the database).
>
> **Add to the current query :** If your query is too broad or too narrow you can extend it by selecting "Add to the current query". The process is very similar to "Create a query" ie select the field, select the search operation and then select the logical operator. If you do not have a query either restored or created you will obviously not be able to add to it.
>
> **Remove the current query :** To build a new query it is necessary to remove the current query from memory. If you wish you can save a query using the save option.
>
> **Save a query to disk :** Once you have created a query or added onto an old one, you can save the query to disk so that you do not have to retype it at a later stage. This is useful if you are monitoring similar queries over time.

Restore a query : Once you have saved a query you can retrieve it by selecting this option.

Delete a query : This option allows you to delete previously saved queries.

Display a query: Use this option to check that the query the computer is using will not omit any records you want in the group.

Edit the current query : If, after displaying the query, you discover that one of the values is incorrect or you would like to change it, you can edit the query. It is also useful if you want to build up more complex search criteria.

Use the query : Once you have either restored a query or created a new one you can select this option to locate the actual records. The counting process is fairly time consuming depending on the speed of your machine. Once the database has been searched, the records which matched your query are presented in a browse table on the screen. You can then view these records using the arrow keys.

At this stage all the records and fields are presented. You can mark specific records on this list to narrow it down to records in which you are particularly interested. You do this by pressing SPACE on a particular record. To select all the records in the list, simply leave all records unmarked and press ENTER. You are then presented with a field list to select which specific fields you want to view. The fields and specific records are then presented in a new browse table.

When you press ENTER from the second browse table you will be offered the chance to save the selected records to disk or to print them. To **save** the records, select the save option from the output menu and give the records a filename consisting of LETTERS ONLY. This will then be saved in the **C:\ERO** directory where the EROSION DATABASE SYSTEM was installed with a **.dbf extension.** This file can then be imported into a spreadsheet package eg LOTUS 1-2-3 or Quatro Pro after running their TRANSLATE facilities (For more information consult your spreadsheet handbook on translating .dbf files).

To print out the records and fields you selected choose **Print out the records** from the output menu. You will be offered the choice to print the records to a text file or to a printer. A **text file** is an ASCII file with a .TXT extension which can be included in your other documents. After selecting **print to text file**, supply a filename when prompted and press ENTER. Selecting the **Printer** option sends the output directly to a local printer. To use the text file in a wordprocessor select a non-scalable font such as courier and set the line spacing 1 to ensure the print-out is correct.

Add/edit/delete a record : If you work with erosion or material testing and are able to contribute records to the central erosion database select this option to input data. The data you input here will also be queried during a search so that you can isolate particular records. If you are going to process your results input as much of the information as possible into the database and then locate the records using an appropriate search condition. Save these particular records and take them into a spreadsheet for processing. By doing this you will automatically collect records which can be sent to DRTT to update the national database. Your disk will then be returned to you with a country wide update.

It is important to remember the following points when inputting data. The heading of each column gives a description of what is expected in each field. There are two types of data in the database: numeric fields and character fields. All numeric fields have 0.0 values to begin with and will not accept characters. Where it is appropriate, the heading of a numeric field indicates the units required. Character fields can accept any letters or values. Letters typed in are automatically converted to upper case to simplify search procedures. When filling in a character field make the description as meaningful as possible. If you have any doubt what should be inputed at each field, consider how another user might want to retrieve this data using a query.

When a new record is created in the database, it is automatically dated in the first column. This column is frozen on the screen when inputting the rest of the record. Using the date is a useful way of keeping track of a record. The record number, given in the top, right corner of the browse table, is also useful for this purpose.

There are a number of features which can speed up data inputting. Once a record has been created (indicated by the number of records in the right corner of the browse) the block above a certain field can be copied by pressing ALT-C. This is useful when a number of records have similar fields. For example, in a batch of tests the material descriptions and properties may be the same and the Erosion result and percentage stabiliser differs. Instead of retyping the descriptions the values can be copied by pressing ALT-C.

If you wish to remove an entire record, press DELETE when you do not have input focus. Input focus is indicated by a flashing cursor in one of the highlighted blocks and is activated by typing a character. Once DELETE is pressed you will be asked to confirm that you want the entire record deleted. Press **N** if you do not want the record deleted and **Y** if you do.

If you make a mistake while typing pressing DELETE will remove the character at the cursor. By pressing INSERT the cursor will toggle between overwrite and insert mode. Insert mode is indicated by a flashing block cursor (inputed characters are inserted between existing characters at the cursor) and overwrite is indicated by a flashing line cursor (inputed characters overwrite existing characters from the cursor position).

When you press ESCAPE input focus is de-activated. Pressing it again will automatically save the records and take you back to the main menu.

Prepare a disk to send for update : Once you have sufficient records in your own database, select this option to prepare a disk to send to the DRTT. Insert a EMPTY disk into drive A and press ENTER. Please send this disk to:

EROSION DATABASE SYSTEM
DRTT, CSIR
P.O.Box 395
Pretoria
0001

This disk will then be returned to you with the update records.

Install an update : When you receive an update disk select this option and follow the screen instructions. Insert the update disk into drive A and press ENTER. The new records will then be added to the main database file. The process is time-consuming, depending on the speed of the machine. The records in the update file are first compared with the records in your own database. Any duplicates are deleted from your collection of records. The update file is then checked against the master data file to ensure that no duplicates are added. The new records are then appended to the master data file on your disk.

About the Erosion database: This is information on the program release date and version number.

Return to Dos : To exit the program and return to the DOS prompt select this option.

REPORT OF PROGRAM ERRORS

Although every effort has been made to test the program on a variety of machines, it is still possible that it the version supplied may crash when running on your system. If your program does not function correctly, please make a copy of this form, fill in the details and return it to:

DRTT: The Erosion Database
P.O.Box 395
Pretoria
0001

Hardware Description

Computer Make:____

CPU speed(286,386 etc):____

Free memory on your harddisk at present: ____________________________

Error Description

Menu name where error occurs:____________________________________

____

Describe the attempted operation:____________________________________

____

____

____

____

____